TURUN YLIOPISTO

Standards and their practical use in powder handling procedures and reuse in industrial laser-based powder bed fusion of metals

Master of Science in Technology Thesis

Materials of Energy Technology

Material Engineering

Department of Mechanical and Material Engineering

Author:

Erkka Lehtihuhta

Supervisors:

Professor Antti Salminen D.Sc. (Tech.)

Adjuct professor Heidi Piili D.Sc. (Tech.)

30.1.2024

Turku

Master's thesis

Subject: Material Engineering
Author: Erkka Lehtihuhta
Title: Standards and their practical use in powder handling procedures and reuse in industrial laser-based powder bed fusion of metals

Supervisor(s): professor Antti Salminen, adjunct professor Heidi Piili
Number of pages: 55 pages
Date: 30.1.2024

Additive manufacturing is a process of making objects to make parts from 3D-model data, usually layer upon layer, as conversely to conventional manufacturing methods. The rapid development within the branch of additive manufacturing has resulted that standardization of materials, procedures, equipment etc. are left more or less behind in this expansion. This lack of standards can even be the main reason of the slow adoption of additive manufacturing technology.

There are various technologies within additive manufacturing, one of the most widely used being laser-based powder bed fusion. In this method it is possible to reuse the metal powder remaining intact after producing a final part. Reusing practice reduces the manufacturing costs of the product, thus making powder bed fusion economically more feasible as a choice for manufacturing. This thesis concentrates on standards related to powder reuse in laser-based powder bed fusion.

This thesis is a part of a larger project, DREAMS (Database for Radically Enhancing Additive Manufacturing and Standardization). This project is the first systemic AM development project in Finland, and it has potential to boost the Finnish AM industry widely. There is also a large-scale American co-project going on since 2016, aiming to globally fill the gaps in additive manufacturing standards. One of standards, published in 2021 (*ASTM F3456-22, Standard Guide for Powder Reuse Schema in Powder Bed Fusion Processes for Medical Applications for Additive Manufacturing Feedstock Materials*) is the core in this thesis. In this standard seven (7) different powder reuse schemes are defined. Based on these different modes of powder reuse, a questionnaire was sent to Finnish additive manufacturing companies to gain understanding about powder reuse in practice. Also a few interviews were carried out to deepen the results.

The results of the questionnaire and interviews show that there are different schemes for powder reuse among AM manufacturers, as expected. Sieves of specified mesh size are needed in reuse procedures, and there was a lot of variation between the sieves that were applied. Sometimes the size of the sieve was not even known accurately. Also, when new powder was to be added, the exact amount of this new powder was poorly followed. Powder reuse history seems to be documented well enough, but not in a standardized way. Powder handling procedures were in most cases not certified, but customers rarely asked anything about powder handling.

Based on the answers given by Finnish additive manufacturing industry companies even this limited amount of research material shows that powder handling and reuse procedures are far from being standardized. This thesis reveals an urgent need to find ways of standardizing powder reuse practices as one part in an attempt to raise the quality of Finnish additive manufacturing industry to next level. Further studies may follow as new standards are being published – even if are yet not recognized as international standards, like in this case. All this can by now done in a coordinated fashion by DREAMS project.

Key words: Additive manufacturing, laser-based powder bed fusion, metal, standard, powder handling, powder reuse, procedure, quality

Figures and tables

Figure 1. Global market value in 3D printing

Figure 2. Maturity of additive manufacturing products

Figure 3. The principle of subtractive manufacturing

Figure 4. The principle of additive manufacturing

Figure 5a. Difficult to produce by subtractive manufacturing

Figure 5b. Parts impossible to produce by subtractive manufacturing

Figure 6. Comparison between the cost of production in traditional production and additive manufacturing, as a function of complexity of units and as a number of units in production

Figure 7. Operating principle of laser-based powder bed fusion; 2-dimensional presentation

Figure 8. Operating principle of laser-based powder bed fusion; 3-dimensional presentation

Figure 9. The number of publications according to Scopus with different combination of search words

Figure 10. A schematic of the recycling strategy, demonstrating the addition of 50 % new powder after each cycle

Figure 11. Quality pyramid with levels of quality in Finnish AM services

Table 1. Questionnaire answers

Contents

Figures and tables 3

1 Introduction 5

2 Background for laser-based powder bed fusion 10

2.1 The principle of additive manufacturing 10

2.2 Laser-based powder bed fusion of metals 14

3 Standards and the idea of standardization 16

3.1 Benefits of standardization 16

3.2 Organizing standardization work 17

3.3 Standards in additive manufacturing 18

4 Powder reuse in additive manufacturing 20

4.1 Powder sieving 21

4.2 The effects of reuse 22

4.3 Standards and the reuse of powder in additive manufacturing 24

5 Experimental part 27

5.1 Aim and purpose of the experimental part 27

5.2 Experimental set-up and procedure 27

6 Results and discussion 32

7 Further analysis 37

8 Conclusions 40

9 References 42

Appendix 1: Technologies within additive manufacturing

Appendix 2: Questionnaire (in Finnish).

1 Introduction

Additive manufacturing, also known as 3D printing, is a novel technology, most of the current technologies being invented in around 1980s. In additive manufacturing the data from virtual solid 3-dimensional model is first sliced into a series of 2-dimensional cross sections that are fed into additive manufacturing machine, as instructions, and after that constructing layers upon layer to form the physical part (Gibson (2021)). The other source defines this slightly differently. According to American Society for Testing and Materials:

> *"Additive manufacturing is a process of making objects to make parts from 3D-model data, usually layer upon layer, as conversely to conventional manufacturing methods" (ASTM F2792-12a. 2012).*

The whole branch of technology has been expanding during recent years as new innovations are being discovered. Additive manufacturing is expected to grow also in the years to come. Figure 1 shows both recent growth and expected growth of global 3D printing market (3Dprintingindusty.com).

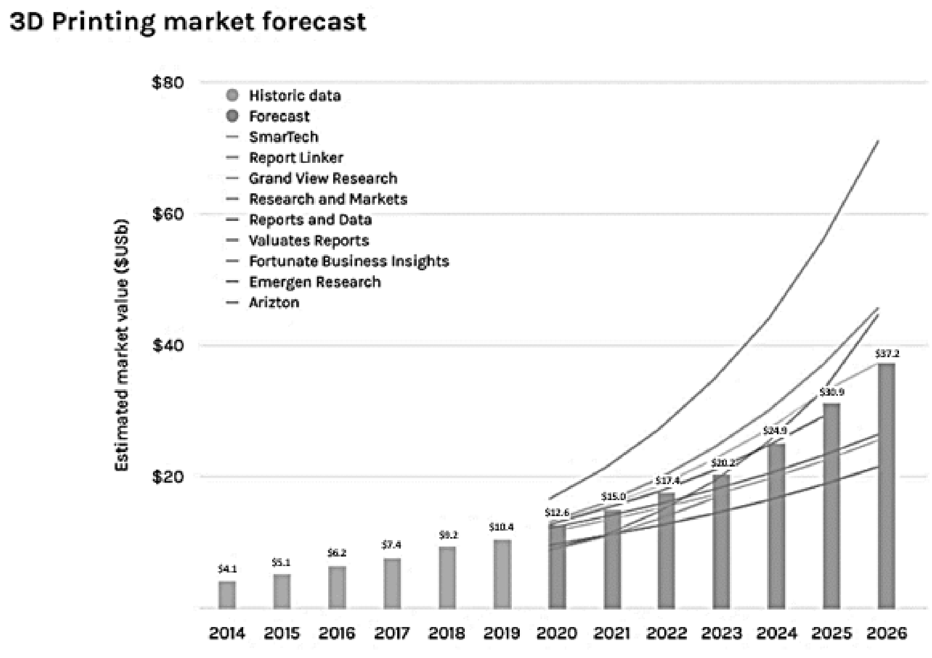


Figure 1. Global market value in 3D printing (3Dprintingindustry.com).

As can be seen in figure 1, in year 2020 all nine research institutions expected growth of additive manufacturing market in future. Since additive manufactory is in an early stage of its life cycle, many things are still in progress (Stavropoulos et al. (2023)). The downside of this expansion is that standardization of materials, procedures, equipment etc. used in additive manufacturing are behind to some extent (according to a co-project by America Makes and the American National Standards Institute (ANSI) called “America makes and ANSI Additive Manufacturing Standardization Collaborative (AMSC)” launched in 2016). Also, the quality of final products is not as high as with products manufactured by traditional technologies. This can be partly explained by the relatively short time since the first inventions of additional manufacturing techniques – a few decades for the former, several centuries or even thousands of years for the latter. Figure 2 shows the maturity level of some fundamental areas within additive manufacturing (Carlota (2019)).

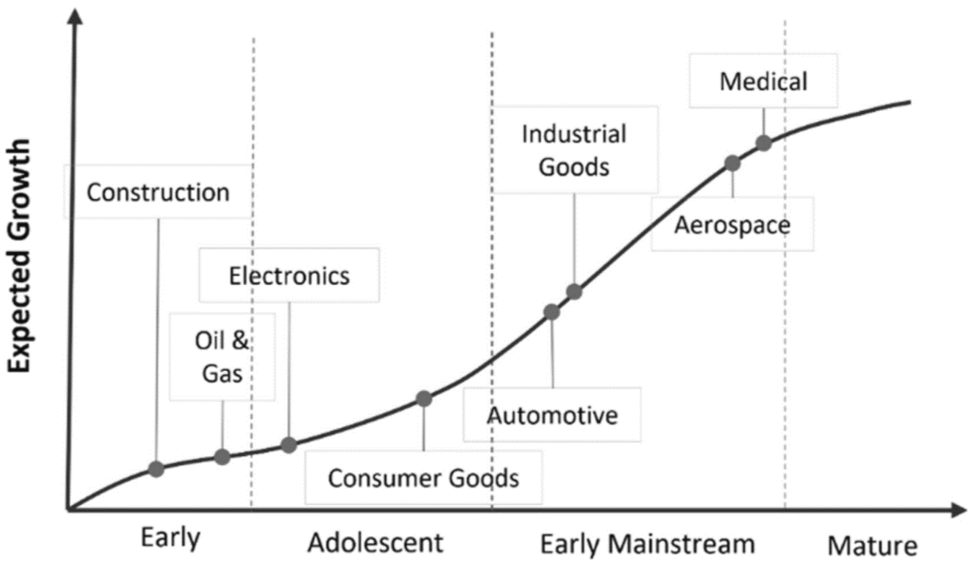


Figure 2. Maturity of additive manufacturing products (Carlota, V. (2019)). (https://www.3dnatives.com/en/industries-additive-manufacturing-120820195/)

As can be seen in figure 2, only medical and aerospace industry are even close to maturity at making products by additive manufacturing. As part of a wider Finnish joint project there is a special interest in the Department of Mechanical and Materials and Engineering in the University of Turku to get more relevant information about the standards applied to additive manufacturing – or shortly just “AM”. This is particularly true for a technology called laser-based powder bed fusion. This thesis concentrates on laser-based powder bed fusion (PBF-LB) as it is a wide-spread technology with good prospects. An overview concerning some of the standards applied to this technology are presented in the thesis. In a larger picture the aim is to find guidelines to estimate the qualities of final products more reliably.

The lack of standards has resulted in slow adoption of AM technology, particularly in industries that require certification, such as aerospace, medical, automotive, and so on (Chua et al. (2017)). It is even claimed that the acceptance of AM in all aspects of manufacturing is always subjected to lack of additive manufacturing standards (Kawalkar et al. (2022)). State-of-the art products are manufactured with PBF-LB technology, but unawareness of the applied standards seems to be some kind of a bottleneck. The aim of this study is to give new insights into this technology. Special emphasis will be on standards and practices that apply to the reuse of metal powder within the process. Mixing the used powder with new one is a general way to reduce costs in powder bed fusion technology, but the exact procedures among industrial operators are not very well known. These procedures will be to studied to get more information about the practises of mixing used powder with new powder. A comparison with an existing standard related to powder reuse will be applied as well (ASTM F3456-22).

This thesis is a part of a larger project, DREAMS (Database for Radically Enhancing Additive Manufacturing and Standardization), coordinated by a Finnish company named DIMECC Oy (https://www.dimecc.com/dimecc-services/dreams/). As the abbreviation of the name of the company DIMECC (Digital, Internet, Materials & Engineering Co-Creation) already hints, the objectives of this joint project are quite high. DREAMS project is the first systemic AM development project in Finland, and it has potential to boost the Finnish AM industry widely by creating new and local high-level demand and supply in cooperation of eight industrial partners with three science partners, (University of Oulu, University of Turku and Lappeenranta-Lahti University of Technology (LUT)). According to the project plan "*Additive manufacturing is still underutilized in the Finnish manufacturing industry. Reasons for the underutilization are not technical restrictions of the manufacturing method but lack of expertise and standardization, and difficulties to certificate additively manufactured products. Finnish AM companies have had continuous growth in sales and number of AM systems installed in Finland has multiplied in just few years, which indicates that demand is still higher than supply*." (DIMECC project plan.)

