Ultrasonic testing of components produced with additive manufacturing

Towards improved detection and classification of defects

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I would like to thank Mr. Jonas Olsson for his unwavering support with big as well as small issues.

On a more personal note, I cannot express enough gratitude to my wife, Maria, for her loving support, patience, and understanding. Maria, you have been my rock through the ups and downs of this ongoing journey.

To my family, who has always believed in me, thank you for your endless love and support. I am eternally grateful for everything you have done for me.

In closing, to everyone who is and has been a part of my ongoing PhD journey, the most heartfelt thank you!

Mikael Sahl
Trollhättan, March 2024
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Populärvetenskaplig Sammanfattning

Titel: Ultraljudsprovning av komponenter tillverkade med additiva metoder
Mot förbättrad detektering och klassificering av defekter
Språk: Svenska
Nyckelord: Non-Destructive Testing (NDT), Super alloys, Microstructure, Ultrasonic Testing (UT), Productivity Enhancement

ISBN 978-91-89325-77-7 (Electronic Version)


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The focus in this work is on the use of ultrasonic testing as a method for inspecting components manufactured through additive manufacturing (AM) processes. The research is rooted in the need for effective non-destructive testing techniques that can adapt to the unique challenges posed by AM-produced materials, including complex defect geometries and surface conditions.

Ultrasonic testing is a versatile form of non-destructive testing, offering the ability to detect internal flaws, such as voids, cracks, and inclusions, with high precision and in real-time. Unlike many competing methods, ultrasonic testing works on most types of materials. Ultrasonic testing has been applied for inspection purposes for a long time. Now with emerging manufacturing methods, there is a need for evaluation techniques to keep up with this development. New data processing algorithms open up possibilities of extracting more information from the acquired signal.

The thesis provides a review of UT's capabilities in detecting and classifying defects within AM components, with a particular emphasis on the subtleties introduced by the layer-by-layer construction method inherent to AM technologies. The work advances development and validation of simulation models aimed at predicting the ultrasonic response from manufactured defects. These models are crucial for understanding the interaction between ultrasound waves and material anomalies, offering insights into the potential for enhanced defect detection strategies.
Abstract

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ABSTRACT

The research also explores the practical case of integrating UT into the quality assurance processes by relying on mathematical simulation rather than experimental data. The findings suggest avenues for the refinement of creation of inspection procedure, including the use of meta-models to cheaply acquire worst-case scenario defects, to better accommodate the specificities of AM materials.
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**Paper D**  Simulation derived Probability of Detection if lack-of-fusion-like defect in additively manufactured materials
Acronyms

AI  Artificial Intelligence
AM  Additive Manufacturing
CNN Convolutional Neural Network
ECT Eddy-Current Testing
FBH Flat-Bottom Hole
FEM Finite Element Method
FMC Full Matrix Capture
GTD Geometrical Theory of Diffraction
HIP Hot Isostatic Pressing
LOF Lack-Of-Fusion
MAPOD Model-Assisted Probability Of Detection
NDE Non-Destructive Evaluation
NDT Non-Destructive Testing
PA Phased Array
PBF Powder-Bed Fusion
POD Probability Of Detection
QNDE Quantitative Non-Destructive Esting
SDH Side-Drilled Hole
UT Ultrasonic Testing
Chapter 1
Preface and Introduction

This publication explores the realm of Non-Destructive Evaluation (NDE) with a focus on Ultrasonic Testing (UT), presents an insight into the ongoing research of the author while also providing a semi-comprehensive exploration of the field's advancements and challenges. This chapter introduces the background of the work, the motivation, and attempts to show the research gaps identified. In the appended Paper A, the reader will find a book-chapter dedicated to the use of NDE in the context of Additive Manufacturing (AM). It is encouraged to read this appendix prior to the main body of text, especially for readers less familiar with Non-Destructive Testing (NDT). This chapter covers relevant topics such as UT, Eddy-Current Testing (ECT) and other methods in a survey level and should bring the reader up to speed. It also goes into some details on UT specific mechanisms. The terms NDT and NDE can often be used interchangeably, though generally, the latter is a broader term that encompasses the former, while also including a more general analysis of component performance based on NDT data. In some contexts, NDT is also limited to defect detection, while NDE includes aspects related to defect characterisation and material properties.

1.1 Background and Motivation

With the ongoing advancements in material science and manufacturing methods, new design opportunities and product categories have emerged. Designers, in a relatively short span of time, have gained access to innovative tools such as multi-axis machining and 3D printing, alongside the significant expansion in alloying techniques[1] and material treatments. These advancements are part of an era of substantial progress, bringing with them high expectations for innovation. At the time of writing, it is widely acknowledged that one of the most pressing challenges is the multifaceted issue of sustainability. It is multifaceted.
Chapter 1

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3D printing, in particular, stands out for its revolutionary approach to manufacturing. It enables the layer-by-layer construction of objects in an additive fashion, transforming design possibilities, especially for complex geometries. This technique comes with a distinct advantage when it comes to fabricating internal features, such as cooling channels, that are essential for functionality but notoriously difficult to produce using conventional methods. Furthermore, 3D printing facilitates the optimization of parts for weight reduction, precisely tailored to specific force and stress distributions. Designers can strategically eliminate unnecessary material and reinforce areas subjected to high stress, thereby manufacturing lightweight yet robust components. This approach significantly contributes to environmental sustainability by minimizing material consumption and enhancing efficiency. Such innovations are especially beneficial in aerospace applications, where the principles of the rocket equation highlight the critical importance of reducing the mass of additional fuel required to transport extra weight. However, for safety critical systems (e.g., air-planes and nuclear) there are steep requirement on a component level to comply with regulations, both legal and technical, not to mention ethical code. It can be argued that an arms-race is ongoing: on the one hand the need and expressed interest in the many advantages which can be unlocked with the new technologies and materials. On the other hand, the resistance to too rapid advancements, aiming to reduce the possibly of introducing risks into systems where safety is paramount. NDT, when implemented smartly, can be seen as an equalizer: reduce the risks of uncertainties in new processes and allow for reduction in redundant (structural) material by ensuring no critically sized defect is present. Smart implementation involves, among other things, where the resources for inspection should be allocated in response to information such as, where defects are likely to appear and where they are the most structurally detrimental. Further more the type of NDT method should carefully be considered, given the limitations of detection resolution for different types of defects (this is addressed further in Paper A). Both the critical size and the detectability is a function of defect type, which is one of the main consideration for the creation of inspection procedures.

Testing is of course a non-value adding process, which in a perfect world would be eliminated through sufficiently good understanding of processes throughout the supply-chain. Until such a day, NDT-advancements needs to keep up with the development in the manufacturing sector to not be the slowest link in the chain, holding back deployment of new products. Some have argued...
NDT is indeed lagging behind its counterparts [2], making manufacturers hesitant in new product/processes adoption. 3D-printed components have started making their way into the aero industry, but the adoption is limited to few component types. This is partially due to difficulty in verifying new processes in the sensitive industries, but also a lack of general knowledge of AM. Oyesola et al. [3], mapped the subjective impression of the knowledge of AM within the organization of a number of aerospace representatives. It was found that 7/13 representatives rated their knowledge as either "low" or "very low". Another roadblock to adoption is the general cost. NDE is costly, partially due to the low level of automation [4], depending on the specific method. In order for implementation of NDT to make sense a cost/benefit equation must be positive. We can say that the resources saved from applying the methods must exceed the cost of implementing them. The cost is not only the actual cost of inspection (capital investment, salaries, etc.), it also consists of the cost of falls calls. NDT-methods are always subject to some degree of uncertainty. As such, falls calls will be a relevant factor. False calls can lead to either further inspection, repair work (e.g., welding) or scrapping of the part. On the other side of the equation is the resources saved: the cost of preventable failures and the possible reduction of cost of design redundancy (i.e., design with sufficient structural buffer to absorb a defect which could occur from any particular process). The cost of preventable failures are the failures which were avoided thanks to the introduction of the testing process, where the cost represent for example, loss of component, process downtime, cascading damages or personal damage. With this in mind, controlling the investment capital and ongoing expenses of NDT is an important factor. With these sets of context in mind, this work aims to facilitate the creation of inspection procedures by advancing the use of mathematical models. This has the potential of increasing the understanding of UT interaction with defects as well as increasing the likelihood that Model-Assisted Probability Of Detection (MAPOD) can be applied for qualification purposes. Research question were formulated as:

RQ1) Are the existing mathematical models valid in the relevant domain, i.e., immersion phased array?

RQ2) Research question addressed: What is the effect of build-direction on the UT signal response of seeded spheroidal cavities in PBF-LB?

