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107

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Metal additive manufacturing for industrial applications

LUT University
School of Energy Systems
Department of Mechanical Engineering
Laser and AM laboratory

Raportitja selvitykset -Reports

Metal additive manufacturing for industrial applications

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ABSTRACT

This report aims to have an overview to development actions of a knowledge-based know-how cluster of metal additive manufacturing (AM) in Finland's South Karelia region. This report aims also to investigate the needs of regional industries to become more aware and open towards using AM in their production lines. At first, a brief history of additive manufacturing introducing the preliminary concepts of metal AM, its generic principles and available processes are discussed. Next, the status of AM activities in Finland and other Nordic countries is discussed. Finally, it shares the results of a case study to get the reader more familiar with metal AM. The case study of this report shows that 3D printed metals such as stainless steel 316L have a strong potential to compete with their traditionally manufactured counterparts, even excel them regarding many specific material properties and applications.

TIIVISTELMA

Tämän raportin tarkoituksena on läpikäydä Etelä-Karjalan metallien lisäävän valmistuksen (engl. additive manufacturing, AM) osaamiskeskittymän perustamiseen liittyviä näkökohtia. Tässä katsastettu alueellisen teollisuuden tarpeita, jotta lisäävän valmistuksen käyttöönottoa voitaisiin laajentaa paremman tietopohjan kautta. Aluksi tässä raportissa käsitellään lyhyesti metallien lisäävän valmistuksen historiaa, ja esitellään tekniikan keskeisimmät käsitteet, sen yleiset periaatteet ja käytettävissä olevat prosessit. AM-toiminnan tilasta Suomessa ja muissa Pohjoismaissa esitellään myös yhteenveto. Lopuksi raportissa käydään case studien tuloksia läpi, jotta metallien lisäävän valmistuksen käytännön sovelluksia ja niiden mahdollisuuksia voidaan ymmärtää paremmin. Nämä esimerkit osoittavat selkeästi sen, että metallien (kuten 316L) 3D-tulostuksella, on suuri mahdollisuus olla teollisesti varteenotettava valmistustekniikka. Useimmat tulostettujen kappaleiden ominaisuudet ovat samat kuin perinteisestikin valmisteluilla, ja joissain tapauksissa jopa paremmat.

PREFACE

Additive manufacturing has caught the attention of industrial designers, manufacturers, and artists for decades. It has transformed its dominance from prototyping into actual manufacturing (AM) through these years. Considering the current environmental crisis worldwide, using more sustainable technologies with minimized material waste, such as additive manufacturing, is inevitable in the future. However, there are still many niches, either technically or theoretically, to be filled regarding this technology. Therefore, studying this technology and its processing methods and promoting them are essential to facilitate using additive manufacturing for production.

This report aims to provide an overall picture of metal additive manufacturing to gain a piece of basic knowledge about this technology. Then, it presents the aims and activities associated with project of Metal 3D Innovations, Me3DI (Teollisuuden 3D tulostus) which is funded by European Regional Development Fund. This project was carried out 1.9.2018-31.12.2020. Project is carried out by research group of Laser Materials Processing and research group of Steel Structures of LUT University and industrial partners.

The project comprised of educational and training sessions as well as research work. The outcomes of the project have become available to the public as open-access publications. It should be noted that the data, discussions, results, conclusions, and suggestions presented in this report are only its authors' views on the topics, and do not reflect the views of the funding organization and companies associated with this project on the subject matters.

Authors would like to acknowledge project and its co-operation partner to be able to execute studies related to this report and finalizing of it.

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April 2020, Lappeenranta, Finland

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List of abbreviations

AM	Additive Manufacturing
ASTM	ASTM International, formerly known as American Society for Testing and Materials
BIS	Beam interference solidification
BPM	Ballistic Particle Manufacturing
CAD	Computer-aided Design
CAM	Computer-aided Manufacturing
DED	Direct Energy Deposition
DSPC	Direct Shell Production Casting
EBF3	Electron Beam Freeform Fabrication
EBM	Electron-Beam Additive Manufacturing
EOS	Electro Optical Systems
ES	Electrosetting
FAME	Finnish Additive Manufacturing Ecosystem
FDM	Fused Deposition Model
HIS	Holographic Surface Deposition
ICI	Industrial Chemical Industries
ISO	International Organization for Standardization
JWG 5	Joint Working Group 5
LENS	Laser Engineered Net Shaping
L-PBF	Laser-Powder bed Fusion
LM	Layered Manufacturing
LMD	Laser Metal Deposition
LOM	Laminated Object Manufacturing
LTP	Liquid thermal polymerization
PSDO	Partner Standards Developing Organization
RP	Rapid Prototyping
SCS	Solid Creation Systems
SDM	Shape Deposition Manufacturing
SFF	Solid Freeform Fabrication
SFP	Solid foil polymerization
SGC	Solid Ground Curing
SL	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SOUP	Solid Object Ultraviolet Plotter
SRC	Strategic Research Council
UAM	Ultrasonic additive manufacturing
UAV	Unmanned Aerial Vehicle
WAAM	Wire and Arc Additive Manufacturing
3D	Three Dimensional

1. Introduction

Additive manufacturing (AM), as defined by the America Institute of Testing and Materials (ASTM) [1], is the process of making parts from digital three-dimensional (3D) models by joining (adding) materials layer-by-layer. The idea behind this technology is in utter contrast with most traditional production techniques that rely on material subtraction from solid volumes of materials, e.g., machining. Theoretically, it is possible via AM to build a part directly from its computer-aided design (CAD) file without requiring any other tool or equipment. Although, in practice, this single-step manufacturing ideal is sometimes hard to achieve, as it is discussed further in this report, AM certainly simplifies the whole manufacturing process. Although AM has been introduced to the commercial market under different names and labels, e.g., 3D printing, rapid prototyping (RP), layered manufacturing (LM), and solid freeform fabrication (SFF), all these terms point to the same idea behind the manufacturing process. According to standardized terminology, additive manufacturing is used whenever discussing of industrial professional fabrication [2].

Considering the new developments in AM, it can currently be used for either prototyping or manufacturing purposes. However, it is notable that metal AM is typically used for the sake of manufacturing itself. This technology is expected to thoroughly change the future face of industrial manufacturing and customer-to-manufacturer interaction. Employing AM and its integration with computer and information technologies have made designing a more straightforward task for contemporary engineers. Due to this simplicity, more people can now contribute to designing and manufacturing, considering the capabilities of modern software packages in designing and design optimization, and possibilities of file transfer, storage, and sharing via the internet and cloud-based systems.

As an emerging technology for industrial applications, AM provides designers and manufacturers with new opportunities and possibilities to improve their manufacturing efficiency. According to the literature, AM can outshine traditional manufacturing in quality, cost, speed, environmental impact, and innovation, depending on the final product. It should be noted that AM is not supposed to replace traditional manufacturing and subtractive methods. However, it is expected to fill numerous niche areas and conquer many design and production challenges that are impossible by current standard methods. Thus, this technology becomes appealing more and more every year, as its annual investment records show (Fig. 1).

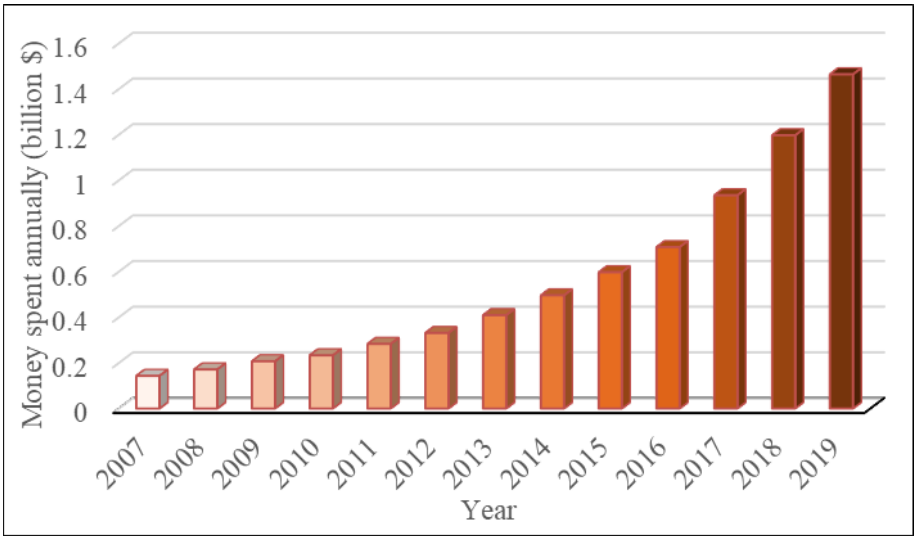

Fig. 1. Money spent annually worldwide on final part production by AM (Data from [5]).

The main advantages of AM over traditional manufacturing can be summarized as follows [3,4]:

1- More design freedom resulting in more efficient products
2- Direct manufacturing from CAD models that simplifies the production procedure
3- AM does not require a complicated process planning, unlike other subtractive technologies requiring careful and detailed analysis of part geometries and their features to determine, for example, the order of production steps
4- Possibility of design customization and optimization
5- Shorter supply chain, reduced logistics, and less storage cost
6- More sustainable production with a smaller environmental footprint and less material waste.

The summation of all these points (Fig. 2) leads us to expect a bright future for AM in the manufacturing paradigm.

