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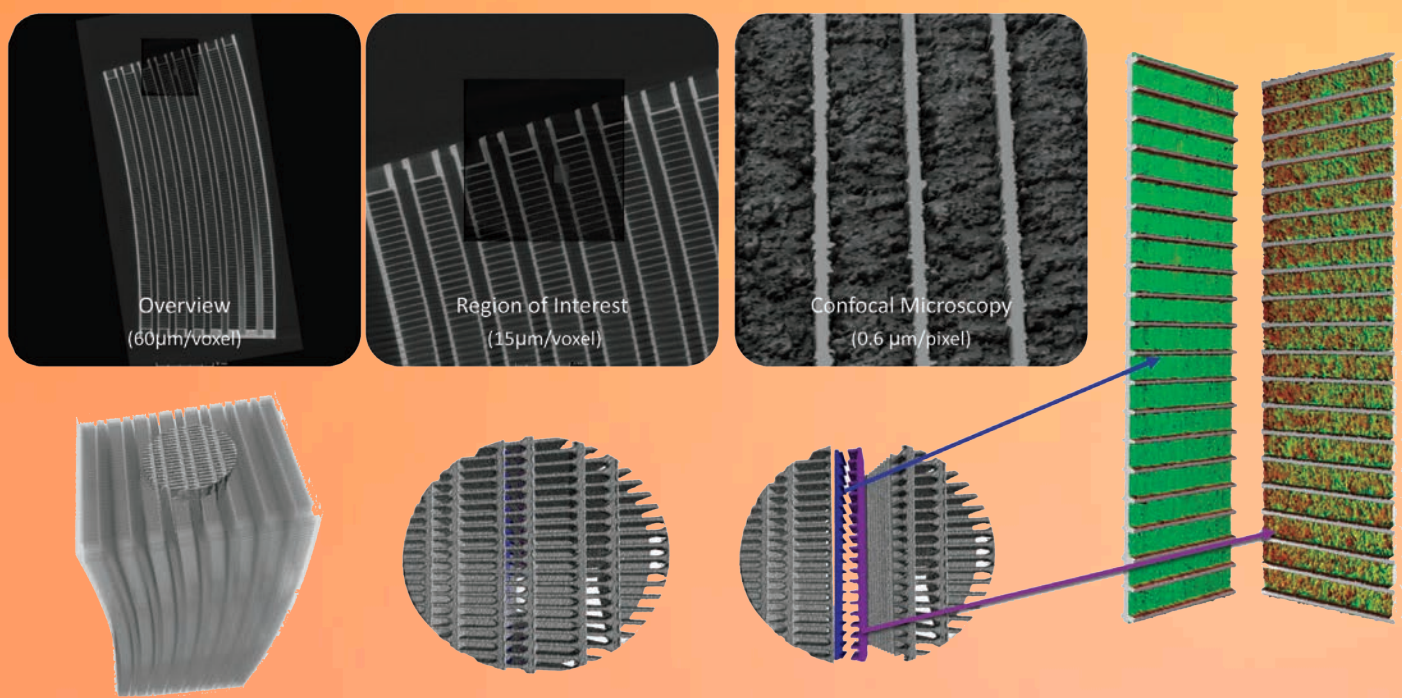
NDE for Additive Manufacturing



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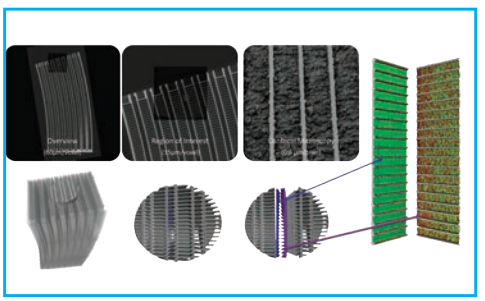

"2D Cross Section CT Scans with increasing resolution of a 3D printed fin and plate heat exchanges."

OBJECTIVE - This Journal of Non Destructive Tesing & Evaluation (JNDE) is published quarterly by the Indian Society for Non Destructive Testing (ISNT) for promoting NDT Science & Technology. The objective of this Journal is to provide a forum for dissemination of knowledge in NDE & related fields. Papers will be accepted on the basis of their contribution to the growth of NDE Science & Technology.

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LETTERS

PRESIDENT TALK



PROF. KRISHNAN BALASUBRAMANIAN

Dear Friends

On behalf of the newly formed National Governing Council, I extend a warm welcome to everyone. I am delighted to reflect on the remarkable progress and achievements of the Indian Society for Non-Destructive Testing (ISNT) over the past year.

Through a series of workshops and training & certification programs, we have facilitated the exchange of knowledge among professionals across the country. The resounding success of NDE 2023, marked by record participation from all spheres, highlighted ISNT's ability to showcase the NDE community's strength and innovation to a broad audience. The increasing participation from industry in NDE 2023 is a positive sign of ISNT's progress and inclusiveness. The feedback has been overwhelmingly positive, making the event as a crucial platform for networking and professional growth in NDE.

The March issue of the Journal of Non-Destructive Evaluation (JNDE) on NDE in Additive Manufacturing features papers that address the unique challenges and opportunities in inspecting additively manufactured components. This special issue provides valuable insights into NDE methods crucial for ensuring the integrity and reliability of these components.

JNDE continues to make steady progress in the quality of its articles and the release of special issues on relevant and futuristic technologies. This series of special issues reflects ISNT's ongoing effort to make the journal interesting and valuable for its readers.

I extend my heartfelt gratitude to all ISNT members and stakeholders for their unwavering support and look forward to our continued journey of excellence and innovation.

Prof. Krishnan Balasubramanian
President
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MANAGING EDITOR TALK



BIKASH GHOSE

Greetings from Indian Society for Non-destructive Testing.

We at ISNT are delighted to bring out a special issue of the Journal of Non-Destructive Testing & Evaluation (JNDE) on an interesting domain "NDE for Additive Manufacturing." This issue features six original invited technical papers in this very promising area of Additive Manufacturing (AM) and also one contributory paper on canned pulsed eddy current testing sensor for creep measurement. The invited papers delve into the capabilities, advantages and limitations of radiography and ultrasonic testing techniques for the assessment of defects and reliability evaluation of NDT application for additive manufactured components. Papers also discusses about NDE in assessing the quality of AM fabricated carbon and nanocomposites, Machine Learning and use of X-ray CT & Resonant Ultrasonic Spectroscopy in AM components.

I would like to express my sincere gratitude to our guest editor, Dr. Phani Maylavarapu from DMRL, DRDO, Hyderabad for his sincere efforts in shaping this special issue on NDE in Additive Manufacturing.

In addition to the technical contributions, this issue also provides a brief report of hugely successful NDE 2023 held in Pune in last December. The vibrant activities of ISNT chapters over the past three months are also placed.

Once again, my heartfelt thanks to the guest editor, the authors, advertisers, and our readers for their continued support. I hope this special issue serves as a valuable resource for researchers, practitioners, and enthusiasts in the field of non-destructive testing.

Bikash Ghose
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GUEST EDITOR'S TALK



DR. PHANI SURYAKIRAN

The rapid growth being observed in the field of additive manufacturing (AM) is pivotal for fulfilling the requirements of Industry 4.0. Inspite of its tremendous potential, numerous challenges for non-destructively qualifying different forms of additively manufactured components exist and as we speak more and more studies are being carried out to fulfill them. In this special issue focusing on "NDE for Additive Manufacturing," an attempt is made to briefly delve upon the core facets of issues while performing NDE in AM.

The special issue covers six interesting articles on detection capabilities of radiography and ultrasonics for AM components, applications of resonant ultrasound spectroscopy for assessment of anisotropic elastic properties in AM components, a brief overview of in-situ and ex-situ NDE techniques for AM composites, applications of computed tomography technique for characterization of powder to components, and future perspectives of NDE in the era of AM and machine learning in AM and reliability of AM components. Needless to say that we have barely scratched the surface in this ever exciting field of NDE of AM. More and more deliberations are the need of the hour and may be topics of further issues in this Journal of NDE.

A special thanks to all the authors for contributing these interesting articles. I am extremely delighted to read each and every article and hope the readers of this special issue will experience the same.

Dr. Phani Suryakiran
Guest Editor, JNDE Special Issue
on NDE for Additive Manufacturing
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CHAPTER ACTIVITIES

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EC Member meeting Dated 27.01.2024

Bengaluru

Other Activities :

Preparation and meeting with respect to NDE 4.0 International conference scheduled during March 2025 at Bengaluru.

Kolkata

Other Activities :

EC Meeting held on 30th December 2023: Discussion on TMB Audit Forming a team for addressing various issues for Audit purpose.

EC Meeting held on 7th February 2024: Regarding Amalgamation Deed for development of Chapter office along with all adjacent building

Pune

Courses & Exams conducted:

Level II VT Training course was conducted for TUV NORD on 8th, 10th and 17th of September 2023.

Other Activities :

NDE 2023 was successfully conducted between 7th to 9th December 2024 at Pune along with ISNT HO. The total delegate registration was 926. Exhibitors were 85. Non exhibition Sponsors were 22. Total footfall for the exhibition was 1400+.

1st Executive committee meeting for the tenure 2023-2025 was held on 17.01.2024.











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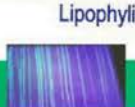

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TECHNICAL TALK :

Workshops / Invited lectures:

- 05-12-2023 - Industrial - Safety An essential vision for better world.
- 12.12.2023 - Building a Sustainable Culture of Online Safety.
- 19.12.2023 - National Energy Conservation DAY.
- 26.12.2023 - 7 habits of highly effective people.
- 02.01.2024 - Farm Mechanization in India: Exploring the Status and Opportunities for Increased Income in Indian Farms.
- 09.01.2024 - Logical reasoning in Artificial Intelligence.
- 18.01.2024 - Sustainable Electronics.
- 23.01.2024 - Bamboo in Architecture & to develop rural students & Clients.
- 03.01.2024 - Job Safety & Its Hazards Analysis - J S H A and Its Training Awareness.
- 06.02.2024 - New trends in Sports wear - construction & features

Other Activities :

EC Meeting conducted:

- 30.12.2023

Membership addition

- 05 life members
- Annual General Body Meeting conducted on 04.02.2023

Vadodara:

TECHNICAL TALK :

Workshops / Invited lectures:

On 07-February-2024, ISNT Vadodara Chapter had organized an evening lecture on topic "Significant Advances in Surface NDT Methods" at Hotel Tarasuns, Vadodara.

Around 105 participants had attended the evening lecture.

The Evening Lecture was jointly organized by Indian Society for Non-Destructive Testing – Vadodara Chapter, The Indian Institute of Welding – Baroda Branch and Baroda Management Association.

The Evening Lecture was sponsored by M/s. MR Chemie India Pvt. Ltd.

Mr. Kashyap Bhatt (Hon. Secretary – ISNT Vadodara Chapter) was the convener of the program.

Shri Deepak Acharya (President: The Indian Institute of Welding – India) had graced the occasion as the Chief Guest speech during inaugural session of the program.

Shri Manoj Shah (President: Baroda Management Association) also addressed the gathering during opening session of the program.

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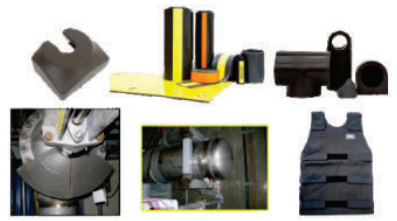

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CHAPTER ACTIVITIES











Other Activities :

Third EC meeting of ISNT Vadodara Chapter was had at Alembic Food Court, Alembic Colony, Vadodara on 19-January-2024.

Following Programs have planned:

1. An evening lecture 07-February-2024. Jointly conducted with IIW – Baroda Branch and Baroda Management Association.
2. Workshop on 'Radiography Film Interpretation' on Date: 24-February-2024. Venue – ISNT Office.
3. Workshop on 'Phased Array Ultrasonic Testing' in second week of April-2024.

ISNT Vadodara Chapter has planned to organize one day Workshop on 'Radiography Film Interpretation'. Date: 24-February-2024. Venue–ISNT Office. Mr. Nimay Ginwalla (Hon. EC Member – ISNT Vadodara Chapter) will be Convener of the Workshop. Participation Certificate will be issued to all the participants.

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CHAPTER ACTIVITIES

Mumbai

Courses & Exams conducted

NDT Radiography Testing Level III Training Program was conducted Hybrid Mode (Physical / Online) **30th Jan, 2024 - 08th Feb, 2024.** 10 Candidates

NDT Ultrasonic Testing Level III Training Program was conducted Hybrid Mode (Physical / Online) **19th Feb, 2024 - 28th Feb, 2024**. 19 Candidates

Technical Talk

Webinar 01/2024 (Virtually)
Topic : Penetrant Inspection System Performance Check in Aerospace Industry **20th Jan, 2024 ,Speaker : Mr. Shakti Singh Lead - Corporate NDT**

Technical Talk 01/2024 (BARC)
Topic: Salient Features in construction Of Mumbai Trans Harbour Link (MTHL) Atal Setu Project. **Date : 14th Feb, 2024, (Speaker : RAJARETHINAM P. Head Quality in MTHL Pkg 1)**

Other Activities

EC Meeting (ISNT Mumbai–Andheri) : **06th Jan 2024 :**15 Members
EC Meeting (BARC-Anushakti Nagar) : **14th Feb. 2024 :** 11 Members

Technical Talk 01/2024 (BARC)









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- Pipe Testing
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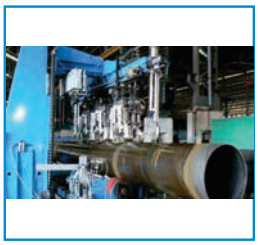
- Component Testing





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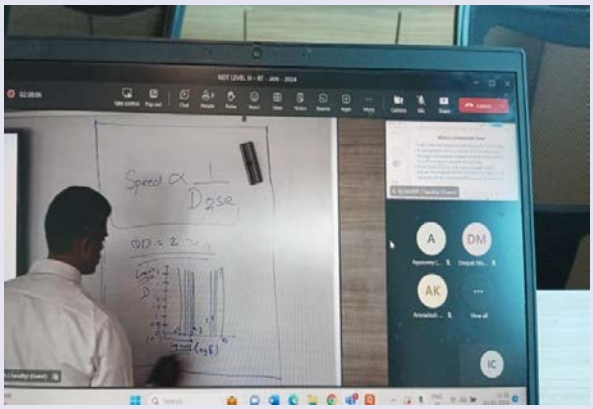
CHAPTER ACTIVITIES

TRAINING AND CERTIFICATION





EC MEETING













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TRAINING MANAGEMENT BOARD

Training Management Board (TMB) – ISNT

The Training Management Board (TMB) was officially formed by ISNT in February 2022 to act as a nodal agency to address all NDT training related activities (which lead to formal certification as Level 1, 2 or 3 personnel under IS 13805 and ICN schemes of ISNT). Over the period of nearly 23 months since its formation, TMB has made good progress on several fronts by creating multiple Task Forces focussing on different tasks including creation of harmonized timetables, Training material for course instructors, Course notes for trainees, Question Bank / Mockup exams, Train-the-Trainers programme. The other major activity which was the focus of TMB was to establish a robust process with appropriate guidelines, mechanisms and teams to establish Authorized Training Centres (ATC) of ISNT across the country (and later abroad) who can conduct effective and harmonized training courses for both the schemes in all the NDT methods at all Levels of certification. This was achieved by the dedicated Task Force set up for the purpose under the leadership of "Controller of Authorization". The "Call for Applications" from interested entities for Full Authorization as an ATC valid for 5 years through an audit and assessment process was announced and we welcome all to take advantage of the same.

As of November 2023, we have 4 ATCs authorized for both IS 13805 and ICN schemes and 5 ATCs for IS 13805 only. Details of these ATCs can be found at https://isnt.in/tmb/list-of-atcs-icn.php & https://isnt.in/tmb/list-of-atcs-is13805.php

Through TMB's focused efforts, it envisages a standardized and harmonized training system to be in place in the near future which ensures a world class NDT training ecosystem in all aspects.

We also welcome volunteers to join and contribute to TMB activities in whatever way they can to help accelerate the fulfilment of our objectives.

To learn more about TMB and its activities please visit https://isnt.in/home/index.php

For any queries related to TMB, please send an email to tmb@isnt.in

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PROGRAM FORMULATION AND MANAGEMENT BOARD (PFMB)

I wish to inform you that the Program Formulation and Management Board of ISNT (PFMB) has been constituted with Shri V. Manoharan as the Chairman, Dr. Deepesh Vimalan as Hon. Secretary and 14 technology/industry experts as members of the board.

PFMB has formed 4 technology groups –Radiological Imaging, Electromagnetic NDE, Thermal Imaging, and Acoustic NDE and Chairman for each working group were identified.

Office Bearers

Shri V. Manoharan, Chairman

Shri Deepesh Vimalan, Hon. Secretary

Members :

Dr. Anish Kumar
Dr. S. Thirunavukkarasu
Mr. A.K. Das
Dr. Phani Suryakiran
Mr. Bhausaheb Pangare
Prof. Prabhu Rajagopal
Dr. Menaka
Prof. Kavitha Arunachalam
Mr. P. Vijayaraghavan
Prof. Ravibabu
Mr. Komma Reddy Vamshi
Dr. Debasish Mishra
Mr. Umankanthan Anand
Shri Girish Namboodri

Ex-Officio Members

President -ISNT
Hon. Gen. Secretary -ISNT
Hon. Treasurer ISNT

Invitees

Chairman-NCB
Chairman -TMB
All Vice Presidents - ISNT

Objectives

The main Objectives of PFMB are as follows:

- To conceptualize, formulate and organise various non-certification programs such as Webinars, Workshops, Conferences, Seminars etc. to create platform for constant interaction with ISNT members, meet the requirement of industry, academia and research community.
- To interact with other international NDT societies, National technical societies to formulate and organise joint programs.

Scope

- To plan and organise two annual conferences of maximum 2 days' duration (other than NDE) and execute through an organizing committee nominated by PFMB
- To conceptualize, formulate and execute programs such as Webinars, Workshops, Conferences, Seminars etc. of relevance to the NDT community to be organised by ISNT throughout the year across the country.
- To publicize the proposed program
- Develop and implement mechanism for executing the programs along with ISNT Chapters or independently (only if no chapter is interested).
- Create various topical working groups within PFMB and formulate programs as stated above for meeting specific requirement.
- To connect with various industries / institutes and formulate program to meet the specific needs
- Interact with international NDT societies (ISNT partner societies with MOUs) for conducting joint programs, pre-dominantly Webinars
- Interact with national technical societies for conducting joint programs
- Establishing a model for sustained revenue generation for continued operations and growth of PFMB

Program Formulation and Management Board (PFMB) with the technical working groups are progressing well under the scope of PFMB.

First Programme of PFMB :

Topic : "2D/3D Industrial Radiological Imaging and it's Applications"

The first ever PFMB workshop was conducted successfully by ISNT Thiruvananthapuram Chapter on August 4th and 5th, 2023, on the theme, "2D/3D Industrial Radiological Imaging and it's Applications. This program had a very good response with a total of 119 Participants for this workshop. Dr. Narayanan V, Director, LPSC inaugurated the program and welcomed all participants to LPSC. He mentioned the important role played by NDE in aerospace sector and its relevance. Shri M.S. Suresh, Associate Director/LPSC, Dr. Arumugam. M, Dy. Director/LPSC and the Program Coordinator, Shri V. Manoharan, Chairman, PFMB, Dr. Mohan Kumar. L, Chairman, ISNT Thiruvananthapuram Chapter, and Shri Roykuttan K.K, were the organising Committee Chairman addressed the gathering.

Second Programme of PFMB :

Topic : "2D/3D Industrial Radiological Imaging and it's Applications".

The second workshop on the same theme, "2D/3D Industrial Radiological Imaging and it's Applications", was also conducted on 25th and 26th of September at IIT, Chennai jointly organised by PFMB-ISNT and QUNEST Fdn. in association with CNDE, IIT. This program was also well received with good response with a total of 85 Participants.

Shri H. Shankar, Director Technical, CPCL, Chennai was the Chief Guest for workshop. Shri S. Ramakrishna was the Programme Director and Shri V. Manoharan, Chairman-PFMB.

The workshop was well represented by various industrial sectors and was a grand success.

IGNITE :

During NDE 2023 (7-9, Dec 2023), a special session : IGNITE (Carrier in NDE) specifically for the student community was conducted on 8th December, 2023, during NDE 2023 at Pune.

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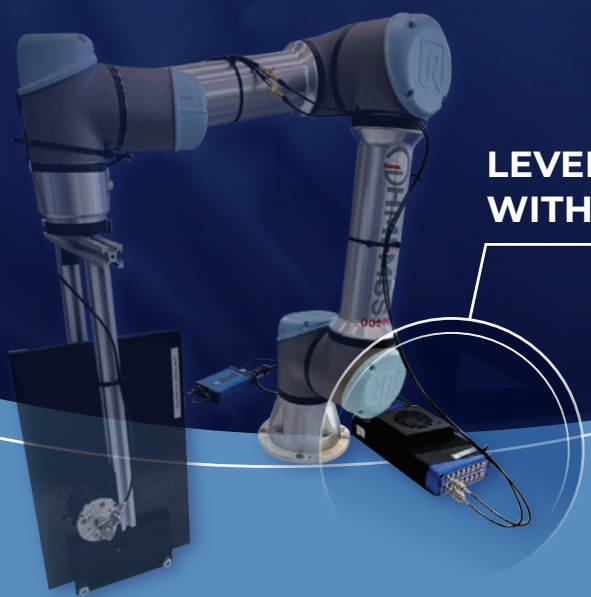

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Abstract

Non-destructive evaluation (NDE) is widely used to ensure the quality and integrity of components. Various non-destructive testing methods have been developed and implemented to evaluate Additively manufactured (AM) products. Modern techniques in the AM production route enable the fabrication of complicated geometries with smaller lead time and minimum material wastage. Though this technique has many advantages; many bottlenecks are encountered during evaluation of the quality of products made in this route. The common defects noticed in the AM components are porosities, clusters of porosities, micro-cracks, lack of fusion and layer delamination. The detection and evaluation of defects plays a significant role prior to its application. Most of the existing NDT techniques are based on the analysis of electromagnetic radiation interaction with matter and the response of the sound or heat energy transmitted in the component to be tested. Different energy bands of the electromagnetic spectrum, ranging from gamma rays to radio waves, are used for quantitative and qualitative analysis in NDT applications. All conventional NDT techniques are not viable for the AM components owing to their complex geometrical and material characteristics. Radiography is suitable for the evaluation of the volumetric defects and Ultrasonic testing gives good results for the planar defects in the AM components. The defect detection capability of these techniques is based on the size and orientation of the defects with respect to the source beam direction. Radiography and Ultrasonic testing are experimentally tested for evaluating the artificial defects in SS316L stainless steel coupon made by laser powder bed fusion (LPBF) additive manufacturing technology. This paper presents and demonstrates the capabilities, advantages and limitations of radiography and ultrasonic testing techniques for the assessment of defects in SS316L coupon made by the AM route.

Keywords: *Additive manufacturing, SS316L, Radiography, Ultrasonic testing, Defects*

1. INTRODUCTION

Additive manufacturing [AM] is an advanced manufacturing technique for the production of three dimensional shape of components using layer by layer deposition of material using 3D models. The major advantage of this process is the possibility of making complex geometries with minimum wastage and fabrication time. The deposition of the individual layer is made with the help of high power laser or electron beam. With the help of the high power source the powder material is melted and after cooling the desired shape of the component is produced [1]. AM techniques have a significant role in the production of component for aerospace applications. This technique is widely used for the fabrication of complex engine components and replacement of critical parts of the aerospace industries. Since this technology is only in an evolving phase, studies found some difficulties in the quality control of the parts produced in this route. The sudden cooling of the metal in the AM process causes material defects and changes in the microstructure of these

products compared to the conventional wrought/ cast alloys. Since the solidification characteristics of any additive manufacturing process are extremely influential on the build quality, the chances of defect formation can be easily controlled by adapting the appropriate process and environmental parameters. The probable defects noticed in the AM components are the dissimilarity in the grain structures, porosities and lack of fusion. Since the additively manufactured alloys have multipart configurations and rough surfaces, non-contact NDT techniques are more appropriate for the quality evaluation. NDT tools are competent to establish a relationship of mechanical properties with the response of signal from the NDT responses. Studies show that the structural integrity of the AM component can evolve itself from the NDT observations rather than collecting the data from a coupon-level destructive test [2]. As a high temperature gradient occurs during AM processes, residual stresses are generated that affect the performance of the components during its operation. Recently research is being carried out for the assessment of residual stress in the AM components by Ultrasonic testing techniques.

