NPL REPORT MAT 108

REPORT OF STAKEHOLDER CONSULTATIONS ON MEASUREMENT NEEDS FOR ADDITIVE MANUFACTURING - WORKSHOP 1 AND 2

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Report of Stakeholder Consultation on Measurement Needs for Additive Manufacturing - Worksop 1 and 2

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Approved on behalf of NPLML by
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CONTENTS

1 INTRODUCTION

The COVID-19 pandemic has offered a preview of the potential of Additive Manufacturing (AM). Various industries were able to leverage their distributed AM networks to quickly jump start production of vital medical equipment amid supply chain disruptions. AM opens the door to highly advanced designs coupled with decentralised manufacturing. Among other benefits, it can facilitate light-weight vehicle designs to boost efficiency and extend range, replace spare part inventories with digitised part libraries, and enable on-location production in remote locations, including for the military, energy and space exploration.

Whilst AM has been around for some time, using it to produce durable end-use products is an emerging market. This global market has grown at about 25% CAGR since 2015 but remains below $15 billion by most estimates. This represents about 0.10% of the global manufacturing industry, signalling tremendous upside potential [1]. AM allows for greater design freedom with little or no added cost for greater complexity, and results in less waste overall. It can create lighter, better performing, greener and potentially cheaper industrial products, all with enhanced operational flexibility, speed-to-market, plant productivity and supply chain resilience. The US Department of Energy recently estimated that 3D printing has the potential to reduce energy costs by 50% and cut material costs by 90% [2]. Using the design and manufacturing freedom of AM has real benefits and will play a major part in achieving net zero targets.

In an April 2020 survey of 700 US manufacturing professionals by the Society of Manufacturing Engineers, 25% said they had to change their supply chain in response to the pandemic, and seven industries ranked AM in the top three technologies taking priority for investment post-COVID [1].

The UK has 4.19% of all industrial AM systems installed since 1988, making the UK the 5th largest manufacturer of AM parts globally. The UK has 9 masters courses dedicated to AM, has had over 100 PhD projects related to AM and 3D printing and hosted 75 AM events between 2018 and 2019 [3]. Despite the huge potential for AM, uptake has been slower than anticipated. A recent European Union Aviation Safety Agency- Federal Aviation Administration (EASA-FAA) workshop (November 2019) identified a key barrier to widespread adoption as being insufficient applicability of results from one geometry-material-process combination to another. Quality assurance of manufactured parts requires measurements that describe these structures, and which can be related to manufacturing processes and final material properties. AM materials have complex microstructures with feature sizes ranging from micrometres to millimetres and with highly anisotropic and irregular shapes making the definition of the microstructure difficult. Development of digital twins requires the ability to determine and fully describe the component. To support the digital twin, models are required that will functionalise the digital twin and these require representative volume elements which would be duplicated across the mesh of the model to form the final structure.

There are many aspects that continue to be worked on and developed to enable greater uptake and utilisation of AM materials. As with many other areas in materials science, data is at the heart of all this. Appropriate measurements generate the trust and assurance in the data needed to develop the models and digital twins allowing them to be used to predict in service performance and accelerate product design. Measurements are also essential to enable the correct control of processing conditions and parameters to ensure high quality products are produced.

With so many potential areas of measurement requirements, two consultation workshops were held. The first on 22nd June 2021 to generate a more detailed insight on the metrology requirements of the AM industry and where they feel a focussed effort from NPL would be of benefit to provide the greatest impact to the industry and accelerate the uptake of AM parts. The second held on 3rd December 2021 and was more of a deeper dive into regulations, codes and standards. The following report summarises the two workshops.

2 WORKSHOP ONE

The workshop was attended by representatives from ten industrial organisations, three Government/RTOs and three universities. In total there were twenty-one external attendees and six NPL attendees. The workshop itself consisted of an overview of NPL's Strategy, a review of the previous programme on AM and a summary of the NPL AM Strategy Review document [4]. This was followed by a review of the responses received to a questionnaire circulated prior to the meeting and finally a breakout session was held to discuss further points. The intention of the workshop was to provide a forum for stakeholders to discuss key issues and to prioritise activity for NPL moving forwards with its NMS[1] programme. Key questions discussed at the workshop included:

- What are the main challenges for wider adoption of AM in the UK?
- What are the current application limitations for AM materials?
- Which AM production process do you feel has the greatest measurement challenges?
- Which materials/processes do you feel need the greatest support?
- Areas you feel NPL is best placed to provide support?
- Specific area you think NPL should engage in
- What properties do we most need assured data for?
- NPLs role in standards development

2.1 QUESTIONNAIRE RESPONSES

Prior to the meeting the invitees were circulated a questionnaire to complete to provide initial steer and focus for a more in-depth discussion during the workshop. The questionnaire received 26 responses, with industry forming 70% of these, 4% from academia, 22% from Gov/RTO and 4% other (Figure 1). The organisations that did respond represented a cross section of manufacturers, end users, standards development organisations, consultants, and defence.

From the results of the questionnaire, it was clear that the areas that the respondents felt needed the greatest level of support were higher TRL techniques, with powder bed fusion and directed energy deposition (DED) of metallic materials rating highest, as shown in Figure 2.

1 National Measurement System - The National Measurement System (NMS) provides the UK with an infrastructure of laboratories that deliver world-class measurement science and technology and provide traceable and increasingly accurate standards of measurement. We maintain a National Measurement System because of the substantial impact it has on every aspect of UK life and its economic success. The NMS enables the UK to compete in global trade and manufacturing by ensuring consistency and recognition of measurement units and standards throughout the world. Internationally leading knowledge and expertise is passed on to UK stakeholders by a coordinated programme of knowledge transfer [6].

Figure 1 Breakdown of questionnaire response by sector.

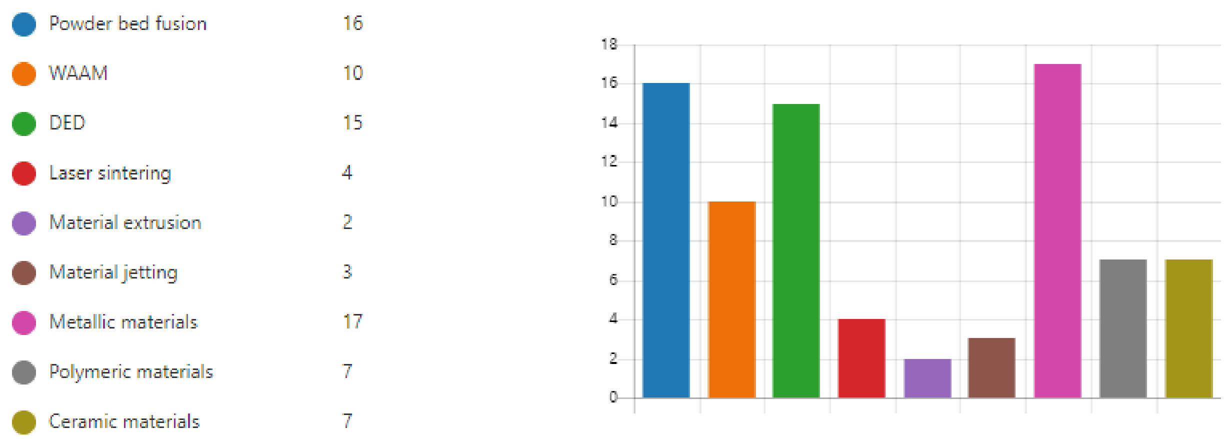

Figure 2 Responses to - Which materials/processes do you feel need the greatest support?

Post build measurements and non-destructive evaluation (NDE) were highlighted as being areas with the greatest measurement challenges, Figure 3. NDE continued to be an area of much discussion, with aspects such as rapid low-cost techniques being needed and NPL possibly having a role in the validation of these techniques.