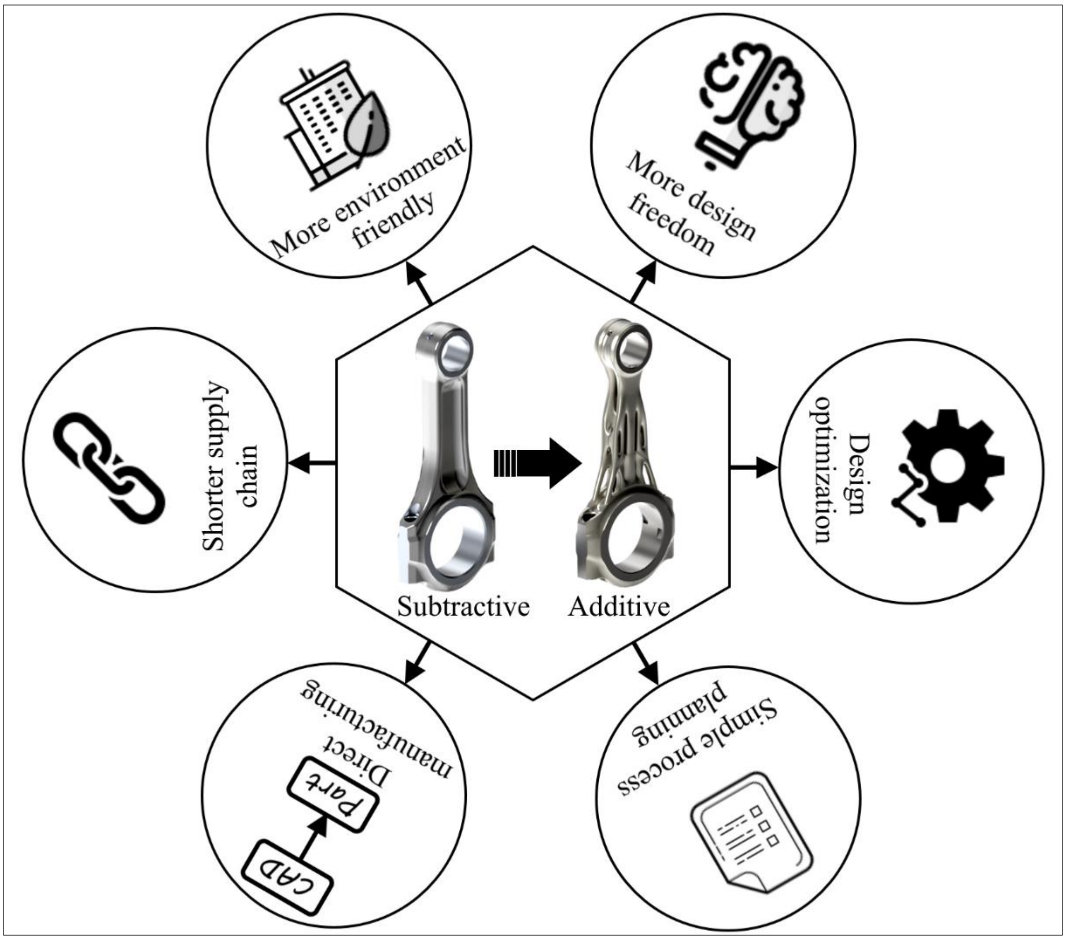

Fig. 2. Typical advantages of AM over traditional manufacturing (Parts shown in the middle as examples are from Streparava [6])[1].

1.1 A brief history of additive manufacturing

Early ideas around layer-by-layer manufacturing go back to the 1900s when some patents were registered on this concept. Half a century later, in the 1950s, the benefits of layer-wise manufacturing were considered more seriously. Consequently, some additional patents were registered from the 60s to 80s. This chain of events set the stage for the development of processes that used layer-by-layer material addition to produce 3D parts. Finally, AM was officially born with the invention of Stereolithography by Charles Hull, the founder of 3D Systems, in 1987. Hull registered the patent for stereolithography in 1984, founded 3D Systems in 1986, and officially launched the first commercialized 3D printer in 1987 (Fig. 3). Other techniques and companies have started to emerge since then, and a highly competitive market has been formed [2,7,8].

[1] Graphical icons from: https://icons8.com/

Fig. 3. The SLA-1 system launched in 1987 (left), and the SLA-1 system with Charles Hull standing beside it, in the National Inventors Hall of Fame (right) [9,10].

Collaboration between 3D systems and Ciba-Geigy in 1988 resulted in developing the first generation of acrylate resins, as the ancestor of current photopolymer resins commonly used in AM. Meanwhile, AM machines such as Solid Object Ultraviolet Plotter (SOUP) and Solid Creation System (SCS) were commercialized in Japan by NTT Data CMET and Sony/D-MEC. All these systems relied on photopolymerization for AM. Concurrently, Asahi Denka Kogko introduced the first epoxy-based photocurable resin. Thus, a new generation of AM techniques became available based on these resins. In the same era, Electro Optical Systems (EOS) and Quadrax started manufacturing AM systems in Europe by introducing the first stereolithography system in this region. All these systems cured resins via an ultraviolet laser. This laser type was mainly the only one in use until Imperial Chemical Industries (ICI) introduced the first photopolymer that was curable via visible light [7,11,12].

Yet, it is possible to consider the early 1990s as the era that shaped the current AM landscape since five determining technologies were developed and commercialized during these years. These technologies were Fused Deposition Model (FDM), by Stratasys, Solid Ground Curing (SGC), by Cubital, Laminated Object Manufacturing (LOM), by Helisys, Selective Laser Sintering (SLS), by DTM, and Direct Shell Production Casting (DSPC), by Soligen. Many systems used for AM nowadays rely on mechanisms stemming from FDM, SLS, and DSPC techniques. Since the beginning of the 21st century, an ongoing boost in AM development has started, and new technologies have emerged continuously.

Through the past 20 years, novel techniques such as Polyjet Materials Printing, Laser Engineering Net Shaping (LENS), Aerosol Jetting, Ultrasonic AM, Selective Laser Melting (SLM), and Continuous Liquid Interface Production were commercialized for industrial applications. Meanwhile, raw materials have also been improved, developed, and modified to be used in AM. Many materials, including metals, ceramics, composites, and organic ones, are currently available for AM. Thus, this technology is no longer considered as a prototyping technology, but it is introduced as a manufacturing technique that is capable of production of components as small as Micro-Bull to big enough to be considered as infrastructures, such as bridges and buildings as shown in Fig. 4 [7,12].

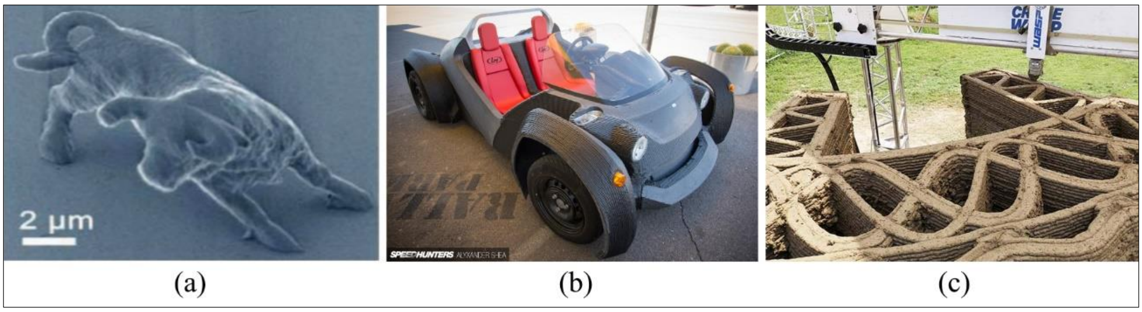

Fig. 4. (a) Micro-scale model of a bull made via a newly developed AM technique known as Femtosecond Laser Direct Writing [13]; (b) Strati, the first car with a 3D printed body [14]; (c) the TECLA house made of 3D printed local materials [15].

1.2 Generic principles and AM processes

Although every AM process has its unique mechanism to form a solid part from the layer-wise consolidation of different materials, the general workflows of these processes are quite similar. Most AM processes and technologies include these eight steeps from initial designs to final products [4,16]:

1- Generating a CAD file: AM is a computer-aided manufacturing (CAM) technology. Consequently, every design idea must initially be converted into a CAD file to make the manufacturing process possible. Thus, as the first step of additive manufacturing, the design idea should be transferred into a CAD file via some 3D modeling software. This routine is slightly different when AM is used for reversed engineering. In this approach, the actual component is scanned with a 3D scanner. Then, the data from the scanner is converted into a CAD file via some 3D modeling software.
2- Converting the CAD file into STL format: STL format was invented in the 1980s for 3D Systems stereolithography machines. Currently, almost all AM systems accept STL files as their input data. This format redefines CAD designs as arrays of triangles and vectors. This approach makes it possible to slice a design into numerous layers to make it suitable for a layer-by-layer manufacturing technique, as shown in Fig. 5.
3- Transferring the STL files to the AM machine: The STL files prepared through the last step should be uploaded on the AM machine. It is possible to transfer the files of several parts and manufacture them all together. It is also possible to manipulate the size, position, and orientation of every part in this step.
4- Setting up the AM system: Each AM machine, regardless of its type and technology, requires some preparation steps to carry out the manufacturing job properly.
5- Manufacturing: The building step is an automated process, considering the nature of AM as a CAM technology. Thus, after pressing the start button, the AM system can continue the building job without further supervision. However, during an AM job, the system must be checked periodically to make sure it has not faced any error through its procedure.
6- Part removal: After the manufacturing procedure is finished, completed parts must be removed from the machine.
7- Post-processing: After removing the parts from the AM system, they might require some post-processing such as additional cleaning, surface polishing, machining, or heat-treatment to become ready to be used. As a typical example, parts manufactured via

powder-bed techniques should be separated (cut) from their building plate (also known as the stage).

The generic workflow of AM is graphically summarized in Fig. 6.

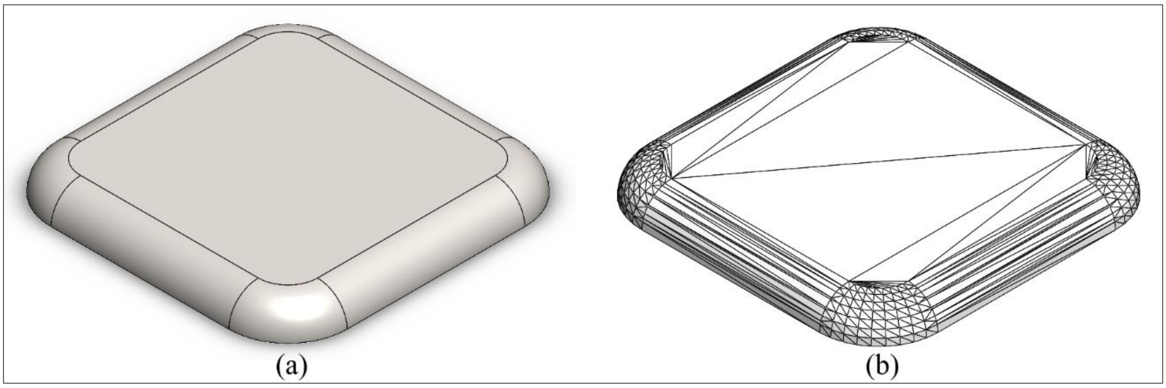

Fig. 5. Differences between the design data of a component in (a) CAD format and (b) STL format [Courtesy of LUT University].

