LUT UNIVERSITY
LUT School of Energy Systems
LUT Mechanical Engineering
BK10A0402 Bachelor’s thesis

SUOMALAISEN TEOLLISUUDEN METALLIMATERIAALITARPEET LASERPOHJAISESSA JAUHEPETISULATUKSESSA

METAL MATERIAL NEEDS OF FINNISH INDUSTRY IN LASER POWDER BED FUSION

Lappeenranta 30.3.2018
Markus Oltamo
Examiner Docent Heidi Piili, D. Sc.
Supervisor Docent Heidi Piili, D. Sc.

TIIVISTELMÄ

LUT-Yliopisto
LUT School of Energy Systems
LUT Kone

Markus Oltamo

Suomalaisen teollisuuden metallimateriaalitarpeet laserpohjaisessa jauhepetisulatuksessa

Kandidaatintyö

2019

42 sivua, 10 kuvaa ja 1 taulukko

Tarkastajat: Dosentti Heidi Piili, TkT

Hakusanat: Lisäävä valmistus, AM, 3D-tulostus, jauhepetisulatus, PBF, laserpohjainen jauhepetisulatus, L-PBF, metalli, teollisuuden tarpeet

Tämän tutkimuksen tarkoituksena oli kartoittaa suomalaisen teollisuuden metallimateriaali tarpeita laserpohjaiseen jauhepetisulatukseen (L-PBF), joka kuuluu lisäävän valmistuksen eli ns. 3D-tulostuksen piiriin (AM). Tarkoitus oli myös selvittää, että onko löydettyjä metallimateriaaleja myytävänä kaupallisina jauheina, joita voidaan käyttää laserpohjaisessa jauhepetisulatuksessa. Työn alussa esitetään kirjallisuustutkimuksen avulla metallien lisäävää valmistusta, laserpohjaista jauhepetisulatusta sekä myytävänä olevat kaupalliset metallijauheet, jotka soveltuvat käytettäväksi laserpohjaisessa jauhepetisulatuksessa. Työn lopussa esitetään kvantitatiivisen kyselyn tulokset, johon vastasi 15 yrityksestä 17 työntekijää.

Haastattelusta ilmeni, että haastateltavat tunsivat metallien 3D-tulostuksen keskiarvoltaan kohtalaisesti. Kolme vastaajaa oli käyttänyt metallien 3D-tulostusta työssään aikaisemmin ja 14 ei ollut. 12 vastaajaa koki tarvitsevansa metallien 3D-tulostusta tulevaisuudessa. Kolme vastaajaa ei osannut sanoa, tarvitsevatko he metallien 3D-tulostusta tulevaisuudessa vai ei, ja kaksi koki sen tarpeettomaksi.

Aiemmin metallien 3D-tulostusta työssään käyttäneet kertoivat tehneensä tulosteita kymmenestä eri metallimateriaalista. Vastaajat, jotka haluaisivat käyttää metallien 3D-tulostusta tulevaisuudessa, kertoivat haluavansa tehdä tulosteita 12:sta eri metallimateriaalista. Näistä materiaaleista 11 löytyy laserpohjaisen jauhepetisulatukseen soveltuvana metallijauheena kansainvälisiltä markkinoilta vähintään yhdeltä myyjältä, mutta yhtä ei löydy. Kansainvälisiltä markkinoilta löytyi yhteensä 224 eri metallimateriaalia, jotka soveltuvat laserpohjaiseen jauhepetisulatukseen.

ABSTRACT

LUT University
LUT School of Energy Systems
LUT Mechanical engineering

Markus Oltamo

Metal material needs of Finnish industry in laser powder bed fusion

Bachelor's thesis

2019

42 pages, 10 figures and 1 table

Examiner: Docent Heidi Piili, D. Sc.

Supervisor: Docent Heidi Piili, D. Sc.

Keywords: Additive manufacturing, AM, 3D printing, powder bed fusion, PBF, laser-based powder bed fusion, L-PBF, metal, industrial need

This study was carried out to investigate the metal material needs of Finnish industry for laser-based powder bed fusion (L-PBF), which belongs to additive manufacturing (AM) technologies, which are also known as 3D printing technologies. Another purpose was to investigate commercial powder availability of the found materials for L-PBF. This thesis comprises of a literature research about metal additive manufacturing, L-PBF and a table of available metal powders for L-PBF as well as of results of a quantitative survey about the metal materials needs of Finnish industry for L-PBF. 17 representatives from 15 Finnish industrial companies were interviewed for the survey.

Familiarity of metal 3D printing of the respondents were found to be moderate on average. Three respondents had used 3D printing of metal materials professionally and 14 had not. 12 respondents expressed needs for 3D printing of metal materials in the future, while three were uncertain and two did not find it relevant.

The respondents had previously used ten different metal materials for 3D printing and expressed future needs for 12 different materials. 11 of these materials were found to be available for L-PBF from at least one powder supplier and one material was found to be unavailable for L-PBF. In total, 224 different metal materials were found to be available from different manufacturers.

TABLE OF CONTENTS

ABREVIATIONS

AM	Additive manufacturing
ASTM	American Society for Testing and Materials
CAD	Computer adjusted design
CAGR	Compound annual growth rate
ISO	International Organization for Standardization
L-PBF	Laser-based powder bed fusion
PBF	Powder bed fusion

1 INRODUCTION

This bachelor's thesis was conducted to investigate metal material needs of Finnish industry in laser-based powder bed fusion (L-PBF), which belongs to metal additive manufacturing (AM) technologies, which are also known as 3D printing technologies. Another focus of interest was to survey if these materials are commercially available for laser-based powder bed fusion.

1.1 Background

The current transformation in manufacturing industries related to the rise of digital technologies in production processes and business models is often referred to as the fourth industrial revolution. New digital industrial technologies are transforming industry to a new era. Additive manufacturing (AM) refers to a category of technologies, by which three-dimensional objects can be created by adding layer after layer of a material according to a 3D model (Gibson, Rosen & Strucker 2015, p. v). In many industries, AM is considered to have potential for increasing competitiveness by optimizing supply chains and production processes. For instance, in the case of a production process being halted due to the mechanical failure of a component in a machine, using AM technology on site or nearby to build a replacement component can reduce costly down-time (Milewski 2017, p. 272). Overall, utilization of AM can be beneficial to industrial businesses in many areas. (Gerbert et al. 2015.)

AM works by adding material layer by layer, rather than subtracting material from a block (Gibson, Rosen & Strucker 2015, p. 7). Therefore, the technologies therefore enable construction of complex parts, which cannot be manufactured with conventional methods (Milewski 2017, p. xxv). By enabling production of complex shapes, parts can be designed to be lighter weight or to have higher performance e.g. less restricted fluid flow in a nozzle (Gerbert et al. 2015; Kover 2018).

As material is added rather than subtracted, less material is used and less waste is produced, therefore AM enables the use of expensive materials such as titanium more cost effectively (Gerbert et al. 2015). In addition to decreasing waste in the production process, AM also producing small batches or even individual pieces cost effectively, enabling a fast time to market, which can be an advantage in one-off applications such as rarely needed spare parts (Leong 2019).

AM industry is growing rapidly, reflecting the increasing industrial demand for AM technologies. First commercial AM systems were brought to market in the late 1980s, after which AM industry has been mostly growing annually, with rapid annual growth after the global industry started to recover from the financial crisis of 2008. During 1988–2016, compound annual growth rate (CAGR) of all worldwide revenues produced by AM industry was 25.9%, and 28.0% during 2013–2016, bringing total revenue to $6.06 billion in 2016. Yearly metal AM system sales have steadily grown from 202 pcs in 2012 to 957 pcs in 2016, with an average selling price of $567000. Rapid growth of yearly metal material revenues is shown in figure 1. (Wohlers 2017, p. 18, 148, 150, 154, 161.)

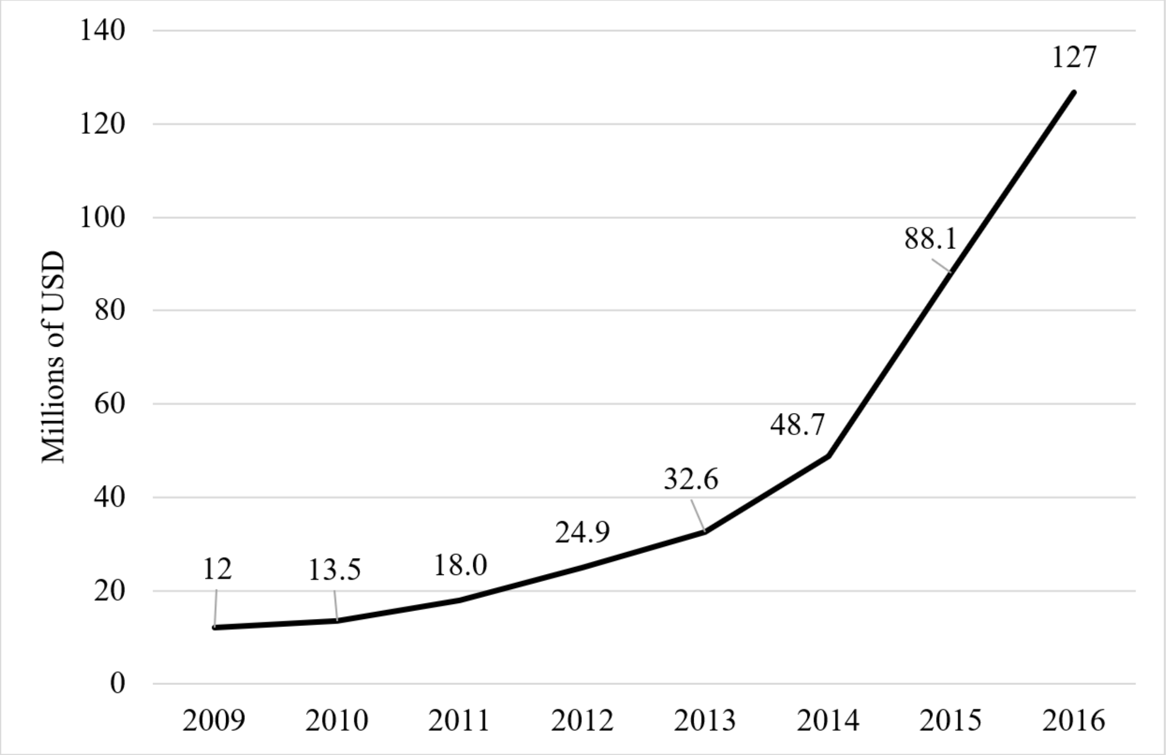

Figure 1. Global market size of metal materials in M$ (Wohlers 2017, p. 161).

