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QUALIFICATION CHALLENGES WITH ADDITIVE MANUFACTURING IN SPACE APPLICATIONS

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Abstract

Additive Manufacturing (AM) has the potential to remove boundaries that traditional manufacturing processes impose on engineering design work. The space industry pushes product development and technology to its edge, and there can be a lot to gain by introducing AM. However, the lack of established qualification procedures for AM parts has been highlighted, especially for critical components. While the space industry sees an advantage in AM due to expensive products in low volumes and long lead-times for traditional manufacturing processes (e.g. casting), it also acknowledges the issue of qualifying mission critical parts within its strict regulations. This paper focuses on the challenges with the qualification of AM in space applications. A qualitative study is presented where conclusions have been drawn from interviews within the aerospace industry. The results highlight important gaps that need to be understood before AM can be introduced in critical components, and gives insight into conventional component qualification.

I – Introduction

The space industry is seeing an increase in demand for access to space to enable space-based services and human space flight, with new actors opting for market shares. This implies a need for a business-oriented evolution of technology development, decreasing cost and time to market. Additive Manufacturing (AM) is a manufacturing technology where a lot of potential is seen concerning free-form design, short lead-times and economical low-series or customized production (Gibson et al., 2015). This paper focus on applications manufactured by metal AM, and AM will hereafter refer to metal processes. For reviews of metal AM processes, see for example Frazier (2014) and Uriondo et al. (2015). The use and development of AM is growing rapidly within the aerospace industry, and this study focuses on the application of AM in space applications, ranging from satellite components (e.g. antennas) to launcher sub-systems (e.g. rocket engines). Some of the characteristics of the space industry are; expensive product development, high-performance products in harsh environments, low volumes (from one-off production to tens of parts per year) and strict regulations. However, AM also comes with challenges, and one of paramount importance for space applications are process qualification and part qualification (Dordlofva et al., 2016). The purpose of this paper is to identify the challenges with qualification of AM parts for space. It gives an insight into the qualification of traditional manufacturing processes and the results will give a direction for future research in understanding the implications AM has on the engineering design process. The paper is based on a literature review to establish the state of the art of AM qualification, and case study interviews conducted at a sub-system supplier in the European space industry. First, the theoretical framework for the study is presented, followed by a description of the method used for data collection and analysis. The results from the interviews are thereafter presented and then discussed in the end to conclude on implications for designing and qualifying AM parts for the space industry.

II – Challenges with Additive Manufacturing

The introduction of low TRL level technologies (Mankins, 1995) in critical space applications (e.g. launcher applications) is associated with high risks due to the cost of development and potential market impact (Underhill et al., 2016). AM is considered a technology with the potential to reduce development and production cost, as well as increasing product performance (Begoc et al., 2017). There are examples in literature and popular media on flight proven or qualified space components (see e.g. Rawal et al. (2013), SpaceX, (2014)), but they are still few. This is mainly due to the requirements on high reliability on space hardware, and it is still considered that there is development needed on the AM processes to facilitate their use (Martin-iglesias et al., 2017). While the efforts for developing AM for space flight are many (see e.g. Lasagni et al., (2016); Soller et al., (2016); Orme et al., 2017)), the need for established qualification methods is highlighted (Seifi et al., 2016; Uriondo et al., 2015). Areas in need of further development to enable qualification of AM and its implementation on a larger scale as production method include those listed in Table 1.

