LUT UNIVERSITY
LUT School of Energy Systems
LUT Mechanical Engineering

Markus Korpela

MATERIAL NEEDS OF FINNISH METAL AND MECHANICAL ENGINEERING INDUSTRY FROM THE PERSPECTIVE OF ADDITIVE MANUFACTURING

Examiners: Professor Antti Salminen
Docent Heidi Piili

TIIVISTELMÄ

LUT-Yliopisto
LUT School of Energy Systems
LUT Kone

Markus Korpela

Suomalaisen metalli- ja konepajateollisuuden materiaalitarpeet lisäävän valmistuksen näkökulmasta

Diplomityö

2019

76 sivua, 13 kuvaa, 19 taulukkoa ja 12 liitettä

Tarkastajat: Professori Antti Salminen
Dosentti Heidi Piili

Hakusanat: lisäävä valmistus, 3D-tulostus, metallit, materiaalit, metalliteollisuus, konepajateollisuus

Tämän diplomityön tarkoituksena oli selvittää, mitkä ovat suomalaisen metalli- ja konepajateollisuuden eniten käyttämiä metallimateriaaleja, ovatko nämä materiaalit lisäävästi valmistettavissa sekä löytyvätkö materiaalit suomalaisten metallien lisäävän valmistuksen palveluntarjoajien valikoimista tai tarjoavatko laitevalmistajat niitä. Saatavilla olevien materiaalien ominaisuuksia verrattiin kirjallisuustutkimuksena perinteisillä menetelmillä valmistettujen kappaleiden ominaisuuksiin. Kone- ja metalliteollisuuden yrityksiä haastateltiin kvantitatiivisen kyselyn avulla. Yhteensä 78 yritystä haastateltiin. Tämä työ keskittyi teräksiin ja alumiineihin lasersädettä hyödyntävän jauhepetisulatuksen näkökulmasta.

18 % kyselyssä vastatuista materiaaleista oli saatavilla suoraan lasersädettä hyödyntävien laitteiden valmistajien materiaalivalikoimista. 78 % materiaaleista oli teräksiä, 16 % alumiiniseoksia ja loput muita metallimateriaaleja. 35 % teräksistä oli rakenneteräksiä ja 30 % ruostumattomia teräksiä. Kaikki ruostumattomat teräkset olivat joko 304, 304L, 316, 316L tai näiden EN-vastaavia. 92 % rakenneteräksistä oli S355- tai S235-luokan rakenneteräksiä. 31 % vastatuista alumiiniseoksista oli suoraan saatavissa yhden tai useamman laitevalmistajan materiaalivalikoimasta. 82 % yrityksistä eivät olleet koskaan kokeilleet metallien lisäävää valmistusta omalla laitteella tai alihankintana. 51 % näistä yrityksistä kertoi syyksi, että heillä ei ole ollut tarvetta. 40 % vastasi tietotaidon puuttumisen olleen syynä siihen, ettei metallien lisäävää valmistusta oltu kokeiltu.

Systemaattinen tieto metallien lisäävällä valmistuksella valmistettujen kappaleiden mekaanisista ominaisuuksista puuttuu, sekä saatavilla olevien materiaalien valikoima on edelleen rajallinen. Tutkimusten mukaan mekaaniset ominaisuudet ovat lähtökohtaisesti samalla tasolla perinteisesti valmistettujen vastakappaleiden kanssa, mutta eivät kuitenkaan aina.

ABSTRACT

Lappeenranta-Lahti University of Technology LUT
LUT School of Energy Systems
LUT Mechanical Engineering

Markus Korpela

Material needs of Finnish metal and mechanical engineering industry from the perspective of additive manufacturing

Master's thesis

2019

76 pages,13 figures, 19 tables, and 12 appendices

Examiners: Professor Antti Salminen
Docent Heidi Piili

Keywords: additive manufacturing, 3D printing, metals, materials, Finnish metal and mechanical engineering industry

Aim of this master thesis was to find out which specific metal materials are the most widely used by Finnish metal and mechanical engineering industry. Other goals were to find out are the materials additively manufacturable and which materials are generally available by Finnish pure commercial metal additive manufacturing service providers or by system producers. In addition, properties of the materials available by the service providers were examined and compared with the properties of conventionally manufactured ones via a literature review. A quantitative survey for Finnish metal and mechanical engineering industry was executed and a total of 78 companies were interviewed. This thesis focused on steels and aluminums from the perspective of laser-based powder bed fusion.

18 % of materials answered in the survey were available by one or more laser-based powder bed fusion system producers. 78 % of all materials were steels, 16 % aluminum alloys and rest other metals. 35 % of the steels were strucural steels, and 30 % were stainless steels. All the stainless steels were either 304, 304L, 316, 316L or their EN equivalents. 92 % of the structural steels were S355 and S235 steels. 31 % of the aluminum alloys were directly available by one or more system producers.

82 % of the companies had never tried metal additive manufacturing by own machine nor by subcontracting. 51 % of these companies answered that they have not had need for that. 40 % of the companies told that lack of expertise was one of the reasons.

Systematic knowledge about the properties of metal additive manufacturing parts is missing and the repertoire of available materials is still very limited. Basic mechanical properties of metal additive manufacturing parts have been reported to be on par with their correspondents of conventional materials, but that is not always the case.

ACKNOWLEDGEMENTS

This thesis was carried out in research group of Laser Material Processing of LUT University as a part of FIDIMA Co-Creation project funded by national Finnish funding agency of Business Finland and Manufacturing 4.0 funded by Strategic research council of Finland. The FIDIMA Co-Creation project was going on during 15.8.–31.12.2018. This thesis would not have been possible without the financial supports of the projects.

I would like to thank my thesis advisors Professor Antti Salminen and Docent Heidi Piili of the School of Energy Systems at LUT University. My questions were always answered whenever I ran into a trouble and support was always provided.

I must express my very profound gratitude to my supportive parents and especially to my spouse, Veera, for providing me with unfailing support and for making sacrifices to make this happen.

Finally, my special thanks go to Aatos Virtanen who has always believed in me.

Markus Korpela

Markus Korpela
Lappeenranta 25.2.2019

TABLE OF CONTENTS

APPENDICES

LIST OF SYMBOLS AND ABBREVIATIONS

E	energy density (J/mm^3)
h	hatch spacing (mm)
P	laser power (W)
t	layer thickness (mm)
v	scan speed (mm/s)

AM	Additive Manufacturing
AISI	The American Iron and Steel Institute
CEN	The European Committee for Standardization
EOS	Electro Optical Systems
HIP	Hot isostatic pressing
ISO	International Organization for Standardization
L-PBF	Laser based powder bed fusion
PBF	Powder bed fusion
SAE	Society of Automotive Engineers
SFS	Finnish Standards Association SFS

1 INTRODUCTION

Metal additive manufacturing is a decades old manufacturing method which has now grown to a point where it is a potential way of manufacturing for certain applications. Parts manufactured with the most common and widely applied metal additive manufacturing process are only semi-finished, but in some cases can be used directly as end parts (Cabrini et al. 2016, p. 346; Milewski 2017, p. 37; Wei et al. 2017, p. 38).

Economic impact of metal additive manufacturing is low due to niche market. Current systems of metal additive manufacturing are not anything to revolutionize way of manufacturing or to replace traditional ones. Metal additive manufacturing is an addition to repertoire of manufacturing which more likely replaces manufacturing methods of certain applications rather than a complete manufacturing process. Additive manufacturing (AM) has some advantages, which can build geometries that conventional subtractive manufacturing cannot (Leary 2017, p. 99). In general, the manufacturing process is very expensive. Systematic knowledge about the properties of metal AM parts is missing and the repertoire of available materials is still limited (Sun, Brandt & Easton 2017, p. 69; Kurzynowski et al. 2018, p. 68; Yang et al. 2017, p. 83). Materials are neither discussed deeply in recently published books available for this thesis in the field of metal additive manufacturing (Brandt 2017; Gibson, Rosen & Stucker 2015; Gu 2015; Milewski 2017; Wohlers 2018; Yang et al. 2017).

Despite the limitations and high expenses, utilization level of additive manufacturing is presumable lower than it could be in Finland. This was part of the motivation of this thesis. Certain parts, originally designed to manufacture with subtractive manufacturing methods, would be cheaper to manufacture with additive manufacturing but are still manufactured with conventional methods. Lack of knowledge might be a reason for that. Finding of the parts requires lot of knowledge about advantages and disadvantages of metal additive manufacturing. This knowledge has not been taught to most engineers of current working life. Therefore, some companies have no knowledge about additive manufacturing whilst some use it daily.

Additive manufacturing in general was originally used for prototyping purposes. Nowadays, most additively manufactured parts are functional parts (Wohlers 2018, p. 25). AM is already utilized in many industries globally, but still lacks for example quality assurance systems and required standards for requirements of aerospace industry (Wohlers 2018, p. 17; Yang et al. 2017, p. 45).

AM industry has grown fast globally (Figure 1) but is still a fraction of the size of the industry of conventional manufacturing. For example, the number of sold robots was 25 times higher than the number of sold industrial additive manufacturing systems in 2017 (Halpenevat robotit lisäävät investointeja 2019, p. 12). As a definition, industrial additive manufacturing system stands for a system that costs more than 5000 USD. (Wohlers 2018, p. 145.)

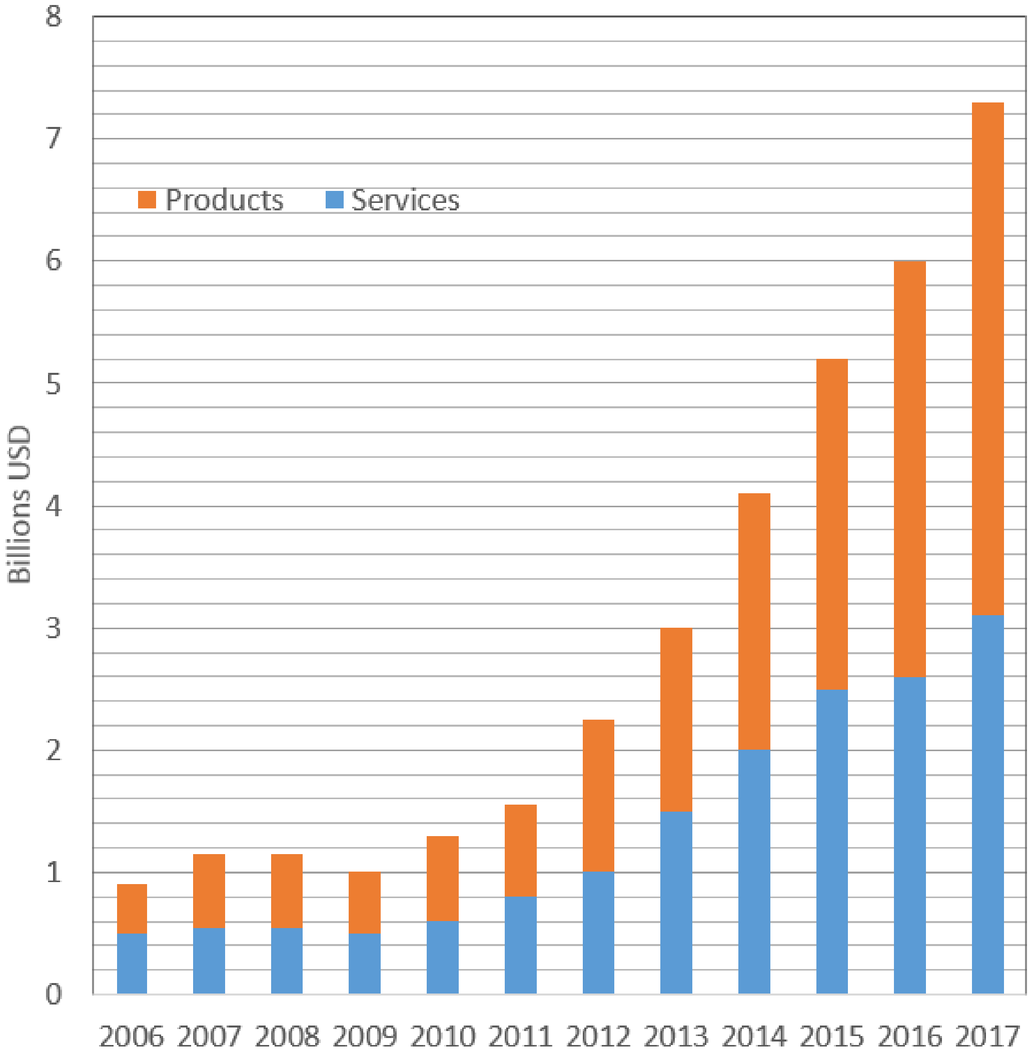

Figure 1. Growth of additive manufacturing industry between years 2006–2017 (Mod. Wohlers 2018, p. 144).

Figure 1 depicts that market size of AM was approximately 7.2 billion US dollars in 2017. The average annual growth rate of the industry was 26.6 % from the past 29 years. (Wohlers 2018, p. 142). To put this on perspective, about 200 persons each had more net wealthy in 2018 than the entire additive manufacturing industry was worth in 2017 (Forbes 2019). Growth of metal additive manufacturing by sold systems is presented in Figure 2.

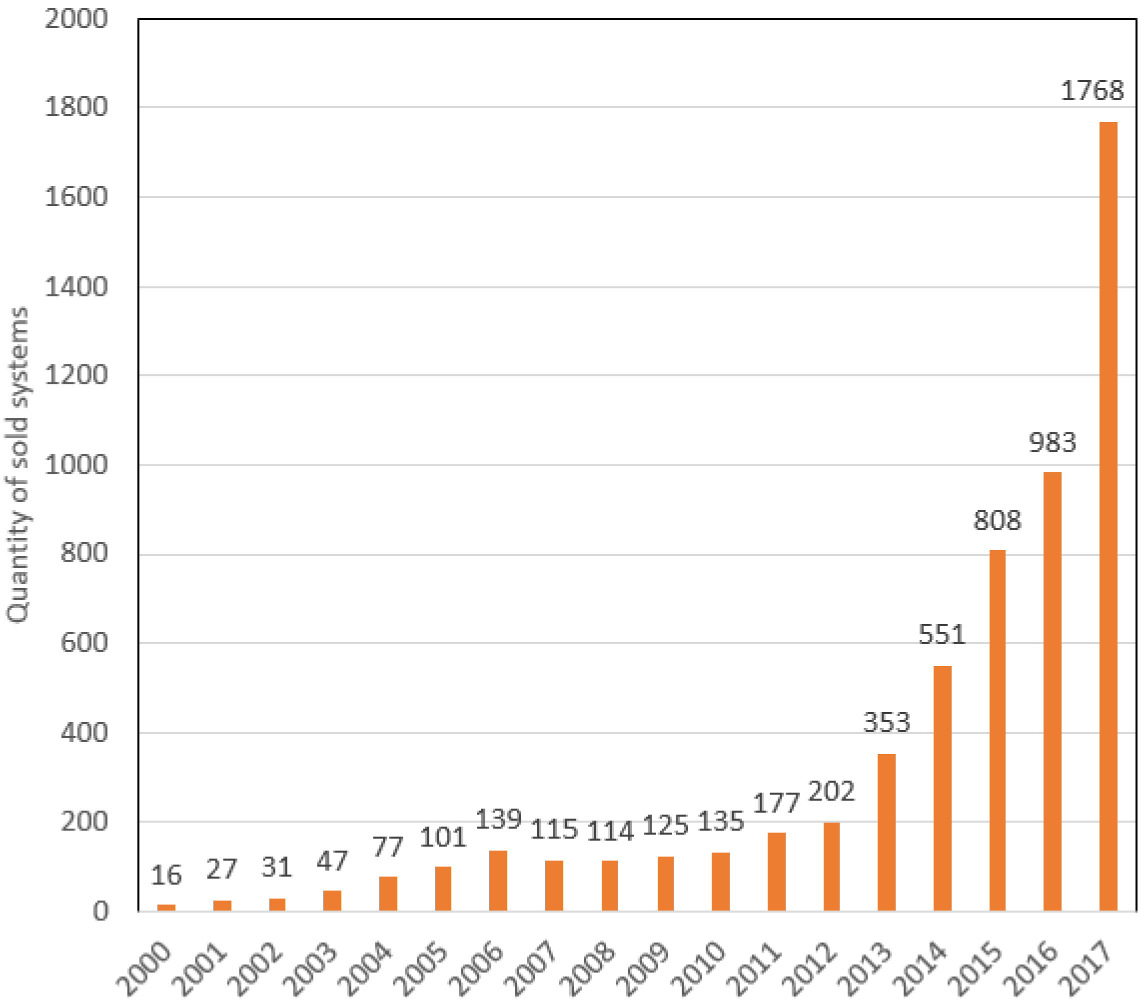

Figure 2. Sales of metal additive manufacturing systems between years 2000–2017 (Mod. Wohlers 2018 p. 149).