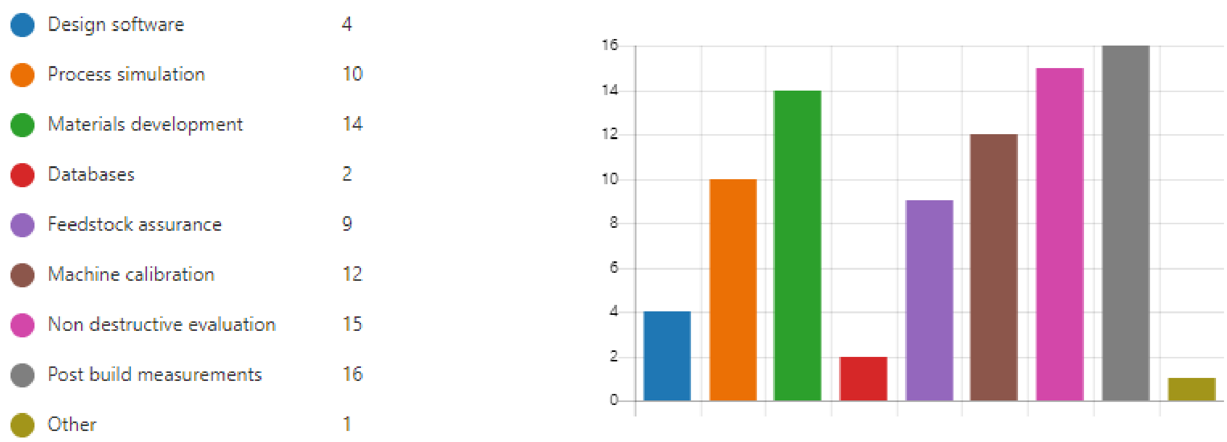

Figure 3 Responses to - Which AM production process do you feel has the greatest measurement challenges?

Materials development and machine calibration also ranked quite highly in the measurement challenges in production processes. In terms of where the respondents felt NPL should be focussing their efforts there were three main areas: material property measurement (particularly dynamic measurements), dimensional and surface measurements, and novel NDE methods for part validation (Figure 4). These responses were based on the responder's clear appreciation of the role NPL plays, and our measurement capabilities as shown by Figure 5 and 6. The replies to where they thought NPL was best placed to provide support align with our internal strategy to provide measurement capabilities and standards for materials assurance.

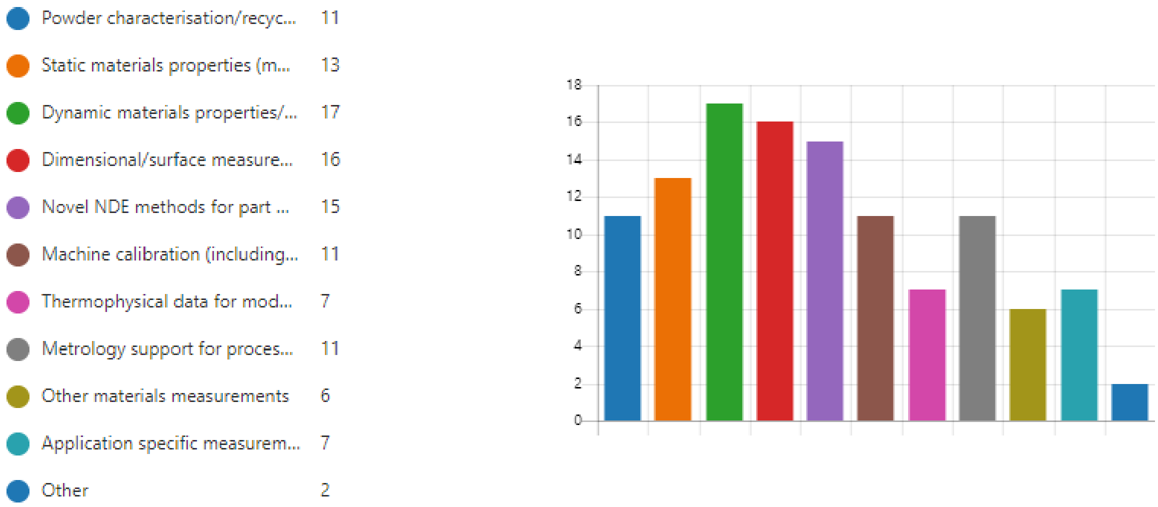

Figure 4 Responses to - Specific area you think NPL should engage in?

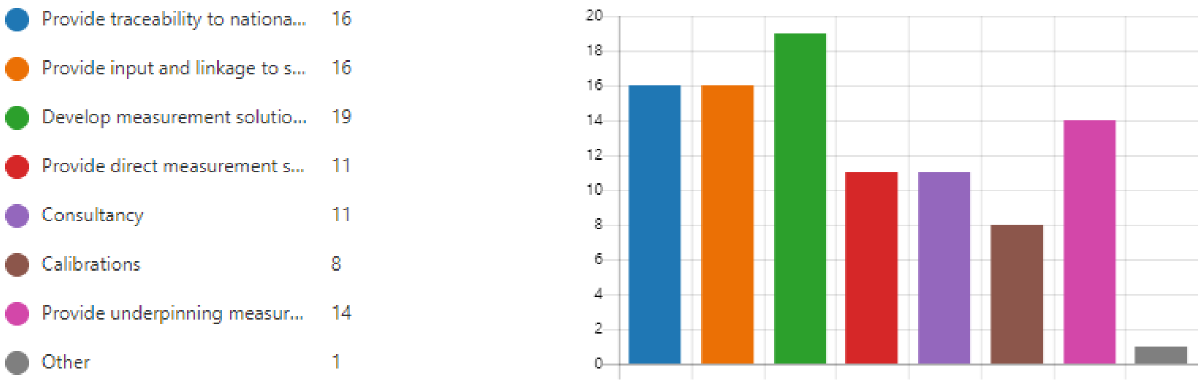

Figure 5 Responses to - Your understanding of NPL's role and measurement capabilities?

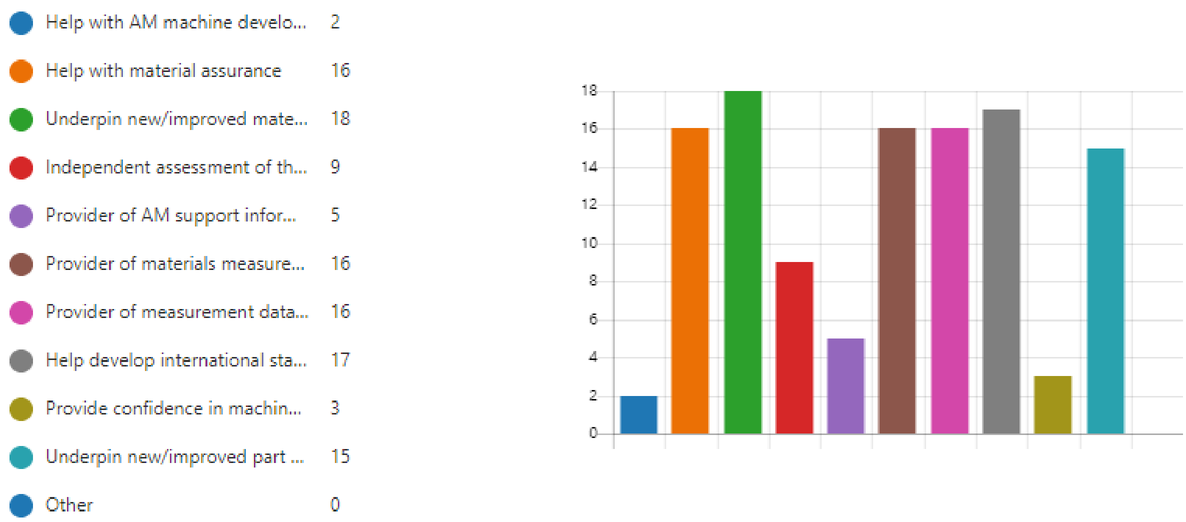

Figure 6 Responses to - Areas you feel NPL is best placed to provide support

Figure 7 Responses to - Potential future support you could offer?