Table 1 – Areas in need of development for AM qualification

ID	Development need	Reference
(a)	Methods to identify suitable parts for AM, both from an economical perspective and manufacturability	(Lindemann & Koch, 2016)
(b)	Standards for AM materials and processes	(Seifi et al., 2017)
(c)	Design methods for engineers to utilize the possibilities with AM	(Thompson et al., 2016)
(d)	Understanding of process and geometry impact on material properties	(Seifi et al., 2017)
(e)	Machine-to-machine as well as process variation	(Frazier, 2014)
(f)	In-situ measurements systems for mapping and controlling the AM process	(Everton et al., 2016)
(g)	Process modeling as a mean to understand and develop AM processes	(Martukanitz et al., 2014)
(h)	Post-processing methods, including surface treatment and heat treatment	(Frazier, 2014)
(i)	Non-Destructive Testing (NDT) methods suitable for AM	(Waller et al., 2015)

Many organizations and universities are dealing with the issue of qualification for aerospace applications, and some approaches have been suggested. Portolés et al. (2016) propose a generic qualification procedure that has to be adapted for each combination of AM technology, material and component. They point out the importance of raw material control, the development of an allowable process window and the importance of identifying the key variables impacting the manufacturing. Taylor et al. (2016) made a comparison of qualification methods for conventional manufacturing processes and concluded that an approach for qualification of AM parts would have to combine the knowledge and methods from the qualification of different manufacturing processes. Central in their reasoning is the use of a building block approach similar to what is used for fiber composites (CMH-17, 2012).

As a highly-regulated industry, the space industry is especially dependent on the maturity of AM technologies (as is the aerospace industry in general). Standards and specifications are central in product development of products in the space industry, where for example ESA (European Space Agency) based projects are regulated by the *European Cooperation for Space Standardization* standards (ECSS, 2017). The requirements for the qualification of a product depends on its criticality. External (or third-party) standards are widely used in the space industry. However, in the introduction of new technologies, internal standards are usually developed (Seifi et al., 2017) since companies cannot wait for external standards to be developed and formalized. An example of this for AM is NASA with their *Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware* (Clinton, 2017). However, Seifi et al., (2017) point out the importance of the establishment of external standards since that would help the implementation of AM in industry by setting a minimum level of requirements as a reference for organizations developing the technologies for their needs. Current applications of AM in space products have mainly focused on secondary structures or other non-critical applications (Brandão et al., 2017). The interest of this work is the possibility to introduce AM in mission critical components, enforcing the need for applicable specifications.

Many products for space are complex systems-of-systems involving several companies and organizations. In the development of such engineering systems, e.g. a rocket engine, there is usually one Original Equipment Manufacturer (OEM) responsible for the system, while there are several sub-system suppliers. The product development usually follows a stage-gate process, to assure product design and manufacturing processes (Lindwall et al., 2017). The introduction of AM is expected to have an impact on the design process (Kumke et al., 2016), and the need for an end-to-end AM process for initial design, material supply, manufacturing, post-processing and qualification is highlighted by the space community (Brandão et al., 2017). There are examples of adaptions to the product development process for space products for AM (Begoc et al., 2017; Orme et al., 2017; Soller et al., 2016). A review of different work methods identifies key steps when working with AM PBF processes, and these have been illustrated in Figure 1. Included in the figure is also a reference to the areas (a) to (i) in Table 1 that are in need of development, showing where they are needed. The purpose of the illustration is to show that the whole product development process is impacted by the introduction of AM, and that development is needed through all steps. Although the suggested work methods usually include the verification of an AM part, this step is still a challenge. Martin-iglesias et al. (2017) acknowledge that knowledge about the effect of defects is needed, as well as acceptable verification criteria since complex geometries make it difficult (if at all possible) to use conventional NDT. X-ray Computerized Tomography (XCT) is often mentioned in the context of AM as a mean to detect internal defects.

However, complex geometries become a challenge also for this technology (Seifi et al., 2017) and further development is needed. Soller et al. (2016) showed that XCT is useful for verification of cleanliness after production (internal remnants of material) which is important for many space applications. The impact of product geometry on the material microstructure is an inherent characteristic of the AM processes, especially PBF technologies. This is due to that the microstructure is dependent on the thermal environment of the built part, which in turn is influenced by the build set-up (Fitzgerald & Everhart, 2016). The use of reference (traveler) specimens is a common approach to monitor the quality of the build (Orme et al., 2017; Soller et al., 2016). However, due to the geometrical dependency on the microstructure, the representativeness of such reference specimens is not evident and needs to be further researched (Seifi et al., 2017). Test specimens have to represent the actual part and should therefore be taken from a geometry as similar to the product as possible (Taylor et al., 2016). The understanding of geometry impact is crucial for the verification of AM parts and should be addressed already in the design phase. This need for early consideration of the built part's influence on qualification is represented in Figure 1 by the area (d) from Table 1 as part of the verification step. In-situ monitoring (f) is also included for the same reason; to highlight that qualification of AM is dependent on up-stream activities in the product development process, and not only done in the end.