RQ3) How can mathematical modelling aid in reducing the uncertainty in amplitude response prediction from elongated flaws?
1.1.1 POD

When designing safety critical components, the engineers account for the static and dynamic stresses which the material will be exposed to. Beyond that nominal material properties and component geometry, they also need to account for any defect present, either at the surface or inside the component. Defects such as cracks and porosities have a detrimental effect on the mechanical properties of the component, and can lead to premature failure unless accounted for. POD is a measure of likelihood of finding a defect of a specific size in any particular inspection system. POD provides a means of communication between NDT- and strength of materials- teams, where the most important piece of information is the biggest defect that is likely to be missed by the inspection process. The POD in NDT is therefore a critical concept, signifying the likelihood of detection of defects in materials. Determining POD is inherently challenging and resource-intensive, primarily due to the large number of samples required for statistical reliability. Traditionally, a sample of defects to be investigated has been introduced into materials for inspection systems (operators and equipments) to inspect and the POD being determined by the hit rate. The sample size depends on various factors, including the variability in defect characteristics (size, shape, orientation) and the consistency of the testing method. As we shall see, the smallest defect is not always the most difficult to detect, and the
effort to determine POD depends on the distribution of defect characteristics. In typical scenarios, a statistically significant sample size might range from several dozen to hundreds of samples, considering the need to accurately reflect the spectrum of potential defects and variances in the inspection process. In order to statistically prove a POD of 90% and with a confidence of 95% a sample size of 29 pieces is required for a binomial point estimation, where all of them are correctly identified [5]. This measure of POD is defined as \( a_{90/95} \).

MAPOD emerges as a strategic approach to mitigate these challenges. By integrating empirical data with simulation models, MAPOD can substantially reduce the requirement for extensive physical testing. This integration allows for a more efficient, cost-effective means of estimating POD. However, the success of MAPOD depends on the precision and reliability of the predictive models used. These models need to accurately (enough to be useful) represent the physical- (e.g., transducer characteristics and couplant effect) and material properties (e.g., attenuation) relevant to the NDT processes. Developing such models demands a deep understanding of both the NDT techniques and the intricacies of material behaviours under various conditions. As new materials and manufacturing methods (like 3D printing) are introduced, the mathematical models must be verified to show they are still valid. Accurate models are not only essential for the feasibility of MAPOD but also for ensuring that the NDT process keeps pace with the rapid advancements in the manufacturing sector by participating in early stages of product development.

1.1.2 Additive Manufacturing (AM)

AM is a term encompassing any manufacturing method which continuous or sequentially adds material to build up a part. This is in contrast to what is often referred to as conventional manufacturing which is removing excess material to leave the intended shape intact. Powder-Bed Fusion (PBF) is a subcategory of AM which builds components by spreading a layer of powder on a build platform, followed by melting using either a laser or an electron beam. Figure 1.1 shows a simplified view of the process.

There are a number of technical factors of PBF, all of which can introduce defects into the final part if not functioning perfectly.

1. Layer-by-Layer Fabrication: PBF builds parts layer by layer. Each layer corresponds to a cross-sectional slice of the final product. This layer-wise approach allows for the creation of complex internal structures and geometries that are not feasible with traditional manufacturing methods. While the unmelted powder can provide support to some degree, features with overhang generally requires dedicated printed support struc-
2. Melting Strategies: In SLM and EBM, the energy source (laser or electron beam) follows a pre-programmed path to melt and fuse the powder particles. The melting strategy involves careful control of parameters such as laser power, speed, beam diameter, and scan pattern. While there are exceptions, the aim is generally to produce a fully dense part (i.e., porosity free). The micro-level mechanism leading to defect formation is well outside the scope of this work, but the general insight can be condensed down to that too much volumetric energy density ($J/mm^3$) leads to key-hole porosities or thermal cracking, while insufficient energy density causes Lack-Of-Fusion (LOF) [8], where LOF also falls under the porosity category. The microstructure of the manufactured component is generally columnar in the build direction, but AM does allow for tailoring of the grain morphology based on the required properties, e.g. [9]. This tendency towards columnar microstructure, with the associated anisotropic behaviour has a negative effect on the UT signal, as the wave will be scattered, reflected, or refracted in a non-uniform manner, leading to signal loss and reduced resolution in the detection of flaws or inconsistencies within the material.

3. The quality of powder is crucial aspect to the resulting component. Particle size distribution and morphology have an impact on the manufacturing process, for example through the impact these parameters have on the re-coating process [10]. There are of course a multitude of other factors such as moisture content, porosity, and material composition which also are relevant for the process.

4. Heat Management. As the laser or electron beam is focused onto the surface, a temperature gradient is formed. Energy is over time transferred...
away via the mode of radiation, convection (for PBF-LB) and conduction through the built structure and unmelted powder. As the heat conduction is a function of part geometry, so is also the optimal set of build parameters [11]. A changing in the flow of temperature will lead to differences in the residual stresses, potentially leading to impact on the geometrical accuracy of the part or cracking [12].

5. Parts produced by AM are often subject to some form of post-processing steps, be-it machining, heat-treatment or Hot Isostatic Pressing (HIP). Heat treatment can relieve residual stresses but can also cause significant grain growth [13]. Increase in grain size is generally associated with an increase of ultrasonic attenuation and backscatter [14], having a detrimental impact on the inspectability of the part.

The main defect of interest for this thesis is the LOF, in Paper D modelled as an elongated pore. Of course several defects associated with AM are addressable with UT. The aforementioned cracks are well suited for UT given that the interface (the change of wave speed) is the main contributor to the signal response (unlike radiographic based methods). Other flaws which are detectable include distortion (geometrical) and inclusions. However, metallurgical defects such as freckles are generally not detectable by UT, but also not very prevalent in PBF-processes due to much greater cooling rate [15].
Chapter 2
Ultrasonic Testing and Non-Destructive Evaluation

UT works through the principles of how elastodynamic waves interact with material. The reader is hereby directed to chapter "Ultrasonic Testing" in Appendix Paper A for an introduction. In this chapter, we will expand the theory slightly into Phased Array (PA)-systems.

2.1 Phased array Ultrasonic Testing

A PA probe consists of an array of smaller piezoelectric elements, Fig. 2.4, where each element can be driven with a tuned time-delay. PA can thus steer and/or focus an effective beam-front by applying appropriate delay laws leading to a more effective inspection system\cite{16}.

Figure 2.1: Shows steering and focusing possibilities with PA, as well as an equivalent use-case with a monocrystal probe. Arrow shows the effective beam propagation direction. Courtesy Drinkwater et al.\cite{17}

Fig. 2.1 illustrates different modes of operations, as well as an equivalent conventional steering method (Fig. 2.1 (d)). If a PA probe is driven with uniform time-delay, it will behave similar to a conventional unfocused probe with equal size. In this case, a spherical pressure front will radiate from each element, where the constructive interference between these waves forms the effective wave front.
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Figure 2.1: Shows steering and focusing possibilities with PA, as well as an equivalent use-case with a monocrystal probe. Arrow shows the effective beam propagation direction. Courtesy Drinkwater et al. [17]
PA systems are used extensively in the medical field with impressive visual reconstruction of the received signal. While PA can help in volumetric reconstruction [18], it still a highly indirect measurement, and a lot of work needs to be performed to get any kind of near reality volumetric representation. Arguably, there are a number of factors which makes the task in the medical field more manageable, for example the relatively homogenous tissue and the size of the features of interest. Reconstruction in less homogenous parts (e.g., engineering materials), and parts which can carry shear-waves as well as longitudinal waves suffers from the need to consider signal of both these modes (with different propagation velocities). Given that PA consists of several elements, each capable of recording the full A-scan, the amount of data and information collected can be vastly higher than for a conventional system. Further more, the arrays can be run in Full Matrix Capture (FMC)-mode where the data-set is the complete set of time-domain signals from all possible transmitter-receiver pairs [19]. This kind of data collection facilitates modern data processing options such as Total Focusing Method (TFM). TFM allows for image reconstruction where all the pixels are in focus. A benefit of classical phased array over conventional (monocrystal) probes is illustrated in Fig. 2.2.

![Figure 2.2](image_url)

**Figure 2.2**: Detection of defects with non-optimal orientation for detection. The blue arrows represent effective beam propagation direction (ray theory). PA (left) shows the ability to get a good reflection based on the spectral reflection of the effective beam. Whereas the monocrystal probe (right) needs to rely on scattered noise to detect the defect.

The flexible beam direction of the PA-system increases the opportunity to interact with the defect in an advantages direction. In general, spectral reflection contains a much greater (amplitude) signal than scatter noise from defect surface roughness. The monocrystal thus suffers from higher probability of missing misoriented defects. Additionally, the productivity benefit of PA-systems
2.1. Phased array Ultrasonic Testing

can be vast. In conventional systems, it is not unusual to use focused probes to increase the sensitivity of the system. However, a naturally focused probe has a more narrow depth of field (length of the high intensity acoustic zone near the focus distance) than an unfocused probe. As such, often multiple probes needs to be used to inspect the entire volume under any given area. With PA-systems the focus can be swept and the entire depth recorded in a single pass. The time delay principle resulting in focusing and/or beam steering is illustrated in Fig. 2.3. The illustrations are based on a 1-D linear probe, but of course not all modes are applicable for all possible probe configurations. For example, the annular probe can not steer the beam at all, only adaptable focus along the probe normal \( z \)-direction is possible.