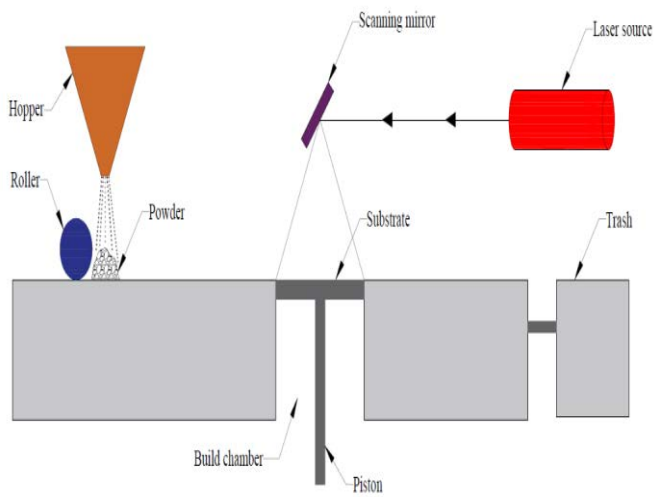

Fig 1: Schematic diagram of Laser Powder bed fusion method of additive manufacturing

Based on the material layer deposition, AM can be classified into two types: Additive layer manufacturing (ALM) and Additive non-layer manufacturing (ANLM). The major ALM processes are powder bed fusion, fused deposition modelling etc. Selective laser sintering (SLS) and selective laser melting (SLM) are sub classifications of the laser powder bed fusion (Figure-1) technique. The programmed CAD model of the geometry enables the joining of the selective layers corresponding to a slice of the respective metal surfaces. Direct energy deposition (DED) is widely used for the manufacturing of Titanium and nickel-based super-alloys. Currently, various metallic components such as stainless and tool steels can be manufactured using PBF-based AM processes.

In summary, for the manufacturing of the large-scale components, the AM technique has shown its capability and many developments are expected in this domain to grow over the near future. Significant research in the NDT of the components needs to be developed in order to use this technique in aerospace applications. The important aspect to address is the assessment of the capability of the accessible non-destructive testing technique to ensure the quality of SS316L stainless steel parts produced through the AM route is the focus of the present paper.

2. NON-DESTRUCTIVE TESTING (NDT)

NDT has a considerable role in the quality verification protocol of AM components. Conventional NDT techniques have limitations in this manufacturing route due to the geometrical and material texture constraints. X-ray computed tomography (XCT) is extensively used in this domain for good results. The huge inspection cost is the major drawback of using, XCT for larger AM components. The resolution of the CT image is not good enough for the screening of minute defect signatures. The advanced Ultrasonic testing techniques are capable of detecting of delamination between the layers precisely. Tight cracks and high-density inclusions can be detected reliably by the UT technique. The online inspection by thermography during metal deposition enables to optimize the process parameters which help to reduce the rejection of the final product.

Currently non-contact NDT techniques are investigated a lot in the NDT of AM components due to the poor surface finish of the components in the as-print condition.

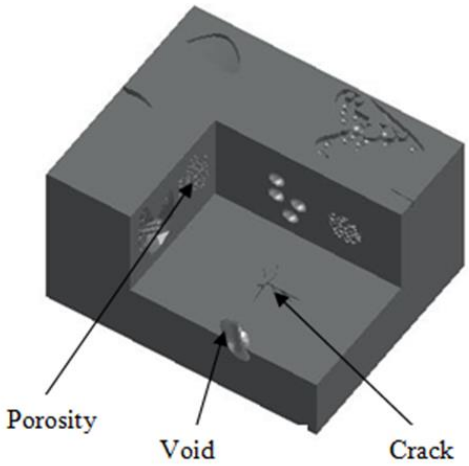

Fig 2: The common defects noticed in the AM route

Laser ultrasonic testing technique using a pulsed laser to generate acoustic waves is widely practiced for investigating the surface and subsurface flaws of AM components. Dye penetrant testing and Eddy current testing (ECT) show potential results for the surface and subsurface flaws. ECT is an emerging technique for material inclusions and micro cracks. The advancement in image processing widens the capacity of digital technology in the NDT domain for AM routes.

3. MAPPING OF THE NON-DESTRUCTIVE TESTING FOR SS316L COUPON MADE BY AM ROUTE

In the area of NDT techniques already used for the AM components, most of the research has shown ultrasonic testing and radiography testing outcome in the defects like cracks, porosity and cracks without any much surface treatment and preparation in general. The film radiography technique can experimentally detect an artificial crack of 0.4 mm width and length 8 mm located in the steel at depth of 3 mm from the coupon surface. But with the same exposure the scattered pores of Ø0.2 mm size are not discernible due to the poor sensitivity of the technique. Digital Radiography has proven the capacity to detect the defect of size above 400 μm.The application of XCT for the AM components has already studied by many researchers and reported porosity ranging of 50-200 μm can be detected by CT. In the case of powder bed fusion, the probability of detection of flaws by pulsed ultrasonic testing found 90% POD for the surface defects of Ø0.2 mm and Ø0.8 mm at 5 mm depth [3]. The Eddy current testing (ECT) showed the detection capability of faint subsurface defects than ultrasonic method. The major difficulty in the application of ECT to AM components is the surface roughness. The adversity in the distinction of the signals arises from the surface roughness and crack is a major challenge and the noise generated was significant for the exact identification of the defect.

From the reviewed literature, many NDT techniques XCT, Digital radiography, ultrasonic testing and eddy current testing were extensively used for the quality control and qualification of the AM components [4]. However, in spite of the existence of various technical publications related to NDT of AM components there is no significant data available for the defect estimation of SS316L components [5]. In this paper an experimental investigation of Radiography testing (RT) and Phase array ultrasonic testing for the inspection of SS316L sample produced by Laser powder bed fusion technique is presented.

4. MATERIALS AND METHODS

SS316L sample including artificial defects used for the study were developed using Magics^{TM} Software considering frequently occurring defects in the Laser Powder Bed Fusion (LPBF) technique. The designed geometry of the coupon was transferred into a STL file and printed by STLR400 LPBF machine from M/s. Amace, Bangalore with a laser power of 1 kW and scanning speed of 9 m/s. The printing technology used was Laser Powder Bed Fusion (LPBF) technique and during this technique the SS316L powder was melted and solidified after the laser impingement over the powder bed. In this process the powder was melted to its melting point and after cooling a homogenous layer was formed. Similarly many layers are deposited as per the CAD file for making of the test coupon. The powder selected for the experiment was SS powder with label SS316L supplied by M/s. Indo-MIM, Bangalore. The powder was printed as per the defined process parameters and artificial defects were incorporated as per the design of the final coupon.

Stainless steel SS316L is an austenitic chromium-nickel stainless steel containing an amount of molybdenum which increases general corrosion resistance and especially improves its pitting resistance to chloride ion solutions. SS316L is the extra low carbon version of SS316 that minimizes the harmful carbide precipitation. It is widely used in exhaust manifolds, heat exchangers,

cryogenic piping, valve and pump subsystems of aerospace applications.

For ultrasonic testing and radiography testing one coupon of size 60x40x20mm was made on the top of the substrate plate. The deposited coupon was separated from the substrate using EDM wire cutting. The artificial defects are plotted in the CAD is illustrated in figure 3.

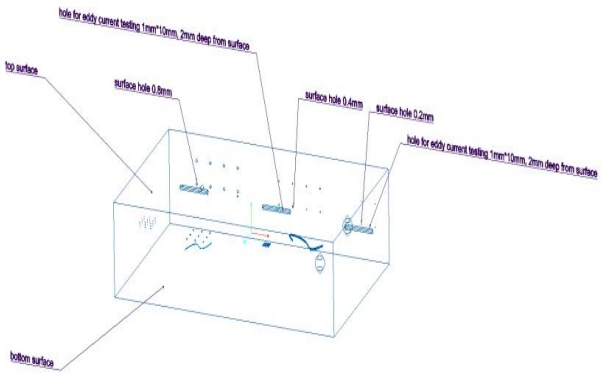

Fig 3. Sketch with artificial defects plotted in the Magics^{TM} Software

The cut coupon was subjected to visual inspection and no surface preparation was done before carrying out the ultrasonic and radiography inspection. The SS316 coupon for the evaluation of NDT techniques described in this paper is shown in figure 4.

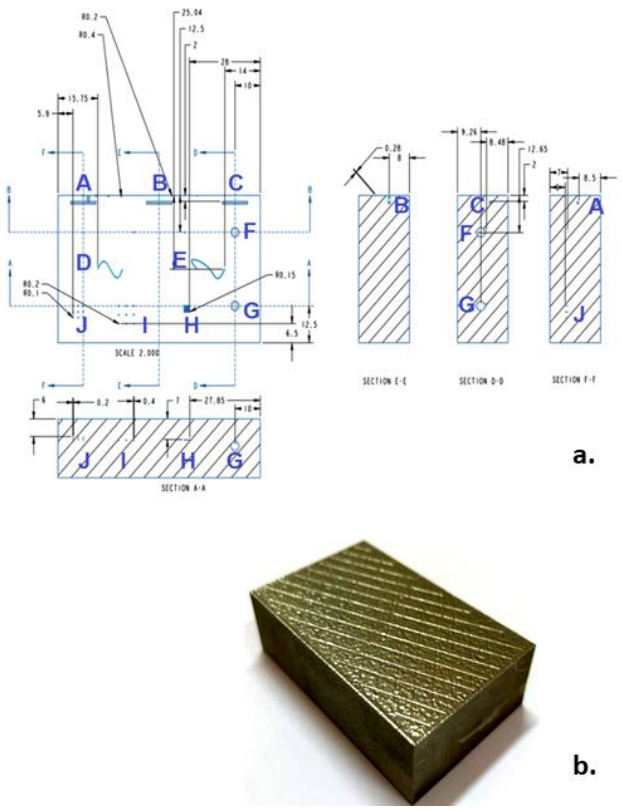

Fig 4. a. Schematic and b. actual SS316 coupon in as-printed condition for evaluation of defects using NDT techniques

4.1. Non Destructive Testing Technique

For detecting the artifical defects made in the SS316L coupon, radiography testing (X-ray) and Phased Array Ultrasonic testing (PAUT) testing were carried out.The X-ray was carried out in 450 kV Titan E,GE X-ray machine and 6MeV LINAC, Varian make X-ray machine. The exposure parameters are adjusted to get an optical density of 2 to 3D. Shots are taken in three orientations to cover the full coupon as per the standard radiography procedure for metallic components. The maximum thickness covered by 450 kV for getting an optical density of 2D is 50 mm. The exposure parameters for covering the width of 20 mm are 400 kV, 5 mA, 3 min. The radiography using LINAC was carried out with 2000 Rad and 1250 Rad for 40 and 60 mm length respectively. The radiography films used for the study are D4 and D7 Agfa make.

In this study, the ultrasonic testing method, by Phased Array Ultrasonic Testing (PAUT) approach was used to investigate the defects embedded in the SS316L coupon. The equipment consisted of different transmitting probes of 5 MHz, 16 Element, 0.6 mm pitch with 0^0 wedge and 55^0 wedge (A10 type probe). 5 MHz, 64 Element, 1 mm pitch probe with 0^0 wedge was also used. The scanning was carried out in linear 0^0 and with angle beam of 40^0 to 60^0 orientations. The PAUT equipment used for the study was OLYMPUS, OMNISCAN MX2.

5. EXPERIMENTAL EVALUATION OF NDT TECHNIQUES

Digital radiography of the coupon was carried out in YXLON X-ray machine using energy 300kV, Current: 6mA and Focal spot size: 1 mm. The flat panel detector used was 100 µm pixel pitch of GE make. As shown in Figure-5, linear hole type indications and voids were

clearly discernable by film radiography testing. From the images it is clear that the volumetric defects more than 2 mm size are visible from radiography with 2% sensitivity. The planar defects like layer separation and very small pores of less than Ø0.5mm. are not detectable in the image. Since most of the defects comprise of unmelted SS316L metallic powder, the attenuation coefficient gradient is very less to get a good optical density for defect detection.

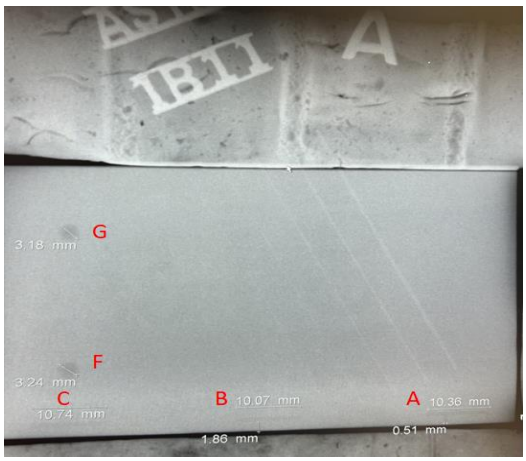

Fig. 5. Digital radiography image of the SS316L coupon

Also the defects detection in the radiography depends on the radiation beam orientation. Multiple radiography images with different beam angles and different film combinations are essential to get the maximum defect information of the defect. Figure 6 shows the radiography image from 6 MeV LINAC X-ray machine. Since the low energy X-ray is not adequate to penetrate the linear portion of the coupon, radiography was carried out in LINAC X-ray machine. The defects G and F are clearly visible in the radiograph. The image film quality is not that much good compared to the digital imaging. Further studies using X-ray Computed Tomography (XCT) are planned for the evaluation of other defects which are not explored in the 2D radiography.

Phased array ultrasonic testing was performed in order to compare the previous RT results and reach conclusions about the capability of this testing method. The scanning was carried out on the wire cut surface of the coupon.

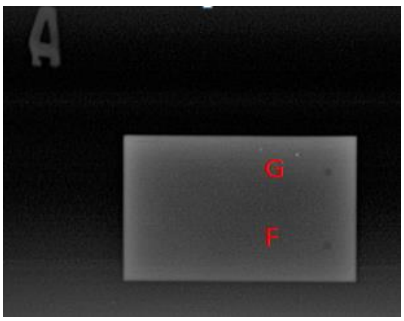

Fig 6. Film based Radiography image of SS316L coupon

The surface finish in as print condition was not fit for ultrasonic testing to the desired sensitivity level. This is the major drawback of the contact NDT technique for the AM components. The scanning set up is shown in figure 7.

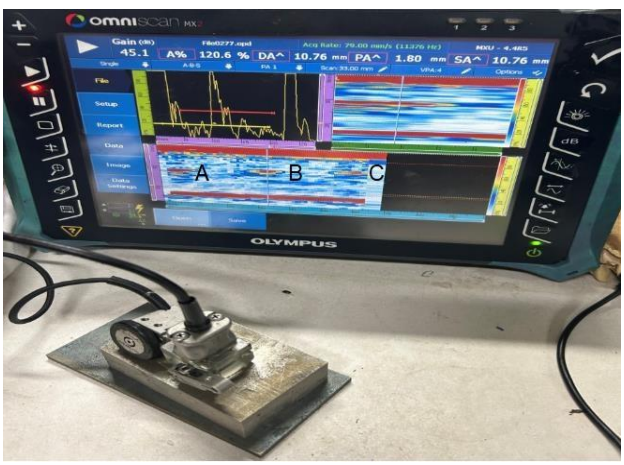

Fig 7. PAUT Scanning set up of SS316 coupon (Also shows Defect A, B and C)

5.1. PAUT Scanning Results for the Voids and Crack Indication

Results shown in the following figures using A-Scan, S-Scan and C-scan are validating the defect detection capacity of the PAUT technique for this study. Defects A, B and C could be detected in PAUT (figure-7) and measured to be of 11.1, 11.5 and 10.9mm in C Scan at a depth of 12.03, 12.05 and 12.02 mm respectively. The crack (Defect D) indication showed in the figure 8 is not captured in the radiography testing due to its micro nature of the crack and the defect orientation which is perpendicular to the X-ray beam.

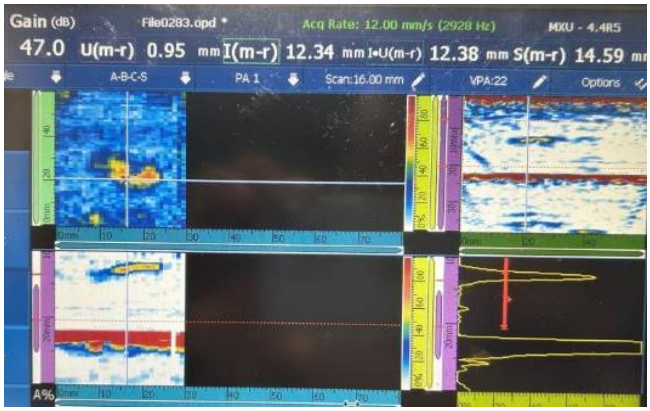

Fig 8. Planar curved crack indication (Defect D) in SS316 coupon

The artificial crack was not made in a linear fashion but it was printed in a planar curved shape. The crack was noted at a depth of 12.9 mm from the top of the sample with a maximum detectable length S(m-r) of 14.6 mm, width I(m-r) of 12.34 mm and height U(m-r) of 0.95 mm. All length and width parameters were evaluated with the help of encoder and height from B-Scan

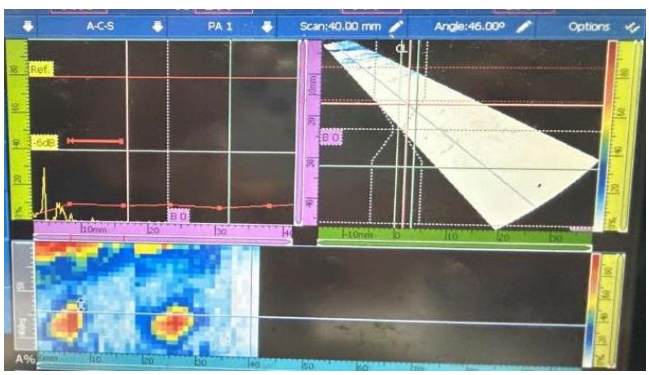

Fig 9. Void indications (Defect G and F) in SS316L coupon

The two voids of size 5mm are detectable using the angle beam sectorial scan(40º to 60º). The peak amplitude is noticed at 44º scanning. The C-scan image shown in figure 9 reveals the presence of the voids in the coupon which is in line with the radiography observation.

Ø0.4 mm cluster porosity (Defect I) could be detected in PAUT from the top surface. The cluster of Ø0.2 mm pores (Defect J) is not identified both in PAUT and radiography technique.

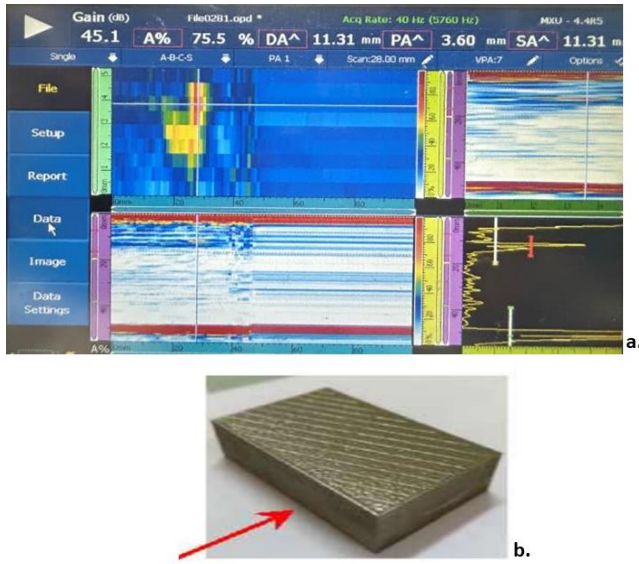

Fig 10. Pore indication (Defect J) in SS316 coupon, detected from side surface

However the same could be detected when scanned from the side, as shown in the C scan image of PAUT in figure 10. PAUT has detected cluster of porosities as a single indication peak only and not as a multiple defect. This is because, the beamwidth is much higher than the diameter of individual pores.

The closely placed Ø0.3 mm pore cluster (Defect H) could not be detected by both PAUT and RT. Since these are very closely placed, there are chances that these pores could have fused during printing itself. Defect 'E' which was printed in an inclined plane, could not be detected both by PAUT and RT.

In summary, most of the artificial defects made in the AM route SS316L coupon were clearly detected by radiography and PAUT technique. The size and orientation of the defects are critical in both the detection aspects. In PAUT technique, the detection capabilities are similar to the conventional UT technique, but multiple-angle scanning in PAUT, enables detectionof defects in most of the orientations.

6. CONCLUSIONS

The NDT and evaluation of SS316 coupon made by LPBF route using radiography and ultrasonic testing technique was considered in this study. The evaluation of the artificial defects made in the coupon was successfully demonstrated by both techniques. The geometry and orientation of the defects influence the ability of any NDT technique to detect them.

Conventional ultrasonic testing and PAUT need couplants and accessibility of the probes. The advanced Laser ultrasonic technique is a non-contact technique and can be a good testing domain for the AM components that have poor surface finish. Customised probes can be designed to overcome the surface irregularities during the scanning by PAUT. The 2D X-ray is capable of revealing the volumetric defects within the sensitivity limit. XCT is the most suitable technique for the volumetric defect detection in any orientation. The geometric complexities of the AM components in the aerospace applications are the major challenge in the selection of a suitable NDT technique. This study shows that the PAUT can be used (components having probe accessibility) as a complementary technique with the X-ray radiography for the non destructive evaluation of LPBF AM route SS316L components.

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The Way to Reliable and High-Quality Additive Manufacturing Components

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Abstract

One of the challenges within the reliability evaluation, is the fact that every inspection situation should be evaluated separately. The evaluation of a non-destructive testing application is depending on a various number of different influences, including geometry, material, and testing equipment. An obvious fact will be mentioned a lot within the selling process of NDT equipment. But on the other hand, it is often ignored in the planning and realization of reliability evaluations, due to the cost of the evaluation data set, e.g. through reference parts.
Mentioned fact is in the center of the evaluation of NDT application for additive manufactured components. The main reason for Additive Manufacturing (AM), the single lot production, is an almost impossible task for the reliability evaluation.
This article will discuss the topic reliability evaluation of NDT application for additive manufactured components, starting with the need for the evaluations, according to the quality management view. Followed by the evaluation of the possibilities to enable NDT equipment to gain reliable results despite the small lots and ending with an optimistic outlook within the NDE 4.0 framework.
Keywords: *Additive Manufacturing*, *NDT, Reliability, Probability of Detection, NDE 4.0*

1. INTRODUCTION

The Need For NDT Reliability Evaluation In AM

Additive Manufacturing (AM) has revolutionized the way components are designed and produced, offering unparalleled design flexibility and the ability to create complex geometries. However, ensuring the quality of AM components is challenging due to the intricate layer-by-layer deposition process. Hence, the reliability and integrity of the final product are paramount. Non-Destructive Evaluation (NDE) techniques play a pivotal role in quality assurance across various manufacturing industries. It ensures that defects and imperfections are identified before they compromise the structural integrity of components. NDE techniques, such as ultrasonic testing, X-ray computed tomography, and eddy current testing, provide valuable insights into the internal structure and defects of AM-produced parts. In the conventional manufacturing processes, these different types of NDE methods are employed to detect and characterize defects such as cracks, porosity, and inclusions. These techniques are applied to materials with known properties and homogeneous structures, allowing standardized inspection procedures. Additive manufacturing introduces a paradigm shift in the manufacturing landscape, presenting both unique challenges and opportunities for NDE. Unlike traditional methods that involve subtractive manufacturing from bulk materials, AM builds up the components layer by layer, introducing complexities in material composition, porosity, and anisotropy. Several challenges like anisotropy of materials, complex internal geometries, build orientation effects, etc. make NDE of AM products difficult.
In recent years, the topic of reliability evaluation has taken center stage in the NDT community. After five decades of research and practical application in highly safety-critical sectors such as aviation, military, and nuclear power, there is now a growing demand for objective key performance indicators to assess the capability of NDT applications.

Several key factors have contributed to this shift:

1. **Emergence of the Second Generation of Reliability Scientists:** The first generation focused on gaining acceptance for statistical evaluation tools within the NDT community and acknowledging the absence of a 100% Probability of Detection (POD). The second generation is now actively working on implementing these procedures in real-life applications.
2. **Shift from Research Institutes to Industrial Companies:** While the first generation primarily developed reliability evaluations within research institutes, the second generation is often based in industrial companies. Their role is to transform accepted reliability processes into a technological demonstration phase, as illustrated in Figure 1: TRL-Scale for Reliability Evaluations.
3. **Necessity Driven by NDE 4.0:** The advent of NDE 4.0 has heightened the need for reliability Key Performance Indicators (KPIs). In the cyber-physical world, reliability evaluations are not just optional; they are the cornerstone for building a functional NDE 4.0 framework. This is evident in various aspects:

- Within feedback loops on the production floor, reliability KPIs play a vital role in making informed decisions for quality management [1].
- For AI, the reliability framework is the most meaningful indicator of its capabilities, emphasizing transparency, explainability, and safety for planned certifications within the EU-AI framework [2].
- Even in human-machine-interaction, reliability serves as the appropriate tool to guide and evaluate human decision-making and collaboration with NDE 4.0 technology.