As mentioned earlier, the standardization of things related to additive manufacturing are not always in synchrony with rapid development of the technology as new inventions emerge (Stavropoulos et al. (2023)). The main topic of this work is to find out what standards there are already available to gain more insights on the reliability of evaluation of final products in the research community and to make this information known. As a novel technology AM lacks expertise and standardization and as a consequence industrial companies have difficulties in making AM products with certificates. Conventional manufacturing standards are of little use with AM since they are based on known homogenous microstructure – which is not the case with AM.

In DREAMS project, one objective is to create a comprehensive material database, that can substitute the missing AM material standards. More than one thousand test specimens would be manufactured by service providers and research institutions and analyzed in-depth to obtain enough information for the database. Test specimens would be analysed for fatigue and tensile strength and impact toughness with metallographic microstructures to create the database. This database could in part compensate the missing standards, so that manufacturing components with higher level of quality would be possible to make in Finland. At the moment only two first levels of quality out of five AM products can be produced in Finland (Business Finland, 2019). An open material database could be utilized in producing components that have higher requirements of certifications, like in aviation, oil & gas, and nuclear industry. Finnish Additive Manufacturing Ecosystem (FAME) is also supporting this project. FAME is a professionally facilitated, business-driven and co-creative additive manufacturing ecosystem, established in 2020. The focus of FAME is to increase the use of Additive Manufacturing in the Finnish manufacturing industry. (https://fame3d.fi)

However, due to time frame of this thesis, experimental tests were not carried out. It was also not possible to try to gather every piece of information available in scientific papers and in Finnish AM companies, but to choose one topic to concentrate on. The topic could have been a physical or chemical quantity of an AM product, but the common practice of mixing intact and reused powder seemed to be an interesting question, a procedure that is supposedly not highly standardized. The consequences of LBF-LB powder reuse of physical properties of AM products could be of interest, but it would also be good to know how the companies carry out reuse operations in reality. Furthermore, there could be some standards available on this subject, that would supplement our understanding on this specific topic. There is plenty of research done related to the effects of reusing of the powder on the quality of products (Ardila et al. (2014), p. 99–107; Moghimian (2021); Tang et al. (2015), p. 555–563; Nandwana et al. (2016), p. 754–762). So, these were not studied in this work, neither the economical viewpoints in AM. From this point forward the term “additive manufacturing” will always refer to PBF-LB, or more specifically to laser-based powder bed fusion of metals (PBF-LB/M) in this thesis work unless otherwise stated.

Manufacturing metal alloys, including steel, is an old invention. The first pieces of ironware are almost 4000 years old. This may explain why a product from a steel factory has precisely defined qualities, like composition, yield and tensile strength, ductility, hardness, surface roughness etc. This is because the processes of making steel products are thoroughly standardized. Welding is a somewhat newer invention. However, it is also old enough to have gone through profound procedures of standardization. Today it is easy to get information about the most suitable practises related to welding in varying circumstances. However, this is not the case with additive manufacturing: the process is still partially uncompleted. Furthermore, even with standards that do exist there seems to be gaps between standard publishers and end users. This work aims to narrow these gaps by trying to give more publicity for a selected set of chosen standards and to study the ways they are applied in reality.

Research questions in this thesis were:

1. Are there standards dealing with powder reuse in PBF-LB?

2. What do standards say about powder reuse in PBF-LB?

3. How is powder reuse performed in Finnish AM industry?

2 Background for laser-based powder bed fusion

Before going deeper into the topic, it would be good to define the themes of central importance. As this writing falls into a category of a thesis work, the basics of the work should be illustrated somewhat wider than in a scientific article. In the following chapters this is done by revising concepts like additive manufacturing, standardization and the specific manufacturing method applied to the topic of interest. Finally, along with the aims of this study, the work is put into a wider perspective in the context of Finnish additive manufacturing.

2.1 The principle of additive manufacturing

There are many ways to manufacture materials. A simple way to illustrate this has been to categorize these processes into five groups. These manufacturing categories are:

- forming,
- separating,
- joining,
- subtracting and
- adding (additive)

The first four (Ihalainen, E. et al (2003)) can be described as “traditional manufacturing processes” as their origins are deeply rooted in the history of mankind. The last one – additive manufacturing – is very new compared to these, as it is not even mentioned in this book.

Forming manufacturing processes include what potter is doing with clay and metal casting or producing plastic parts with injection molding machine. Separating means moving a piece by cutting (mechanically or by other means). The most common method for joining is welding, that is widely used in industry to put separate pats together by melting. Subtractive manufacturing includes various traditional machining techniques like milling, lathe work, borring etc.

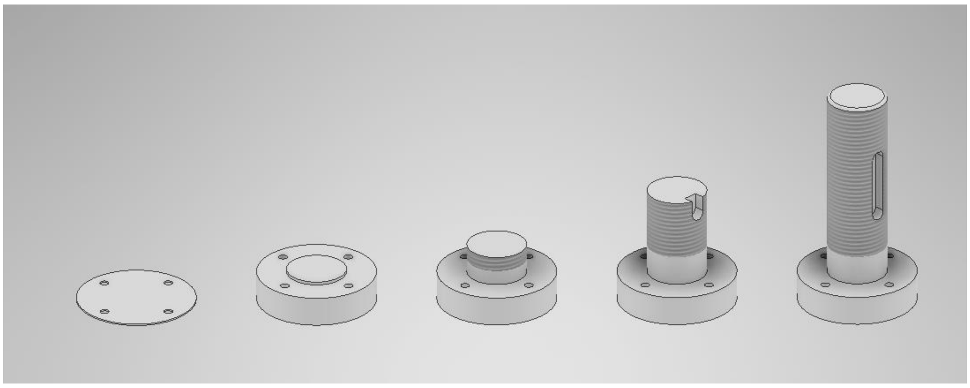
In the case that the material to be added is metal, additive manufacturing resembles welding. In welding the material is melted and then let it cool down to build up the final product. However, in additive manufacturing the material is added gradually, layer-by-layer, not by joining two parts together, to form a 3-dimensional part. In a way, the philosophy of additive manufacturing resembles also subtractive manufacturing, but contradictory to it. In the former a bulk of material is chosen and then material is removed (little by little, not like in cutting) to obtain the desired product. In additive manufacturing thin layers of material are placed onto previous layers in a process that melts the desired parts to form the final product. The term 3D printing is a synonym for additive manufacturing but nowadays 3D printing is more associated with lower price and/or capacity ("home-use" or "commercial"), whereas additive manufacturing is becoming to be the term to be used for industrial manufacturing processes. In subtracting manufacturing material is removed from a bigger piece in order to produce the final part. This is also considered the "conventional "way of manufacturing. The principle of subtracting manufacturing is illustrated figure 3.

A B C D E

Figure 3. The principle of subtractive manufacturing (drawn by Autodesk Inventor Professional).
(A) intact metal cone, (B) after turning, (C) borring four holes, (D) milling a slot, (E) threading.

In figure 3 there is a fictional (metal) part that could have been produced by subtractive manufacturing. The maximum diameter of the part would be 80 mm and the length would be 150 mm. The manufacturing process would have started by cutting a piece of a shaft, with a few millimetres extra. After turning, borring, milling, and threading the piece could look like that shown on the right in figure 3.

The part could be produced by additive manufacturing as well – at least in theory. Additive manufacturing has a different approach. The principle of additive manufacturing is illustrated figure 4.



A B C D E

Figure 4. The principle of additive manufacturing (drawn by Autodesk Inventor Professional). (A) starting with a circle with four holes, (B) increasing height, starting with the smaller circle, (C) increasing height, starting with thread, (D) increasing height, starting with milling a slot, (E) finishing milling slot and thread.

If the piece (figure 3) were to be manufactured by additive manufacturing, the process could look like that shown in figure 4. However, in this case additive manufacturing would not be beneficial. It would be expensive (because of special machinery needed to be able to produce 3D-parts) and slow (even tens of hours, compared to a few seconds with subtractive manufacturing) and less accurate with final dimensions. So, why use additive manufacturing?

The answer lies in the complexity of manufactured parts. If there is little complexity, subtractive manufacturing will in most cases be a better choice. In figure 5a and figure 5b there is a lot more complexity in the final part than in the previous example.

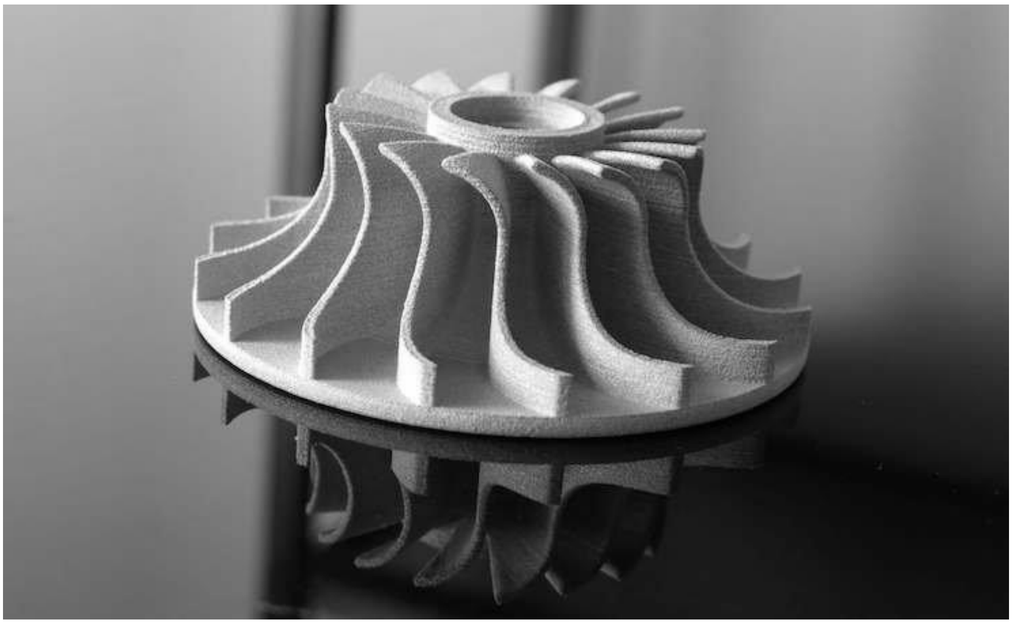


Figure 5a. Difficult to produce by subtractive manufacturing (TCT Magazine).

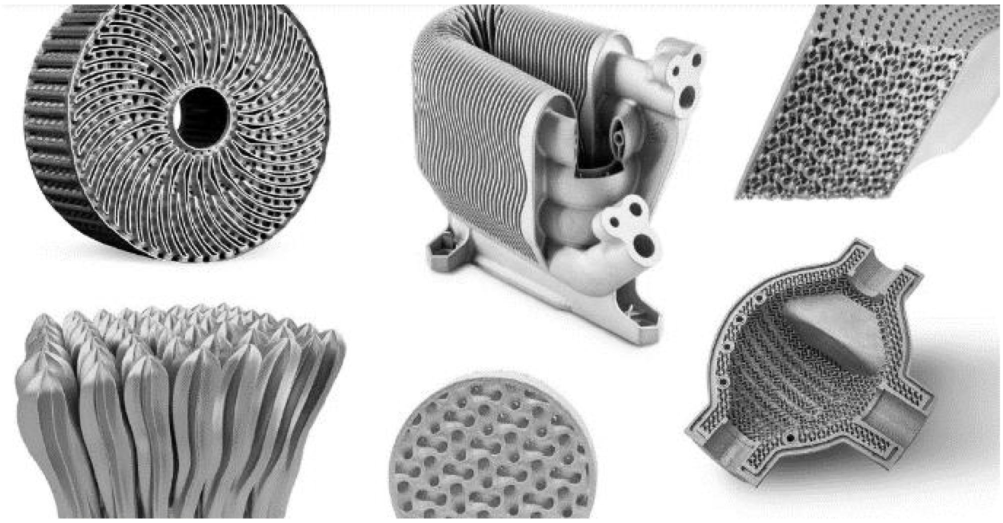


Figure 5b. Parts impossible to produce by subtractive manufacturing (All 3DP).

The reason for exploiting this emerging technology is that it has some clear advantages over traditional manufacturing. Some shapes or features that improve the performance of the manufactured part by adding more functions to it are very difficult (figure 5a; curved shapes) or even impossible (figure 5b; very complicated structures with a large surface/volume -ratio) to obtain by removing material. This is where the use of additive manufacturing is superior to other techniques, as the production of complicated structures would be cheaper, fewer parts would be needed, and in some cases AM is the only technology applicable.

Complex geometries, which can be used to improve functions of the final product, that would otherwise be costly, time-consuming or impossible to manufacture, can by produced by additive manufacturing without any additional costs. Also design freedom followed by the opportunity to optimize geometry makes additive manufacturing superior compared to traditional manufacturing technologies. Also, the size of the series has little or no effect on the costs of manufactured parts. The advantages being obvious, there are limitations when using this technology as well. Besides the already mentioned low speed and high costs of the production, there are other concerns about surface roughness, dimensional accuracy and maximum size of parts produced (Gao et al.(2015)). Support structures for the product and post processing treatments may be needed as well in some cases.