Figure 7 shows the areas where future support could be offered to any NPL activity demonstrating a willingness to support fundamental metrology and standard activity in this area. During this exercise NPL also received comments on areas the responders did not think NPL should be conducting activity in (Figure 8). This was in powder characterisation/recycling, dimensional and surface measurements, and machine calibration, which contradicts the responses presented in Figure 4. But it should be noted that there were minimal responses to this question, as opposed to the high number of responses presented in Figure 4.

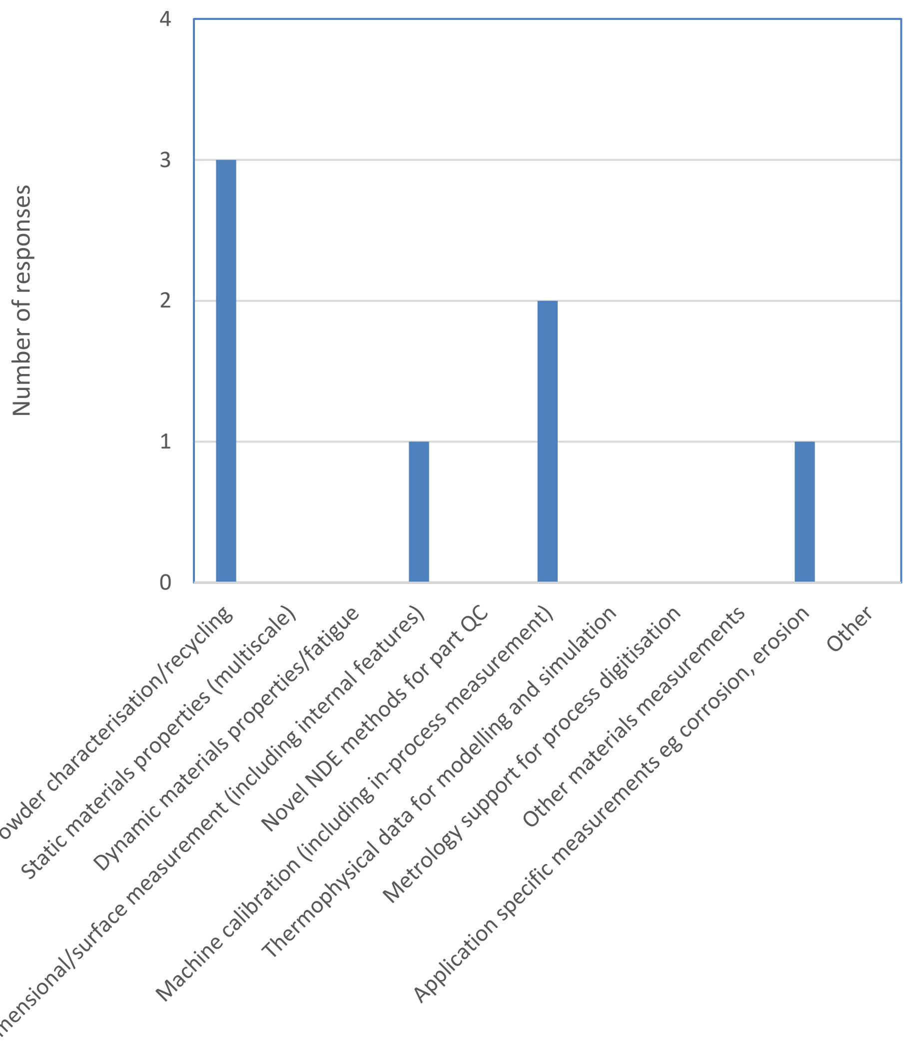

Figure 8 Responses to - Areas NPL should not be engaged in

2.2 DISCUSSION SESSION

After a review of the initial questionnaire responses the attendees were invited into breakout sessions to explore some of the questions further. We asked what were the current application limitations for additively manufactured materials? Six key issues were identified, as shown in Figure 9. These were:

- Regulations to support use in safety reliant applications
- Cost
- Trust in material performance
- Standards to support use
- Issues with surface performance
- Issues with surface finish
- Other

These indications show that there are general issues with both the assurance of materials data with regards to the performance of the AM material and in the availability and confidence in standards and regulations, particularly in safety critical applications. In the area of material certification and quality control, it was explained that the implication for industrial users is that the certification for billet material is widely accepted and as yet the industry is not able to do this for AM materials. There was a concern regarding traceability and being able to demonstrate due diligence in case of any failure that might occur. There was also a need for more standards aimed at establishing test methods for testing lattice structures and functionally graded materials, especially micro- tensile and fatigue, as it would give more industrially relevant end-use application confidence.

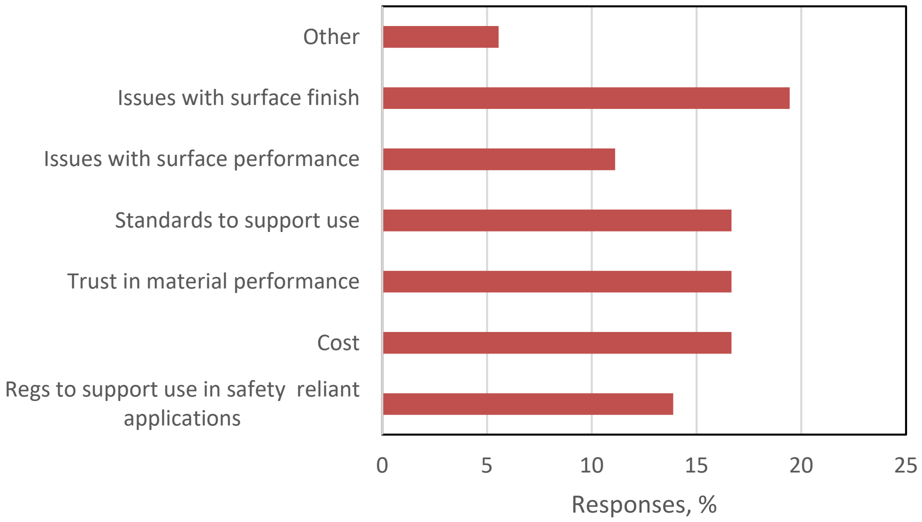

Figure 9 What are the current application limitations for AM materials?

The initial questionnaire showed that the more established and higher TRL AM methods required the greatest support from NPL, Figure 2. The attendees confirmed that this was mainly due to the maturity of the technology and its uptake and appeal to industrial use, and the fact that given the higher TRL level it was closer to regulatory approval (see Figure 10).

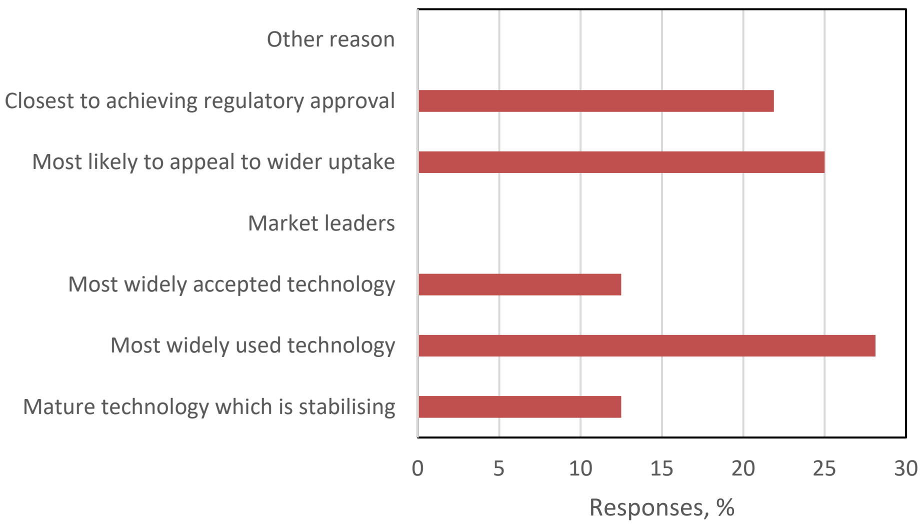

Figure 10 The reason that the more established processing methods need the greatest support.