As Figure 2 shows, quantitative growth started to accelerate in the year 2013 almost resulting to 1800 sold systems in 2017. The growth was approximately 80 % since 2016 (Wohlers 2018 p. 149).

Aim of this thesis was to find out which specific metal materials are the most widely used by the Finnish metal and mechanical engineering industry. Other goals of the thesis were to find out which of the materials are additively manufacturable and which materials are available by Finnish pure commercial metal AM service providers. In addition, material properties of the materials available by the service providers were examined and compared with the properties of conventionally manufactured ones via a literature review. A quantitative survey for Finnish metal and mechanical engineering industry was executed.
Peer reviewed articles and topic-related books were used for the literature review. General knowledge about metal AM was gathered by visiting several national and one international AM related events, interviewing professionals, and visiting Formnext 2018 trade fair. Formnext is one of the largest AM related trade fairs in Europe.

Hypothesis of the thesis was that low-level-utilization of metal AM in Finland is not caused by unavailable materials but by lack of knowledge as well. This thesis focuses mainly on steels and aluminums.

The thesis was carried out in research group of Laser Material Processing of LUT University as a part of FIDIMA Co-Creation project funded by national Finnish funding agency of Business Finland and Manufacturing 4.0 funded by Strategic research council of Finland. The FIDIMA Co-Creation project was going on during 15.8.–31.12.2018.

2 FINNISH METAL AND MECHANICAL ENGINEERING INDUSTRY

Turnover of Finnish metal and mechanical engineering industry was approximately 30 % of whole turnover of industry of Finland in 2017 (Official Statistics of Finland 2018). Income of exportation of goods of Finland by industries is presented in Figure 3.

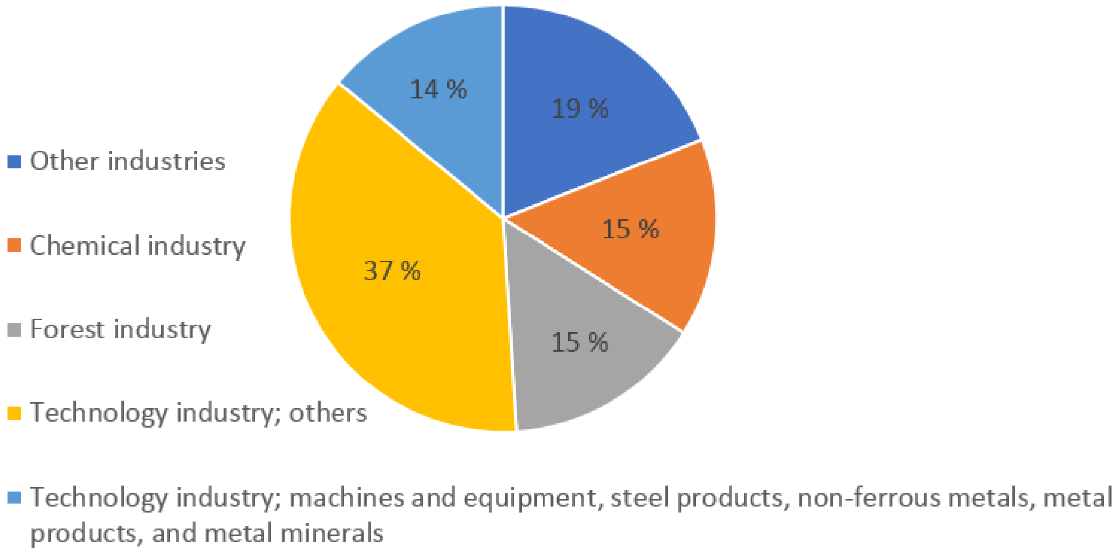

Figure 3. Relative division of export of goods of Finland by industries in 2017 (Mod. Technology Industries of Finland 2018a).

As Figure 3 shows, machines and equipment, steel products, non-ferrous metals, metal products, and metal minerals alone delivered 14 % of income of export of goods of Finland in 2017. It can be concluded that the industry plays an important role in Finnish economy. In 2017, industrial production of Finland was still about 20 % lower than the level before the financial crisis of 2008. In general, the gap compared to other European countries was 15 %. (Technology Industries of Finland 2018a; Technology Industries of Finland 2018b.)

About 25 % of the turnover of metal and mechanical engineering industry consisted of processing of metals. Rest 75 % of the turnover came from machines, metal products, and vehicles. During years 2016–2017, growths of these sections were 2 % and 5 %, respectively, but the level before the financial crisis of 2008 was not reached (Technology Industries of

Finland 2018a). Many parts of these products are made in roughly 10 000 Finnish machine shops (Konepajojen sorveista on moneksi 2018, p. 32).

Approximately 40 mines operate in Finland. Mined metals are mainly Au, Ag, Cu, Co, Cr, Fe, Li, Ni P, Pd, Pt, and Zn. (Sorsa 2015, p. 13). Ore reserves of Finland are low when compared with production volume and use of steels (Koivisto & Tuomikoski 2008, p. 77). Reasons for this are historical. In the 17th century, Finland was under Swedish rule and Sweden was one of the leading producers of iron and copper globally. Despite the lack of iron ore in the soil of Finland, the authorities invested in mining industry and therefore Finland has roots in it. (Alho 1949, pp. 15–29.)

2.1 Materials

Finnish industry uses mainly traditional materials, such as steels and aluminum. Strength and toughness of steels are being improved by Finnish steel technology. Improvement in purity level, simplicity of thermomechanical treatments, and decreasing of production costs are topics investigated by Finnish steel technology. Research and development of aluminum alloys is relatively low in Finland because Finland does not have its own primary aluminum production (Raaka-ainekäsikirja 5: Alumiinit 2002, p. 15). Instead, production technology of aluminum has been invested in Finland. (Tiainen & Laitinen 2008, p. 262.)

2.1.1 Steel

Steel is the most produced metal material in the world (Tiilikka 2008, p. 34). Steels consist of more than 50 % of iron and, generally, 2 % or less of carbon. Some chromium steels exceed the limit of 2 % of carbon. (SFS-EN 10020 2000, p. 7.) Ferrous metals consisting of more than 2 % of carbon are cast irons. (Koivisto & Tuomikoski 2008, p. 76.)

Steels have many different grades and names. Worldwide, different standards organizations have classified steels by their physical and chemical properties. Common standards organizations with standard acronyms are listed below:

- International Organization for Standardization - ISO
- European standards - EN
- The Society of Automotive Engineers - SAE

- American Society for Testing and Materials - ASTM
- The American Iron and Steel Institute - AISI
- British Standards - BS
- Unified numbering system - UNS
    - Of ASTM International and the Society of Automotive Engineers (SAE)
- Japanese Industrial Standards - JIS
- German Institute for Standardization - DIN
- China National Standards - GB standards.

Steel standards of different national and international standards organizations are not equivalent. For example, one ASTM International steel grade might be comparable with EN standard steel name by its chemical composition and mechanical properties, but still have differences in those. (Bringas 2004, pp. 1–4.)

Finnish Standards Association SFS (SFS) works as a central organization of standardization in Finland. SFS, with its affiliates, co-ordinate the participation in the international standardization work. SFS is a member of the International Organization for Standardization (ISO) and the European Committee for Standardization (CEN). SFS represents Finland in both CEN and ISO. Most of SFS standards are originally EN standards. Examples of standards related to steels and steel products are given below (SFS 2019a; SFS 2019b):

- SFS-EN 10079:en *Definition of steel products*
- SFS-EN 10020:en *Definition and classification of grades of steel*
- SFS-EN 10027-1:2016:en *Designation system for steels. Part 1: Steel names*
- SFS-EN 10027-2:en *Designation system for steels. Part 2: Numerical system.*

Steels are defined in three different classes; to non-alloy steels, stainless steels, and other alloy steels by their chemical composition in EN 10020. Stainless steels are steels with minimum 10.5 % of chromium and with maximum 1.2 % of carbon. Non-alloy steels are steel grades that do not exceed limit of percentual mass of specified elements defined in EN 10020. The elements and their limit value percent by mass are shown in Appendix I. Other alloy steels are steel grades exceeding at least one of these limits, but not complying with the definition of stainless steels. (SFS-EN 10020 2000, p. 9.)

EN 10027-1 was published in the year 1992 and it was a big change for designations of steels. It was confirmed in Finnish in 1993. (Pere 2003, p. 197.) The standard "specifies rules for designating steels by means of symbolic letters and numbers to express application and principal characteristics, e.g. mechanical, physical, chemical, so as to provide an abbreviated identification of steels" (SFS-EN 10027-1 2016, p. 4). As an example, comprised data of name of stainless steel X2CrNiMo17-12-2 is shown in Table 1.

Table 1. Comprised data of name of stainless steel X2CrNiMo17-12-2 (Mod. SFS-EN 10027-1 2016, p. 21).

Principal symbol	Definition
X	the average content of at least one alloying element ≥ 5 %
2	100 × specified average carbon percentage content
CrNiMo	chemical symbols indicating alloying elements
17-12-2	numbers, separated by hyphens representing respectively the average percentage of the elements rounded to the nearest integer

As Table 1 shows, average carbon percentage content of stainless steel X2CrNiMo17-12-2 is 0.02. Its alloying elements are chromium, nickel, and molybdenum and their average percentages rounded to the nearest integer are 17, 12, and 2. Steel number of X2CrNiMo17-12-2 is 1.4404 (SFS-EN 10088-1 2014, p. 17). The list of stainless steels is founded from standard EN 10088-1. The numerical system is defined in the standard EN 10027-2. Structure of steel numbers is presented in Figure 4.

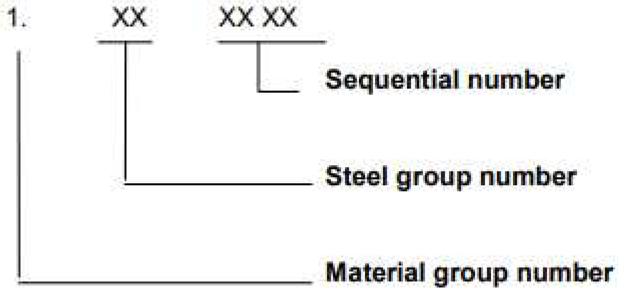

Figure 4. Structure of steel numbers (Mod. SFS-EN 10027-2 2015, p. 5).

In Figure 4, material group number 1 stands for steels, the steel group is in this case is stainless and heat resisting steels, and, according to standard SFS-EN 10027-2 (2016, p. 6), definition of 44 is “Stainless steel with ≥ 2,5 % Ni and Mo, but without Nb and Ti” (SFS-EN 10027-2 2016, p. 6).

Designation system of ASTM International often apply to specific products. The system consists of a letter followed by an arbitary sequentially assigned number. For example, letter A of material A 548 stands for ferrous materials. Previously, certain grades of alloy and carbon steels were designated by AISI/SAE four-digit numbering system, but the American Iron and Steel Institute does not write material specifications anymore. Since 1995 the four-digit designations are referred only as SAE designations. Austenitic stainless steels 304 and 316, which are common steels in Finland, are based on the SAE designation system. (Bringas 2004, pp. 13–14.)

2.1.2 Aluminum

Aluminum is the second most used metal after iron. Its density is only third of density of iron. Pure aluminum is a soft low-strength material. Therefore, its utilization level is low. Aluminum alloys are divided to wroughts and casts. Typical alloying elements are Cu, Mn, Si, Mg, and Zn (Kyröläinen & Lukkari 2002, p. 263). (Raaka-ainekäsikirja 5: Alumiinit 2002, pp. 8; 55–56.) Focus of the alloying is typically to increase strength, but also to increase corrosion resistance, castability, and weldability (Kyröläinen & Lukkari 2002, p. 263). Weaknesses of aluminum are low strength, fatigue strength, stiffness, and temperature resistance (Tiainen & Laitinen 2008, p. 263).

Basis of codification of aluminum and alloyed aluminums are defined in EN 1780-1 for casts and in EN 573-1 for wroughts and are shown below (SFS-EN 573-1 2005, p. 7; SFS-EN 1780-1 2003, p. 5):

- the prefix EN followed by a blank space;
- the letter A representing aluminum;
- a letter representing the form of the product:
  - the letter B representing alloyed aluminum ingots for remelting; or
  - C representing castings; or
  - M representing master alloys; or

    - W representing wrought products
- a hyphen;
- four figures, for wroughts, representing the chemical composition:
    - aluminum 99.00 % and greater 1xxx (1 000 series);
    - aluminum alloys grouped by major alloying elements:
        - copper 2xxx (2 000 series);
        - manganese 3xxx (3 000 series);
        - silicon 4xxx (4 000 series);
        - magnesium 5xxx (5 000 series);
        - magnesium and silicon 6xxx (6 000 series);
        - zinc 7xxx (7 000 series);
        - other elements 8xxx (8 000 series);
    - unused series 9xxx (9 000 series).
- five figures, for casts, representing the alloy composition limits. First of the five indicates alloying elements:
    - copper: 2XXXX;
    - silicon: 4XXXX;
    - magnesium: 5XXXX;
    - zinc: 7XXXX.

The second number of the five figures indicates the alloy group. The groups are listed in Appendix II. The third figure is generally zero. The last is zero as well except in aerospace applications (SFS-EN 1780-1 2003, p. 7). As an example, EN AC-43000 is a casting aluminum alloy which main alloying element is silicon. Its alloying group is AlSi10Mg by the number 3. In addition to the numerical system, the aluminum alloys are defined according to their chemical compounds. As an example, the designation by chemical compound of EN AC-43000 is EN AC AlSi10Mg. In this designation system, the numbers express the mass percent contents of the considered element. (SFS-EN 1706 2010, pp. 8; 16.) Designation of wrought aluminum alloys according to the main alloy and temper designations mentioned in this thesis are presented in Appendix III.