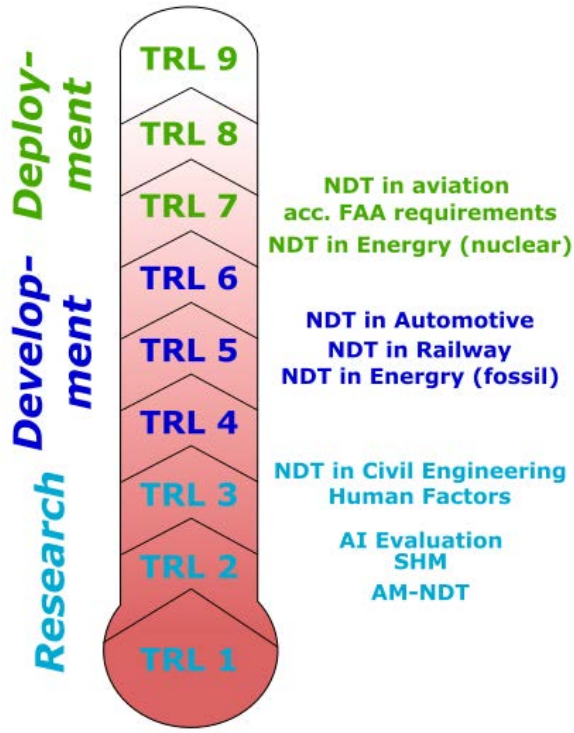

Fig. 1: TRL-Scale for Reliability Evaluations

The trend is unmistakable: modern NDT applications are now rooted in their objective capability indices. Algorithms, in an unquestionable manner, demonstrate the capabilities of inspection methods [3]. This shift marks a change from disregarding the imperfections of inspection methods to a subjective assessment of their capability, all aimed at achieving the highest possible quality.

2. STANDARDIZED RELIABILITY APPROACH IN NDT

In the past five decades, the assessment of the value derived from inspection systems has been implemented in various sectors, including aviation, petrochemical industries, railways, automotive, civil engineering, and more. Scientific advancements in these fields have led to the formulation of a general working procedure, resulting in the publication of initial standards. These standards aim to ensure the safety of products and services through the utilization of reliable inspection systems.

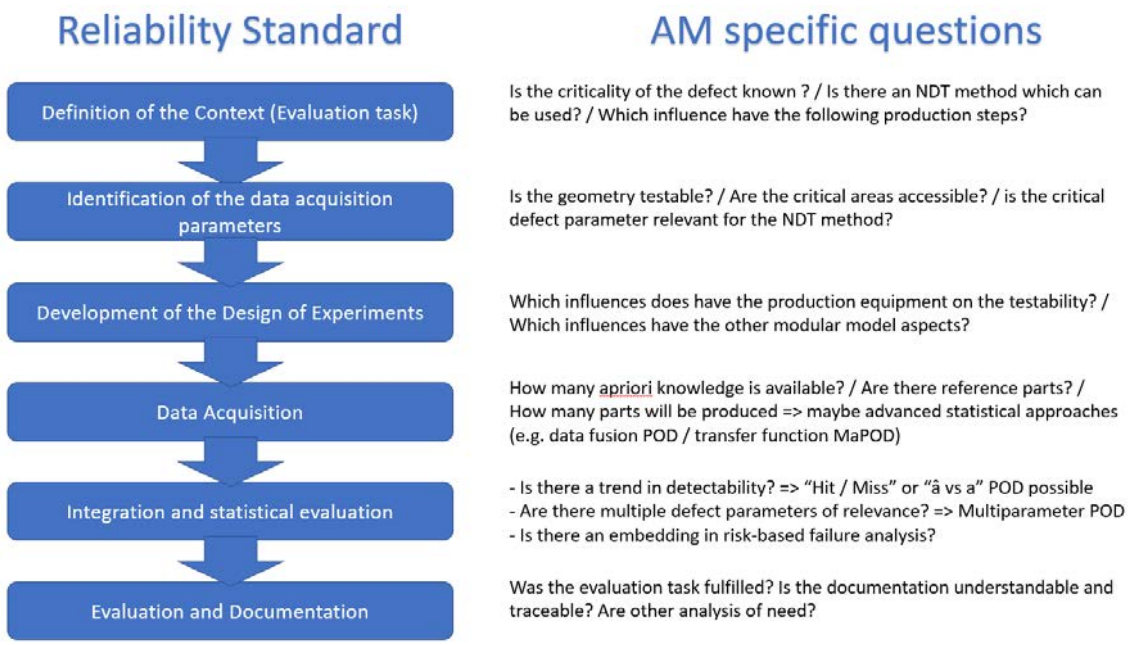

Fig. 2: Steps of Reliability Evaluation [5] in comparison with specific AM needs

Within the NDT community, Key Performance Indicators (KPIs) are well-known for evaluating testing systems. One prominent example is the Probability of Detection (POD), representing the likelihood of detecting a defect of a specific size with defined statistical confidence. In aviation, the POD is a critical parameter for determining safe testing intervals. Behind the POD, a substantial body of knowledge describes the testing system, intertwined with statistical methodologies. The outcome often takes the form of an easily interpretable POD curve (see Figure 2).

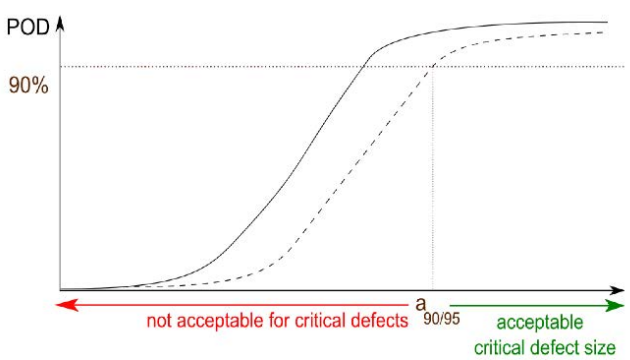

Fig. 3: The probability of detection curve, as a tool to decide the capability of inspection systems, e.g. worldwide usage in military aviation

However, beneath the umbrella of reliability evaluation lies a comprehensive procedure designed to extract maximum information from the testing system (illustrated in Figure 3). This procedure involves the identification of influencing parameters and entails a specific form of reporting. This reporting structure serves as a crucial intersection point with digital twins and modern digital industry applications, such as Industry 4.0.

The assessment based on the reliability evaluation of the testing system results in an objective KPIs. This KPI serves the management by facilitating comparisons between inspection methods, estimating structural integrity, and planning maintenance intervals. Its transparency allows third-party evaluations, if required, without divulging excessive internal knowledge about the testing systems or the tested components. Further information about the standardized reliability evaluation can be found under [5].

It is obvious that this process is strongly depending on the application itself. For AM it is not possible to use a predefined process, due to the specific nature of additive manufacturing, see Figure 3.

3. THE SPECIFIC NATURE OF ADDITIVE MANUFACTURING

While this transformation is applicable across all safety-relevant industries, the field of AM presents unique challenges:

3.1. Design Vs. Inspection:

The shift toward bionic structures, lightweight engineering, and transitioning material layers poses a considerable challenge for NDT professionals. Some components are currently non-inspectable, raising safety concerns and placing liability on designers, which is unacceptable in safety-critical NDT fields.

An old but relevant concept, design-for-testing, calls for equal collaboration between designers and inspection experts. Although designers may be resistant, accepted guidelines are essential to strike a compromise between quality control and design limitations. This connection between design and quality control not only facilitates structural integrity discussions but also accelerates the transition to NDE 4.0, fostering a cyber-physical environment [4].

3.2. Defects and Features

In AM reliability evaluation, the primary consideration is the goal of the testing application [5]. Unlike well-known processes, such as casting and welding with defined defects, AM introduces a new set of challenges. Questions arise about the relevance of the smallest detectable defect and how defects behave in post-processing. Factors like defect size, behavior during post-processing (e.g., "Hot Isostatic Pressing"), and the detectability of defects, like residual stresses, necessitate a thorough reliability evaluation. This process enables the assessment of undetected structures, defects, and material inhomogeneities.

3.3. IN-SITU VS. EX-SITU (Or Post-Production):

As explained on the complexity of POD analysis due to the evolving morphology of defects during the AM process, it is obvious to use both the in-situ and ex-situ inspection technologies for obtaining the more information on the defects (Figure 4). In-situ techniques involve monitoring and collecting data directly from the manufacturing process while it is happening. Despite the challenges, AM presents significant potential. Its layer-by-layer production allows for the implementation of NDT methods during production [6]. For AM, this could include real-time monitoring of parameters such as temperature, pressure, material deposition and most importantly the defect detection. Employing sensors, real-time imaging, spectroscopy, and other methods. These techniques enable the identification of anomalies in material deposition, layer quality, and structural integrity during the printing process. In-situ defect detection provides real-time feedback, allowing for immediate corrective actions and contributing to an enhanced quality control process in additive manufacturing. In-situ evaluations of individual layers provide the opportunity to halt the AM process if defects are detected, mitigating costs associated with defective material. Quality control of input materials, such as powder, is crucial for ensuring a high-quality end product. Additionally, a final inspection at the end of production, following traditional NDT practices, remains a viable option [7]. Ex-situ techniques involve collecting data after the manufacturing process has been completed. This could include inspecting finished products through techniques like non-destructive testing (NDT) or imaging.

In the context of AM, data fusion could involve combining information from both in-situ and ex-situ techniques to enhance the overall assessment of the manufactured parts. By fusing data from both in-situ and ex-situ techniques, a more comprehensive assessment of the manufacturing process and the quality of the final product can be achieved. Combining multiple data sources increases the confidence in the results. If a flaw is detected both in real-time (in-situ) and during post-production inspection (ex-situ), the reliability of the assessment is enhanced. Insights gained from data fusion can be used to optimize the manufacturing process, leading to improved efficiency and quality. It has to be noted that in the cases of data fusion obtained from different in-situ and ex-situ techniques, the POD obtained is never the reliability of one technique. Instead, the POD is the combined reliability of all the inspection systems used for the purpose. As AM belongs to the Industry 4.0 technologies, the entire inspection scenario has to be under the NDE 4.0. This is mainly due to the fact that no one inspection technique can just be used for the inspection of AM component both during the production and after the production. However, understanding the reliability of each method is also

important so that the overall reliability of all the inspections systems could be better. How much better, is depending on the NDT methods itself and the detectability of the defect. The solution can only be estimated by an advanced reliability estimation.

Understanding the capabilities of each method is essential due to the various positions within the production timeline. The integration of different phases in this production method can facilitate the creation of high-quality products through collaboration between different departments—a vision embraced by the NDE 4.0 community. This interconnectedness is a significant factor contributing to the strong association between Additive Manufacturing (AM) and NDE 4.0.

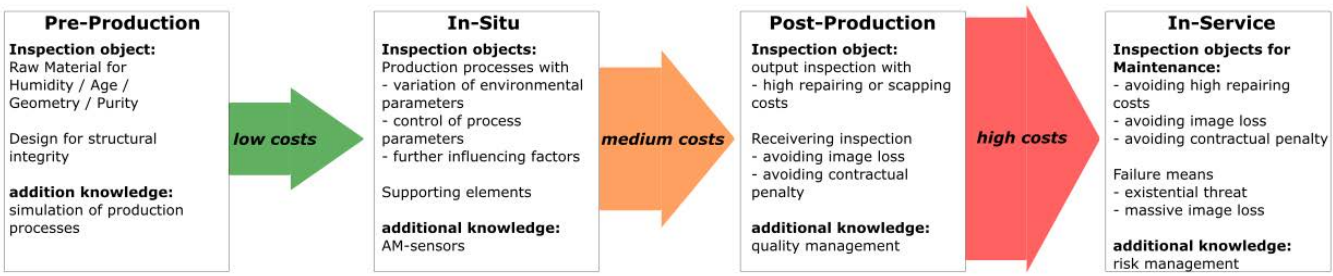

Fig 4: NDT in the AM-production process

4. THE AM CHALLENGE IN RELIABILITY

Either with conventional NDE technologies or with NDE 4.0 technologies, the reliability evaluations of inspection and monitoring techniques are extremely important without which the defective AM products cannot be avoided. POD is being a standard metric for understanding the capability and reliability of NDE techniques. POD analysis quantifies the ability of NDE methods in detecting flaws of varying sizes. In the context of AM, where defects may manifest differently at different stages, understanding POD is critical. High POD values indicate a higher likelihood of detecting defects, contributing to improved reliability in AM components. However, there are several challenges for doing POD analysis of AM products. The diverse range of potential defects in AM, coupled with the variability introduced by different materials and printing parameters, makes it challenging to establish comprehensive datasets for POD analysis. The evolving morphology of defects during the layer-by-layer AM process adds complexity to POD analysis. Defects may change in size, shape, and location, requiring dynamic analysis throughout the printing process. Traditional POD models, often developed for homogeneous materials, may require adaptation for AM samples with complex internal structures and varying material properties.

Despite the wealth of knowledge gathered from other production methods, the safety-critical evaluation of additively manufactured parts is still in its early stages. In a simplified graph as shown in Figure 5, considering the accumulated knowledge over time and the anticipated probability of failure, it is evident that AM is currently mainly focused on quality assurance, prioritizing it even at considerable costs.

However, obtaining this evaluation is not straightforward. Established methods rely on frequentist statistical approaches, demanding a large number of components with known defects, to establish statistical confidence. Given the small lots typical for AM parts, producing a large quantity solely for the qualification of a single part is impractical.

There are already available first reliability evaluations done for AM parts. In specific cases the known Probability of Detection (POD) approaches (â vs a) were successfully introduced into the AM framework, as seen in [8]. Therefore, it was possible to qualify NDT methods on similar parts with defects, to create a qualification procedure for similar parts. Nevertheless, the challenge lies in transferring these results to the actual future component. While research is underway to develop transfer functions, the process requires careful consideration. In specific fields, dedicated research projects are necessary to ensure the validity of these methods. Simultaneously, the absence of safety standards, crucial for deploying parts in safety-critical

applications that demand POD studies, further complicate the matter.

Adding another layer of complexity, despite AM being utilized across various industrial sectors like railway, aviation, and aerospace, its primary applications are often found in medicine. In the medical field, where material issues are pertinent [9], a close alliance with NDT is not anticipated. The divergent focus in medicine, influenced by additional requirements related to the biological environment and the abundance of chosen defect-free materials, diminishes the likelihood of a robust collaboration with the relatively smaller sibling, NDT.

research activity is going on the direction of reliability of NDE techniques used for AM products for the industrial use. This is mainly due to the several challenges involved in the AM process as explained earlier. In order to overcome the aforementioned challenges, there needs to be taken care of certain requirements. Developing and updating national standards and certifications for AM processes and NDT techniques can ensure consistency and reliability in inspections. Collaboration with international standards bodies can also be beneficial. Investing in research to understand the unique challenges of inspecting AM components and developing reliability methods tailored to these challenges is crucial. This includes addressing the complexity of AM geometries and the potential presence of internal defects. Providing wide-ranging of

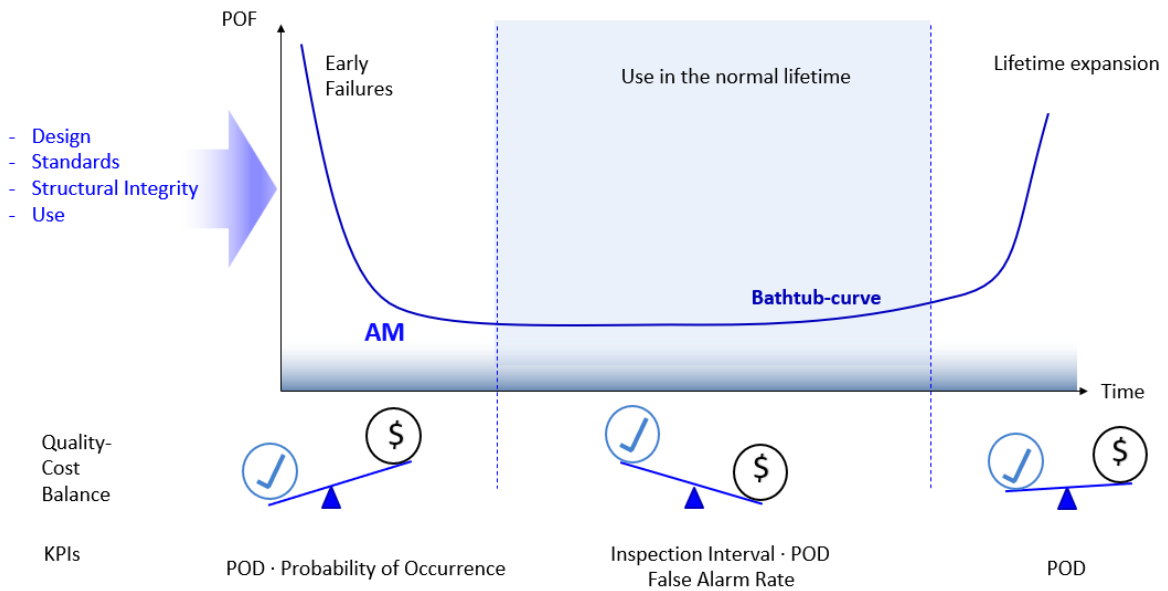

Fig. 5: Probability of Failure model based on the knowledge through time

5. REQUIREMENTS FOR RELIABLE AM PRODUCTS IN INDIA:

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. Indian NDT community is also involved in the NDE aspects of AM components. However, the biggest challenge lies with the qualification of new NDT techniques or methods or probes when planned for the actual industrial application. Even though, there are few researchers [10-14] working on the topics of NDT reliability, there is no

training programs for NDT technicians and engineers for inspecting AM components can enhance the reliability of inspections. Implementation of advancements in technology, such as the integration of artificial intelligence / machine learning, can improve the efficiency and reliability of NDT techniques. These technologies can assist in data analysis and anomaly detection. Facilitating collaboration between industries, research institutions, and regulatory bodies can substitute knowledge sharing and the adoption of best practices. This can accelerate advancements in reliable NDT techniques for AM components. Conducting validation studies and benchmarking exercises for

various NDT techniques on AM components can help establish their reliability. This involves comparing the performance of different methods under controlled conditions. Increasing awareness among industries about the importance of reliable NDT techniques for AM components and educating them on the latest advancements can drive adoption and continuous improvement.

6. OUTLOOK

An optimistic outlook envisions a robust collaboration with medical departments. Leveraging the substantial number of implants in medical applications could effectively address the statistical challenges, paving the way for generalized transformations to tackle reliability evaluations for single-lot components.
Currently, two major trends are unfolding in the field of NDT:

1. ***Standardization***: In recent years, numerous standardization projects worldwide have been initiated. Notably, there is a specific emphasis on standardization for reliability evaluations. Unlike past approaches, future guidelines are designed to accommodate transfer functions and alternative evaluations based on a limited dataset. These methods are crucial for addressing the reliability concerns associated with AM-POD, see e.g. [15].

2. ***NDE 4.0***: Simultaneously, a significant trend is emerging in NDE 4.0 technology. The integration of additional knowledge and data spanning from material properties to production and usage allows for a comprehensive evaluation of components. Moreover, the rise of AI provides NDT professionals with an opportunity to clarify capabilities and foster collaboration with other departments.

By focusing on both, standardization and NDE 4.0, there is a promising avenue to address reliability concerns even in cases involving small lots. The ongoing trends in AI, coupled with evolving legislative frameworks, may necessitate a strong demand for NDE in medical applications for AM parts, and the NDT community is poised to meet this need.

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Overview of In-Situ and Ex-Situ NDE Inspection Methods Coupled with Additive Manufacturing of Composites

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Abstract

Additive manufacturing (AM) is growing at a rapid pace with the advancements in efforts to address the sustainability and climate change. Researchers around the world are seeking to improve the two fundamental aspects of additive manufacturing namely: speed and accuracy. By increasing the speed of fabrication, AM is all set to take over the major chunk of conventional manufacturing by the end of this century. While AM has developed from its initial stage of prototyping to industrial production, integration of non-destructive evaluation (NDE) becomes inevitable. NDE being able to inspect the AM fabricated products for its defects and accuracy, is necessary in production line to ensure the quality of the product meets the required standards. This paper gives an insight into the integration of NDE techniques into the various AM processes to accustom the mass production and batch production. The NDE techniques are classified into in-situ and ex-situ examinations, and conceptual design is drawn accordingly. Furthermore, the advantages of NDE in the additive manufacturing of composites are discussed in detail. AM fabricated composites are often dealt with interface delamination, defects, porosity, and adhesive issues which needs to be carefully addressed. While various kinds of composites do exist, the fabrication of ceramic matrix composites (CMCs) and nanocomposites through AM is recently developed. Thus, the study mainly focuses on recent involvement of NDE in assessing the quality of AM fabricated CMCs and nanocomposites.

Keywords: *Non-destructive evaluation, additive manufacturing, ceramic matrix composites, nanocomposit*

1. INTRODUCTION

Non-destructive evaluation (NDE) is a collection of testing methods that is employed in many industries to evaluate the characteristics, reliability, and quality of materials, and/or structures without inflicting any damage. The main objective of NDE is to identify and analyse defects, flaws, anomalies, or inconsistencies in materials and/or structures, to ensure their quality, safety, and efficiency. These procedures utilize a range of physical principles, comprising of electromagnetic, ultrasonic, radiographic, thermal, optical, and other approaches, to examine materials and components without causing damage.

These procedures are essential in high-end manufacturing sectors that require customized parts and components. They enable the inspection of porosity, crack size, defects, and other vital components without compromising their operation. Through the utilization of these evaluation techniques, experts can promptly detect potential flaws, carry out necessary maintenance or repairs, and guarantee the safety and quality of materials and structures. This ultimately reduces risks

and improves efficiency across a range of industrial uses.

1.1. Role of Non-Destructive Evaluation in Additive Manufacturing

NDE and additive manufacturing (AM) are closely linked in the context of manufacturing, particularly in the quality assurance and reliability of parts fabricated through the additive manufacturing processes. Additive manufacturing, also known as 3D printing, is a process that fabricates components by adding material layer-by-layer (including plastics, metals, ceramics, and composites). Although additive manufacturing (AM) presents various benefits such as the ability to customize, design, and minimize material waste, it is essential to ensure the safety and quality of the printed components. The NDE can play a crucial role from the beginning of material preparation to the final quality inspection of the fabricated product. The importance of NDE in AM are listed as follows:

a) Printing parameters optimization: Manufacturing industries can ensure real-time quality monitoring of components by utilizing NDE techniques during the printing process. This allows for optimizing printing parameters, reducing flaws, and enhancing the manufacturing process to achieve superior quality and efficiency.

b) Economic evaluation: Conventional destructive testing entails the production of samples, conducting experiments, and finally disposing of the fabricated samples. NDE enables inspection without causing damage to the components, thereby minimizing material wastage and the need for reprinting. This results in reduced fabrication time and expenses.

c) Quality, safety, and reliability: AM technologies can produce complicated structures which poses some difficulties in ensuring structural integrity. NDE techniques are capable of identifying flaws, such as voids, fractures, or abnormalities, thereby assuring that the printed components comply with the necessary quality standards. Apart from that, in industries such as aerospace and healthcare, safety and reliability are of paramount importance. NDE assures that crucial parts produced by AM adhere to strict regulations. Early detection of possible failures or defects eliminates the risk of catastrophic failures during operation.

d) Lifecycle monitoring and overhaul: NDE techniques are also utilized for the ongoing repair, maintenance, and monitoring of components fabricated through AM during their entire service life. Periodic inspections can detect degeneration and enable prompt repairs or replacements.

1.2. Additive Manufactured Composites

This article emphasis on the use of NDE techniques in additive manufactured composites. Additively manufactured composites are largely used nowadays due to their ability to tune the required structural and functional properties as per the requirements. AM enables the design and material flexibilities to generate the range of mutually exclusive properties which were not possible with the conventional methods. Moreover, it does not require complex manufacturing processes. The process can be self-designed and constructed indigenously without much modifications [1,2]. Furthermore, the ease of handling various range of materials has paved the way to fabricate several classes of composites such as: Metal Matrix Composites (MMCs), Ceramic Matrix Composites (CMCs), Polymer Matrix Composites (PMCs), and nanocomposites. Despite the several advantages involved with AM composites, the lack of process monitoring results in interfacial defects and poor bond strength. Thus, it is necessary to monitor the in-situ fabrication process and ex-situ testing of parts to ensure the safety and reliability. Several studies have effectively utilized various NDE techniques to fabricate composites without any defects and flaws. This study has attempted to briefly outline all the NDE techniques involved in the in-situ and ex-situ fabrication of different classes of AM composites.

2. NDE TECHNIQUES COUPLED WITH AM FOR MASS PRODUCTION AND BATCH PRODUCTION

Additive manufacturing has evolved from prototyping in the early stage of introduction to high-speed manufacturing process. The technologies have evolved to compete with traditional manufacturing processes to meet the quality and quantity standards. It is predicted that the 50% of global manufacturing investments will go to the AM related production facilities by 2040 or

2060 [3]. Thus, the AM processes are set to dominate both batch production (that requires customization) and mass production markets. With the evolution of more prominent technologies in composites fabrication, the AM market will be propelled with further boost to dominate the manufacturing sector. With a promising future of additive manufacturing, it is equally important to couple the production lines with the NDE techniques to ensure the products meet industrial standards. For this purpose, the NDE techniques can be classified into in-situ and ex-situ inspection methods as shown in Figure 1. In the in-situ methods, the production and inspection take place simultaneously to ensure proper production of components. Figure 1a shows the in-situ inspection method wherein, the inspection is being carried out along with the production. The inspection algorithm is created in such a way as to detect the deviations from the set standards (i.e. porosity, dimensions, % of composition, etc) and thus, carryout corrective measures. However, involvement of inspection along with production would increase the production time. Hence, these methods are of interest in batch production where customization and accuracy are of prime importance. Moreover, in the case of composites manufacturing, these methods would ensure proper adhesion between the matrix and particles, lamination, interfacial diffusion, etc. Figure 1b shows the ex-situ inspection methods wherein, the high-speed AM processes would fabricate the components first, followed by which, inspection is carried out. Since the production is decoupled from the inspection, the rate of fabrication would be faster. Thus, these methods would be suitable for the mass production of components.