![Figure 2.3](image)

Figure 2.3: This image illustrates how delay laws applied to a series of elements produce the desired effect, i.e., focusing and/or steering. Courtesy of Erhard et al. [20]
2.2 Alternative NDT methods

In the context of additive manufacturing there are of course multiple applicable NDT methods depending on the component and process requirements. ECT uses electromagnetic induction to detect flaws. It comes with some clear advantages over UT, e.g., that there is no need for a couplant. This makes the method often easier to implement in a automated setting, see for example Todorov et al. contribution for in-situ monitoring of the PBF process \[21\]. ECT complements UT well because of their inherently different preferred inspection zone, i.e., ECT for surface-breaking and near-surface flaws and UT for internal flaws. For a review of post-build inspection use cases of radiography based methods, please refer to Paper A, section "Radiographic testing".
Chapter 3

Mathematical modelling

As previously discussed in Chapter 1.1.1, one of the use cases of mathematical modelling is the reduction in resources required for qualification purposes (see also [22]). An ultrasonic measurement model typically encompasses the generation of incident ultrasound by the transmitting probe, its interaction with various defects, and the creation of the output signal at the receiving probe stimulated by the wave field scattered by the defect. Additionally, it often considers different propagation characteristics like potential material anisotropy, attenuation, and noise mechanisms. Essential to the model is the inclusion of calibration with standard defects, such as Side-Drilled Hole (SDH). The cornerstone of all models is the method used to solve the elastic wave propagation problem, which includes the ultrasound’s interaction with defects. Since exact, closed-form solutions are rare or non-existent in this context, approximate numerical methods are usually the only viable option. The key challenge is to find approximations that balance acceptable computation times and sufficient accuracy for reliable results. Achenbach [23] gives an overview of UT NDT models. There exist essentially three main methods applied to predict the scattering of reflectors relevant for NDT:

1. High frequency approximation methods (e.g., Geometrical theory of diffraction and Kirchhoff theory).
2. Numerical methods (e.g., Finite-element method).
3. Analytical methods (e.g., The null-field / T-matrix method).

Furthermore, while the propagation of waves inside material is well described by the linear elastodynamic wave equation, it is often successfully modelled by simple ray tracing methods, i.e., considering the propagation of the energy as rays. While underlying mathematics of the different methods are out of scope.
for this thesis, a brief overview will be helpful in reading the later chapters. Finite Element Method (FEM) is the only purely numerical method, where the wave equation is solved by sub-dividing the medium into discrete elements (the mesh). This method is generally computationally expensive, but on the other hand is highly flexible in terms of dealing with geometry of both test specimen and defect. The null-field approach, also known as the T-matrix method, was proposed in 1965 [24] for the use in electromagnetic problems. It was later used for acoustic scattering [25]. Similar to numerical methods, the null-field approach can handle defects with non isotropic properties, but the shape is required to be simple. The properties of a defect are captured in the T-matrix and the boundary conditions outside the volume of the defect are appropriately calculated. Geometrical Theory of Diffraction (GTD) in the context of acoustics was largely developed by Keller [26] and extends the geometrical behaviour of optics. The method accounts for diffracted signals, e.g., UT-waves interacting with edges or corners of features. GTD can along with Kirchhoff method be considered a high frequency approximation method, i.e., it can model interaction with features which are not several wave-length or greater in size. Kirchhoff method relies on the Huygens-Fresnel principle which posits that each point in a wavefront is a source of secondary spherical wave (wavelet), where the interference of these wavelets give rise to the observed wave phenomena.

3.1 simSUNDT

The simSUNDT software-suite is a solution for predicting the ultrasonic signal response as a function of both inspection setup and material/defect parameters. The software consists of a mathematical kernel UTDefect [27] and graphical user interface providing the ability to configure the simulated testing environment, including probe type (contact or immersion, with phased array options), probe arrangement (pulse-echo, tandem, crack tip diffraction or Time-Of-Flight Diffraction). UTDefect uses analytical methods of solving the 3D elastodynamic wave equation. This includes separation-of-variables and integral equations (to calculate the T-matrix [28] as well as green functions and Fourier transforms). The simplest mathematical models of UT probes are usually considered to be piston-like. Here, the full surface of the probe is assumed to exert a constant traction over the entire surface. UTDefect can model probes as pistons-like, but it can also taper the traction from the centre point. For the implementation for this work, the probe is always piston-like. The effect of the traction distribution has been investigated e.g. in [29] and found to be negligible in some cases, particularly when evaluating maximum value on an area.
The traction for a longitudinal probe for example is given by:

\[
    t = A f i \mu k_p \left[ \left( \frac{k_s}{k_p} \right)^2 - 2 \sin^2 \gamma \right] \hat{z} + \delta \sin 2\gamma \hat{x}
    e^{-ik_p x \sin \gamma}
\]

(3.1)

where:

- \( A \) represents the unaffected amplitude of the plane wave given a strict piston model, i.e., \( \delta = 1 \) and \( f = 1 \).
- \( f \) is a traction tapering function \( f \).
- \( i \) is the imaginary unit.
- \( \mu \) is the shear modulus.
- \( k_p \) is the wavenumber for P-waves.
- \( k_s \) is the wavenumber for S-waves.
- \( \gamma \) is the wave angle.
- \( \hat{n} \) is the unit vector in the normal direction.
- \( \delta \) is a coefficient setting the viscosity of the coupling fluid, where 1 represents a glued probe, allowing full transmission of transversal waves.

Figure 3.1 shows the simSUNDT software in two different versions. simSUNDT v2.0 is the stable version while simSUNDT v3.0 is currently under development using more modern programming languages and frameworks.
The exact mathematical handling of the interaction between the displacement field (Ultrasonic waves) and the defect (described by the T-matrix) is out of scope of this thesis, but is well covered by e.g., Boström et al [30] and J. Westlund [31]. It should be noted that the methods employed by UTDefect are considered "exact" in that from a mathematical point of view, it should be possible to reach arbitrarily good accuracy by increasing the number of terms in series expansions and the resolution of integral calculations. "Exact" does of course not mean a perfect representation of reality, given the numerous assumptions in the simulation software, e.g., not modelling non-linear effects or the non-active material between elements of a phased array system. UTDefect allows for the calibration of the amplitude response towards a reference reflector. For this purpose, a SDH or Flat-Bottom Hole (FBH) can be used. The use of reference reflectors are ubiquitous in NDT. SDHs are neat in the sense that they are consistent in one direction though the sample piece, i.e., in theory only one direction have to be searched with the probe to find the maximum amplitude response from the reflector.

3.2 Validation of UTDefect

For a simulation software like UTDefect, the output needs accurately enough represent reality to be useful. To this end, several validation projects have been performed and reported prior to the work done in this thesis. Validation can essentially be performed in two ways: comparison to other simulation software or to physical experiments. Eriksson et al. [29] compared the responses from surface-breaking cracks in pulse-echo mode in carbon steel plates. Here, not only was the maximum amplitude investigated but also the overall shape of the time-domain signal. Pecorari [32] investigated the scattering of the ultrasonic beam in an anisotropic medium as well as investigated the behaviour in near-field region. Niklasson et al., [33] investigated the responses from SDH, FBH and a spherical cavity. This was done with both a planar and a spherically focused transducer in an immersion setting. Jansson et al. [34], contributed to the 2008 benchmark problems managed by Commissariat à l’Énergie Atomique (CEA) in France. This also considered cases with immersion pulse-echo mode. The problem consisted of flat as well as curved (concave and convex) surfaces, but for this contribution only the flat surface was investigated. Lei et al. [35], started the validation for phased array systems. In this 2020 paper a contact probe with 64x1 elements was investigated. SDHs were used for the validation work. In the appended Paper B is the contribution in this thesis to the ongoing validation work of UTDefect. Here a phased array system is used in immersion setting. An annular probe is used, see Fig. 2.4c. The validation work looked at 14 SDHs and used swept focusing techniques for the experimental as well
as simulated work. In order to accommodate the annular probe modifications were done to UTDefect to allow for a dynamic size definition of the elements, whereas it was earlier assumed that the element width was constant for a circular probe. We found that the normalized error was minor at maximum 0.32 dB when the beam propagation direction was normal to the test block surface. However, the error grew with introduction of tilt angle of the probe. In this case, a maximum error of 2.97 dB was recorded. It is hypothesised that this discrepancy is dependant on the way the pressure field is converted from the probe to the surface: the shape of the pressure field is inherited by surface directly, i.e., it remains circular while in actuality a elliptical field might be closer to reality.

\footnote{For the phased array case, the probe is obviously sub-divided into the elements defined by the physical probe. However, it is worth noting that a conventional focused probe uses a similar mathematical framework, i.e., sub-dividing the probe into discrete elements to simulate the continuos geometrically based delay system of the physical probe.}
Chapter 4

Future work

In this chapter, the continuation of the project is outlined, along with a summary of some preliminary research work that has been performed. Additionally, a brief literature review of previous work in the research area is provided.

4.1 Information contained in the signal

<table>
<thead>
<tr>
<th>Time (sample)</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>800-1600</td>
<td>-1.5-0</td>
</tr>
</tbody>
</table>

Probe: 45 degree shear wave, 1.25 MHz center frequency, 75% bandwidth
Defect: Circular crack. Diameter: 2 mm. Depth: 30 mm

(a) A-scan signal from circular crack. Three cracks with tilt, 0°, 45° and 90°, respectively, are shown. Two regions (A and B) of interest are marked with circles.

<table>
<thead>
<tr>
<th>Time (sample)</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000-2800</td>
<td>-1.5-0</td>
</tr>
</tbody>
</table>

Probe: 45 degree shear wave, 2.0 MHz center frequency, 100% bandwidth
Defect: Spherical inclusion. Diameter: 5 mm. Depth: 30 mm

(b) Spherical inclusion with different densities.