A simplified comparison between the cost of production in traditional and additive manufacturing can be seen in figure 6 (Becker 2016, p. 16; adapted from Dolenc (1993) and Hopkinson & Dickens (2001)).

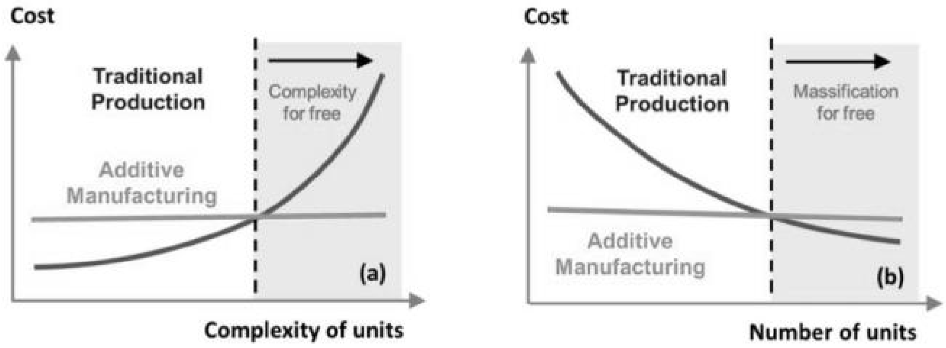


Figure 6. Comparison between the cost of production in traditional production and additive manufacturing, as a function of a) complexity of units and as a b) number of units in production (Becker 2016, p. 16; adapted from Dolenc (1993) and Hopkinson & Dickens (2001)).

As can be seen in figure 6, production costs tend to increase by complexity of units in traditional manufacturing (a) and decrease by number of units (b). In additive manufacturing the costs they remain close to constant in both cases.

2.2 Laser-based powder bed fusion of metals

Laser-based powder bed fusion of metals (PBF-LB/M) is a complicated process with a multitude of variables. Metal powder fusion is carried out in a closed chamber containing inert gas in order to avoid oxidation of the product being manufactured. Oxidation during laser processing is one of the key concerns in AM, as an increased amount of oxygen in the powder can alter the melt pool dynamics, powder layer wettability, laser beam absorptivity and initiate oxide formation on the surface of the particles (Fedina et al. (2021)). In electron beam powder bed fusion oxidation of the product is avoided by using high vacuum build chamber (Gibson, 2021).

The basic procedure of PBF-LB/M is as follows:
1) a thin layer of metal powder is spreaded on building platform
2) the locations that are part of the product in this layer are melted by a laser beam
3) the building platform, powder bed and part billet is moved downwards, the dispenser platform upwards
4) the cycle illustrated above is repeated by spreading a new powder layer on top of the previous layer etc.
5) the final product is removed and possible post-processing (heat treatment, machining…) follows

A schematic of the operating principle of PBF-LB are presented in a 2-dimensional form in figure 7 and in a 3-dimensional form in figure 8.

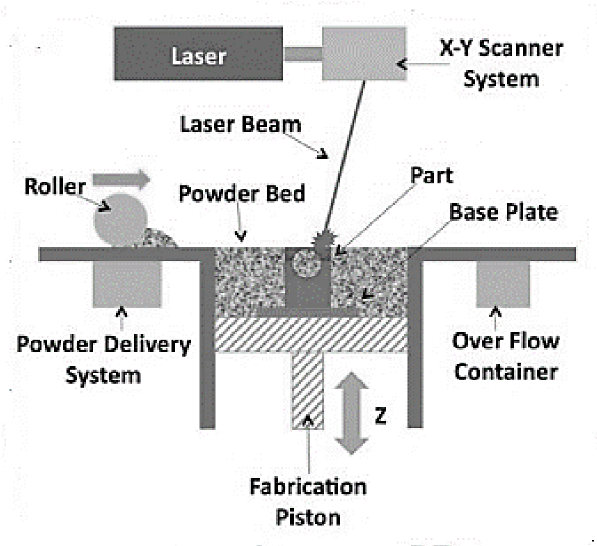


Figure 7. Operating principle of laser-based powder bed fusion; 2-dimensional presentation (Thompson et al. (2015)).

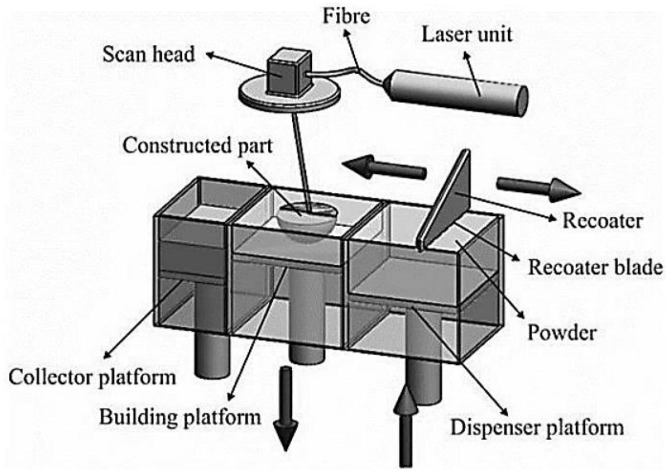


Figure 8. Operating principle of laser-based powder bed fusion; 3-dimensional presentation (Mercelis & Kruth (2006)).

As can be seen in figures 7 and 8 there are four types of movements within the system. Building platform moves downwards (Z) as the material on it accumulates, platforms (or containers) at the side move upwards (Z). Recoater or roller moves horizontally back and forth spreading the powder on the building platform and the moves of the scanning system take place in two dimensions (X and Y) (Gibson et al. (2016)).

Besides powder bed fusion, a short reviews of different technologies within AM can be found in Appendix 1.

3 Standards and the idea of standardization

Although the process of establishing a new standard is hierarchical, it is also very democratic. Standards are created in a coordinated fashion by different stakeholders so that uniform terminology could be used. Anyone may suggest a new standard, become involved in the process of joining a standardization group or commenting on a draft for a standard or make suggestions for improvements. This includes those as well that may benefit of a standard suited for their purposes. So, the initiatives of standards are rather from down to top, not on the contrary.

3.1 Benefits of standardization

A standard is a technical document designed to be used as a rule, guideline or definition. It is a consensus-built, repeatable way of doing something. Standards are created by bringing together all interested parties such as manufacturers, consumers and regulators of a particular material, product, process or service. All parties benefit by standardization through increased product safety and quality as well as lower transaction costs and prices. (https://cencenelec.eu/europea-standardization/europea-standards)

Standardization means creating agreed ways of doing things. The purpose of standardization is to simplify the work of authorities, facilitate trade, and make consumers' everyday lives easier. Standardization increases product compatibility and safety, protects the consumer and the environment, and facilitates domestic and international trade. A product manufactured according to standards is accepted in the international markets. Using standards removes barriers to trade. (Finnish Standards Association, SFS ry.)

Living in a world where many thing are standardized, it could be difficult to imagine how different life would be without proper standards. The advantages of standardization is illustrated in the following examples. Take, for example, a bolt with the designation “M10”. That denotes a (nominal) diameter of 10 mm threaded bolt. It fits perfectly into M10 treaded nut, since both parts are standardized using tolerances defined in ISO 68-1:1998. The profiles of threads are extremely accurately defined; the outer diameter of M10 bolt thread must fit between 9.97 – 9.73 mm, the inner diameter between 8.13 – 7.89 mm. The same accuracy (together with the precisely defined geometry) is applied for an M10 nut as well (ISO 68-1:1998, ISO general purpose screw threads — Basic profile — Part 1: Metric screw threads).

However, this has not always been the case. For example, in weapon industry there were separate callipers for each type of weapons – without scales for millimetres or inches. This kind of policy worked well within one factory, but exact copies of callipers had to be applied when a new production line were to be set up in a different location. Great Exhibition of the Works of Industry of all Nations was held in London year 1851. According to Karjalainen (lecture material, publishing year unknown) this was the first time a set of machine-manufactured parts were introduced to audience. A weapon smith disassembled ten rifles, put them into a box, and assembled them again from random parts. The weapons turned out to be wholly functional after a procedure like this. People were told to have been astonished to see what happened. (Karjalainen, E. (n.d.).) Today we might be astonished for their reaction.

Another example for the necessity of standardization: The famous Swedish sail ship named Wasa (today world's best preserved 17th century ship and the most visited museum in Scandinavia) sank after sailing roughly 1300 meters in its maiden voyage year 1628. Later it turned out that – together with the fact that the centre of gravity being very high relative to the centre of buoyancy – during construction part of the rulers used by workmen who built the ship were calibrated in Swedish feet (12 inches or 29.69 cm) and part in Amsterdam feet (11 inches or 28.31 cm). That caused the ship to be heavier on the port side and more prone to heel on the other side, thus pushing the lower gunports under the surface with tragic consequences. (Chatterjee, R. & Mullins L. (2012).)

These examples may cause us to feel supremacy over people in the early days of industrialization, but after all, we are all products of our culture. Despite the huge progress in standardization there is still work to be done. Globalization posed challenges to us that were not present as much when the manufacturing processes were mainly carried out locally. (Karjalainen, E.) Without standardization even additive manufacturing could fail to make a breakthrough in the field of new technologies.

3.2 Organizing standardization work

Most standards approved in Finland are of international origin, but a nationally developed standard may eventually become an international standard if there is a need for it in European or global market. It is also possible to complement an international standard by a nationally developed standard, but some national standards are exclusively for domestic use only . The standardization work in Finland is controlled by SFS (Finnish Standards Association; the national standardization organization in Finland). It coordinates all national standardization work in Finland, excluding electrotechnical and telecommunications standardization, which are coordinated by SESKO (abbreviation for “Suomen Elektrotekninen StandardisoimisKOmitea”) and Traficom, respectively.

CEN, the European Committee for Standardization (“Comité Européen de Normalisation” in French) brings together the national standardization organizations of all EU and EFTA countries. The same European standards are valid in all CEN member states, which are obliged to nationally approve European standards and to withdraw any conflicting standards. Standards approved by CEN have the designation “EN”.

Global standardization includes national standardization organizations from over 160 countries. However, national adoption of ISO standards in Finland is not mandatory unlike CEN standards. In Europe, CEN approves some of the ISO standards as EN standards, in which case they must be implemented by all CEN member countries as an ISO standard. In Finland they thus become SFS-EN-ISO standards.

One national standardization organization deserves special mention here: American National Standards Institute (“ANSI”). It is just an ordinary member of ISO — just like SFS. However, because the size of ANSI, its influence is more comparable to CEN than to a national standardization organization. The contribution of ANSI standards will be later evident in this thesis work.

3.3 Standards in additive manufacturing

Additive manufacturing is a novel technology. The amount of standards in additive manufacturing is increasing every year, but it is still far from for example the number of standards needed to define around 70000 commercially available types of steel (https://metsta.fi/wp-content/uploads/2020/05/Terasstandardit_2019.pdf). Standards in additive manufacturing are mainly being prepared in various working committees of ISO in conjunction with ASTM (American Society for Testing and Materials). CEN working committees have recently started to work with additive manufacturing standards as well.

At the moment the standardization work by SFS is concentrated on qualifications of the personnel working with additive manufacturing and on the safety of preservation of powder-like raw materials in additive manufacturing (https://sfs.fi/osallistu-ja-vaikuta/aihealueet/kone-ja-tuotantotekniikka-metallit). These are not very interesting on the point of view of the properties of final products in additive manufacturing. The organization responsible for establishing European standards (CEN) does not seem to have new standards of special interest either. At least they are not ready to be applied so that the technical properties of final products could be proven unambiguously to potential customers. Therefore, the topic of this thesis could be justified as new information is expected to be gained.

4 Powder reuse in additive manufacturing

Powder recycling is a standard procedure in LBF-LB/M. A more accurate term for powder recycling could be **powder reuse** (not to get confused with recycling in general). Yet powder reuse seems not to be standardized well enough. A widely used database named Scopus will give new insights into to subject. With the search word “powder bed fusion” a total of 27 368 results between years 2015-2023 were found. By search words “powder bed fusion” AND “laser” AND “metal” a total number of 23 935 publications were found. When two more words, namely “standard” and “powder reuse”, were added, the number of publications drops to 304. So, of the total number of articles related to LBF-LB/M about 1 % deals (only 0.5 % in year 2023) with standards and powder reuse (figure 9).