3 METAL ADDITIVE MANUFACTURING

According to standard of terminology of additive manufacturing (SFS-EN ISO/ASTM 52900:en 2017) seven different process categories exist in additive manufacturing. The process categories with definitions are shown in Table 2.

Table 2. Process categories with definitions of additive manufacturing according to SFS-EN ISO/ASTM 52900:en (Mod. SFS-EN ISO/ASTM 52900:en 2017, p. 7).

Process category	Definition: An additive manufacturing process in which…
Material extrusion	material is selectively dispensed through a nozzle or orifice.
Powder bed fusion	thermal energy selectively fuses regions of a powder bed.
Binder jetting	a liquid bonding agent is selectively deposited to join powder materials.
Vat photopolymerization	liquid photopolymer in a vat is selectively cured by lightactivated polymerization.
Material jetting	droplets of build material are selectively deposited.
Directed energy deposition	focused thermal energy is used to fuse materials by melting as they are being deposited.
Sheet lamination	sheets of material are bonded to form a part.

Directed energy deposition, powder bed fusion, and sheet lamination are single-step processes in which basic material properties, such as density of more than 90 %, are achieved in a single operation. Material extrusion and binder jetting are multi-step processes in which the parts require consolidation by secondary process such as sintering in order to result to parts with density greater than 90 %. (SFS-EN ISO/ASTM 52900:en 2017, pp. 18–20; Yang et al. 2017, p. 18). Standard ISO/ASTM 52900 does not define whether the material jetting process is a single or multi-step process. At least one metal AM system producer utilizes material jetting and according to them, their technology is a single-step process (Cohen 2019; Xjet webpage 2019).

This thesis is mainly about laser beam based powder bed fusion because it is the most common, widely applied, and possible the most evolved metal additive manufacturing technology (Milewski 2017, p. 37; Yang et al. 2017, p. 63). It is also the most used metal AM technology for production of engineering components (Yang et al. 2017, pp. 18–19; 63). In addition, it was not known whether there had been commercial systems utilizing any other process to additively manufacture metal parts in Finland in 2018 (Salminen 2018). Possibly the first system utilizing other metal AM process was the one acquired by company of Wärtsilä Finland in the early 2019 (Raukola 2019).

3.1 Standards

Large databases of performances and material properties of conventional materials exist over the past 100 years. Same kind of databases do not exist for metal additive manufacturing but are being developed currently. This lack of databases restricts utilization of metal additive manufacturing notably. (Milewski 2017, pp. 54; 253.) As a reference, it took about 20 years to publish main European standards related to aluminum (Raaka-ainekäsikirja 5: Alumiinit 2002, p. 83).

24 pieces of ISO and/or ASTM international standards related to additive manufacturing have been published (ISO 2019; ASTM International 2019). In addition, webpage of ISO shows 24 additive manufacturing standards to be under development. Designations of the published standards have been compiled to Appendix IV. Two of these standards, 52900 and 52901, have been published in Finnish by SFS (SFS 2019c):

- SFS-EN ISO/ASTM 52900:2017 *Materiaalia lisäävä valmistus. Yleiset periaatteet. Terminologia*
- SFS-EN ISO/ASTM 52901:2018 *Materiaalia lisäävä valmistus. Yleiset periaatteet. Vaatimukset hankittaville kappaleille.*

Beside the international standards related to additive manufacturing, national standards such as British standards have also been published (BSI 2019).

3.2 Powder bed fusion

In powder bed fusion of metals, parts are built layer by layer from metal powder. Melting is achieved by focused thermal energy of laser beam or electron beam. Both can be used for manufacturing high precision parts. However, electron beam based systems are rare and therefore not introduced more deeply in this thesis.

The laser beam is focused and guided to the surface of metal powder bed. Energy density of the laser beam must be high enough for sufficient melting of metal powder. Part of the beam reflects away from the powder bed whilst part of it absorbs to the material and melts it. The absorption is significantly higher than in flat surface of solid metal because there are gaps among the particles (Sun et al. 2017, p. 59). (Milewski 2017, pp. 88; 97.) Rapid cooling rate applies to L-PBF causing significantly different microstructure than in counterparts made with conventional manufacturing (Sun et al. 2017, p. 61).

Imperfections, such as undesired microstructures, high residual stresses, and porosity, do occur in powder bed fusion. (Kurzynowski et al. 2018, p. 64.) Thermal expansions can lead to differences in temperatures of a part causing bending or distortions because some parts of the workpiece are contracting on cooling while others expanding on heating during the building process. Bending and distortions can lead to cracking of the metal. (Milewski 2017, p. 54.)

Many system producers use their own commercial name for PBF such as direct metal sintering (DMLS), selective laser sintering (SLS), direct metal laser sintering (DMLS), selective laser melting (SLM), and electron beam melting (EBM) (King et al. 2015, p. 2). Despite the word “sintering”, current metal PBF systems completely melt the particles instead of sinter (Milewski 2017, p. 60).

Quantity of different PBF system producers is more than 30. The system producers and their machine base prices are published in annual report by Wohlers Associates. (Wohlers 2018, pp. 65–127.) These systems and prices of the report of 2018 can be seen in Appendix XI. It can be calculated that average base price of a L-PBF system was approximately 480 000 euros and average maximum building volume 21 liters. Average price of a small system, with maximum building volume less than 10 liters, was 200 000 euros and average building volume 1.5 liters. For the medium size systems with building volume of more than 10 liters but less than 30, the same values are 410 000 euros and 21 liters. Average maximum building volume of the largest systems, with building volume more than 30 liters, was 67 liters and average price 1 070 000 euros.

As mentioned, PBF is possibly the most evolved AM technology. Nevertheless, the production speed is still slow and expensive compared to conventional manufacturing, and the parts are usually semi-finished products requiring post-processing (Cabrini et al. 2016, p. 346; Milewski 2017, p. 37; Wei et al. 2017, p. 38). According to webpages of four large L-PBF system producers, production speeds of their flagship models are informed to be between 100–171 cm^3 per hour. The machines are equipped with two or four 400, 500, or 700 W lasers. (Concept Laser 2019a; EOS 2019a; Renishaw 2019a; SLM 2019a.) Parameters of the manufacturing with the best production speeds have not been told and therefore it might be that these values do not correlate with manufacturing speeds of best achievable accuracies. For example, layer thickness has a major effect on building time.

In theoretical situation, in which thermal distortions would not exist and a system with large enough building volume would exists, solid part of volume of one cubic meter would be manufactured with the highest production speed of 171 cm^3 per hour in 250 days. It can be concluded that current L-PBF systems are not particularly suitable for manufacturing of very large metal parts. A L-PBF machine with build volume of 400 x 400 x 400 cm^3 can cost more than one million euros (Appendix XI). With the price of a million euros and 8 years of period of amortization, direct hourly cost of these 8 years would be 14.3 euros. Similarly, direct machine costs of a part would be 3 000 euros with machine utilization level of 80 % and manufacturing time of one week. Volume of the part would be 28.7 liters of solid metal with the best building speed of 171 cm^3 per hour. This amount of solid steel would weigh approximately 226 kg which would cost 22 600 euros with material price of 100 euros per kg. These direct material and machine costs of this theoretical part would be total of 25 600 euros.

3.3 Effect of process parameters

Process parameter values and geometry of a part can have major effects to mechanical properties of additively manufactured metal parts (Ahmadi et al. 2016, p. 329; Kurzynowski et al. 2018, p. 69; Pace et al. 2017, p. 445; Yang et al. 2017, pp. 82–83). Parameter values of systems manufactured by same manufacturer may also vary inside the same material. This makes it difficult to verify general process parameters when compared with traditional subtractive processes. More than 20 process parameters can affect quality of a part. (Yang et al. 2017, pp. 82-83.) Volumetric energy density *E* is the result of main parameters (Ahmadi et al. 2016, p. 333). Too low or high energy density leads to weakened strength and density of a part (Zhang et al. 2017, p. 253). Volumetric energy density can be determined (Gu 2015, p. 60; Kurzynowski et al. 2018, p. 65):

$$E = \frac{P}{v \times h \times t} \tag{1}$$

In the equation 1 the *E* is volumetric energy density (J/mm^3), *P* is laser power (W), *v* is scan speed (mm/s), *h* is hatch spacing (mm), and *t* is layer thickness (mm).

3.4 Laser

A laser system capable to melt metal was already invented in the 1970s. Nowadays, power of the laser beam can be thousands of watts and diameter of the beam fraction of a mm. Molten pool can be very small with process speed of meters per second. Many different lasers exist, but L-PBF systems mostly use fiber lasers due to their high beam quality, reliability, low maintenance, and compact size. The systems utilize one or multiple ytterbium doped silica glass fiber lasers with typical laser power between 200–1000 watts. (Gu 2015, p. 3; Murr 2015, p. 666.) These modern fiber lasers can operate without problems for tens of thousands of hours. CO_2 laser, which was commonly used in different laser applications last decade, do not suit well for L-PBF. Its beam quality and absorption to metal materials and energy efficiency are relatively low when compared with modern single-mode fiber lasers. (Milewski 2017, pp. 87–90.)

3.5 Metal additive manufacturing in Finland

First metal parts (Figure 5) were additively manufactured in Finland already in the early 1990s. The company still exists and is called Electro Optical Systems (EOS) Finland Oy nowadays. Today the company develops and produces metal powders and processes for additive manufacturing. It is part of EOS Group which is one of the largest system producers in the field of metal additive manufacturing. (Kotila 2019.)

Figure 5. One of the firsts additively manufactured metal parts in Finland (Mod. Piili 2017).

More than 30 PBF metal additive manufacturing systems existed in Finland in 2018, and the repertoire is known to grow at least by two in 2019 (LUT University 2019; Lindqvist 2019). The systems and their locations can be seen in Table 3. All the machines utilize laser-based powder bed fusion process (3D Systems 2019; Concept Laser 2019b; SLM 2019b; Wohlers 2018, p. 76).

Table 3. Known metal AM systems and their locations in Finland in 2018. (3DStep 2018; 3D Formtech 2018a; Koivisto 2019; Ladec 2019; Moilanen 2019; Oulupmc 2019; Kotila 2019; Salminen 2018; Seppälä 2018; Vossi Group 2015; Vossi Group 2016; Vossi Group 2018).

Location	System(s)
Electro Optical Systems Finland Oy	>20 EOS systems
Materflow Oy	Concept Laser Mlab cusing
3DStep Oy	SLM 280 HL Twin
3D Formtech Oy	EOS M290

Table 3 continues. Known metal AM systems and their locations in Finland in 2018. (3DStep 2018; 3D Formtech 2018a; Koivisto 2019; Ladec 2019; Moilanen 2019; Oulupmc 2019; Kotila 2019; Salminen 2018; Seppälä 2018; Vossi Group 2015; Vossi Group 2016; Vossi Group 2018).

HT Laser Oy	SLM 280 2.0 Twin 700 W
Lillbacka Powerco Oy	3D Systems ProX DMP300
V.A.V Group Oy	SLM 125 HL
VTT Technical Research Centre of Finland LTD	SLM 125 HL
Nivala Industrial Park Ltd	SLM 280HL
SASKY Municipal Education and Training Consortium	SLM 125 HL
LUT University	EOS EOSINT M270
Oulu Precision Mechanics Manufacturing Centre	EOS EOSINT M270

Data of Table 3 was gathered by Google searches and discussing with people involved to field of additive manufacturing at different national and international events in 2018. If a company with an own metal system was discussed, but its webpage included no information about the system, information was confirmed by contacting the company. 3 out of the 12 quarters of Table 3 were pure commercial service providers. 3 others out of the 12 used systems mainly for their own production and existing customers but did not rule out possibility of providing metal AM services to outsiders in the future. Each of the companies had one system or will acquire their first one during 2019. (3DStep 2018; 3D Formtech 2018a; Koivisto 2019; Ladec 2019; Lindqvist 2019; Moilanen 2019; Seppälä 2018.)

Other metal AM systems might have existed in Finland in 2018, but information was not publicly available. In addition to already mentioned companies, seven other Finnish companies announced to provide metal AM in the catalogue of the Subcontracting Trade Fair 2018 (Subcontracting 2018 Fair Catalogue 2019). This trade fair is the largest one related to manufacturing industry in Finland. The companies most likely offer these services outsourced from the already mentioned service providers or from Europe as no public information about their own systems was available. If other metal AM systems exist in

Finnish companies, they are probably only used for own production. Finnish Rapid Prototyping Association has a list (Finnish Rapid Prototyping Association 2019) about the systems in Finland on their webpage, but it has not been valid for at least three years (Korpela 2016, p. 19).

Only two Finnish pure commercial service providers had their own metal AM system in Finland in 2017 (Salminen 2018). Their combined turnovers, which another included non-metal AM as well, were half a million euros in 2017 (Finder 2019a; Finder 2019b). Based on the turnovers, volume of metal AM was quite low in Finland in 2017. More detailed information of the size of Finnish metal AM industry was tried to find out for this thesis by sending emails to Finnish AM companies, but unfortunately responses were not given.

Finnish industry utilizes metal AM parts not just in prototyping but in end use as well. Company of Raute has more than 30 metal AM items in their system and about half of them are end use parts (Kousa 2018). Company of Metso has announced their use of metal AM parts (Tekniikka & Talous 2018). As mentioned above, V.A.V Group Oy, HT Laser Oy, and Lillbacka Powerco Oy have their own systems for production use.

4 MATERIALS IN LASER BASED POWDER BED FUSION OF METALS

Parts are built from metal powder in L-PBF. The powder is similar to ones used in conventional powder manufacturing processes (Yang et al. 2017, p. 84). The particles are spherical and particle size is 15–45 microns in the most L-PBF systems (Wohlers 2018, p. 53). Conventional powders cannot be used due to unspherical shapes and wider range of particle size (Milewski 2017, p. 72). Unspherical shapes would result to lower powder bed packing density because more air would exist between the particles. The higher the packing density is, the better quality can be achieved. (Sun et al. 2017, pp. 57–58.) AM powders are a fraction of powder markets and they require special processing. These both negatively affect prices and development of the powders (Milewski 2017, p. 82; Yang et al. 2017, p. 46). Commercially available AM materials by system producers are listed below (Milewski 2017, pp. 69–71; Wohlers 2018 pp. 50–51):

- Tool steels
- Stainless steels
- Commercially pure titanium
- Titanium alloys
- Aluminum alloys
- Nickel-based superalloys
- Cobalt-chromium alloys
- Copper-based alloys
- Gold
- Silver
- Platinum
- Palladium
- Tantalum.

Repertoire of available L-PBF materials is narrow because of low demand and high costs (Yang et al. 2017, p. 83). Despite the narrow repertoire, all materials that are fusion weldable are potential L-PBF materials. Many new materials are under development. (Gibson et al. 2015, p. 110; Milewski 2017, p. 58.) Typical applications are ones used in wrought or cast forms, but not safety-critical ones (Yang et al. 2017, p. 46). Systematic knowledge about properties of L-PBF manufactured parts is missing (Kurzynowski et al. 2018, p. 65).