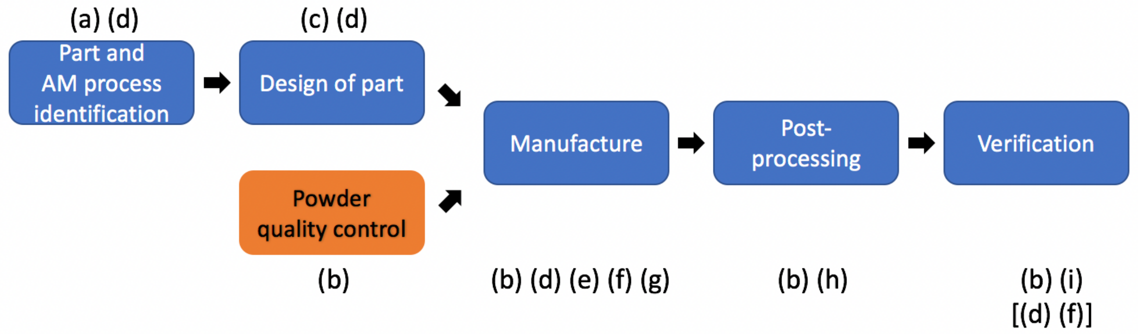

Figure 1 – Important steps in the development of products for AM, inspired by Begoc et al., 2017; Gibson et al., 2015; Orme et al., 2017; Soller et al., 2016*. The letters (a) to (i) refer to the development needs for AM in Table 1.*

III – Research Design

The present research is based on an interview study with engineers in a large manufacturing company focusing on aerospace and space design. In the design of the interview study, the aim was to understand how qualification is currently done, how new manufacturing processes are introduced as well as challenges regarding qualification of AM. The interview series was divided into two phases; the first focused on understanding qualification in the aerospace industry and the second on the introduction of new materials. The sampling of engineers was created to get a mixture of people with component responsibility, process specialists (i.e., forging, casting, welding) as well as materials experts and experts responsible for newly introduced materials such as composites and AM. For the first phase (understanding of qualification) eight people were interviewed, and for the second phase (introduction of new materials and processes) seven people were interviewed. Semi-structured interviews were selected as the main data collection method; all interviews were based on an interview guide with the following focus:

- How are conventional material processes qualified?
- How are new manufacturing processes introduced and qualified?
- What are the challenges regarding qualification of AM processes?

After analyzing two of the interviews, it became apparent that the first question needed to be divided into sub-categories, such as definition of qualification and requirements; how materials and products are tested; how the product influences the qualification; design methods being used and work methods for qualification. The interview also included more general questions relating the respondent's background, experience, current and previous roles. The respondents were free to elaborate when answering the questions and follow-up questions were used to encourage detailed descriptions and explanations. All interviews were performed in Swedish, recorded and transcribed; all quotes in this paper are consequently translated by the authors. The interviews were conducted by one of the authors that have several years of experience in design of space systems and is situated as an industrial Ph.D. student at a company within the space industry. The internal author brought understanding and knowledge of the particular context, official processes, internal lingo, etc. for the analysis. The external author contributed with the objectivity that was utilized when analyzing the material and drawing conclusions. To clarify the empirical data and identify recurring and dominant themes, selective coding was used. Data reduction in the form of pattern matching followed by displays of the data was utilized to draw conclusions and synthesize the findings (Miles & Huberman, 1994). Data coding and analysis consisted of the following steps:

1. The selective coding involved the selection of central categories based on the main research issues identified before performing the interview series.
2. Interview transcripts were read through and instances relating to research issues highlighted.

