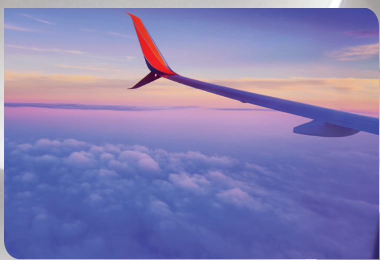
Report from the Workshop on Additive Manufacturing for Aerospace

Aerospace Workshop

10 April 2018 | BAWA Centre, Bristol, UK



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THE BRITISH INSTITUTE OF NON-DESTRUCTIVE TESTING

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Workshop on Additive Manufacturing for Aerospace

Compiled by: Tom Bertenshaw, NDT Research Engineer, GKN Aerospace

This workshop was organised by the Aerospace Committee of BINDT in order to help to bring together research and developments in NDT for additive manufactured (AM) parts that are being undertaken and to support their introduction and use in the aerospace sector.

The workshop also included a panel session, providing the opportunity to discuss and debate some of the key research challenges that AM parts pose to NDT and what success in this area may look like for the aerospace NDT sector.

The specific objectives of this session include:

- *To present current research and developments in NDT for AM parts that are being undertaken to support their introduction and use in the aerospace sector;*
- *To inform delegates of some of the ongoing NDT activities in this area, from in-situ process monitoring through to as-built components, and to provide an insight into the direction of future research; and*
- *To discuss and debate some of the key challenges and future opportunities for NDT of AM parts.*

This workshop was aligned to the following BINDT Aerospace Committee objectives:

- *To define NDT requirements to meet future aerospace industry goals;*
- *To develop roadmaps for NDT technologies to guide knowledge generators (for example universities, RTOs) towards aerospace industry goals; and*
- *To promote and enable the introduction of new NDT technologies by identifying and tackling barriers, and through scientific evaluation, validation and education of manufacturing and maintenance supply chains.*

Spatially resolved acoustic spectroscopy and NDE for additively manufactured components

Rikesh Patel, University of Nottingham

Research at the University of Nottingham focuses on using spatially resolved acoustic spectroscopy (SRAS) for imaging and characterising additive manufactured (AM) parts. Problems in AM builds, such as defects and inappropriate microstructure, can prevent the part from being used optimally or at all if these problems are not detected. The University of Nottingham's research focuses on selective laser melting (SLM), but has been applied for other AM technologies.

SRAS is a laser ultrasonic inspection technique that is not based on time-of-flight measurements. A surface acoustic wave (SAW) packet is generated using a pulsed beam through a grating pattern. The wavelength of this, as well as the material properties, dictatethe frequency of the signal in the packet: the frequency is proportional to the velocity of the wave. The material properties include the orientation of the grain that the wave travels on; through knowledge of the elastic constants and the measured wave velocity, it is possible to determine the grain orientation, allowing for microstructure imaging. SRAS is also capable of measuring changes in the material subsurface, *ie* it is able to detect subsurface pores. The depth sensitivity is determined by the wavelength of the grating pattern used.

The currently established system is able to measure on surfaces with Ra < 100 nm on materials including nickel, aluminium, titanium and steel, with an inspection speed of 1500 point/s. While the spatial resolution of the technique is less than that of electron backscatter diffraction (EBSD) (60 nm), SRAS is cost efficient and is unlimited in its scan area.