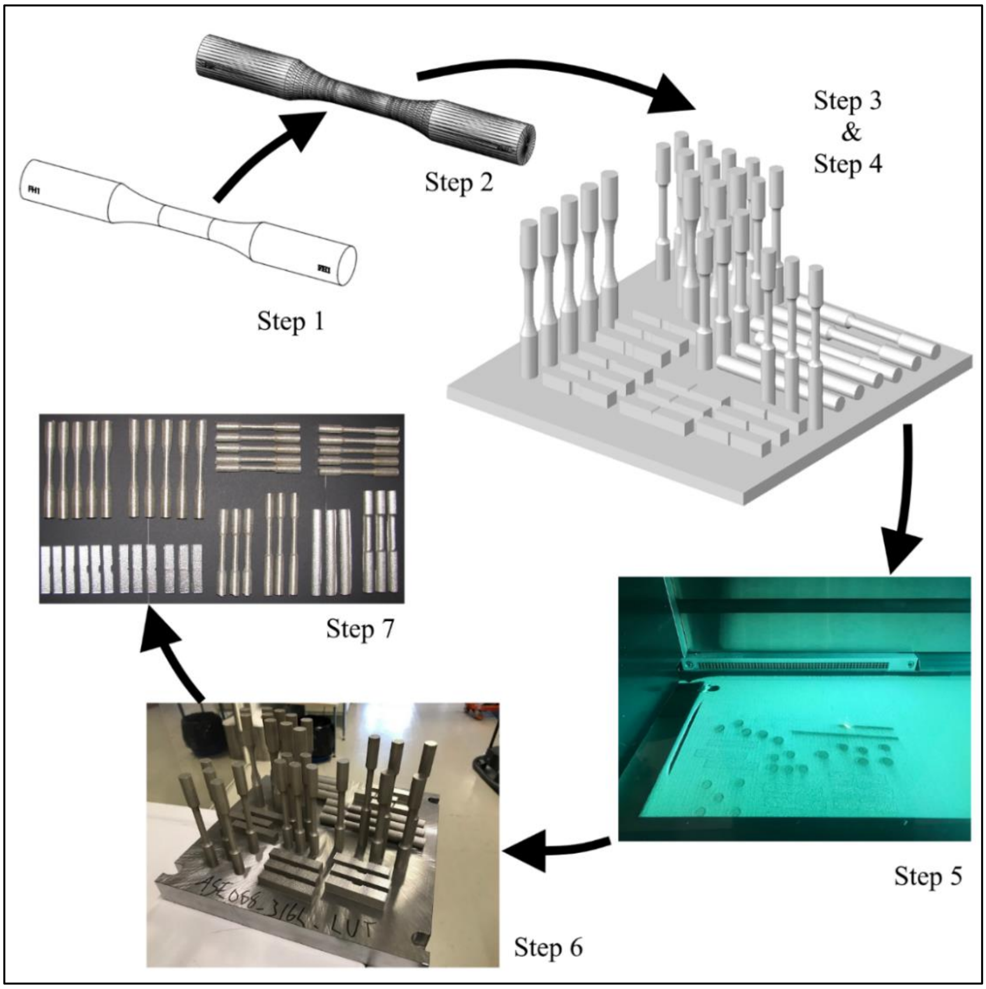

Fig. 6. The typical workflow of metal AM processes [Courtesy of LUT University].

1.3 AM processes

Through the short history of AM, numerous processes were introduced to the market, but only a few of them have survived enough to be commercialized as an industrial manufacturing process. The most common AM processes can be categorized into different groups, as shown in Fig. 7, based on the shape and type of their raw materials and consolidation mechanisms. It should be noted that although there are numerous AM technologies available on the market, only a limited number of them are suitable for manufacturing metallic components applicable in industrial applications [11,17–19].

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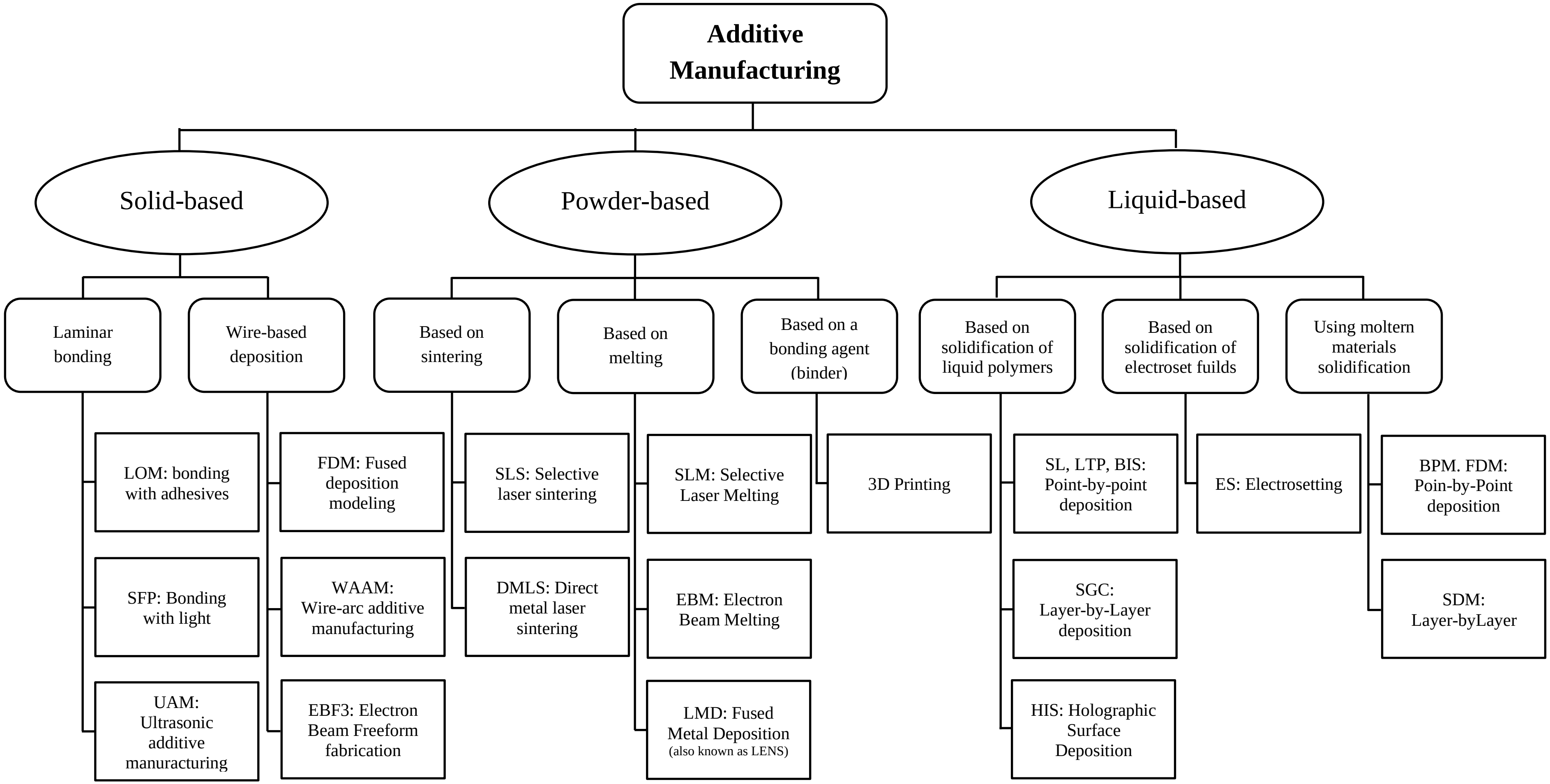
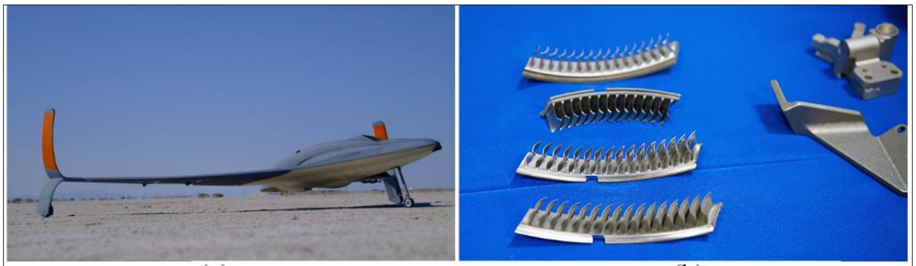


Fig. 7. Additive manufacturing methods according to their mechanisms and raw materials [11,17–21].

1.4 AM in Finland and other Nordic countries

Metal AM has become very popular worldwide in medical, aerospace, and aeronautic industries due to its capabilities of processing expensive metals without material waste and manufacturing complex geometries. AM design optimization capabilities make it a suitable alternative for aeronautics, aerospace, and automotive sections to consider lighter, more energy-efficient, and sustainable components in their designs, as shown in Fig. 8. Although AM has been used on an industrial scale in Nordic countries since decades ago, metal AM has not entirely found its place in this region yet. Considering the history of aircraft manufacturing in Swedish and Finnish companies, such as Flynano and Patria, in unmanned aerial vehicle (UAV) production, AM can provide great alternative opportunities in design and manufacturing in Nordic countries [22]. In addition, Metal AM has become quite popular among manufacturers of automobiles and supercars. As one of these manufacturers located in Sweden, Koenigsegg uses AM parts in its high-end products to improve their performances (Fig. 9) [23,24].



(a) (b)

Fig. 8. (a) A 3D printed UAV developed and manufactured by Aurora Flight Sciences in collaboration with Stratasys; (b) AM printed parts of aircraft engines [25].

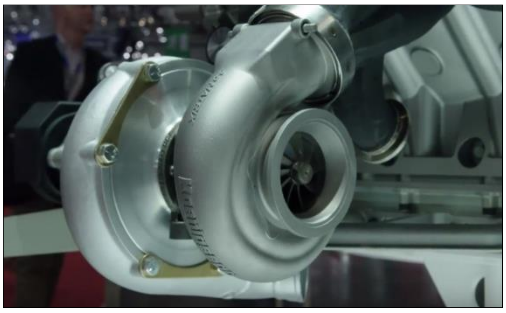


Fig. 9. World's first AM printed automobile turbocharger used in Koenigsegg One [26].

Among Nordic countries, Sweden dedicated €120 million to AM studies in 2019. In addition, Swedish key industrial stakeholders formed AMEXCI as an AM innovation center in 2017 to raise awareness on this technology. The primary mission of AMEXCI is to provide the possibility of collaboration between companies to master AM faster in the competitive international market and act as a resource for the shareholders to adopt AM in their manufacturing sectors rapidly [21,26]. In Norway, the AM industry has a rapid growth in metal AM, focusing on offshore and onshore industries. In addition, foundry, and molding industries, medical, and defense companies initiated using AM techniques in their production lines [22,27]. In Denmark, about 25% of manufacturers had started utilizing AM and by 2019, but most of the companies still used this technology for prototyping. However, reports from 2018 showed that 30% of Danish companies are determined to use AM soon [22].

Like other Nordic countries, Finland has witnessed an increased interest in AM recently with a focus on metals and high-performance polymers. Projects in Finland include manufacturing spare parts, applications of AM biomaterials, and renewable materials. The Strategic Research Council (SRC) of Finland is also interested and has funded studies on manufacturing digitalization, automation, and service-driven platforms. In Addition, Finnish research corporations such as VTT are highly focused on AM and its capabilities. For example, VTT tries to achieve novel 3D printed solutions for industrial challenges to have more sustainable and economical products. As another example, DIMECC Ltd launched an industrial AM platform known as FAME ecosystem (Finnish Additive Manufacturing Ecosystem), gathering more than 20 companies together to promote AM in Finnish industries and raise Finland to be among the leading countries in AM utilization. Finnish defense forces have also expressed their interest in utilizing AM for industrial cooperation [22,28–31].

As AM has been commercialized since the late 1980s, one of the early plastic AM systems was delivered to Finland by Electrolux in the early 1990s. In addition, Aalto University (Helsinki University of Technology back in time) has started research on AM since 1992. However, the significant rise in interest in metal AM by Finnish companies has just started recently since a few years ago. By 2020, there are five active commercial service bureaus in Finland. Thus, there are currently five Finnish companies providing metal AM services to their customers (Fig. 10) [30]. However, all these AM service providers in Finland are focused on the Laser-Powder bed fusion (L-PBF) technique. This inclination might act as a hindrance when other companies try to approach AM as an alternative since L-PBF is the most expensive metal AM method (Fig. 11).