The result from the coding was compiled in a spreadsheet with columns for the central categories and one column labeled other. During this step, relevant quotes were copied into the table.

IV – Empirical Findings

The following sections present the results from the interviews analysis performed for this paper based on the respondents' answers.

Concept of Qualification

Throughout the interviews, it was clear that the word "qualification" had a different meaning depending on the viewpoint, and often also depending on the background of the respondent (civil aerospace, military or space products; material, design or process engineering). There is also a confusion with other words that are used in similar contexts, e.g. verification or certification, which tend to depend on what word a customer is using. The respondents were asked to distinguish between material, process and product qualification, however, most of them expressed that they are linked to each other, and in the end, it is the product qualification that matters. Regardless of the terminology, the purpose was the same; to gather evidence showing that a product meets a certain set of defined requirements on e.g. loads, life cycles and performance. In other words, to show that the design intent of a product is met. Being part of a sub-system supplier in the aerospace industry, the respondents reflected on the responsibilities in product qualification. Working with systems of products, e.g. a rocket engine, the end system is qualified by the system responsible, while the sub-system product is qualified by its design responsible. Due to practical reasons, sub-systems are usually qualified as part of the system qualification. Depending on the agreement between the system responsible and the sub-system supplier, the formal responsibility of the sub-system qualification in such cases can be on either. If it is on the system responsible, the sub-system design responsible delivers a design data package showing compliance to the requirements. The space industry is based on levels of regulations and requirements. On the highest level, there are authority (or customer) specifications instructing organizations how to work with product development and include such quantitative requirements as what margins are needed in the design, what type of material data is needed and how to qualify products. On the next level, there are the product technical specifications written by the system responsible that holds the requirements on the sub-systems. The design responsible for the sub-system plans the product qualification to meet this specification. Requirements for product qualification are therefore set by the design responsible, in accordance with the design specifications, and according to the needs of the product.

A – Product Qualification

The approach to qualification has changed over the years, where testing was the dominant way of showing compliance in the past. Simulation and analysis have received a larger role in the qualification work during the last 50 years, but still with complementary testing. “Not all things are possible to calculate that needs testing” as one respondent expressed it. Often, calculations are correlated towards testing for validation. One part in establishing analytical methods is the availability of material data used for design. An approved database is built on material testing, both through standardized material testing and product specific material testing. The respondents frequently came back to that a manufacturing process needs to be verified with material data. Hence, product qualification is closely linked to the manufacturing processes, and in the end, it is the produced (or manufactured) material that needs to be qualified in its application. The relation between the product qualification and the manufacturing process qualification can be depicted as in Figure 2.