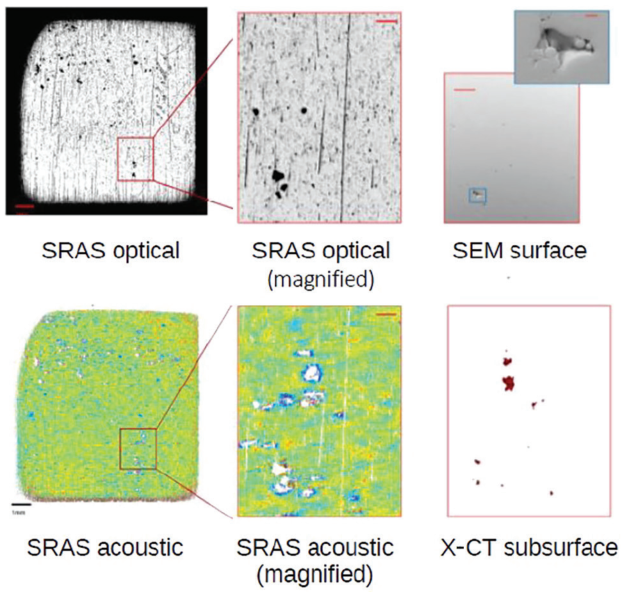

Figure 1. SRAS scans of Ti64 AM cubes (polished)

The key advantages of SRAS are that it is scalable and adaptable. For instance, the surface roughness restriction exists due to detector limitations. Using a rough surface ultrasound detector allows the technique to be used on as-deposited AM surfaces, which opens up the opportunity to use SRAS for in-process inspection of AM components. Additionally, the grating wavelength can be adapted to enable deeper inspection into a material.

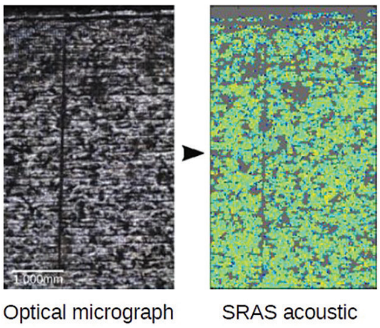

Figure 2. SRAS scan of as-deposited Ti64 AM section

In-process laser ultrasound inspection of AM parts

Ben Dutton, MTC

AM offers the freedom to design complex geometries or add material in order to extend the useful life, which is not possible with conventional manufacturing methods. Nevertheless, in order for such benefits to be realistic, the product quality must first be ensured. Typically, quality inspections are performed after the build of the full part, which becomes difficult for complex geometries, adds cost to the whole process and potentially creates more scrap. Taking advantage of the unique layer-by-layer or bead-by-bead build methods, an ideal place to verify the part quality is after a layer or bead, with the potential advantage of reducing or eliminating the need to inspect after the full build or after machining.

A number of in-process methods, such as optical and thermal imaging, are being tested in AM machines; however, they mainly focus on surface information. Although these methods have shown some capability in detecting layer surface defects in AM built parts, we have confirmed that the following layers affect such defects found. Due to the high temperature that these processes operate at, non-contact NDT methods are the only ones to consider. Laser ultrasound testing (LUT) is one such method, which has the added capability of detecting surface, close-to-surface and bulk defects since it generates surface and bulk waves at the same time (see Figure 3).

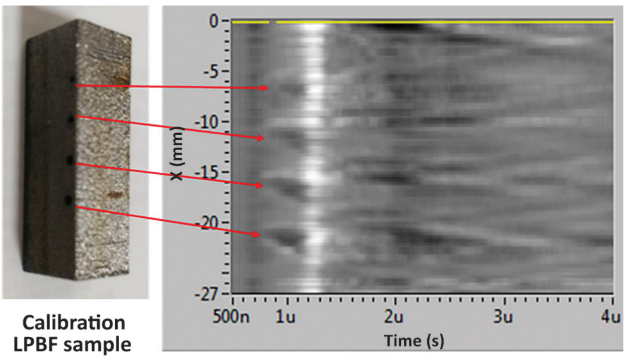

Figure 3. Laser ultrasound testing (LUT) has demonstrated the capability to detect subsurface side electrical discharge machined (EDM) holes (0.3 to 0.8 mm diameters) on as-built surface laser powder bed fusion (LPBF) calibration sample

LUT has shown potential for in-process monitoring of such processes in a number of projects, both finished and in progress, at the MTC. Initial validation has being performed using calibration samples and integrated demonstrations will follow.