4.1 Mechanical properties

Basic mechanical properties of AM parts have been reported to be on par with their correspondents of conventional materials (Ganesh et al. 2014, p. 37). Relative density and microstructure of the parts have strong effects on the properties (Sun et al. 2017, p. 67). Mechanical properties vary between parts manufactured by different systems because the system producers utilize different scanning strategies and laser powers. Different scanning strategies affect mechanical properties due to different thermal gradients caused by the laser. (Yang et al. 2017, pp. 92–93.) For the same reasons, the resulting material properties can even vary with different models by the same system producer (EOS 2019e; EOS 2019f).

Building direction affects mechanical properties of AM parts. In general, the properties of an AM part are weaker if loading is parallel to the building direction of the part. This does not apply to AM aluminum alloy parts. L-PBF manufactured 316L, aluminum alloys, and titanium alloys have refined and metastable microstructures and therefore comparable or higher yield and tensile strengths than to those manufactured by traditional manufacturing. However, ductility of these AM materials is poorer. (Sun et al. 2017 p. 68.)

Fatigue strengths and creep strengths of AM materials are not so well known, and information cannot be found from material data sheets of main system producers (Concept Laser 2019c; EOS 2019b; Renishaw 2019b; SLM 2019c; Yang et al. 2017, p. 85). Lower fatigue strength than in conventional materials can be expected because of porosity and possible unbonded regions, especially with parts that have not been heat treated after manufacturing (Yang et al. 2017, p. 46; Zhang et al. 2017, p. 251). Metal powders include nearly unavoidable small spherical gas pores. Increase of porosity results to decrease of fatigue life and ductility (Sun et al. 2017 p. 68). In some cases, better fatigue properties than of conventional material have been achieved with optimum parameter values and build direction (Sun et al. 2017 p. 69; Zhang et al. 2017, pp. 251; 260).

The build orientation, surface roughness, and layered microstructure can have an effect to fatigue in additively manufactured parts. The effects can be tried to avoid with polishing, machining, and heat treatments. (Milewski 2017, p. 56.) Fatigue resistance of AM parts is higher if loading direction is upright to the building direction (Sun et al. 2017 p. 69). In as-built parts, fatigue properties are generally lower compared to wrought ones. (Gibson et al. 2015, p. 118.)

4.2 Metal materials available by Finnish service providers

Available materials by Finnish commercial companies with an own metal AM system are given in Table 4.

Table 4. Available materials by Finnish commercial companies with own metal AM system in 2018 (3Dstep 2018; 3D Formtech 2018b; Koivisto 2019; Materflow 2019; Moilanen 2019; Seppälä 2018).

Service provider	Material repertoire
Materflow Oy*	316L, CoCr alloy remanium star® CL
3Dstep Oy*	316L, AlSi10Mg, Maraging 1.2709
3D Formtech Oy*	AlSi10Mg, Maraging MS1, 316L, Ti64
HT Laser Oy	AlSi10Mg
Lillbacka Powerco Oy	LaserForm Maraging Steel (B)
V.A.V Group Oy	316L
*pure commercial service provider	

As Table 4 depicts, five different metal AM materials were available by the Finnish pure commercial service providers with own AM systems in 2018; stainless steel 316L, tool steel 1.2709, titanium Ti64, aluminum alloy AlSi10Mg, and cobalt-chromium alloy remanium star® CL. 316L was available by three different system providers, the aluminum alloy and the tool steel by two, and the titanium and cobalt-chromium alloys by one. It is possible that other materials were available, but information was not available in webpages of the companies. It was assumed that the service providers used materials sourced from the system manufacturer because that usually guarantees the best quality in parts (Milewski 2017, p. 68). In addition, company of Delva announced to offer at least Inconel 718 with their own machine in 2019 (Lindqvist 2019).

Same materials of different system providers have minor differences in chemical compounds. A minor difference in chemical compound might still have a major effect on quality of a part. As mentioned, the best quality is often achieved by use of powders of system producers. System producers study their own materials and optimize parameters according to them. (Milewski 2017, pp. 58; 89.)

Chemical compounds and main mechanical properties of the materials available by the Finnish pure commercial service providers are given later in this thesis. Information was taken from material data sheets of the system providers available on their webpages. In general, the material data sheets exclude information about fatigue and relative density properties, which might refer to poor values compared with traditional manufacturing. Some system producers do not share any material data sheets online. When considering the system producers and the materials dealt with in this Chapter, only material data sheets of EOS include information about relative densities (Concept Laser 2019c; EOS 2019b; SLM 2019c). These values are given in Table 5.

Table 5. Densities and relative densities of materials of EOS available by Finnish pure commercial service providers. (Mod. EOS 2019c; EOS 2019d; EOS 2019e; EOS 2019g).

Material	Density	Relative density
EOS 316L	approx. 7.9 g/cm^3	N/A
EOS MaragingSteel MS01	8.0–8.1 g/cm^3	approx. 100.00 %
EOS Aluminum AlSi10Mg	2.67 g/cm^3	approx. 99.85 %
EOS Ti64	ca. 4.41 g/ cm^3	N/A

Based on the values given in Table 5, it can be noted that relative density is high with the tool steel and aluminum alloy. Relative densities of 316L and Ti64 were not given in the data sheets, which might refer to lower relative densities. EOS is the only company out of these companies that provides material data sheets for different materials and models on their webpage. Material data sheet values of EOS presented in this thesis are taken from material data sheets of M280 and M290.

4.2.1 316L

316L is a common low carbon austenitic stainless steel with face centered cubic crystalline structure. However, some studies have shown that small amounts of ferrite might occur in AM parts (Kurzynowski et al. 2018, p. 66). 316L is widely used in different industries in different engineering applications and was available by the all three Finnish pure commercial service providers. (Pham, Dovgyy & Hooper 2017, p. 102.) ASTM standard about standard specification for AM of 316L exist (Appendix IV). Name of 316L comes from steel grade system of SAE International. Number 3 stands for SAE designation of nickel-chromium steels and “L” stands for low carbon alternative. (Bringas 2004, pp. 4; 13.) Its UNS designation is S31603 (Kurzynowski et al. 2018, p. 65). Following European steels share similar chemical composition with 316L (SFS-EN 10088-2 2014, p. 12):

- X2CrNiMo17-12-2/1.4404
- X2CrNiMo17-12-3/1.4432
- X2CrNiMo18-14-3/1.4435.

316L has relatively high corrosion resistance and strength (Gray et al. 2017, p. 141; Pham et al. 2017, p. 102; Bevan et al. 2017, p. 577). When compared to martensitic or precipitation strengthened stainless steels, 316L has lower yield and ultimate tensile strengths, but higher resistance to electrochemical corrosion and creep resistance (Kurzynowski et al. 2018, p. 65; Pham et al. 2017, p. 102). 316L has good weldability due to its immunity to grain boundary carbide precipitation. (Bevan et al. 2017 p. 578.) This can prevent intergranular corrosion in heat affected zone (Kyröläinen & Lukkari 2002, p. 15; Finnish Constructional Steelwork Association 2017, p. 4). Fatigue properties are expected to be different with conventional version due to porosity and different microstructure. (Zhang et al. 2017, pp. 252; 259).

According to study of Mower & Long (2015, pp. 200; 212), 316L was measured to have approximately 85–95 % of fatigue strength of wrought correspond. Hot isostatic pressing (HIP) improved high-amplitude and low cycle fatigue life, but it did not improve high cycle fatigue behavior. Similar results have been reported by Zhang et al. (2017, p. 252). In the study of Mower & Long (2015, p. 199), the studied material was obtained from EOS GmbH and the parts manufactured with EOS system.

Comparison of chemical compounds between three AM 316L materials, 1.4404, and wrought 316L is shown in Table 6. The chosen AM materials are the ones that are available by the Finnish pure commercial service providers.

Table 6. Chemical compounds of different 316L AM materials, 1.4404, and wrought 316L. (Mod. Bringas 2004, p. 4; Concept Laser 2019d; EOS 2019c; SFS-EN 10088-1 2014, pp. 17–18; SLM 2019c).

Element	CL 20ES	EOS 316L	SLM 316L	1.4404	Wrought 316L**
Fe	balance	balance	balance	balance	Balance
C (w%)	0–0.03	0.03	0.03	≤ 0.03	0.03
Cr (w%)	**16.5–18.5**	**17.0–19.0**	16.0–18.0	16.5–18.5	16–18
Ni (w%)	10.0–13.0	**13.0–15.0**	10.0–14.0	10.0–13.0	10.0–14.0
Mo (w%)	2.00–2.50	**2.25–3.00**	2.00–3.00	2.00–2.50	2.00–3.00
Mn (w%)	0–2.00	2.00	2.00	≤ 2.00	2.00
Si (w%)	0–1.00	0.75	1.00	≤ 1.00	1.00
P (w%)	0–0.045	0.025	0.045	≤ 0.045	0.045
S (w%)	0–0.030	0.010	0.030	0.008–0.030*	0.030
Cu (w%)	N/A	0.50	N/A	-	N/A
N (w%)	N/A	0.10	0.10	≤ 0.10	N/A
O (w%)	N/A	N/A	0.10	N/A	N/A
* 0.008 % to 0.030 % is recommended and permitted for weldability. Basic value is ≤ 0.015 ** ASTM A 276-03					

As can be seen in Table 6, only minor differences and exceedings of limits (bold in the table) of conventional materials exist. EOS 316L could exceed limits of nickel by 1–2 %, chromium by 0.5–1 %, and molybdenum by 0.5 %. CL 20ES could exceed the limit of chromium by 0.5 %. SLM 316L could exceed the limit of molybdenum by 0.5 %. However, EOS 316L is not claimed to be exact equivalent of ASTM A 276-03 wrought 316L but is claimed to have chemical composition corresponding to 18Cr-14Ni-2.5Mo of ASTM F138 (EOS 2019c). Effects of these mixtures of minor exceedings in chemical compounds were not possible to analyze with used literature of this thesis. Yield strengths of the materials are given in Table 7.

Table 7. Yield strengths of different 316L AM materials, 1.4404, and 316L rolled sheet (Mod. Concept Laser 2019d; EOS 2019c; Kurzynowski et al. 2018, p. 71; SFS-EN 10088-2 2014, pp. 8; 25; SLM 2019c).

Yield Strength $R_{p0.2}$ test method	CL 20ES [MPa]	EOS 316L [MPa]	SLM 316L [MPa]	1.4404 sheet [MPa]	Rolled sheet AISI 316L [MPa]
1	374 ± 5	N/A	N/A	N/A	N/A
2	385 ± 6	N/A	N/A	N/A	N/A
3	330 ± 8	N/A	N/A	N/A	N/A
4	N/A	530 ± 60	N/A	N/A	N/A
5	N/A	470 ± 90	N/A	N/A	N/A
6	N/A	N/A	519 ± 25	N/A	N/A
7	N/A	N/A	N/A	220–240	N/A
8	N/A	N/A	N/A	N/A	220–270

1=Yield strength $R_{p0.2}$, DIN EN 50125, 90° (upright), heat treated, µm N/A
2=Yield strength $R_{p0.2}$, DIN EN 50125, 45° (polar angle), heat treated, µm N/A
3=Yield strength $R_{p0.2}$, DIN EN 50125, 0° (horizontal), heat treated, µm N/A
4=Yield strength $R_{p0.2}$, ISO 6892/ASTM E8M, horizontal (XY), as built, 20 µm
5=Yield strength $R_{p0.2}$, ISO 6892/ASTM E8M, vertical (Z), as built, 20 µm
6=Offset yield stress $R_{p0.2}$, standard N/A, direction N/A, as built, 50 µm
7=EN ISO 377
8=N/A

As Table 7 depicts, yield strength values given by the system producers varies between 328–544 MPa in L-PBF 316L materials. According to data of 11 studies, yield strength of L-PBF 316L varies between (Kurzynowski et al. 2018, pp. 71–72):

- 385–590 MPa in as-built parts
- 375–463 MPa in heat treated parts
- 220–231 MPa in hot isostatic pressed parts.

Yield strengths of as-built L-PBF 316L parts are considerable higher than yield strengths of the conventionally manufactured 1.4404 and 316L sheets. Post heat treatments of the parts decrease yield strengths, but not to level below of conventionally manufactured 316L/1.4404. However, the value of 1.4404 is a minimum value. Yield strengths of austenitic stainless steel plates with thickness of less than 25 mm can be 25–40 % higher than the given minimum value (Finnish Constructional Steelwork Association 2017, p. 16). The value can be 20 MPa lower if the material was hot rolled instead of cold rolled (Kyröläinen & Lukkari 2002, p. 34). This would raise the value of Table 7 to 275–336 MPa. According to these values, hot isostatic pressed AM 316L parts might be weaker than conventionally manufactured. Post heat treatments are semi mandatory for AM 316L because of stress relieving. (Kurzynowski et al. 2018, p. 69; Riemer et al. 2015, pp. 441; 445).

Values of CL 20ES show that horizontally manufactured test parts would have lower yield strength than vertically manufactured parts. This would be against common knowledge about effect of building directions in AM parts and therefore might be just a mistake in the material data sheet. In general, horizontally manufactured test parts have better mechanical properties due to perpendicular loading to the layer plane (Sun et al. 2017, p. 68). Tensile strengths of the materials are given in Table 8.

Table 8. Tensile strengths of different 316L AM materials, 1.4404, and 316L sheet. (Mod. Concept Laser 2019d; EOS 2019c; Kurzynowski et al. 2018, p. 71; SFS-EN 10088-2 2014, p. 8; 25; SLM 2019c).

Tensile Strength R_m test method	CL 20ES [MPa]	EOS 316L [MPa]	SLM 316L [MPa]	1.4404 sheet [MPa]	Rolled sheet 316L [MPa]
1	650 ± 5	N/A	N/A	N/A	N/A
2	640 ± 7	N/A	N/A	N/A	N/A
3	529 ± 8	N/A	N/A	N/A	N/A
4	N/A	640 ± 50	N/A	N/A	N/A
5	N/A	540 ± 55	N/A	N/A	N/A
6	N/A	N/A	633 ± 28	N/A	N/A
7	N/A	N/A	N/A	520–680	N/A
8	N/A	N/A	N/A	N/A	520–680

1=Tensile Strength R_m, DIN EN 50125, 90° (upright), heat reated, µm N/A
2=Tensile Strength R_m, DIN EN 50125, 45° (polar angle), heat reated, µm N/A
3=Tensile Strength R_m, DIN EN 50125, 0° (horizontal), heat reated, µm N/A
4=Ultimate tensile strength, ISO 6892/ASTM E8M, horizontal (XY), as built, 20 µm
5=Ultimate tensile strength, ISO 6892/ASTM E8M, vertical (Z), as built, 20 µm

Table 8 continues. Tensile strengths of different 316L AM materials, 1.4404, and 316L sheet. (Mod. Concept Laser 2019d; EOS 2019c; Kurzynowski et al. 2018, p. 71; SFS-EN 10088-2 2014, p. 8; 25; SLM 2019c).

6=Tensile strength, standard N/A, direction N/A, as built, 50 µm
7=EN ISO 377
8=N/A

As Table 8 illustrates, tensile strength value given by the system producers varies between 485–690 MPa in L-PBF 316L materials. According to data of 15 studies, tensile strength of L-PBF 316L varies between (Kurzynowski et al. 2018, pp. 71–72):

- 524–717 MPa in as-built parts
- 555–687 MPa in heat treated parts
- 428–570 MPa in hot isostatic pressed parts.