Fig. 10. Current metal AM service providers in Finland [30].

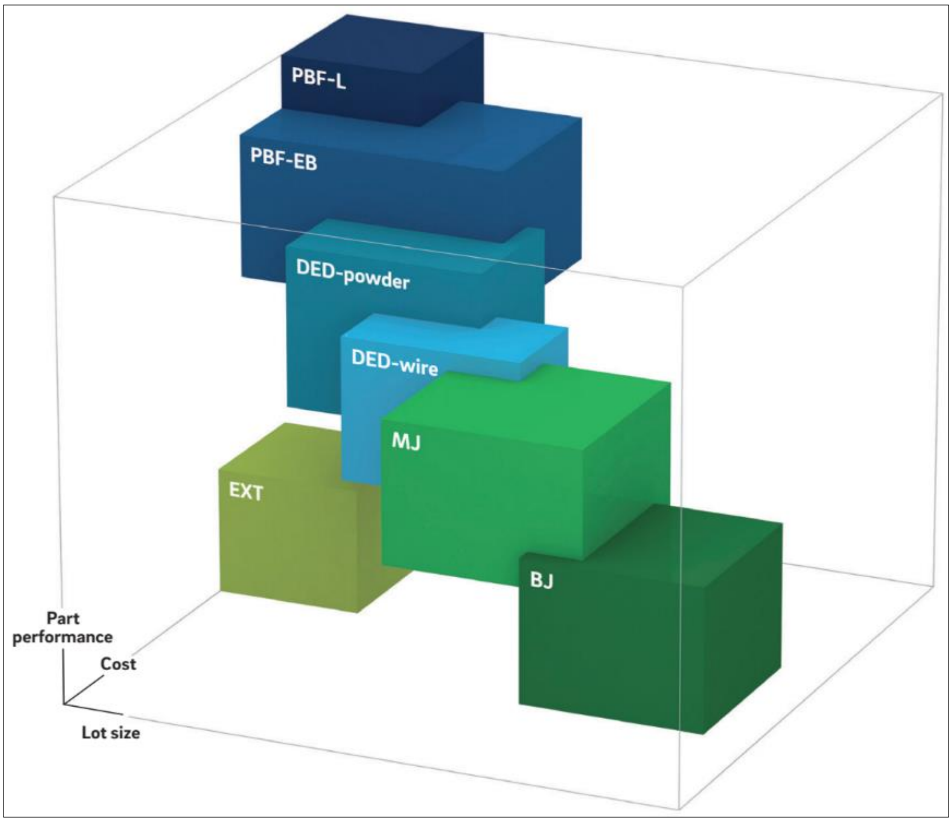


Fig. 11. Comparison of metal AM methods in terms of performance, cost, and lot size [32]. (PBF-L: Powder bed fusion by laser, PBF-EB: Powder bed fusion by electron beam, DED-powder: Direct energy deposition powder by laser, DED-wire: Direct energy deposition wire by laser, EXT: Material extrusion, MJ: Material jetting, BJ: binder jetting.)

Finnish service providers have been so far focused on manufacturing AM metal components with low to medium quality levels, and this limitation does not allow Finnish industries to consider metal AM for highly sensitive and critical parts. Hämeenaho et al. [30] divided quality levels of metallic AM parts into five levels (Fig 12). According to their report, AM service providers in Finland are currently able to reach only the second quality level for their AM services. They concluded that the lack of knowledge and experts are among the most critical challenges to utilizing metal AM in Finland's industrial sectors [30]. Furthermore, a study carried out at the Luleå University of Technology in Sweden reached a similar conclusion about the whole Nordic region: the lack of knowledge is among the most significant challenges to implement AM in Nordic countries [22]. In another study from 2017, it is shown that metal AM had a minor role in Finnish industries compared to other AM materials (Fig. 13), and Finland's reliance on outsourcing AM is higher than that of other European countries, and the rest of the world (Fig. 14). Thus, it is essential for Finnish manufacturers to minimize outsourcing in the future, especially international outsourcing, to keep themselves as independent as possible [31].

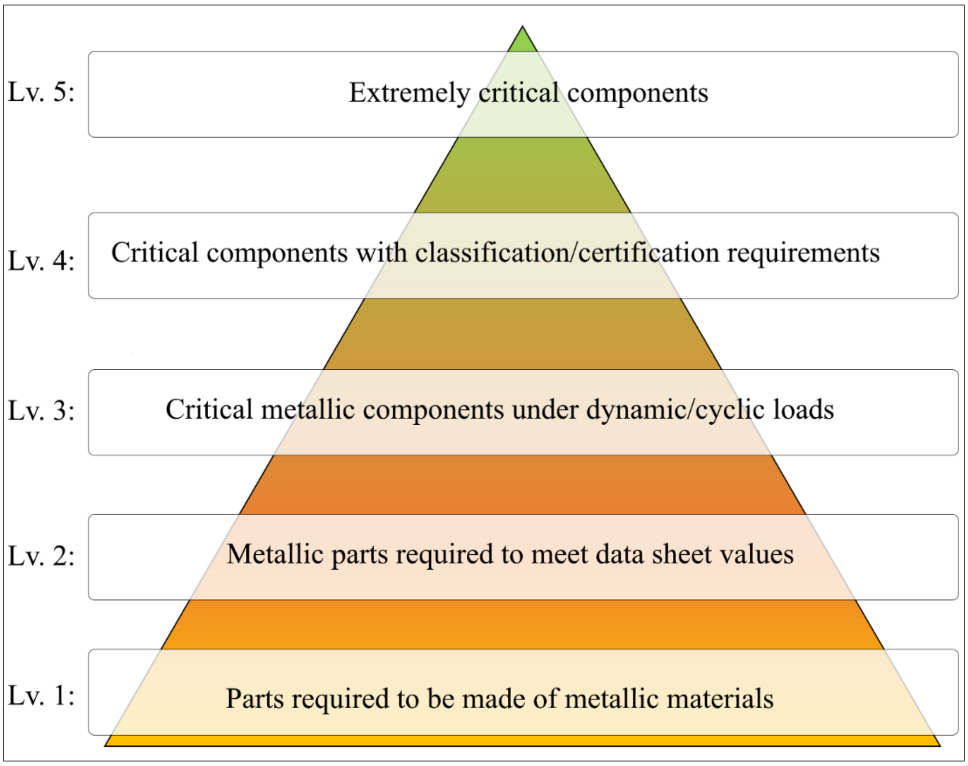


Fig. 12. Different levels of metal AM quality, according to LAMQ^{TM} [30].

1.5 Metal 3D Innovations: objectives and scope

Project Metal 3D Innovations, Me3DI (Teollisuuden 3D tulostus): started in 2018 to form a know-how cluster of metal AM in Finland's South Karelia region. As a project funded by the European Regional Development Fund. Metal 3D Innovations, Me3DI (Teollisuuden 3D tulostus) aimed to elevate local knowledge and capabilities on metal AM. This aim was carried out by utilizing academic, educational, and technical resources and equipment provided mainly by LUT University. As the first step, the LUT research teams identified the training needs for local companies to enable them to overcome limitations associated with conventional manufacturing technologies. The identifications also enabled the local companies and educational centers to recognize metal AM better, know geometrical limitations and freedom from conventional manufacturing and AM, respectively, and to understand the differences between metals processed via traditional manufacturing and AM. For better clarification different aims and actions considered and carried out through Metal 3D Innovations, Me3DI (Teollisuuden 3D tulostus) are shown in Fig. 15.

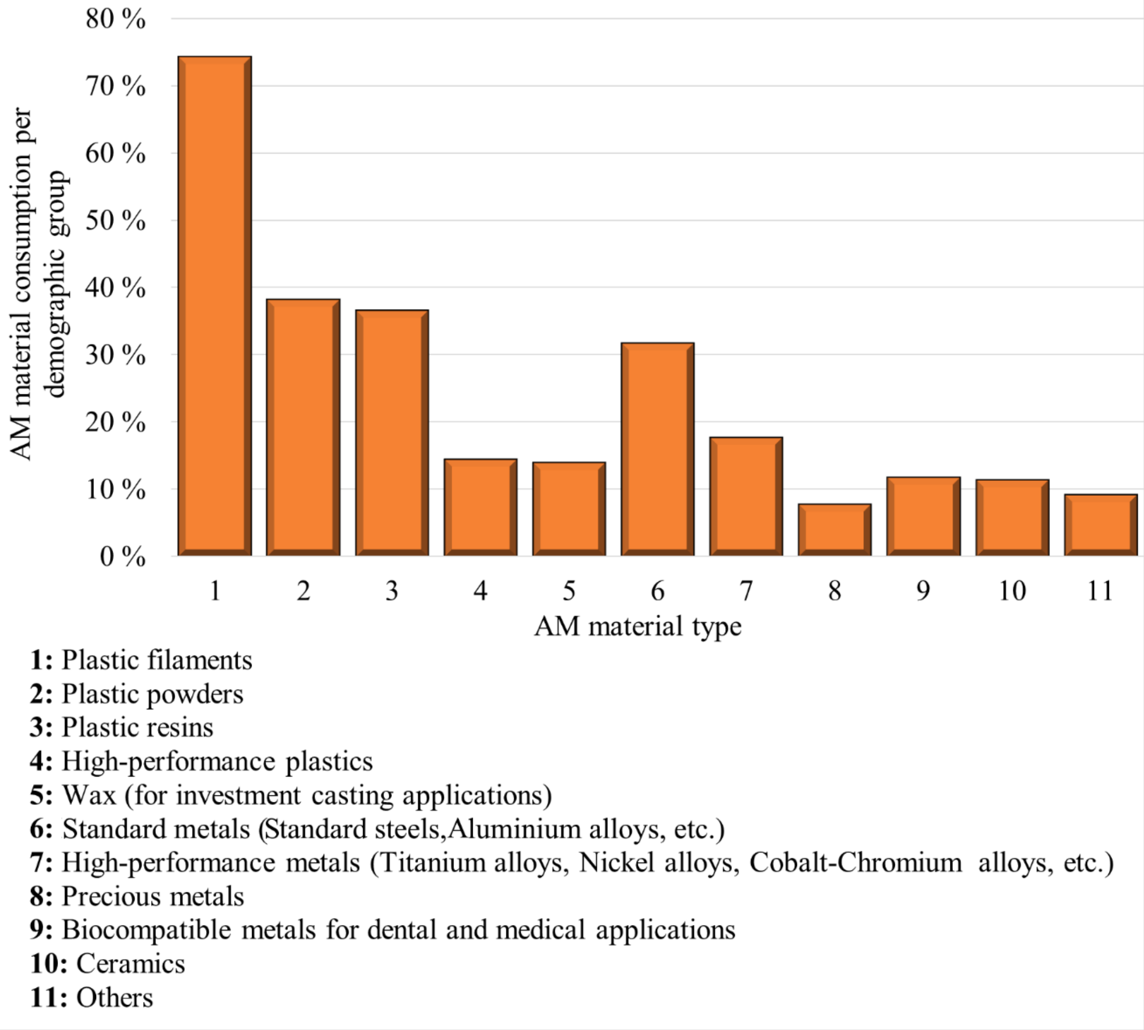


Fig. 13. Types and consumption ratio of AM materials in selected Finnish companies in 2017 (the accumulated percentage is higher than 100% due to multiple selections), based on data from [31].