There was a feeling that the workshop attendees were mostly representative of the metal AM industry, suppliers, and users, and that this might influence the responses regarding the need for standards and regulations. To address this concern the participants were asked directly whether metallic AM materials require more research or help with standards, legislation, and regulations than other material classes. One third of the responses did indicate that metallic

AM materials were now mature enough to require more effort in the development of standards and regulations. However, two thirds of the respondents believed that standards were needed across all material classes and so a broader approach across different materials would need to be considered. It was clear that there was a perceived need for standards. Figure 11 shows the prioritisation of areas that the attendees thought that NPL should be active in to support AM in the UK. As Figure 11 shows there was a wide spread of activity where it was felt NPL could contribute and lead, ranging from leading pre-normative intercomparisons to working with industry to develop standards and helping regulatory bodies to validate standards. Broadly speaking it is possible to group the reply into two broad activities.

- Are current standards appropriate?
    - Demonstrate the applicability of current standards (intercomparisons)
    - Help with the uncertainty in standard test methods applied to AM
- Development of new standards
    - Help regulatory bodies validate test methods for standardisation
    - Work with industry by developing new standards
    - Lead pre normative intercomparisons

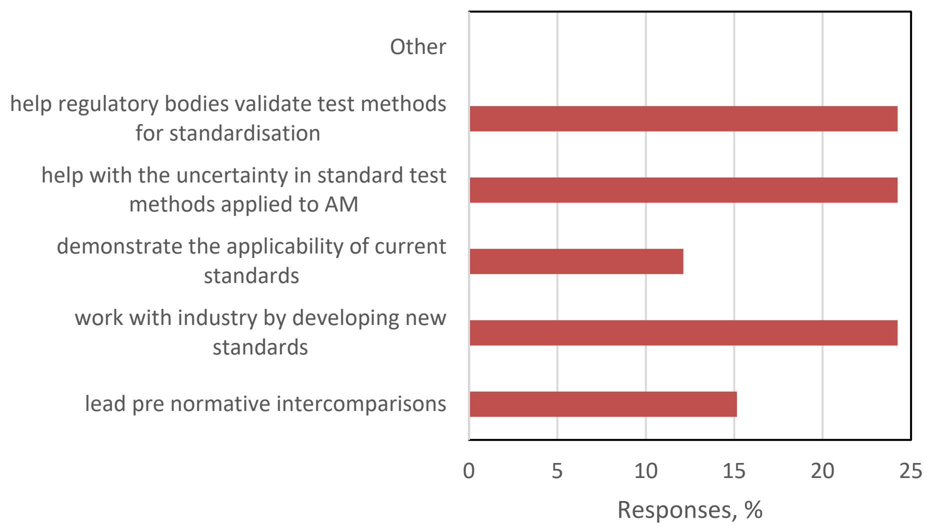

Figure 11 What do you think NPLs role in standards development should be?

Over the course of the workshop, comments from the attendees were received that have not been captured in the questionnaire responses above. These are summarised below.

- *"What about fast ways of verifying quality at intermediate steps of the process chain, e.g. fast ways of detecting trapped powder? I also don't see anything in this list about detection of defects."*
- *"I have seen you mention design, but you do not include it into the priority areas, what is your position on this stage of the AM process?"*
- *"The challenges of techniques such as XCT and in situ defect identification ultimately don't come down to an instrument/detail perspective but are more about what you do with the data. A wider look at assurance of image processing and decision making could have application across a range of techniques."*
- *"We need more standards aimed at establishing test method for testing lattice structures and, functionally graded materials (especially micro- tensile & fatigue as it would give more industrial relevant end-use application confidence)."*

- *“The big issue for us is material certification and quality control. The implication being that certification for conventional billet material is widely accepted and AM is not yet. We're thinking traceability and a demonstration of due diligence.”*
- *“Not taking full advantage of the in-process data captured. Need effective and speedy data management to enable decision and correlation with results.”*
- *“Standardisation of machine calibration at the start of the build.”*
- *“Internal channel characterisation of complex parts.”*
- *“Multi lattice structure material”*
- *“Work towards validated NDE techniques that can provide a pass / no-pass indication.”*
- *“In process laser alignment for multi-laser machines especially when using multiple lasers on the same part.”*

3 WORKSHOP TWO

The second workshop was intended as a follow on to the first and aimed to allow the participants the opportunity to take a closer look at regulations, codes, and standards (RCS) within the AM industry. There was a focus on the current use and application of standards, the limitations of currents codes and standards and where there was a requirement for further development of these to assist the AM industry and accelerate uptake of AM materials.

This workshop was attended by twenty attendees, with much of the industrial contribution coming from large organisations with the majority having research and technology as the main activity of the organisation or their part of the organisation. Participants representing Aerospace, Defence, Oil & Gas and Material Suppliers were present for the workshop. The workshop itself consisted of an overview of the first workshops findings and some background scene setting of the AM market opportunities, growth and barriers. This is summarised in Appendix 1 and Figure 12.

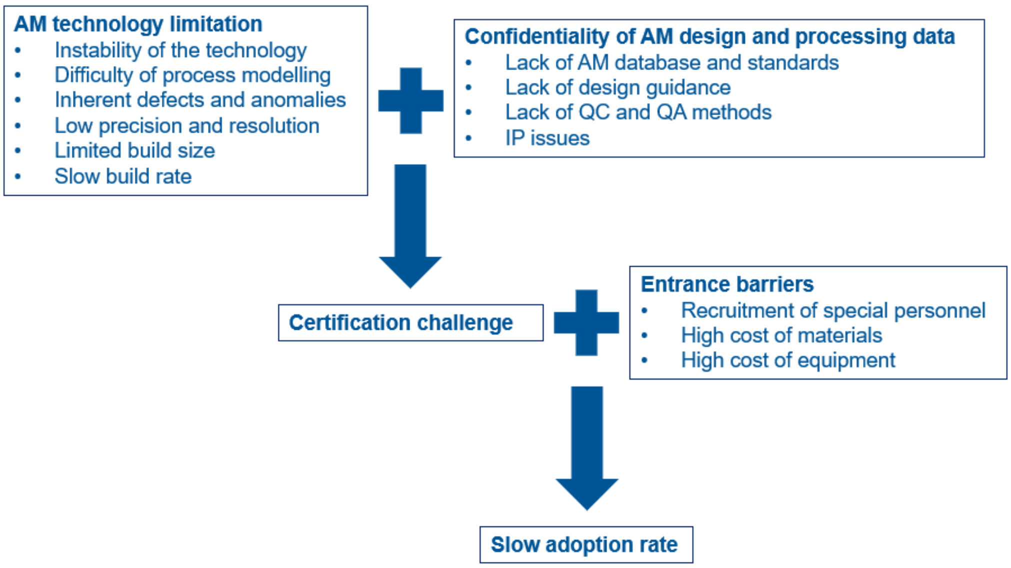

Figure 12 Challenges in the certification of AM parts [5].

The structuring of current standards for AM was introduced and a timeline of published standards to date presented (Figures 13 and 14).