40% density
80% density

Figure 4.1

As we can see in Fig. 4.1a there are multiple features of the signal, beyond the maximum signal amplitude, which differentiate the defect parameters and types. The indicated region A shows the non-primary wave mode signal (in this case a longitudinal wave) which is practically non-existent for the 45° case but quite prominent for the 0° case. Furthermore, there is an apparent phase shift between...
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(b) Spherical inclusion with different densities.

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(a) Circular crack and rectangular crack. Apparent phase shift is marked with circle in the image.

(b) Sphere and Circular crack.

Figure 4.2

the 45° case and the others. The above illustrations are a sub-selection of possible features of the UT signal which can be used to deduce useful information about defects. Similar illustrations, but for SDH, FBH, counterbore and notch, have been made for example in [36]. Of course, extraction of information from the UT-signal is not novel. Quantitative Non-Destructive Eesting (QNDE) is a research field with roots earlier than 1980 [37]. QNDE emphasises the quantitative side of NDE, rather than the traditionally more qualitative. As such, it is used characterize defects in terms such as size, orientation, and shape. While QNDE is not new, in recent years there has been a great deal of development in signal processing, namely AI. This has opened up the path to new ways of quantitatively extract more useful information from the UT-data.
4.2 AI

The fundamental mathematics of any AI-model is not covered in this thesis. Instead, more practical use cases is presented along with a pre-study to give credence to future research endeavours. Here we adopt the most liberal interpretation of AI; the term encompasses other terms such as deep learning, support vector machine and machine learning. It can be useful for communication reasons to categorize AI efforts. On the highest level two methods can be defined: supervised and unsupervised (in the literature there exists also references to semi-supervised).

Supervised AI is trained by teaching with example. Data that has been labelled based on some ground truth (e.g., by humans) is fed into the algorithm for learning. For unsupervised systems, there are no labels on the data which is fed to the algorithm. Instead, the AI extract features of interest in a automatic fashion. The majority of articles related to UT and AI are focused on the supervised category, which is the only one which will be addressed further in this text. Under the supervised group, there exist End-to-End Learning and Feature Engineering Approach, where the former relies on feeding raw data into a network (along with labels for training). The latter relies more on pre-processing steps which have been determined useful for the task defined, for example [38] where seventy-two features were evaluated from vibration data.

Several methods have been incorporated to extract useful information from the UT data collected, though for the modern methods two main factors hinder their adaptation, namely the lack of real world annotated data and benchmarked performance of deep learning models. This was partially addressed by Ye et al. [40], who benchmarked seven models from developed between 2012 and 2018. The model scoring highest on most benchmarks was DenseNet [41] consisting of 120 convolutional layers and 1 fully connected layer. All the data was images in the form of B-scan data.

Mumir et al. [42] used a Convolutional Neural Network (CNN) in a noisy UT testing environment to classify defects of type LOF, Lack of Penetration, Porosity, Cracks and Slag Inclusion. This was done on experimental data without explicit feature extraction prior to data processing (i.e., feature extraction is inherent to the CNN-function). Though the data was strictly experimental, data augmentation was used in the form of time-shifting (equivalent to transla-
Data augmentation is a technique used to address the sparseness of available real-work data by extending the existing data-set through manipulation. This is used extensively and is described well in [43] where the authors also applied it on acoustic data prior using a CNN for speech recognition. Virkkunen et al. [44] similarly used augmented data extensively. In this case for flaw detection using a CNN.

Sambath et al., [45] used a back propagation network to classify defects into Porosities, LOF or tungsten inclusion. The network was fed pre-determined features of the UT data and a classification rate of 94 % was obtained.

Beyond data augmentation for data-set expansion is simulation based methods. Liu et al. [46] used FEM in combination with boundary integral equation to simulate the A-scan and train a neural network for identification and classification. Similarly, Cau et al. [47], used FEM to generate synthetic data for pipe inspection. The data was further reduced by feature extraction and then fed into a feed-forward network for notch size determination.

The aim for the future work in this thesis is to use computationally cheap (e.g., based on UTDefect, see chapter 3.1) to compliment experimental data-sets for defect classification and characterization. To achieve this, the plan involves initially working with strictly simulated data to further hone in on an appropriate network structure and hyperparameters (defining the overall behaviour of a AI-model). Following this, experimental data will be incorporated and transfer-learning along with data augmentation applied to investigate how good performance can be achieved in a practical setting.
A pre-study was performed which used strictly simulated data generated using the UTDetect software. The data was restricted to one type of defect: a spheroidal cavity. This defects were modelled as a non-conducting vacuum and is described by two dimensional axis as well as two rotations. The data was split into four categories based on the ratio of the dimensional axis. The size and angle of the defect was normally distributed around 1.2 mm and 0° respectively. The data was then split into a training set and a validation set. A CNN was constructed using MATLAB Deep Learning Toolbox. Fig. 4.4 shows the overall structure of the network. An algorithm for searching the hyperparameters for the optimal performance was created. Fig. 4.5 shows the performance of the network as a function of two of those parameters.
Figure 4.5: Shows the classification accuracy of the CNN as a function of a sub-selection (convolutional layer size) of hyperparameters

In addition to the size of the two convolutional layers used, the number of neurons was also a controlled parameter in the search. Finally, a categorization of the spheroids in the validation data was concluded with a 94.6% accuracy.

The continuation of this work stands a good chance at advancing the possible use of synthetic data for both defect classification and characterization, in the extension leading to an important input for lifing assessment.
Chapter 5

Summaries of Appended Papers

A summary of the appended papers and the main findings are presented below. Note that Paper A is a chapter contribution to a book, and not a peer reviewed paper.

Paper A

*Non-Destructive Evaluation of Additively Manufactured Components.* This book chapter is an excerpt from the book *Additive Manufacturing of High-Performance Metallic Materials.* It reviews some of the methods used for NDE of additively manufactured components, as well as highlight some use cases applied in the field of AM.

**Author’s contribution:** wrote the majority of the content.

Paper B

*Experimental verification of phased array annular probe in ultrasonic immersion setting.* This paper focuses on validating the PA-UT technique in an immersion setting. The study aims to experimentally verify the responses of sim-SUNDT/UTDefect simulation software. This validation is done using well-defined defects, such as side-drilled holes, at various depths. The material is also practically noise free wrought aluminium to isolate the model behind the probe itself. An adaptive focusing strategy is used both in the simulated and experimental case to maximize the amplitude response respectively. The results demonstrate a strong correlation between the simulations and experimental data, especially when the probe is perpendicular to the surface. This finding further expands the domain of validity for UTDefect.

**Author’s contribution:** performed the literature review. Generation of simu-
lated data. Collection of experimental data. Data analysis. Wrote the draft and final manuscript.

**Paper C**

*Ultrasonic Signal Response from Internal Manufactured Defects in PBF-LB manufactured superalloys.* The article focuses on using UT as a NDT method for detecting internal defects in components manufactured through Additive Manufacturing (AM), specifically using the PBF-LB method. It explores the impact of as-built surface conditions of PBF-LB on the ultrasonic signal response and defect detectability. The study involves creating controlled defects in manufactured blocks and examining them using phased array UT and conventional UT. The results reveal how the surface roughness and build direction affect the morphology of defects and the UT signal response, offering insights for optimizing defect detection in AM processes. Furthermore, the study investigates the characteristics of the UT response depending on the build-direction for spheroidal cavities. It is shown that the build-direction has a meaningful impact on actual morphology (and in extension, the UT response).

**Author’s contribution:** collected most of the experimental UT data. Performed the literature review. Defined (in collaboration) and designed test pieces. Performed the data analysis. Wrote the draft and final manuscript.

**Paper D**

*Simulation derived probability of Detection of lack-of-fusion-like defects in additively manufactured materials.* This article focuses on the amplitude response from LOF-like defects by modelling them as spheroidal cavities. Spheroidal cavities are a mathematically simple shape and can be readily dealt with a computationally cheap manner. Two separate meta-models are constructed using a limited set of parameters defining the defect (in terms of morphology and position), as well as inspection set variation. The set of critical parameters with regards to inspection was determined through sensitivity analysis. A POD analysis was performed based on the output of the meta-models. It was shown that performance indicator i.e., $d_{95/95}$ was much greater for all defect sizes in the far-field region. The output from the models were compared in a limited domain to experimental data.