As it can be seen from figure 1, revenues from metal materials have grown from $12.0 million to $127 million during 2009–2016. Seven metal powder producers expected market growth to exceed 59.0% in 2017. (Wohlers 2017, p. 161)

As has been shown in figure 1, the metal materials market for AM has been growing in recent years, and growth is expected to continue in coming years. However, it is not clear, if the material demands of Finnish industrial companies are met in all cases by the supplying market, as the technology is rapidly developing and growing.

Research concerning the needs of metal materials of Finnish industry has previously been studied to some extent. Korpela (2019) has studied the issue in his master's thesis. While the scope of this study is similar to Korpela, the industrial companies surveyed are different and the present study therefore serves to fill in the picture of metal material demands of Finnish industrial companies.

In this study, literature review was conducted to look at the range of materials currently available on the market. To find out the metal material needs of Finnish industry, a survey was sent to 15 Finnish industrial companies, all of which provided a response.

1.2 Research problems and questions

The research questions of this thesis are:

- Which metal materials are Finnish companies interested in using in powder bed fusion?
- Are the metal materials in question suitable for powder bed fusion?
- Do the metal materials in question exist in powder bed fusion applicable powder form?

1.3 Objectives and motive

The objective of this bachelor's thesis is to clarify metal material needs of Finnish industry and analyse commercial availability of these metal materials. Understanding the metal material needs of industrial companies involved in the applications of AM provides insight on which metal material groups more research should be done into as well as providing companies with useful information about the current market situation.

1.4 Scope

The scope of this thesis is such that not all AM technologies could be included in the study. In this thesis, metal AM processes were limited to laser powder bed fusion (L-PBF), because it is the most commonly used metal AM process (Wohlers 2017, p. 43). PBF utilizes material in powder form, so AM materials in wire form were not investigated. The scope of this study allowed for the surveying of only about 15 Finnish industrial companies, which means that the results of this study should not be generalized to industry widely.

2 ADDITIVE MANUFACTURING OF METAL MATERIALS

Parts in metal AM, more precisely in L-PBF, are made from 3D model data by adding material layer by layer with each layer being a thin cross-section of the part. Since every layer has a finite thickness, all parts made with AM are approximations of the original 3D model, where as thin as possible layers produce as close as possible approximations. All commercial metal AM machines produce parts layer by layer, but differentiate in which materials can be used, and how layers are created and bonded. These differences affect accuracy, material properties and mechanical properties of the manufactured part as well as lead time, amount of post processing, the size of the AM machine, and cost of the machine and process. In metal additive manufacturing, parts are made from 3D model data by melting metal powder or wire feedstock with a thermal energy source layer by layer (Milewski 2017, p. vi). (Gibson, Rosen & Strucker 2015, p. 2.)

In some cases, the ability to manufacture complex geometries with metal AM leads to new designs, where end-parts combined from multiple conventionally manufactured parts, can be manufactured as a single part with complex geometries with metal AM. Ability to produce parts with complex geometries with metal AM, may also provide considerably higher performance in end-part use e.g. lighter weight or less restrictive fluid flow. Higher performance in end-part use may excuse higher production cost of AM. (Kellner 2017; Gerbert et al. 2015.)

An example of the capabilities of AM are fuel nozzle tips inside LEAP jet engines made by GE Aviation. GE Aviation was able to combine 20 previously welded pieces into one additively manufactured piece. The additively manufactured fuel nozzle tip was also 25.0% lighter, five times more durable, 30.0% cheaper to produce and had 14 fluid passages. In October of 2018, GE Aviation had made 30 000 additively manufactured fuel nozzle tips at their 3D-printing facility. The fuel nozzle can be seen in figure 2. (Kover 2018.)

Figure 2. Fuel nozzle of a LEAP jet engine (Kover 2018).

Metal AM offers various benefits for producing metal parts. Time to market and cost is decreased with metal AM, because of a highly automated process. Manufacturing of complex parts is generally performed in one step leading to part size driven costs excluding complexity driven costs. In conventional manufacturing, complexity adds more production steps, which lengthens production time and may require more advanced manufacturing methods leading to higher cost. Furthermore, metal AM is an additive process where material is added rather than subtracted as in conventional manufacturing, which produces less scrap and waste. Therefore, metal AM is a more environmentally friendly and cost-efficient manufacturing method, especially when producing parts from specialty materials e.g. titanium alloys. Metal powders used in metal AM can also be recycled. (Gibson, Rosen & Strucker 2015, p. 9, 394; Leong 2019; Milewski 2017, p. 59; Brandt 2017, p. 3.)

Metal AM is mainly used for low-volume production as per-unit cost is not dependent on volume and there are almost no overhead costs. E.g. casting and injection moulding have high overhead costs, but low per part costs. Cost per part compared to production volume of metal AM and conventional manufacturing is shown in figure 3. (Leong 2019.)

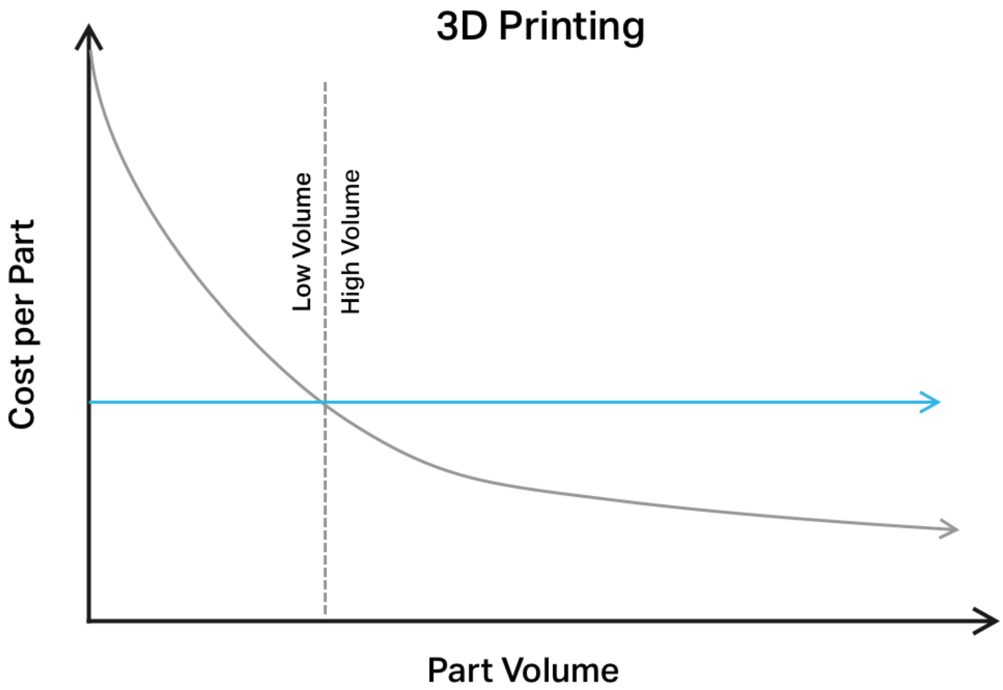

Figure 3. Cost per part and part production volume comparison of metal AM in blue and conventional manufacturing in grey (Leong 2019).

As it can be seen from figure 3, metal AM is not economical for high-volume production, if the part can be manufactured with conventional manufacturing methods. Metal AM will only be suitable for high-volume production, if the part has complex geometries which cannot be manufactured with conventional methods. (Gibson, Rosen & Strucker 2015, p. 375.)

Cost of additively manufactured metal parts is mainly dependent on machine time (3D-tulostusta kovaan käyttöön 2019). Therefore, producing parts with metal AM from expensive materials with high volume rates can be more cost effective compared to producing parts from cheaper materials with lower volume rates. E.g. EOS M 100 FlexLine metal AM machine can produce titanium alloy Ti64 6.05 cm^3/h and stainless steel 316L 4.17 cm^3/h (EOS StainlessSteel 316L; EOS Titanium Ti64 Flexline).

2.1 Powder bed fusion

SFS-EN ISO/ASTM 52900 standard describes powder bed fusion as an “additive manufacturing process in which thermal energy selectively fuses regions of a powder bed”

(ISO/ASTM 52900 2017, p. 7). As it can be seen from the schematic illustration of a powder bed machine in figure 4, objects are manufactured by melting thin layers of metal powder with a thermal energy source layer by layer according to CAD data. Between each melting pass of the thermal energy source, the build platform is lower by a distance equal to one layer, which is typically 30.0 to 60.0 micrometres. After the build platform is lowered, powder is spread and levelled from feed cartridges or hoppers with a recoater and the process is repeated. (Zenou & Grainger 2018, p. 76; Vock et al. 2017, p. 2, 4.)