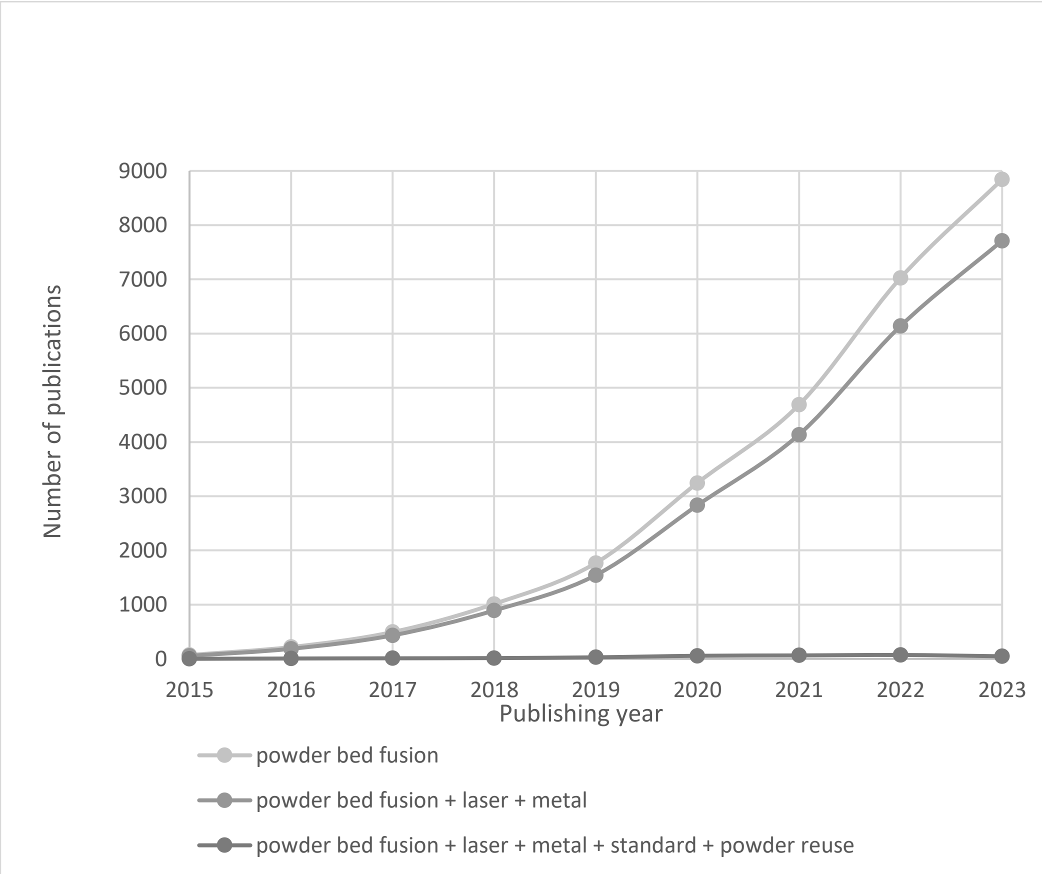


Figure 9. The number of publications according to Scopus with different combination of search words.

As figure 9 implies, powder reusing procedures still needs further exploration. It is assumed that there is a lot of variety among the manufacturers in procedures related to reusing metal powder – and it turned up to be true according to this work. Based on the findings with the questionnaire and interviews there is a lot of work in the field of standardization to be done.

In traditional manufacturing the material removed is not to be used again in the same process, but only after sorting out, melting and refabricating to be usable. However, unused material can be gathered in PBF-LB for later use to save expenses. The quality of the powder already used (unmelted powder) during the process is not exactly the same as with new unused powder but can be reused as far as the properties of the new product are within a desired range.

Reusing powder in AM (as soon as possible) is a normal procedure to make the process more feasible primarily on an economical and practical viewpoint – not to underestimate ecological reasons. The powder is at least moderately expensive and if not reusing the powder would also increase logistic challenges in the form of more powder needed and more waste produced. Choosing the best feedstock for powder materials with the right parameters is not enough to optimize the performance of AM production. The handling of powder material needs some attention as well. According to Carreño-Morelli preprocession steps like sieving, blending, and drying may be necessary for preparing metal AM feedstock; these steps must be carefully controlled for consistent quality assurance (Carreño-Morelli et al (2020)).

Spattering is a common issue in PBF-LB/M and can affect the success and quality of the final part. Spattering occurs when tiny droplets of molten material is ejected from the melt pool during the process. Moreover, spattering can cause contamination of the powder bed, which can affect the quality of the final part (Khairallah et al (2020)). If the remaining powder is to be reused, it has to be sieved to make it as homogenous as possible. Spatter particles are usually of a larger size than the feedstock material. Several molten particles may also merge and form larger droplets or a powder agglomerate that can potentially lead to defects like lack of fusion (Fedina et al (2021)). Most of the unwanted particles can be excluded from the used powder by using a sieve of an appropriate size. Sieving the larger particles away from the used powder would make it applicable for another round in the process. Some other treatments for the powder may also follow before it is to be reused.

4.1 Powder sieving

The morphology of the powder particles used in additive manufacturing play crucial roles in the performance of the process and in the quality of the final part. Ejected material and agglomerated particles are to be excluded from the powder by a sieving procedure. Non-sphericity, internal porosity and incorrect alloying can in turn produce defects in the end part including pores, cracks, residual stresses, and undesired roughness. Particle size and particle distribution of the AM powder are among the most influential factors. Smooth, spherical particles can flow more easily and therefore produce higher apparent densities, which is an advantage in powder bed fusion. (Whiting et al. (2022).)

A common way to make sure that powder particles are of roughly homogenous size is by sieve analysis using sieves of predefined mesh sizes. During sieve analysis, powder is passed through a series of sieves, each with progressively smaller mesh sizes, while the stack is vibrated (manually or by using some kind of device suitable for that). The particles that pass one sieve and fail to pass the next smaller sieve are considered to have particle sizes between the two sieve sizes. (Whiting et al. (2022).) Sieving is of specific importance when the powder remaining intact after producing a final part is to be reused. Sieve analysis is a standard test method (ISO 3310-1:2016; ASTM B214–16).

Commissioning of the powder is dependent on the instructions given by the AM machine or the powder provider. Powder handling may also contain different practices if the powder is to be reused later. These practices may concern powder drying or storage. Powder storage may require different conditions that normal room temperature with normal atmosphere (like keeping powder in an inert gas to prevent undesirable chemical changes – like oxidation – in the powder composition).

4.2 The effects of reuse

Studies have been conducted to test the effects of recycling the unused powder and they all have concluded that the sieved powder can be reused multiple times without a significant effect to the quality of the parts manufactured. This applies both to laser-based systems (Ardila et al. (2014), p. 99–107; Moghimian et al. (2021)) and electron beam-based systems (Tang et al. (2015), p. 555–563; Nandwana et al. (2016), p. 754–762). Currently, there are two concerns associated with powder reuse: (1) alterations in chemical and physical properties of the powder due to multiple interactions with the laser beam and machine environment and (2) minor defects in the final part caused by powder handling and sieving or exposure to the environment outside the AM system (Heiden et al. (2019)). A schematic drawing of the reuse of powder is presented in figure 10 (Fedina et al. (2021)).

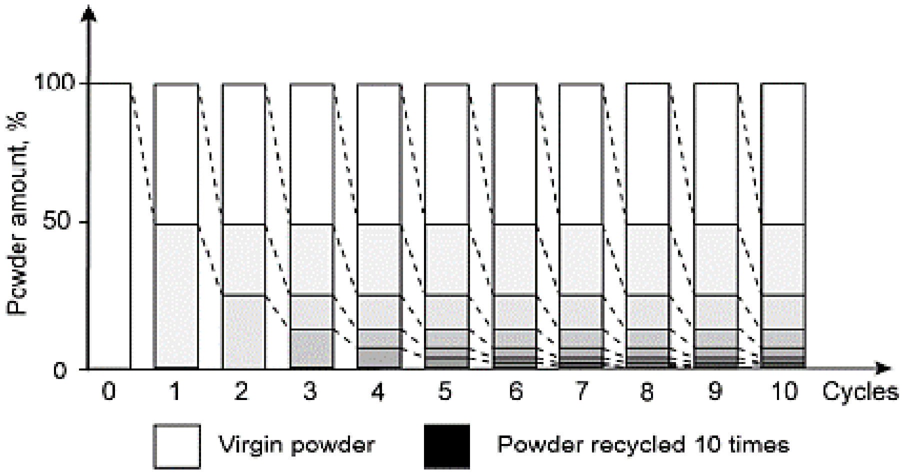


Figure 10. A schematic of the recycling strategy, demonstrating the addition of 50 % new powder (virgin powder) after each cycle. The powder amount per cycle is assumed to be constant (no losses accounted). The grayscale indicates continuous change of the powder state from virgin (white) to recycled 10 times (black). (Fedina et al. 2021.)

As figure 10 shows, powder composition changes in every cycle. Part of the used (recycled in this picture) powder may have gone through different number of cycles. Using new powder every time would actually make the products more homogenous, but the reason for not doing that is quite simple. For example, if tensile strength of an AM product is within allowed limits by reusing powder, it is useless to keep using new powder only. Using new powder could decrease variation, but not quality. One definition of quality is to meet customer expectations whilst remaining economically competitive (Oliver, R. L. et al. (1994)). In this case the customer expectations are met, but it is unsure if they are met with a double material cost with less variation. Although material costs comprise only a fraction of the costs of a finished part, the handling of used powder would cause a challenge for storage since the powder also has harmful effects on individuals and environment (Dugheri et al. (2022)).

Even if the expected quality would have been achieved, reusing powder can have some effects on the quality of an AM product. The effects of laser exposure together with the mechanisms of aging do have effects on the chemical and morphological characteristics of the powder. Some effects are indirectly related to physical properties of AM products (like the increase in oxygen content resulting more porosity, increase in grain size and decreasing in density), but also tensile strength may be affected (Fedina et al. (2021)). Besides reusing of powder, somewhat similar effects can be seen by aging of the powder (Fedina et al. (2022))
– a phenomenon that may make the quality of the powder questionable as well.

The reuse of powder is generally understood as reusing of powder that remained intact after the production of an AM part, but also the usability of AM waste streams to generate powder has been studied. In a master's thesis by Reijonen (2016) new metal feedstock was attempted to be produced from AM waste products, like sieve residues, support structures and defected parts. Mechanical milling (together with plasma spheroidization of agglomerated residual powder) or gas atomization was used to produce new feedstock. The results showed only small differences between tensile properties of feedstocks made from waste streams and commercial powders. However, waste streams comprise only an insignificant fraction of the total need for AM material. So, it is very unlikely that new feedstocks would be produced from waste products in the future in a larger scale, but the thesis by Reijonen (2016) gave more reason to continue the practice of reusing metal powder in powder bed fusion.

While reusing powder seems to have only minor effects on the quality of AM products, it does not mean that there is no need of standardization of these procedures. There are still questions to be answered related to powder reuse. Reused powder is more than just the source of the qualities of the production material. Proper answers to these questions could decrease variation between final parts – and make it possible to raise the level of quality in Finnish AM products in general.

4.3 Standards and the reuse of powder in additive manufacturing

Despite partial lack in standards of AM there is also new information available. There is a big project going on to define the gaps related to standards in additive manufacturing. In March, 2016, America Makes and the American National Standards Institute (ANSI) launched the America Makes & ANSI Additive Manufacturing Standardization Collaborative (AMSC). The AMSC was established to coordinate and accelerate the development of industry-wide additive manufacturing standards and specifications consistent with stakeholder needs and thereby facilitate the growth of the AM industry. In a working draft (year 2023) more than 1000 established standards were mentioned and a total of 134 gaps (partly or totally missing standards year 2023) in additive manufacturing; in this case consisting of the whole technology in AM, not just PBF-LB/M.

Of these finished standards six pieces seem to be of special interest related to this thesis. Unfortunately, it is not possible to make long citations from standards that are not freely available. Nevertheless, in this thesis it should be adequate to give short mentions concerning even commercially available standards.

ASME Y14.5-2018, Dimensioning and Tolerancing

A revised standard for geometric dimensioning and tolerancing by American Society of Mechanical Engineering is a document of over 300 pages. Although not dealing with the reuse of metal powder, its fundamentals can be applied to AM design on a general level as well. So, having this standard is recommended. Use of this large standard could prevent derailment of whole branch of emerging technology of additive manufacturing, since new inventions are always ahead of standardization of those inventions.

ASTM F3456-22, Standard Guide for Powder Reuse Schema in Powder Bed Fusion Processes for Medical Applications for Additive Manufacturing Feedstock Materials

This standard (2021) defines key features within powder reuse schemes. Besides defining some terms within the topic, it presents seven different schemes in flow chart concerning powder reuse. These schemes include:

(1) No Reuse
(2) Discrete Reuse
(3) Continuous Reuse
(4) In-process Powder Reuse
(5) Continuous Refreshing with Virgin Powder
(6) Use of blended Virgin/Used Powder and
(7) Continuous Reuse While Replenishing with Virgin Powder.

SAE AMS7031, Batch Processing Requirements for the Reuse of Unused Powder in Additive Manufacturing of Aerospace Parts

This standard with the illustrated reuse schemes resembles quite a lot the standard mentioned previously. However, it also contains lists that should be taken into account in powder reuse processes. In the appendices of this standard there is valuable information concerning the key process variables required for powder reuse and calibration and verification requirements. These variables and requirements deal with powder recovery, reconditioning, blending and desorption.

SAE ARP7044 - Powder History Scoring Metric and Labeling Schema

Besides representing the labeling scheme for characterizing the history of powder feedstocks, it also has mathematical formulae for calculating the powder needed to be able to run the designated number of build cycles. In these calculations powder remaining in hopper, processes with AM machine and losses caused by separating oversized particles during reconditioning activities were included.