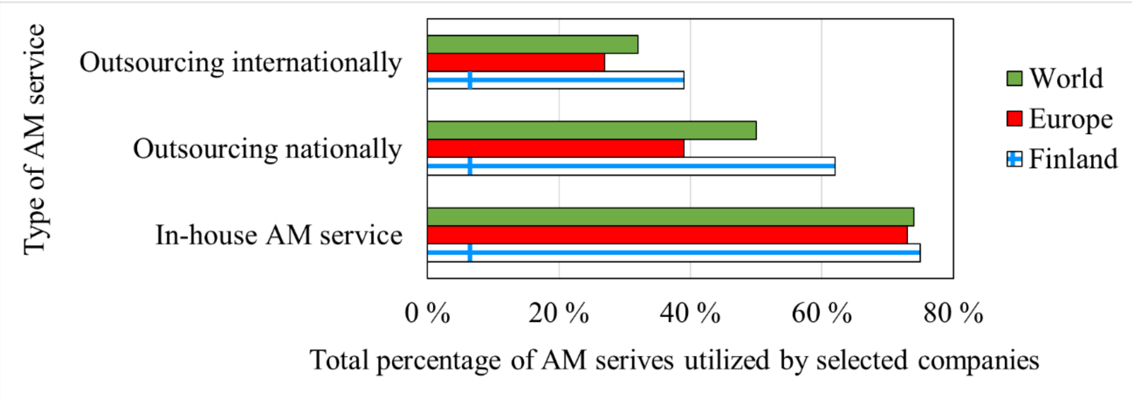


Fig. 14. Types of AM services in selected companies in 2017 (the accumulated percentage is higher than 100% due to multiple selections), based on data from [31].

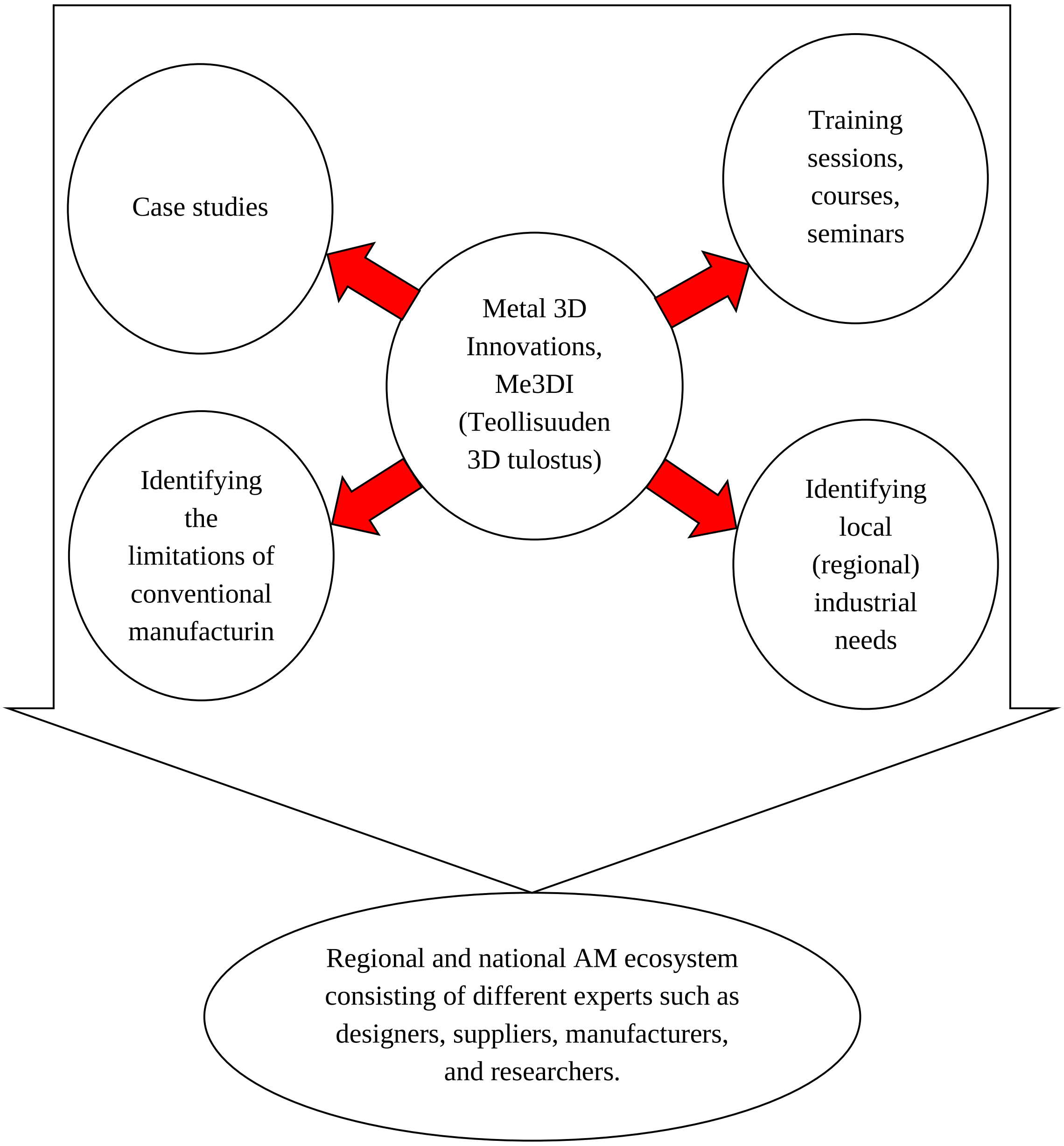


Fig. 15. Graphical presentation of the general aims and actions that are included in project Metal 3D Innovations, Me3DI (Teollisuuden 3D tulostus).

2. Methodology

Metal 3D Innovations, Me3DI (Teollisuuden 3D tulostus) project is based on both educational and research activities. Thus, this project included a series of training sessions (e.g., the online lecture "Fatigue Characteristics of AM metals" held on 21.05.2019 and the training session "Fatigue properties of 3D printed metals" held on 03.12.2019 at LUT University). The research studies of this project were mainly carried out in LUT University, sometimes in collaboration with other universities and research centers. The nature of the research activities was based on experimental procedures and analytical simulations. As the outcomes of these activities, a series of peer-reviewed articles, technical and training reports issued by the LUT publication center have been published. A list of these publications is presented in table 1. As an example of the experimental work carried out through this project, one of its case studies is more thoroughly introduced in section 4.

Table 1. *Published materials associated with project Metal 3D Innovations, Me3DI (Teollisuuden 3D tulostus).*

Title	Publisher	Status
Effects of manufacturing parameters and mechanical post-processing on stainless steel 316L processed by laser powder bed fusion	Elsevier (Journal of Materials Science and Engineering: A)	Open access
Effective parameters on the fatigue life of metals processed by powder bed fusion technique: A short review	Elsevier (Journal of Procedia Manufacturing)	Open access
Integration of Simulation Driven DfAM and LCC Analysis for Decision Making in L-PBF	MDPI (Metals)	Open access
Katsaus metallien 3D-tulostukseen: Tutkimuksen lähtökohdat	LUTPub (Report)	Open access
Lähtökohdat 3D-tulostuksen opetukseen ja koulutukseen	LUTPub (Report)	Open access
Characterization of heat effects on deformations occurring during the L-PBF based on simulation	LUTPub (Thesis)	Open access
Utilization of whole build volume in laser-based powder bed fusion	LUTPub (Thesis)	Open access
Effect of the most important parameters on properties of Inconel 718 manufactured by laser powder bed fusion	LUTPub (Thesis)	Open access

3. Metals and additive manufacturing

Some different AM technologies, among the ones introduced in Fig. 7, can be used for metal additive manufacturing. It is possible to divide these processes into two groups:

1- Indirect methods include binder jetting and laser sintering, which require further processing after AM to improve density and reach fully dense parts.

2- Direct methods, such as laser melting, electron beam melting, and laser engineered net shaping (LENS), do not require any further processing after AM.

It should be noted that even AM parts processed via the direct processes sometimes require post-processing heat treatments, machining, or surface treatments to improve their characteristics and reach their designated performance [7,33].

The powder bed processes, including powder bed fusion and binder jetting, have reached a level of maturity that they are the most common AM techniques for manufacturing industrial parts. In addition to powder bed processes, direct deposition techniques such as laser engineered net shaping and electron beam freeform fabrication (EBF3) are also quite popular in the industry, especially for repair and maintenance purposes. In addition, newly developed arc-based wire-DED, has been recently developed as an economical alternative for other direct deposition techniques that use laser or electron beam as their intensified heat sources. Some of the currently most common application areas for AM metals are also presented schematically in Fig. 16 [7,33].

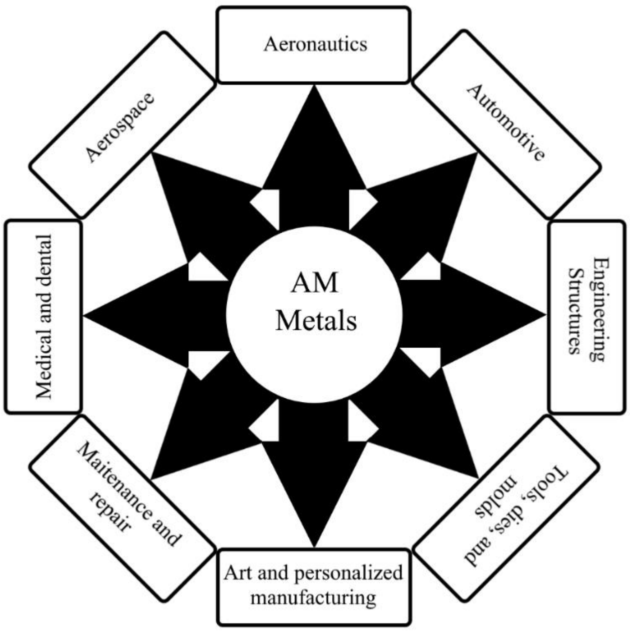


Fig. 16. Typical applications of AM metals in contemporary industries.

A wide variety of metals are nowadays available to be used as raw materials for additive manufacturing. The number of these metallic materials is continuously increasing. A list of current common metals in additive manufacturing is presented in table 2.