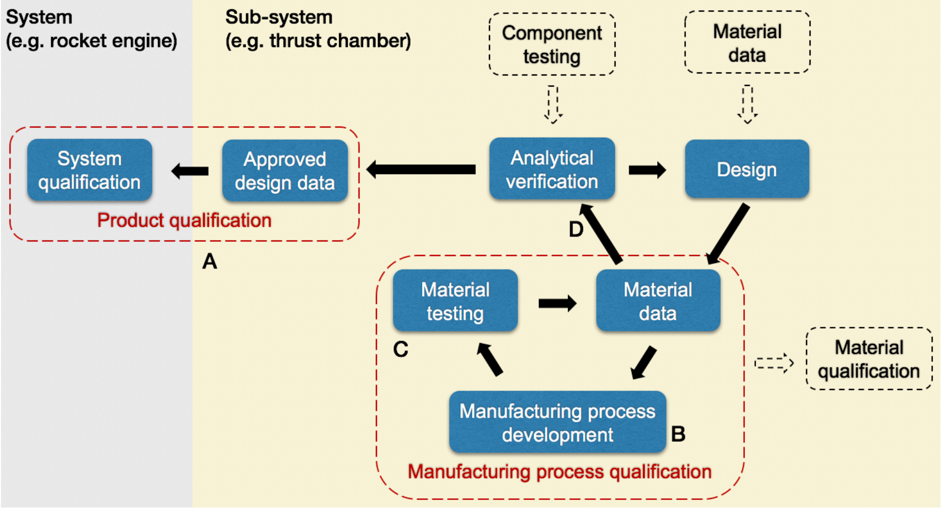

Figure 2 – The role of manufacturing process qualification in product qualification. The letters A-D refer to the corresponding sections in the text.

B – Manufacturing Process Development

Authority regulations require that a design organization must have control over the manufacturing of critical components (hence a company's management system). Within the scope of this study, four traditional manufacturing processes were discussed; forging, casting, welding and fiber composites. The following synthesis is based on the common approach that could be deduced for all of them. The term *qualification of processes* is used for manufacturing processes that are considered critical. A critical process is a process that can render what the respondents call `hidden properties´, e.g. pores, cracks or inclusions that cannot be measured using NDT techniques (standard operations such as milling or drilling are not such processes). Given the question if the qualification procedure is different depending on manufacturing process or product, the respondents answered that the logic is always the same, but the exact activities may differ. In general, it was also said that the exact qualification approach is dependent on the customer since they have different experience and different philosophies on how products and processes are qualified. The following general logic could be deduced from the interviews.

1. Give approval for the manufacturing method based on standards or specifications
2. Develop a specific process that fulfills the material requirements of the product
3. Freeze the final process

The approval of a manufacturing method (1) is usually done on a generic level (independent of the part) and is based on internal knowledge (internal specifications aided by third-party material standards) specifying the parameters, machines, etc. that have an impact on part quality and that need to be controlled. Raw material control is practiced for all manufacturing methods and material standards are normally used as a reference. In the development of the manufacturing method to comply with the product specific needs (2), concurrent engineering with the process owner (often a supplier for traditional materials) is practiced to utilize the process capabilities and limitations. Once a process is developed, evidence is gathered for how the product will perform with that process. Since hidden properties are evaluated, destructive testing is always included in the qualification of a critical process, i.e. one or more parts are sacrificed. The purpose is to identify what hidden properties there are that cannot be measured on the final product using NDT, and verify the ones that are dimensioning for the life of the part. Normally this is done using microstructure evaluation and material testing, comparing it with a known material database to show that it is within the population. In serial production, NDT has to be used to find indications for process drift which requires that the used NDT methods are shown to find the type of defects that are sought for in parallel with the process development. Having enough evidence that the product will meet the design intent, the process is finally frozen (3). The idea behind freezing a process is to make sure that a product is manufactured the same way, every time.

Compared to forging and casting, welding is based on a machine set-up and method approval is usually done through the qualification of a process parameter window for each machine individually and a process parameter window. Furthermore, due to the tough, and usually product specific, requirements in aerospace, it is difficult to use the same welding parameters for two different products. Fiber composites processes also differentiate since the mechanical properties of products made of fiber composites are dependent on the geometry of the product. One respondent expressed that "the principle for processes where your properties depend on your product and process is to break it down into sub-process and sub-materials, and finally to freeze your process". Practically this is done by approving the suppliers of the materials used in the process, e.g. fibers or the epoxy. At manufacturing process level, there is normally no material specification that is used as a reference, rather the requirements on the fiber composite process are set based on the application.