ISO/ASTM 52900:2021, Additive Manufacturing - General Principles – Terminology (incl. used powder)

This standard was the only one that was freely available without a paywall (on average a standard costs around 100 – 200 $). This standard concentrates on updated terms used in additive manufacturing (ISO/ASTM 52900:2015). For example, the abbreviation for laser-based powder bed fusion has been changed from "L-PBF" to "PBF-LB". If the basic type of material is to be mentioned, it is followed by a slash and an abbreviation (M for metal, P for polymer, C for ceramic and Cp for composites). Therefore, in a process where AlSi10Mg powder (aluminium alloyed silicon of mass fraction up to 10 %, small quantities of magnesium and iron, along with other minor elements) is to be used, the abbreviation would be "PBF-LB/M/AlSi10Mg" ("M" can be omitted, since using a metal alloy already tells that the material is metal).

ASME B46.1-2019, Surface Texture (Surface Texture, Waviness, and Lay)

This standard might help in defining the surface texture of an AM product. Most products processed by additive manufacturing create surface textures that may require post-build steps, like polishing. The standard contains additional information beyond definitions, such as measurement methods, instrument classification, etc.

5 Experimental part

The experimental part of this thesis is relatively compact, consisting of a single questionnaire, followed by some deeper interviews. The results were intended to be analyzed qualitatively, as the data would not be large enough for a more statistical approach. The interest of the work was on metal powder handling and reuse procedures. Although the topic was about concrete PBF-LB/M technology, no laboratory work was included in this work.

5.1 Aim and purpose of the experimental part

The aim of the experiment was to gain information about the metal powder reuse procedures of Finnish AM companies using PBF-LB/M technology. The purpose was to pay more attention to AM procedures and - ultimately - to raise quality of the AM technology. A rough estimation was that there would be wide variance among different manufacturers. To test this hypothesis manufacturers were to be asked directly about the powder reuse.

Experimental part was divided in two:

1. *Questionnaire* (a set of eight questions sent to Finnish AM manufacturers)
2. *Interviews* (another set of eight questions sent to those who got the questionnaire; those willing to participate were interviewed to gain deeper insight)

Outcome of this experimental part is to gain information on real practices on powder reuse practices, as it has not been studied before. The results have only little scientific relevance, but the impact on Finnish AM industry can be remarkable. Now it is shown that the need for standardization in powder handling and reuse procedures is real, and that something should be done on the situation.

5.2 Experimental set-up and procedure

Questionnaire

The central interest in this questionnaire (Question 4) concerns the previously mentioned standard ASTM F3456-22. Other questions that seemed to be the most relevant ones in metal powder handling and reusing procedures were created. The final number of questions was limited to eight. This was done partly to raise the expected number of answers, partly to ensure that the answers would be thoroughly evaluated. The questionnaire was written in Finnish – this could possibly make answering the questions a little easier (and neglecting the whole thing more difficult). The receivers of the questionnaire were also asked if they could take part in a deeper interview (about 45 min). The aim of these interviews was to get more information about the powder reuse and handling practices, as there could be viewpoints that have not been dealt with in the questionnaire.

With the aid of networks of the second supervisor of this work the questionnaire was sent to Finnish AM companies and research institutions. The questionnaire with some introducing words is presented in Appendix 2 (in Finnish). Nevertheless, here the questions and answers were translated into English. Long answers may be shortened to save space. No important information is missing, however. The questions (table 1) were as follows:

Question 1. What material(s) your company is using in laser bed fusion?

Question 2. If the material used is metal, what is the (main) composition of the material?

Question 3. If the powder is to be reused, what is the percentage of the new powder (%)?

Question 4. Based on the standard ASTM 3456-22 different schemes of powder reuse are presented in the following pictures (names of different reuse schemes in chapter 4.3). Which of these are in use in your company?

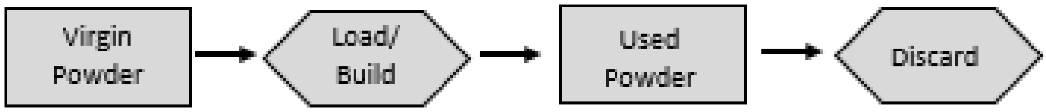


Figure 1. No Reuse

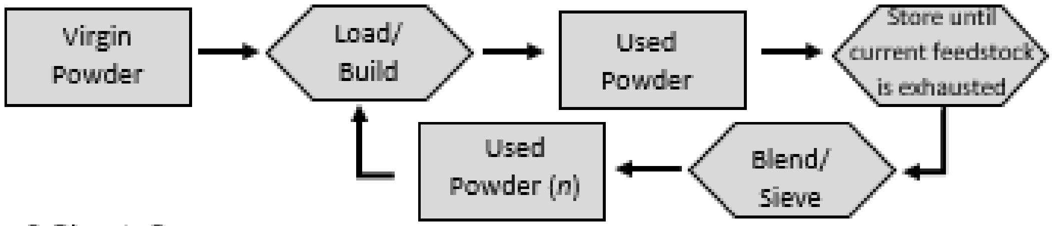


Figure 2. Discrete Reuse

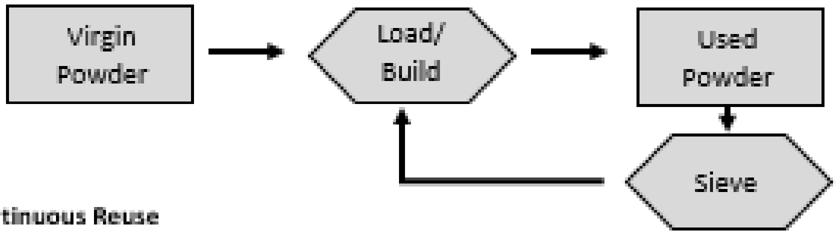


Figure 3. Continuous Reuse

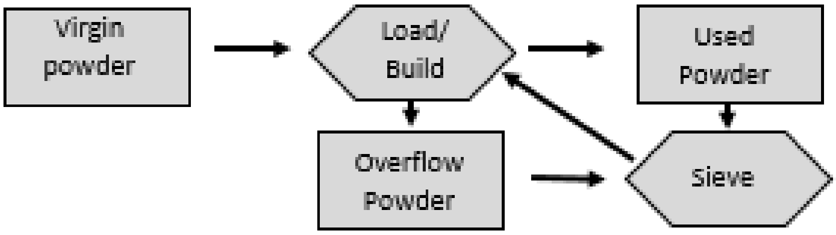


Figure 4. In-process Powder Reuse

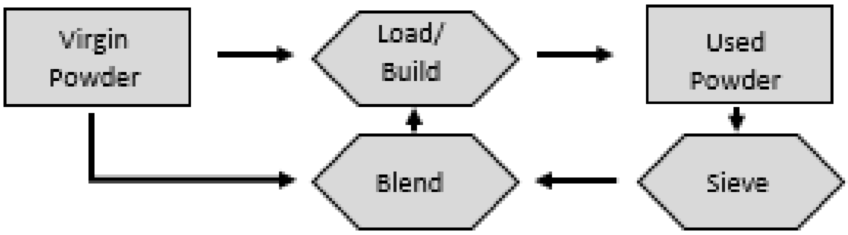


Figure 5. Continuous Refreshing with Virgin Powder

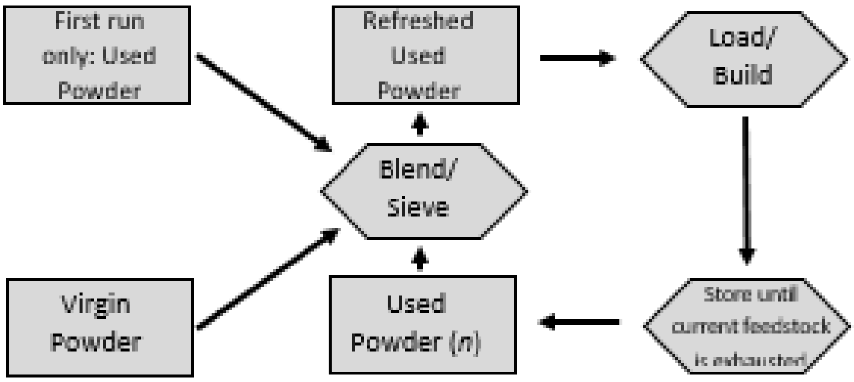


Figure 6. Use of blended Virgin/Used powder

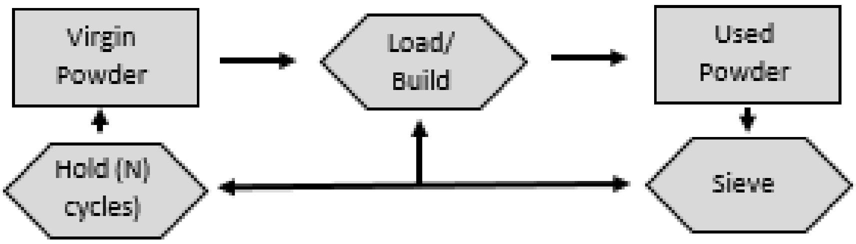


Figure 7. Continuous Reuse While Replenishing with Virgin Powder

Question 5. If none of these schemes describe the powder reuse in your company, could you tell more about your reuse procedures?

Question 6. How long is the powder to be used? For example, to the end of a batch, mixing with new powder?

Question 7. If the powder is to be reused, what is the mesh size of the sieve?

Question 8. Are there any differences in the powder reusing procedures between parts that are manufactured requiring special attention and with "normal" parts?

The first question was about the material used in PBF-LB/M. If it were metal, further questions would follow. The second question was about the type(s) of metal/metal alloys mostly used and the third question about the percentage of new powder in the final product. The fourth question was the most important one in the questionnaire. The pictures in the standard were redrawn and translated into Finnish. The manufacturers were asked which scheme would best describe their practices in powder reuse. The fifth was an open question: if none of the schemes would describe their procedures, the receivers could tell by own words about how they operate.

The sixth question was about how long a time a powder batch will be used, for example until the end of a batch by adding new powder. The seventh question was about the mesh size of the sieve and the eight – and last – question about possible differences in routines of operation. It was asked whether there are any differences in practices between parts that require special consideration when manufactured and parts that could be described as "ordinary".

Company interviews

After answering the questionnaire the companies were asked if they would like to take part in a deeper (~45 min) interview. Another set of questions was created, based on the consideration of what important questions remain unanswered after the questionnaire.

Interview question 1. How would you describe the routines related to starting the production with a new batch of powder?

Interview question 2. How would you describe the routines related to starting the production with a reused batch of powder?

Interview question 3. What data will be stored using a) new batch or b) reused batch?

Interview question 4. How much powder is lost in sieving processes (estimation in percentage)? Is there any variations between different powder materials?

Interview question 5. Is the quality of the powder controlled by other means than just by sieving analysis?

Interview question 6. How is the powder stored? Are the storage conditions (temperature/moisture) controlled?

Interview question 7. Are the routines of powder handling or printing certified? If yes, then how are they certified?

Interview question 8. Do you provide the customers information about the powder handling procedures? If yes, then how do you provide it (automatically or when asked for)?

6 Results and discussion

Questionnaire

The answers to the set of questions listed in the first part of chapter 5.2 (***Questionnaire***) are presented in table 1.

Table 1. Questionnaire answers (seven Finnish AM manufacturers).

AM manufacturer / Question number	A	B	C	D	E	F	G
1	metal	metal	metal	metal	metal	metal	metal
2	all	most of the metals	stainless steel	titanium	stainless steel	aluminium	all + copper (excl. carbon steel)
3	10-50 %	new powder not always needed	variable			not known	
4	**scheme 2: discreet reuse (mostly)**	**scheme 5: refreshing with virgin powder**	**scheme 5: continuous refreshing with virgin powder**	**scheme 3: continuous reuse**	**scheme 2: discreet reuse**	**scheme 2: discreet reuse**	**scheme 3: continuous reuse**
5			lasering/sieving monitored, new powder may be added, the batch is named after the highest amount of sieving				
6	depending on the requirements set by customers or project (reusing as a default)	until the end of the batch, adding new powder (the proportions of reused powder will be monitored)	until the end of the batch, adding new powder from the same batch (the remaining powder will be stored)	until the end of the batch	until the end of the batch, adding new powder	until the end of the batch, adding new powder	until the end of the batch, adding new powder
7	63 and 90 µm most common	63 and 90 µm (AlSi10Mg) most common	63 µm		sieve provided by the manufacturer	100 µm	depends on the material
8	depending on the requirements set by customers or project (reusing as a default)	in rare cases no reuse may be applied	no differences	no differences	not manufacturing parts with special requirements	if needed	if needed (the amount of reuse will be monitored, quality will be analysed, no mixing of batches)

As can be seen in table 1 there is a lot of variation in powder reuse practices among Finnish AM manufacturers. All were using metals in powder bed fusion but apart from that standardization seems to be something that has not gained enough attention. Three different powder reusing schemes were in applied, at least three different sieves mesh sizes were in use, and the manufacturers were not aware of the exact amount of new powder that was added in the process (only one could give a rough estimate). When reuse is applied the size of the sieve depends on the material.