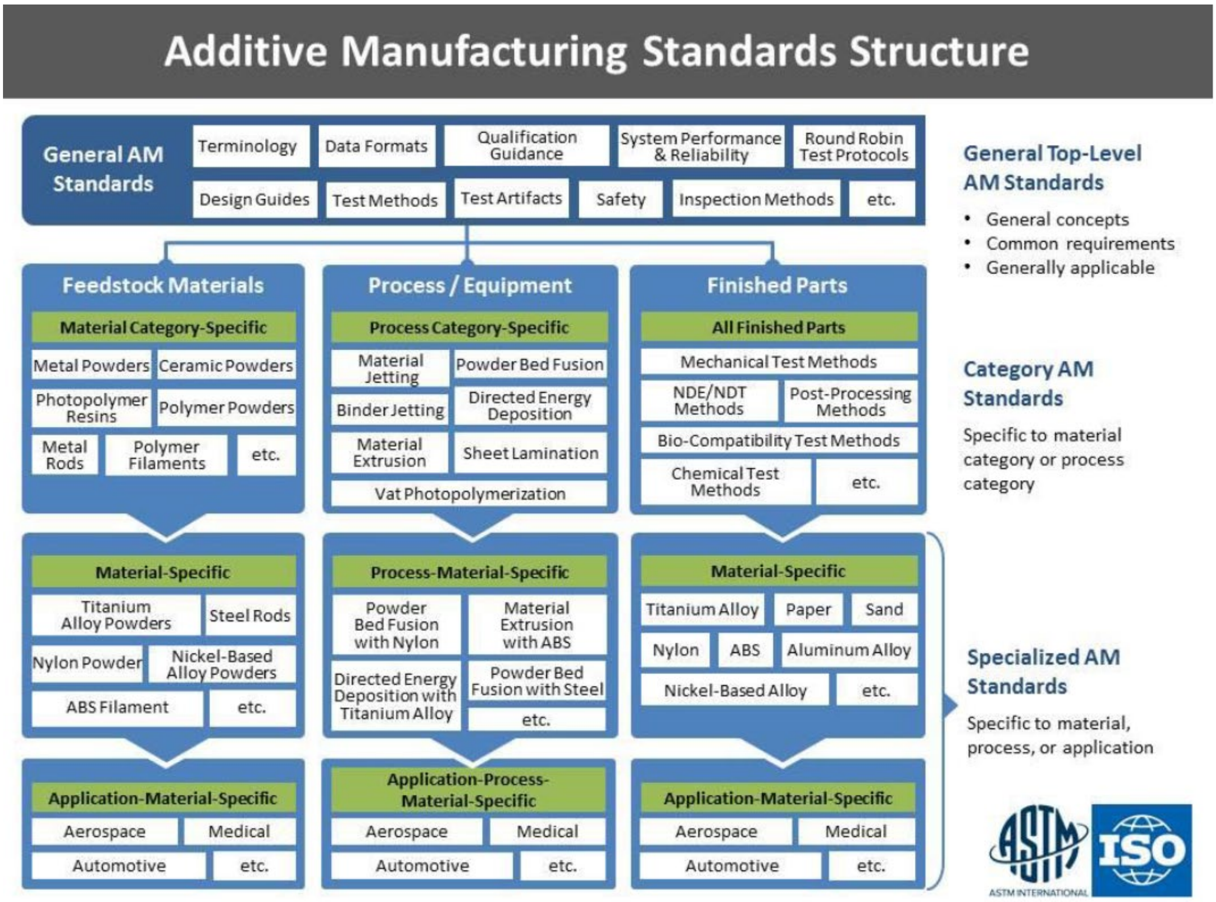

Figure 13 General structure of AM standards being developed by ISO and ASTM.

The first workshop highlighted that materials development, non-destructive evaluation and post build measurements were the areas that present the greatest measurement challenges. With application limitations due to standards to support use, trust in material performance and regulations to support use in safety reliant applications. The aim therefore of the second workshop was to:

- Understand how regulations, codes and standards might help remove barriers to greater uptake for additive materials across industry sectors.
- Identify and prioritise critical areas where there is low level of industrial confidence and/or missing methods, codes and standards and consider a generic product validation chain that would support a faster and more robust AM product verification
- Capture the need and appetite for a shared materials database

It was clear from the discussion within the workshop that the level of awareness of RCS was generally quite high (Figure 15), with the vast majority (73%) of organisation being involved in the development of revision of codes and/or standards.

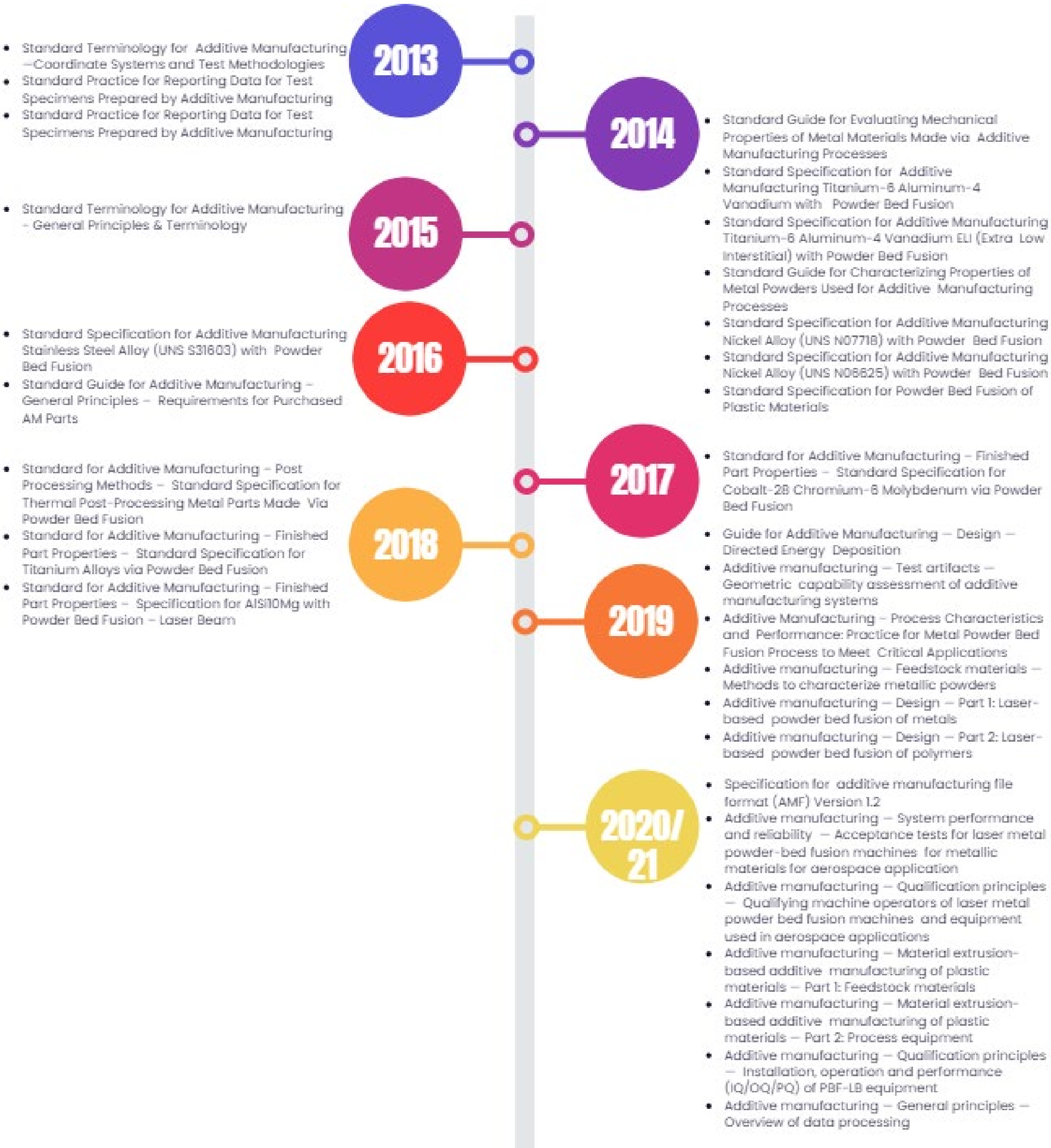

Figure 14 Timeline of standards published in the AM area.