Table 2. *Common metals currently used in AM as raw materials [34,36–38].*

Type	Name / Alternative name	DIN specification
Stainless steel	Stainless steel 304	1.4301
	Stainless steel 316L	1.4404
	Stainless steel 316L	1.4441
	Stainless steel 410	1.4006
	Stainless steel 440	1.4110
	Stainless steel 15-5 PH / PH1	1.4540
	Stainless steel 17-4 PH / GP1	1.4542
	Stainless steel CX	-
Tool steel	AISI 420	1.2083
	Maraging steel 300	1.2709
	Maraging steel 18Ni300	-
	20MnCr5 / EN10084	-
	H13	1.2344
	AISI D2	1.2379
	AISI A2	1.2363
	AISI S7	1.2357
Aluminum alloys	AlSi10Mg	3.2381
	AlSi7Mg	3.2371
	AlSi7Mg0.6 / SAE AMS 4289	-
	AlSi12	3.3581
	AlMg1SiCu	-
	AA 2139 (AlCu, Mg)	-
Cobalt alloys	ASTM F75	2.4723
	CoCrWC	-
Nickel alloys	Inconel 718	2.4668
	Inconel 625	2.4856
	Inconel 713	2.4670
	Inconel 738	-
	Inconel 939	
	Hastelloy X	2.4665
Titanium alloys	Grade 2 Titanium	3.7035
	Ti6Al4V	3.7165
	Ti6Al4V ELI	3.7165 ELI
	TiAl6Nb7	-
	ASTM F67 / ISO 5822-2	-
Copper alloys	CC 480 K	2.1050
	High purity copper	-
	Commercial pure copper	-
	C18150 / CW106C	-
Precious metals	Gold	-
	Silver	-
Refractive Metals	W (Pure tungsten)	-

This diversity of AM metals provides its users with an acceptable possibility of choosing the right material for their specific purposes. A trade-off of the primary mechanical properties of the common AM metals is shown in Fig. 17. However, each metallic material cost should also be considered when compared with other AM metals. Similar to traditional manufacturing, steel is the most economical option covering a broad range of industrial applications [34,35].

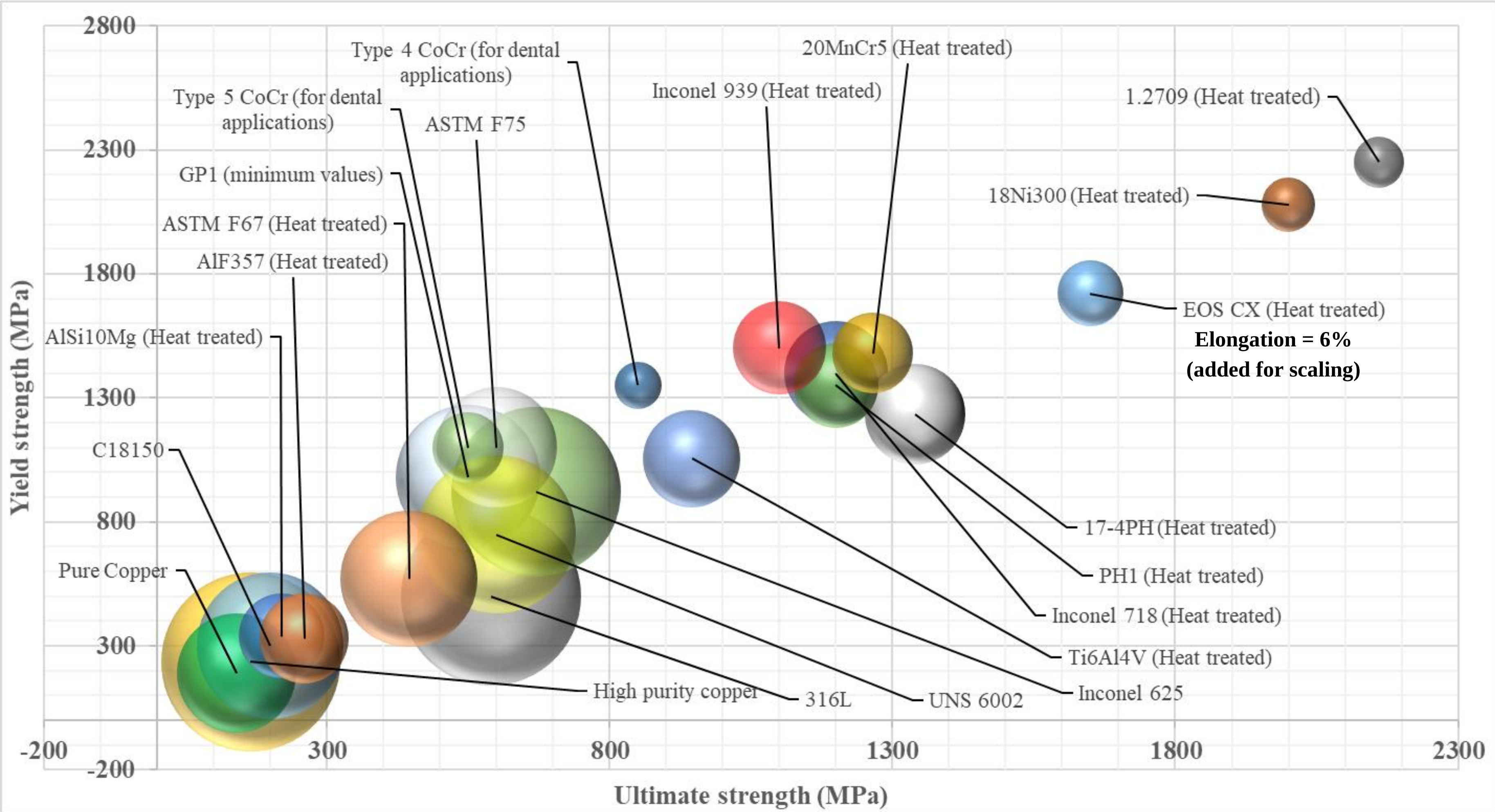


Fig. 17. General mechanical properties of common AM Metals (diameters of spheres represent their elongations), data from [37].

3.1 Metal AM: an opportunity to design optimization

The transition from traditional manufacturing and data management to digitalization has such a massive impact on human lives that it is called the fourth industrial revolution (Industry 4.0). Additive manufacturing is compatible with the Industry 4.0 paradigm due to its capabilities in supporting cloud-based technologies and an art-to-part approach. In addition, AM capabilities in design optimizations provide industries such as medical with case-specific designs for products like prosthetics and dental/medical implants, as shown in Fig. 18 [39–41]. Furthermore, metal AM provides designers with more freedom to optimize traditional ideas to have more durable and sustainable products, as shown in Fig. 19 [42].

Fig. 18. (a) Modified dental implants, and (b) cross-sectional view of a customized hip implant manufactured via metal AM [40,43]**.**

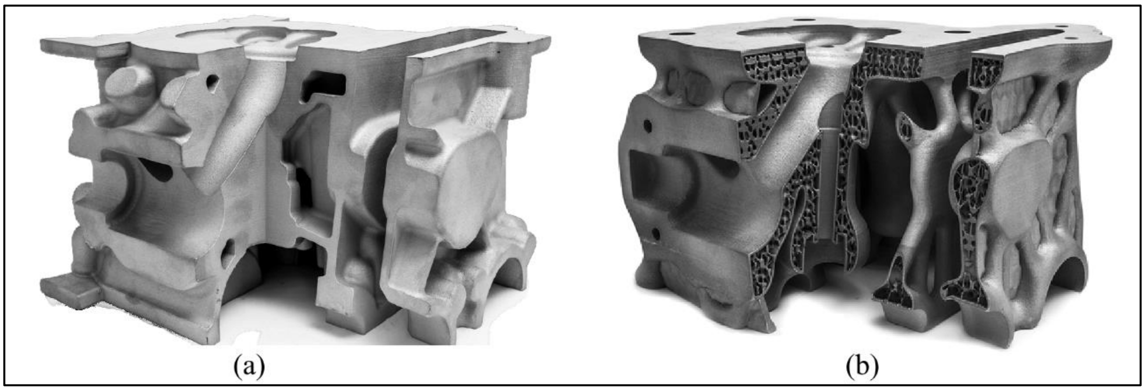


Fig. 19. Design optimization via metal AM: (a) traditional design, (b) modified AM design [42].

3.2 Standardization, ISO/TC 261, and ASTM F42 committees

AM and other industries that seem to be suitable candidates to leverage AM in their services and products demand different requirements and considerations to have an optimum manufacturing line with reliable products. This consideration is specifically valid for industries with more critical components, e.g., aerospace, aeronautics, and medical. Consequently, standard development committees for AM, such as ASTM F42 and ISO/TC 261, have formal agreements with committees from other industries, such as ISO/TC 44/SC 14, for working groups to develop standards for metal AM for different applications and industries, considering the needs of either side. Standards Joint Working Groups, such as JWG 5 for aerospace applications, are examples of such collaborations [44–47].

TC-261 and F42 are both standard committees developed for AM by ISO and ASTM, respectively. These organizations have signed a Partner Standards Developing Organization (PSDO) agreement to issue joint standards together to have a faster and more smooth procedure for AM standards development. For example, ISO/ASTM 52941:2020[2] is one of the latest products of such collaboration between the standard committees [48–50]. A list of active standards issued by ASTM and ISO for additive manufacturing is presented as an appendix at the end of this document.

[2] ISO/ASTM 52941:2020: Additive manufacturing — System performance and reliability — Acceptance tests for laser metal powder-bed fusion machines for metallic materials for aerospace application

4. Case study: physical and mechanical properties of stainless steel 316L processed via L-PBF

Project Metal 3D Innovations, Me3DI (Teollisuuden 3D tulostus) comprised of both educational (training) and research activities. As a part of the works carried out through this project, some studies were accomplished so that their results could get published in peer-reviewed scientific journals. For example, the physical and mechanical properties of stainless steel 316L after additively manufactured were evaluated, and its results have been published as an open-access article in the prestigious journal of Materials Science and Engineering (A) [51][3]. This research was carried out as a joint study between the Laboratory of Steel Structures and Laser Materials Processing and Additive Manufacturing at LUT University. The workflow of the study is shown schematically in Fig. 20. According to this figure, the study comprised of 8 steps:

1- Manufacturing: all samples were made of gas atomized stainless steel 316L powder developed by EOS.
2- Quality control: the quality of the manufactured samples was evaluated by measuring their density and comparing its value with the density of wrought 316L. Then, the porosity contents of various specimens were estimated via image processing technique and optical microscopy. Some of the sample images used for porosity measurement are shown in Fig. 21.a and b. Finally, the surface roughness values of the samples were measured to investigate their surface quality (Fig. 21.c).
3- Microstructural analysis: the microstructural features of 3D printed 316L were investigated via optical and scanning electron microscopy (SEM), as shown in Fig. 21.d and e.
4- Hardness measurement: the Vickers hardness values of the samples were measured after their microstructural investigation. Two measurement marks can be seen in the SEM image from Fig. 21.e.
5- Quasi-static tensile test: the yield and ultimate strengths, ductility, and elastic modulus of the specimens were indicated via quasi-static tensile test (Fig. 21.f). In addition, the strain hardening behavior of 3D printed 316L was evaluated based on the data achieved by the tensile tests.
6- High-cycle fatigue test: the performance of 3D printed 316L was evaluated under high cyclic loads until up to 1000000 cycles.
7- Charpy test: Notch-toughness values of 3D printed 316L were measured via Chapry impact test.
8- Fractography: the fracture surfaces of the broken specimens from quasi-static tensile, high-cycle fatigue, or Charpy tests were investigated by optical microscopy and SEM. The fractography analysis was used to evaluate fracture mechanisms of the material under different types of loads. Furthermore, influential factors and defects in each kind of fracture were indicated through the fractography analysis.