C – Material Testing

The material data is the link between the product design and the manufacturing process as one respondent expressed it. Once a manufacturing process is developed, or in the process of being developed, material testing is therefore commenced to establish the material data which is then used to verify the product. The authority regulations include what accuracy/confidence you need in the data (how much testing you need, how many batches that have to be included, etc.), but given the cost and time of establishing a complete database, there is usually a dialogue with the customer to set a practical and appropriate level, and what safety factors that have to be used in the design to compensate. This is especially the case within space programs where there can be a lack of produced material due to the low number of products. There are usually no requirements from the customer on what the material should look like in a cut, it is up to the design responsible to verify its fulfillment. Engineering judgment and experience plays a vital role in the process acceptance, and the amount and size of defects that can be accepted are set by the design responsible. Periodical cut-ups (e.g. sacrificing every 10th part) was mentioned among the respondents indicating that it was used on occasions. Although sacrificing a part is the best approach to get representative material data, it is expensive for follow-up testing. The use of 'hang-on bars' is therefore practiced, where additional material is added to the part to be cut-off for inspection. For forgings, a prolongation of the forged material is used which usually makes it easier to show it to be representative. For castings, it is more difficult since the geometry of the product and placing of the gates (used to pour the metal into the tool) has an impact on the material flow and the solidification of the material. Castings are therefore more dependent on the geometry of the product. Hang-on bars can be used to evaluate the bulk material, but defects are dependent on location and sacrificing a part is therefore often needed for castings. For composites and welding, there are usually test pieces that are manufactured in parallel with the process development for cut-up and testing to show the product properties fulfillment. Periodical testing is also rather common for composites, but then statistical data is used to reduce (or increase) the interval.

D – Material Data and Design Verification

A challenge for the design responsible is to develop the manufacturing process quick enough to be able to establish the material data needed for the design. Usually, the product design is already set and when the manufacturing process has been developed, you need to show that the product meets the analytical calculations. Normally, a known material database is used for the product design, but then for the manufacturing process, this data is not necessarily the same since it will be product specific. Many of the respondents associated the term "material qualification" with the development of a new material and the building of generic database for its properties. However, building material data is time-consuming (and costly), and within a development project where you usually have less manufacturing in the beginning, this becomes a challenge. Furthermore, the situation is not always ideal and sometimes there is a need to develop a material or a process in parallel with the product development, knowing that the material data is a risk.

Some of the respondents stressed that to qualify a product, it is not a requirement to have a qualified material since in qualifying a product the aim is to show that the product, with its manufacturing process(es), meets the design intent. Often, specific material requirements for a product are therefore defined explicitly for that product. Following that logic, material standards or specifications are not necessary for the qualification of a product, although they make it easier.

The product requirements are less precise early in the design process but become more set as the development progress. This uncertainty in requirements puts a need to set a plan for the verification already in the early design phases, and to consider how design choices will impact the qualification. An example is casting where much thought is put into the product design. Castings are usually designed for less stress in the material since the robustness of the process (i.e. spread in material characteristics) is larger than compared to e.g. forgings. Given the question on how castings can be approved although they include material defects (e.g. pores), the respondents came back to that the amount of experience in using castings for many years gives confidence. The material specialists can draw conclusions based on earlier applications and use *similarity* to either approve or require re-design of a product or process. Again, appropriate safety factors can be used for the design. Compared to AM, there is also confidence within the industry that the processes are stable enough. As for castings, composites include defects (e.g. pores), and a certain level has to be accepted, e.g. a percentage of the material volume is allowed. Safety margins are used to reduce the material properties accordingly. However, this requires that there is a proven NDT method that is capable of finding defects to this level, and this will decide in practice if you can use the material or not in the given application.

Verification of space products through testing is more difficult since the real loads are not experienced until they are launched, either as part of a rocket or a payload. At the same time, a low production volume means less material data from produced components, adding to the challenge of building knowledge and material data for the verification. The criticality level of a product adds another factor to the qualification. While the qualification *procedure* of a critical process is the same, the critical level of a product might impact the *requirements* on the qualification since they are part specific. It can also have an impact on follow-up testing in serial production, how often and how tough the requirements are on the NDT.