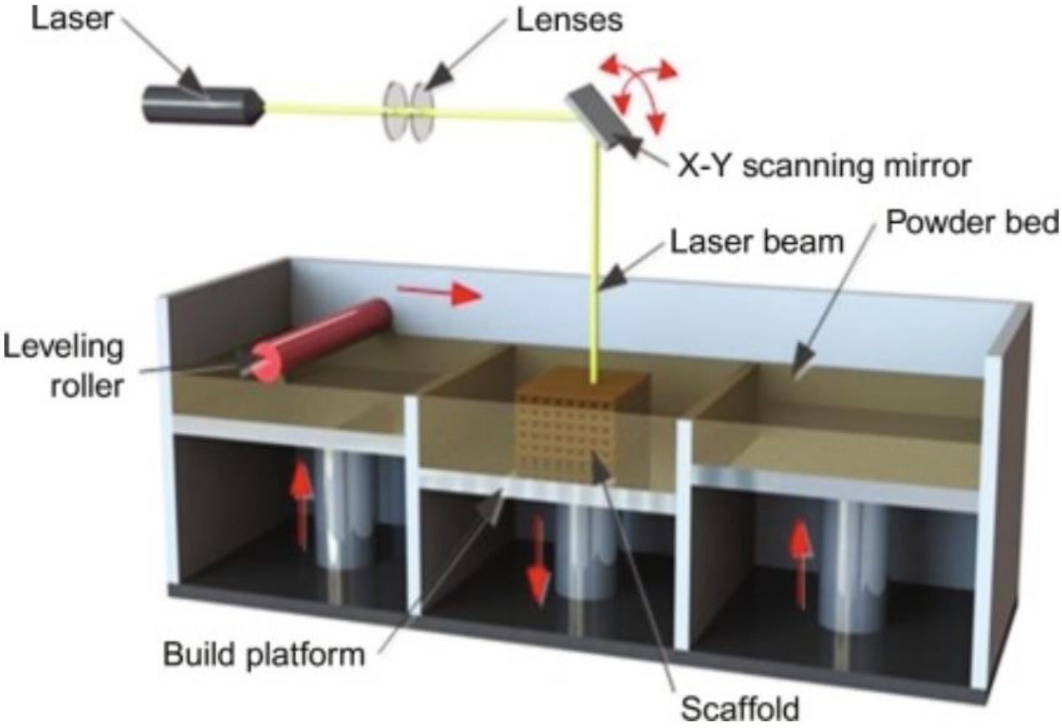

Figure 4. Schematic illustration of powder bed fusion (Vyas et al. 2017, p. 282).

During first pass of the thermal energy source, the metal powder is melted and ”welded” onto the build platform. As it can be seen from figure 5, during subsequent layers, the thermal energy source melts new metal powder into the previous layer, which ensures dense components. For manufacturing to be safe and produce parts in specification, the process is done in an enclosed moisture free chamber filled with inert gas. (Zenou & Grainger 2018, p. 76; Gibson, Rosen & Strucker 2015, p. 108.)

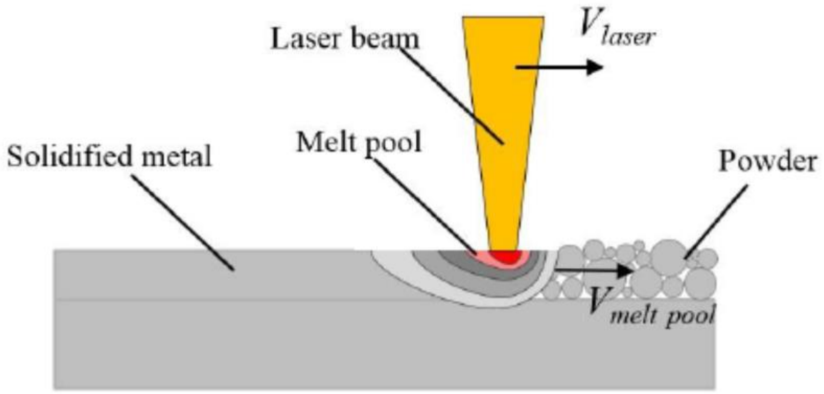

Figure 5. Schematic illustration how layers are produced (Gong et al. 2013, p. 432).

Finished parts need stress relieving heat treatment, because they are susceptible to rapid temperature changes during manufacturing when thermal energy source locally melts metal powder rapidly. In order to reduce internal stresses from rapid temperature changes, build plates can be heated up to 200°C in most L-PBF systems. Depending on the system used and the material, parts have a rougher surface finish compared to machined parts and they need polishing or machining as post processing to achieve required tolerances. E.g. EOSINT M 280 machine can produce EOS Aluminium AlSi10Mg_200C material with as low as R_a 4 µm (EOS Aluminium AlSi10Mg_200C 2013). (Zenou & Grainger 2018, p. 79–80.)

Each material and alloy require their own set of machine parameters for optimal production. Optimal parameters can be provided by the system manufacturer for each material they supply, but they can be developed by the user, if the machine has an open system. Developing optimal parameters for specific purposes is difficult and expensive due to the amount and interacting nature of the parameters (Milewski 2017, p. 107).

Laser and electron beam thermal energy sources are used in PBF processes, but this thesis focuses on laser powder bed fusion (L-PBF) processes. Fiber lasers are the most common type of laser used in L-PBF systems currently (Laitinen et al. 2019, p. 177). Fiber lasers are used because of their short wavelength of 1.06–1.07 µm (compared to CO_2 lasers with 10.6 µm), high efficiency, excellent beam quality, robustness and compactness. Shorter wavelengths have a better absorptivity to metal materials, because metals reflect less light from shorter wavelengths. Laser power of fiber lasers in modern metal AM systems vary from 50.0 to 1000 W, with 200–500 W being mostly used. (Zenou & Grainger 2018, p. 76; Lee et al. 2017, p. 310; Brandt 2017, p. 6.)

2.2 Metal powders

Powder particle morphology and size are critical properties in L-PBF, as they affect powder flowability, laser energy absorption and thermal conductivity of the powder bed (Brandt 2017, p. 57). Size of the powder particles typically range from 10.0 to 60.0 micrometres (Vock et al. 2017, p. 2). Spherical particles are commonly favoured, as these properties increase flowability and allow the recoater to spread the powder more evenly than angular, irregular and agglomerated particles (Milewski 2017, p. 72).

A wide powder size distribution and spherical morphology allows for higher packing density of the powder bed, as small and spherical particles can flow without entangling together and fill the gaps between larger particles. Parts built in a powder bed with high packing density have lower internal stresses, part distortion, porosity and surface roughness compared to parts built in a powder bed with low packing density. High packing density is also the most important factor for heat conductivity of loose powder while material properties are less significant. (Brandt 2017, p. 57–58.)

Laser energy is absorbed by the particles by multiple reflections when light passes through the gaps between particles and reflects from one particle to another. E.g. aluminium and copper are highly reflective metals, which benefit more from multiple reflections compared to iron and titanium, which are moderately reflective metals. Low particle size and high optical thickness of powder layer decreases laser energy absorption to the particles and previously built solid, because they decrease the amount of reflections and laser energy penetration. (Brandt 2017, p. 58.)

Metal powders for L-PBF can be produced by gas atomization, water atomization, plasma atomization, electrode induction melting gas atomization, centrifugal atomization, plasma rotating electrode and hydride-dehydride processes (Milewski 2017, p. 72; Carpenter Additive 2019). Each process and material/alloy produce particles of different size, shape and chemical purity, and is later sieved to obtain desired range of sizes. Production costs also vary between each production method. Because of strict requirements for metal powders, all commercially available metal powders may not be suitable for metal AM e.g. metal powders produced with water atomization. (Milewski 2017, p. 71–74.)

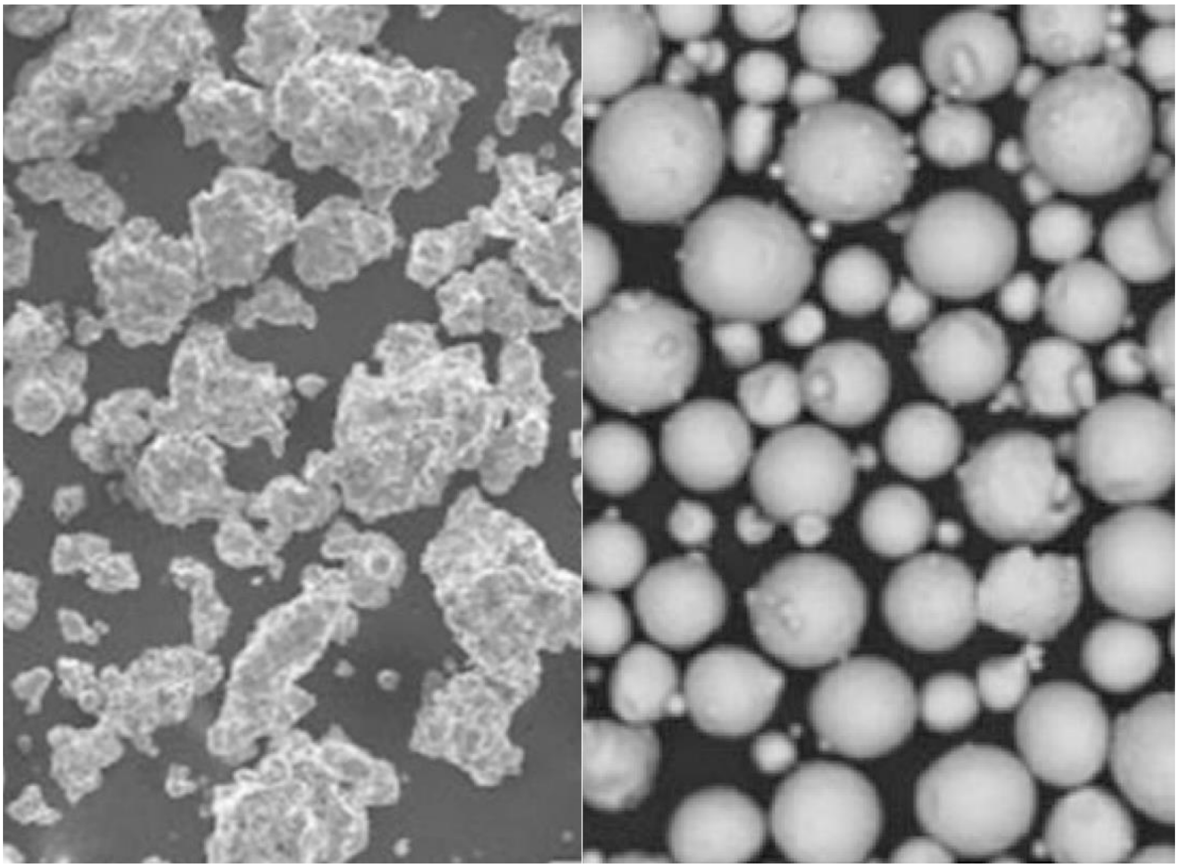

Figure 6. Iron based alloy powder produced by water atomization (left) and Ti6Al4V powder produced by gas atomization (right) (Milewski 2017, p. 72–73).