Effect of heat treatments is lower for tensile strength than it is for yield strength (Kurzynowski et al. 2018, p. 71). According to the values of the literature, tensile strengths of hot isostatic pressed parts are lower than of traditionally manufactured parts. As-built and other way heat treated than HIP parts are on the same level with conventional 1.4404 and 316L. Elongation values of the materials are given in Table 9.

Table 9. Elongation values of different 316L AM materials, 1.4404, and 316L sheet. (Mod. Concept Laser 2019d; EOS 2019c; Kurzynowski et al. 2018, p. 71; SFS-EN 10088-2 2014, p. 8; 25; SLM 2019c).

Elongation test method	CL 20ES [%]	EOS 316L [%]	SLM 316L [%]	1.4404 sheet [%]	Rolled sheet 316L [%]
1	65 ± 4	N/A	N/A	N/A	N/A
2	63 ± 5	N/A	N/A	N/A	N/A
3	63 ± 5	N/A	N/A	N/A	N/A
4	N/A	40 ± 15	N/A	N/A	N/A
5	N/A	50 ± 20	N/A	N/A	N/A
6	N/A	N/A	31 ± 6	N/A	N/A
7	N/A	N/A	49 ± 11	N/A	N/A
8	N/A	N/A	N/A	40–45	N/A

Table 9 continues. Elongation values of different 316L AM materials, 1.4404, and 316L sheet. (Mod. Concept Laser 2019d; EOS 2019c; Kurzynowski et al. 2018, p. 71; SFS-EN 10088-2 2014, p. 8; 25; SLM 2019c).

9	N/A	N/A	N/A	N/A	40–45
1=Elongation, DIN EN 50125 A, 90° (upright), heat treated, µm N/A 2=Elongation, DIN EN 50125 A, 45° (polar angle), heat treated, µm N/A 3=Elongation, DIN EN 50125 A, 0° (horizontal), heat treated, µm N/A 4=Elongation at break, ISO 6892/ASTM E8M, horizontal (XY), as built, 20 µm 5=Elongation at break, ISO 6892/ASTM E8M, vertical (Z), as built, 20 µm 6=Break strain A, standard N/A, direction N/A, as built, 50 µm 7=Reduction of area Z, standard N/A, direction N/A, as built, 50 µm 8=EN ISO 377 9=N/A					

As shown in Table 9, elongation value given by the system producers varies between 25–70 % in L-PBF 316L materials. According to data of 11 studies, value of elongation of L-PBF 316L varies between (Kurzynowski et al. 2018, pp.71–72):

- 15–54 % in as-built parts
- 25–51 % in heat treated parts
- 28–54 % in hot isostatic pressed parts.

Elongation values can be significantly lower or higher in L-PBF parts than in conventionally manufactured 1.4404 or 316L parts. According to the data sheet of CL 20ES (Concept Laser 2019d), the higher elongation value is achieved by unspecified special heat treatment. Young's modulus along with coefficient of thermal expansion are the main factors that determine the level of residual stresses (Gu 2015, p. 61). Hardness values of the materials excluding 1.4404 are given in Table 10.

Table 10. Hardness values of different 316L AM materials and wrought 316L. (Mod. Bevan et al. 2017, p. 580; Concept Laser 2019d; EOS 2019c; SLM 2019c).

Hardness test method	CL 20ES	EOS 316L	SLM 316L	Conventional 316L
1	20	N/A	N/A	16
2	N/A	89*	N/A	N/A
3	N/A	N/A	209 ± 2	N/A

Table 10 continues. Hardness values of different 316L AM materials and wrought 316L. (Mod. Bevan et al. 2017, p. 580; Concept Laser 2019d; EOS 2019c; SLM 2019c).

1=Rockwell hardness C (HRC), standard N/A, surface N/A, as built 2=Rockwell hardness B (HRB), EN ISO 6508-1, grinded surface, as built 3=Vickers hardness (HV10), standard N/A, surface N/A, as built *typical

Different hardness test methods are not comparables (Koivisto et al. 2008, p. 15). The only comparison between values of Table 10 can be done with CL 20ES and conventional 316L. According to the values, CL 20ES is 25 % harder than conventional 316L. According to data of studies gathered by Kurzynowski et al. (2018, p. 70) measured microhardness of L-PBF manufactured, heat treated, and hot isostatic pressed parts were 1–40 % higher than of wrought and annealed 316L. Young's modulus values of the materials excluding 1.4404 are presented in Table 11.

Table 11. Young's modulus values of different 316L AM materials and 316L rolled sheet. (Mod. Concept Laser 2019d; EOS 2019c; Kurzynowski et al. 2018, p. 71; SLM 2019c).

Young's modulus test	CL 20ES [GPa]	EOS 316L [GPa]	SLM 316L [GPa]	Rolled sheet 316L [GPa]
1	ca. 200	N/A	N/A	N/A
2	N/A	185*	N/A	N/A
3	N/A	180*	N/A	N/A
4	N/A	N/A	184 ± 20	N/A
5	N/A	N/A	N/A	187–205
1=manufacturing direction N/A, heat treated 2=manufacturing in horizontal direction (XY), as built 3=in manufacturing vertical direction (Z), as built 4=manufacturing direction N/A, as built 5=N/A *typical				

As Table 11 depicts, Young's modulus value given by the system producers varies between 180–200 GPa in L-PBF 316L materials. The range is same than in conventional correspondents. According to data of 4 studies, Young's modulus of L-PBF 316L varies between (Kurzynowski et al. 2018, p. 71–72):

- 150–219 GPa in as-built parts
- 169–212 GPa in heat treated parts
- 171–201 GPa in hot isostatic pressed parts.

Surface roughness values of the materials excluding 1.4404 are given in Table 12.

Table 12. Surface roughness values of different 316L AM materials and surface roughness range of conventional manufacturing methods (Mod. EOS 2019c; Pere 2012, p. 21-16; SLM 2019c).

Surface roughness, as built	EOS 316L [µm]	SLM 316L [µm]	Conventional manufacturing methods [µm]
R_a	13 ±5	10 ± 2	0.006 – >250
R_z	80 ±20	50 ± 12	N/A

R_a stands for arithmetical mean roughness and R_z for maximum height (Pere 2012, pp. 21-6–7). Surface roughness values of CL 20ES were not given in the material data sheet (Concept Laser 2019d). Surface roughness (R_a) ranges of certain traditional manufacturing methods are listed below (Pere 2012, p. 21-16):

- sand casting 6.3–250 µm
- shell mold casting 3.2–60 µm
- die casting 0.8–60 µm
- precision casting 0.8–6.3 µm
- metal injection molding 0.4–3.2 µm
- turning 0.8–12.5 µm
- milling 1.6–6.3 µm.

As Table 12 and the list above illustrates, AM 316L parts need to be post-treated if the surface roughness of conventionally manufactured parts is wanted to achieve. However, traditionally manufactured parts typically have better surface quality than function of the part requires (Leary 2017, p. 115).

4.2.1 AlSi10Mg

Alloys of aluminum group AlSi10Mg are widely used as casting alloys in conventional manufacturing (Thijs et al. 2012, p. 1809). According to SFS-EN 1706 (2010, p. 6), six different aluminum alloys belong to aluminum alloy group AlSi10Mg. Silicon based aluminum alloys are characterized by relatively low melting temperature, low shrinkage, and good castability. However, the variation in size of silicon particles can have a major effect on the mechanical properties of AM AlSi10Mg parts (Li et al. 2016, p. 116). Age hardening of the alloys can be achieved by help of magnesium. (Fiocchi et al. 2016, p. 3402). In general, Al-Si and Al-Mg casting aluminum alloys are the ones used in L-PBF. The most used is Al-Si (Wei et al. 2017, pp. 38–39). Weldability, corrosion resistance, strength/density ratio, and hardenability of AlSi10Mg are good (Thijs et al. 2012, p. 1809; Wu et al. 2016, p. 311). The microstructure of L-PBF AlSi10Mg is a fine cellular-dendritic solidification structure. (Thijs et al. 2012, p. 1809). AM process of AlSi10Mg is harder to control than processes of stainless steels or titanium alloys (Thijs et al. 2012, pp. 1809–1810). ASTM standard about standard specification for AM of AlSi10Mg exist (Appendix IV).

According to study of Mower & Long (2015, pp. 199–200; 212), AM AlSi10Mg was measured to have approximately 60 % of fatigue strength of wrought and machined Al6061. Electrochemical nor mechanical polishing had no effect on fatigue. The studied material was obtained from EOS GmbH, but the parts manufactured with SLM system. However, fatigue resistance of L-PBF AlSi10Mg is very high when compared to its casted equivalents of EN 1706 (Brandl et al. 2012, p. 169). In SFS-EN 1706 (2010, p. 36), the minimum values of fatigue strengths of the alloys of the alloy group AlSi10Mg are between 80–110 MPa. The values are based on “for rotating bending conditions up to 50 x 10^6 cycles (Wöhler curves)”. (SFS-EN 1706 2010, p. 36.) Brandl et al. (2012, p. 169) report that post heat treatment would affect more fatigue of L-PBF AlSi10Mg parts than building direction.

AM AlSi10Mg is the only aluminum alloy available by Finnish pure commercial service providers and by only two of them. Comparison of chemical compounds between these two AM AlSi10Mg materials and EN AC-Al Si10Mg(a) of the alloy group AlSi10Mg is shown in Table 13.

Table 13. Chemical compounds of EOS Aluminum AlSi10Mg, SLM AlSi10Mg, and EN AC-Al Si10Mg(a) (Mod. EOS 2019e; SFS-EN 1706 2010, p. 16; SLM 2019c).

Element	EOS Aluminum AlSi10Mg	SLM AlSi10Mg	EN AC-Al Si10Mg(a)
Al	balance	balance	balance
Si [w%]	9.0–11.0	9.0–11.0	9.0–11.0
Fe [w%]	≤ 0.55	0.55	≤ 0.55
Cu [w%]	≤0.05	0.05	≤ 0.05
Mn [w%]	≤0.45	0.45	≤ 0.45
Mg [w%]	0.20–0.45	0.20–0.45	0.20–0.45
Ni [w%]	≤0.05	0.05	≤ 0.05
Zn [w%]	≤0.10	0.10	≤ 0.10
Pb [w%]	≤0.05	0.05	≤ 0.05
Sn [w%]	≤0.05	0.05	≤ 0.05
Ti [w%]	≤0.15	0.15	≤ 0.15
Others [w%]	N/A	0.05	≤ 0.05
Total others [w%]	N/A	0.15	≤ 0.15

As Table 13 shows, the materials are equivalent by their chemical compositions. Chemical compounds of other alloys of the group AlSi10Mg differ from these AM alloys (SFS-EN 1706 2010, p. 6). It can be concluded that the conventional material equivalent of AM AlSi10Mg materials of EOS and SLM is EN AC-Al Si10Mg(a)/EN AC-43000. Yield strength values of these materials are given in Table 14.

Table 14. Yield strength values of EOS Aluminum AlSi10Mg, SLM AlSi10Mg, and EN AC-Al Si10Mg(a) (Mod. EOS 2019e; SFS-EN 1706 2010, pp. 22; 26; SLM 2019c).

Yield strength test method	EOS Aluminum AlSi10Mg [MPa]	SLM AlSi10Mg [MPa]	EN AC-Al Si10Mg(a)
1	270 ± 10	N/A	N/A
2	240 ± 10	N/A	N/A
3	230 ± 15	N/A	N/A

Table 14 continues. Yield strength values of EOS Aluminum AlSi10Mg, SLM AlSi10Mg, and EN AC-Al Si10Mg(a) (Mod. EOS 2019e; SFS-EN 1706 2010, pp. 22; 26; SLM 2019c).

4	230 ± 15	N/A	N/A
5	N/A	268 ± 8	N/A
6	N/A	N/A	min. 80–90
7	N/A	N/A	min. 180–220
8	N/A	N/A	min. 200
1=Yield strength $R_{p0,2}$, ISO 6892-1:2009, horizontal (XY), as built, N/A µm 2=Yield strength $R_{p0,2}$, ISO 6892-1:2009, vertical (Z), as built, N/A µm 3=Yield strength $R_{p0,2}$, ISO 6892-1:2009, horizontal (XY), stress relieved, N/A µm 4=Yield strength $R_{p0,2}$, ISO 6892-1:2009, vertical (Z), stress relieved, N/A µm 5=Offset yield strength $R_{p0.2}$, standard N/A, direction N/A, as built, 50 µm 6= Yield strength $R_{p0,2}$, EN 10002-1, as casted 7= Yield strength $R_{p0,2}$, EN 10002-1, solution heat treated and fully artificially aged 8= Yield strength $R_{p0,2}$, EN 10002-1, solution heat treated and artificially under-aged			

According to Table 14, variation between the AM materials is low and they exceed minimum values of casted EN AC-Al Si10Mg(a). Both AM materials are almost identical when it comes to the yield strength of as-built parts. Stress relieved EOS AlSi10Mg parts have lower yield strengths than vertically manufactured as-built parts. Similar results have been reported by Wu et al. (2016, p. 319). In some cases, as-built parts have higher yield strengths than heat treated parts (Wu et al. 2016, p. 319). Building direction seems to have no effect on yield strength if the part was stress relieved. The values of the casted part were formed from values of die casting and sand casting. Comparison between yield strength of stress relieved EOS AlSi10Mg and common conventional Aluminum alloys is presented in Figure 6.