**Author’s contribution:** defined and designed test pieces for experimental data. Collected the experimental UT data. Conducted the literature review. Performed the data analysis. Wrote the draft and final manuscript.
Chapter 6

Conclusion

This thesis presents an early path towards improvements in detection and classification of defects using UT. Firstly, a mathematical model was validated against experimental results, answering the first research question and verifying the validity of the models. Secondly, experimental work was done to investigate the effects of build direction in a PBF on the UT signal response. Given the demonstrated effects of morphology differences of defects, a meta-model was introduced to facilitate a search the parameter space (describing defect morphology and location) in a mathematically efficient matter. This was used to highlight valleys in the detectability of defects: there exists configurations where an increase in size decreases the UT signal response amplitude. Furthermore, the model was used to quantify the POD in certain inspection scenarios based on log-normal POD model. Finally, an outlook for future work was described, relying on preliminary data based on a pre-study based on strictly simulated data.
References


References


REFERENCES


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Paper B

Experimental verification of phased array annular probe in ultrasonic immersion setting

M. Sahl, H. Wirdelius

Presented at the 13th ECNDT Conference, Lisbon, Portugal

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Experimental verification of phased array annular probe in ultrasonic immersion setting

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Abstract

With the ongoing development of materials and manufacturing techniques, new product design opportunities manifest themselves. However, care must be taken when applying techniques and material where there is less inherent knowledge about different parameters' effect on the integrity of the final component. In conjunction with destructive testing of components, non-destructive evaluation (NDE) provides valuable insight into the manufacturing process reliability, as well as the possibility for subsequent future in-service inspection. Phased array ultrasonic testing (PAUT) facilitates the inspection of complex geometries on a wide set of material. Mathematical modelling of ultrasonic signal facilitates the optimization of inspection procedures by e.g., maximizing the probability of detection (POD) of specific defect types. In this paper, the response from an immersion annular phased array probe is experimentally validated to the output of the simulation software simSUNDT. In order to only validate the probe model (as both transmitter and receiver) a set of well-defined defects are used. The validity of the simulated amplitude response from side-drilled holes at a depth range of 20-115 mm is investigated. A total of 14 SDH holes in one test piece of is used as cases for validation. The results show a good correspondence between simulated and experimental data for the case where the probe is normal to the component surface.

KEYWORDS: Experimental Verification; MAPOD; Sensitivity Analysis; Ultrasonic Inspection

1. Introduction

For any product, each subcomponent needs to be designed and dimensioned in such a way that it does not fail prior to the designed lifespan. This can often be ensured by applying simple mathematical models, followed by applying a healthy safety margin. For weight critical application it is important to minimize the need for this safety margin. Reducing the size of this safety margin increases the sensitivity to variation in the manufacturing process; any variation from the expected strength of material can cause a failure of component. New alloys and manufacturing techniques facilitates new design opportunities. However, care must be taken when applying techniques and...
Experimental verification of phased array annular probe in ultrasonic immersion setting

Mikael Sahl¹ and Håkan Wirdelius¹
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Abstract

With the ongoing development of materials and manufacturing techniques, new product design opportunities manifest themselves. However, care must be taken when applying techniques and material where there is less inherent knowledge about different parameters’ effect on the integrity of the final component. In conjunction with destructive testing of components, non-destructive evaluation (NDE) provides valuable insight into the manufacturing process reliability, as well as the possibility for subsequent future in-service inspection. Phased array ultrasonic testing (PAUT) facilitates the inspection of complex geometries on a wide set of material. Mathematical modelling of ultrasonic signal facilitates the optimization of inspection procedures by e.g., maximizing the probability of detection (POD) of specific defect types. In this paper, the response from an immersion annular phased array probe is experimentally validated to the output of the simulation software simSUNDT. In order to only validate the probe model (as both transmitter and receiver) a set of well-defined defects are used. The validity of the simulated amplitude response from side-drilled holes at a depth range of 20-115 mm is investigated. A total of 14 SDH holes in one test piece of is used as cases for validation. The results show a good correspondence between simulated and experimental data for the case where the probe is normal to the component surface.

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material where there is less inherent knowledge about different parameters’ effect on the integrity of the final component.

Non-Destructive Evaluation (NDE) is a process of finding flaws in materials and components without affecting the integrity of the material. NDE gives the freedom to design without unnecessary amount of mass by verifying there are no defects of critical size and characteristics in the component.

Ultrasonic Testing (UT) is a well-established method to locate and evaluate internal defects. UT works on most materials and has a high degree of sensitivity [1]. These characteristics contribute to the fact that the method is used extensively in several industries, including aerospace. To increase the sensitivity of the inspection (the ability to detect small defects), a focused beam probe is often used. A focused beam concentrates the ultrasonic wave front to a specific depth-range which increases the amount of energy reflected by any potential indication. Consequently, constraining the energy focus to a certain depth limits the amount of volume inspected for a given time unit. Phased Array (PA) can steer an effective wavefront by applying delay laws to a series of ultrasonic elements shown in Fig. 1b. The refraction of the beams as they enter the component is calculated according to Snell’s Law [2].

![Annular PA probe configuration and application](image)

**Figure 1. General configuration and application of annular array probe. (a) shows the configuration of the individual piezoelectrical elements (not all elements are rendered in image), (b) illustrating the focusing effect, where the red bars represent time delay, and the blue line the effective beam propagation direction.**

Annular PA probes are probes that have the elements configured in a circular configuration (Fig. 1a) as such applying delay laws does not allow for beam steering away from the normal of the probe surface but does facilitate adjustable focus distance in a symmetrical fashion compared to a 1-dimensional linear PA probe. As such an annular probe can focus the beam energy in a similar way to a conventional ultrasonic probe, but with a flexible focus depth. This solid state based focusing method can switch in milliseconds, allowing for multiple focus depth to be captured continuously during probe scanning. This means for practical applications that a component can be scanned on a single pass compared to a conventional setup where a series of conventional focused probes would be required to focus on the entire depth. Inspection procedures for critical components needs to be qualified. There needs to be statistical data providing some degree of confidence in that defects that could affect the performance of a component will be identified reliably. Traditionally, these qualifications are performed by having sufficient number of physical specimens with real or artificially created flaws. The testing procedure can then be qualified by applying it to these samples and evaluating the degree to which the flaws were detected. By
applying statistical methods to the acquired results, a Probability Of Detection (POD) indicator value can be calculated. POD is a well-established method to measure reliability in NDT and is often acquired using well defined procedures, e.g. [3]. However, this approach is expensive, especially when the testing procedure heavily relies on operator input, which tends to introduce more variability to the system and a greater sample size is required. Model Aided Probability Of Detection (MAPOD) has gained more interest in recent years. MAPOD utilizes simulated data, potentially supplemented with physical experimental data, to calculate a POD value for a specific test case. By simulating the entire test setup, including the defect characteristics and probe-parameters, the number of samples can be made vastly greater than what would be feasible for strictly physical experimental data.

To simulate the propagation of ultrasonic signals within materials there are two main mathematical methods, analytical or numerical. UTDefect [4] uses analytical methods and solves the elastodynamic wave equation. The models are applicable to homogenous materials only, however the material can be isotropic or anisotropic. UTDefect has previously been validated for both contact phased array [5], as well as immersion testing with non-focused and focused conventional probes [6] [7]. There is however a gap in validation for immersion phased array probes.

In this paper, the implemented mathematical models of UTDefect are experimentally verified in an immersion setting using phased array technology with well-defined 3 mm Side-Drilled Hole (SDH) as reference defects in a homogenous noise free component. 3 mm SDH is the reference indicator used in ISO standard for weld inspection [8] which makes it a reasonable choice for the validation. The validation of simulated amplitude response is limited to a specific case with few parameter variations:

- **Angle of incidence**
  - $0^\circ$
  - $5^\circ$

- **Frequency distribution of simulated wave-front.**
  - Monochromatic
  - Cosine square distributed.

simSUNDT/UTDefect can either simulate the wave propagation in a single frequency (monochromatic), or as a spectrum. When a cosine square distribution is chosen and a bandwidth is specified, the software automatically discretizes the signal into a number of independent sub-signals of different frequencies, with the highest energy content at the selected frequency. This is a reasonable model of an actual ultrasonic transducer. The amplitude difference will be presented in dB which is a logarithmic measurement and defined according to (1)

$$dB = 20 \cdot \log_{10} \frac{\text{signal } A}{\text{signal } B}$$

(1)

where $\text{signal } A$ and $\text{signal } B$ are two signals in any linear measurement system [3].

2. **Method**

The work consists of comparing the data from physical experiments and simulated experiments. The method of collection of the two datasets are presented in the following two sub-chapters.
2.1 Experimental approach

The experiments were performed with the probe indicated in Table 1. The probe was driven by the TOPAZ64 portable Ultrasonic Testing system, and the data was transferred to a PC for analysis via Ethernet. The tests were all performed by positioning the probes using a mechanized gantry system, Fig 2b. The gantry consists of two mechanized axes (X and Y), allowing for planar scanning of surfaces, as well as three manually actuated axes. The Z-axis as well as the rotational axes for two probe Euler angle adjustment (φ and ψ) are manually actuated. For the 0° incidence test the Euler angles were adjusted manually until the response of the surface echo was maximized to ensure a normal incidence to the surface. For the 5° incidence test a calibration block was manufactured (Fig. 2a) with one surface tilted 5° and the amplitude response from that surface was maximized in a similar fashion.

All tests were performed in a 70-litre water-tank. The water was tap-water and was allowed to de-air and reach room temperature (~21 degrees Celsius) before experiments were performed.

Table 1. Overview of the ultrasonic probe used in the experiment.