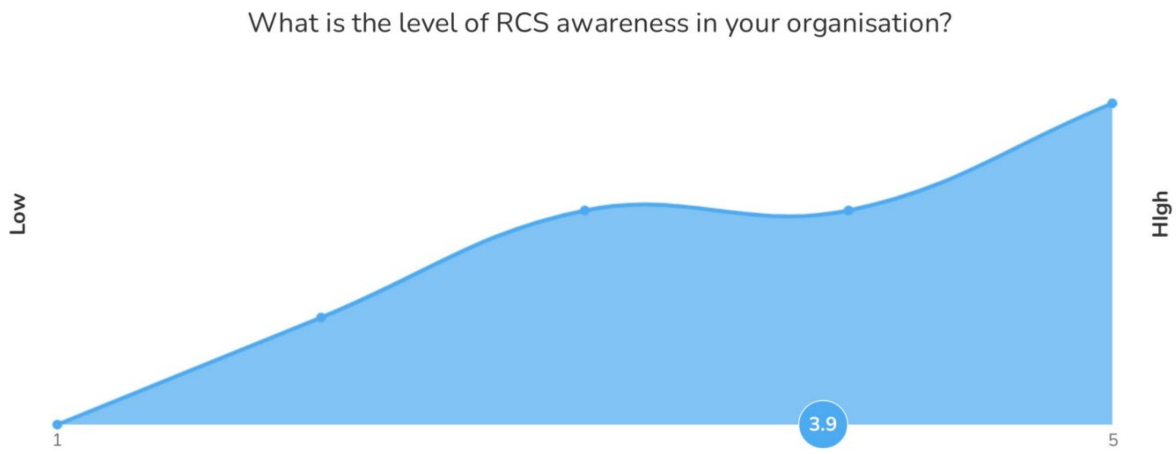

Figure 15 Level of awareness of Regulations, Codes and Standards in participant organisations.

An example of a product approval pyramid for an aerospace component was presented showing how this approval process starts with a large number of coupon-based tests and progresses up the pyramid with a decreasing number of tests but with increasing complexity (Figure 16). In the case of AM materials and components 50% of the attendees stated that their organisation employs a similar building block approach to evaluating the performance and qualifying AM products.

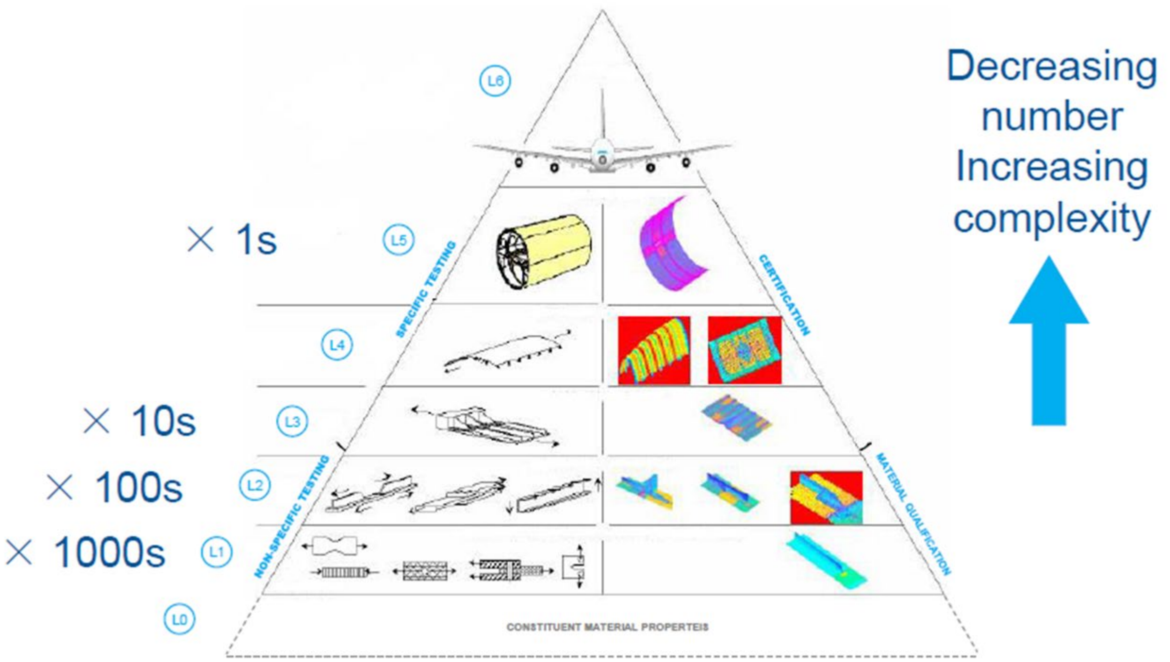

Figure 16 Product approval testing pyramid example for an aerospace component.

For those that didn't use such an approach there were a range of different reasons why they didn't.

- *"Single point design qualification is currently the adopted methodology in Industry. Companies are qualifying parts doing single qualification, machine process part code dependent."*

- *"It depends on the level of criticality - but generally speaking industry will follow a customary process (the pyramid) with certain "know how" about how to assure that coupons are representative of the part. This know how could include traveller specimens, microstructural standards, etc."*
- *"We do not qualify products, but we are interested in qualifications and requirements."*
- *"Not applicable to Dstl, but Military Aviation Authority (MAA) regulator would expect to see a very customary approach to qualification through regulation and acceptable means of compliance (AMC). Can we develop alternative acceptable means of compliance, say though technology (in situ monitoring, NDE) that, in time, the MAA can adopt?"*
- *"Dependent on which industry. We look at production parameters. Ask customer how they are going to test it."*

Discussion turned to the use of physical and virtual testing in the validation of materials and components. As can be seen in Figure 17 most people still rely on physical testing. Several organisations did express using a combination of the two, but there is a reliance on physical tests.

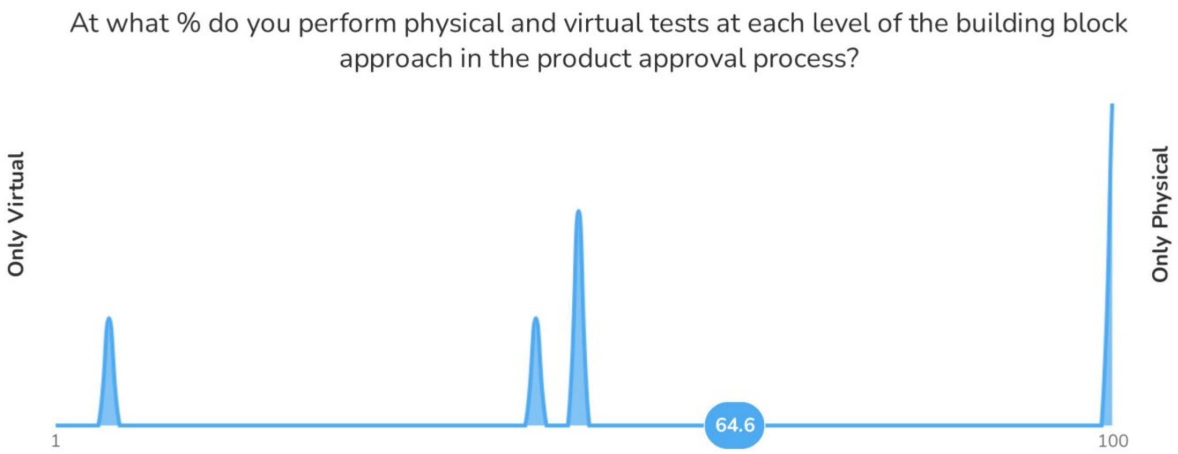

Figure 17 Proportional of organisation conducting physical and/or virtual testing.

When asked to characterise the use of RCS in their industrial sector the participants responded with a fairly diverse view, shown in Figure 18. There was a general feeling that the use of RCS was generally prescriptive; that they explicitly or implicitly call for materials other than AM materials to be used. This most likely reflects the current issues with RCS and problems with trust in material performance and regulations to support use in safety reliant applications. There was a polarisation of opinion when it came to equivalence (explicitly or implicitly call for materials with similar properties to other, more traditional materials or manufacturing routes), with some agreeing more strongly than others. Whilst the use of RCS based on performance (explicitly or implicitly permit the use of any material as long as it achieves the desired level of performance) was generally accepted. Still the general impression was that the RCS were overall prescriptive leaning towards showing equivalence in properties and performance.