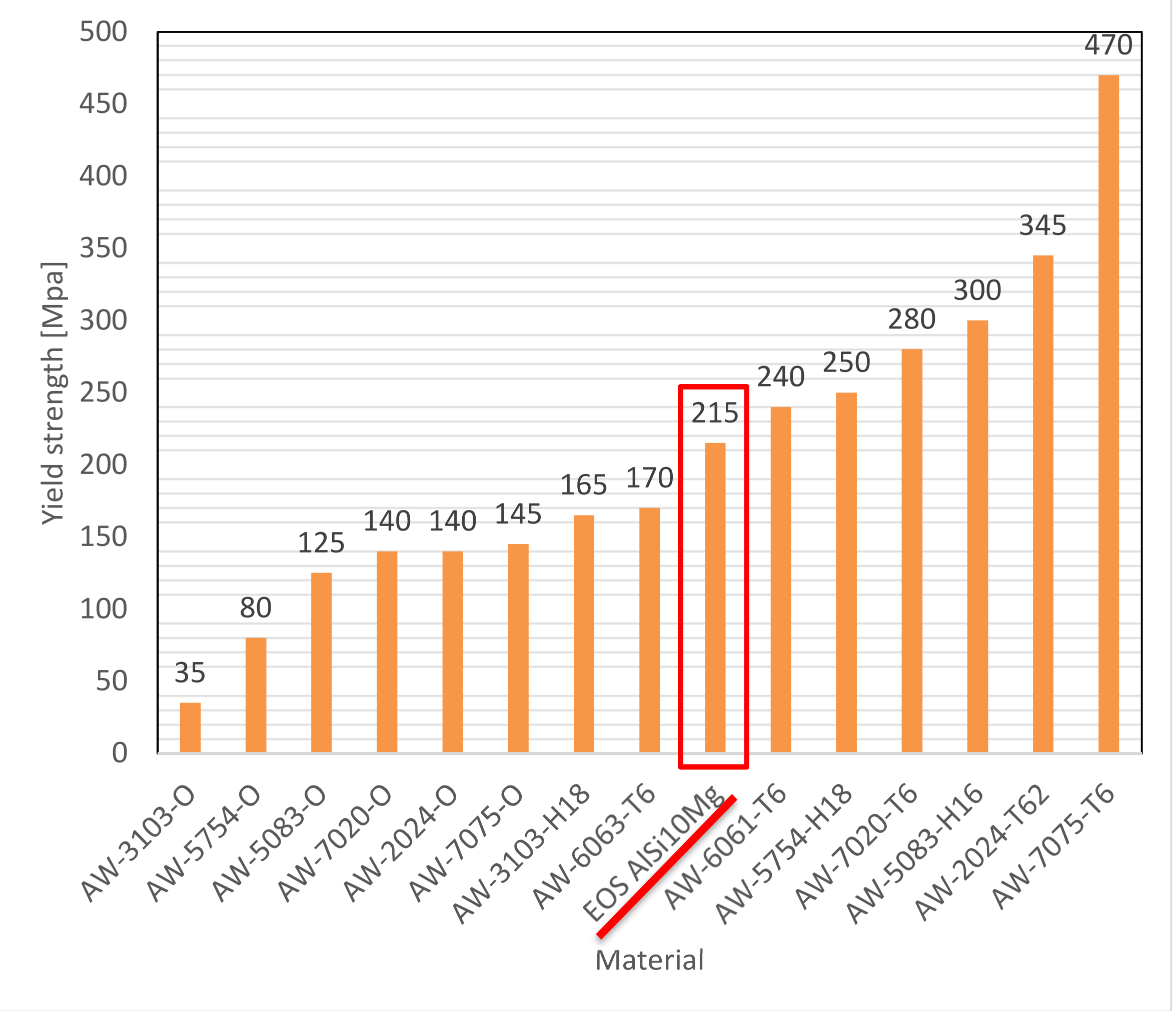

Figure 6. Yield strengths of stress relieved EOS AlSi10Mg and common conventional wrought Aluminum alloys (Mod. Raaka-ainekäsikirja 5: Alumiinit 2002, p. 74; SFS-EN 485-2:2016+A1:2018:en, pp. 23–24; 31–32; 53; 55; 72–73; 78; 88; 91; SFS-EN 755-2 2016, p. 42).

As Figure 6 illustrates, yield strength of EOS AlSi10Mg is somehow comparable to common conventional wrought aluminum alloys positioning it to the middle range in the comparison. However, the quantity of the compared materials was only 14. Yield strengths of 35 pieces of different wrought aluminum and aluminum alloys are presented in Raaka-ainekäsikirja 5: Alumiinit (2002, p. 73). Average yield strength of those materials is 145 MPa. The used value for EOS AlSi10Mg was the lowest one given in the material data sheet, but still exceeding the average value by 48 %. Tensile strength values of these materials are given in Table 15.

Table 15. Tensile strength values of EOS Aluminum AlSi10Mg, SLM AlSi10Mg, and EN AC-Al Si10Mg(a) (Mod. EOS 2019e; SFS-EN 1706 2010, pp. 22; 26; SLM 2019c).

Tensile strength test method	EOS Aluminum AlSi10Mg [MPa]	SLM AlSi10Mg [MPa]	EN AC-Al Si10Mg(a) [MPa]
1	460 ± 20	N/A	N/A
2	460 ± 20	N/A	N/A
3	345 ± 10	N/A	N/A
4	350 ± 10	N/A	N/A
5	N/A	386 ± 42	N/A
6	N/A	N/A	min. 150–180
7	N/A	N/A	min. 220–260
8	N/A	N/A	min. 200

1=Ultimate tensile strength, ISO 6892-1:2009, horizontal (XY), as built, N/A µm
2=Ultimate tensile strength, ISO 6892-1:2009, vertical (Z), as built, N/A µm
3=Ultimate tensile strength, ISO 6892-1:2009, horizontal (XY), stress relieved, N/A µm
4=Ultimate tensile strength, ISO 6892-1:2009, vertical (Z), stress relieved, N/A µm
5=Tensile strength, standard N/A, direction N/A, as built, 50 µm
6=Tensile strength, EN 10002-1, as casted
7=Tensile strength, EN 10002-1, solution heat treated and fully artificially aged
8=Tensile strength, EN 10002-1, solution heat treated and artificially under-aged

According to the values of Table 15, stress relieving decreases tensile strength in AM AlSi10Mg parts. EOS recommends stress relieving, but not hardening heat treatments for AlSi10Mg (EOS 2019e). The opposite applies to casted equivalents in general. In casting, the cooling rate is much lower than in L-PBF which negatively affects the microstructure in this case (Li et al. 2016, pp. 116–117). In as-built L-PBF AlSi10Mg parts, the microstructure is already similar to solution heat treated casted parts (EOS 2019e). However, tensile strengths of these AM materials are higher than minimum tensile strengths of casted AlSi10Mg. The values of the casted part were formed from values of die-casting and sand casting. Elongation values of EOS and SLM AlSi10Mg and their EN equivalent materials are presented in Table 16.

Table 16. Elongation values of EOS Aluminum AlSi10Mg, SLM AlSi10Mg, and EN AC-Al Si10Mg(a) (Mod. EOS 2019e; SFS-EN 1706 2010, pp. 22; 26; SLM 2019c).

Elongation test method	EOS Aluminum AlSi10Mg [%]	SLM AlSi10Mg [%]	EN AC-Al Si10Mg(a) [%]
1	9 ± 2	N/A	N/A
2	6 ± 2	N/A	N/A
3	12 ± 2	N/A	N/A
4	11 ± 2	N/A	N/A
5	N/A	6 ± 1	N/A
6	N/A	7 ± 1	N/A
7	N/A	N/A	min. 2–2.5
8	N/A	N/A	min. 1
9	N/A	N/A	min. 2
1=Elongation at break, ISO 6892-1:2009, horizontal (XY), as built, N/A µm 2=Elongation at break, ISO 6892-1:2009, vertical (z), as built, N/A µm 3=Elongation at break, ISO 6892-1:2009, horizontal (XY), heat treated, N/A µm 4=Elongation at break, ISO 6892-1:2009, vertical (z), heat treated, N/A µm 5=Break strain A, standard N/A, direction N/A, as built, 50 µm 6=Reduction of area Z, standard N/A, direction N/A, as built, 50 µm 7=Elongation, EN 10002-1, as casted 8=Elongation, EN 10002-1, solution heat treated and fully artificially aged 9=Elongation, EN 10002-1, solution heat treated and artificially under-aged			

The values of Table 16 show that the elongation values of the AM parts exceed the minimum values of the casted part. The values of the casted part were formed from values of die-casting and sand casting. According to Li et al. (2016, p. 117), the elongation of L-PBF AlSi10Mg parts is lower when compared to high pressure die cast equivalent. Hardness values of these materials are given in Table 17.

Table 17. Hardness values of EOS Aluminum AlSi10Mg, SLM AlSi10Mg, and EN AC-Al Si10Mg(a) (Mod. EOS 2019e; SFS-EN 1706 2010, pp. 22; 26; SLM 2019c).

Hardness test method	EOS Aluminum AlSi10Mg	SLM AlSi10Mg	EN AC-Al Si10Mg(a)
1	ca. 119 ± 5	N/A	min. 50–90
2	N/A	122 ± 2	N/A

Table 17 continues. Hardness values of EOS Aluminum AlSi10Mg, SLM AlSi10Mg, and EN AC-Al Si10Mg(a) (Mod. EOS 2019e; SFS-EN 1706 2010, pp. 22; 26; SLM 2019c).

1=Brinell (HBW 2.5/62.5), standard DIN EN ISO 6506-1, surface N/A, as built/as casted 2=Vickers hardness (HV10), standard N/A, surface N/A, as built

According to the material data sheet of EOS Aluminum AlSi10Mg (EOS 2019e), EOS has tested the hardness according to requirements of SFS-EN 1706 of casted parts. As Table 17 presents, values of EOS Aluminum AlSi10Mg and SLM AlSi10Mg exceed the minimum values of the casted equivalents. The value range of the casted part was formed from values of die casting and sand casting with and without different heat treatments. EOS recommends stress relieving for its AlSi10Mg, but the hardness value after the treatment was not given. (EOS 2019e)

Thijs et al. (2012, p. 1812) have reported 30 HV0.5 units higher hardness value for L-PBF AlSi10Mg than the value of high pressure die-casted AlSi10Mg. However, the value was almost the same if the high pressure die-casted AlSi10Mg was aged.

Young's modulus values of the AM materials are presented in Table 18. Young's modulus values for casted aluminum alloys were not given in SFS-EN 1706 (SFS-EN 1706 2010, pp. 1–42).

Table 18. Young's modulus values of EOS Aluminum AlSi10Mg and SLM AlSi10Mg (Mod. EOS 2019e; Raaka-ainekäsikirja 5: Alumiinit 2002, p. 77; SLM 2019c).

Young's modulus test method	EOS Aluminum AlSi10Mg [GPa]	SLM AlSi10Mg [GPa]	Conventional Al alloys, wrought or casted [GPa]
1	75 ± 10	N/A	N/A
2	70 ± 10	N/A	N/A
3	70 ± 10	N/A	N/A
4	60 ± 10	N/A	N/A
5	N/A	61 ± 9	N/A
6	N/A	N/A	69–75
1=manufacturing in horizontal direction (XY), as built 2=in manufacturing vertical direction (Z), as built			

Table 18 continues. Young's modulus values of EOS Aluminum AlSi10Mg and SLM AlSi10Mg (Mod. EOS 2019e; Raaka-ainekäsikirja 5: Alumiinit 2002, p. 77; SLM 2019c).

3=manufacturing in horizontal direction (XY), heat treated
4=in manufacturing vertical direction (Z), heat treated
5=manufacturing direction N/A, as built
6=casted or wrought

As presented in Table 18, the Young's modulus values of the AM materials are on a same level with conventional ones. Surface roughnesses of the AM materials and conventional manufacturing are presented in Table 19.

Table 19. Surface roughnesses of EOS Aluminum AlSi10Mg, SLM AlSi10Mg, and conventional manufacturing (Mod. EOS 2019e; Pere 2012, p. 21-16; SLM 2019c).

Surface roughness test method	EOS Aluminum AlSi10Mg [µm]	SLM AlSi10Mg [µm]	Conventional manufacturing [µm]
R_{a1}	6–10	N/A	N/A
R_{z1}	30–40	N/A	N/A
R_{a2}	N/A	8 ± 1	N/A
R_{z2}	N/A	63 ± 10	N/A
R_a	N/A	N/A	0.006 – >250

1=as built, cleaned, standard N/A
2=as built, cleaning N/A, standard N/A

Surface roughness (R_a) ranges of certain traditional manufacturing methods of aluminum alloys are listed below (Pere 2012, p. 21-16):

- sand casting 6.3–250 µm
- die casting 0.8–60 µm
- turning 0.8–12.5 µm
- milling 1.6–6.3 µm.

As Table 19 and the list above shows, AM AlSi10Mg parts need to be post-processed if the best surface roughness values of conventionally manufactured parts need to be achieved. According to values of Tables 12 and 19, better surface quality can be achieved with AM AlSi10Mg than with AM 316L.

4.2.2 Others

As listed in Table 4, other L-PBF materials available by the Finnish pure commercial service providers were maraging tool steels EOS MaragingSteel MS1 and SLM Tool Steel 1.2709, titanium alloy EOS Titanium Ti64, and cobalt-chromium alloy remanium® star CL in 2018. Focus in this thesis was on stainless steels and aluminums and therefore these other AM materials are only discussed shortly. Inconel 718, which was announced to be available in 2019, is not discussed in this thesis because it was not available during writing of it.

Word “maraging” comes from martensitic age hardened steel. Maraging tool steels are used in tooling, injection molding, and in die casting molds in conventional manufacturing. Yield strength of maraging steels is typically very high, up to 1600–1800 MPa (Raaka-ainekäsikirja 1: Muokatut teräkset 2001, p. 293). (Milewski 2017, p. 69.) EOS MaragingSteel MS1 and SLM Tool Steel 1.2709 are same materials based on their chemical compounds (EOS 2019d; SLM 2019c). Steel name of 1.2709 is X3NiCoMoTi 18-9-5 (Kucerova & Zetkova 2016, p. 141). However, it is not a common steel as it cannot be found from standard SFS-EN ISO 4957 (2018). The standard lists only common internationally used tool steels. (SFS-EN ISO 4957 2018, p. 5). An international standard about standard specification for AM of 1.2709 neither exist (Appendix IV).

Chemical compounds and mechanical properties of the AM tool steel materials are collected to appendices V and VI. It needs to be noted that according to the material data sheet of SLM Tool Steel 1.2709, yield strength can be higher than the tensile strength (SLM 2019c). This is hard to explain with any other reason than being a typo in the material data sheet.

Titanium alloys are light weight alloys having high strength and corrosion resistance. Titanium is difficult to machine and cast due to low heat conductivity and high reactivity of the melt, but it is additively manufacturable. EOS Titanium Ti64 is a Ti-6Al-4V alloy which is one of the most common titanium alloys and was the only AM titanium material available by the Finnish pure commercial service providers in 2018 (Milewski 2017, p. 70; Voisin et al. 2018, pp. 113–114). Ti-6Al-4V combines 6 % aluminum and 4 % vanadium as the name states. Aluminum and vanadium contents of EOS Titanium Ti64 vary between 5.50–6.75 % and 3.50–4.50 %, respectively. (EOS 2019g; Milewski 2017, p. 70) ASTM standard about standard specification for AM of Ti-6Al-4V exist (Appendix IV). Main mechanical properties and specific chemical compound of EOS Titanium Ti64 are presented in Appendix VII.

AM cobalt-chromium alloys are super alloys used in dental, medical and aerospace applications. They offer high strength and corrosion resistance in high temperatures. Cobalt-chromium alloys are difficult to machine and therefore often casted in conventional manufacturing. remanium® star CL is a cobalt-chromium alloy consisting of 60.5 % of cobalt, 28 % of chromium, and 9 % of tungsten as main alloys. (Concept Laser 2019e; Milewski 2017, p. 70.) In 2018, it was the only AM cobalt-chromium alloy available by the Finnish pure commercial service providers. An international standard about standard specification for AM of material with same chemical compound than remanium® star CL does not exist. However, ASTM F3213–17 is a standard of standard specification for AM of similar alloy with addition of molybdenum. (Appendix IV.) Specific chemical compound and basic mechanical properties of remanium® star CL are shown in appendix VII.

5 RESEARCH METHODS

This thesis was executed in research group of laser Material Processing of LUT University. The thesis was carried out as a part of FIDIMA Co-Creation project funded by national Finnish funding agency of Business Finland and Manufacturing 4.0 funded by Strategic research council of Finland. Aim of the FIDIMA Co-Creation project was to prepare larger main project of FIDIMA Co-Innovation which aims to investigate and develop metal AM materials for needs of Finnish industry. The FIDIMA Co-Creation project was going on during 15.8.–31.12.2018.

A quantitative face-to-face survey for Finnish metal and mechanical engineering industry was executed. The survey was Google Forms based and in Finnish language. The face-to-face interviews were done at the Subcontracting Trade Fair 2018 on September 2018. The trade fair is the largest one with its 1000 exhibitors in Finland and, according to its webpage, it gathers the entire Finnish manufacturing industry together (Subcontracting Trade Fair 2019). The interviewed companies were chosen randomly, but the first question of the survey outlined irrelevant companies outside of the survey.