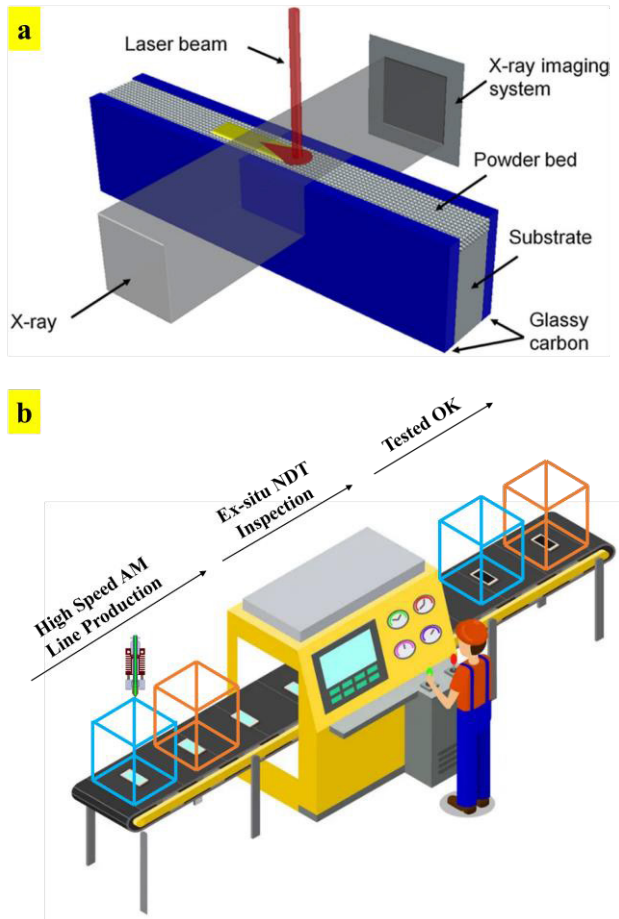

Fig 1: NDE techniques coupled with AM processes: a) in-situ inspection method and b) ex-situ inspection method.

2.1. In-Situ Monitoring Techniques

As explained in section 2, these techniques provide the real-time feedback which helps in taking necessary actions to improve the quality of production. Usually, the fabrication process controlling algorithm involves the real-time feedback coupled with the corrective measures without any human intervention. Everton et al. studied all the in-situ NDE techniques that are employed with powder-bed fusion (PBF) and direct energy deposition (DED) AM processes [4]. In the case of PBF process, the extreme heat that is responsible for melting the powder particles also generate gas which are entrapped as pores in the products being fabricated. Apart from that, the lower energy density may result in partially un-melted powder that results in poor integrity of the product. Conversely, over melting may result in the creation of turbulence in the melt-pool, thereby causing excessive evaporation.

2.1.1. In-Line Process Monitoring and Control

Berumen et al. used a set-up consisting of camera as shown in Figure 2 [4]. The electromagnetic radiation that was emitted by the melt pool is transmitted into an image to a high-speed camera and a photodiode. The camera effectively measured the dimensions of the melt-pool and photodiode measured the emitted mean radiation. The closed-loop feedback is used to stabilize the melt-pool within the predefined temperature range, through which the over and under melting is controlled. A similar set-up was utilized by Furumoto et al. to investigate the effect of layer thickness on the quality of the product [5]. A similar set-up with pyrometer and IR camera is used as well by Pavlov et al. [6]. Similar process can also be carried out with other

electromagnetic radiations such as infrared, ultraviolet, etc.

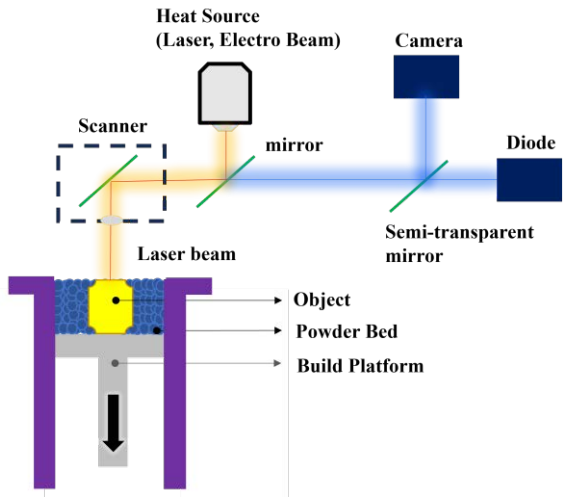

Fig 2: Schematic of in-line process inspection.

2.2. Ex-Situ Monitoring Techniques

2.2.1. Double Active Transient Thermography (DATT)

This technique is specially used to inspect the PMCs which have low electric and thermal conductivity. In this method, hot and cold thermal excitations are applied on the opposite sides of the component to be inspected. Figure 3a shows the working principle of the DATT NDE [7]. The defects such as flaws, voids, cracks and delamination are identified by the thermal contrast obtained. Silva et al. used this technique to determine the delamination in AM (material extrusion) processed Kevlar fibre reinforced polymer [7]. The test set up shown in Figure 3b consisted of a thermographic camera to capture the heat radiated from the specimen. The set-up utilized infrared lamps of 700 W power as the heat source. The specimen is placed using the specimen support as shown in Figure 3b. The vortex tube is used to blow the cold air from the opposite direction as shown in Figure 3b [7].

2.2.2. Ultrasonic Testing (UT)

This technique utilizes the ultrasonic vibration to assess the quality of the component. Nadimpalli et al. utilized this technique to investigate the interfacial quality of the specimen fabricated using sheet lamination AM process using the ultrasonic waves [8]. This process is seldom used in the fabrication of single material components. However, this process has several advantages in the fabrication of composites owning to the ease and rapid manufacturing. While Figure 4a shows the experimental procedure to assess the bond strength, Figure 4b shows the dependence of bond strength on the ultrasonic amplitude that is utilized for the manufacturing [8]. Although, using ultrasonic waves to assess the quality of the component is much common, this technique delivers poorer resolution. Along with that, the testing of complex shaped morphology become difficult to assess, fabrication of which is the main advantage of AM processes.

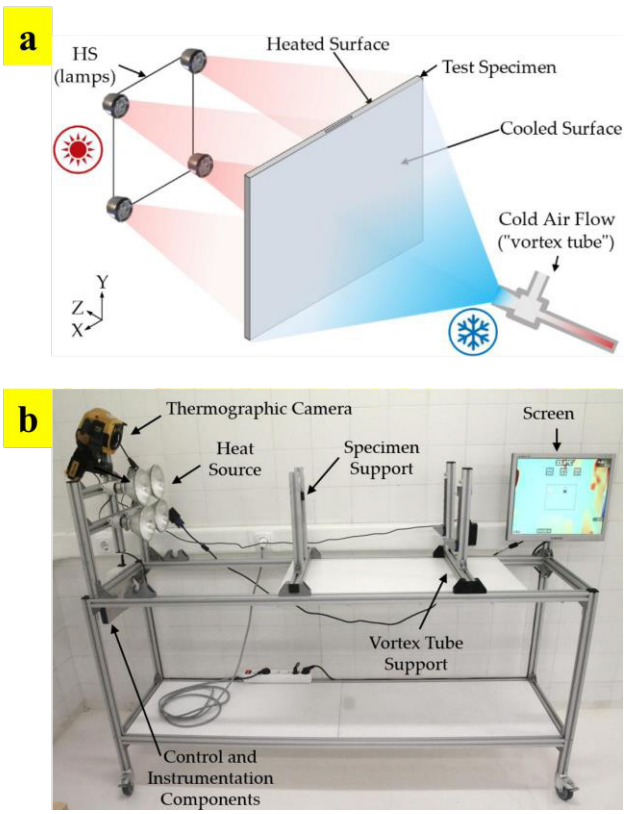

Fig 3: Double active transient thermography technique used to inspect AM fabricated composite: a) working principle and b) in-built test set-up [7].

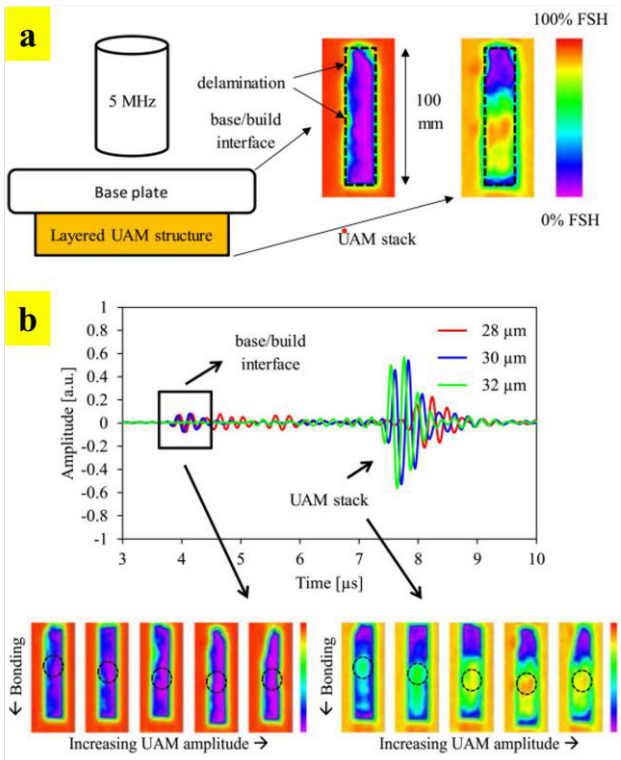

Fig 4: (a) Ultrasonic C-scan method for observing the base/build and stack images (b) Ultrasonic signatures of components built using different vibration amplitudes with acoustic microscopy C-scans of the two gated signals at the bottom [8].

2.2.3 Resonance Acoustic Method (RAM)

The concept behind RAM is that every part possesses a distinct resonant signature or pattern that indicates its integrity as a structure. An anomaly from the anticipated signature or pattern may indicate the existence of a defect [9]. The resonances of a structure/material are defined by its mass, stiffness and damping. The system detects resonant frequency shifts which can be caused by imperfections such as cracks and voids, as well as variances in material properties, dimension, geometry, weight, density and manufacturing processes [9]. This technique is specifically used in the evaluation of composite lattice structures due to high resolution material specific signatures [10].

3. TYPES OF NDE TECHNIQUES FOR ADDITIVE MANUFACTURED COMPOSITES

In the recent days, composite fabrication by using the additive manufacturing method is an emerging field of study. AM methods are helpful for the process that helps to manufacture the complex geometries of these composites. Some of the unique composites that are recently fabricated by additive manufacturing processes and evaluated by NDE techniques are as follow:

3.1. NDE Of Additive Manufactured Ceramic Matrix Composites (CMCS)

The advancement of materials technology has contributed to increased interest in ceramic matrix composites as an innovative option for a variety of applications. Amidst these advancements, non-destructive evaluation (NDE) is critical to verifying the materials' reliability and optimal performance. NDE of ceramic composite matrices uses a range of procedures to assure material integrity. Some of the primary methods include Ultrasonic Testing, Infrared Thermography, X-ray, Laser Ultrasonics, Acoustic Emission, Tapping Sound, and Machine Vision.

In the context of monitoring defects in ceramics, each NDE technique has its own limitations. Ultrasonic Testing encounters challenges in the detection of small and intricate defects within brittle ceramics. The presence of delamination defects, characterized by air gaps, further diminishes the ultrasonic responses, presenting an additional obstacle in achieving accurate defect identification [11]. Infrared thermography may have limitations in detecting defects in ceramics with large thickness and complex structures. X-ray tomography, while offering highly detailed three-dimensional visualization, may face challenges with complex and large ceramics, also this system is high cost [12]. The flexibility of X-ray method also is one of the limitations [13]. Ultrasonic lasers, despite their potential for high resolution, can be challenging to apply to ceramics with rough surfaces or complex structures. The limited ability to penetrate materials to a sufficient depth may also restrict its detection capabilities, another challenge is the low signal to ratio due to the high wave attenuation and low ablation threshold [14]. Acoustic Emission may have limitations in detecting very small defects or defects localized in hard-to-access areas, as it relies on the release of acoustic energy during material deformation, the material thickness and the sensor distance to the

receiver also effected to the damage identification [15,16]. The tapping sound method, while straightforward, may be less effective in detecting small defects in ceramics and often only provides surface-level indications, lacking in-depth information about the internal structure, and it need low environmental disturbance to detect the defect [17]. Machine vision is capable of detecting visual changes to a surface, but it may be less sensitive to small defects or abnormalities that do not significantly affect the surface's visual appearance, due to the algorithm identifications and precise control system [18, 19]. It is important to understand these limitations when selecting and applying a NDE method that is appropriate for the specific needs and characteristics of the ceramic material being evaluated.

Due to the limits of each NDE methodology, utilizing multiple test methods is the best way to obtain reliable data related to the condition and defects in ceramic materials. Ultrasonic Testing can provide detailed information about internal structures, whereas Infrared Thermography can detect temperature changes that may be related to failures. This multi-technique strategy can balance the disadvantages of one method with the benefits of another.

4. NDE OF ADDITIVE MANUFACTURED NANOCOMPOSITES

The NDE of additive manufacturing (AM) nanocomposites is complex and essential. Its goal is to carefully evaluate the overall performance, structural integrity, and quality of materials produced when additive manufacturing techniques integrate nanoscale reinforcements into a matrix. The combination of AM and nanotechnology opens up new possibilities for material functionality and design [20], but it also presents particular difficulties that call for sophisticated NDE techniques.

A significant obstacle in the non-destructive evaluation of AM nanocomposites is the uneven distribution of nanoparticles in the matrix [21, 22]. Unlocking the full potential of nanocomposites and guaranteeing the manifestation of their intended qualities requires achieving a uniform distribution of these nanoparticles and understanding that this is a primary aspect of nanotechnology. Clusters or agglomerations of nanomaterials can be a symptom of inhomogeneous dispersion, resulting in discrete areas with different concentrations of reinforcement. A significant concern is posed by this non-uniform distribution, which could jeopardize the nanocomposite's mechanical, thermal, and electrical qualities.

Advanced imaging techniques like scanning electron microscopy (SEM) and high-resolution X-ray computed tomography (HRXCT) are essential for addressing this problem because they offer comprehensive insights into the microscopic internal structure of nanocomposites [23]. By visualizing the dispersion of nanomaterials, these imaging techniques make it possible to identify regions with aggregation or uneven distribution. These methods provide a microscopic view that enables NDE techniques to identify areas susceptible to structural failures or material property differences resulting from inhomogeneous dispersion.

Measuring the energy loss of ultrasonic elastic waves and wave propagation speed is a significant focus of ultrasonic testing (UT) tailored for AM nanocomposites [24]. To be more precise, this is accomplished by submerging the nanocomposite (e.g., laser-sintered nanocomposite of carbon nanotube-reinforced polyamine 12) in an appropriate liquid using the immersion ultrasonic process. An extensive evaluation of the interaction between ultrasonic elastic waves and the nanocomposite material is possible thanks to the immersion ultrasonic technique. UT becomes an effective instrument for analysing layer-by-layer structures, offering insights into bonding quality and the existence of flaws by carefully measuring energy loss and wave propagation speed. This provides a more sophisticated understanding of the structural integrity of the composite and is especially useful in identifying locations where the dispersion of nanomaterials deviates from the expected uniformity. In ultrasonic testing, it is imperative to consider the mechanical moduli and orientation-dependent wave attenuation of nanocomposites in three orthogonal directions. The microstructures and internal defects caused by layer-by-layer fusion are closely linked to this orientation dependence. Because additive manufacturing procedures are layer-by-layer, anisotropy is naturally introduced into the material properties. This affects the direction in which ultrasonic waves propagate through the composite. This realization becomes especially important when attempting to comprehend the anisotropic behaviour of nanocomposites, as it offers a thorough grasp of their mechanical properties and possible locations for defects.

A complex layer of analysis is added in thermal imaging techniques, such as active pulsed thermography. With active pulsed thermography, the material's surface is heated in brief bursts, and temperature changes are tracked over time. This method offers dynamic insights into the material's thermal behaviour in the context of AM nanocomposites. Active pulsed thermography [25] accurately detects changes in thermal conductivity caused by the dispersion of nanomaterials. This method provides a real-time, dynamic view of heat dissipation and thermal performance beyond just identifying regions with unequal nanomaterial distribution. This level of comprehension is essential, particularly in fields like electronic components and aerospace materials, where heat management is a significant factor.

Ultrasonic Phased Array Technology [26] elevates the field of acoustic emission (AE) monitoring to a new level of sophistication. With several ultrasonic elements arranged in an array, this technology enables electronic control over the time and focus of individual elements. It is based on the principle of Huygens, where multiple independent piezoelectric wafer array elements are used to emit acoustic waves. By controlling the excitation of each array element in a specific sequence, a specific acoustic field is formed, resulting in beam focusing and phase-controlled deflection. When receiving reflected waves, the same method is used to synthesize the signals received by each array element, and the synthesized results are displayed in an appropriate form. The process is schematically shown in Figure.

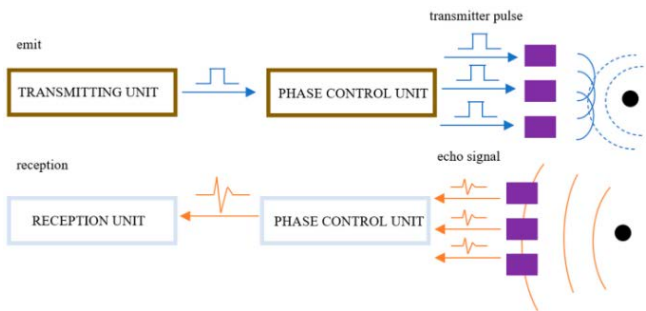

Fig 5: Schematic working principle of ultrasonic phased array technology [26].

The phased array controller triggers high-voltage electric pulses based on the signals transmitted by the ultrasonic detector. Each array element receives an electrical pulse, generating an ultrasonic beam at a specific angle and depth according to the focusing law. When the beam encounters a defect, it is reflected back, and the phased array controller changes the delay time according to the receiving focus law to combine the received signals and form a pulse signal that is then transmitted to the instrument display unit.

This technology provides various beamforming capabilities that improve the accuracy of AE monitoring in the context of AM nanocomposites. This enables the localization and targeted detection of acoustic signals linked to damage or deformation. A more thorough knowledge of the structural integrity of nanocomposites is made possible by the technology's capacity to modify the ultrasonic beam's angle and focal point, especially in areas where the distribution of nanomaterials may be uneven. Combining inhomogeneous dispersion analysis with ultrasonic phased array technology provides a comprehensive picture of any possible weak spots or integrity-compromised locations [26].

As a non-contact technique, eddy current testing adds more depth to evaluating inhomogeneous dispersion. Variations attributed to inhomogeneous dispersion can be identified by modifying this technique for assessing nanocomposites' electrical conductivity and magnetic permeability. In eddy current testing, measurements of the alternating current field [27] are essential to comprehending the electromagnetic response of nanocomposites. These measurements enable a thorough assessment of the material's overall quality, particularly concerning the uniform distribution of nanomaterials, by illuminating how the material reacts to varying magnetic fields and electrical currents.

When evaluating AM nanocomposites, one of the most important factors is the uneven distribution of nanoparticles inside the matrix. A multidisciplinary approach is needed to address this challenge: advanced imaging, eddy current testing with alternating current field measurements, thermal imaging with active pulsed thermography, acoustic emission monitoring, ultrasonic testing using immersion techniques, and Ultrasonic Phased Array Technology must all work together. Such a phenomenon is called as ‘data fusion’. This thorough assessment guarantees a sophisticated comprehension of the internal structure of the nanocomposite, empowering researchers and engineers to recognize, measure, and manage differences in the dispersion of nanomaterials. This level of comprehension is becoming more and more necessary as NDE techniques advance to realize the promise of AM nanocomposites in various industries fully.

5. CONCLUSIONS

The key for the success of industry 4.0 is inevitable without the integration of non-destructive evaluation. Based on the mode of production (i.e. batch or mass), the various NDE techniques are integrated into in-situ and ex-situ examinations. While the in-situ technique examines the quality of fabrication while the components are additively manufactured, ex-situ examination technique inspects the product post-fabrication. This study gives a valuable insight into the number of ways, in which NDE techniques can be integrated into additive manufacturing line. NDE integrated AM process is of significant importance in the fabrication of composites which are often dealt with interface delamination, improper adhesion, crack propagation, and failures. This paper reviews various studies wherein additive manufacturing of ceramic matrix composites and metal matrix composites are significantly improved by NDE techniques. With the promising future of AM, it is obvious that NDE techniques would find an irreplaceable role in the Industry 4.0 sub-functions.

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Data availability: The data will be made available upon request to jcp@mail.ntut.edu.tw.

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Future of Non-Destructive Testing in the Era of Additive Manufacturing and Machine Learning

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Abstract

Additive manufacturing (AM) methods have become mainstream in many industry sectors, especially aeronautics and space structures, where production volume for components is low and designs are highly customized. The frequency of launching space missions is increasing around the world. Some of these missions are sending landers and rovers to moon, mars, and other planets. Such space structures require numerous parts that are unique in design or are produced in just one or a very small production run. Such parts produced for high stake and very expensive missions require complete confidence in the quality of each part. Characterization of parts manufactured by AM is a significant challenge for many existing methods due to the geometric complexity, feature size in the structure, and size of the part. This paper discusses various challenges in applying current characterization methods to the AM sector. Machine learning (ML) methods are considered promising in materials and manufacturing fields. However, generating the training dataset by creating a large number of parts is expensive and impractical. New methods are required to train the ML algorithms on small datasets, especially for parts of unique geometry that are produced in limited production run such as space structures.
Keywords: *non-destructive testing, additive manufacturing, machine learning, thermal imaging, artificial intelligence.*

1. INTRODUCTION

Manufacturing has gone through three industrial revolutions and is now well into the 4th revolution [1]. The third industrial revolution (IR3) was focused on automation for large-scale production of parts to make them cheaper and widely available. Various kinds of manufacturing machines and methods developed in IR3 enabled production runs from a few thousands to several millions, where economy of scale ensured that the cost of each part decreased as the size of production run increased. Such methods allowed economical production in many sectors at large scales. For example, almost 90 million automobiles were produced around the world in 2023. Most of these cars were produced by a small number of companies of a handful models, which leads to many components to be manufactured in millions of quantities as original and replacement parts. There are many such examples in the industrial production sectors where production runs are in millions. Such large production runs require a complete ecosystem for testing and characterization because testing each component for all desired parameters is impractical and expensive.

The current methods of materials characterization can be divided into destructive and non-destructive methods. These methods work in conjunction with each other to provide the desired parameters that range from microstructure and defects to mechanical properties. These test methods are governed by standards that are developed by technical societies such as American Society for Non-Destructive Testing and American Society for Mechanical Engineers or national boards created by governments of various countries. The focus of the fourth industrial revolution (IR4) on individually customized products manufactured using general purpose machines such as 3D printers has made it difficult to apply the existing principles of materials characterization to these limited production runs. The present article is focused on analysing the role of existing materials characterization methods as additive

manufacturing (AM) and machine learning (ML) become mainstream in the manufacturing field and the needs for developing next generation non-destructive testing (NDT) methods incorporating AM and ML for objectives such as defect detection and mechanical property measurements.

2. DIGITAL MANUFACTURING

One of the main thrusts of IR4 is to introduce network connectivity in the entire manufacturing process chain, from the design to manufacturing to materials characterization stages. Even though companies may not connect their printers to internet due to the potential cybersecurity vulnerabilities, they may create an intranet within their company to connect designers to printers [2]. An example of such system is shown in Fig 1, which is called digital manufacturing (DM). The DM system is based on the connectivity and all the steps are based on the flow of data until the physical object is produced on the 3D printer. There are several other manufacturing methods that can also be connected in such a system. For example, toolboxes are available for CNC machines to connect them in a DM system. It is well understood that the development of AM methods will not replace the traditional manufacturing methods, rather they will provide additional options to select the appropriate method based on the part design and material. Over time many other traditional methods will be connected in such data driven networked systems. Hence, DM represents a larger concept of manufacturing system, where actual manufacturing is only one of the many steps and the actual part may or may not be manufactured by AM. The entire DM system can be connected to the same cloud platform.

3. NON-DESTRUCTIVE TESTING APPLIED TO ADDITIVE MANUFACTURING

One of the major benefits of AM is the production of small number or even a single part without having to apply the economy of scale. In addition, a flexible production method like AM can switch between manufacturing parts of different designs without having to change any dies, molds or tooling. The traditional testing scheme based on large production run has many steps, which include sampling of parts based on statistical analysis followed by testing a small number of parts for destructive and non-destructive testing. Usually a number of replicas of a part are tested and statistical analysis is conducted on the data.