<table>
<thead>
<tr>
<th>Probe</th>
<th>Frequency (MHz)</th>
<th>Number of Elements</th>
<th>Diameter (mm)</th>
<th>Minimum operating distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMASONIC</td>
<td>10</td>
<td>32</td>
<td>45</td>
<td>50</td>
</tr>
</tbody>
</table>

2.2 Simulated experiment

To perform the simulation the software simSUNDT was used. simSUNDT is acting a pre- and post-processor for the mathematical solver UTDefect. The focusing distance of the probe was consistently set to maximize the amplitude response. This distance was found by iterative approach near the theoretical optimal value. In a similar fashion the probe position was determined to maximize the amplitude response. This was also based roughly on mathematical calculation derived from Snell’s law, and fine tuned with an iterative approach.
The focusing distance in simSUNDT is expressed as a primary focusing distance, that is for an immersion setting the distance to the focusing point if the beam was not refracted along its path. To account for the refraction when the sound wave enters the component a MATLAB script was created to calculate the desired primary focusing distance from the actual “refracted focusing distance”. simSUNDT was set to run with an accuracy index of 3, which defines the step length of the integral solver.

3. Results

Fig. 3 shows the amplitude for tests at different defect depth with simulated and experimental data. The amplitude response for both sets of data has been normalized to the respective SDH at 50 mm. For the simplest case with an incidence angle of 0°, Fig. 3a, the greatest discrepancy between simulation and experimental data is less than 1 dB. This can be put into some context by looking at the ISO standard for acceptance level of evaluation of welds [8] which defines a difference between a reference level (based on a 3 mm SDH) and acceptance level 2 at (-6) dB for short (0.5-1 mm) indications. The result from the normal incidence test with a cosine square distributed frequency is not presented here but is near identical (the greatest difference in normalized amplitude between two simulations at equal depth is 0.32 dB). Similar results have been presented previously, e.g., in [9].

Fig. 3b shows the difference between experimental and simulated data with a probe incident angle. The greatest normalized difference is for the hole at 85 mm depth, where there is an amplitude discrepancy of 2.97 dB.

4. Discussion

The discrepancy between simulated and experimental response can likely partially be explained by how UTDefect defines the surface pressure boundary condition. In the current implementation the pressure zone on the top surface of the component is necessarily modelled as a circle with constant pressure (piston-like model). In reality for an immersion setting with the probe offset from the surface normal, a non-circular pressure zone will be introduced onto the top surface.
Future work should involve re-writing the algorithms to model the pressure boundary condition in a more realistic fashion.

5. Conclusion

This paper investigated to what degree the ultrasonic amplitude response in simulated test cases corresponds to experimental tests. It was concluded that for the most used case, i.e., with a 0° incidence angle of the probe the correlation is in the same approximate range from what has been concluded from earlier studies for different test configurations. Whether or not the correlation is sufficient for any application needs to be determined on a case-to-case basis. It should be noted that the domain of the validation is limited and deviation in the simulated test configuration could alter the correlation in a non-linear fashion. The results from the tests with the angled probe revealed possible shortcoming of the current implementation and should be considered carefully before applying the model to cases where they might be relevant.

Acknowledgements

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Paper C

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Ultrasonic Signal Response from Internal Manufactured Defects in PBF-LB manufactured superalloys

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Abstract. In the emerging field of Additive Manufacturing (AM), the promise of unparalleled design flexibility, resource efficiency, and rapid prototyping has captivated both industry and academia. While AM techniques offer a wide range of manufacturing possibilities, they also present unique challenges in ensuring structural integrity and material properties. Non-Destructive Testing (NDT) methods, including Ultrasonic Testing (UT), have emerged as invaluable tools for evaluating the internal structure of AM components without compromising their integrity. By employing NDT techniques, it is possible to detect flaws such as porosities, cracks, and other inhomogeneities early in the manufacturing process, thereby improving reliability, extending the lifespan, and reducing the overall environmental footprint of AM products. While the occurrence of defects from processes such as welding is well-established, documented and standardized with regards to NDT, a knowledge gap exists for defects in the field of AM. Specifically, reference reflectors commonly used in the industry, such as side-drilled holes and flat bottom holes, are well understood when machined into components using traditional (subtractive) means. AM offers more flexibility, e.g., adding closed internal reference reflectors directly from the build-process. Twelve straight blocks were manufactured using Laser Powder Bed Fusion (PBF-LB) with carefully selected artificial defects. All defects were created by CAD (Computer Aided Design) seeding, i.e., introducing voids into the CAD-model. The blocks were inspected using Phased Array Ultrasonic Testing as well as conventional ultrasonic testing. It was shown that the as-built surface of PBF-LB has an adverse impact on the ultrasonic testing signal response, and the detectability of defects was quantified under the different conditions (machined surface compared to as-built). It was shown that the build direction has an impact on the morphology and the UT signal response from internally seeded defects.

Keywords. Ultrasonic Testing, Non-Destructive Testing, Additive Manufacturing

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1. Introduction

With the maturing of Additive Manufacturing (AM) technology, designers have been given new tools which enable unprecedented design- and prototyping flexibility. Near-net shape components can be manufactured using an array of different AM options, depending on the specific requirements. One of the most significant advantages of AM
is the ability to optimize the weight of components through intricate internal structures that are often impossible to produce using traditional manufacturing methods. This capability not only contributes to material efficiency but also facilitates the design of components with improved mechanical properties, such as increased stiffness or reduced weight. Furthermore, AM allows for the tailoring of microstructures to achieve desired mechanical and thermal properties, a feature hardly feasible in conventional manufacturing processes.

Yet, the full potential of AM can only be realized when the components produced are of verified quality and integrity. Non-Destructive Testing (NDT) techniques are therefore integral to the AM process, particularly when the components are intended for critical applications such as aerospace, medical devices, or in automotive sectors. Rapid advancements in AM processes, alongside new material development, are causing hesitation among manufacturers. The limited accumulated experience, especially for safety-critical applications, makes adoption of these technologies uncertain. Ultrasonic Testing (UT) is one of the most widely recognized NDT methods used to verify component quality and compliance. It is effective on a vast range of materials and boasts impressive sensitivity [1]. UT works on the principle of ultrasonic waves interacting with matter and any inhomogeneities the wavefront might encounter. Ultrasonic waves can be focused, thereby increasing sensitivity of detection in a region of interest. Such attributes have led to its widespread adoption in various sectors, notably the aerospace industry. For increased sensitivity in defect detection, focused beam probes are commonly used. Such a beam focuses the ultrasonic wave front onto a particular depth, amplifying the reflection from any potential defect. However, this focused energy at a specific depth means that only a limited volume is inspected at any given moment, leading to the need for several probe changes for any particular volume to be inspected. Phased Array (PA) can adjust this effective wavefront by implementing delay laws to a set of ultrasonic elements. When these beams penetrate a component, their refraction is determined based on Snell’s Law [2]. Annular PA probes are uniquely designed with elements in a ring-like arrangement. Due to this configuration, while delay tactics do not permit beam direction changes away from the probe surface's normal, they do enable modifiable focus distances in a symmetrical manner, unlike from a 1-dimensional linear PA probe where the pressure profile between two perpendicular planes will be different. Thus, an annular probe can focus the beam energy in a similar way to a traditional ultrasonic probe, but offers adjustable focus depth. In practical terms, this means a component can undergo a single-pass scan, in contrast to traditional setups that would necessitate multiple focused probes to cover the entire depth of the component.

Accurate sizing of defects in materials is essential for evaluating the structural integrity and reliability of components. One of the most commonly applied methods is the 6 dB drop (or half-value) method. This method is predominantly used in ultrasonic testing (UT) and is based on the principle that as the position of the probe focus point moves away from the centre point of the defect, the amplitude of the reflected ultrasonic wave decreases. The 6dB drop method involves detecting the point at which the amplitude of the reflected wave drops by 6dB from its peak value. This amplitude drop corresponds to the edge of the defect. By analysing the points of amplitude drop on both sides of the peak, the width of the defect can be obtained. This method provides a relatively quick and reliable means of defect sizing, especially in cases where the defect shape is irregular and hard to determine through other means. A complementary/alternate method relies on utilizing known reflectors, typically in the form of Side-Drilled Holes (SDH) or Flat-Bottom Holes (FBH), provides a calibration standard against which
defects can be compared. By measuring the amplitude of the reflected wave from these known reflectors, the system can be calibrated to account for variations in material properties, equipment settings, and other factors that might affect defect detection and sizing. The use of amplitude as a proxy for defect size is only moderately accurate when the defect is smaller than the effective beam width. Thus, the combined use of the 6dB drop method with known reflector references ensures a more comprehensive and accurate assessment of defect sizes, enhancing the reliability of evaluations.

Among the reference reflectors employed to simulate and understand potential defects in materials, SDH, FBH and notches stand out as the most commonly applied. SDHs primarily simulate small, round defects such as porosities or inclusions. Drilled perpendicular to the material's surface, SDHs are also frequently utilized for distance calibration in ultrasonic testing, e.g., DAC (Distance Amplitude Correction). Their consistent reflection surface facilitates the uniform detection of signals, making them adept at representing defects that might be located away from the inspection surface. FBH on the other hand, are tailored to represent planar defects that might exist parallel to the material's surface, such as de-laminations or circular cracks. These holes possess a flat bottom, offering a vast reflection surface that produces a robust echo in ultrasonic testing. This consistent reflected signal renders FBHs ideal for amplitude calibration. [3]

Notches come into play when simulating defects such as surface breaking cracks (fatigue cracks or stress corrosion cracks) or weld seam anomalies such as lack of fusion. Their introduction at various orientations, depths, and widths allows them to mimic a wide range of potential crack-like defects in materials.