As it can be seen from figure 6, water atomization produces powder, which is angular, irregular and agglomerated, and therefore may not be suitable for L-PBF. In comparison, gas atomization produces particles with spherical morphology and high purity. (Milewski 2017, p. 72, 74.)

2.3 Metal materials

Metal materials used in L-PBF processes vary widely, as most weldable metals can be used. Weldability is considered to be a benchmark for determining usability of a metal material for L-PBF processes. Alloys which crack under high solidification rates are not well suited for L-PBF processes, as L-PBF processes have a high solidification rate which causes different metallurgical structures and mechanical properties than other manufacturing processes, and may therefore need different heat treatment to produce standard microstructures (Gibson et al. p. 111–112). (Zenou & Grainger 2018, p. 79.)

Most used metal materials in L-PBF processes are stainless steels, tool steels, aluminium alloys, titanium alloys, nickel alloys, cobalt chromium, and copper (Zenou & Grainger 2018, p. 79). Senvol, a company providing data about additive manufacturing lists 224 different metal materials available for PBF from different manufacturers (Senvol 2019). Although there are many available metal materials, optimal parameters may be unavailable for some of them, which can take a metal AM professional 2–3 months to search and find. Most commercially sold metal materials are not named according to standard, as they do not meet the metallurgical structure and mechanical property requirements of conventional material standards. Due to time limitations of this thesis, a list of commercially available metal materials for L-PBF was compiled from Senvol only and can be seen in table 1. (Piili 2019.)

Table 1. Commercially available metal powders for L-PBF (Senvol 2019).
**Values depending on powder producer and/or powder size distribution and/or whether post processing has been done.*

Metal material type	**Material name**	**Ultimate tensile strength, min - max (MPA)**	**Tensile modulus, min – max (1000 MPA)**	**Elongation at break, min – max (%)**	**Material supplier(s)**
Aluminium	2024				United States Metal Powders, Valimet
Aluminium	6061				LPW, United States Metal Powders, Valimet
Aluminium	7050				LPW
Aluminium	7075				LPW, United States Metal Powders, Valimet
Aluminium	A10SIM-AM				Hana AMT
Aluminium	A11SIM-AM				Hana AMT
Aluminium	A12SI-AM				Hana AMT
Aluminium	Addalloy	327–396*		17–31	NanoAl
Aluminium	Al-ET255	554–584	8.14–8.3	5–5	Arconic
Aluminium	AL-ET389	546–546	8.5–8.5	4–4	Arconic
Aluminium	AL-1000-AM	100–110	70–70	30–36	Elementum

*Table 1 continues. Commercially available metal powders for L-PBF (Senvol 2019). *Values depending on powder producer and/or powder size distribution and/or whether post processing has been done.*

Metal material type	**Material name**	**Ultimate tensile strength, min - max (MPA)**	**Tensile modulus, min – max (1000 MPA)**	**Elongation at break, min – max (%)**	**Material supplier(s)**
Aluminium	AlCu4Li1				TLS Technik
Aluminium	AlMgSc				TLS Technik
Aluminium	AlSi7Mg0.6	240–460*	70–76*		3D Systems
Aluminium	AlSi7Mg	277–311			CNPC Powder, LPW, SLM Solutions, TLS Technik
Aluminium	AlSi9Cu3	400–430	52–62	4–6	SLM Solutions, TLS Technik
Aluminium	AlSi10Mg	220–480*	54–98.8*	2–18*	3D Systems, AMC Powders, APWORKS, CNPC Powder, EOS, Ermaksan, GKN Sinter Metals, Hunan Farsoon, LPW, Renishaw, SLM Solutions, SOLIDTEQ, Sondasys, TLS Technik, United States Metal Powders, Xi'an Bright Laser Technologies, ZRapid Tech
Aluminium	AlSi10Mg-0403	333–448*	48–84	2–11	Renishaw
Aluminium	AlSi12	220–500*	75–75	2–24*	3D Systems, CNPC Powder, Concept Laser, LPW, United States Metal Powders
Aluminium	AlSi12				United States Metal Powders
Aluminium	AM-103				Valimet
Aluminium	AM-103C				Valimet
Aluminium	AM-120				Valimet
Aluminium	AM-205				Valimet
Aluminium	AM-357				Valimet
Aluminium	CuAlNiFe				CNPC Powder
Aluminium	F357				United States Metal Powders
Aluminium	Scalmalloy	Min 350	Min 70	Min 13	APWORKS
Amorphous Metal	ZrCuAlNb			85–85	Heraeus
Bronze	80CU	500–500	1.2–1.2	5–5	Concept Laser

*Table 1 continues. Commercially available metal powders for L-PBF (Senvol 2019). *Values depending on powder producer and/or powder size distribution and/or whether post processing has been done.*

Metal material type	Material name	Ultimate tensile strength, min - max (MPA)	Tensile modulus, min – max (1000 MPA)	Elongation at break, min – max (%)	Material supplier(s)
Bronze	CuSn10	450─550	100─132	12─40*	CNPC Powder, Hunan Farsoon, Sandvik, SLM Solutions
Bronze	EOS DirectMetal 20	400─400	80─80		EOS
Cobalt	6AM				Powder Alloy Corporation
Cobalt	21AM				Powder Alloy Corporation
Cobalt	25AM				Powder Alloy Corporation
Cobalt	188AM				Powder Alloy Corporation
Cobalt	509AM				Powder Alloy Corporation
Cobalt	694AM				Powder Alloy Corporation
Cobalt	CarTech CCM				Carpenter
Cobalt	CarTech CCM Plus 1				Carpenter
Cobalt	CarTech CCM-MC				Carpenter
Cobalt	CarTech Micro-Melt CCM-MC	1076─1383			Carpenter
Cobalt	CarTech H188				Carpenter
Cobalt					
Cobalt					
Cobalt	Co-308 (similar to L605 / Haynes 25				Praxair
Cobalt	Co-Cr Alloy (MP1)	Min 1000			ZRapid Tech
Cobalt	CoCr	1100─1360*	200─200	8─17*	3D Systems, Ermaksan, LPW, Material Technology Innovations, Praxair
Cobalt	CoCr-0404	1081─1121	183─257	14─22	Renishaw
Cobalt	CoCr-2Lc (MP1)	1100─1100	200─200	10─10	Sondasys
Cobalt	CoCr F75	910─1130*	220─230	20─35*	3D Systems, Arcam
Cobalt	CoCr28Mo6	948─1179	181─203	6─14	SLM Solutions
Cobalt	CoCrMo	Min 1150		Min 10	CNPC Powder, H.C.Starck, Hunan Farsoon

*Table 1 continues. Commercially available metal powders for L-PBF (Senvol 2019). *Values depending on powder producer and/or powder size distribution and/or whether post processing has been done.*

Metal material type	**Material name**	**Ultimate tensile strength, min - max (MPA)**	**Tensile modulus, min – max (1000 MPA)**	**Elongation at break, min – max (%)**	**Material supplier(s)**
Cobalt	CoCrMoW	Min 1100		Min 10	Hunan Farsoon
Cobalt	CoCrW				CNPC Powder
Cobalt	EOS CobaltChrome MP1	1000—1450*		8—28	EOS
Cobalt	EOS CobaltChrome SP2	1350—1350	200—200	3–3	EOS
Cobalt	F75	1120—1120		8—10	Sandvik
Cobalt	F750AM				Powder Alloy Corporation
Cobalt	F90				Sandvik
Cobalt	MetcoAdd 75A				Oerlikon Metco
Cobalt	MetcoAdd 76A	1189—1235*		38—49	Oerlikon Metco
Cobalt	MetcoAdd 78A				Oerlikon Metco
Cobalt	MetcoAdd H188-A	984—1085		31—47	Oerlikon Metco
Cobalt	MetcoAdd MM509-A	1156—1212		4—6	Oerlikon Metco
Cobalt	MTI C02				Material Technology Innovations
Cobalt	PACUltra				Powder Alloy Corporation
Cobalt	Remanium star CL	1030—1030	230—230	10—10	Concept Laser
Cobalt	SLM-Medi-Dent	1016—1108	109—119		SLM Solutions
Cobalt	TruForm 188 / Co-273 (similar to Haynes 188)				Praxair
Cobalt	Truform 509 / Co-222 (similar to MAR-M-509)				Praxair
Copper	BR6-P6	400—400	90—90	5—5	Sondasys
Copper	C18000				Praxair
Copper	C18150				Praxair
Copper	C18200				Carpenter

*Table 1 continues. Commercially available metal powders for L-PBF (Senvol 2019). *Values depending on powder producer and/or powder size distribution and/or whether post processing has been done.*