3D printers, as well as many other manufacturing platforms such as additive-subtractive hybrid machines, can be heavily instrumented with many different kinds of sensors such as temperature sensors, vibration sensors, acoustic emission sensor, optical cameras, and thermal cameras, among many others as shown in Fig 2. These sensors provide continuous information when the part is being printed. The information obtained from these sensors can be used to verify the print parameters or find a defect while the part is still being printed. Use of optical and thermal cameras has allowed obtaining real time information on defects right at the onset of these defects as the part is still being printed. A comprehensive review of in-situ monitoring methods for subsurface and internal defect detection during additive manufacturing has been published previously [3]. Early detection of parts allows the possibility of implementing intervention to either repair the defect or discard the print early without wasting time and material in completing a defective print. Hence, there is a strong interest in the AM field for applying in-situ NDT methods to improve the process quality and economy. AM equipment based on material extrusion and powder bed processes often either come with many types of sensors already installed or an option to install sensors and cameras.

3.1. Defect Detection in Additive Manufacturing

A significant amount of literature is now available on the use of sensors for process monitoring and control during AM. If the product quality is not satisfactory based on various observation methods, including direct visual observation, observation of camera feed or sensor readings, then the parameter set can be adjusted to improve the quality.

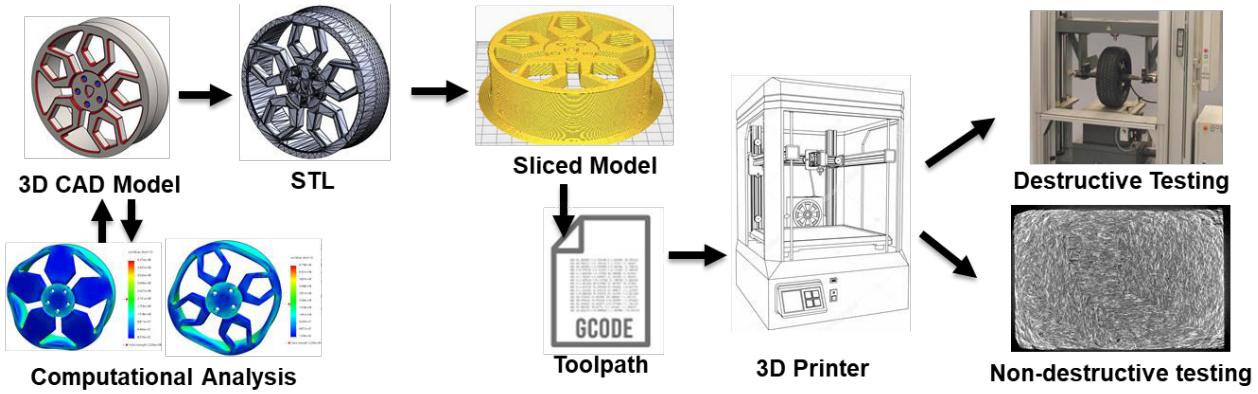


Fig 1. Digital manufacturing process chain that includes all the steps from design to characterization connected and driven by data files.

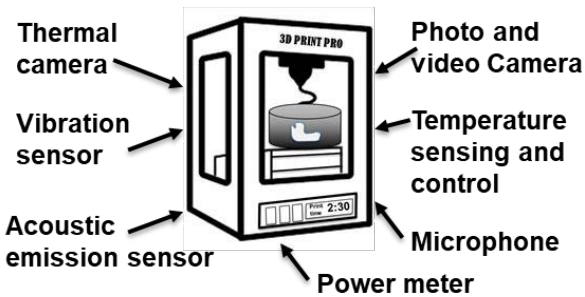


Fig 2. An example of many sensors that can be mounted in a material extrusion 3D printer.

In addition, determination of defect type, location, size and orientation are important for a manufactured part. Optical and thermal cameras have been widely used for monitoring of in-process print quality of individual layers in AM [4, 5]. An example of the use of optical and thermal cameras in a fused filament fabrication (FFF) 3D printer is shown in Fig 3. The results of defects detected from such methods have been compared with those from other methods such as ultrasonic imaging [6]. Post-manufacturing NDT methods such as ultrasound, radiography and CT-scan have been used for defect detection in AM parts [7, 8]. However, quality determination and defect detection during the manufacturing process itself can make this process significantly faster and cheaper.

3.2. Embedded Feature Detection and Recognition

The undesired features occurring inside the structure of a part are usually defects in traditional manufacturing methods. However, a unique feature of AM compared to the most other manufacturing methods is the capability of embedding features deliberately inside the structure of a part due to the layer-by-layer construction process. Fig 4 shows an example of a QR code embedded inside a part. The code can be embedded either in one layer or segmented in a number of slices and each slice can be embedded in a different layer for making it difficult to decode it [9, 10].

Non-destructive imaging methods are required to read such embedded codes without having to section the part. There are several challenges in reading the embedded codes intended for product identification or authentication. These codes are usually designed considering the minimum printable feature size of a particular 3D printing method so that their presence does not compromise the microstructure. It is known that the information can be lost in STL conversion or slicing of the part if the STL resolution or the slice thickness are not appropriately selected to preserve the required information. A variety of methods such as radiography, CT-scan and ultrasonic imaging can be used to read the embedded codes. Among these techniques, ultrasound has the lowest resolution and can read larger size codes, while CT scan and radiography are able to read the individual features that are in the range 5-10 μm or even finer, depending on the material type, feature orientation and scan settings.

In addition to embedding information inside the part structure, sensors are also embedded to monitor temperature, strain, or many other parameters in the additively manufactured parts and it is required to extract the data from these sensors without having to damage the part [11]. NDT methods can help in locating such embedded sensors and preserving them.

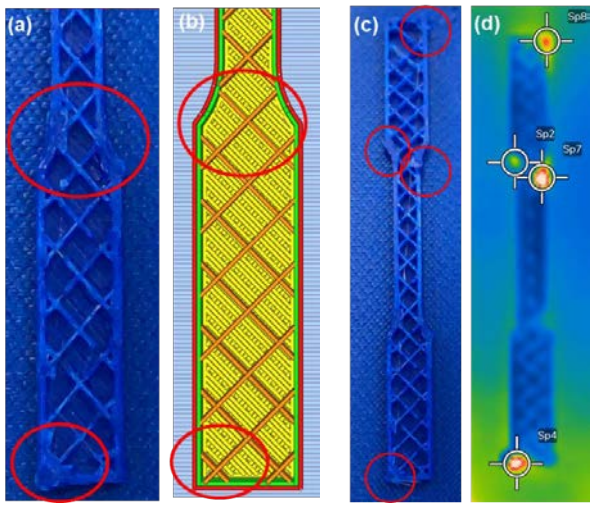


Fig 3. (a) An image captured from optical camera compared with the (b) digital twin to find defect. (c) An image obtained from optical camera compared with an image obtained from (d) thermal camera for finding defects in sub-surface region.

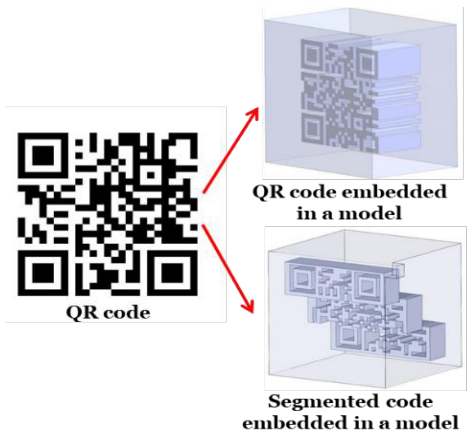


Fig 4. AM allows embedding information inside a part. The information can be embedded either in one layer or in multiple layer. Non-destructive imaging methods are required to read the embedded information.

3.3. Mechanical Property Measurement During Manufacturing

Mechanical properties of the manufactured parts need to be measured to ensure their quality. In the current practice the mechanical properties are measured only after the part is manufactured and taken off the built plate. However, this approach has several limitations. The first limitation is that if there is a defect in the part then the detection of a defect during the manufacturing process itself by a camera would inform about the defect but is not able to determine the level of mechanical property loss. In such a situation, researchers have considered several options, which include conducting finite element analysis with a defect in the structure to assess the reduction in mechanical properties. However, the methods to directly measure the mechanical properties of an object during the manufacturing process are currently unavailable. Enhancing the capabilities of NDT methods for mechanical property measurement is extremely important for AM methods. NDT methods such as ultrasound have shown capabilities of measuring Young's modulus from the measured wave velocity and attenuation inside a specimen [12, 13], however, application of such methods inside the print chamber of a 3D printer is very challenging because it needs air coupling and the temperature is high inside the build chamber.

4. MACHINE LEARNING IN MANUFACTURING

ML methods are now widely used in materials and manufacturing research. The field of new material development has particularly benefited from machine learning methods where trained algorithms can be used to identify promising compositions from a large number of possible compositions [14]. In manufacturing domain, ML methods have been very helpful in optimizing the process parameter sets containing hundreds of parameters involved in AM methods. The specific challenges involved in using NDT methods in AM and DM ecosystems are described below.

4.1. Machine Learning Challenges in Additive Manufacturing

Optical and thermal cameras have now become an integral part of 3D printers. These cameras can be configured to obtain images at regular intervals, which could be one image per layer or images obtained at a set time interval. In large dimension parts the imaging methods may acquire hundreds to thousands of images in each build. Processing of such large number of images manually in a reasonable amount of time is impossible. ML methods have provided a powerful tool in analysing these images for detection of defects and anomalies compared to the more traditional batch processing methods. However, there are numerous

challenges in applying the ML methods to AM at the production scale level.

The images acquired from the built plate often required substantial pre-processing. Even if the lighting is well adjusted before the start of the print, the increasing height of the print in many 3D printing methods creates shadow effects and other imperfections in the images. Hence, the acquired images often require contrast correction, brightness correction, cropping of the image to obtain only the desired region and other image enhancement steps. In addition to fine tuning parameters for each of these corrections, the large size of the database is still a challenge for processing the images in real time for defect detection so that possible interventions can be implemented. The image data set can be processed using compression methods or filters to reduce the size of these images without compromising the features that need to be identified. Fig 5 shows an example where a Laplacian filter is applied to an optical image to reduce its size, which has also increased the clarity of the image for featured detection. While a large number of images are obtained during a single build, the use of AM methods for producing unique or low production run parts makes it difficult to generate a large training data set to train the ML algorithm. Innovative methods are required for training of such algorithms. As one of the possibilities, the digital twin of the part is always available that can be compared with the acquired images to identify deviations from the design and label them as anomalies generated during manufacturing. The data acquired from multiple channels such as optical camera and thermal camera can be compared to improve the accuracy of feature detection.

4.2. Machine Learning Challenges in Digital Manufacturing

As depicted in Fig 1, the DM ecosystem comprises of a number of steps that start from the part CAD model development, toolpath development, and part manufacturing. Ideal DM process will include sharing the data from each step to the same database and using this database to train ML algorithms that can predict the part quality and also drive the part design development based on the data obtained from the previous builds.

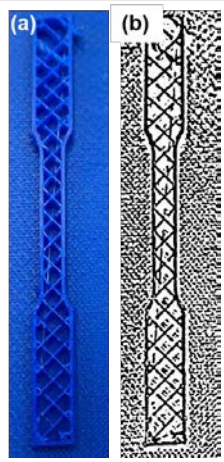
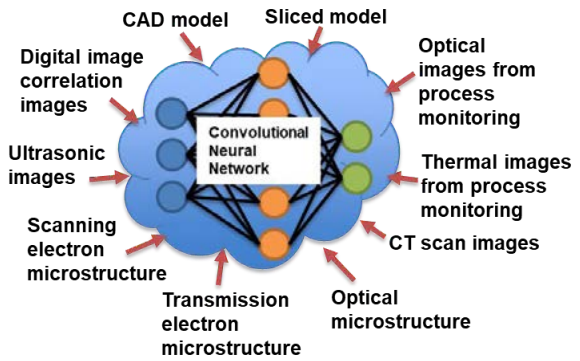


Fig 5. (a) Optical image of a specimen while it is being 3D printed and (b) Laplacian of the image showing improved brightness, contrast and feature details.

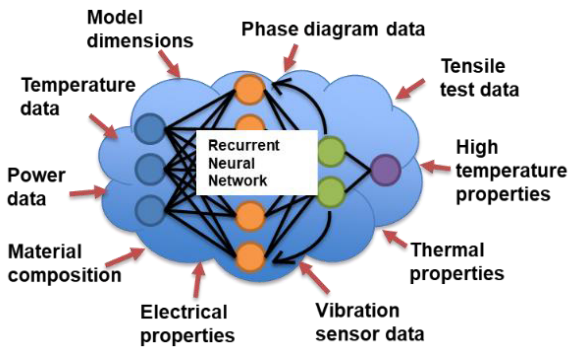
4.2.1. Nature of Different Data Stream

The significant challenge in developing the database backbone for the entire DM is that the data obtained from various steps are in several different formats which are not compatible with each other in the same machine learning algorithm. For example, the CAD programs provide output as proprietary format CAD files, the process parameter data from 3D printers can include images as well as time and frequency domain data streams. Different types of ML algorithms are available to effectively handle the data coming in such different formats. New algorithms or ML methods are required to integrate all types of data streams on one platform and conduct the part design from the information generated in the previous build.

A number of different ML algorithms are available. Many of these algorithms are designed to work efficiently with different type of data streams. For example, convolutional neural networks (CNN) are a class of deep learning algorithms that are used for classification and object identification in images (Fig 6a). Recurrent neural networks (RNN) are widely used for time series data (Fig 6b).



(a)



(b)

Fig 6. (a) A convolutional neural network with various possible input image streams and (b) a recurrent neural network with possible input data streams.

There are many other neural networks available that specialize on different types of data. Once the CNN and RNN are trained with the available data on processing conditions, raw material properties, material microstructures, mechanical properties and destructive and non-destructive testing data, their outputs need to be designed carefully to provide useful synergistic information to improve the process or the material.

The Industry 4.0 roadmap aspires to develop ML platforms that can host such a variety of data streams, process them and then use the output to drive the manufacturing innovation automatically by making decisions about the design modification, process improvement and product quality assessment. This automated manufacturing cycle coupled with the customized design of each product eliminates the possibility of destructive testing and can only be sustained by implementing the next generation NDT methods as integral part of the system.

4.2.2. Challenges Related to Training Dataset Size

ML methods require large datasets to train the model. One of the limitations in material field is that manufacturing and testing a large number of specimens is very expensive. This is especially a challenge when unique products are being manufactured in small production runs. Innovative methods are required to generate large data sets that can train the ML models from a very small number of specimens. Fig 7 demonstrates one possibility where a CT scan dataset is used to generate a large number of images from the scan of a single specimen [15, 16]. This example shows in Fig 7a a reconstructed 3D model of a composite specimen having about 100 image slices. Fig 7b shows a single image slice where the fiber directions can be observed in a 3D printed specimen. This one image is sectioned into a grid of 18×18 sub-images in Fig 7c. Finally, each of the sub-images can be rotated by 360° angle at a step of 1° rotation. This kind of expansion scheme can generate over 11.66 million images from a single CT scan data set and can be used for training a ML model to identify the direction of fibers in the microstructure of a composite material. The number of images that can be sub-sectioned from a full image depends on the resolution and size of the features of interest. Image compression methods can be applied to reduce the size of the database and make the process faster.

Other methods of expanding the datasets may include using theoretical models to generate parametric plots and the data can be used to train the models. Finite element analysis, molecular dynamic analysis and multi scale models can be used for appropriate problems to generate data at different length scales to train the ML model. In many cases, the ML models are limited to conduct interpolation within the parameter ranges used for training the model. Nonetheless, ML models have been utilized to identify the material compositions that are promising for various applications or for predicting the properties of materials of certain compositions.

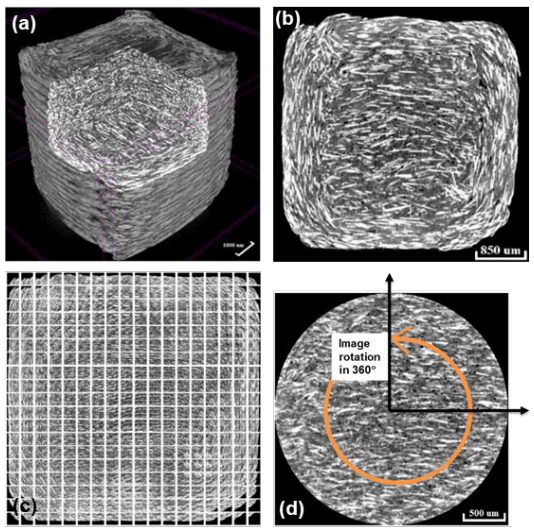


Fig 7. (a) A convolutional neural network with various possible input image streams and (b) a recurrent neural network with possible input data streams [15].

5. ROADMAP FOR NDT FOR INDUSTRY 4.0 AND BEYOND

The industry 4.0 framework of DM requires seamless connectivity among all parts of a manufacturing process and supply chain. As sensors are integrated in every part of the manufacturing process and the data acquired from these sensors are used to determine the influence of processing parameters on the part quality, it is of critical importance that the information obtained from the NDT methods is interpreted in terms of the mechanical properties of the manufactured parts. Search relations are currently missing for most of the methods in the published literature. Although ultrasound has shown limited use in measuring the Young's modulus of metallic materials, high wave damping in the polymer materials makes it difficult to apply the same framework for calculating the Young's modulus of polymeric materials. Accurate prediction of Young's modulus of polymeric materials requires expanding the existing framework to soften materials to account for their viscoelastic nature and high damping.

While research continues in extending the capabilities of NDT methods to measure the mechanical properties of different types of materials, meanwhile, it is of immediate interest to find new methods to reduce the traditional test matrix so that fewer parts are needed for destructive and non-destructive testing. Traditional test matrices require testing at least five replica specimens for each test to obtain their properties over a wide range of parameters such as temperature strain weight frequency and environmental conditions. The existing NDT methods do not guarantee detection of every defect in the specimen and have their own limitations [17], which now need to be interpreted in terms of AM process. New methods are being developed that can provide cross-correlation between the properties under different kinds of loading and environmental conditions so that only a few specimens are tested to obtain properties over a wider range [18].

It is also important to consider the skillset that will be required in the NDT professionals as the testing methods and requirements change in the industry 4.0 framework. It is expected that increased automation combined with machine learning methods will lead to automatic data acquisition and processing. In such case, the personnel involve in this process will have different roles ranging from only maintaining the equipment to decision making based on the processed data provided by the system. Eventually the decision making may also be taken over by the trained ML algorithms when enough confidence in their capability is reached. Development of new NDT methods for industry 4.0 environment, where these methods can be implemented in or alongside the manufacturing machines, well remain as a major priority and an area of growth. It is likely that the imaging and image processing skills will gain more prominence in the NDT field in the coming years.

6. CONCLUSIONS

The industry 4.0 framework is now firmly established in manufacturing sector where it is leading to a revolution by connecting the machines, implementing sensors for acquiring data and developing machine learning methods to process the data automatically. The role of NDT methods is enhanced in such manufacturing environment where data obtained directly from the manufacturing machines needs to be interpreted in terms of embedded defects or mechanical properties of the manufacture parts. It is expected that the industry 5.0 framework will include a more human centric approach where individuals involved in the process will move to higher level roles such as new method development, supervision of the system, and decision making based on the sensor and ML algorithm outcomes. To prepare for such future, not only development and deployment of new NDT methods is required but also preparing a trained workforce is essential. As the machines and processes become more

and more connected, there will be additional requirements such as cybersecurity [19], which are not yet of focus in this field. However, such requirements will play a central theme in the next industrial revolution.

ACKNOWLEDGMENTS
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X-Ray Computed Tomography for Holistic Inspection of Additively Manufactured Heat Exchangers

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Abstract

Additive manufacturing provides a unique opportunity to create complex parts without the need for extensive tooling. This capability has led to a significant reduction in assembly requirements, opening the design space to create efficient and compact heat exchangers. As the additive manufacturing (AM) industry progresses towards producing complex parts and fully assembled products, existing dimensional measurement tools are proving to be insufficient for qualifying these components. Moreover, traditional part defects that could lead to leakage or cross-mixing of fluids become harder to inspect.

Since most AM processes produce a rough surface, and the internal surfaces in heat exchangers are not available for inspection or surface-smoothing treatment, it is even more imperative that the parts are printed with the correct print parameters to produce as smooth and defect-free surfaces as possible. All these inspection challenges could be addressed using X-ray CT, and the technique can also prove to be a holistic inspection tool, addressing even raw material for impurity, size, and shape, as well as for developing print parameter optimization for a known or a novel material.

Keywords: *X-Ray CT, dimensional measurements, powder characterization, porosity detection, surface roughness.*

1. INTRODUCTION

Most new heat exchangers applications are space-constrained, with increasing thermal requirements driving a need for smaller, more efficient designs. There are many studies describing advantage of producing additively manufactured heat exchangers, main advantages being ability to create efficient large surface area and low in volume and weight heat exchangers, reduction in assembly from hundreds of components just to one, reduction in brazing and welding, which often leads to quality issues which are hard to address. However, as these parts get very complex and fully assembled, quality checking becomes difficult without destroying the part. The traditional dimensional measurement and dye penetrant test does capture all the quality related issues such as through pores & cracks, which can lead to intermixing of the fluids, residual powder, deformation, dimensional inaccuracies, and surface roughness, which can have a huge impact on the performance of the heat exchanger.

X-ray computed tomography (CT) is a widely used non-destructive inspection tool and is best suited for the complete evaluation of the additively manufactured heat exchangers. There are number of publications showing the use of X-ray CT from powder quality inspection[1,2], defect detection[3–6] as well as dimensional measurements[7–11]. It offers non-destructive imaging of a broad range of materials in three dimensions, and is particularly valuable for understanding critical aspects in process development, and optimization of print parameters especially for the widely used laser powder bed fusion process, calibrating in-process monitoring observations, etc. One advantage of X-ray CT over the other technologies is that the data will be acquired once

and subsequently, various analysis can be performed on the same dataset.
In this paper using the example of Additively manufactured heat exchangers, we will explore the use of X-ray CT to qualify the entire LPBF process chain starting from powder to the finished article and even explore the how the CT can be utilized in the failure analysis of the AM products using an example of additively manufactured parts.

2. BASIC PRINCIPLES OF X-RAY COMPUTED TOMOGRAPHY

In this paper we will cover the basic minimum of the X-ray CT technology needed to follow the paper, however for the most comprehensive review of the X-ray CT, image reconstruction and CT analysis please read the given references [12–17]

In principle, an industrial X-ray CT set up consists of three main components, X-ray source, X-ray detector and rotating sample stage where the parts are placed. When X-ray pass through a sample, depending on the composition and thickness of the sample, some of the X-rays gets absorbed and remaining gets transmitted through the sample towards the detector to create an image. The amount of X-rays that get absorbed is given by the Beer-Lamberts law, where the initial X-ray intensity (I_0) decreases exponentially as it passes through the material with linear absorption coefficient (μ) the distance (x) it travels through the material. To simplify it further, denser materials such as metals have higher linear absorption compared to air / polymer, so metals have X-ray absorption. If the material is composed of multiple materials, then the total amount of X-ray transmitted can be calculated by equation below.

$$I = I \qquad (\sum \mu$$

There are three main controls that affect image quality. The voltage differential applied across the anode and cathode controls the X-ray energy, i.e., higher energy X-rays have better penetration ability through denser material. The second control is the current, which controls the X-ray brightness, and this enables better image quality with lower noise. The third control is the X-ray focal spot, small spot on the anode from where the X-rays are generated. This controls the sharpness of the image; a small X-ray focal spot produces shaper images compared to larger focal spot, however there is limit of power (Current * voltage) that can be generated from a smaller focal spot (~1W/µm^2). For a given detector, there are several controls as well, the most important ones being the exposure time and frame averaging. Both are aimed towards correct contrast and noise level in the image.

3. MATERIALS AND METHODS

In this paper, our primary focus is on X-ray CT analysis, exemplified through two distinct types of additively manufactured heat exchangers. Both were produced using the Laser Powder Bed Fusion (L-PBF) technique with EOS M290 (EOS Gmbh) printers employing AlSi10Mg material. Through the example of manufacturing of the AM Heat exchanger journey we would like show the versatility of X-ray CT in all aspects of AM (see Figure 1) from the powder to the qualification of the finished part.



Fig 1: Figure shows a typical L-PBF workflow from powder to the finished part. X-ray CT can be used in all the stages of the process either for the quality inspection or as feedback tool for the process development process.

The first example is a fuel-oil cooler (figure 2), part of the sustainment program by the University of Dayton Research Institute. This program aims to maintain the supply chain of old and acquired parts in the sustainment program.

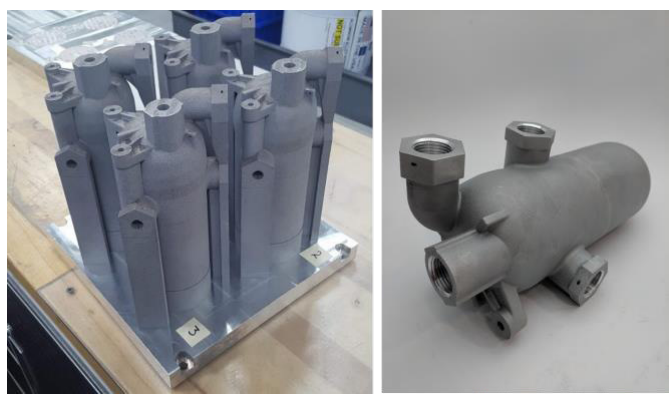


Fig 2: Figure shows additively manufactured shell and tube heat exchanger on the build plate (left) and after heat treatment and removal from the build plate. (right).