Challenges with new Processes and Additive Manufacturing

The respondents were also asked about the challenges with process qualification and the discussions that followed went into both challenges for traditional processes and what challenges there are with AM. One respondent said that on a high level, “the challenge is to find the appropriate and relevant requirements on products”, and that the key to process qualification is process knowledge and understanding. Setting the right requirements is a question of both product function and economical production. Depending on the previous experience of a process, the level of development will differ. If it is a new material, then a new set of material data has to be deduced through testing. However, testing in itself is also a challenge since it might not be evident what you should measure, as compared to traditional processes where there are established methods. *Similarity* can be used for proven manufacturing processes, and if the same notion can be used for AM, showing that it is at least as good as some known material, then that might be one approach. However, then you need to gather enough evidence to show that it is feasible. In literature, AM is often compared to forging and casting, with examples of AM having similar properties as forging (Frazier, 2014). However, one of the respondents believed that if the AM processes cannot be shown to be more or less defect free, they will be difficult to compare with forgings, ending with the option to compare with castings. Small variations in the material can be handled through statistics, it is, however, the larger surprises that are more difficult (e.g. inclusions (Brandão et al., 2017)). New manufacturing methods should therefore be methodologically introduced to minimize the risk, i.e. start with less critical components to gather experience. This step-by-step introduction has been the approach with Metal Deposition (MD) technologies within the studied company. The process has been used in low stressed areas or in non-critical applications to gather experience and periodical testing has been used to follow the process. MD has also been treated much like a welding process with the requirements for acceptable defects specified explicitly. One respondent compared AM to welding and mentioned that the elimination of process defects in welds has been pursued for years, without succeeding, and questioned if it will be possible to get fully rid of them in AM. Another respondent said that; ”if we are working with powder, pores are something that we are not going to be able to avoid. I don't think so […] we are going to have to live with pores, just like in castings.” In line with this, one concern for AM processes that was brought up by several of the respondents was the characterization and quality assurance of raw material, especially powder. The lack of standards for AM materials is believed to be another hurdle for AM in space applications according to one of the respondents. It is a conservative industry and before a new process is introduced you need all the facts on the table before you move on, hence the logic to follow the TRL scale. The customer is often involved in setting the requirements for each TRL level if a technology is developed for an application, and the experience is that increasing the TRL level is easier if there is an application.

V – Discussion

Throughout this study, it has been clear that knowledge about material behavior is the foundation for product qualification. In a conservative industry as the space industry, this becomes a challenge for mission critical components if sufficient knowledge and material data are not available. The structure of working with TRL levels stems from the need of maturing a technology before it can be used in real applications. Based on the interviews for this paper, basically three approaches for qualifying a manufacturing process in a product can be deduced:

1. Rely on a generic material database which can be used as a reference for any product to be built using that process, as is the case for many of the traditional processes with known materials.
2. Use a known material database as the reference and show that the known material database can be used as minimum properties for the new material, i.e. that the new material is at least as good as the reference. This approach does put a need for sufficient material testing to show that the new material is statistically within the minimum properties.
3. Start from the application and look at its specific requirements, much like with composites. This approach gives the possibility to tailor the manufacturing process according to the product requirements, at the same time as knowledge about the process is built, step by step.

Working from the bottom-up with these approaches gives the possibility to build knowledge and data about the process, and is the logical path to build a materials database that can be used to possibly qualify a material in the end. However, since the material properties are highly dependent on the AM process (e.g. machine type, process parameters), the question should be asked if a generic database is feasible and practical, considering the fast development of AM technologies, the cost of material testing, and the application driven mechanical properties. The complexity of coupling between part and process has made it necessary to have a part-based qualification approach for already implemented applications. It has been discussed in this paper that analytical verification is an important part of the product qualification. However, given that there are still many unknowns with the AM processes, component testing is likely to be important in product qualification of AM. Fiber composites use this type of working methodology where the approach towards defects has been that a certain amount has to be accepted. However, for AM this approach has to be assessed and the design responsible needs to develop an understanding of what type of defects that could be present, and what implications these have on the design, the "effect of defect". Seifi et al., (2017) summarize this in three questions to ask: (1) what is the largest defect that can go undetected, (2) what is the effect of a given defect type, size and distribution on part performance and safety, and (3) what is the consequence of catastrophic part failure stemming from such inspection misses? Regardless of the approach, there is a strong need for reliable inspection methods, both in-situ and NDT.