The most interesting results, however, were the answers given for question number 4. Three manufacturers had discreet reuse (scheme 2; one of them “mostly”), two had continuous reuse (scheme 3) and two continuous refreshing with virgin powder (scheme 5). Besides these answers, at Machine Technology Center Turku (a non-commercial AM manufacturer) there are two machines that apply discreet use (scheme 2), one for aluminium and one for cobalt-chrome. Furthermore, there is one machine for various metals where no reuse (scheme 1) is applied as well, in addition to discreet use. This can be partly explained by the nature of its use: for research purposes it is generally better to have products of highest possible quality.

Company interviews

Interviews were carried out after the questionnaire. First, only two manufacturing companies or research institutions were interested in taking part in a deeper interview, and further one after contacted later on. The questions were asked in Finnish, and the answers of the three AM manufacturers are summarized below. The answers to the set of questions listed in the latter part of chapter 5.2 (***Company interviews***) are listed here with the questions.

Interview question 1. How would you describe the routines related to starting the production with a new batch of powder?

- new batch opened inside the machine (equipped with an air lock), powder fed to the hopper reserved for new powder
- new powder (10 kg) fed to the machine
- every chemical used will be registered (incl. metal powders), new batch always dried in vacuum chamber before fed to the machine (equipped with an air lock)

Interview question 2. How would you describe the routines related to starting the production with a reused batch of powder?

- reused batch opened inside the machine as well, but reused powder fed to the hopper reserved for reused powder (sieving takes place inside the machine by an automated fashion)
- reused powder stored in a bigger container, reloaded to the machine by a conveyer
- no real differences between new and reused powder, except that for reused powder the number of using cycles will be followed

Interview question 3. What data will be stored using a) new batch or b) reused batch?

- date, amount of powder added, batch number, b) date, amount of powder remaining (roughly), amount of powder added, batch number, number of cycles
- a) powder documents scanned, batch registered into Enterprise Resource Planning (ERP), every job registered (with the input of the batch number) to the machine before production ("Quality Report") and every job registered to ERP, with the reduced amount of powder for the batch b) all mentioned above + the amount of cycles by an increasing batch number
- a) all available information related to the batch (date of arrival, amount, manufacturer, analysis certificates), depending on the project some further analysis may be followed b) all mentioned above + the amount of powder remaining and the amount of cycles by an increasing batch number

Interview question 4. How much powder is lost in sieving processes (estimation in percentage)? Is there any variations between different powder materials?

- less than 5 %, the amount not followed, probably no differences between materials
- 5-10 %, depends on the process (increased with higher laser power)
- 2-5 %, depends on used parameters, higher with tool steel (more spattering) and with aluminium (light material that is more difficult to sieve than heavier materials)

Interview question 5. Is the quality of the powder controlled by other means than just by sieving analysis?

- drawing tests of final products can be applied if the quality of the product is of specific importance (also occasionally once in 2-3 months)

- visual inspection (spreadability of the powder), occasionally temperature, quality controlled mostly when demanded of the customer, the powder is certified by the provider – so the quality of the powder is not questionable in general
- not routinely, but particle distribution tests, flowability analysis, electron microscopy (sphericality), chemical composition (especially oxygen content) and humidity may be applied

Interview question 6. How is the powder stored? Are the storage conditions (temperature/moisture) controlled?

- temperature/moisture not controlled, new powder container sealed until use, reused powder stored with silica gel, moisture control not considered critical in a closed-loop system
- temperature controlled, but not moisture, powder stored in the machine or in a closed container, silica gel used when needed
- temperature/moisture not controlled, stored in containers reserved for storage of chemicals

Interview question 7. Are the routines of powder handling or printing certified? If yes, then how are they certified?

- not certified, customers usually do not ask for certificates (majority of the production consists of the company's own products, AM is the only subcontracting business of the company)
- not certified, customers usually do not ask for certificates, some standards for the production applied generally
- not certified

Interview question 8. Do you provide the customers information about the powder handling procedures? If yes, then how do you provide it (automatically or when asked for)?

- usually not provided (only few customers understand enough about AM to be able to ask), in most cases the products of the company are tools, not critical (or moving) parts
- not very much, but the information is openly provided is asked for, with demanding jobs the customers may be better informed about powder handling procedures
- information given if asked for, depends on the project

These seven manufacturer's answers to the questionnaire together with three deeper interviews will not tell the whole truth about powder handling and reuse procedures in Finnish AM industry, but the variability of practices can be observed. Powder handling procedures and reuse in Finnish AM industry express a wide variety of practices. Besides things like different ways of monitoring the amount of new and reused powder and the sieves with different mesh sizes, the most remarkable observation was the diverse ways of reusing metal powder. At least four different reuse schemes are applied.

There are also machines that are able to do the powder handling by an automated fashion (closed loop). Nevertheless, as the machines with automated powder handling procedures are becoming more common, the need for standardization of powder reuse cannot be neglected by this emerging trend. Even in automated sieving procedures the sieves have a defined mesh size, and batch information should be applied somehow. There seem to be various practices on labeling and documentation of powder batches and AM products, but it also seems that documentation practices of different manufacturers are consistent when used in-house. So, traceability of batches should be good enough, but problems may arise when having to work in cooperation. Two new standards already mentioned in section 4.3 (SAE AMS7031, Batch Processing Requirements for the Reuse of Unused Powder in Additive Manufacturing of Aerospace Parts and SAE ARP7044 - Powder History Scoring Metric and Labeling Schema) might be of specific importance when creating best practices for powder reuse and labeling. Overall, the results show that there is a real need to standardize these procedures.

7 Further analysis

Standardization is delicate, well-organized process, but it is also like an endless swamp. Unlike with legislation, where new laws and statutes are openly released, free of charge, this is not the case with new standards. As the procedure of making new standards are at least partly financed by paying customers, it also means that all information is not freely available. New laws are launched following an information campaign needed to make the changes known to citizens, but standards have far less publicity. It may require quite a lot of work to find out whether there are standards available for a specific issue or not. Even in this thesis work new, valuable information on standards was found mainly by accident, not with a systematic research effort.

The long-time intention of the DREAMS project is to raise the levels of quality in Finnish AM industry. This shown in figure 11 (Business Finland (2019)).

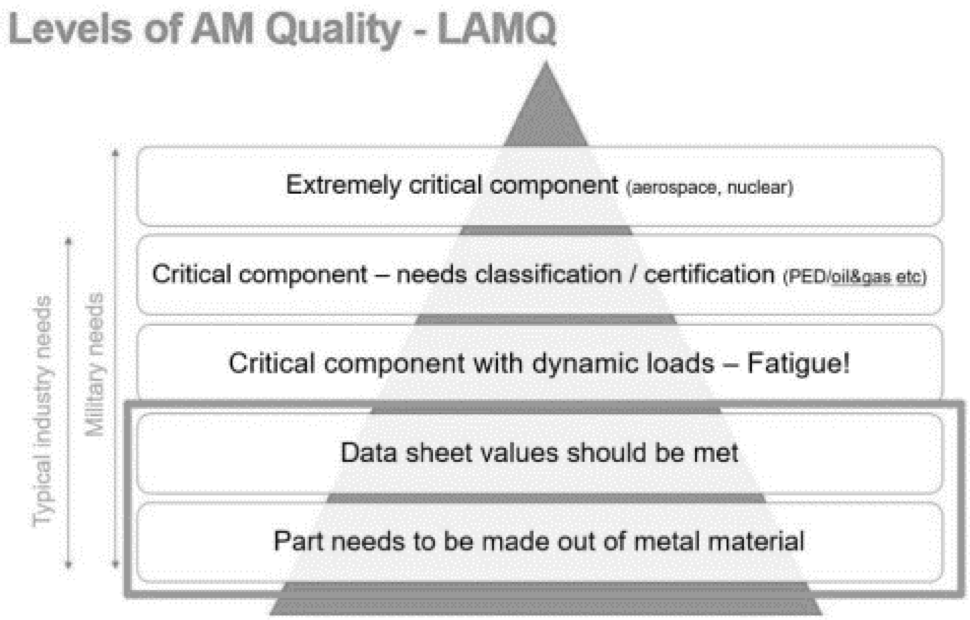


Figure 11. Quality pyramid with levels of quality (two lowest bars) in Finnish AM services (Business Finland (2019)).

As can be seen in figure 11, at the moment quality of AM products reaches only the two first levels. One objective of the DREAMS project is to create a comprehensive database with test specimens from partner companies. Unfortunately, within the time frame of this work, there was hardly any progress. The companies seemed to be busy with their primary duties, so that very little test specimens were obtained. Therefore, the focus of this work was directed to the reuse of powder in PBF.

Industrial partners with AM have their practices they are following in their production (this includes the procedures related to the reuse of metal powder as well). Whether they have some kind of standards or not, these practices must be accepted by their customers. It is possible that for customers it is enough that they get a certification for the AM product regardless of the contents of those certifications. It is also possible that companies do not direct their resources enough for more profound understanding and transparency of their processes. Deficiencies in standardization makes the whole question of quality improvement in AM industry more difficult to be solved, and it looks like most Finnish AM companies are not willing to share their practices even in an anonymous survey. As a part of the solution, it would be good to inform the DREAMS partners that there exists some non-ISO standards (and some are in development), in order to promote Finnish AM industry to take one step higher in the issue of quality. It could also be beneficial to inform that new standards are being published and to tell that following the progress of standardization within additive manufacturing is highly recommended.

Further studies might concern the exact ways of starting the use of a new batch of powder. Whether the quality of powder is secured by other means than by sieving or not could be one question to be asked. The storage conditions of the powder need more accurate analysis. It would be interesting to know whether there are differences between materials excluded from reusing by sieving. Also, the questions regarding the possible certification of powder management and/or printing procedures remain to be answered.

Besides standards already published, some standards in the previously mentioned large-scale American co-project were under the title “Standards in development”. In the following (purely subjective choice) standards that are both in development phase and that may have an importance in the future are listed below.

- ASTM WK65929, New Specifications for Additive Manufacturing-Finished Part Properties and Post Processing – Additively Manufactured Spaceflight Hardware by Laser Beam Powder Bed Fusion in Metals
- ASTM WK66030, New Guide for Quality Assessment of Metal Powder Feedstock Characterization Data for Additive Manufacturing

- ASTM WK66682, Guide for Evaluating Post-processing and Characterization Techniques for AM Part Surfaces
- ASTM WK75184, New Guide for Additive Manufacturing of Metals – Powder Bed Fusion – Guidelines for Feedstock Recycling and Sampling Strategies
- ASTM WK80171, New Guide for Additive Manufacturing of Metals – Feedstock Materials – Measurement and Classification of Feedstock Contamination
- ASTM WK82776 – Additive Manufacturing for Medical – PBF – Assessment of Residual Powder
- ASTM WK83979, New Guide for Corrosion Fatigue Evaluation of Absorbable Metals (formerly WK61103)
- ISO/ASTM DIS 52928, Additive Manufacturing of metals – Feedstock materials – Powder life cycle management

8 Conclusions

Additive manufacturing (AM) is a new technology that is continually growing. One of the most common technologies used in AM is Powder Bed Fusion (PBF). In PBF it is possible to reuse the metal powder that has not been incorporated into the final part during the process, thus reducing costs and making the production method economically more feasible. Mixing the unused powder with new one is a general practise with this technology, but the exact procedures among industrial operators are not very well known. The lack of standards has resulted in slow adoption of AM technology, and this applies to the reuse of powder as well. There is a big American co-project going on since 2016. Its aim is to fill the gaps in standardization of additive manufacturing. One of the standards (published in 2021) is of special interest in regard to this work, as it defines the different practices of powder reuse. Although not an ISO standard, it turned out to be useful in studying PBF powder reuse in domestic companies. In this thesis Finnish AM companies were asked about their metal powder reuse based on a recently published standard dealing with the powder handling and reusing procedures. A questionnaire was sent to a selection companies known to use additive manufacturing in their production.

This thesis is a part of a larger project, DREAMS, that is the first systemic AM development project in Finland. According to the project plan "*Additive manufacturing is still underutilized in the Finnish manufacturing industry. Reasons for the underutilization are not technical restrictions of the manufacturing method but lack of expertise and standardization, and difficulties to certificate additively manufactured products.*" The long-term intention of the DREAMS project is to raise levels of Finnish AM industry quality higher, as it now mainly reaches only first two steps of a five-level quality pyramid. One thing necessary in enabling to raise the quality in AM industry is to make the processes more transparent so that new standardized ways of using AM could be created, and new recommendations given by a coordinated way. This thesis represents one small but important piece in that process.

The main conclusion of this work is that Finnish AM companies express a large extent of variation when LBF-LB/M is concerned. This work makes some part of that variation visible. The metal powder reusing schemes were diverse, but also sieves mesh sizes and the documentation of powder handling procedures showed different kind of practises. However, the number of reusing cycles within a batch seems to be recorded consistently within an individual company, but not necessarily in a way defined by standards.

Research questions in this thesis were:

1. Are there standards dealing with powder reuse in PBF-LB?

Regarding research that has been done in recent years on AM, only little attention has been paid on standards. Especially about powder reuse there are very few standards. However, one standard was of special importance, and the main results of this thesis concentrates on the use of this standard.

2. What do standards say about powder reuse in PBF-LB?

Standard ASTM F3456-22 defines seven different schemes on powder reuse: one without powder reuse and six with different ways to reuse powder.