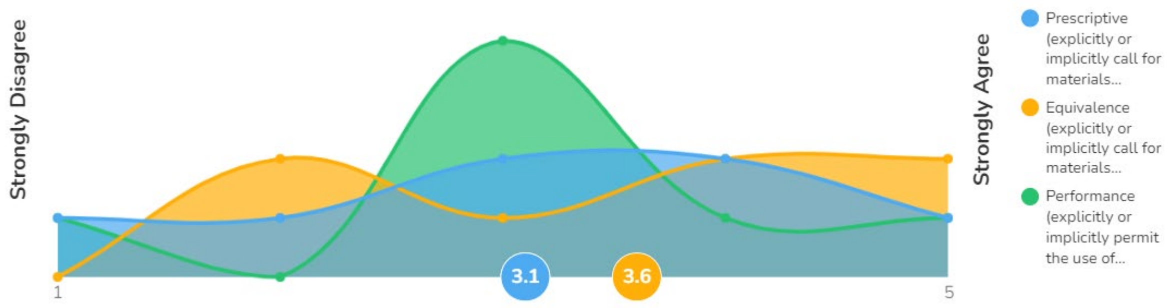

Figure 18 Characterisation of the use of regulations, codes and standards in industry.

The participants were asked to express the degree to which formal, agreed specifications, procedures, standards, and test methods exist and are publicly available. It was generally agreed that the availability of these documents was low. Where they did exist the degree to which the organisations can and do use these procedures was also generally low (Figure 19).

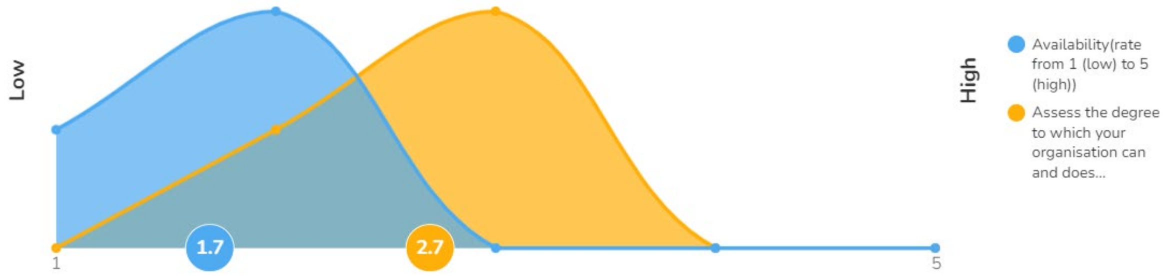

Figure 19 Assessment of the degree to which formal, agreed specifications, procedures, standards, test methods exist and are publicly available.

When asked to be more specific and highlight particular RCS that need to change or be created the following responses were received.

- Material design allowable
- Defects design allowable
- In-Situ Monitoring
- NDE and Inspections
- From measurement, it is mainly good practice that is needed, not new methods
- Product standards and regulations, such as ASME BPTCS, EN 13445, PD 5500, PED, need to allow use of AM materials provided that an equivalent level of safety is demonstrated

There were a few areas that were specifically mentioned in terms of material requirements, repair and NDE for RCS. These were:

- Acceptance criteria for non-destructive examination

- Guidance for selecting appropriate specimen size, shape and number to truly represent geometry within the part to be certified
- Acceptability of powder morphology (e.g. satellites)
- Testing and control of build environment (oxygen, moisture etc)
- Acceptability of powder recycling
- NDT. Currently using casting and forging acceptance limits
- Not much information available regarding the acceptance of lattice structures
- Understanding how to apply existing measurement techniques to AM. Also, development of new measurement technologies
- Specifications on lattice structures
- Inclusion of AM in product standards to allow use of novel material forming methods, provided that an equivalent level of safety can be demonstrated (with acceptance criteria)
- Acceptance criteria for different imperfections produced in materials formed using different AM processes (ideally, with different quality levels so that different industries could refer to the quality level required for a particular criticality of component)
- What different flaws should be inspected for that are specific to a particular AM process (e.g. trapped powder) and what methods can be used to detect them
- Internal structure measurement

The final aspect discussed in the workshop was industry sectors having a shared database of material properties for design/benchmarking purposes. There were some mixed feelings but generally this was thought to be a good idea. The comments received are summarised below.

- *"This is fundamental to drive the adoption of AM technologies for critical applications further ahead"*
- *"I don't think this is really required. Ideally, existing material specifications would be used for properties and additive manufacturers would be required to produce materials that complied with them. If bespoke specifications were required (e.g. to gain advantage of enhanced properties achievable through some AM processes) then those could be created by specific manufacturers."*
- *"I think this would enable 'general properties of different materials' to be standardised for different laser etc parameters. Whilst companies want to 'defend' their IP they lose out on sales due to lack of confidence. An 'independent' organisation such as NPL collating the data and delivering it as 'power level' result format may encourage companies to deliver the settings data."*
- *"A connection between bulk material properties and the final product performance. For instance, are the fatigue properties of the bulk material forecasting the lifetime of the AM component as they do from conventional processes?"*
- *"I think data is essential to improve standards, we collect a lot of data regarding viscosity, density, modulus, and currently collecting measurement data."*
- *"It would be a great tool for supporting the adoption of AM."*
- *"Great idea."*

4 SUMMARY

Additive manufacturing is a rapidly expanding and developing area. As such it is important to focus the activity of a National Laboratory to where it would be of most benefit.
NPL held two industrial consultation workshops, the first to ascertain where it should focus its activity in future National Measurement System activity and Collaborative Research and Development. This consultation delivered several key messages:

1. NPL should provide support that aligns with our internal strategy to provide measurement capabilities and standards for materials assurance. There are general issues with both the assurance of materials data with regards to the performance of the AM material and in the availability and confidence in standards and regulations, particularly in safety critical applications.
2. Post build measurements and non-destructive evaluation (NDE) were highlighted as being areas with the greatest measurement challenges and so NPL should be focussing their efforts on these. There were three main areas that were prioritised: material property measurement (particularly dynamic measurements), dimensional and surface measurements, and novel NDE methods for part validation.
3. NPL should provide the greatest level of support to higher TRL techniques, with powder bed fusion and directed energy deposition of metallic materials rating highest. Although it was made clear that standards were needed across all material classes.

The second workshop had the aim of:

- Understanding how regulations, codes and standards might help and remove barriers to greater uptake for additive materials across industry sectors.
- Identify and prioritise critical areas where there is low level of industrial confidence and/or missing methods, codes and standards and consider a generic product validation chain that would support a faster and more robust AM product verification
- Capture the need and appetite for a shared materials database

A large proportion of the attendees were involved in the development of codes and/or standards. Whilst this was the case the general impression was that overall the RCS were written in a prescriptive manner and focussed on showing equivalence in properties and performance. It was also interesting to note that the workshop felt that the availability of RSC documents was low and that where they did exist the degree to which the organisations can and do use these procedures was also generally low.