All stages of the product development process need adaption for AM (see Figure 1), which implies that a close cooperation is required among the parties involved. Designing for AM will require engineers to not only think in new ways to utilize the potential of the technology but also in how they work with the prerequisites of each AM process. In the field of systems engineering where there are multiple levels of requirements and suppliers, this becomes more challenging since the design of sub-systems might impact other sub-systems (Lindwall et al., 2017). The present paper highlights the importance of taking the product qualification into consideration early in the design process. This is especially important in processes like casting where the material is created in the process and is sensitive to the part geometry, similar to AM. There are different approaches for product qualification, and engineering experience and understanding of manufacturing processes are key ingredients to set sufficient requirements to fulfill regulations. Building knowledge is therefore important in the introduction of AM, and the identified areas in need of development (see Table 1) have to be addressed in parallel.

Implications for Space Applications

The space industry is built on regulations, standards and specifications, and the lack of standards for AM materials could, therefore, be a hurdle for AM in space applications. However, since the experience is that it is easier to mature a technology for an application, this should be utilized for a more efficient development of AM. This approach favors the qualification approach of developing your process from the needs of the product, again building knowledge towards a more comprehensive process understanding.

The tough environments on many space applications push the limit on what the materials are capable of. These extreme conditions could lead to unnecessary conservative designs and requirements when working with AM due to the current status of the technologies with many unknowns. Setting the right level of the requirements was mentioned as a challenge by the respondents, but by involving the customer (or OEM), this could be achieved.

Another challenge for the space industry compared to e.g. the civil aerospace industry is the lack of possibility to implement an AM part in its application and use regular inspection to monitor its behavior. Once a part is launched, it will be inaccessible and a failure could have severe consequences for the mission. This makes it difficult to have a gradual introduction of AM components. The use of technology demonstrators is an established approach for the introduction of new technologies within the space industry and is recommended for mission critical AM components.

While the characteristically low production volumes of the space industry are usually seen as one enabler of economical AM production, it is also a challenge. To build confidence in a new manufacturing method, statistically based production data is needed to be able to show its robustness. However, the low volumes imply less produced material, and given the rapid development of AM technologies, this could be a hurdle since the idea of a frozen process makes it difficult to adapt new and better technologies.

Finally, from an engineering design perspective, AM brings many possibilities to find new design solutions given the design freedom and possibility to consolidate parts. However, in the development of a system (e.g. a satellite or a rocket engine) there are often several sub-systems, and the use of "free form design" might lead to making the traditional interfaces between these sub-systems more diffuse. The possibility to challenge traditional interfaces or not might impact both the ability to utilize the capabilities of AM, but also how to maintain the responsibilities of each sub-system.

VI – Conclusions

The qualification requirements for a space product are set by the design responsible, but is influenced by customer and authority regulations. Product and manufacturing process qualification are linked together, where the purpose of the qualification is to show that the design intent of the product is fulfilled. This purpose should be seen as a guideline for the qualification of AM products. Resemblances can be seen between AM and the traditional metal processes welding and casting. Both AM and welding are dependent on specific machines and machine-by-machine qualification is the practice for welding. Castings are sensitive to the manufacturing process and part destruction is vital to understand the material structure in a specific product. At the same time, the geometry dependence on mechanical properties that is seen in AM can be seen in composites where component testing is common. Hence, elements from the qualification of traditional manufacturing should be considered and combined in the qualification of AM. Building industry confidence in AM technologies is probably the biggest challenge in the conservative space industry, and process knowledge is important. Balancing the requirements of qualification is a question of understanding the requirements of the product and the capabilities of the process, making sure not to over specify the qualification.

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