3. How is powder reuse performed in Finnish AM industry?

Seven AM companies or research institutions answered to the questionnaire and three were willing to part in a deeper (~ 45 min) interview. Considering that the companies should be aware of the urgent need for standardization in additive manufacturing, this is less than expected, but even this limited amount of research material will tell something. According to the questionnaire and interviews on powder reuse, there is a lot of variability among Finnish AM companies on the topic of powder reuse. In general, the procedures do not seem follow standards properly. This can be explained by lack of standards.

Scientific relevance of this thesis is only modest, but industrial relevance may have a significant impact on Finnish AM industry. There has been no research on the topic so far, and the results show that there is a real need to standardize practices related to powder reuse in PBF-LB. This could be one important step in raising the quality of Finnish AM industry quality to next level.

As a bluntly articulated final statement of this work: Finnish AM companies have to decide whether they want to continue their protectionist approaches against possible competitors or to allow free trading of information for the common good. Every company has a right to make their own choice, but the choice has to be done.

9 References

Ardila, L. C., Garciandia, F., González-Díaz, J. B., Álvarez, P., Echeverria, A., Petite, M. M., Deffley, R. & Ochoa, J. (2014). Effect of IN718 recycled powder reuse on properties of parts manufactured by means of Selective Laser Melting. Physics Procedia, 56, pp 99–107.

Becker, A. F. A. (2016). Characterization and prediction of SLS processability of polymer powders with respect to powder flow and part warpage. St. Gallen: October 2015. Doctoral Dissertation. Swiss Federal Institute of Technology in Zürich. 168 p.

Business Finland (2019). Feasibility study: Additive manufacturing center of excellence (AMCE) in Finland. 11 November 2019.

Carreño-Morelli, E., Alveen, P., Moseley, S., Rodriguez-Arbaizar, M. & Cardoso, K. (2020). Three-dimensional printing of hard materials. International Journal of Refractory Metals and Hard Materials, Vol. 87, February 2020.

Chatterjee, R. & Mullins, L. (2012). New Clues Emerge in Centuries-Old Swedish Shipwreck. Public Radio International. 23 February 2012.

Chua, C. K., Wong, C. H. & Yeong, W. Y. (2017). Standards, Quality Control, and Measurement Sciences in 3D Printing and Additive Manufacturing. Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore. Elsevier Ltd, 250 p.

Dolenc, A. (1993) Software Tools for Rapid Prototyping Technologies in Manufacturing, Doctoral Dissertation, Helsinki University of Technology, Helsinki, Finland.

Dugheri, S., Cappelli, G., Trevisani, L., Kemble, S., Paone, F., Rigazzi, M., Bucaletti, E., Squillaci, D., Mucci, N. & Arcangeli, G. (2022). A Qualitative and Quantitative Occupational Exposure Risk Assessment to Hazardous Substances during Powder-Bed Fusion Processes in Metal-Additive Manufacturing. Safety; Base. Vol 8, Iss. 2, (2022): 32, 21 p.

Fedina, T. Sundquist, J. & Kaplan, A. F. H. (2021). Spattering and oxidation during recycling of low alloy steel powder in Laser Powder Bed Fusion. Materials Today Communications 27 (2021) 102241, 10 p.

Fedina, T., Belelli, F., Lupi, G., Brandau, B., Casati, R., Berneth, R., Brueckner, F. & Kaplan, A. F. H. (2022). Influence of AlSi10Mg powder aging on the material degradation and its processing in laser powder bed fusion. Powder Technology 412 (2022) 118024, 12 p.

Gao, W., Zhang, Y., Ramanujan, D., Ramani, K., Chen, Y., Williams, C. B., Wang, C. C. L., Shin, Y. C., Zhang, S. & Zavattieri, P. D. (2015). The status, challenges and future of additive manufacturing in engineering. Computer-Aided Design, 69, pp 65–89.

Gebhardt, A. (2011) Understanding Additive Manufacturing. Hanser. ISBN 978-3-446-42552-1, 164 p.

Gibson, I., Rosen, D. W., Stucker, B. & Khorasani, M. (2021). Additive Manufacturing Technologies. Springer Nature Switzerland AG, 675 p.

Haddad, M., Nixon. K. B. & Wolff, S. (2023). Sheet Lamination. Springer Handbook of Additive Manufacturing, pp 407-423.

Heiden, M. J., Deibler, L. A., Rodelas, J. M., Koepke, J. R., Tung, D. J., Saiz, B. H. & Jared, B. H. (2019). Evolution of 316L stainless steel feedstock due to laser powder bed fusion process. Additive manufacturing, Vol. 25, pp 84-103.

Hopkinson, N. & Dickens, P. (2001). Rapid prototyping for direct manufacturing, Rapid Prototyping Journal, 7(4), pp 197-202.

Ihalainen, E., Aaltonen, K., Aromäki, M. & Sihvonen, P. (2003). Valmistustekniikka. Otatieto, Helsinki, 488 p.

Karjalainen, Eero. (n.d.). Laatutieto Oy / Quality Knowhow Karjalainen Oy.

Kawalkar, R., Dubey, H. K. & Lokhande, S. P. (2022). A review form advancements in standardization for additive manufacturing. Materials Today: Proceedings 50 (2022), pp 1983-1990.

Khairallah, S. A., Martin, A. A., Lee, J. R. I., Guss, G., Calta, N. P., Hammons, J., A., Nielsen, M. H., Chaput, K., Schwalbach, E., Shah, M. N., Chapman, M. G., Willey, T. M., Rubenchik A. M., Anderson, A. T, Wang, Y. M., Matthews, M. J. & King, W. E. (2020). Controlling interdependent meso-nanosecond dynamics and defect generation in metal 3D printing. Science, 368(6491), pp. 660-665.

Mercelis, P. & Kruth, J. (2006). Residual stresses in selective laser sintering and selective laser melting. Rapid Prototyping Journal, Vol. 12 No 5, pp 254–256.

Moghimian, P., Poirié, Habibnejan-Korayem, M., Zavala, J. A., Kroeger, J., Marion, F. & Larouche, F. Metal powders in additive manufacturing: A review on usability and recyclability of common titanium, nickel and aluminum alloys. 14 p.

Nandwana, P., Peter, W. H., Dehoff, R. R., Lowe, L. E., Kirka, M. M., Medina, F. & Babu S. S. (2016). Recyclability Study on Inconel 718 and Ti-6Al-4V Powders for Use in Electron Beam Melting. Metallurgical and Materials Transactions B, 47: 1, pp 754–762.

Oliver, R., Balakrishnan, P. V. (Sundar) & Barry, B. (1994). Outcome satisfaction in Negotiations: A test of expectancy disconfirmation. Organizational Behavior and Human Decision Processes. Vol. 60, Issue. 2, November 1994, pp 252-275.

Rashid, A. A., Ahmed, W., Khalid, M. Y., & Koç, M. (2021). Vat photopolymerization of polymers and polymer composites: Processes and applications. Additive Manufacturing 47 (2021) 102279, 35 p.

Reijonen, J. (2016). Utilizing metallic waste streams as raw material for powder-based additive manufacturing. Lappeenranta University of Technology, M. Sc thesis.

Stavropoulus, P., Foteinipoulos, P., Stavridis, J. & Bikas, H. (2023). Increasing the industrial uptake of additive manufacturing processes: A training framework. Advances in Industrial Manufacturing Engineering, Vol. 6, 17 p.

Sun, X., Mazur, M. & Cheng, C.-T. (2023). A review of void reduction strategies in material extrusion-based additive manufacturing. Additive manufacturing 67 (2023) 103463, 10 p.

Tang, H. P., Qian, M., Liu, N., Zhang, X. Z., Yang, G. Y. & Wang, J. (2015). Effect of Powder Reuse Times on Additive Manufacturing of Ti-6Al-4V by Selective Electron Beam Melting. The Journal of The Minerals, Metals & Materials Society, 67: 3, pp 555–563.

Thompson, S. M., Bian, L., Shamsaei, N. & Yadollahi, A. (2015). An Overview of Direct Laser Deposition for additive manufacturing; Part I: Transport phenomena, modelling and diagnostics. Additive Manufacturing, Vol. 8, pp 36–62.

Whiting , J. G., Garboczi, E. J., Tondare, V. N., Scott, J. H. J., Donmez, M. A. & Moylan, S. P. (2022). A comparison of particle size distribution and morphology data acquired using lab-based and commercially available techniques: Application to stainless steel powder. Powder Technology, Vol 396, Part B, January 2022, pp 648-662.

ONLINE MATERIAL (retrieved 1 November 2023):

3D Hubs AM Trends Report reveals 3D printing grew 21% despite Covid-19, 3D Printing Industry (2021).
https://3dprintingindustry.com/news/3d-hubs-am-trends-report-reveals-3d-printing-grew-21-despite-covid-19-189087/

Better Heat Exchangers with Additive Manufacturing, DfAM Focus (2021).
https://all3dp.com/1/better-heat-exchangers-with-additive-manufacturing

Carlota, V., 3D Natives (2019). How are different industries adopting additive manufacturing?
https://www.3dnatives.com/en/industries-additive-manufacturing-120820195/

CEO Clément Moreau on a decade of Sculpteo, the BASF acquisition and 3D printing's real killer application, Sculpteo (2020).
https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/sculpteo-ceo-basf-acquisition-3d-printing-killer-app

European Standards.
https://cencenelec.eu/european-standardization/european-standards

Osallistu ja vaikuta, Aihealueet, Kone- ja tuotantotekniikka, metallit, Suomenstandardoimisliitto SFS ry.
https://sfs.fi/osallistu-ja-vaikuta/aihealueet/kone-ja-tuotantotekniikka-metallit

Sheet Lamination, Engineering Product Design.
https://engineeringproductdesign.com/knowledge-base/sheet-lamination

Terässtandardit, Metalliteollisuuden Standardoimisliitto ry (Metsta).
Suomen Standardoimisliitto SFS ry, November 2019
https://metsta.fi/wp-content/uploads/2020/05/Terasstandardit_2019.pdf

STANDARDS:

ASME B46.1-2019, Surface Texture (Surface Texture, Waviness, and Lay)

ASME Y14.5-2018, Dimensioning and Tolerancing

ASTM B214–16, Standard Test Method for Sieve Analysis of Metal Powders, 2021

ASTM F2792-12a. 2012. Standard Terminology for Additive Manufacturing Technologies, ASTM International, West Conshohocken, PA

ASTM F3456-22, Standard Guide for Powder Reuse Schema in Powder Bed Fusion Processes for Medical Applications for Additive Manufacturing Feedstock Materials

ISO 68-1:1998, ISO general purpose screw threads — Basic profile — Part 1: Metric screw threads

ISO 3310-1:2016, Test Sieves - Technical Requirements and Testing, 2021

ISO/ASTM 52900:2015, Additive manufacturing — General principles — Terminology, International Organization for Standardization (ISO), Geneva, Switzerland, 2015

ISO/ASTM 52900:2021, Additive Manufacturing - General Principles - Terminology

SAE AMS7031, Batch Processing Requirements for the Reuse of Unused Powder in Additive Manufacturing of Aerospace Parts

SAE ARP7044 - Powder History Scoring Metric and Labeling Schema

Appendix 1: Technologies within additive manufacturing

The development of additive manufacturing has been rapid. The first patented inventions were from 1980's. All these patents described a similar of concept of fabricating a 3D object by selectively adding material layer-by-layer. Simultaneous development can be seen in the fields of 3D graphics and computer-aided design (CAD) that now comprise a prerequisite for modern additive manufacturing technologies. Before the standardization of terms additive manufacturing and 3D printing could also be called Rapid Prototyping or Rapid Tooling or Rapid Manufacturing. These terms, however, all refer to the same technology, that will shortly be illustrated in the following paragraphs. (Gibson (2021).)

There are many ways to classify additive manufacturing categories. One of these classifications is to divide the technologies into seven different categories as defined by the standard ISO/ASTM 52900:2015 (https://www.iso.org/standard/69669.html).

ISO/ASTM 52900:2015

AM Technologies / Processes, *Prosessit*

1. **Binder jetting,** *n*—an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials. *Sideaineen suihkutus*
2. **Directed energy deposition,** *n*—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. *Kohdennettu sulatus/ Suorakerrostus*
3. **Material extrusion,** *n*—an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice. *Materiaalin pursotus*
4. **Material jetting,** *n*—an additive manufacturing process in which droplets of build material are selectively deposited. *Materiaalin ruiskutus*
5. **Powder bed fusion,** *n*—an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed. *Jauhepetisulatus*
6. **Sheet lamination,** *n*—an additive manufacturing process in which sheets of material are bonded to form an object. *Arkkilaminointi*
7. **Vat photopolymerization,** *n*—an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization. *Allas valokovetus*

The first inventions of vat polymerization are from 1980's. Photopolymers are resins that react to ultraviolet or visible light thus turning into solid polymers. Unlike other main technologies vat photopolymerization takes place in a vat containing liquid, radiation curable resin as the source material (where the names comes from). (Rashid, A. A. et al. (2021).) Traditionally the method of photopolymerization is in use for example in dentistry, where ultraviolet light is used to solidify teeth filling material, but nowadays there are also more materials to be used in vat photopolymerization than just polymers.