Total of 78 companies were interviewed. 2 companies sifted out after the first question due to unsuitable field of industry. The remaining companies were asked to estimate their three most-used metal materials. The questions were:

- What is the most-used metal material in your company?
- What is the second most-used metal material in your company?
- What is the third most-used metal material in your company?

If the respondent answered inaccurately, such as “steel” or “aluminum” he or she was asked to give more detailed answer if possible.

Utilization of metal additive manufacturing of the companies was asked. If metal AM was not utilized, or it was tried without success, reasons for that were asked. The options were:

- No need
- Too high costs
- Lack of know-how

- Quality requirements
- Too long lead time
- The process turned out to be too hard
- Limited material repertoire of additive manufacturing
- Limited size of a part
- I don’t know
- We have always succeeded
- Other.

All the questions of the survey can be seen in appendices IX and X.

6 RESULTS AND DISCUSSION

All respondents of the survey were owners or employees of the companies. Spread of titles of the respondents is presented in Figure 7.

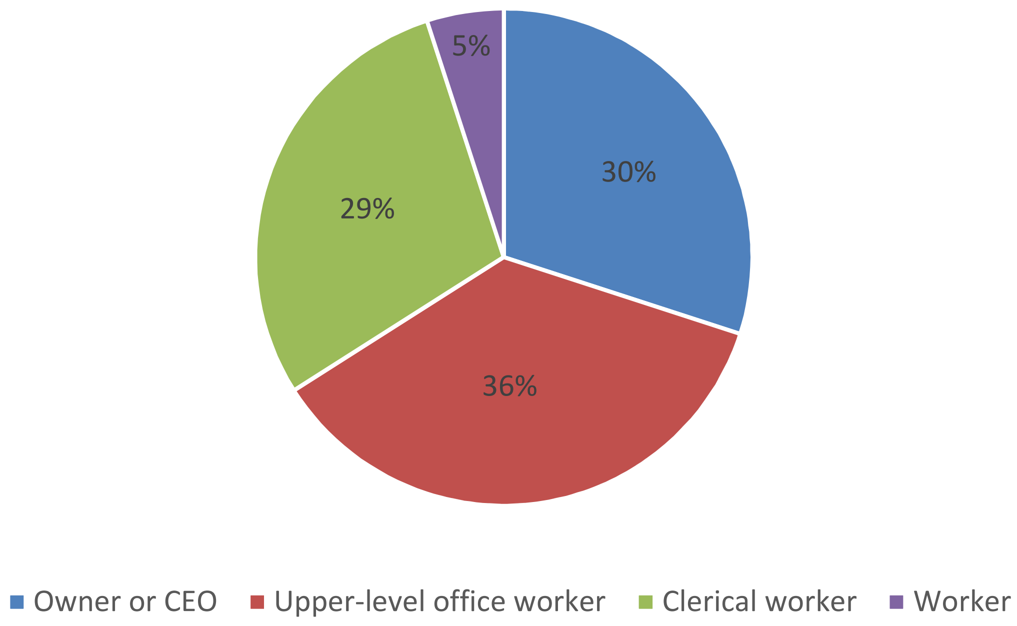

Figure 7. Spread of titles of the respondents.

More than half of the respondents, 65 %, were clerical workers or upper-level office workers. 29 % of the respondents either owned the company or worked as a chief executive officers (CEO). Breakdown of number of employees of the interviewed companies is presented in Figure 8.

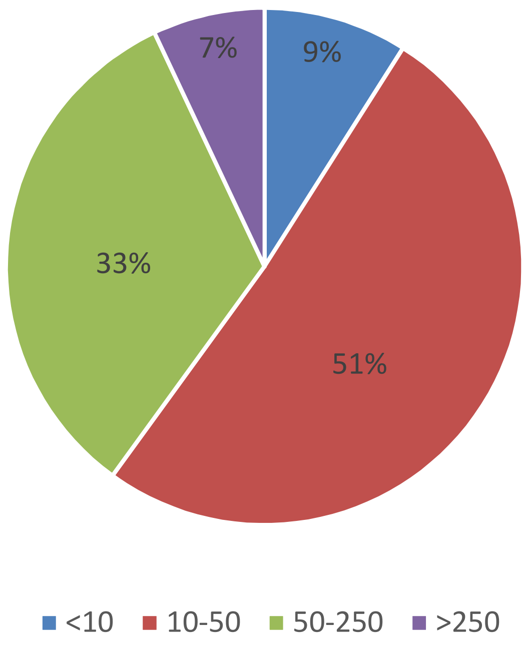

Figure 8. Breakdown of number of employees of interviewed companies.

93 % of the companies were medium-sized or smaller companies. In 2016, 93.3 % of all Finnish companies were micro companies (Yrittäjät 2018). Therefore, it must be noted that structure of companies of this survey do not correlate with the actual structure of Finnish companies. Division of locations of the companies interviewed for this survey by region can be seen in Figure 9 as percentages.

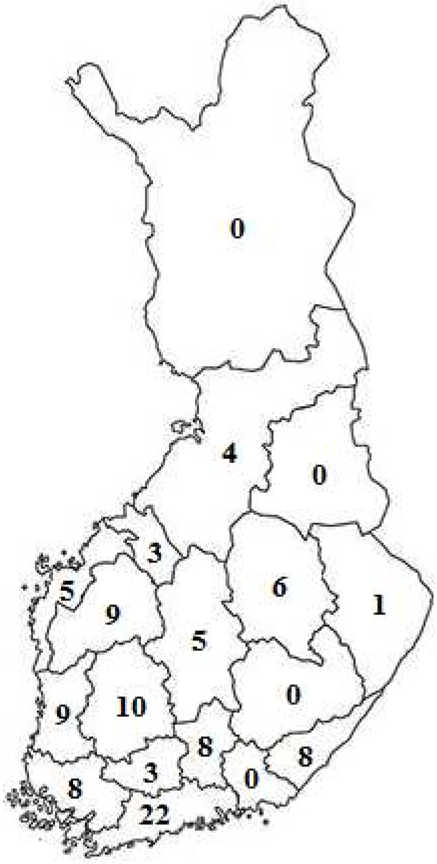

Figure 9. Division of locations of interviewed companies by region in percentages.

As it can be seen from Figure 9, most of the companies were located to south, west, and south-west parts of Finland. More than fifth of the companies were located to Uusimaa. Åland Islands cannot be seen in the figure, but none of the companies was located there.

75 companies gave three answers and 1 company gave two answers to questions about three most used metal materials. Total of 227 answers were given. Most of the respondents answered with a material designation or material number or commercial name of material, but some of them did not give more accurate answers than “metal” or “metal alloy”. In case of answering with a designation, additional symbols of designations were included to answers in only two cases and neither of these included the Group 2 symbols. Division of the answers can be seen in Figures 10 and 11.

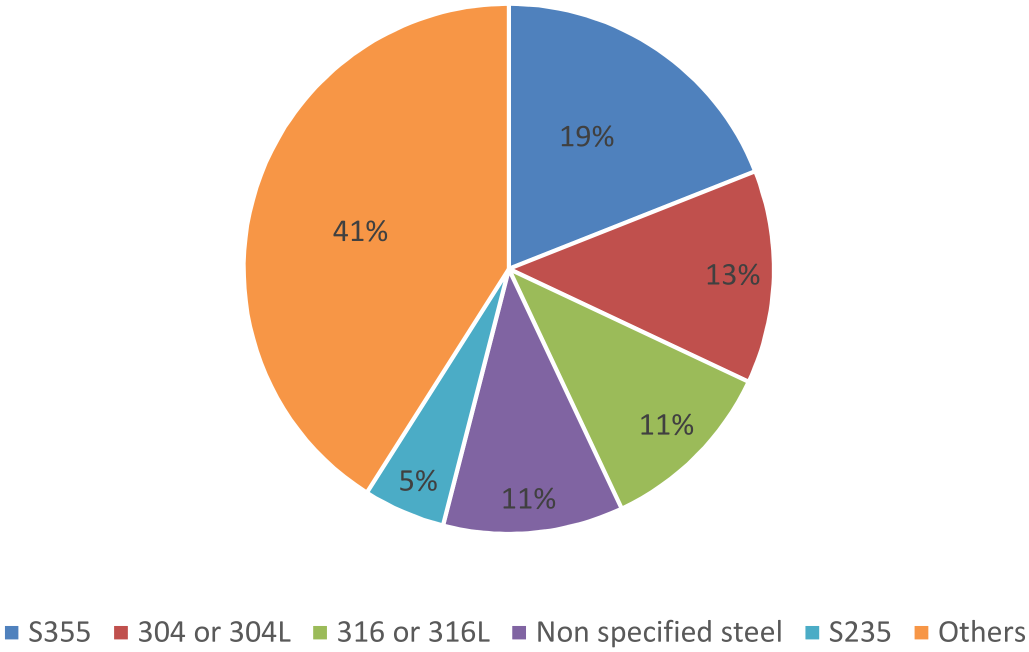

Figure 10. Breakdown of answers to questions about three most-used materials.

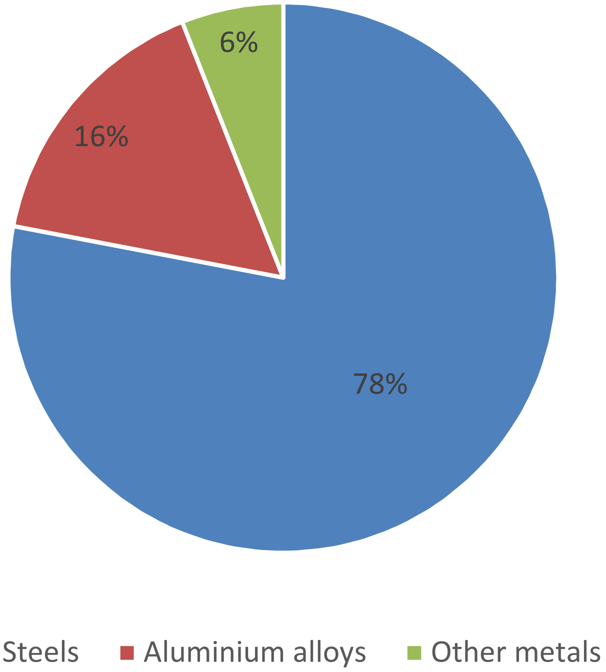

Figure 11. Division of categorized answers to questions about most-used materials.

171 out of the 227 answers were different kinds of steels. Only five companies did not have any steels in their three most used materials. Steel types of these 171 answers are presented in Figure 12.

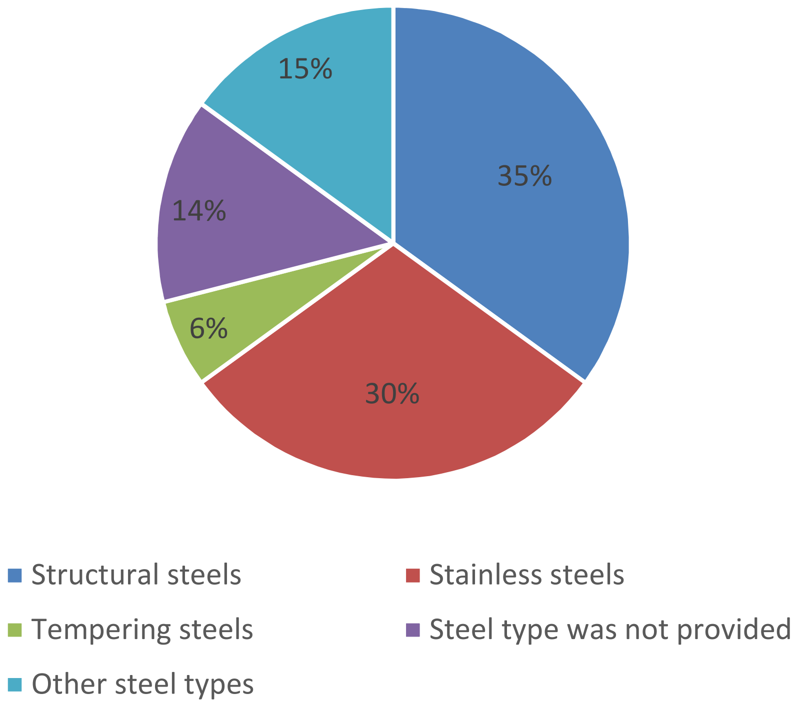

Figure 12. Breakdown of steel types of steel-related answers to questions about three most-used materials.

The most steels answered in the survey were structural steels and stainless steels. In 14 % of the cases, the respondent was not able to specify steel type. Therefore, share of other options than “steel type was not provided” in percentages could be up to 14 units higher in reality.

A comparison between commercially available materials by the L-PBF system producers and answers of this survey was made. According to webpages of all L-PBF system producers mentioned in the report of Wohlers Association, 18 % of the materials answered in the survey were commercially available by one or more system producers. 316L was the most frequent material out of answers that were commercially available materials by the system manufacturers in the survey.

73 % of the structural steels answered in the survey were S355 steels whereas 19 % were S235 steels. The letter “S” stands for structural steel. In general, structural steels 355 and 235 are low-alloy steels having minimum yield strengths according to their names (Koivisto & Tuomikoski 2008, p. 134). Minimum yield and tensile strengths of common structural steels used in Finland vary between 225–355 MPa and 340–630 MPa, respectively. Minimum elongation at brake value of the same materials vary between 20–24 %. (Hitsatut profiilit 2000, p. 12.) Structural steels were not to be found from material repertoire of L-PBF system producers. However, based on the values of the literature review of this thesis, mechanical properties of AM 316L can exceed the values of the structural steels mentioned in this section.

54 % of the stainless steels answered in the survey were 304 or 304L steels and 46 % were 316 or 316L steels. EN standard equivalents of 304, 304L, 316, and 316L are shown below (Kyröläinen & Lukkari 2002, pp. 11; 35):

- 304 – X5CrNi 18-10 – 1.4301
- 304L – X2CrNi 18-9 – 1.4307
- 304L – X2CrNi 19-11 – 1.4306
- 316 – X5CrNiMo 17-12-2 – 1.4401
- 316 – X3CrNiMo 17-13-3 – 1.4436
- 316L – X2CrNiMo 17-12-3 – 1.4432
- 316L – X2CrNiMo17-12-2 – 1.4404
- 316L – X2CrNiMo 18-14-3 – 1.4435.

These steels are austenitic stainless steels. 304 is actually the same steel than the first alloyed stainless steel in the beginning of 20th century. 304L is a low carbon version of it. 316 and 316L are upgraded versions of 304 and 304L with addition of molybdenum. The addition of 2–3 % of molybdenum makes these steels more corrosion resistant and increases yield and tensile properties slightly. In extremely corrosive environments, for example heat exchangers in seawater, amounts of molybdenum and chromium are not enough in these steels. However, costs of the higher alloying of molybdenum and chromium are significant, even higher than costs of titan and nickel-based superalloys. (Kyröläinen & Lukkari 2002, pp. 16.)