Metal material type	**Material name**	**Ultimate tensile strength, min - max (MPA)**	**Tensile modulus, min – max (1000 MPA)**	**Elongation at break, min – max (%)**	**Material supplier(s)**
Copper	Cu	210─210	119─119	8─8	CNPC Powder, Elementum, LPW, TLS Technik
Copper	Cu10Mn3Ni				Sandvik
Copper	CuAl10Fe5Ni5				TLS Technik
Copper	CuCr1Zr	235─243	80─110	14.9─16.9	GKN Sinter Metals
Copper	CuCrZr				TLS Technik
Copper	CuNi2SiCr				TLS Technik
Copper	CuNi3Si				TLS Technik
Gold	18K 3N (yellow)				Concept Laser, Cookson gold
Gold	18K 5N (rose)				Cookson Gold
Gold	18K Pd 13.9% Ni free (white)				Cookson Gold
Iron	S04				Material Technology Innovations
Magnesium	MAP+21				Magnesium Elektron Powders
Magnesium	MAP+43				Magnesium Elektron Powders
Magnesium	MAP+91				Magnesium Elektron Powders
Magnesium	MPAZ31B				Hana AMT
Magnesium	MPAZ91				Hana AMT
Magnesium	MPWE43				Hana AMT
Nickel	247 LC				H.C.Starck, Carpenter, LPW
Nickel	263				Carpenter, LPW, Powder Alloy Corporation
Nickel	276				LPW
Nickel	282				H.C.Starck, Praxair
Nickel	500				Powder Alloy Corporation
Nickel	622				Powder Alloy Corporation
Nickel	713				Carpenter, LPW, Powder Alloy Corporation

*Table 1 continues. Commercially available metal powders for L-PBF (Senvol 2019). *Values depending on powder producer and/or powder size distribution and/or whether post processing has been done.*

Metal material type	**Material name**	**Ultimate tensile strength, min - max (MPA)**	**Tensile modulus, min – max (1000 MPA)**	**Elongation at break, min – max (%)**	**Material supplier(s)**
Nickel	8814				Powder Alloy Corporation
Nickel	8830				Powder Alloy Corporation
Nickel	CL 101NB	920–990	200–200	20–32	Concept Laser
Nickel	EP741NP				Sino-Euro Materials Technologies
Nickel	GH3536	790–890		25–35	Hunan Farsoon
Nickel	Hastelloy C (HC) (or similar)				CNPC Powder
Nickel	Hastelloy X (HX) (or similar)	614–890*	151–220*	14–58*	Aubert & Duval, Carpenter, CNPC Powder, EOS, H.C.Starck, Oerlikon Metco, Praxair, SLM Solutions, Xi’an Bright Laser Technologies
Nickel	Haynes 230 (or similar)	818–907		28–49	Carpenter, LPW, Praxair
Nickel	Inconel 617 (or similar)				Powder Alloy Corporation, Praxair
Nickel	Inconel 625 (or similar)	827–1140*	120–245*	16–49*	3D Systems, AMC Powders, AP&C, APWORKS, Aubert & Duval, Carpenter, CNPC Powder, EOS, Ermaksan, H.C.Starck, Hana AMT, Hunan Farsoon, LPW, Oerlikon Metco, Powder Alloy Corporation, Praxair, Renishaw, Sandvik, SLM Solutions, SOLIDTEQ, VTECH, Xi’an Bright Laser Technologies

*Table 1 continues. Commercially available metal powders for L-PBF (Senvol 2019). *Values depending on powder producer and/or powder size distribution and/or whether post processing has been done.*

Metal material type	**Material name**	**Ultimate tensile strength, min - max (MPA)**	**Tensile modulus, min – max (1000 MPA)**	**Elongation at break, min – max (%)**	**Material supplier(s)**
Nickel	Inconel 718 (or similar)	800─1500*	90─200	6─38*	3D Systems, AMC Powders, AP&C, Aubert & Duval, Carpenter, CNPC Powder, Concept Laser, ZRapid, LPW, Tech, EOS, Ermaksan, GKN Hoeganaes, H.C.Starck, Hana AMT, Hunan Farsoon, Oerlikon Metco, Powder Alloy Corporation, Praxair, Renishaw, Sandvik, Sino-Euro Materials Technologies, SLM Solutions, Sondasys, VTECH, Xi'an Bright Laser Technologies
Nickel	Inconel 738 (or similar)	1223─1441		5─13	H.C.Starck, LPW, Oerlikon Metco, Powder Alloy Corporation, Praxair
Nickel	Inconel 939 (or similar)	974─1405*	149─201	9─34*	Carpenter, LPW, Praxair, SLM Solutions
Nickel	Kovar				CNPC Powder, Carpenter
Nickel	MTI N01				Material Technology Innovations
Nickel	MTI N02				Material Technology Innovations
Nickel	Ni				CNPC Powder, Praxair
Nickel	Rene 142				Praxair
Nickel	WASP				LPW
Nickel	X				Powder Alloy Corporation
Nickel	XLC				LPW
Niobium	Nb				H.C.Starck
Platinum	950 Pt/Ru				Cookson Gold
Platinum	Ptlr 50				Heraeus

*Table 1 continues. Commercially available metal powders for L-PBF (Senvol 2019). *Values depending on powder producer and/or powder size distribution and/or whether post processing has been done.*

Metal material type	**Material name**	**Ultimate tensile strength, min - max (MPA)**	**Tensile modulus, min – max (1000 MPA)**	**Elongation at break, min – max (%)**	**Material supplier(s)**
Platinum	PtRh20	92.7–92.7	246–246	43–43	Heraeus
Refractory	CNPC-SWC				CNPC Powder
Refractory	CNPC-WCCo				CNPC Powder
Refractory	GAM AM 200, Ta				Global Advanced Metals
Refractory	GAM AM 400, Ta				Global Advanced Metals
Refractory	Mo, pure/99.9%				H.C.Starck, LPW
Refractory	Ta, 99.9%				LPW
Refractory	TEKMAT Mo-45				Tekna
Refractory	TEKMAT Mo-90				Tekna
Refractory	TEKMAT Ta-25				Tekna
Refractory	TEKMAT Ta-45				Tekna
Refractory	TEKMAT Ta-75				Tekna
Refractory	TEKMAT W-25				Tekna
Refractory	TEKMAT W-45				Tekna
Refractory	TEKMAT W-90				Tekna
Refractory	TEKMAT W-150				Tekna
Refractory	W, pure/99.9%				H.C.Starck, LPW
Refractory	WC				LPW
Silver	Ag				CNPC Powder
Silver	930 Sterling				Concept Laser
Silver	Brilliante Sterling				Cookson Gold
Steel	1.2709 / MS1 / M300 / A646	1025–2150*	135–235.3*	2–16*	APWORKS, Carpenter, Concept Laser, GKN Hoeganaes, GKN Sinter Metals, SLM Solutions, SOLIDTEQ, Renishaw, EOS, Sondasys, ZRapid Tech
Steel	1.4006 / 410				Carpenter, Hana AMT, VTECH
Steel	1.4034 / 420	Min 1100		Min 2	Carpenter, Hana AMT, Hunan Farsoon, VTECH
Steel	1.4125 / 404C				Carpenter, Sandvik

*Table 1 continues. Commercially available metal powders for L-PBF (Senvol 2019). *Values depending on powder producer and/or powder size distribution and/or whether post processing has been done.*

Metal material type	Material name	Ultimate tensile strength, min - max (MPA)	Tensile modulus, min – max (1000 MPA)	Elongation at break, min – max (%)	Material supplier(s)
Steel	1.4301 / 304				VTECH
Steel	1.4307 / 304L				Carpenter, CNPC Powder, Daye Metal Powder, Hana AMT, LPW, Sandvik, VTECH
Steel	1.4401 / 316				Powder Alloy Corporation, VTECH
Steel	1.4404 / 316L / A276	530–790*	115–230*	14–71*	3D Systems, APWORKS, Aubert & Duval, Carpenter, CNPC Powder, Concept Laser, Daye Metal Powder, EOS, Ermaksan, GKN Hoeganaes, GKN Sinter Metals, H.C.Starck, Hana AMT, Hunan Farsoon, LPW, Oerlikon Metco, Praxair, Renishaw, Sandvik, SLM Solutions, SOLIDTEQ, Sondasys, VTECH, ZRapid Tech
Steel	1.4404 / 316L High Productivity	440–464	166–178		GKN Sinter Metals
Steel	1.4511 / 430L				Daye Metal Powder, Sandvik
Steel	1.4540 / 15-5 PH / PH1 / XM-12	850–1550*	140–170*	12–25*	Carpenter, H.C.Starck, Hunan Farsoon, LPW, Oerlikon Metco, Powder Alloy Corporation, Praxair, APWORKS, SLM Solutions, EOS, Xi’an Bright Laser Technologies

*Table 1 continues. Commercially available metal powders for L-PBF (Senvol 2019). *Values depending on powder producer and/or powder size distribution and/or whether post processing has been done.*

Metal material type	**Material name**	**Ultimate tensile strength, min - max (MPA)**	**Tensile modulus, min – max (1000 MPA)**	**Elongation at break, min – max (%)**	**Material supplier(s)**
Steel	1.4542 / GP 1 / 630 / 17-4PH	770–1439*	140–200*	6–35*	3D Systems, AMC Powders, APWORKS, Aubert & Duval, Carpenter, CNPC Powder, Concept Laser, EOS, GKN Hoeganaes, H.C.Starck, Hunan Farsoon, LPW, Oerlikon Metco, Powder Alloy Corporation, Praxair, Sandvik, SLM Solutions, EOS, Sondasys, VTECH, Xi'an Bright Laser Technologies
Steel	1.6511 / 4340				Carpenter
Steel	1.7225 / 4140				Carpenter, LPW, Sandvik
Steel	2205				Carpenter
Steel	4365				Sandvik
Steel	8620				Sandvik
Steel	20MnCr5	865–1196*	197–221*	13.4–20*	GKN Sinter Metals
Steel	BioDur 108				Carpenter
Steel	BLDRmetal L-40	1500–1650*		Min 14	Formetrix
Steel	BOHLER AMPO M789	1780–1880		4.5–7.6	BOHLER Edelstahl
Steel	BOHLER AMPO N700				BOHLER Edelstahl
Steel	BOHLER AMPO W360	1970–2010	150–167	6.6–8.1	BOHLER Edelstahl
Steel	BOHLER AMPO W722				BOHLER Edelstahl
Steel	C300	2018–2119*		2–10*	Oerlikon Metco
Steel	CarTech Custom 465				Carpenter