Non-destructive testing of additive manufactured components

Ian Cooper, TWI

The use of additively manufactured components is increasing due to the opportunities it affords in terms of weight saving, conservation of raw materials and the freedom to design complex parts that could not be made using existing established manufacturing processes. Proving the integrity and fitness-for-purpose of components made in this way is challenging. Non-destructive testing can be applied in line as each layer is deposited, or post build on the completed component. There are a number of challenges for in-line and post-build inspection.

For in-line inspection, these challenges include:

- High temperatures;
- Small contact area;
- Must not contaminate the surface;
- Curved or complex surfaces;
- Must keep pace with deposition process; and
- Automated or instant identification of flaws.

Potential *in-situ* inspection solutions include laser ultrasound, eddy current, thermography and melt pool monitoring. The advantages of in-line inspection are that some flaws, such as voids or cracks, can be repaired. Fatal flaws can be identified before additional value is added to the part.

For post-build inspection, challenges include:

- Complex geometries, including internal features;
- Rough surfaces;
- Entrapped powder;
- Large and/or dense components not suitable for computed tomography (CT);
- Anisotropic or unequiaxed grain structure; and
- The time-consuming nature of the inspection.

Potential inspection solutions must include imaging of the internal volume and are likely to include more than one method. Consider radiography (including CT and laminography) and advanced ultrasonic testing (phased array ultrasonic testing (PAUT) and full matrix capture (FMC)), as well as surface methods such as eddy currents, liquid penetrant inspection (LPI) and metrology.

Advantages to post-build inspection are that flaws such as shrinkage cracking, entrapped powder and dimensional inaccuracies may be detected.

A significant barrier to uptake has been the lack of standards support. This is being addressed through a number of bodies including ISO/TC 261, ASTM F42 and the harmonised working group JG59.

Additive manufacturing within BAE Systems' air sector

Kevin Pickup, BAE Systems

Additive manufacturing within the military air domain is not just about topologically fancy-looking metallic parts. AM gives us the chance to be agile in terms of manufacture, that is we can use it to replace traditional manufacturing techniques, like forging to reduce costs, both in terms of fly-to-buy ratio and also by significant reduction in process qualification activities. The AM method of manufacture also allows us to manufacture variations of a part, to meet specific customer requirements with minimal redesign and qualification input.

AM is also being used to replace 'fiddly' fabrications and welded assemblies, reducing manufacture time, inspection requirements and failure rate. For non-critical systems, polymer AM is also being used to reduce weight and increase function.

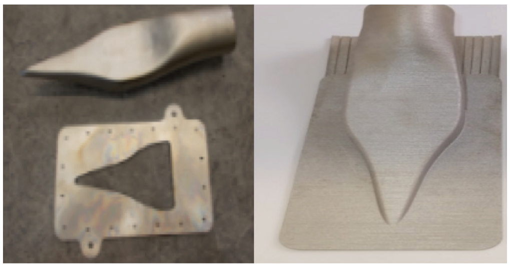

Figure 4. Old standard (left) and new AM part (right)

That said, topologically optimised designs for maximum strength-to-weight ratio are being looked at, but inspection of these items is currently limiting their use, due to accessibility of the optimised structure using current traditional inspection methods and surface finish. To help to reduce post-manufacture inspection requirements, we are looking at in-line inspection to monitor the build as it happens. These techniques are covering both discrete defects, such as voids and unfused regions, and also macrostructure to ensure that the metallic deposition has the correct structure.

X-ray CT inspection of Ti6Al4V parts – A review of current progress at GKN Additive Bristol

Linda Squillaci, GKN Aerospace

Metal additive manufacturing provides increased design freedom, as it allows complex geometries with internal cooling channels, ducts, vanes and lattice structures to be built layer by layer, with little need for post-manufacture machining operations.

The AM industry continues to accelerate as more businesses from the aerospace, medical and oil & gas sectors choose to invest in this technology, to re-engineer their products and take advantage of the highly customisable opportunities that it offers.

As a result, new machines are frequently introduced on the market to address repeatability, reliability issues, accommodate larger parts and improve as-built surface finish, automate the powder distribution and recovery systems, increase beam power to ensure part integrity and eliminate the occurrence of unfused material.