Several key areas were highlighted where RCS were desirable:

1. Material design allowable
2. Defects design allowable
3. Acceptance criteria for non-destructive examination
4. Guidance for selecting appropriate specimen size, shape and number to truly represent the geometry within the part to be certified
5. Specifications on lattice structures

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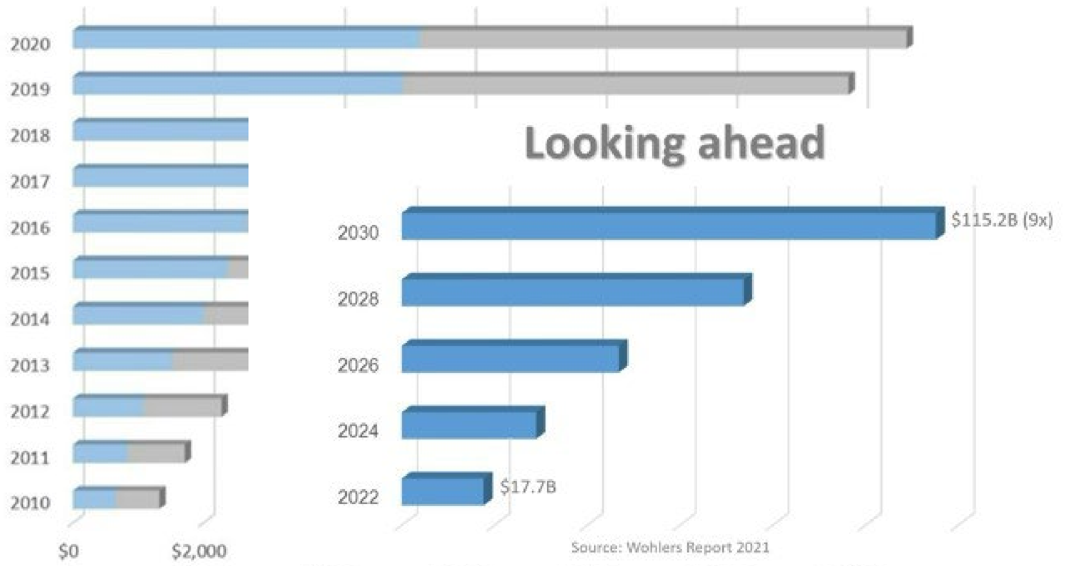
6 APPENDIX 1

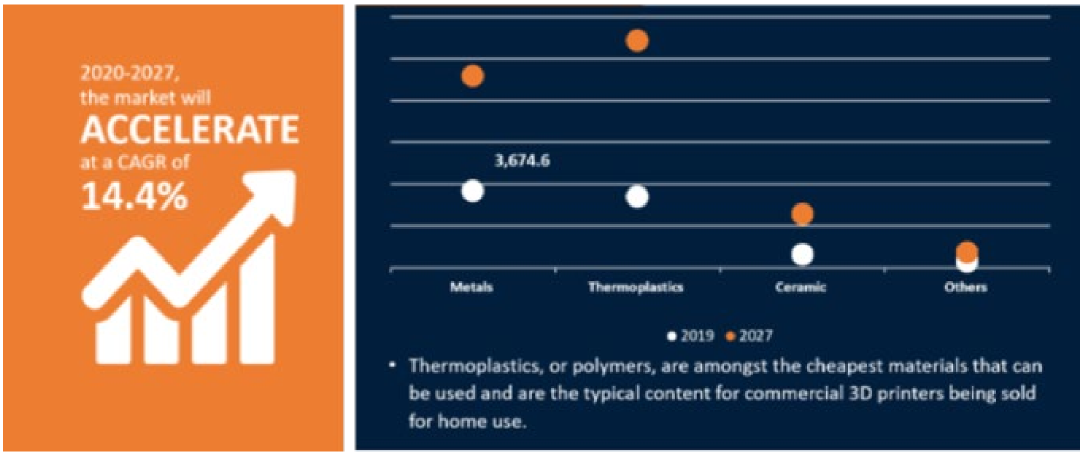
Industry Growth in last 10 years



$12.758 billion
0.1% of world manufacturing economy

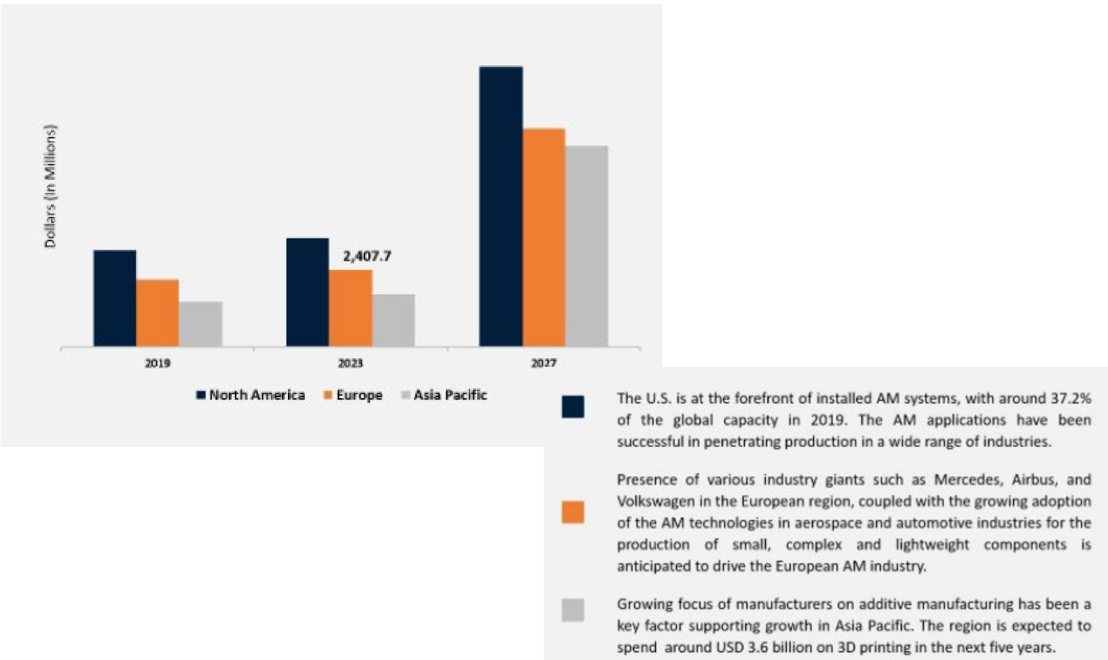
Source: Wohlers Report 2021

- Whilst AM has been around for some time, using it to produce durable end-use products is an emerging growth market.



Additive Manufacturing Market Analysis By Material Type (Metals, Thermoplastics, Ceramics, Others), By Metal Type (Titanium, Stainless Steel, High-Performance Alloys, Aluminum, Precious Metals, Others), By Polymer Type, By Ceramics Type, By Process, By End-use, And Segment Forecasts To 2028. Reports and Data

AM Growth



Additive Manufacturing Market Analysis By Material Type (Metals, Thermoplastics, Ceramics, Others), By Metal Type (Titanium, Stainless Steel, High-Performance Alloys, Aluminum, Precious Metals, Others), By Polymer Type, By Ceramics Type, By Process, By End-use, And Segment Forecasts To 2028. Reports and Data

Barriers

A recent report (October 2019) outlined the common challenges facing AM.

- *Slow production speeds*
  - Need faster ways to consolidate material, to make the process more cost effective and scalable to larger production scales.
- *Materials development and inconsistences in materials properties*
  - New optimised materials and databases to deliver greater performance with less validation.
- *Manual post processing*
  - Automated methods to remove supports and process steps.
- *Limited capabilities on data preparation and design*
  - Combination of design, model, build prepare, and process simulation are appearing to speed design and avoid mistakes in transfers.
- *Part to part variation*
  - In-process sensing, control and better process understanding can reduce variation.
- *Lack of industry wide standards*
- *Lack of understanding and expertise in AM.*
- *Making the initial investment.*
- *Disjointed AM Ecosystem.*
- *A lack of digital infrastructure.*

(https://amfg.ai/2019/10/08/10-of-the-biggest-challenges-in-scaling-additive-manufacturing-for-production-expert-roundup/)

Barriers

- A European Union Aviation Safety Agency - Federal Aviation Administration (EASA-FAA) workshop (November 2019) identified a key barrier to widespread adoption as being insufficient applicability of results from one geometry-material-process combination to another.

- Quality assurance of manufactured parts requires measurements that describe these structures, and which can be related to manufacturing processes and final material properties.

Barriers

- Product pricing
- Supply chain development
- Processing speed
- Understanding of DfAM
- Adoption of standards
- Still “new” to many
- Repeatability and reliability (Melissa Orme, Boeing)

Source: Wohlers Report 2021