*Table 1 continues. Commercially available metal powders for L-PBF (Senvol 2019). *Values depending on powder producer and/or powder size distribution and/or whether post processing has been done.*

Metal material type	**Material name**	**Ultimate tensile strength, min - max (MPA)**	**Tensile modulus, min – max (1000 MPA)**	**Elongation at break, min – max (%)**	**Material supplier(s)**
Steel	CL 91RW	1700─1700	200─200	2─2	Concept Laser
Steel	D2				Sandvik
Steel	EOS CX	1080─1760*		7─14*	EOS
Steel	Ermaksan Maraging Steel				Ermaksan
Steel	FeNiCoMo / 18Ni300	1000─1200		9─15	CNPC Powder, H.C.Starck, Hunan Farsoon, LPW, Sandvik
Steel	H11	1992─2022		7─9	Oerlikon Metco
Steel	H13 / 1.2344	1150─1870*	200─200	4─12*	Carpenter, CNPC Powder, LPW, Oerlikon Metco, Praxair, Sandvik, SLM Solutions, Sondasys
Steel	Hiperco 50				Carpenter
Steel	Invar36	484─490	108─164*	31─33*	CNPC Powder, Praxair, Carpenter, SLM Solutions
Steel	LaserForm Maraging Steel (A)	1160─2290*		1─15*	3D Systems
Steel	LaserForm Maraging Steel (B)	1060─1160		8─14	3D Systems
Steel	M2				CNPC Powder, Sandvik
Steel	MTI S01	690─690	170─170	30─30	Material Technology Innovations
Steel	MTI S02	520─520	190─190	29─29	Material Technology Innovations
Steel	MTI S03	1100─1100	195─195	10─10	Material Technology Innovations
Steel	MTI S10	1100─1100	180─180	9─9	Material Technology Innovations
Steel	SAF2507				Sandvik
Steel	SKD-11				Sandvik

*Table 1 continues. Commercially available metal powders for L-PBF (Senvol 2019). *Values depending on powder producer and/or powder size distribution and/or whether post processing has been done.*

Metal material type	**Material name**	**Ultimate tensile strength, min - max (MPA)**	**Tensile modulus, min – max (1000 MPA)**	**Elongation at break, min – max (%)**	**Material supplier(s)**
Steel	TruForm MS / Fe-339				Praxair
Steel	Uddeholm AM Corrax	1150─1700*	200─200	10─16	Uddeholm
Tin	Sn				CNPC Powder
Titanium	Beta 21S				GKN Hoeganaes
Titanium	CarTech Puris 5+				Carpenter
Titanium	CarTech Puris Nitinol				Carpenter
Titanium	Cp-Ti (grade unspecified)	445─620*	85─110*	15.5─20	AP&C, Becken Technology Development, Carpenter, CNPC Powder, Concept Laser, EOS, Hana AMT, LPW, VTECH
Titanium	Gr1 / Cp-Ti	430─530*	105─120	24─41*	3D Systems, AP&C, GKN Hoeganaes
Titanium	Gr2 / Cp-Ti	290─570*	105─105	20─21*	AP&C, Arcam, GKN Hoeganaes
Titanium	Gr5 / Ti6Al4V	900─1343*	100─126*	6─18*	3D Systems, AP&C, APWORKS, Arcam, Carpenter, EOS, Ermaksan, GKN Hoeganaes, Heraeus, Hunan Farsoon, LPW, Praxair, Sino-Euro Materials Technologies, SLM Solutions, Tekna, TLS Technik, VTECHvv
Titanium	Gr23 / Ti6Al4V ELI	860─1300*	88─135*	2─22*	3D Systems, AP&C, Arcam, Carpenter, Concept Laser, EOS, GKN Hoeganaes, LPW, Oerlikon Metco, Renishaw, Sino-Euro Materials Technologies, TLS Technik

*Table 1 continues. Commercially available metal powders for L-PBF (Senvol 2019). *Values depending on powder producer and/or powder size distribution and/or whether post processing has been done.*

Metal material type	**Material name**	**Ultimate tensile strength, min - max (MPA)**	**Tensile modulus, min – max (1000 MPA)**	**Elongation at break, min – max (%)**	**Material supplier(s)**
Titanium	NiTi 4				GKN Hoeganaes
Titanium	NiTi (unspecified)				LPW
Titanium	MTI T01	510—510	110—110	18—18	Material Technology Innovations
Titanium	MTI T04	1160—1160	120—120	10—10	Material Technology Innovations
Titanium	TA15	950—1426*	96—124	2—14*	SLM Solutions
Titanium	TC4	895—1130*	110—110	8—18	AMC Powders, Becken Technology Development, CNPC Powder, QBEAM, SLM Solutions, Sondasys, Xi’an Bright Laser Technologies, ZRapid Tech
Titanium	TC6	1140—1220		7.5—17	Xi’an Bright Laser Technologies
Titanium	TC11	1080—1150		6—15	Xi’an Bright Laser Technologies
Titanium	TC18	970—1170		7—16	Xi’an Bright Laser Technologies
Titanium	Ti4822				Praxair
Titanium	Ti5553				AP&C, GKN Hoeganaes
Titanium	Ti6242				AP&C, GKN Hoeganaes, LPW, Praxair
Titanium	Ti2AlNb				Sino-Euro Materials Technologies
Titanium	Ti48Al2Cr2Nb	360—500	160—175	1—3	Carpenter, Heraeus
Titanium	Ti6Al2Sn4Zr2Mo				Carpenter
Titanium	Ti6Al2Zr1Mo1V				Sino-Euro Materials Technologies
Titanium	TiAl				LPW
Titanium	TILOP64				OSAKA Titanium Technologies
Titanium	Rematitan	1005—1005	115—115	10—10	Concept Laser

*Table 1 continues. Commercially available metal powders for L-PBF (Senvol 2019). *Values depending on powder producer and/or powder size distribution and/or whether post processing has been done.*

Metal material type	**Material name**	**Ultimate tensile strength, min - max (MPA)**	**Tensile modulus, min – max (1000 MPA)**	**Elongation at break, min – max (%)**	**Material supplier(s)**
Titanium	ZTi-Med	950─950	35─35		Z3DLAB
Titanium	ZTi-Powder	1035─1035	115─115		Z3DLAB
Zinc	Zn				CNPC Powder
Zirconium	CarTech Zr-702				Carpenter

All material property values are compiled as minimal minimum to maximal maximum from different manufacturers and may not represent values for each of the listed providers.

3 METHODS

This chapter describes the conducting of this study. An overview of the conducted literature review is provided, and the experimental survey part of the study is described in detail.

3.1 Literature review

At the start of this study, a review of relevant scientific literature was conducted to build an understanding of the context of this study. Afterwards books and other literature describing metal additive manufacturing and applications were studied, and a more thorough review was done into the specific metal materials used in L-PBF.

In total 5 professional books, 10 online resources and 8 scientific articles were used as references. A more detailed table of references can be found at the end of this study.

The results of the literature review were used to build an understanding of the practical industrial applications of AM technologies as well as to build a foundation for the experimental part of the study.

3.2 Experimental part

In the experimental part of the study, a survey was sent to 15 Finnish industrial companies to find out their current and future use of various metal materials in AM applications in October 2019. The companies surveyed were from different areas of Finnish industry and they were selected as businesses that might potentially have experience with AM technologies. As the technology is still rapidly developing, only a part of Finnish industrial companies has experience in the field. Names of the interviewed companies are kept confidential and are not mentioned in this study.

The original questionnaire was in Finnish, and an English translation of the questions asked is as follows:

1. Are you familiar with metal 3D printing?
2. Have you 3D printed metal products in your business?
    a. If yes, which materials have you used for printing?
    b. If not, are you familiar with 3D printable metal materials?
3. Would you like to 3D print metal materials in the future?
    a. If yes, which metal materials would you be interested in metal 3D printing? If you do not know specific metal materials, you can describe the material properties needed.
    b. If not, why?

The aforementioned questions were decided, as they were deemed to provide sufficient data about the situation of metal 3D printing in Finnish industrial companies as well as which metal materials the companies had used and would have future interests in using to produce parts with metal AM.

4 RESULTS AND ANALYSIS

Overall 17 answers were received from 15 different companies to the survey sent out. All companies that received the survey eventually gave a response. One of the companies surveyed provided three answers from people in different parts of the organization. As it can be seen from figure 7, the responds came from companies in five different industries.