The non-destructive evaluation of AM parts is, in theory, no different to that of components of the same geometry that are currently cast or forged, where years of testing have led to formalised inspection requirements. Typical AM defects such as critical porosity and contamination levels, surface roughness and detrimental sizes for lack of fusion are still being mapped out and evaluated using conventional NDT methods, to understand their impact on fatigue life.

At GKN AMC Filton, the currently available methods employed for material screening are fluorescent penetrant inspection and film radiography.

However, as the size of the features to be investigated decreases (for example pores of approximately 50 μm), more powerful inspection methods are required. This is why the AMC R&T team has also assessed the capability of X-ray CT systems present on the market, on a wide range of components of varying size, thickness and surface finish combinations. It was found that X-ray CT works well on small machined parts and that automated defect algorithms give good results (see Figure 5).

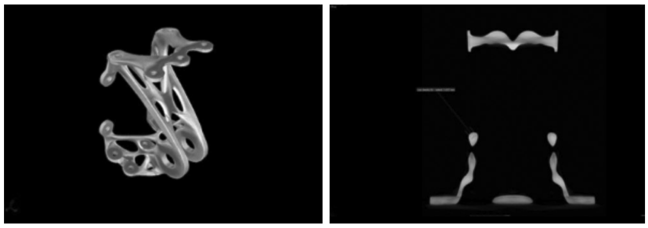

Figure 5. X-ray CT 3D views of a topology optimised bracket

In the future, from an NDT perspective, it is essential that X-ray CT is qualified as an aerospace-approved method for the inspection of AM material and that specific personnel are suitably trained to use it. To have a reliable NDT inspection method will allow AM process engineers to obtain feedback on the machine output and perform further development on manufacturing parameters (melt theme). This will ensure that the heat source is tuned so that parts have sealed contours, no lack of fusion open to the surface and no layer defects.

AM inspection / NDT: is X-CT the solution?

Nick Brierley, MTC

The MTC session on X-CT focused on the challenges of post-build inspection of AM parts, how X-CT can be used for post build, its limitations, commercial developments on X-CT and the work that has been carried out at the MTC on this topic.

The ability of AM to produce highly complex shapes to optimise weight and mechanical performance poses a significant inspection challenge. Furthermore, the poor surface finish in the as-built condition (depending on processing route) will also rule out or make inspection more complicated for contact NDT techniques.

Figure 6. AM can produce complex shapes to optimise performance, but this also brings challenges

For this reason, X-ray CT has an advantage: it is a non-contact technique, where operation is independent of sample surface condition and geometric complexity. It also has the advantage that it can provide information about geometrical conformance (metrology). However, its limitations include: size of part (must fit and fully rotate 360° within the enclosure), the X-rays must be able to penetrate the part, speed (the inspection technique is relatively slow), data volumes produced can be prohibitively large, quantitative inspection performance is not well understood, reconstruction artefacts and noise can mask features of interest and the spatial resolution decreases with sample size. Coupled with a lack of inspection standards and official personnel training, these are barriers to X-CT being used as a certified inspection technique for aerospace.

Commercial developments are currently focused on improving the speed of scanning by using robots for loading. Work is also being carried out on unconventional scanning such as helical CT and laminography, which can overcome some of the identified limitations for some sample geometries. The MTC has been actively working on tackling the challenges highlighted through a range of projects, considering, for example, simultaneous X-CT and dimensional inspection, X-CT data management and an assessment of X-CT metrology for dimensional accuracy.

NDE of additive layer manufacturing for aero engines

Tim Barden, Rolls-Royce plc

The market for AM components at Rolls-Royce plc has some applications. These include complex-shaped components with internal cooling passages, some brackets and potentially parts with variable material properties. Repair of components by rebuilding damaged/worn surfaces is also possible. AM components have defects, which are likely to be similar to cast products. These could include linear pores, lack of fusion and preferred grain orientation.