Sheet lamination is one of the earliest commercialized AM techniques. In sheet lamination sheets of material is re-cut, stacked and bonded to form an object. Although the number of applications for sheet lamination are somewhat limited, the technique itself is one of the cheapest and easiest to handle. The method has been used for example in layer-by-layer lamination of paper material, but is can also be used in other materials, like metal, polymer or ceramic. (https://engineeringproductdesign.com/knowledge-base/sheet-lamination/).

Material extrusion is an AM technology where semisolid material is forced through a nozzle when pressure is applied. The extruded material must fully solidify while remaining in the deposited state and must also bond to the material that has already been extruded. In this technology the solidifying of extruded material is induced by temperature change, reaction with air (or drying) or chemically by a curing agent. Various polymers are the most common materials to be used in material extrusion. (Sun et al. (2023).)

Material jetting applies the same principle of jetting material through a nozzle as in material extrusion. What makes the difference is that in material jetting the material is contained in small droplets that are sprayed on top of the building platform or onto the previous layer. To facilitate jetting, materials that are solid at room temperature must be heated so that they liquefy. Materials can be polymers, ceramics or metals. (Gebhardt, A. (2011).)

Binder jetting is an AM process in which liquid bonding agent is selectively deposited to join powder material. To some extent binder jetting resembles powder bed fusion – a technology that will be discussed later more closely. In binder jetting a specific binder material is injected into a powder bed to fabricate the part. In both technologies the raw material is in powder form, but in binder jetting no heat is applied in the printing process. For metal and ceramic binder jetting processes the printed part undergoes a furnace operation to vaporize polymer constituents of the binder. (Gebhardt, A. (2011).)

Directed energy deposition (DED) is a technology for adding material as it is being deposited layer-by-layer. Directed energy deposition as a method is probably closest to welding as material (in wire or powder form) is delivered along the energy required to melt it. DED is particularly suited for repair and adding features to an existing part. During the process powder material is deposited onto the surface through nozzle(s), which is then melted by a focused heat source (typically an electron or laser beam or electric arc) to build up three-dimensional objects in a manner similar to material extrusion. Unlike other technologies, direct energy deposition is almost exclusively applied to metals. (Gibson (2021).)

Powder bed fusion (although last in this list) is one of the earliest inventions in additive manufacturing and still widely used. It is a method of specific interest here, since it is in use in the research institute in charge for this work. In powder bed fusion materials as varied as plastic, composites or metals can be manufactured by this process. (Gibson (2021).) However, in this thesis only metals (focus of the research at the moment) will be discussed. According to ISO/ASTM terminology:

> *"Powder bed fusion is an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed. Thermal energy can be laser beam or electron beam. Powder material can be metal, plastic, composite etc. Components of powder must have melting point, and melting point of these components in powder have to be close to each other and their behaviour in molten stage has to be known."*

(ISO/ASTM 52900:2015, Additive manufacturing — General principles — Terminology, International Organization for Standardization (ISO), Geneva, Switzerland, 2015.)

Appendix 2: Questionnaire (in Finnish)

Kysely metallien jauhepetisulatuksen (engl. powder bed fusion) jauheen uudelleenkäytöstä

Hyvä vastaanottaja,

Lisäävä valmistus (additive manufacturing, AM) on yksi nopeimmin kasvavista teollisuudenaloista maassamme. Laajasta tutkimuksesta ja tuotekehittelystä huolimatta käytetyistä prosesseista ei ole Suomessa riittävästi tarjolla vapaasti saatavilla olevaa tietoa. Eräs merkittävä syy tilanteeseen on se, että alan teknologiaan liittyvä standardointi ei pysy kehityksessä mukana. Standardien puute taas vaikeuttaa valmistettavien tuotteiden sertifioimista.

Business Finlandin rahoittama **yhteistyöprojekti nimeltä DREAMS**
(Database for Radically Enhancing Additive Manufacturing and Standardization, lisää: *https://www.dimecc.com/dimecc-services/dreams/*) on eräs kokonaisvaltainen hanke, jonka tarkoituksena on nostaa suomalaisen lisäävän valmistuksen tasoa. Hankkeessa on mukana FAME (Finnish Additive Manufacturing Ecosystem, lisää: *https://fame3d.fi/*), Suomen johtavia alan tutkimus- ja oppilaitoksia sekä alan yrityksiä. Yksi projektiin osallistuvista toimijoista on Turun yliopiston kone- ja materiaalitekniikan laitoksen DMS-tutkimusryhmä (Digital Manufacturing and Surface Engineering, lisää: *https://www.utu.fi/en/university/faculty-of-technology/mechnical-and-materials-engineering/research/digital-manufacturing-and-surface-engineering*).

Äskettäin on julkaistu standardi, joka koskee jauheen uudelleenkäyttöä. Standardissa ASTM F3456-22 (Standard Guide for Powder Reuse Schema in Powder Bed Fusion Processes for Medical Applications for Additive Manufacturing Feedstock Materials) on kuvattu mallit, joilla jauhetta voidaan käyttää uudelleen.

Tämä kysely on osa Erkka Lehtihuhdan Turun yliopistolle tehtävää diplomityötä, joka koskee jauhepetisulatuksen (PBF-LB/M) metallijauheen uudelleenkäyttöä. Kyselyssä nämä mallit on jäljennetty ja käännetty suomeksi. Kyselyyn liittyvä aineisto on suppea, mutta se on tiivistä asiaa.

Nämä tulokset on tarkoitus julkaista osana Turun yliopistoon tehtävää diplomityötä, yritysten nimiä mainitsematta. Yritysten nimiä ei myöskään tässä kyselyssä kysytä.
Diplomityö on valmistuessaan avoin ja julkinen ja valmistuu 1/24.

Lisätietoja saa Turun yliopiston teknillisen tiedekunnan DMS-tutkimusryhmän Erkka Lehtihuhdalta (erkka.k.lehtihuhta at utu.fi) tai työn ohjaajalta dosentti Heidi Piililtä (heidi.piili at utu.fi)

* Pakollinen kysymys

Kysymys 1: *

Teidän yrityksenne jauhepetisulatuksessa käytettävä materiaali:

Merkitse vain yksi soikio.

- ⬭ Metalli
- ⬭ Polymeeri
- ⬭ Muu: ______________________________

Kysymys 2:

Mikäli käytettävä materiaali on metallia, onko se (pääasialliselta) koostumukseltaan

Merkitse vain yksi soikio.

- ⬭ Hiiliterästä
- ⬭ Ruostumatonta terästä
- ⬭ Alumiinia
- ⬭ Koboltti-kromia
- ⬭ Titaania
- ⬭ Nikkeliä
- ⬭ Muu: ______________________________

Kysymys 3:

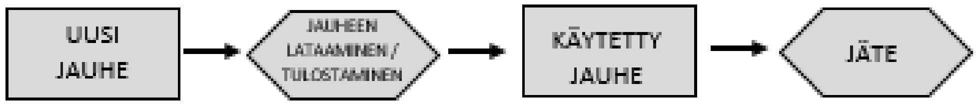
Mikäli jauhetta käytetään uudelleen, mikä on uuden jauheen osuus valmiista tuotteesta (%)?

____

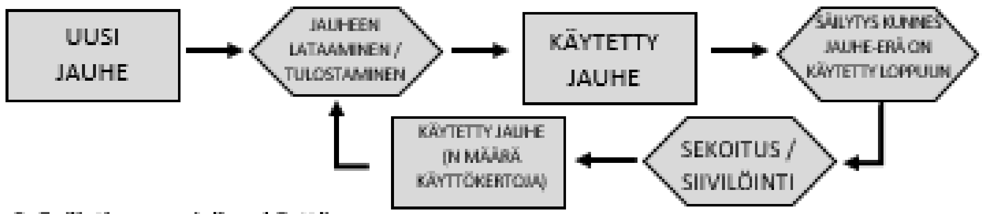
Kysymys 4:

Standardissa ASTM F3456-22 on esitetty eri tapoja (oheiset kuvat 1-7) siitä, miten metallijauheen uudelleenkäyttö voi tapahtua. Jos kuvasta on kysymyksiä, laita email erkka.k.lehtihuhta at utu.fi ja/tai heidi.piili at utu.fi

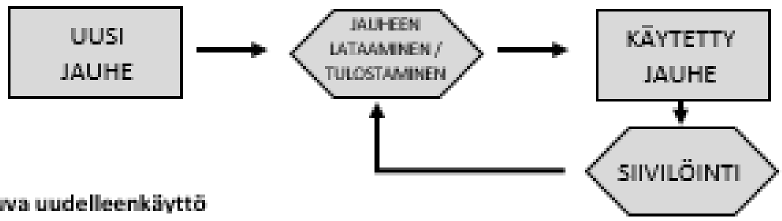
Mikä/mitkä näistä kuvaa tapaa, joka on käytössä edustamassanne yrityksessä (Tilaa vastaukselle kuvan jälkeen)



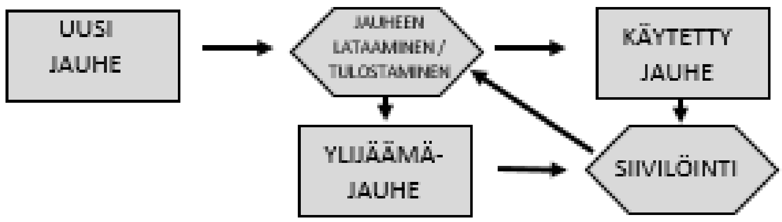
Kuva 1. Ei jauheen uudelleenkäyttöä



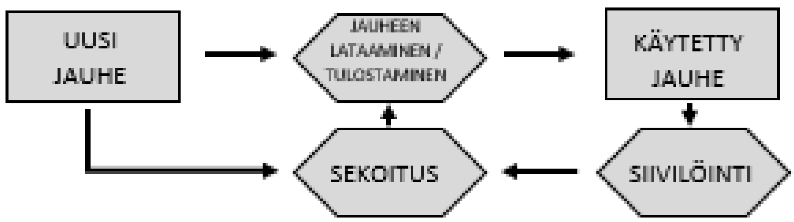
Kuva 2. Epäjatkuva uudelleenkäyttö



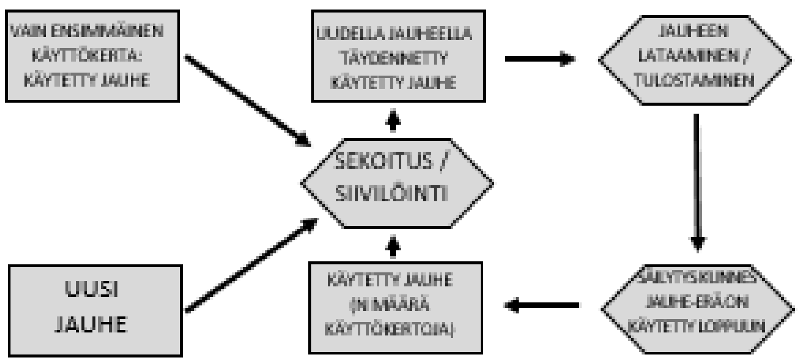
Kuva 3. Jatkuva uudelleenkäyttö



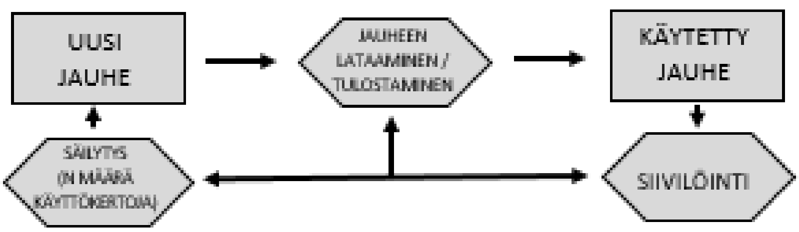
Kuva 4. Jatkuva prosessinaikainen uudelleenkäyttö



Kuva 5. Jatkuva uudelleenkäyttö + uusi jauhe + sekoitus



Kuva 6. Uuden ja käytetyn jauheen seoksen käyttö



Kuva 7 Jatkuva uudelleenkäyttö + uusi jauhe (ei sekoitusta)

Kysymys 5:

Mikäli yksikään liitteessä kuvatuista tavoista ei vastaa käytäntöjänne, voitte kertoa sanallisesti miten toimitte.

Kysymys 6:

Miten kauan käytätte jauhetta? Esim. erän loppuun asti, jatkaen sitä uudella jauheella.

Kysymys 7:

Mikäli jauhetta käytetään uudelleen, minkä kokoista siivilää käytetään siivilöintiin?

Kysymys 8:

Onko jauheen käyttörutiineissa eroa kun valmistetaan erityisen tarkasti säädeltyjä osia verrattuna ”tavanomaisiin” osiin?

Kiitos vastauksestanne!

Jos haluatte osallistua tarkempaan haastatteluun liittyen tähän aiheeseen, lähetä sähköpostia Erkka Lehtihuhdalle (erkka.k.lehtihuhta at utu.fi) tai työn ohjaajalle dosentti Heidi Piilille (heidi.piili at utu.fi).