The second type is a scaled-down model created by Raytheon Technologies (United Technologies

Corporation), serving the purpose of understanding specific print parameters (Figure 9).

Although these two studies had different end goals, we present them collectively here as they cover various aspects of quality issues. All parts underwent depowering, stress relief, removal from the build plate, and support removal before the scans were conducted. X-ray CT scans were carried out using Metrotom 800HR and Xradia Versa 620 from Zeiss Industrial Metrology. 3D image analysis was performed using VG Studio and Mountains to evaluate surface roughness.

Our paper delves into CT analysis with a focus on typical quality issues, such as defect detection, deformation, depowering, and surface roughness resulting from the manufacturing process or requalification of the heat exchangers post-use or testing. In this paper, our primary focus is on X-ray CT analysis, exemplified through three distinct types of additively manufactured heat exchangers. All three were produced using the Laser Powder Bed Fusion (L-PBF) technique with EOS M290 printers employing AlSi10Mg material.

4. POWDER CHARACTERIZATION

X-ray micro and nano CT are well-suited for characterizing the metal powder used in Laser Powder Bed Fusion (LPBF) due to its smaller particle size. To capture details of the powder particles in post-imaging analysis, it is recommended to have a high definition of the particle with at least 20 voxels across the diameter. This limit dictates the type of CT scanner needed to analyze the powder particles and still obtain a statistically significant number of particles in a single measurement.

X-ray microCTs with a resolution of 1um/voxel are necessary to characterize smaller particles ranging from 5-40um, although coarser resolutions can be used for e-beam and other applications. In this example, we measured AlSi10Mg powder with X-ray microCT at 0.6um/voxel resolution(figure 3). The advantages of X-ray microCT for inspecting powder over typical light scattering or 2D imaging using light microscopy lie in the ability to capture the entire 3D volume, determine contaminants/inclusions, and observe internal porosity (figure 4). Additionally, in a single scan, it is possible to capture >10,000 particles, providing better statistical characterization.

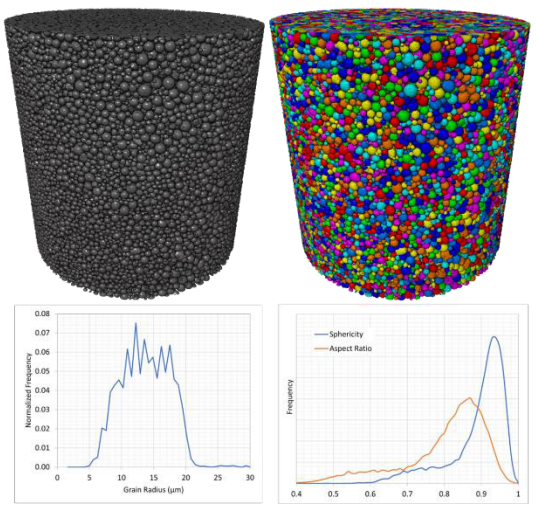


Fig 3: High resolution CT scan and analysis of AlSi10Mg powder. (a) 3D visualization showing grayscale image of a CT scan (b) Image analysis showing paritcle seapration (c) particle size analusis and, (d) particle shape analsysis

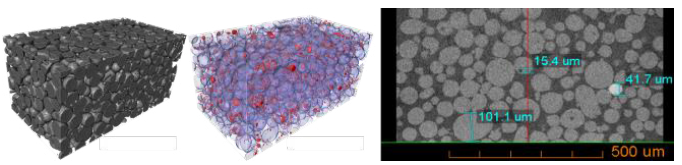


Fig 4: Figure showing porosity within the powder particles inspected using X-ray microCT at 600nm/voxel resolution. Left images shows a grayscale volume and image on the right is the same volume with material made transparent and pores colored red. Image on the right shows a bright powder particle which in contaminant of higher density material (Inconel) compared to the AlSi10Mg due to incorrect powder handling.

5. PARAMETER DEVELOPMENT

Parameter development includes optimizing laser power, velocity, spot size, part position in the printer, gas flow, layer thickness, and various other parameters associated with the laser or the printer to achieve prints free of porosity, with minimal surface roughness, and geometric deformation. The parameter development process often involves

printing coupons, cutting, and polishing them to determine porosity. Similar to density coupons, specific coupons are printed to ascertain optimum print parameters. However, this process can be time-consuming, expensive, and only offers a partial solution.

X-ray CT plays a crucial role in replacing many prints and the time-consuming coupon preparation process. Since X-ray CT provides an internal view of the entire sample, it can inspect coupons and offer rich data on porosity, deformation, and even surface roughness. To expedite the inspection process, we have designed coupons that combine multiple features, such as bulk and contour porosity, various wall thicknesses, cylinders, as well as inclines at multiple angles to determine multiple geometry-based optimums within a single build. The process is further accelerated with the use of deep learning-enabled model-based iterative reconstruction (details can be found in this reference [18,19]

The results in figure (5) illustrate such a parameter development process for a novel Al-Ce alloy with very high thermal performance, suitable for heat exchanger applications.
In a similar study with AlSi10Mg, conducted with just 8 coupons, we demonstrate that the parameters producing the least number of defects within the same build may not necessarily be the best parameters to produce thin wall features typically used in heat exchangers (figure 6). This process allows us to map out geometric feature-based optimums within a single build.

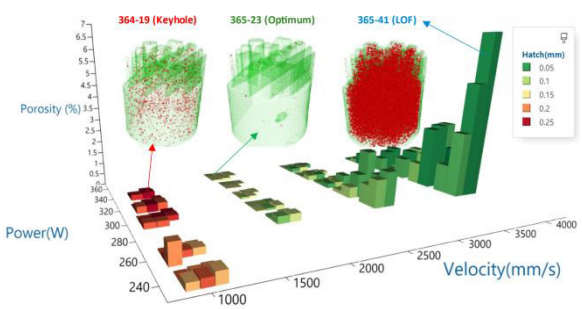


Fig 5: Figure showing print parameter optimization process with the aid of X-ray CT.

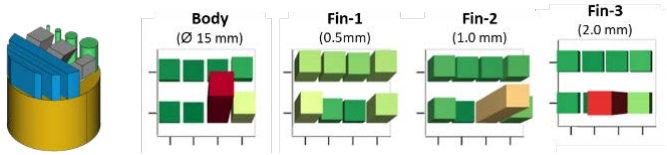


Fig 6: *Figure showing various features of the parameter testing coupon. Plots shows the porosity map chagning as we isolate just the bulk or the fins.*

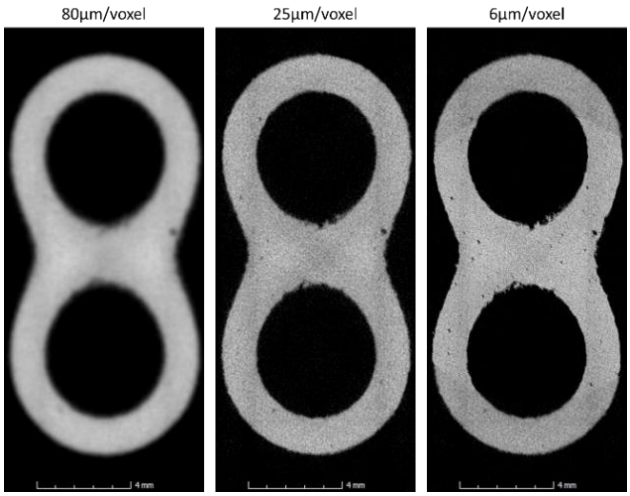
6. POROSITY DETECTION

Porosity detection has been the primary application of CT in many industrial processes such as casting or additive manufacturing. However, when it comes to additively manufactured heat exchangers, which are designed as single fully assembled parts, detecting defects like porosity, through-pores, or cracks becomes challenging. X-ray CT emerges as a valuable non-destructive inspection technique.

As discussed in the X-ray CT section of this paper, inspecting the entire part proves challenging due to poor resolution, making only large pores visible. To address this limitation, guided multi-resolution imaging is suggested, where an overview image guides higher resolution inspection. In figure 7, porosity, especially keyhole pores, becomes visible, and increasing magnification uncovers successively smaller-sized pores. Detecting pores and cracks using X-ray imaging requires a resolution of at least three times higher than the smallest feature size to be detected. Achieving a fine balance between scan time and resulting image quality is crucial.

In the example of the shell and tube heat exchanger, the part was first inspected to get an overview of the entire heat exchanger system. Given the large size of the part, the maximum resolution achievable was 80 µm/voxel. At this coarser resolution, the entire part could be inspected, but only large pores were visible. The part was then imaged at a higher magnification, where only a smaller portion of the heat exchanger was in the field of view but at higher resolution, revealing more pores. The same part was also

inspected using the Xradia 620, a nano-focus X-ray CT capable of producing much higher resolution, resulting in even smaller portions of the heat exchanger being revealed with more details. This highlights the importance of knowing the correct imaging techniques for the feature size. For instance, to inspect pores larger than 10µm, it is recommended that the part be inspected at 3-5 µm/voxel resolution. Additionally, it is worth noting that among other parameters, the size of the focal spot plays a crucial role in determining the true resolution of the CT scan. Therefore, small features are better inspected with nano/micro-focused X-ray sources compared to high-power larger focal spot X-ray sources.



Dimensional Measurement and Deformation

Fig 7: Figure showing multi-resolution inspection of a same small section of the heat exchanger imaged non-destructively at three resolutions.

With CT, one can measure once and perform various analyses, provided the resolution is sufficient. X-ray CT is also used for quantitative analysis to measure the size and shape of features in the part or compare them to the ideal part geometry for potential deformation. Dimensional analysis on the heat exchanger after stress relief revealed direct measurements such as wall thickness, diameter, and distance between features. Heat-treated LPBF parts may deform during the process. Comparing the X-ray CT scan of the part to the CAD drawing used in printing showed interesting features, with deformation changing around the baffles used for guiding the flow. Strain buildup during the print, relieved during heat treatment, causes the part to deform. This feedback is valuable for design for AM as iterations are made, and X-ray is crucial in the feedback process.

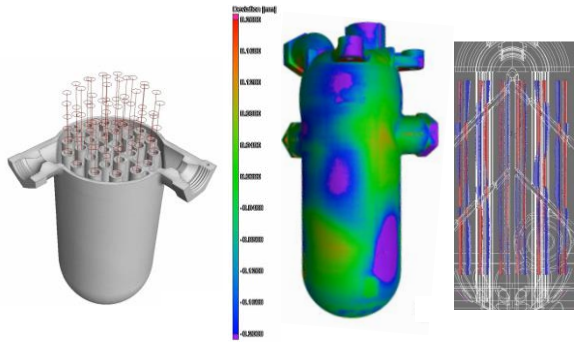


Fig 7: Figure showing dimensional measurement on a CT volume. (left) Measurement of diameter, thickness, and straightness of the tubes, (middle) Heat map showing surface deviation from the CAD and (right), cross secton showing the deformation of the tubes comapred to the CAD model.

7. SURFACE ROUGHNESS

Additive Manufacturing (AM) offers the ability to create a very large surface area, typically needed for air-cooled heat exchangers, in a small volume. However, Laser Powder Bed Fusion (LPBF) produces rougher surfaces, and these rough surfaces increase the pressure drop needed to drive fluid through the heat exchanger, potentially negating any advantages achieved through advanced designs. Moreover, depending on the orientation of the printed surface, downskin produces significantly higher roughness compared to upskin due to printing on loose powder rather than continually building on fused layers.

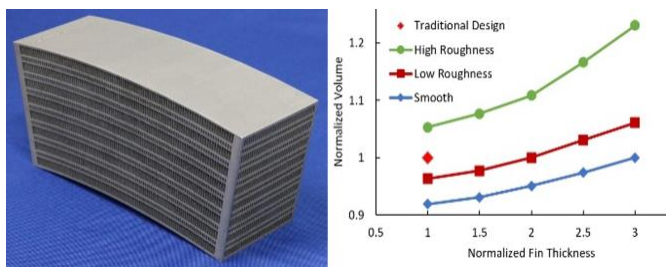


Fig 8: Figure showing the fin & plate heat exchanger designed to study the effect of CT image resolution on accurate determination of surface roughness. The plots on the right shows the detrimental effects of surface roughness on the effective performance of the AM heat exchangers.

A fin and plate heat exchanger designed to study surface roughness was scanned at various imaging resolutions and later cut open for imaging using confocal optical microscopy of the same surface analyzed with X-ray CT. We also explored the effects of CT scan resolution on various surface roughness measures. The part was initially scanned at 60um/voxel resolution to provide a complete view of the sample. However, finer features were not visible at this resolution. Increasing the image resolution using geometric magnification to 15 revealed more details, but a smaller portion of the heat exchanger could be scanned. To study the effect of image resolution on surface roughness measurement, we imaged the sample at a higher resolution (3.35um/voxel), showing very small pores and surface roughness. A confocal microscope at 0.6um/pixel resolution was used as the ground truth, revealing some issues at the intersection where measurement was not possible due to hindrance from the microscope optics.

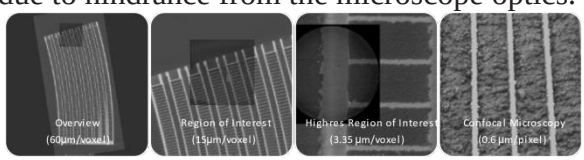


Fig 9: 2D Cross section showing CT scans at (a) 60um/voxel (b) 15um/voxel), (c) 3.35um/voxel resolution and (d) figure showing 3D rendering of confocal microscopy of a small section of the heat exchanger collected at 600nm/pixel resolution.

Once the CT scanning was completed, the section matching the confocal imaging was isolated from the 3D grayscale image. The surface was extracted from that region in VG studio using default settings and exported to the Mountains Surface Analysis and Metrology software for surface roughness analysis. Measurements were performed according to ISO 25178 procedures, including form removal, ROI extraction (~1.5 mm), micro-roughness filtering (Filter of 2.5 µm), and waviness filtering (Filter of 0.25 mm). Various 2-dimensional surface measures, including Arithmetic Mean Height (Sa), Maximum Peak Height (Sp), and Maximum Valley Depth (Sv), were extracted. The measured values are reported in Figure 11, showing a good agreement between optical and CT measurements in Sa values, even at coarser resolution. However, Sp and Sv are more susceptible to image resolution due because it often always suffers from the surface fitting, which can lead to over smoothing.

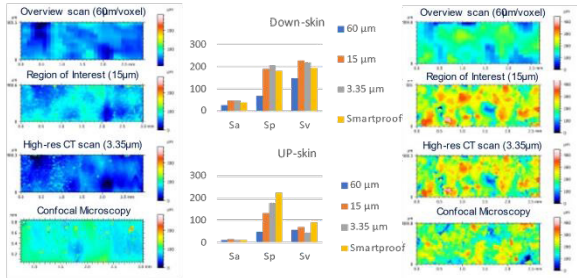


Fig 10: Figure shows the results of CT image resolution on both the smooth upskin (left) and rough downskin (right) surfaces. The graphs in the middle shows numerical values of three surface roughness measures as compared the confocal-optical microscopy imaging technique.

The CT with sufficiently high resolution can provide very reliable surface roughness estimates averaging over an area, however they are not ideal for single point features such as max peak or valley height.

8. CONCLUSION

In conclusion, X-ray CT is a highly versatile non-destructive tool for the comprehensive inspection of additive manufacturing (AM) parts, materials, and the qualification of AM process parameters. With increased availability, familiarity with this inspection technique, as well as improved speed and reduced costs, X-ray CT is transitioning from an R&D lab-based tool to a technology suitable for 100% inspection of high-value, complex components such as heat exchangers.

Traditionally, X-ray CT has been employed primarily for defect detection. However, this paper demonstrates that the inspection technique is also suitable for metrology on entire parts. It can be used to determine print accuracy, study the effects of heat treatment on part deformation, and ascertain 3D metrology on small powder particles,

including size and shape. Furthermore, we illustrate the effectiveness of CT in determining critical parameters of heat exchangers, such as surface roughness, which were previously inaccessible without cutting open the parts.

CT is powerful inspection technology, however there are a few limitations, and the user must be aware when analyzing CT results. The size of the part is inversely proportional to image resolution, and careful analysis of the resulting images is necessary to draw accurate conclusions. Material properties also play a crucial role; denser materials might require higher power, often limiting image resolution.

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Perspective and Challenges of Resonant Ultrasound Spectroscopy for Additive Manufacturing

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Abstract

Additively manufactured specimens are inspected by various non-destructive methods to detect inhomogeneities. To facilitate the inspection by ultrasonic methods, in this work, we emphasize the need to first identify the anisotropic elastic constants of the specimen. The experimental method and numerical procedure to estimate the constants by resonant ultrasound spectroscopy (RUS) are outlined. A simpler tensor-free method to estimate the resonant frequencies is derived. The challenges for a full-fledged use of RUS in additive manufacturing are presented.
Keywords: *NDT; ultrasonics; stiffness matrix; anisotropic, additive manufacturing*

1. INTRODUCTION

The use of ultrasonic non-destructive evaluation (NDE) techniques such as guided waves to identify material and geometric inhomogeneities require prior knowledge of the elastic constants of the material. The number of elastic constants ranges from two for an isotropic material to 21 for an anisotropic material [1]. Both destructive and non-destructive methods exist, each with its advantages and limitations. The tensile test is useful for isotropic materials but requires specific specimen preparation procedures for different types of materials [2]. The dynamic mechanical analyzer (DMA) estimates the static and dynamic properties (for frequencies < 100 Hz) of the specimens smaller than those used in a tensile test [3] [4]. The hardness test, although avoids sample preparation, is also limited due to the local destruction of the material in service [5] [6]. Further, hardness is largely applicable to isotropic materials and provides only the static properties of the materials. The ultrasonic time-of-flight diffraction method estimates the frequency-dependent elastic properties of isotropic [7], transversely isotropic [8], and orthotropic [9], anisotropic [10] materials. In tandem, guided waves were also used to estimate the elastic constants [11] [12] [13]. Both these ultrasonic methods are often suitable for specimens of size in centimeters or higher.

As industrial components are fabricated in bulk, small-sized specimens suitable for a specific destructive or ultrasonic NDE are machined, and the above-mentioned methods are implemented for the estimation of elastic constants. These material properties can then be used in the ultrasonic methods. Although successful, these methods cannot be implemented for all parts, due to limitations in manufacturing and new materials such as alloys. Due to the demand for lighter, thermally stable, and corrosion-resistive materials in aerospace and naval industries, alloys are being continuously developed using thermomechanical processors. While the general isotropic physical properties are measured by physical property measurement systems (PPMS) [14], all the elastic constants are determined by a technique called resonant ultrasound spectroscopy (RUS) [15]. The works of Demarest [16] and Zemanek [17] in the 1970s form the theoretical basis for RUS. In subsequent years, due to their experimental and numerical efforts, Migliori [18] of Los Alamos National Laboratory and Maynard [19] of Pennsylvania State University are widely credited as the pioneers for the development of RUS. This method involves exciting the millimeter-sized specimens with an ultrasonic signal and measuring the displacement at various points on the surface of the specimen. The displacements are analyzed to determine the dominant set of frequencies –- referred to as resonant frequencies. The specimens are either in the form of a cylinder or cuboid. As the frequencies of elastic waves used for the measurement are in kHz or MHz, the size of the metal and ceramic specimens is in millimeters and that of polymer specimens is in cm. RUS was also used to establish the properties of

carbon- and glass-fiber composites, polymers, and ceramics. Recently, RUS was also used to measure the constants of a layered medium [20]. Further, RUS techniques have been extended for nonlinear elastic regimes [21] and high-temperature measurements [22] [23].

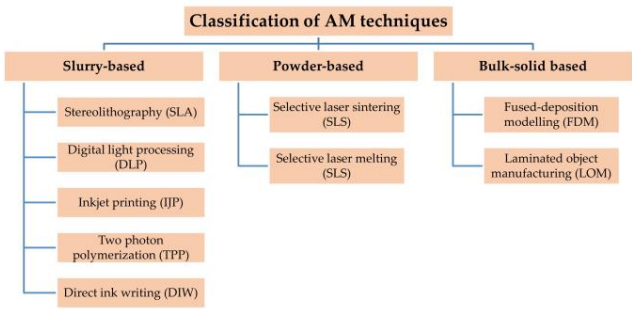

Fig.1 Summary of additive manufacturing (AM) techniques for ceramics.

In recent years, methods of additive manufacturing have led to rapid prototyping of structures, aiding the development of mechanical, acoustic, and electromagnetic metamaterials, as well as bulk specimens including rocket parts [24], [25]. Several specific methods exist for fabricating structures suitable for metamaterials catered for a specific spectral regime [26]. A summary of such additive manufacturing methods is shown in Fig. 1. Specialized methods have evolved for metals, polymers, and ceramics. All these methods are excellent at producing complex structures, functionally graded materials, and composites [27]. A higher precision can be achieved by post-production processes. Like traditional extrusion-based or thermomechanical processing, methods of additive manufacturing can also lead to anisotropy. For example, even in a simple method such as direct ink writing, anisotropy and gradients in material properties occur due to the direction of the solidification; the temperature of the substrate [27], [28]; distribution in the size, shape, and orientation of the particles; and porosity [29] [30] [31]. In addition, post-processing methods such as freeze-drying [32], thermomechanical annealing, sintering [33], [34] can also create anisotropy. As the complexity of additive manufacturing increases, a greater number of operating parameters can influence the anisotropy of the component made.

For robust day-to-day operations and establishing the structural integrity of the metamaterial, it is essential to know the elastic and plastic properties of the material. The knowledge of anisotropic properties is helpful for advanced applications [35]. Various NDE techniques have already been developed for the inspection of additively manufactured materials [36] [37]. With some methods already catering to in-situ measurements [38], a huge need exists for the rapid inspection of the parts [39]. Further, similar to the inspection of traditional materials, the components manufactured by additive manufacturing also needed to be evaluated for the presence of defects. Knowing the value of elastic constants, the defects can be quantified. Keeping these in view, in this work, we present a brief review of the use of RUS for the measurement of all the elastic properties and the challenges ahead.

2. RESONANT ULTRASOUND SPECTROSCOPY

As evident from the name, the technique relies on identifying the resonant frequencies of the material. Estimating elastic constants involves exciting the specimen at a point, measuring the displacements at various points on the specimen, and identifying the dominant frequencies. Thereafter, starting with an estimate of the elastic constants, the resonant frequencies of the specimen are numerically identified. A functional minimizing the difference of the experimentally and numerically identified frequencies is posed and the elastic constants are optimized iteratively until a convergence is achieved. We first present the experimental procedure, theoretical basis, and numerical intricacies.

2.1. Experiment

The specimen of interest is machined or fabricated into a cuboid or a cylinder to a characteristic length of 5-8 mm. Based on a guess value of the elastic constants, the size of the specimen is chosen to have its resonant frequencies lie within the bandwidth of the transducer; the details are explained in Sec 2.2. The schematic of the RUS setup is shown in Fig. 2.

Two ultrasonic piezoelectric transducers, with one working as a transmitter and the other as a receiver are used and these hold the specimen with minimum point-like contact. The transmitter is activated using a function generator-cum-amplifier. For RUS purposes, recently, a portable (10 cm × 5 cm × 1 cm in size) field programmable gate array-based device named

Red Pitaya [STEMLab125-14, RS Group plc, London] has been successfully used to generate and amplify the low-voltage signals. Upon a trigger, the transmitter excites the specimen and the displacement at another point is measured by the receiver. This process is repeated at multiple pairs of points. The received signals are subjected to Fourier transform to determine the dominant (or resonant) frequencies. The recent work by [40] provides two dedicated GUI-based softwares, one each for the acquisition of measured signals and identification of resonant frequencies, and the other for extracting the elastic constants.

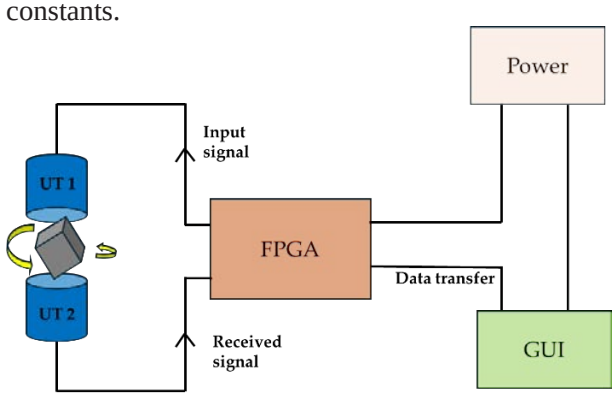

Fig 2: Schematic of the experimental setup used for performing resonant ultrasound spectroscopy. FPGA stands for field programmable gate array, UT for ultrasonic transducer, and GUI for graphical user interface.