Figure 7. The future approach to part quality will be holistic at Rolls-Royce

In terms of the NDE methods being identified for process development, X-ray CT and ultrasonic techniques are used; non-linear UT is also used for low-strength interfaces. However, for manufacturing solutions, X-ray inspection, dye penetrant testing and process monitoring are used instead. X-ray inspection is particularly useful for internal dimension measurement, which is important for determining thicknesses of internal cooling passages.

Alternative inspection methods include in-line inspection (visual, ultrasonic, electromagnetic), process monitoring and performance/functional checks. These can all be seen as methods to determine part quality.

At Rolls-Royce, the future approach to part quality will be holistic. The quality improvement cycle will be between design/structural integrity, manufacturing and inspection, where inspection (NDT) data can be fed back to design and manufacturing, to move towards a proactive approach as opposed to relying on a reactive approach, *ie* just using post-process checks. The future of NDE for AM is to consider in-line inspection as part of a reactive approach, and use new techniques to inform us of material property measurements, such as grain structure and residual stress, as well as conventional defect detection/analysis.

Panel session

The panel comprised of three representatives from the industry: Rikesh Patel, Nottingham University; Linda Squillaci, GKN Aerospace; and Nick Brierley, MTC. They were asked the following four questions in turn, which provoked a general discussion around the room.

1. ***What do you consider to be the main inspection challenges for AM components, and what are your thoughts on how they can be overcome?***

This question provoked a few challenges from the panel, such as surface roughness, understanding the limitations of CT more comprehensibly and understanding design allowables/flaw size for a given application. Questions were also asked about modifying powder bed machines for *in-situ* capability. This is available (for example Arcam Q20) and machine manufacturers are keen to engage since effective NDT is an obstacle in many organisations.

2. ***What future opportunities exist for AM components that we should be focusing research efforts to exploit?***

Examples here included:
- Collaboration between universities and industry to share more data (NDT data into validated models) to help with the certification process;
- Look at 'lifeing' components in relation to their defect data rather than just having a scrap threshold; and
- More work performed through simulation.

3. ***What does success look like for in-process inspection?***

The examples included:
- Ensure that an in-line system has no impact on the production, *ie* speed of inspection;
- The ability to time stamp a machine event to a coordinate of a likely defect in the coordinate system of a specific component's CAD;
- The ability to repair defects in the next layer (note: a subsurface defect can be created during deposition of the layer above);
- The design data needs to be robust enough to be qualified; in-process inspection will need to detect and repair (or scrap). Ideally, processes can be optimised such that post-build NDT is not required on every production part, but still required during the qualification process.
- Understand all of the process variables, for example roller pressure, control of powder stock; these are research projects in themselves.

4. ***What can the BINDT community do to help progress the Technologies surrounding NDT for AM?***

It was requested that the NDT Aerospace Committee could be a referee/third-party supplier into certification. It was suggested that the joint aerospace forum could be the conduit to help to put new technologies into industry.

Author's overview comments

It might be noted that there was a lack of conversation around standards, where most of the session centred on developing *in-situ* inspection technologies. There are a few standards that are being defined by working groups/committees, including the following:

- ISO/ASTM DTR 52905 (ASTM F42) – Additive manufacturing – General principles – Non-destructive testing of additive manufactured products;
- ISO/ASTM WD 52942 – Additive manufacturing – Qualification principles – Qualifying machine operators of metal powder bed fusion machines and equipment used in aerospace applications; and
- ISO/ASTM CD TR 52906 – Additive manufacturing – Non-destructive testing and evaluation – Standard guideline for intentionally seeding flaws in additively manufactured (AM) parts.

It is clear from the comments that collaboration between all parties is required, and the AM industry would benefit from collaborative research projects.