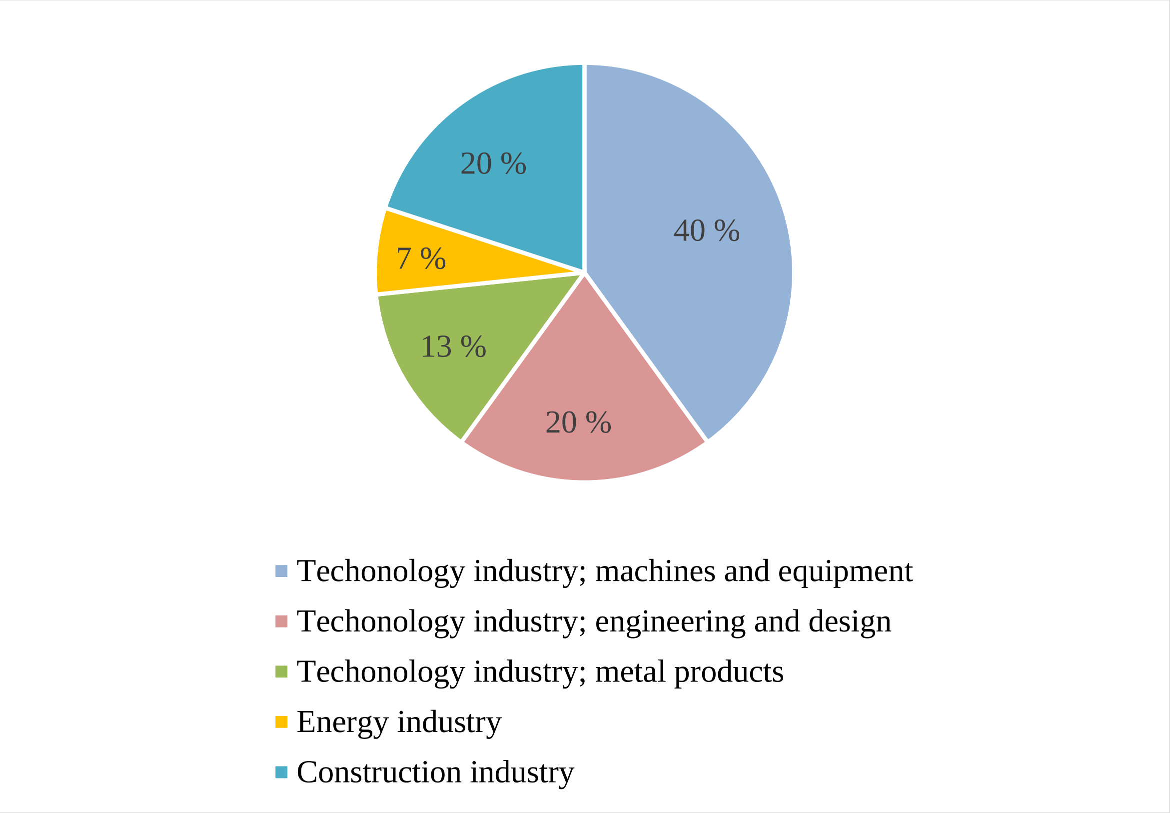

Figure 7. Division of industries of interviewed companies.

The first question in the survey was: “Are you familiar with metal 3D printing?”. While this was originally thought to be a yes or no -question, answers given were broadly on the scale and showed varying levels of expertise related to metal 3D printing. Therefore, answers were analysed on a scale of 0–5, where 0 means no familiarity and 5 means expert familiarity.

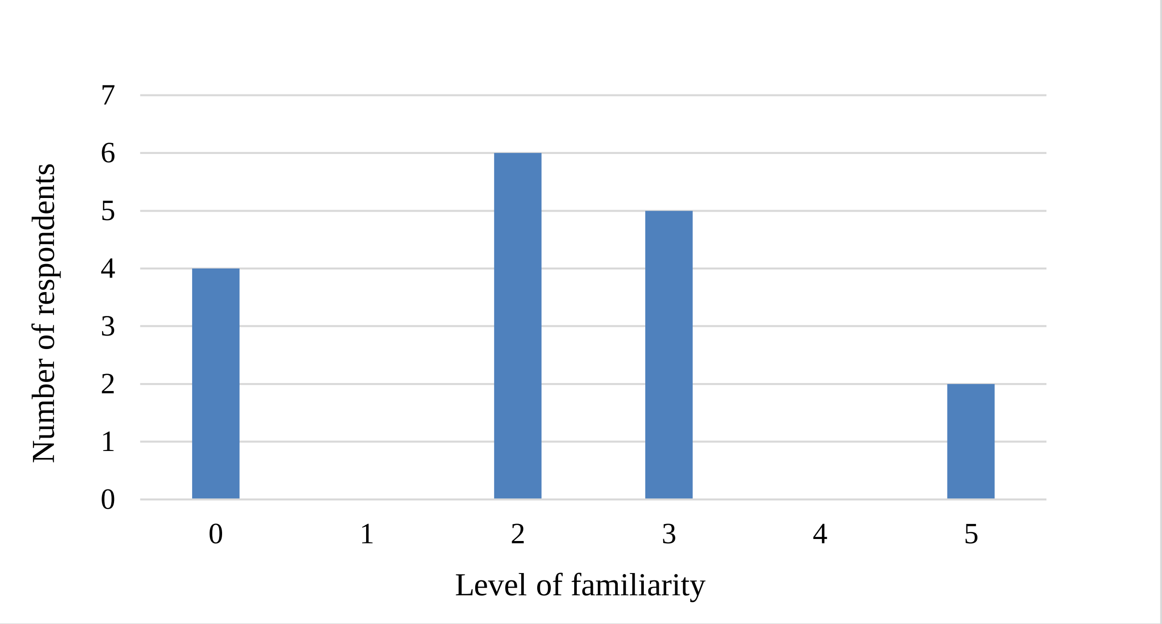

Figure 8. Respondents level of familiarity of metal 3D printing.

As it can be seen from figure 8, respondents had a mediocre familiarity with metal 3D printing technologies and methods, which has implications for the overall results of the study. The average response related to familiarity was 2.18 and the median response was 2.

14 of the respondents had not used metal 3D printing technologies professionally, while 3 respondents had such experience. The respondents with no experience in the field also generally had very little or no knowledge about metal materials for AM.

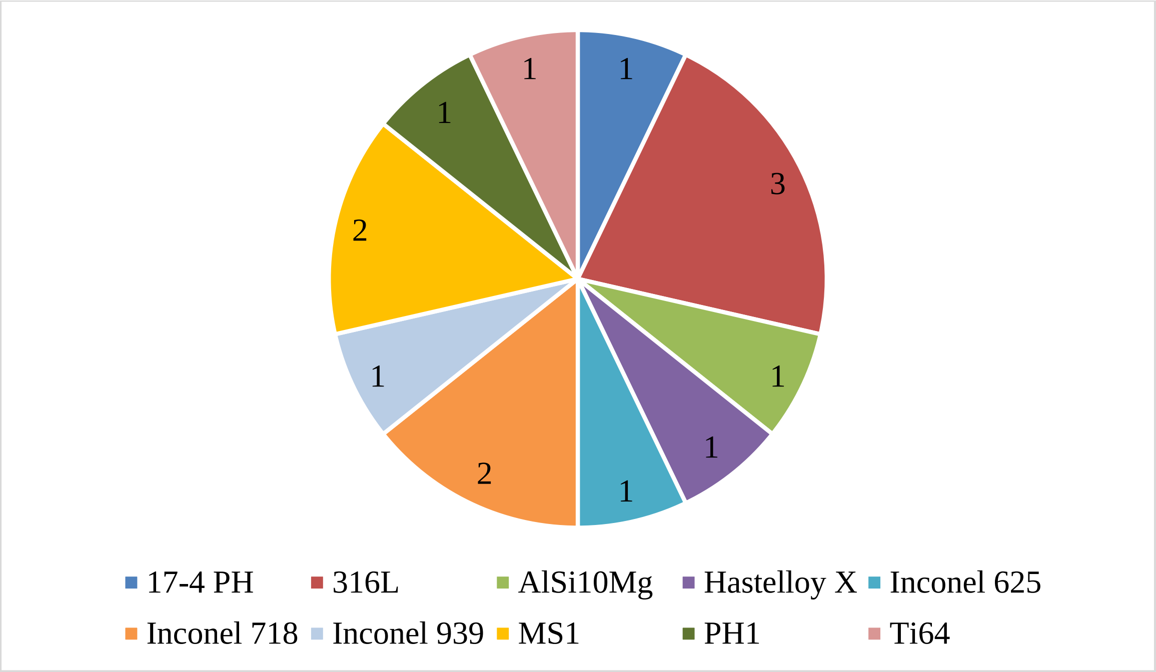

Figure 9. Metal materials which had been used by responding companies.

A can be seen from figure 9, stainless steel 316L was the only metal material which had been 3D printed in all three of the companies who had previously 3D printed parts from metal. Inconel 718 and maraging steel 1 had been used by two companies, while other materials had been used by one company.

Respondents generally expected to use more metal 3D printing technologies in the future. While only three respondents had used metal 3D printing professionally in the past, 12 respondents stated that they would like to do so in the future. Three of the respondents were not certain if they would need metal 3D printing in the future.

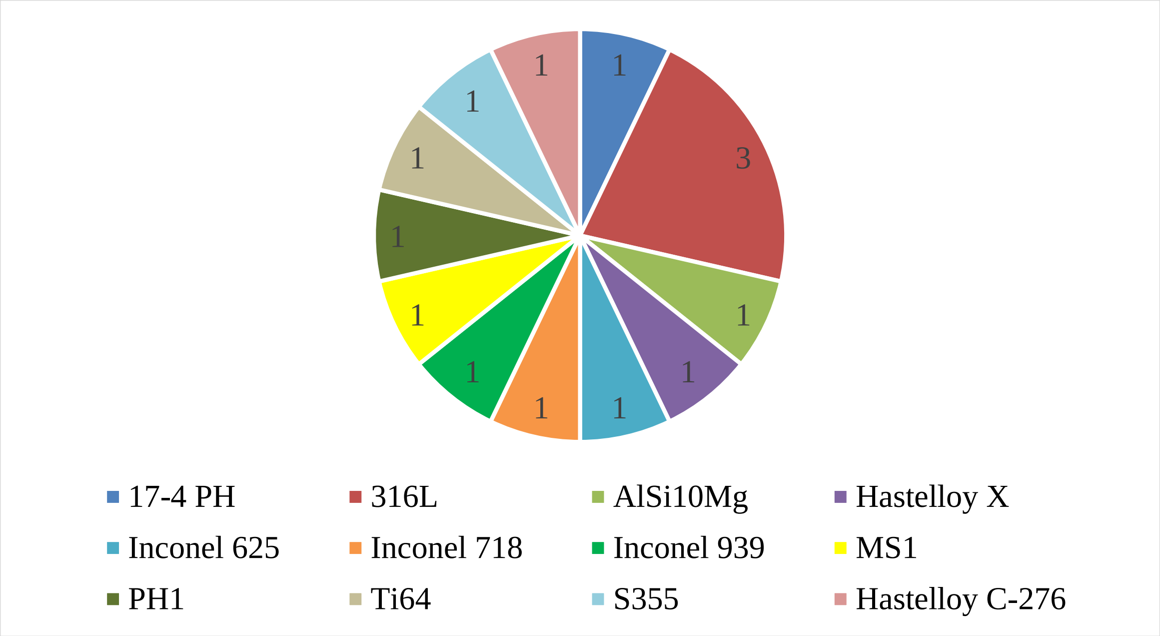

Figure 10. Specific metal materials which responding companies are interested to 3D print in the future.