2.2. Theory

The constitutive equation relates the elastic constants with the second-order stress $\underline{\sigma}$ and strain $\underline{\epsilon}$ experienced by a linear elastic material as $\underline{\sigma} = \underline{\underline{C}}\,\underline{\epsilon}$, with $\underline{\underline{C}}$ being the 4th order elastic tensor. Symmetries in stress and strain tensor, and energy constraints reduced the number of independent elastic constants to 21 [1] [41] These lead to the field tensors being conveniently written in 6-vector form, given by the Voigt or Engineering notation as [1]

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{yy}\\ \sigma_{zz}\\ \sigma_{yz}\\ \sigma_{zx}\\ \sigma_{xy}\end{bmatrix} = \begin{bmatrix}C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16}\\ C_{12} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26}\\ C_{13} & C_{23} & C_{33} & C_{34} & C_{35} & C_{36}\\ C_{14} & C_{24} & C_{34} & C_{44} & C_{45} & C_{46}\\ C_{15} & C_{24} & C_{35} & C_{45} & C_{55} & C_{56}\\ C_{16} & C_{26} & C_{36} & C_{56} & C_{56} & C_{66}\end{bmatrix}\begin{bmatrix}\epsilon_{xx}\\ \epsilon_{yy}\\ \epsilon_{zz}\\ 2\epsilon_{yz}\\ 2\epsilon_{zx}\\ 2\epsilon_{xy}\end{bmatrix},$$

Or in compact form, with $\underline{C}$ as the stiffness matrix, as [42]

$$\left[\underline{\sigma}\right]_{6\times1} = \left[\underline{\underline{C}}\right]_{6\times6}\left[\underline{\epsilon}\right]_{6\times1}. \quad (1)$$

As the experiment is performed in near-traction-free conditions, we solve the eigenvalue problem of the finite-sized specimen subject to traction-free boundary conditions. The conventional form of estimating the resonant frequencies is by a variational form of the eigenvalue problem involving the second and fourth order using tensors, comprising non-unique elements [43]. In this section, we present a simpler derivation suitable for engineers involving the 21 elements of $\underline{C}$ as the unknowns. The following notations are used: All vectors are in upright bold and unit vectors are identified by a caret. T in superscript indicates transpose. The phase for all the fields entities is exp[i($\mathbf{k}\cdot\mathbf{r}-\omega t$)], where $i=\sqrt{-1}$, $\mathbf{k} = k_x\hat{\imath} + k_y\hat{\jmath} + k_z\hat{k}$ is the wavevector, $\mathbf{r} = x\hat{\imath} + y\hat{\jmath} + z\hat{k}$ is the position vector, ω is the angular frequency, and t is time. Accordingly, $\frac{\partial}{\partial x} \longrightarrow ik_x$ and so on. The infinitesimal strain $\underline{\epsilon}$ in terms of displacement $\mathbf{u}_{3\times1} = [u\ v\ w]^{\mathrm{T}}$ is

$$\begin{bmatrix}\epsilon_{xx}\\ \epsilon_{yy}\\ \epsilon_{zz}\\ 2\epsilon_{yz}\\ 2\epsilon_{zx}\\ 2\epsilon_{xy}\end{bmatrix} = \begin{bmatrix}\frac{\partial}{\partial x} & 0 & 0\\ 0 & \frac{\partial}{\partial y} & 0\\ 0 & 0 & \frac{\partial}{\partial z}\\ 0 & \frac{\partial}{\partial z} & \frac{\partial}{\partial y}\\ \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial x}\\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0\end{bmatrix}\begin{bmatrix}u\\ v\\ w\end{bmatrix}$$
$$= i\begin{bmatrix}k_x & 0 & 0\\ 0 & k_y & 0\\ 0 & 0 & k_z\\ 0 & k_z & k_y\\ k_z & 0 & k_x\\ k_y & k_x & 0\end{bmatrix}\begin{bmatrix}u\\ v\\ w\end{bmatrix} \quad (2)$$
$$= \mathrm{D}_{6\times3}\mathbf{u}_{3\times1}$$

The force balance equation in Voigt form is

$$\begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 & 0 & \frac{\partial}{\partial z} & \frac{\partial}{\partial y} \\ 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial x} \\ 0 & 0 & \frac{\partial}{\partial z} & \frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0 \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{zx} \\ \sigma_{xy} \end{bmatrix} + \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} = -\rho\omega^2 \begin{bmatrix} u \\ v \\ w \end{bmatrix},$$

where $\mathbf{b}_{3\times1} = [b_x\ b_y\ b_z]^T$ is the body force and ρ is the material density. In compact form, the force balance equation can be written as

$$\mathrm{D}^{\mathrm{T}}{}_{3\times6}[\underline{\sigma}]_{6\times1} + \mathbf{b}_{3\times1} = -\rho\omega^2\mathbf{u}_{3\times1} \qquad (3)$$

The governing equation can be obtained by combining the constitutive relation with the kinematic equation and force-balance. Combining Eqs. (1) to (3) in displacement formulation, and noting the insignificance of body force for RUS experiments, we have the governing equation as

$$\mathrm{D}^{\mathrm{T}}{}_{3\times6}\left[\underline{\underline{C}}\right]_{6\times6}\mathrm{D}_{6\times3}\mathrm{u}_{3\times1} = -\rho\omega^2\mathrm{u}_{3\times1}. \qquad (4)$$

This is the Christoffel equation written in Voigt form. The eigenvalue problem can be solved only numerically even for the simplest shapes such as a cube [43]. All boundaries of the specimen are considered traction-free, an approximation despite the two point contacts from the transducers.

2.3. Estimation of Elastic Constants

One begins with guess values of the elastic constants. The eigenvalue problem is solved by finite element method and the resonant frequencies are estimated numerically. A functional is posed to minimize the difference between experimentally and numerically identified resonant frequencies, by varying the elastic constants. To date, the Rayleigh-Ritz formulation is widely used to achieve the optimization [43] .The resonant ultrasound toolbox developed in 2019 executes this process semi-automatically [40].

3. CHALLENGES IN RUS

Since its inception in the early 1990s, the equipment to perform RUS has changed only recently from the use of a bulk function generator to a portable small field programmable gate array-based device such as the Red Pitaya. The computational algorithms, the shapes of the specimens, and offline measurements have remained the same. Despite its advantages, certain scientific challenges remain for ease of measurement, understanding of the specimen, and advancements.

3.1. Effect of roughness

Whether manufactured in either an additive, subtractive, or a hybrid method, an inherent roughness exists on the surface of the specimen. Modification of the process parameters or systematic variations in the manufacturing equipment can lead to a range of roughness in the specimen manufactured [44]. As it is known that the roughness of a specimen can affect the measured properties such as Young's modulus and damping [45] [46], comprehensive studies are to be made both experimentally and computationally to precisely determine the influence of roughness on the estimated elastic constants.

3.2. Estimation of Elastic Constants of Arbitrary Shaped Materials

The RUS measurements to date are performed only on cylindrical or cuboidal shaped specimens. Fragments of meteors and engineering materials from various components, rocks, etc are all arbitrary in shape. Machining them to cylindrical or cuboidal in shape is not always feasible. Furthermore, printing a specimen in these two shapes is not possible by all methods of additive manufacturing. Hence, a coupled framework that measures the exact surface profile, measures the resonant frequencies, and integrates these measurements with the numerical eigenvalue problem and identifies for the elastic constants is needed. One recent work has taken the first step in this direction wherein complex shapes which can be analytically described can be used to perform RUS [47]. Other attempts towards this challenge were reported in the 2010s, but are limited to computational experiments [48] [49].

3.3. In-Situ Measurements

As indicated in Fig. 1, many additive and hybrid techniques exist to fabricate metals, ceramics, and polymers at various length scales. The green specimen (as fabricated) is subjected to further processing operations such as electrochemical polishing,

sintering, or even freeze-drying to achieve the desired specimen. To understand the changes in the specimen due to processing, monitoring the changes in $\left[\underline{\underline{C}}\right]$ from the green body would be useful. While using two piezoelectric transducers may not be feasible, a recent method, where the mode shapes are detected by lasers, [50] [51] or electromagnetic acoustic transducers [52] can be used.

3.4. Algorithms for Faster Analysis

Current methods to estimate the elastic constants rely on inverting the eigenvalue problem [53]. While the Levenberg-Marquadt algorithm is commonly used [43], a few attempts were made to use Bayesian modelling and Hamiltonian Monte Carlo methods [54]. The time required for estimating $\underline{\underline{C}}$ of an isotropic material is in minutes. The same for a triclinic material can take a day. Improved or specialized optimization methods could help in reducing the processing time for the identification of the elastic constants.

3.5. Use of Artificial Intelligence

Methods of artificial intelligence have made their way into every sphere of engineering and technology including NDE [55] [56]. This was possible due to the large number of experimental or simulated measurements [57]. Given the larger time needed to estimate the $\underline{\underline{C}}$ of an anisotropic material, efforts to use artificial intelligence in RUS have begun recently [58]. Dedicated, sustained efforts are needed to achieve the grand goal: The development of machine or deep learning models that considers the experimentally identified frequencies, density, and three-dimensional shape of the specimen to determine the $\underline{\underline{C}}$ of a material with any degree of anisotropy.

4. CONCLUSIONS

Starting with the importance of the use of resonant ultrasound spectroscopy (RUS) for estimating the elastic constants of the newly developed structured materials by methods of additive manufacturing, we have described in brief the experimental and theoretical aspects of the RUS. Thereafter, the challenges to advancing RUS measurements and analysis were discussed.

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CONTRIBUTORY PAPER

Study of the Feasibility of Employing Canned Pulsed Eddy Current Testing Sensor in Conventional Eddy Current Mode for Creep Measurement of Test Specimens

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Abstract

Canned pulsed eddy current sensor has been developed for creep measurement, in material testing reactors, of test specimens of metallic alloys to be used in next-generation reactors. Creep measurement in molten metal medium environment, is planned to be carried out by Pulsed eddy current testing technique, by correlation of slope of signals in the lift-off point of intersection zone to creep was designed and tested after elaborative electromagnetic modelling. The methodology using LOI has been depicted with a bare coil in room temperature conditions. This paper finds out the feasibility of using this probe in conventional eddy current testing mode. Through electromagnetic modelling frequency optimization is carried out and experiments are carried out on the sensor by connecting it to eddy current testing instrument. SS 304 shims were used for varying the gap between the sensor face and the test specimen.

Keywords: *Canned pulsed eddy current sensor ; conventional eddy current ; frequency optimisation ; liftoff point of intersection; creep*

1 INTRODUCTION

The improvised metallic alloy testing [1,2] in Material testing reactors (MTRs) is required for validating their use in futuristic high-temperature reactors. Generally, testing of the material samples has to be carried out under a constricted space environment, and it is highly formidable to find and accommodate a suitable and compact sensor for measuring radial dilation of test specimens and surviving hostile testing conditions like high temperature and neutron fluence. An advanced electromagnetic-based technique is proposed for the application that is suitable for the purpose. Dood and Deed [8]have described the analytical solutions [9] for magnetic vector potential for an eddy current testing excitation coil kept over a metallic medium and derived expressions for voltage induced in the pickup coil. Pulsed eddy current testing [24,26-28] is an emerging advanced eddy current testing technique that unravels immense information about the test object, which can be extracted by employing advanced signal processing techniques. In the material testing reactor (MTR), air gauges [10] were used to measure the diametrical expansion of the test specimen. However, this technique suffers from radioactive contamination due to air jets impinging on the target specimen surface. Such a sensing technique cannot be accommodated in narrow annular gap regions available for radial dilation measurement. It has also demonstrated the use of the resonant cavity method [11,12] for axial elongation measurement of test specimens in MTR. However, this method is unsuitable for radial direction dilation measurement due to piston and cylinder arrangement. Diametrical gauges [13] have also been reported for the measurement of

diameters of the test specimen using techniques similar to Linear Variable Differential Transformer (LVDT)[14]. This technique is more suitable for offline measurement. A four terminal potential drop measurement technique [15] by driving current across two terminals and measuring voltages across different terminals has been formulated and correlated to strain measurement. But their application in radiation environment will be not viable due to radiation-induced material property changes.

Pulsed eddy current testing [3-5,19] has salient features like inducing high pulsed electromagnetic fields, which can penetrate through the layers of the protective metallic cladding over the sensor, NaK medium and examine the test specimen. Further, the broadband response of the pulsed eddy current testing system [33] in the time domain can be interpreted for the surface features of the test specimen by examining the early part of the signal. Recently, it has also been shown that the chirped pulsed eddy current testing technique can enhance the specified depth features [6] of the test specimen by using a limited bandwidth of the excitation signal. Work has been carried out by using the Fourier transform of the pulse eddy current signals [7] and plotting their components of the signals to compensate for the liftoff effect by finding the angle between the desired signal response for the feature of interest in the test specimen and the liftoff signals. The lift–off term in eddy current testing terminology [18,29] is defined as the gap between the eddy current sensor face and the test specimen. The lift-off is generally a sensitive eddy current testing parameter, which has a strong bearing on the measurement of other eddy current testing parameters like electrical conductivity and thickness of the test specimen. Similarly, lift-off measurement is affected by a lesser degree by the other eddy current parameters like electrical conductivity and the thickness of the test specimen. One unique phenomenon observed in the pulsed eddy current technique is the lift-off point of intersection (LOI) [20,23], where signal traces intersect at a common point by varying the lift-off parameter. The analytical modeling of the LOI concerning multi layered test specimen is elaborated elsewhere [21].

The lift-off point of intersection has been studied in detail by Mandache1[22], and the occurrence of LOI for transient eddy currents has been investigated systematically. It was observed that harmonic eddy current response to sinusoidal excitation demonstrated harmonic lift-off point of intersection with a lift-off variation. This phenomenon was due to a change in amplitude and shift in the phase of the response signal. It was conclusively established that when harmonic lift-off corresponding to the decomposed Fourier series of the transient eddy current was superimposed, it would result in the same occurrence of the lift-off point-off intersection as in the case of transient eddy current response. Mandache[1] has shown the occurrence of LOI time by the relation shown in eq.(1).

$$A_1 \sin(n\omega t_{LOI} - \emptyset_1) = A_2 \sin(n\omega t_{LOI} - \emptyset_2) \quad \ldots(1)$$

A_1,A_2 = amplitudes of the harmonic eddy current response at two different Liftoff conditions $\emptyset_1, \emptyset_2$ = phases of the harmonic signal at two different Liftoff conditions

t_{LOI} = time of lift-off of point of intersection for the harmonic signal at two different Liftoff conditions.

t_{LOI} was further deduced as shown in eq.(2)

$$t_{LOI} = \frac{1}{n\omega} \tan^{-1}\left[\frac{A_1 \sin \emptyset_1 - A_2 \sin \emptyset_2}{A_1 \cos \emptyset_1 - A_2 \cos \emptyset_2}\right] \quad \ldots..(2)$$

Tian [21] has carried out LOI time analysis for different test conditions. The analytical model using the Extended Truncated Region Eigen function Expansion (ETREE) method was carried out for the PEC probe on stratified test specimens having multiple layers. Tian has provided expression for closed form for frequency-dependent magnetic field. The expression for LOI time, as shown in eq.(3), was derived in analytical format by replacing magnetic vector potential in the integral form with a series of proper eigenfunctions within the truncated region of interest and saving computation time.

$$t_{loi} = \frac{1}{\omega} tan^{-1}\left\{\frac{im[B_Z(\omega)] - im[B'_Z(\omega)]}{re[B_Z(\omega)] - re[B'_Z(\omega)]}\right\} \quad \ldots..(3)$$

where $B_z(\omega)$ is magnetic field generated by coil and ω is the angular frequency of harmonic component within each pulse excitation and $B'_z(\omega)$ is the field with lift off added to the ideal condition. 'im()' and 're()' denotes imaginary and real parts of the function.

Further, the design and modelling of canned PEC sensors for creep measurement, with compatibility to perform in the presence of molten metal medium based on the correlation of slope of PEC signals in LOI zone, has been discussed [16,17]. This paper discusses experiments carried out with a bare PEC probe to demonstrate the methodology applied in pulsed eddy current mode. Further it is explained about the feasibility study of employing the said PEC sensor in conventional eddy current testing for creep measurement. To study the feasibility of using this PEC sensor in conventional eddy current testing configuration by exciting it with harmonic sinusoidal excitation, electromagnetic simulations were carried out to optimize the harmonic frequency. The canned PEC sensor was tested for performance after connecting to the eddy current tester.

2 SYSTEM DESCRIPTION AND METHODOLOGY

For the proposed scheme of creep measurement, it is required to measure creep in radial direction of the test specimens. The test specimen is in the shape of cylindrical capsule with pressurizing port. Each capsule having 10mm outer diameter and 60mm length. The test specimen capsule is pressurized internally, mechanical stresses are generated in hoop as well as radial directions. It is planned to use NaK medium for cooling the test specimen. A schematic of the test setup is shown in the figure 1. For measurement of creep in radial direction, it is proposed to position the non intrusive sensors for creep measurement at diametrically opposite locations of the capsule. The sensors are supported from a outer guide tube which will be integrated with the support of the test specimen capsule at top such that both test specimen and the guide tube will form a single integrated module and defined as sample carrier. Both the sensors will maintain sufficient radial gap with respect to the capsule such that the capsule will not creep beyond the initial gap which was maintained before the experiment.

The experiments proposed to carry out in in-pile with sample carrier tubes having inner diameter of the order of 24 mm. This restrains the dimension of the sensor in radial direction to the order of 5 mm to get accommodated in the sample carrier after allowing a radial gap of 1mm between the sensor face and the test specimen capsule, for creep measurement. The sketch of the canned pulsed eddy current probe is shown in figure 2.

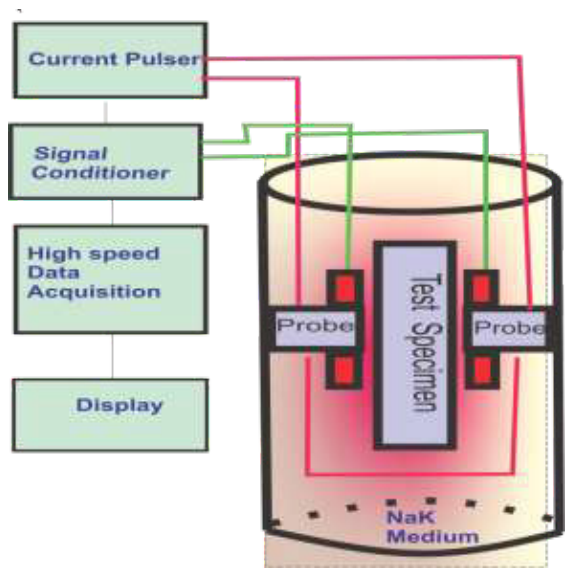

Fig 1: System setup for measurement of creep of test specimen using Pulsed eddy current technique.

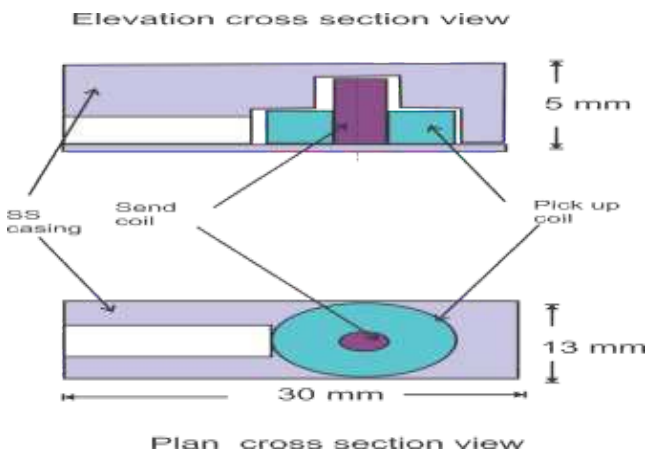

Fig 2: Sketch of Canned Pulsed eddy current sensor.

Pulsed eddy current sensors are placed at diametrically opposite locations to the test specimen capsule through support from an outer guide tube. The constrained space restricts the maximum dimension of the sensor in

radial direction to the order of 5 mm with a radial gap of 1mm between the sensor face and the test specimen capsule for creep measurement.

A pulsed eddy current sensor is excited with a 1 milli second width pulsed current source with a typical amplitude of the order 1 ampere. The pulsed eddy current sensor bombards the test specimen with a broad spectrum of frequencies. The higher frequencies are attenuated and reflected back early from the surface of the test specimen. The lower frequencies penetrate deep into the specimen and are reflected at a later time. The earlier part of the signal depicts the surface features of the test specimen and deeper features of the test specimen are represented in the trailing part of the signal. Figure 3 shows the schematic of typical pulsed eddy current testing setup.

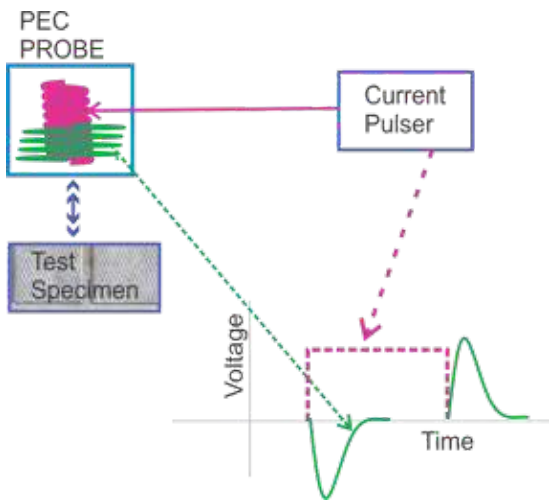

Fig 3: Typical pulsed eddy current testing setup

PEC probe without SS clad/ enclosure was fabricated for testing in room temperature conditions. The send coil has 48 turns of 34 SWG wire and receive coil with 32 turns 34 SWG wire with centre tap. The probe was tested with varying air gap between the probe face and the test specimen. The test specimen was 0.5mm thickness thick square shaped SS 304 plate. The PEC probe without enclosure was tested with a current pulser by setting the voltage at 350 volts. The test setup consists of a 30 ampere rating current pulser having features like settable parameters like pulse width, pulse repetition rate, excitation current amplitude and voltage. The slew rate of the pulser was controlled by voltage rating. Experiments results are shown for excitation current settings at 0.2 ampere. The test setup is shown in Figure 4. Picture of bare/un-canned PEC probe is shown in Figure 5.



Fig 4: Testing setup of uncanned PEC probe



Fig 5: Picture of uncanned PEC probe for gap measurement.

The gap between the test specimen and the probe face were varied by placing multiple layers of paper slips (having thickness of 0.2mm). The signal-conditioned output was fed to the Adlink make PXI based high-speed data acquisition system. The signals were captured using data acquisition card at 10 MHz sampling rate. The zoomed view of LOI zone for 0.2 ampere current excitation is shown in figure 6 and the slope characteristics versus gap is shown in figure 7.

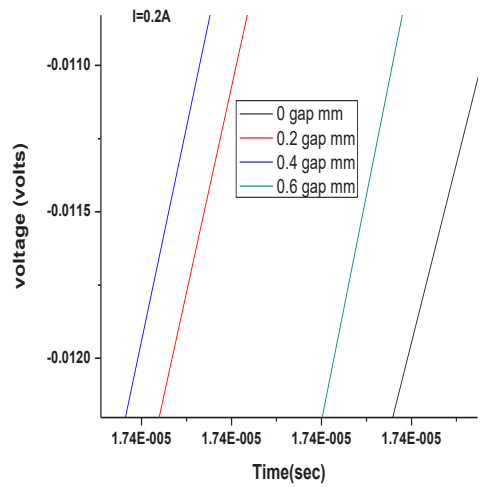

Fig 6: The zoomed view of LOI at 0.2 ampere excitation current

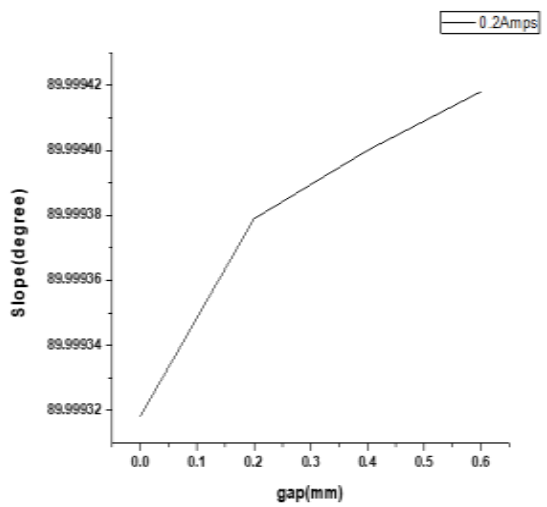

Fig 7: The plot of slope versus gap at LOI with 0.2 ampere excitation current.

Exhaustive experimental studies have been carried out to characterize signals for sensors with canned enclosures by exciting it with pulsed currents. Further to study the feasibility of operating this sensors , which were initially designed for pulsed eddy current testing operation, in conventional eddy current mode. With this motivation, electromagnetic modelling was carried out to optimize the harmonic excitation frequency. After optimizing the frequency, experiments were carried out to check the performance of the PEC probe by connecting to an eddy current tester. The gap between the probe face and the test specimen stacks of SS 304 shims were placed to vary the gap between the probe face and the test specimen.