Appendix A: Contributors

Tim Barden	Rolls-Royce plc
Nick Brierley	MTC
Ian Cooper	TWI
Ben Dutton	MTC
David Hallam	DSTL
Rikesh Patel	University of Nottingham
Kevin Pickup	BAE Systems
Robert Smith	University of Bristol
Linda Squillaci	GKN Aerospace

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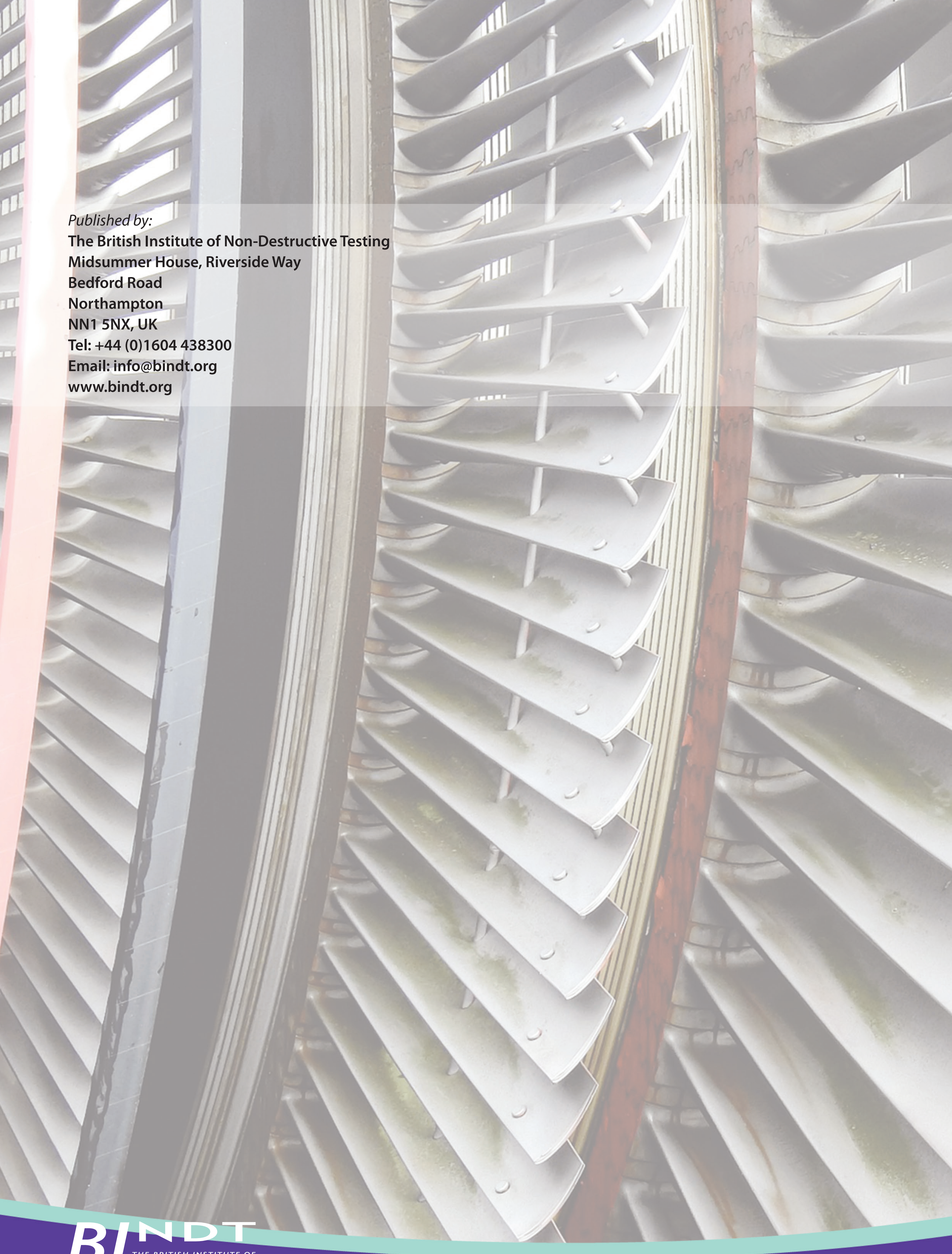

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