The general conclusions of the study show that the performance of 3D printed 316L under quasi-static, cyclic, and impact loads can be as good as or even better in some cases compared with the traditionally manufactured 316L. The reader is referred to [51] for the detailed presentation of the results and more in-depth discussions on the subjects mentioned above.

[3] https://doi.org/10.1016/j.msea.2020.140660

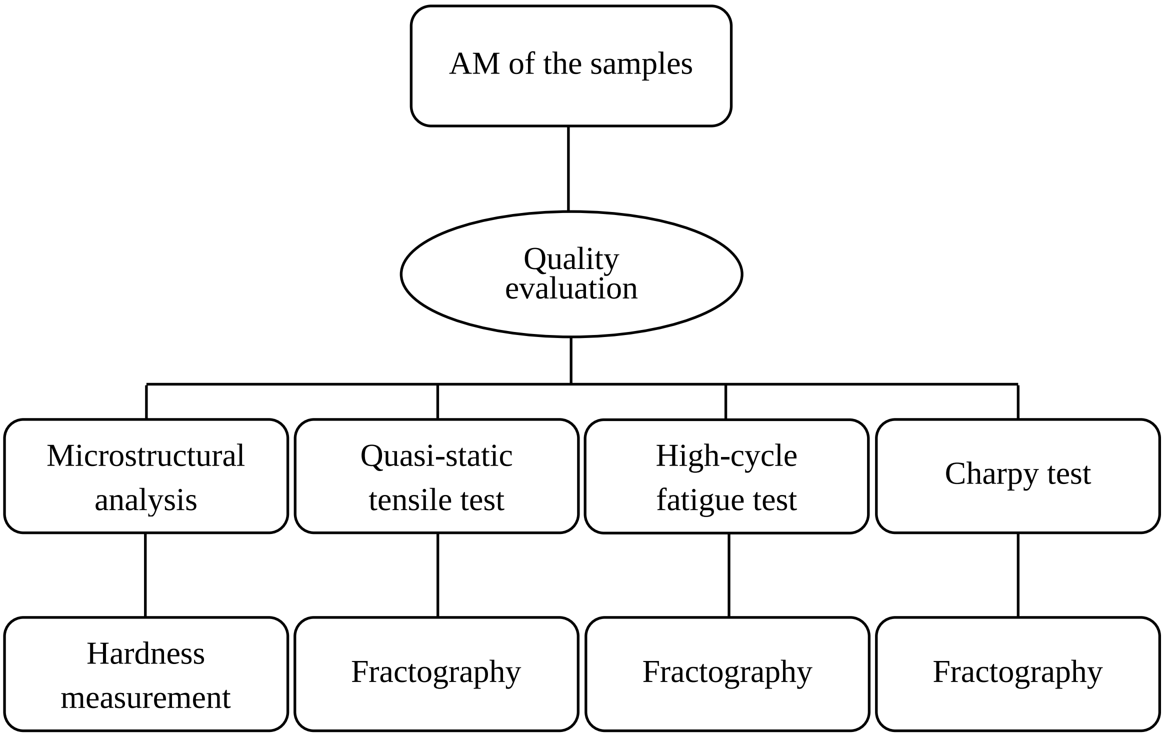


Fig. 20. Workflow of the research carried out on additively manufactured 316L as a part of project Metal 3D Innovations, Me3DI (Teollisuuden 3D tulostus).

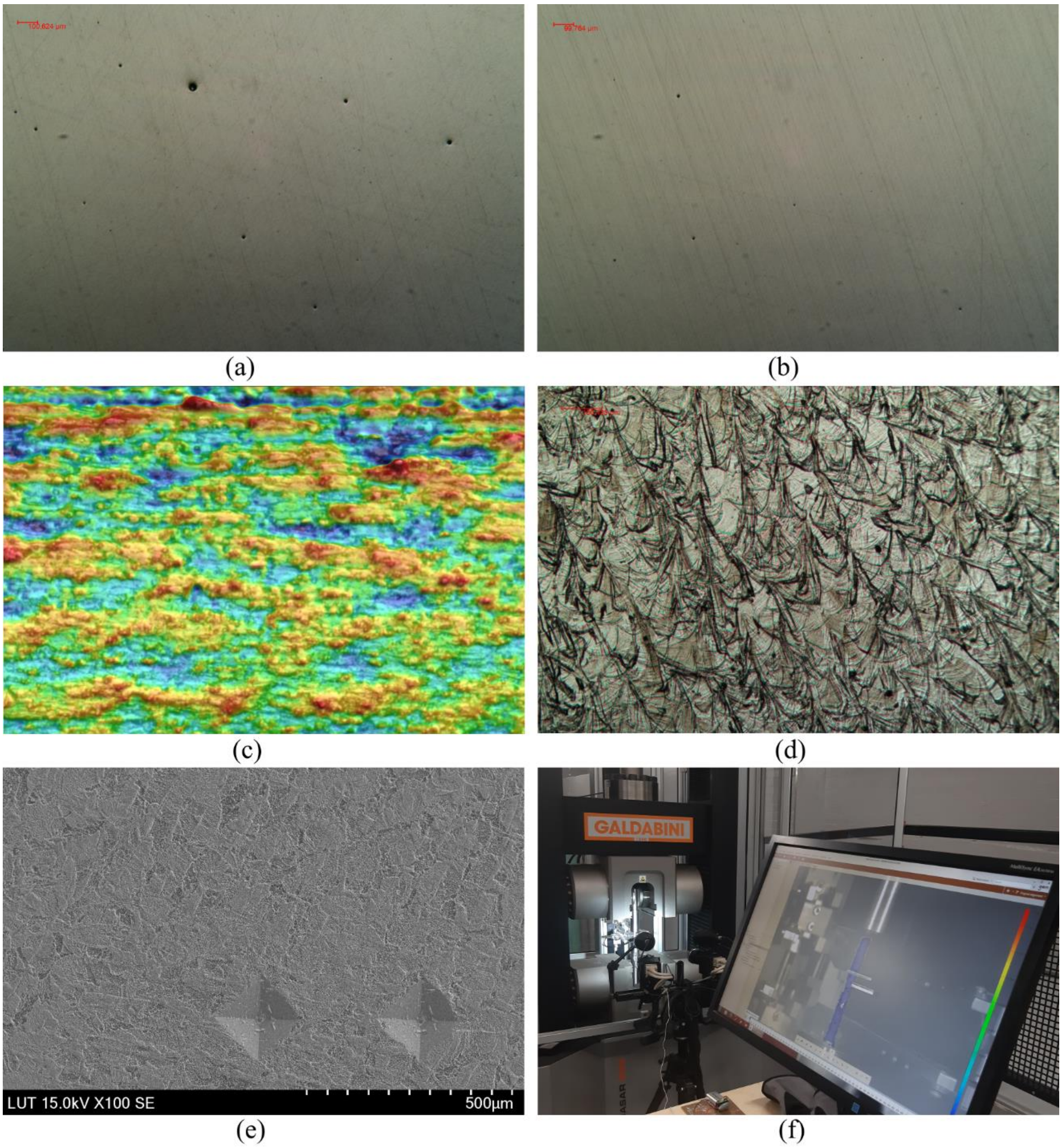


Fig. 21. Experimental procedure of the case study.

5. Conclusions

Metal AM has an assured place in the future of industrial production, considering the current high demand for more sustainable production and minimizing material waste. Thus, more activities should be focused on introducing this technology to designers and local manufacturers. As shown in the case study of this report, some 3D printed metals such as stainless steel 316L have a strong potential to compete with their traditionally manufactured counterparts and even excel them regarding many specific material properties and applications. These facts point to the necessity of projects like Metal 3D Innovations, Me3DI (Teollisuuden 3D tulostus) to promote AM and expand its dominance in the manufacturing paradigm.

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APPENDIX A: AM STANDARDS

Table I. List of Additive Manufacturing standards [46].

Designation	Title	Issued by	Status
ASTM F2971-13	Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing	ASTM	Published
ASTM F3049-14	Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes	ASTM	Published
ASTM F3001-14	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion	ASTM	Published
ASTM F3091/F3091M-14	Standard Specification for Powder Bed Fusion of Plastic Materials	ASTM	Published
ASTM F3122-14	Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes	ASTM	Published
ASTM F2924-14	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion	ASTM	Published
ASTM F3056-14e1	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion	ASTM	Published
ASTM F3055-14a	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion	ASTM	Published
ASTM F3184-16	Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion	ASTM	Published
ASTM F3187-16	Standard Guide for Directed Energy Deposition of Metals	ASTM	Published
ASTM F3213-17	Standard for Additive Manufacturing — Finished Part Properties — Standard Specification for Cobalt-28 Chromium-6 Molybdenum via Powder Bed Fusion	ASTM	Published
ASTM F3302-18	Standard for Additive Manufacturing — Finished Part Properties — Standard Specification for Titanium Alloys via Powder Bed Fusion	ASTM	Published
ASTM F3318-18	Standard for Additive Manufacturing — Finished Part Properties — Specification for AlSi10Mg with Powder Bed Fusion — Laser Beam	ASTM	Published

ASTM F3301-18a	Standard for Additive Manufacturing — Post Processing Methods — Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion1, 2	ASTM	Published
ASTM F3335-20	Standard Guide for Assessing the Removal of Additive Manufacturing Residues in Medical Devices Fabricated by Powder Bed Fusion	ASTM	Published
ISO/ASTM52900-15	Standard Terminology for Additive Manufacturing — General Principles — Terminology1, 2	ISO/ASTM	Published
ISO/ASTM52901-16	Standard Guide for Additive Manufacturing — General Principles — Requirements for Purchased AM Parts	ISO/ASTM	Published
ISO/ASTM52915-16	Standard Specification for Additive Manufacturing File Format (AMF) Version 1.	ISO/ASTM	Published
ISO/ASTM52910-18	Additive manufacturing — Design — Requirements, guidelines and recommendations	ISO/ASTM	Published
ISO/ASTM52902-19	Additive manufacturing — Test artifacts — Geometric capability assessment of additive manufacturing systems	ISO/ASTM	Published
ISO/ASTM52921-13(2019)	Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies	ISO/ASTM	Published
ISO/ASTM52907-19	Additive manufacturing — Feedstock materials — Methods to characterize metallic powders	ISO/ASTM	Published
ISO/ASTM52911-1-19	Additive manufacturing — Design — Part 1: Laser-based powder bed fusion of metals	ISO/ASTM	Published
ISO/ASTM52911-2-19	Additive manufacturing — Design — Part 2: Laser-based powder bed fusion of polymers	ISO/ASTM	Published
ISO/ASTM52904-19	Additive Manufacturing — Process Characteristics and Performance: Practice for Metal Powder Bed Fusion Process to Meet Critical Applications	ISO/ASTM	Published
ISO 17296-2:2015	Additive manufacturing — General principles — Part 2: Overview of process categories and feedstock	ISO	Published
ISO 17296-3:2014	Additive manufacturing — General principles — Part 3: Main characteristics and corresponding test methods	ISO	Published
ISO 17296-4:2014	Additive manufacturing — General principles — Part 4: Overview of data processing	ISO	Published