3 ELECTROMAGNETIC MODELLING FOR OPTIMISATION OF EXCITATION FREQUENCY OF THE CANNED PULSED EDDY CURRENT PROBE TO OPERATE IN CONVENTIONAL EDDY CURRENT MODE

The canned PEC sensor [32] which was earlier modeled for optimization of design parameters of pulsed eddy current probe in NaK medium was proposed to check its performance in conventional eddy current testing mode. The pickup voltages were calculated for various NaK thickness settings between the probe face and the test specimen. The test specimen is set to have a disc shape. The primary and pickup coils are circular in shape having rectangular cross section. The primary coil and pick up coil are placed concentric with each other. The axes of the coils are perpendicular to the face of the disc-shaped test specimen. The geometry model is shown in Figure 8. The primary coil is set to carry a constant frequency sinusoidal current pulse with 0.1 ampere current. The parametric study with different frequencies of excitation under various conditions of NaK thickness between the test specimen and face of SS canning for primary coil and pick up coil assembly were carried out. The Magnetic Field mode in the AC/DC module of the COMSOL Multiphysics was used for the electromagnetic modeling [25,30]. The voltage pick up was computed using the stationary solver of COMSOL Multiphysics package.

In Geometry node, the primary coil geometry, the pick up coil geometry, the test specimen geometry can be defined. The gap filled with NaK between the Test specimen and the Primary Coil and Pick up coil assembly can be defined in rectangular shape. From Material library node, appropriate materials were selected for the primary coil, pick up coil, test specimen , NaK filled gap and air box. Copper was selected as the material for both the coils. Steel SS SS 316 as the material for the test specimen. The

conducutivity of steel and NaK was set to 1.3514 x10^6 S/m and relative permeability 1.005. Air was chosen for air gap, air box and non conductive spacer.

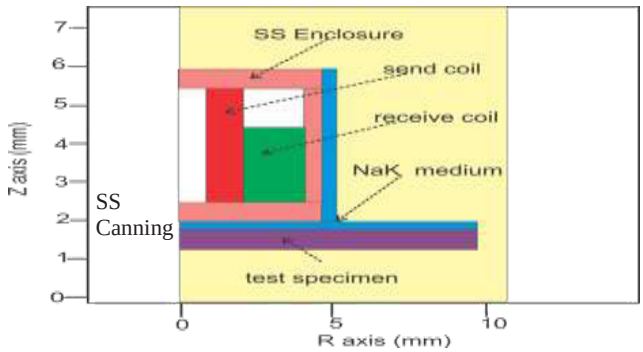

Fig 8: Axis- symmetric Geometry model of the canned PEC sensor in NaK medium (All dimensions in mm).

Multi turn coil configuration setting is assigned to primary coil and pick up coil. The primary coil is driven by 0.1 ampere harmonic sinusoidal excitation. The primary coil is set wound by 34 SWG with 48 turns. The pick up coil is set to wound by 34 SWG with 32 turns.

After computation, in post processing module the magnetic flux density and induced current density were plotted in an around the canned PEC probe in Nak medium for 1000 Hz and 100000 Hz are shown in Figures labeled 9, 10, 11 and 12 respectively.

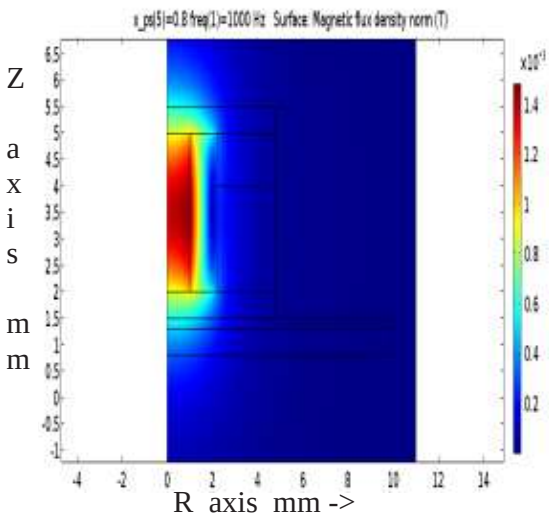

Fig 9: Magnetic flux density distribution in the vicinity of PEC probe in case of 1000 Hz excitation frequency.

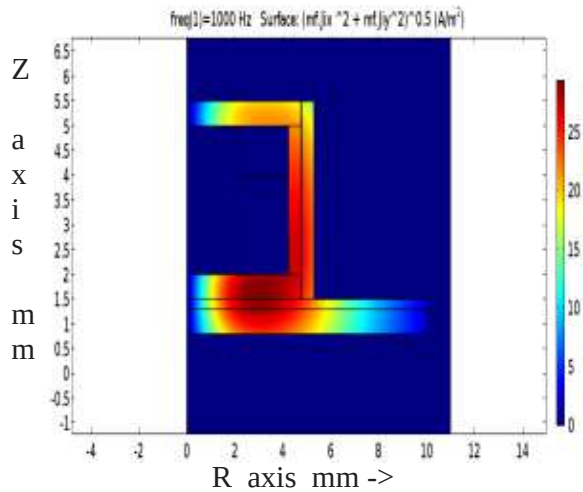

Fig 10: Induced current density distribution in the vicinity of PEC probe in case of 1000 Hz excitation frequency.

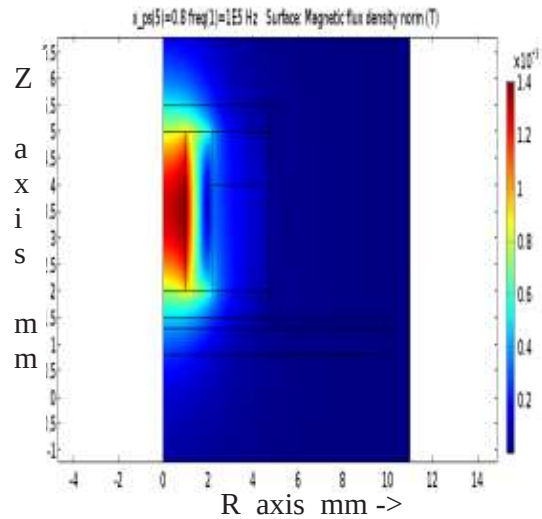

Fig 11 : Magnetic flux density distribution in the vicinity of PEC probe in case of 100000 Hz excitation frequency.

The sensitivity of the sensor with respect to frequency of excitation was gauged by observing the difference in output voltage of the sensor when the NaK medium thickness between probe face and the test specimen was maintained at 0.2mm and 1mm respectively. . The bar chart graph of maximum difference in output voltage with respect to frequency is shown in figure 13. It is seen that as frequency is increased, the sensitivity increases and around 100000 Hz sensitivity plateaus. The frequency of operation was chose as 100000 Hz.

Further increase in operation frequency for practical application leads to undesirable capacitive coupling effects between the coils.

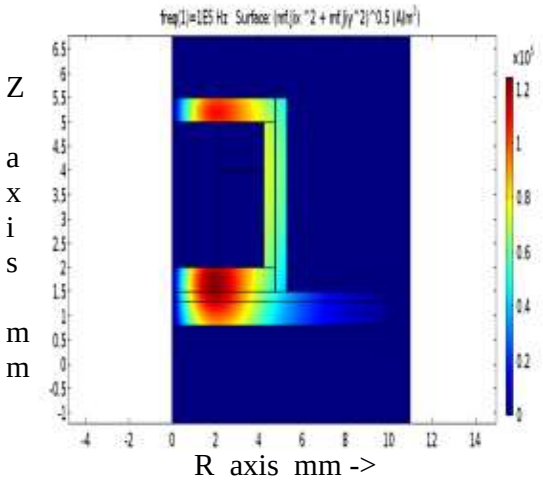

Fig 12: Induced current density distribution in the vicinity of PEC probe in case of 100000 Hz excitation frequency.

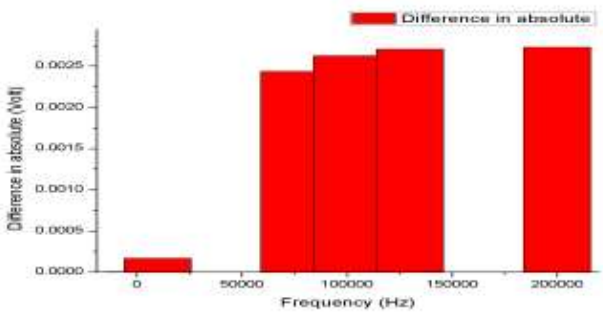

Fig 13: The bar graph showing the maximum difference in output voltage of PEC probe when exited with different frequencies.

4 EXPERIMENTAL STUDY TO FIND FEASIBILITY FOR USING CANNED PEC PROBE WITH CONVENTIONAL EDDY CURRENT INSTRUMENT

To test the feasibility of using conventional eddy current instrument based measurement methodology [31] with canned PEC probe experiments were carried out optimized frequency obtained through electromagnetic modeling. For testing the effect of Nak it was decided to use SS foils having thickness around 50 microns in room temperature conditions. Elotest make B 340 conventional eddy current instrument was used for experiment. The experimental setup is shown in Figure 14. Experiments were carried out by varying thickness of SS foils between canned probe and test specimen. 50 micron thick SS foils were used for varying the thickness of SS medium between canned probe face and the test specimen. The setting of the instrument were made as shown in Table 1. The output of the Y Channel output of the Elotest instrument with respect to varying thickness of SS foils between canned probe and test specimen is shown in figure 15.



Fig 14: Experimental set up for testing PEC probe with conventional eddy current instrument for varying thickness of SS foils between canned probe and test specimen

Table 1: Showing the Elotest B340 instrument setting parameters for the experiment.

Sl No.	**ELotest B340 Instrument parameter**	**Value**
1.	Frequency	100kHz
2.	Amplitude	100%A
3.	Preamplifier	9.0dB
4.	Main amplifier	38.0dB
5.	Spread Y	9.0dB
6.	Phase	90°
7.	Low pass	1.3Hz
8.	High pass	Static
9.	Persistence	900ms

The experiments have shown a sensitivity of around 1.3 volts for 0 mm to 0.6mm change in thickness of SS foils. But the conventional eddy current testing suffers from being generally sensitive to eddy current sensitive

factors like conductivity change and difficult to differentiate the output change with respect to other eddy current sensitive factors due to single frequency excitation. Further the output was found noisy due to cumulative gain of around 56 dB was applied in 'Y' channel.

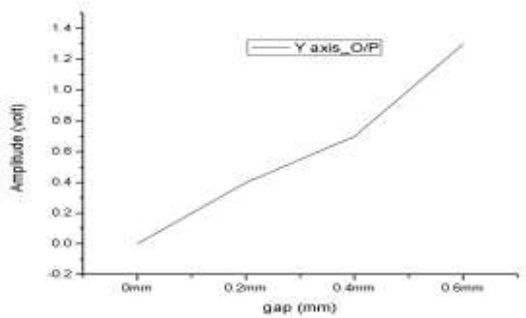

Fig 15 : Amplitude of 'Y' channel output of conventional eddy current instrument for varying thickness of SS foils between canned probe and test specimen

5 CONCLUSION

A compact canned pulsed eddy current probe designed for creep measurement of test specimens in material testing reactors which have molten metal medium is fabricated. The performance of the bare pulsed eddy current testing probe was tested to demonstrate the slope variation versus gap between probe and test specimen. Further, the canned pulsed eddy current probe was modelled and tested to check its feasibility of operating with a conventional eddy current instrument. The frequency optimization was done through electromagnetic simulation. A stack of SS shims was used to vary the gap to simulate the molten metal medium between the probe face and the test specimen for creep measurement in lab conditions. The experiments have shown that using the pulsed eddy current probe in conventional eddy current mode is feasible. However, conventional eddy current mode of operation in absolute mode is observed to suffer from inherent amplifier drifting issues. To circumvent the drifting issues, a differential mode of operation can be implemented. This study paves the way for implementing the pulsed eddy probes in conventional mode to re-assess the measurement with additional methodology.

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NDE PATENTS

Dr.Shyamsunder Mandayam

Through this feature every quarter, we intend to provide you a snapshot of some latest and important patents in the world of NDE. We also intend to use this feature to encourage the Indian NDE community to file more patents based on your innovations. We will be happy to provide guidance and assistance in different ways – Answering queries, Conducting Tutorials and webinars, One-on-one discussions, Networking with Intellectual property experts, etc.

Need help understanding? What are Patents? Why to Patent? When to Patent? What is the Patenting Process? …… Please feel free to reach out to me by email at mandayam.shyamsunder@gmail.com

Here we list below a few interesting patents related to a mix of different modalities and adjacencies in ***NDE and Inspection.***

US Patent 11892322 B2

Inspection Robot for Horizontal Tube Inspection Section having Sensor Carriage

Inventors: Kevin Low, Pittsburgh, Edward Bryner, Logan Mackenzie, Joshua Moore, Michael S. Auda, Mark Cho, Edwin H. Cho

Assignee: Gecko Robotics, Inc., Pittsburgh, PA, USA

An example inspection robot may include a drive module structured to engage a top tube of a vertically arranged layer of tubes, at least one telescoping pole, and a lowering mechanism operationally coupled to the at least one telescoping pole and structured to selectively extend or retract the at least one telescoping pole, thereby providing a selected vertical position of a sensor carriage assembly. The sensor carriage assembly may be coupled to the at least one telescoping pole, and structured to accept at least one of a plurality of sensors.

US Patent 11885768 B2

Semi-Automatic Scanner for Ultrasonic Inspection of Branch Pipe Weld

Inventors: Seong Jin Lim, In Gon Jung, Min Jung Park, Ik Keun Park, Tae Sung Park

Assignee: Korea Inspection Eng. Co., Ltd, Seoul (KR); Foundation for Research and Business, Seoul National University of Science and Technology, Seoul (KR)

The present invention relates to a semi-automatic scanner for ultrasonic inspection of a branch pipe weld that has a small size and is able to perform an inspection while moving in a state of being attached to a test object by a magnetic force, thereby being applied to fittings having various shapes, such as a branch pipe and an elbow. The semi - automatic scanner for ultrasonic inspection according to the present invention includes a probe configured to inspect a weld by irradiating ultrasonic waves onto a surface of a test object, a probe holder configured to couple the probe by applying an elastic force so as to be pressed against the surface of the test object, an installation bracket having a rod shape, to which the probe holder is coupled so as to be laterally movable, four wheel units installed on both front and rear side surfaces of the installation bracket so as to be vertically slidable, and four magnet parts, each of which is installed on one of the four wheel units and presses the one of the wheel units against the test object with a magnetic force.

US Patent 11885767 B2

Automated Scan Data Quality Assessment in Ultrasonic Testing

Inventors: Bruno Abreu Calfa, Vernon, Mahmoud El Chamie, Rocky Hill, Amit Surana, Ozgur Erdine

Assignees: RTX Corporation, Farmington, CT, USA

A system comprising a computer readable storage device readable by the system, tangibly embodying a program having a set of instructions executable by the system to perform the following steps for detecting a sub-surface defect, the set of instructions comprising an instruction to receive scan data for a part from a transducer; an instruction to collect the scan data; an instruction to

determine an indication in the scan data that indicates a distractor, wherein the indication is based on a learning phase module and an inference phase module that the processor uses to self-assess the indication; and an instruction to create a defect indication report.

US Patent 20240027401 A1

Non-Destructive Testing of Composite Components

Inventors: Isabel McBrayer, Fady F. Barsoum, Dallas Nagle, Benjamin Stanford

Assignee: Delta Engineering Corporation, Newark, DE, USA

This disclosure describes systems, methods, and an apparatus for non-destructively assessing composites. The behaviour of propagating elastic waves through a structure can provide significant information on the structure and has thus been studied extensively for development of structural monitoring techniques. In thin plates guided waves can develop, which are inherently dispersive, with highly mate- rial dependent dispersion characteristics. The identification of the different parameters within a laminate that may affect their mechanical properties is an important step in the assessment of laminate structures.

US Patent 20230408453 A1

System and Method for Real-Time Visualization of Defects in a Material

Inventors: David A. Jack, Benjamin M. Blandford, Nathaniel J. Blackman

Assignee: Verifi Technologies, LLC, Waco, TX, USA

The present disclosure provides a system and method for real-time visualization of a material during ultrasonic non- destructive testing. The system includes a graphical user interface (GUI) capable of showing a three-dimensional (3-D) image of a composite laminate constructed of a series of two-dimensional (2-D) cross sections. The GUI is capable of displaying the 3-D image as each additional 2-D cross section is scanned by an ultrasonic testing apparatus in real time or near real time, including probable defect regions that contain a flaw such as an air pocket, delamination, or foreign object within the composite. Furthermore, in one embodiment, the system includes an artificial intelligence capable of highlighting foreign objects within the 3-D image in real time or near real time and providing data regarding each object area, such as the depth, size, and/or type of each defect.

National Accreditation Board for Certification Bodies

Accreditation Certificate

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Certification of Persons

The Scope of Accreditation is described
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Accreditation Certificate No.:		**PR 005**
Date of Initial Accreditation	:	May 19, 2020
Date of Last Renewal	:	June 28, 2023
Validity of Accreditation	:	May 18, 2027

June 28, 2023
Issue Date

(Rajesh Maheshwari)
Chief Executive Officer

(Please refer http://nabcb.qci.org.in for validity of the certificate or contact NABCB for any related queries)

National Accreditation Board for Certification Bodies

Schedule

(Scope of Accreditation)

National Certification Board (Indian Society for Non-Destructive Testing)

Certification of Persons

Description of Personnel Certification Scheme	Standards/Regulations/ Normative document(s)
International Certification in NDT (ICN) Scheme for Qualification and Certification of Non-Destructive Testing Personnel as per ISO 9712:2021	NCB/ICN Scheme (ISO 9712)/R- 2 Ultrasonic Testing (Level 1, Level 2, Level 3) - Butt Weld Joint in plates and vessels - Butt Weld Joint in pipes - Casting - Forging - Tubes/Pipes - Wrought products (Plates, Bars & Rods) Magnetic Testing (Level 1, Level 2, Level 3) - Weld - Casting - Forging - Tubes/Pipes - Wrought products (Plates, Bars & Rods) Penetrant Testing (Level 1, Level 2, Level 3) - Weld - Casting - Forging - Tubes/Pipes

June 28, 2023
Issue Date

(Rajesh Maheshwari)
Chief Executive Officer

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National Accreditation Board for Certification Bodies

Schedule

(Scope of Accreditation)

National Certification Board (Indian Society for Non-Destructive Testing)

Description of Personnel Certification Scheme	Standards/Regulations/ Normative document(s)
	- Wrought products (Plates, Bars & Rods) Visual Testing (Level 1, Level 2, Level 3) - Weld - Casting - Forging - Tubes/pipes - Wrought products (Plates, Bars & Rods) Radiographic Testing (Level 1, Level 2, Level 3) - Weld - Casting Radiographic Testing-Film Interpretation (Level 2) - Weld - Casting

June 28, 2023
Issue Date

(Rajesh Maheshwari)
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ICNDT
INTERNATIONAL COMMITTEE FOR NON-DESTRUCTIVE TESTING
The World Organisation for NDT

ICNDT Multilateral Recognition Agreement (MRA) for Personnel Certification in NDT

Certificate of Registration

National Certification Board of Indian Society for NDT (India)

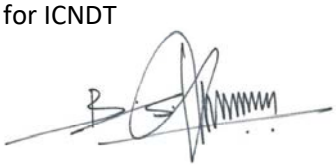
The above named NDT Personnel Certification Body (PCB) has satisfied all of the eligibility criteria for registration under the ICNDT Multilateral Recognition Agreement (MRA) for PCBs, including having undertaken to abide by the ICNDT Code of Practice, and has been nominated and accepted for registration within the terms of the Agreement signed by those Members of the International Committee for NDT (ICNDT) listed in Schedule 1 to the Agreement.

The Personnel Certification Body may therefore announce that holders of its certificates issued under these arrangements are certificated by a PCB which is registered by the ICNDT as meeting the requirements of the applicable Standards (including ISO 9712:2012 and ISO/IEC 17024:2012) and Technical Documents referenced in the schedule of conformity (scope) issued by the accreditor and/or the ICNDT.

A copy of the MRA, including a list of the signatories and a schedule of those certification bodies satisfying the criteria for registration, is available at www.icndt.org and from all parties that are signatory to the Agreement.

All signatories to the Agreement, and all PCBs registered under the Agreement, are bound to promote the recognition and acceptance of the certificates issued by all other ICNDT Registered NDT Personnel Certification Bodies.

Signed for ICNDT



Chairman

Initial registration date:	2 August 2021
This certificate number:	4 (2021)
Issue date:	2 August 2021
Expiry date:	2 August 2024

Disclaimer: ICNDT accepts no liability for the use of certification awarded by PCB registered under the MRA. In accordance with ISO 9712 the responsibility for the quality of NDT rests with the employer of the certificated person.

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REPORT NDE 2023

The 33rd Annual Conference and Exhibition on Non-Destructive Evaluation and Enabling Technologies (NDE 2023) organised by the Indian Society for Non-Destructive Testing (ISNT), the Official Technical Society for NDT/NDE in India, at The Hotel Orchid in PUNE held during 7th – 9th Dec 2023. The event was inaugurated by Dr Sameer V Kamat, Secretary Department of Defence R&D and Chairman DRDO on 7th Dec 2023. Dr V Narayanan, Distinguished Scientist and Director of Liquid Propulsion Systems Center (LPSC), ISRO was the Guest of Honour of the inaugural function. The theme of the conference was "Transformative NDE: Unleashing the Power of Advanced Technologies".

In the keynote address during the inaugural function, Dr V Narayanan talked about the role of NDE for the success of space mission. He mentioned about the criticality of the components for the functioning of the space system and how NDE technologies are unavoidable for safety and functioning of systems. He highlighted that NDE is a critical component across various industries, ensuring structural integrity, safety, efficiency, ageing, life estimation and life assessment.

In the inaugural function of the Conference, Dr Sameer V Kamat highlighted the importance of Non-Destructive Evaluation Technologies for each industry. He highlighted how the destructive test is important for R&D but NDE is the solution for quality assurance of usable systems. He appreciated about the fact that the conference is attended by the participants from wide spectrum of industries which indicates about the large stakeholders involved in NDE. He suggested all to frame a technology road-map at the end of the conference for the NDE community. Dr S V Kamat released the souvenir and also launched NDT certification programme of ISNT named as International Certification in NDT (ICN). Dr Kamat and Narayanan distributed various National NDT awards during the inaugural programme.

During the inaugural function, D D Joshi, President ISNT briefed about ISNT and its activities. Uday Kale Convener NDE2023 delivered welcome address and Bikash Ghose, Chairman of NDE2023 briefed about the Conference. J Hiremath had delivered vote of thanks.

The state-of-the art exhibition with 71 exhibitors from India and abroad showcasing NDE products, technology and services was inaugurated by Dr V Narayanan. Exhibitors provided live demonstrations and give insights into the tools and methodologies driving advancements in the field.

After the inaugural function, Dr V Narayanan, Director LPSC, ISRO delivered a memorial talk on "Rise of Indian Space Programme – Pride of our Nation". Another memorial talk was delivered by industry luminary Shri Ashish Bhandari, MD and CEO of Thermax Group on "NDT's connect with the World of Tomorrow".

The 3 days conference was attended by more than 950 enthusiastic delegates from India and abroad from various academic institutions; R&D

REPORT NDE 2023

Institutions such as various labs of DRDO, DAE, ISRO, CSIR; industrial public and private sectors such as from Defence, Space, Nuclear, Oil & Gas, Civil Infrastructure, Manufacturing, Aerospace, Aviation, Automotive, Power, Railways, Shipping, Chemical Fertilizer etc. The 3 days' conference had a footfall of about 1400 participants. The event was well supported by industries such as Reliance Industries, Tata Steel, DRDL, BDL, Bharat Forge, Solar Industries, Thermax Ltd, KSB Pumps etc. The local industries in and around Pune got greatly benefited from the conference. The conference provided firsthand exposure to innovations in the area of Non-Destructive Evaluation that will support the industry 4.0 revolution. NDE 2023 shaded light on how these technologies impact and transform sectors ranging from aerospace and automotive to energy and infrastructure.

In addition to the above, the conference had 162 technical presentations, 4 interactive workshops; Student session on NDE, special session on ICN, Scientific Writing by Springer and special industry session on aerospace & Power; and 70+ exhibitors, both national and international, showcased the latest technologies and advancements in the field. There was a Startup Pavilion exclusively for the startups in the field of NDE. In addition, 49 keynote speeches from leading experts from R&D community and Industry sectors that provided insights into the current trends and future directions of NDE and in their associated domains. The industry plenary session was one of the highlight of the conference.

ISNT launched its own skill development certification scheme "International Certification in NDT (ICN)" fully compliant with ISO 9712:2021. ICN is the only scheme from India that has been included in ICNDT Mutual Recognition Agreement that will ensure recognition of ICN certification with the partner countries. National Certification Board (NCB) of ISNT is the only NDT certification body in the country that has been accredited by NABCB, Quality Council of India as per ISO 17024. This scheme will give a boost to the industry and in line with the industrial revolution 4.0 and will meet the call of Atmanirbhar Bharat.

In the valedictory function, ISNT has launched a new website and an Android App of ISNT. Key contributors of NDE 2023 were felicitated during the event and best paper, best stalls and exhibitors were announced.

REPORT
NDE 2023









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