As it can be seen from figure 10, 316L was stated by three companies and was the only specified material which was stated by more than one company. Additionally, Inconel, aluminium alloys, acid resistant steel and tool steels were stated as generalisations once, and titanium and stainless steel as generalisations twice.

Most of the respondents did not describe specific metal materials they are interested in 3D printing. Instead they described important material properties. Each of the bullet points listed in the following list contain all the material properties described for one sought after material, and each was mentioned once. They are as follows:

- Ultra-high strength
- Corrosion resistance (and aluminium based)
- High heat resistance of at least 600°C
- Good wear resistance with the strength of at least that of a typical structural steel
- Lightweight, high yield/ultimate strength and good machinability
- Corrosion resistance, good thermal conductivity and good wear/abrasion resistance
- Acid resistance

One of the companies stated that weldability, fatigue strength, impact toughness and manufacturability with conventional manufacturing methods are the most important material properties, but the respondent did not describe whether or not all the properties were for a single material.

One respondent mentioned the potential of metal 3D printing in R&D applications, possibly referring to uses in prototyping. Two of the three companies in the construction industry that responded to the survey did not expect to have uses for metal 3D printing in the future, while the third was only optimistic and did not know any future uses yet.

5 DISCUSSION, LIMITATIONS AND FURTHER RESEARCH

The research questions for this thesis were as follows:

- Which metal materials are Finnish companies interested in using in powder bed fusion?
- Are the metal materials in question suitable for powder bed fusion?
- Do the metal materials in question exist in powder bed fusion applicable powder form?

Based on the data gathered from the survey in this thesis, Finnish industrial companies use a small variety of metal materials in AM applications. All except for one metal material indicated by the companies surveyed is available as L-PBF applicable powder. The only metal material found in the survey which is not available for L-PBF applicable powder is S355.

Based on this study, industrial companies mostly use AM for specialty applications, which is understandable given that the unit cost of metal 3D printing is high. The bias of AM applications towards specialty products can also be seen in the materials used, as the used metal materials are stainless steels or specialty metals.

One of the notable take-aways from the gathered data was how almost all respondents mentioned an interest in using AM in the future. In these future printing scenarios, the special qualities of 3D printable materials were considered a key factor. The respondents mentioned heat resistance, acid and corrosion resistance, high strength properties, wear resistance, good machinability and light weight as key factors for material choices in the future. This points to the conclusion that metal 3D printing is seen as a potential area for producing products and components with premium materials for specialty applications also in the future.

Another notable take-away from the gathered data was that most of the respondents had considered the use of metal 3D printing but had not found suitable parts to 3D print. The stated reasons for this were the large size, cheap bulk material and/or simplicity of the parts as well as problems finding information about the material properties and available materials for metal 3D printing.

Due to time limitation when executing this thesis, it was decided that the table of available metal materials for L-PBF was only compiled from Senvol, and it was not complemented with data from metal powder manufacturers and suppliers. In further research, it is suggested that a more thorough table is compiled from not only Senvol, but from metal powder manufacturers and suppliers as well, to obtain a more valid understanding of the available metal materials for L-PBF.

A major limitation to the reliability of this study is the fact that the sample of companies surveyed was very small. Only three respondents mentioned that they had used metal 3D printing professionally, which decreases the reliability of this study. In further research on the subject it would be interesting to first survey a larger sample of companies and then do in-depth interviews with those companies that indicated to have used AM technologies.

Another limitation is that no conclusions can be drawn from the data of this study about the situation of the companies surveyed in general. The respondents to the survey were not in managerial positions, so they generally did not represent an overall picture of the situation of the whole company, but rather their own field of work.

REFERENCES

3D-tulostusta kovaan käyttöön. 2019. [web document]. Lahti: Delva, 2019. [Referred 17.11.2019]. Available: https://www.lamk.fi/sites/default/files/2019-05/Jarmo%20Kastell%20Delva.pdf

Brandt, M. 2017. Laser additive manufacturing. Elsevier. 479 p.

Carpenter Additive. 2019. Resources. [Carpenter Additive webpage]. [Referred 18.11.2019]. Available: https://www.carpenteradditive.com/technical-library/

EOS Aluminium AlSi10Mg_200C. 2013. [www- data sheet]. München: EOS, 2013. [Referred 12.11.2019]. Available: https://cdn0.scrvt.com/eos/public/6e028aad98066392/0240b76c22b39bb375b0b8ccaafff222/AlSi10Mg200C-M280_Material_data_sheet_06-13_en.pdf

EOS StainlessSteel 316L. 2017. [www- data sheet]. München: EOS, 2017. [Referred 17.11.2019]. Available: https://cdn.eos.info/ebcaa94e0c234042/83202420d4a1/SS-316L_9011-0032_M100_Material_data_sheet_FlexLine_12-17_en.pdf

EOS Titanium Ti64 Flexline. 2017. [www- data sheet]. München: EOS, 2017. [Referred 17.11.2019]. Available: https://cdn.eos.info/28a338fd58dfc1c6/c2c56e738083/Ti-Ti64_9011-0039-M100_MDS_FlexLine_08-17_en.pdf

Gerbert, P., Lorenz, M., Rüßmann, M., Waldner, M., Justus, J., Engel, P. & Harnisch, M.BCG 2015. Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries. [web document]. [Referred 26.1.2019]. Available: https://www.bcg.com/en-nor/publications/2015/engineered_products_project_business_industry_4_future_productivity_growth_manufacturing_industries.aspx

Gibson, I., Rosen, D. & Stucker, B. 2015. Additive manufacturing technologies. 2nd edition. New York: Springer Science+Business Media. 498 p.

Gong, H., Rafi, K., Starr, T. & Stucker, B. 2013. The effects of processing parameters on defect regularity in Ti-6Al-4V parts fabricated by selective laser melting and electron beam melting. 24th annual international solid freeform fabrication symposium. P. 424-439.

Kellner, T. 2017. An epiphany of disruption: GE additive chief explains how 3D printing will upend manufacturing [web document]. [Referred 11.10.2019]. Available: https://www.ge.com/reports/epiphany-disruption-ge-additive-chief-explains-3d-printing-will-upend-manufacturing/

Korpela, M. 2019. Material needs of Finnish metal and mechanical engineering industry from the perspective of additive manufacturing. Lappeenranta. 102 p.

Kover, A. 2018. Transformation in 3D: how a walnut-sized part changed the way GE Aviation builds jet engines [web document]. [Referred 12.10.2019]. Available: https://www.ge.com/reports/transformation-3d-walnut-sized-part-changed-way-ge-aviation-builds-jet-engines/

Laitinen, V., Piili, H., Nyamekye, P., Ullakko, K. & Salminen, A. 2019. Effect of process parameters on the formation of single track in pulsed laser powder bed fusion. 17th Nordic laser material processing conference. 27-29.8.2019. Elsevier. P. 176-183.

Lee, H., Lim, C.H.J., Low, M.J., Tham, N., Murukeshan, V. M. & Kim, Y. J. 2017. Lasers in additive manufacturing: a review. In: International journal of precision engineering and manufacturing-green technology, Vol 4, No. 3. P. 307-322.

Leong, D. 2019. Three benefits of 3D printing metal parts [web document]. [Referred 18.9.2019]. Available: https://markforged.com/learn/benefits-of-3d-printing-metal-parts/

Milewski, J. 2017. Additive manufacturing of metals. Switzerland: Springer International Publishing AG. 343 p.

Piili, H. 2019. Comments to thesis [private e-mail]. Receiver: markus.oltamo@student.lut.fi. Sent 17.11.2019, 13.46 o’clock (UTC +0200).

Senvol. 2019. Materials search [web database]. [Referred 25.10.2019]. Available: http://senvol.com/material-search/

SFS-EN ISO/ASTM 52900. 2017. Additive manufacturing - general principles - terminology. Helsinki: Suomen standardoimisliitto SFS. 25 p.

Vock, S., Klöden, B., Kirchner, A., Weißgärber, T. & Kieback, B. 2017. Powders for powder bed fusion: a review. In: Progress in Additive Manufacturing. Springer. 2019. P. 1-15.

Vyas, C. Poologasundarampillai, J. Hoyland, P. & Bartolo, P. 2017. 3D printing of biocomposites for osteochondral tissue engineering. In: Ambrosio, L. 2017. Biomedical composites 2nd edition. Elsevier. P. 261-302.

Wohlers associates 2017. Wohlers report 2017. Wohlers associates, INC. 343 p.

Zenou, M. & Grainger, L. 2018. Additive manufacturing of metallic materials. In: Zhang, J. & Yeon-Gil, J. Additive Manufacturing: Materials, Processes, Quantifications and Applications. 1st edition. Butterworth-Heinemann. 2018. P. 53-103.