ISO 27547-1:2010	Plastics — Preparation of test specimens of thermoplastic materials using mouldless technologies — Part 1: General principles, and laser sintering of test specimens	ISO	Published
ISO/ASTM 52903-1	Additive manufacturing — Material extrusion-based additive manufacturing of plastic materials — Part 1: Feedstock materials	ISO/ASTM	In development
ISO/ASTM DIS 52903-2	Additive manufacturing — Standard specification for material extrusion based additive manufacturing of plastic materials — Part 2: Process — Equipment	ISO/ASTM	In development
ISO/ASTM DTR 52905	Additive manufacturing — General principles — Non-destructive testing of additive manufactured products	ISO/ASTM	In development
ISO/ASTM CD TR 52906	Additive manufacturing — Non-destructive testing and evaluation — Standard guideline for intentionally seeding flaws in parts	ISO/ASTM	In development
ISO/ASTM AWI 52908	Additive manufacturing — Post-processing methods — Standard specification for quality assurance and post processing of powder bed fusion metallic parts	ISO/ASTM	In development
ISO/ASTM AWI 52909	Additive manufacturing — Finished part properties — Orientation and location dependence of mechanical properties for metal powder bed fusion	ISO/ASTM	In development
ISO/ASTM PWI 52911-3	Additive manufacturing -- Technical design guideline for powder bed fusion -- Part 3: Standard guideline for electron-based powder bed fusion of metals	ISO/ASTM	In development
ISO/ASTM PRF TR 52912	Additive manufacturing - Design - Functionally graded additive manufacturing	ISO/ASTM	In development
ISO/ASTM PWI 52913-1	Additive manufacturing -- Test methods for characterization of powder flow properties for AM applications - Part 1: General requirements	ISO/ASTM	In development
ISO/ASTM PWI 52914	Additive manufacturing -- Design -- Standard guide for material extrusion processes	ISO/ASTM	In development
ISO/ASTM WD 52916	Additive manufacturing — Data formats — Standard specification for optimized medical image data	ISO/ASTM	In development
ISO/ASTM WD 52917	Additive manufacturing — Round Robin Testing — Guidance for conducting Round Robin studies	ISO/ASTM	In development

ISO/ASTM CD TR 52918	Additive manufacturing — Data formats — File format support, ecosystem and evolutions	ISO/ASTM	In development
ISO/ASTM WD 52919-1	Additive manufacturing — Test method of sand mold for metalcasting — Part 1: Mechanical properties	ISO/ASTM	In development
ISO/ASTM WD 52919-2	Additive manufacturing — Test method of sand mold for metalcasting — Part 2: Physical properties	ISO/ASTM	In development
ISO/ASTM PWI 52920-1	Additive manufacturing — Qualification principles — Part 1: Conformity assessment for AM system in industrial use	ISO/ASTM	In development
ISO/ASTM WD 52920-2	Additive manufacturing — Qualification principles — Part 2: Requirements for industrial additive manufacturing sites	ISO/ASTM	In development
ISO/ASTM DIS 52921	Additive manufacturing — General principles — Standard practice for part positioning, coordinates and orientation	ISO/ASTM	In development
ISO/ASTM PWI 52922	Additive manufacturing -- Design -- Directed energy deposition	ISO/ASTM	In development
ISO/ASTM PWI 52923	Additive manufacturing -- Design decision support	ISO/ASTM	In development
ISO/ASTM DIS 52924	Additive manufacturing — Qualification principles — Classification of part properties for additive manufacturing of polymer parts	ISO/ASTM	In development
ISO/ASTM DIS 52925	Additive manufacturing — Qualification principles — Qualification of polymer materials for powder bed fusion using a laser	ISO/ASTM	In development
ISO/ASTM WD 52926-1	Additive manufacturing — Qualification principles — Part 1: Qualification of machine operators for metallic parts production	ISO/ASTM	In development
ISO/ASTM WD 52926-2	Additive manufacturing — Qualification principles — Part 2: Qualification of machine operators for metallic parts production for PBF-LB	ISO/ASTM	In development
ISO/ASTM WD 52926-3	Additive manufacturing — Qualification principles — Part 3: Qualification of machine operators for metallic parts production for PBF-EB	ISO/ASTM	In development
ISO/ASTM WD 52926-4	Additive manufacturing — Qualification principles — Part 4: Qualification of machine operators for metallic parts production for DED-LB	ISO/ASTM	In development
ISO/ASTM WD 52926-5	Additive manufacturing — Qualification principles — Part 5: Qualification of	ISO/ASTM	In development

	machine operators for metallic parts production for DED-Arc		
ISO/ASTM PWI 52927	Additive manufacturing -- Process characteristics and performance - Test methods	ISO/ASTM	In development
ISO/ASTM PWI 52928	Powder life cycle management	ISO/ASTM	In development
ISO/ASTM NP 52930	Guideline for installation -- Operation -- Performance Qualification (IQ/OQ/PQ) of laser-beampowder bed fusion equipment for production manufacturing	ISO/ASTM	In development
ISO/ASTM CD 52931	Additive manufacturing — Environmental health and safety — Standard guideline for use of metallic materials	ISO/ASTM	In development
ISO/ASTM WD 52932	Additive manufacturing — Environmental health and safety — Standard test method for determination of particle emission rates from desktop 3D printers using material extrusion	ISO/ASTM	In development
ISO/ASTM NP 52933	Additive manufacturing — Environment, health and safety — Consideration for the reduction of hazardous substances emitted during the operation of the non-industrial ME type 3D printer in workplaces, and corresponding test method	ISO/ASTM	In development
ISO/ASTM PWI 52934	Additive manufacturing -- Environmental health and safety -- Standard guideline for hazard risk ranking and safety defense	ISO/ASTM	In development
ISO/ASTM NP 52935	Additive manufacturing — Qualification Principles — Qualification of coordinators for metallic parts production	ISO/ASTM	In development
ISO/ASTM WD 52936-1	Additive manufacturing — Qualification principles — Laser-based powder bed fusion of polymers — Part 1: General principles, preparation of test specimens	ISO/ASTM	In development
ISO/ASTM PWI 52937	Additive manufacturing — Qualification principles — Qualification of designers for metallic parts production	ISO/ASTM	In development
ISO/ASTM DIS 52941	Additive manufacturing — System performance and reliability — Standard test method for acceptance of powder-bed fusion machines for metallic materials for aerospace application	ISO/ASTM	In development
ISO/ASTM DIS 52942	Additive manufacturing — Qualification principles — Qualifying machine operators of laser metal powder bed fusion machines and equipment used in aerospace applications	ISO/ASTM	In development

ISO/ASTM PWI 52943-1	Additive manufacturing -- Process characteristics and performance -- Part 1: Standard specification for directed energy deposition using wire and beam in aerospace applications	ISO/ASTM	In development
ISO/ASTM PWI 52943-2	Additive manufacturing -- Process characteristics and performance -- Part 2: Standard specification for directed energy deposition using wire and arc in aerospace applications	ISO/ASTM	In development
ISO/ASTM PWI 52943-3	Additive manufacturing -- Process characteristics and performance -- Part 3: Standard specification for directed energy deposition using laser blown powder in aerospace applications	ISO/ASTM	In development
ISO/ASTM PWI 52944	Additive manufacturing -- Process characteristics and performance -- Standard specification for powder bed processes in aerospace applications	ISO/ASTM	In development
ISO/ASTM DIS 52950	Additive manufacturing — General principles — Overview of data processing	ISO/ASTM	In development
ISO/ASTM PWI 52951	Additive manufacturing -- Data packages for AM parts	ISO/ASTM	In development
ASTM WK66029	New Guide for Mechanical Testing of Polymer Additively Manufactured Materials	ASTM	In development
ASTM WK66030	Quality Assessment of Metal Powder Feedstock Characterization Data for Additive Manufacturing	ASTM	In development
ASTM WK67454	Additive manufacturing -- Feedstock materials -- Methods to characterize metallic powders	ASTM	In development
ASTM WK69371	Standard practice for generating mechanical performance debits	ASTM	In development
ASTM WK69731	New Guide for Additive Manufacturing -- Non-Destructive Testing (NDT) for Use in Directed Energy Deposition (DED) Additive Manufacturing Processes	ASTM	In development
ASTM WK71391	Additive Manufacturing -- Static Properties for Polymer AM (Continuation)	ASTM	In development
ASTM WK71393	Additive manufacturing -- assessment of powder spreadability for powder bed fusion (PBF) processes	ASTM	In development
ASTM WK71395	Additive manufacturing -- accelerated quality inspection of build health for laser beam powder bed fusion process	ASTM	In development

ASTM WK48549	AMF Support for Solid Modeling: Voxel Information, Constructive Solid Geometry Representations and Solid Texturing	ASTM	In development
ASTM WK72172	Additive manufacturing -- General principles -- Overview of data pedigree	ASTM	In development
ASTM WK65937	Additive Manufacturing -- Space Application -- Flight Hardware made by Laser Beam Powder Bed Fusion Process	ASTM	In development
ASTM WK69730	Additive Manufacturing -- Wire for Directed Energy Deposition (DED) Processes in Additive Manufacturing	ASTM	In development
ASTM WK69732	Additive Manufacturing -- Wire Arc Additive Manufacturing	ASTM	In development
ASTM WK72317	Additive Manufacturing -- Powder Bed Fusion -- Multiple Energy Sources	ASTM	In development
ASTM WK72457	Additive manufacturing processes -- Laser sintering of polymer parts/laser-based powder bed fusion of polymer parts -- Qualification of materials	ASTM	In development
ASTM WK66637	Additive Manufacturing -- Finished Part Properties -- Specification for 4340 Steel via Laser Beam Powder Bed Fusion for Transportation and Heavy Equipment Industries	ASTM	In development
ASTM WK67583	Additive Manufacturing -- Feedstock Materials -- Powder Reuse Schema in Powder Bed Fusion Processes for Medical Applications	ASTM	In development
ASTM WK70164	Additive Manufacturing -- Finished Part Properties -- Standard Practice for Assigning Part Classifications for Metallic Materials	ASTM	In development
ASTM WK71891	Additive Manufacturing of Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion for Medical Devices	ASTM	In development
ASTM WK66682	Evaluating Post-processing and Characterization Techniques for AM Part Surfaces	ASTM	In development

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