Current NDT procedures often rely on standards adapted for conventional manufacturing methods (e.g., ISO 6520-1 for defect classification and ISO10675-1 for acceptance levels in welding). There is a need for more tailor-made guidelines which address the challenges of NDT in the context of additive manufacturing.

Effects of surface roughness of as-built components have previously been investigated, e.g., by Hanks et al. [4] who performed a study focused on the PBF electron beam process. The authors measured the surface roughness of the as built components and it ranged from 27.0 to 58.7 μm. Post milling the surface roughness was in a range of 1.9 to 7.0 μm. It was shown that for 2.25 and 5.0 MHz setups that no 0.51 mm diameter spherical defect was detectable from an unmachined side-surface (relative build-direction). All of them were, however, recorded above Signal-to-Noise Ratio (SNR) threshold post machining. For a 10 MHz probe though, no difference was able to be shown between as built and machined surface. Given this, the authors conclude that for the surface roughness levels investigated, 10 MHz inspection are not affected by surface roughness to the same extent as the lower frequencies. This is in contradiction with common understanding and claims in text books, e.g., [5].

Honarvar et al., [6] used high frequency (up to 50 MHz) to identify and size defects in PBF-LB. It was shown that artificial defects down to 0.75 mm was detectable. The authors applied XCT (X-ray Computed Tomography) to compare methods of sizing defects and got reasonably well level of agreement, though the UT sizing tended to be somewhat higher compared to XCT. UT also had issues separating defects in close proximity.

In this study, the aim is to investigate how changes in the morphology of internally seeded features, influenced by the build direction, affect the UT response. Furthermore, the effect of surface roughness from as-built components on the ultrasonic response is investigated.
2. Method and materials

A total of twelve rectangular blocks were designed and manufactured using Powder Bed fusion with Laser Beam (PBF-LB) consisting of 4 block types, and three pieces of each type. The material used was Inconel 939 (IN939). Virtual defects were seeded into the components in a strategic manner. The defects consisted of Disk-Shaped Reflectors (DSR), Spherical cavities, Through-holes (TH), Flat Bottom Holes (FBH) and Spheroidal cavities. For the latter, the notation of [a, c] will be used, where a is the length of the major axis in millimetres and c is the length of the minor axis in millimeters. Where a single value gives the dimensional information of interest the defect abbreviation will be given followed immediately by the size (in mm). Additionally, four Spheroidal cavities were printed with a drainage channel to facilitate powder removal. The ultrasonic inspection data was collected using a 32 element 10 MHz annular array probe with 35 mm active diameter where all the elements have equal area. Planar scans were performed on the surfaces of the test blocks (Figure 1) using a mechanized positioning system. The step resolution for the scans were adjusted to 0.15 mm along both the scan- and the index axis. The scan axis was always setup to be along the long edge of the component. Scanning (data collection) was done bidirectionally (moving in both positive and negative direction along the scan-axis). A Topaz64 Ultrasonic testing system was driving the probe (as a receiver and transmitter) and acting as a data logger. Most of the post-processing and analysis was done using the Ultravision 3.9R20 software. In addition to the phased array probe, three conventional probes were used to evaluate the individual sensitivity to changes in surface roughness. The following probes are used:

- Harisonic iR1008 with 1.5-inch point focus in water (10 MHz, 0.5- inch diameter),
- Harisonic iR1008 with 2.5-inch point focus in water (10 MHz, 0.5- inch diameter),
- Panametrics V327 with 3.25-inch point focus in water (10 MHz, 0.375 -inch diameter).
- Imasonic Annular array probe (10 MHz, 32 channels, 35 mm active diameter)

The surfaces were scanned in as-built condition and a sub-selection of the surfaces were scanned after milling to investigate the effect of surface roughness. Surface roughness was quantified prior to and after machining.

In addition to UT, a XCT scan was performed on Block 2 containing the flat DSR. This was done to acquire a volumetric view as well as quantitative information about defect size, which in this paper will be considered ground truth. A Phoenix V|tome|x M240 industrial scanner was used with the following settings and parameters:

- Voltage and current: 185 kV, 73 μA
- Filter: 0.7 mm Cu + 0.8Cu
- Focal spot size 13.5 μm
- Voxel size 13 μm
- Exposure time 250 ms
- Frame averaging 7.
Whenever uncertainties are stated in the results section, it based on data captured from three sample points, each derived from the CAD (Computer-Aided Design)-identical manufactured sample.

2.1. Surface roughness

The surface roughness of the samples was evaluated at 10 different positions on two different sides of the manufactured Blocks 4 and 2 prior to machining. It was also evaluated after machining. The measurements were performed with Mitutoyo equipment, and the measurements adhered to the ISO1997 standard.

![Figure 1. Isometric view of the IN939 samples. Blue (narrow) arrows showing UT inspection directions. Red (wide) arrows showing build direction.](image)

2.2. Amplitude and SNR evaluations

The defects were evaluated in terms of their maximum amplitude as well as SNR. SNR was calculated according to
\[ SNR = \max(\text{defectSignal}) - \max(\text{noiseSignal}) \] (1)

where \text{defectSignal} is the maximum amplitude response (dB) recorded from all pixels representing the defect in the C-scan, and \text{noiseSignal} is the maximum amplitude response (dB) in all pixels of the defined noise region. The noise region was as defined as rectangular prism 20x4x2 mm positioned in a defect free and representative volume at approximately the same centre depth as the defect. The defect amplitude was evaluated by searching the volume- and focus space in the defect vicinity. An area and depth was defined in the C-scan representation of the data after which the maximum amplitude was evaluated in a series of focal laws around the predicted optimal focus. As such, any unexpected variance in inspection setup (e.g., surface flatness/waviness or sample parallelism to the gantry axis) was corrected for.

2.3. Sizing

A selection of the seeded defects were sized using the 6dB-drop method. The 6dB-drop was performed along the scan axis unless otherwise specified. The resolution of the axis is 0.15 mm. Linear interpolation was used to find the scan axis position of 6dB-drop with increased resolution.

3. Results

The results from the surface roughness measurement are shown in Figure 2. It can be seen that the variation post machining is low, and the value significantly reduced.

3.1. Effect of surface roughness

Figure 3 and Figure 4 shows both the C-scan and the B-scan representations of Block 1. Figure 3 shows the data captured from an as-built surface, whereas Figure 4 shows
the data captured from a machined surface. The immediate take-away is that the smallest introduced defects in Block 1 are detectable given any reasonable SNR threshold, regardless of the surface being machined or not.

Figure 3. C-scan and B-scan representation of Block 1, scanned from surface B. As-built.

Figure 4. C-scan and B-scan representation of Block 1, scanned from surface B. Machined surface.
Table 1. Showing the Signal-to-Noise ratio for defects in Block 1. Captured from surface B. Note that the defect type is FBH, which is merely for identification purposes. The defects all appear as side-drilled holes from surface B.

<table>
<thead>
<tr>
<th>Signal-to-Noise ratio Block 1 Surface B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>TH2.6</td>
</tr>
<tr>
<td>TH2.0</td>
</tr>
<tr>
<td>TH1.4</td>
</tr>
<tr>
<td>TH0.8</td>
</tr>
<tr>
<td>TH0.4</td>
</tr>
<tr>
<td>TH0.3</td>
</tr>
<tr>
<td>TH0.2</td>
</tr>
</tbody>
</table>

The SNR was evaluated on the defects of Block 1. The variance data is not available for the SNR of the machined surface B (i.e., only one block was milled). As such, no conclusions can be drawn on whether there is a significant difference between any two pair of equivalent defects. It is, however, possible to show that there is a significant difference between the two groups (as-built and machined) of defects. Applying the paired sample t-test reveals that the null hypothesis (normal variations being a plausible (95% confidence) cause of the difference between the groups) can be rejected:

\[ t = \frac{\bar{d}}{s_d/\sqrt{n}} \]

where \( \bar{d} \) is the mean differences between the paired observations, \( s_d \) is the std. deviation of the differences between the paired observations, \( n \) is the number of paired observations. As such

\[ \text{abs}(t) = \text{abs}\left(\frac{1.1143}{0.6149/\sqrt{7}}\right) \approx 4.7945 \]

which is greater than the critical value 2.447 from table [7].

Table 2. Signal-to-Noise ratio Block 3 Surface B.

<table>
<thead>
<tr>
<th>Signal-to-Noise ratio Block 3 Surface B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sphere size</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>0.5 mm</td>
</tr>
<tr>
<td>1.0 mm</td>
</tr>
<tr>
<td>1.5 mm</td>
</tr>
<tr>
<td>2.0 mm</td>
</tr>
<tr>
<td>2.5 mm</td>
</tr>
<tr>
<td>3.0 mm</td>
</tr>
</tbody>
</table>

(a) (b)

Figure 5. The smallest spherical defect in the samples (0.5 mm). Shown as C-scan representation from as-built (a) and machined (b) surface.

Figure 5 shows a closeup C-scan representation of the smallest sphere included in the data-set. It is clear that the morphology is well represented from even a 0.5 mm defect, regardless of the surface being machined or not. Note the difference in the amplitude scale.

Drainage channels were introduced into Block 3 to allow any unmelted powder to be removed, leaving a space with air instead of unmelted powder. The hypothesis was that the lower density of the sphere without powder would facilitate a higher level of reflection, compared to a powder filled cavity. The signal response from the as-built (drainage channel) is not significantly different from the as-built surface (Table 2). We can also see that the response is neither strictly greater nor lesser compared to the As-built..
Table 2 shows the signal response and SNR (where applicable) from the defects in Block 3, scanned from Surface B. The table presents three defect categories: As-built, Machined and As-built (drainage channel). Note the absence of uncertainty in the data for the Machined category. In a similar fashion as for the Block 1 Ampl. response we can determine that there is a significant difference between As-built and Machined surface.

Table 3. Difference in amplitude response machined compared to as-built. Block 1 Surface A.

<table>
<thead>
<tr>
<th>Defect size (in)</th>
<th>As-built</th>
<th>Machined</th>
<th>As-built - Machined</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1.1 ± 0.7</td>
<td>2.9 ± 0.3</td>
<td>1.8 ± 0.7</td>
</tr>
<tr>
<td>0.8</td>
<td>1.4 ± 0.6</td>
<td>2.9 ± 0.3</td>
<td>1.5 ± 0.7</td>
</tr>
<tr>
<td>1.3</td>
<td>1.4 ± 0.6</td>
<td>2.9 ± 0.3</td>
<td>1.5 ± 0.7</td>
</tr>
<tr>
<td>1.8</td>
<td>2.0 ± 0.3</td>
<td>2.9 ± 0.3</td>
<td>0.9 ± 0.6</td>
</tr>
<tr>
<td>3.25</td>
<td>2.0 ± 0.3</td>
<td>2.9 ± 0.3</td>
<td>1.9 ± 0.3</td>
</tr>
<tr>
<td>4.75</td>
<td>2.0 ± 0.3</td>
<td>2.9 ± 0.3</td>
<td>1.9 ± 0.3</td>
</tr>
<tr>
<td>6.25</td>
<td>2.0 ± 0.3</td>
<td>2.9 ± 0.3</td>
<td>1.9 ± 0.3</td>
</tr>
</tbody>
</table>

Table 3 above shows the delta of amplitude response from Block 1 Surface A after compared to before machining. There is only a significant increase in amplitude response from the 2.5'' and 1.5'' probe. The reason that the 3.25'' probe might be more affected by surface roughness is that the probe diameter is smaller and the focus distance larger. Both these properties contribute to a smaller pressure area on the component surface, making it more susceptible to variations.

Figure 5 shows a closeup C-scan representation of the smallest sphere included in the samples (0.5 mm). Shown as C-scan representation from as-built (a) and machined (b) surface.

Figure 5 shows a closeup C-scan representation of the smallest sphere included in the data-set. It is clear that the morphology is well represented from even a 0.5 mm defect, regardless of the surface being machined or not. Note the difference in the amplitude scale.

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The hypothesised effect of a greater signal response from the spectral reflection of a defect which has had its powder evacuated has not been demonstrated. The reason is either an overestimation of the effect of increased density on the transmissivity or that the spheres have not actually been properly emptied of powder. This will need to be investigated further, either through new attempts at removal along with gravimetrical testing, or through the use of XCT.

Figure 6. C-scan representing 2.5 mm in Block 3 defect captured from different surfaces. As built.

Figure 6 shows a C-scan of a spherical defect of 2.5 mm from three different surfaces. The pixels are square. Note that the distance scales differ between the three representations. There is a great difference in the amplitude gradient, particularly as a function of position on the X-axis. It is also clear that a spherical defect manufactured with the build direction into the imaging plane generates a closer-to-expected shape representation. This can be an important consideration when seeding defects as reference, reflectors. Any mechanical system with lower precision than 0.15 mm would risk not capturing the peak amplitude from the smaller defects.

3.2. Defect sizing

The DSR in Block 2 was sized using XCT (contrast algorithm) and UT (6dB drop). See Table 4.

Table 4. Defect sizing of DSR in Block 2.

<table>
<thead>
<tr>
<th>Ultrasonic 6dB drop</th>
<th>XCT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Block</td>
</tr>
<tr>
<td>Block Defect</td>
<td>Block 2 Surface A, as-built</td>
</tr>
<tr>
<td>DSR2.5</td>
<td>2.7</td>
</tr>
<tr>
<td>DSR2.0</td>
<td>1.9</td>
</tr>
<tr>
<td>DSR1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>DSR1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>DSR0.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>
The XCT result should be considered the ground truth, rather than deviating from the designed size. For most defects the UT sizing methods performs well, but for smaller defects a calibration procedure or mathematical model of the pressure distribution around the beam path is clearly required.

3.3. Effect of build-direction

Figure 8 (a, b) below shows C-scan representation of two CAD-identical volumes of two defects in close proximity. The building direction as well as the UT inspection direction is altered 90 degrees, isolating the effect of build direction on the presented data. Symbol on the bottom-left indicate the build-direction. It can be seen that there is signal response-overlap between defects in the case where the build-direction is parallel to the image plane, whereas the case where the build-direction is perpendicular to the image plane the defects seem to be reasonably well separated. This effect is consistent over multiple focal laws. The CAD surface-surface distance between the defects is 0.5 mm. This defect overlap/separation can be an important aspect when considering signals originating from other than the spectral reflection of the defect. For example, the overlap of two defects could interfere with the satellite waves which would otherwise be a component of the A-scan.
In terms of build direction effect on the maximum amplitude response Figure 9 below shows response from the spheroidal defects of different sizes and inspected from different surfaces. The boxes show the 75th Percentile, and the whiskers show the highest/lowest sample. The median value is indicated by a horizontal line. The data is organized into four categories, where each category has a similar feret ratio across the different data-sets (Figure 9 a, b and c). The surface from which the data is acquired is indicated with the associated capital letter below the box plot. The major axis of the defect is always perpendicular to the direction of the inspection. Surface C is acquired where the build direction is parallel to inspection direction. For Surface A and Surface B, the build direction is perpendicular to the direction of inspection. It can be seen that there is a ratio between major/minor axis where amplitude response peaks when built with the major axis perpendicular to build direction. This is corroborated in a simulated setting in not yet published work. Beyond that optimum the amplitude response diminishes with decreased defect size. It can be seen that for some configurations, Surface C offers a significant advantage in terms of amplitude response compared to Surface A and B.

Figure 9. The amplitude response from spheroidal defects of different dimensions and different inspection surfaces.
4. Conclusion and future work

In this study, a number of macroscopical defects were seeded into four different IN939 bars manufactured with the PBF-LB method. While the study suffers from great limitations, mostly in terms of sample size, it was shown that build direction has a meaningful impact on the morphology of the defect as well as the size of the affected volume in proximity to the defect. This can be useful in future studies when designing the CAD-geometries to maximize material- and machine utilization. It was also demonstrated that a spheroid manufactured with the minor axis parallel to the build-direction generally (in the domain explored) produces a greater amplitude response when inspected parallel to the minor axis. Furthermore, it was shown that the as-built surface of IN939 built with the PBF-LB process has a negative (albeit marginal) effect on the SNR of the produced defects. While the level of sensitivity (ability to detect small defects) was not fully explored, a TH of diameter 0.2 mm as well as spheroidal defects of [0.6, 0.2] mm was easily detectable, for both machined and as-built surfaces given any reasonable SNR threshold.

Acknowledgements

The authors would like to thank KK foundation for funding the study through the project “Powder Bed Fusion Additive Manufacturing of Metals for Gas Turbine Applications – PODFAM”. We thank Anupama Surendran for her contributions in collecting the UT and surface roughness data.
References


Ultrasonic testing of components produced with additive manufacturing

Towards improved detection and classification of defects

The focus in this work is on the use of ultrasonic testing as a method for inspecting components manufactured through additive manufacturing (AM) processes. The research is rooted in the need for effective non-destructive testing techniques that can adapt to the unique challenges posed by AM-produced materials, including complex defect geometries and surface conditions.

Ultrasonic testing is a versatile form of non-destructive testing, offering the ability to detect internal flaws, such as voids, cracks, and inclusions, with high precision and in real-time. Unlike many competing methods, ultrasonic testing works on most types of materials. Ultrasonic testing has been applied for inspection purposes for a long time. Now with emerging manufacturing methods, there is a need for evaluation techniques to keep up with this development. New data processing algorithms open up possibilities of extracting more information from the acquired signal.

The thesis provides a review of UT’s capabilities in detecting and classifying defects within AM components, with a particular emphasis on the subtleties introduced by the layer-by-layer construction method inherent to AM technologies. The work advances development and validation of simulation models aimed at predicting the ultrasonic response from manufactured defects. These models are crucial for understanding the interaction between ultrasound waves and material anomalies, offering insights into the potential for enhanced defect detection strategies.

The research also explores the practical case of integrating UT into the quality assurance processes by relying on mathematical simulation rather than experimental data. The findings suggest avenues for the refinement of creation of inspection procedure, including the use of meta-models to cheaply acquire worst-case scenario defects, to better accommodate the specificities of AM materials.

ISBN 978-91-89325-77-7 (Electronic Version)