The steels listed above can be used in structural purposes. 1.4404, 1.4301, and 1.4307 are the most used ones. Mechanical properties of these steels in rolled forms are given in Appendix XII. (Finnish Constructional Steelwork Association 2017, pp. 2–4; Kyröläinen & Lukkari 2002, pp. 11; 15–16; 34–36.) Based on values of Appendix XII, yield and tensile strengths of these materials vary between 200–240 MPa and 520–750 MPa, respectively, and elongation at break minimum value between 40–45 %. AM 316L as-built parts can have almost three times higher yield strength, heat treated parts two times, but hot isostatic pressed parts the same, lower, or higher than these traditional austenitic stainless steels. Tensile strength and elongation at break values of AM 316L can be lower, the same, or higher irrespective of heat treatments.

16 % of the answers of three most used metals were aluminum or aluminum alloys. 31 % of these were AlSi10Mg, AlSi12, or AlSi7. 45 % out of the 31 % were AlSi10Mg. All the three alloys are directly available by one or more L-PBF system producers.

82 % of the companies had never tried metal additive manufacturing by own machine nor by subcontracting, but 28 % of them had plans to do so in the near future. None of the companies had tried metal AM with their own machine, but 10 out of the 76 had tried metal AM by subcontracting parts. 4 respondents did not know whether their company had tried metal AM. It can be concluded that some companies had intrest about AM despite the lack of utilization. However, the companies that had never tried metal AM but had plans to do so the near future were asked to estimate how many different AM parts they will manufacture themselves or by subcontracting during the next 12 months. 20 out of the 21 companies answered zero and 1 answered one. This might mean that concrete actions for use of metal AM were not taken.

The companies that had already tried metal AM were asked to estimate how many parts they had manufactured this far by themselves or by subcontracting. The answers and amounts of companies answered in the question are listed below:

- 1 part: 2 companies
- 1–5 parts: 3 companies
- 5–20 parts: 2 companies
- 20–50 parts: 1 company

- >50 parts: 2 companies.

Based on the list, only some metal parts were additively manufactured and serial production of metal AM was not utilized by most the companies. If a company had not tried metal AM or had without success, reasons for that were asked. Multiple choices were accepted. The answers are presented in Figure 13.

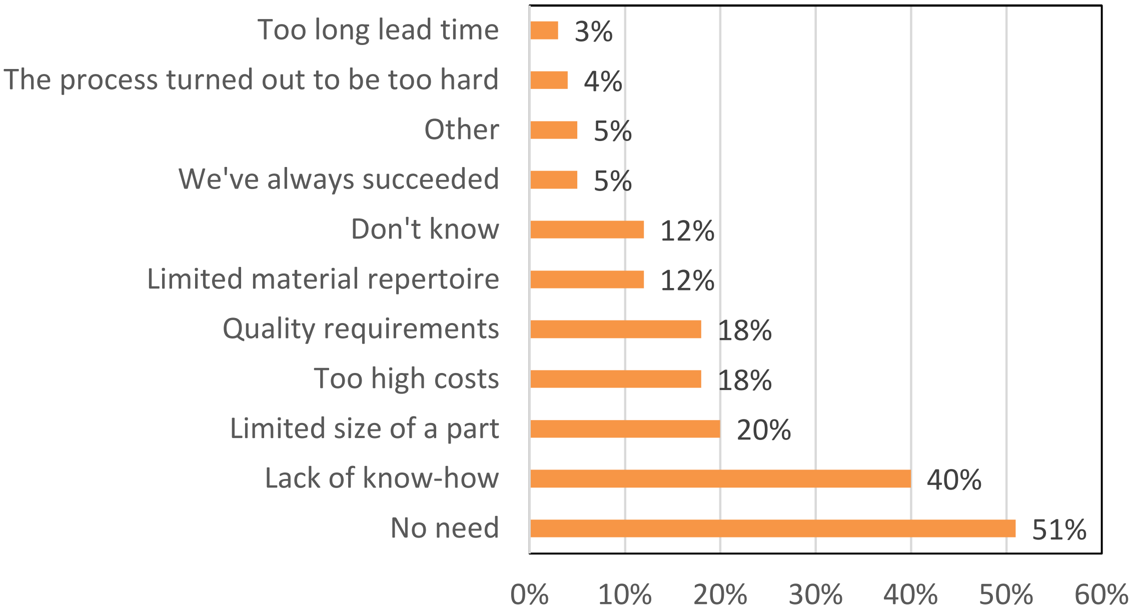

Figure 13. Spread of answers of question “Whether your company has not utilized metal additive manufacturing, or it has without succeeding in it, which of the following options you would estimate to be reasons for that?”.

More than half of the companies answered that they have not had need for metal additive manufacturing. 12 % of the representatives of the companies did not know why they have not utilized metal AM. Lack of expertise was answered by 40 % of the companies. Only 12–20 % of the companies chose answer options “quality requirements”, “limited size of a part“, “too high costs”, or “limited material repertoire” which are seen as basic limitations of metal AM. This indicates that basic limitations of AM are not the main reason for non-utilization of metal AM but lack of expertise might be.

The next question was: “Has your company ever been in a situation where metal additive manufacturing would have been wanted to utilize, but suitable material was not available?”.

Only two companies answered yes. Another mentioned that the material was some tempering steel and another one did not know the material. Therefore, results of this survey did not produce any development ideas about new important metal AM materials. The companies should have been asked about used materials of small, complex and multiple-part components they manufacture.

7 SUMMARY

Aims of this thesis were to find out the three most used metal materials by the Finnish metal and mechanical engineering industry and whether the materials are commercially available by L-PBF system producers and Finnish pure commercial service providers. A quantitative survey was executed at the Subcontracting Trade Fair 2018 in Finland in September 2018. Total of 78 companies, from which 76 were Finnish metal and mechanical engineering companies, were interviewed.

Laser-based powder bed fusion (L-PBF) is a limited manufacturing method with quite narrow material repertoire despite it is the most used and possibly the most evolved additive manufacturing (AM) process for manufacturing of metal parts. Current L-PBF metal systems are not something to revolutionize way of manufacturing, but they are able to produce parts with lower costs than conventional methods in certain small applications. L-PBF is mainly capable of manufacturing semi finished metal parts which almost always require post-processing.

Utilization level of metal additive manufacturing of the Finnish metal and mechanical engineering industry is quite low. 82 % of the interviewed companies had never tried metal additive manufacturing. Only two companies had manufactured more than 50 metal AM parts. The parts were manufactured by a subcontractor. Some Finnish companies utilize metal AM for manufacturing end products and not just for prototyping purposes.

More than 30 metal AM systems existed in Finland in 2018 and the firsts metal AM parts were already manufactured in Finland in the early 1990s. In 2018, at least three companies had their own metal AM system for their own production and three other companies were pure commercial service providers. All the machines were based on L-PBF technology. Detailed information about current market size of Finnish metal AM was tried to gather to this thesis, but unfortunately information was not provided by the service providers.

Repertoire of available L-PBF metal materials is narrow. Five different metal materials were found to be available by the Finnish pure commercial service providers in 2018; 316L, AlSi10Mg, maraging steel 1.2709, CoCr alloy remanium® Star CL, and Ti64. Systematic knowledge about mechanical properties of AM metal materials is missing. Metal AM system producers do not provide detailed information about the properties on their publicly available material data sheets. The material data sheets might also include misinformation. In general, the properties of AM parts have been reported to be on par with properties of their conventional counterparts. However, in some cases properties of 316L and AlSi10Mg fall short of properties of conventional materials. Unambiguous claims about whether metal AM parts are more or less robust than conventionally manufactured parts cannot be stated.

Standardization of additive manufacturing is in its early stages. Total of 24 additive manufacturing related ISO and/or ASTM standards were published by the time of writing this thesis. However, many new standards were under development. Two of the published standards were published in Finnish. Lack of standards and large databases of AM restrict utilization of additive manufacturing.

Based on the results of the survey, Finnish metal and mechanical engineering industry uses mostly steels, mainly structural and stainless steels. Share of aluminum and aluminum alloys was the second highest with 16 % of all the answers. 18 % of all materials answered in the survey were directly commercially available by L-PBF system producers. The most common and commercially available material was stainless steel 316L. Structural steels were not available by the system producers, but 316L seems to be a superior steel, which can replace structural steels in some cases. This might be a reason why parameters have been developed for this particular steel by all L-PBF system producers. However, better results from the perspective of additive manufacturing would have been achieved if the survey had been about materials of small, complex and multiple-part components.

More than 80 % of the companies had never tried metal additive manufacturing, but 28 % of the 80 % had plans to do so in the near future. However, 95 % of the companies planning to try metal AM in the near future estimated that they would not order any metal AM parts or manufacture them with an own machine during the next 12 months. 13 % of the companies had tried metal AM by subcontracting, but only two companies had ordered more than 50 metal AM parts.

Non-utilization of metal AM of Finnish metal and mechanical engineering companies was found to be not just about limitations of metal additive manufacturing but lack of need and expertise as well. More than half of the companies answered that they have not had any needs for metal AM. 40 % answered that lack of expertise was one of the reasons. Answering options “limited size of a part”, “too high costs”, “quality requirements”, and “limited material repertoire”, which are typical limitations of metal AM, were each answered by only 12–20 % of the companies. It can be concluded that Finnish metal and mechanical engineering industry needs education about metal additive manufacturing. Education could be arranged to the industry with different trainings and by educating future employees in technical-related upper secondary and tertiary education.

8 FURTHER STUDIES

Based on the results of this thesis, more systematic and public research about material properties of metal AM should be carried out. In addition, in-depth interviews to companies of Finnish metal and mechanical industry should be executed. Topics below are suggested for further studies by the author of this thesis:

- Survey about materials of small, complex and multiple-part metal components manufactured by Finnish metal and mechanical engineering industry
- Systematic analysis of mechanical properties of AM 316L
- Systematic analysis of mechanical properties of AM AlSi10Mg
- In-depth comparison between common steels used by Finnish metal and mechanical engineering industry and L-PBF steels
- In-depth comparison between common aluminum alloys used by Finnish metal and mechanical engineering industry and L-PBF aluminum alloys
- In-depth comparison between AM 316L and AM titanium
- In-depth comparison between AM 316L and AM nickel-based super alloys
- In-depth comparison between AM titanium and AM nickel-based super alloys.

LIST OF REFERENCES

3DStep. 2018. 3d-tulostus. [3DStep webpage]. [Referred 12.12.2018]. Available: http://www.3dstep.fi/palvelut/3dtulostus/

3D Formtech. 2018. Metallin 3D-tulostus. [3D Formtech webpage]. [Referred 12.12.2018]. Available: https://3dformtech.fi/3d-tulostus/metallin-3d-tulostus/

3D Formtech. 2018b. Materiaalit - metallin 3D-tulostus. [3D Formtech webpage]. [Referred 12.12.2018]. Available: https://3dformtech.fi/3d-tulostus/metallin-3d-tulostus/materiaalit/

3D Systems. 2019. ProX DMP 300. [3D Systems webpage]. [Referred 15.1.2019]. Available: https://www.3dsystems.com/3d-printers/prox-dmp-300

Alho, K. 1949. Suomen uudenaikaisen teollisuuden synty ja kehitys 1860–1914. Suomen Pankin taloustieteellisen tutkimuslaitoksen julkaisuja. Sarja B:11. Helsinki: K. F. Puromiehen Kirjapaino O.-Y. 240 p. [Origin and development of modern industry of Finland 1860–1914] (in Finnish)

Ahmadi, A., Mirzaeifar, R., Moghaddam, N., Turabi, A., Karaca, H. & Elahinia, M. 2016. Effect of manufacturing parameters on mechanical properties of 316L stainless steel parts fabricated by selective laser melting: A computational framework. Materials & Design. Volume 112. 2016. Pp. 328–338.

ASTM International. 2019. Additive Manufacturing Technology Standards. [ASTM International webpage]. [Referred: 12.1.2019]. Available: https://www.astm.org/Standards/additive-manufacturing-technology-standards.html

Bevan, M., Ameri, A., East, D., Austin, D., Brown, A., Hazell, P. & Escobedo-Diaz, J. 2017. Mechanical Properties and Behavior of Additive Manufactured Stainless Steel 316L. In: Ikhmayies, S., Li, B., Carpenter, J., Li, J., Hwang, J., Monteiro, S., Firrao, D., Zhang, M., Peng, Z., Escopedo-Diaz, J., Bai, C., Kalay, Y., Goswami, R. & Kim, J. 2017. Characterization of Minerals, Metals, and Materials 2017. Cham: Springer. Pp. 577–585.

Brandl, E., Heckenberger, U., Holzinger, V. & Buchbinder, D. 2012. Additive manufactured AlSi10Mg samples using Selective Laser Melting (SLM): Microstructure, high cycle fatigue, and fracture behavior. Materials & Design. Volume 34. 2012. Pp. 159–169.

Brandt, M. 2017. Laser additive manufacturing: Materials, design, technologies, and applications. Amsterdam: Elsevier. 479 p.

Bringas, J. 2004. Handbook of Comparative World Steel Standards: Third edition. USA: ASTM International. 669 p.

BSI. 2019. AMT/8 – Additive Manufacturing. [BSI webpage]. [Referred 9.1.2019]. Available: https://standardsdevelopment.bsigroup.com/committees/50226095

Cabrini, M., Lorenzi, S., Pastore, T., Pellegrini, S., Ambrosio, E., Calignano, F., Manfredi, D., Pavese, M. & Fino, P. 2016. Effect of heat treatment on corrosion resistance of DMLS AlSi10Mg alloy. Electrochimica Acta. Volume 206. 2016. Pp. 346–355.

Cohen, A. 2019. RE: A new message from xjet3d.com [private email]. Receiver: markus.korpela@lut.fi. Sent 16.1.2019 00:00 o'clock (GMT +0200).

Concept Laser. 2019a. Brochure of X LINE 2000R. [Concept Laser webpage]. [Referred 15.1.2019]. Available: https://www.concept-laser.de/fileadmin/Machine_brochures/CL_X_LINE_2000R_DS_EN_US_4_v1.pdf

Concept Laser. 2019b. Machines. [Concept Laser webpage]. [Referred 15.1.2019]. Available: https://www.concept-laser.de/en/products/machines.html

Concept Laser. 2019c. Materials. [Concept Laser webpage]. [Referred 15.1.2019]. Available: https://www.concept-laser.de/en/products/materials.html

Concept Laser. 2019d. Material data sheet of CL 20ES. [Concept Laser webpage]. [Referred 23.1.2019]. Available: https://www.concept-laser.de/fileadmin//user_upload/Datasheet_CL_20ES.pdf

Concept Laser. 2019e. Material data sheet of remanium® star CL. [Concept Laser webpage]. [Referred 23.1.2019]. Available: https://www.concept-laser.de/fileadmin//user_upload/Datasheet_remanium_star_CL.pdf

EOS. 2019a. EOS M400-4. [EOS webpage]. [Referred 11.1.2019]. Available: https://www.eos.info/systems_solutions/eos-m-400-4

EOS. 2019b. Materials for Metal Additive Manufacturing. [EOS webpage]. [Referred 11.1.2019]. Available: https://www.eos.info/material-m?_scrivito_display_mode=view&_scrivito_workspace_id=published

EOS. 2019c. Material data sheet of EOS 316L. [EOS webpage]. [Referred 11.1.2019]. Available: https://cdn0.scrvt.com/eos/77d285f20ed6ae89/dd6850c010d3/EOSStainlessSteel316L.pdf

EOS. 2019d. Material data sheet of MaragingSteel MS01. [EOS webpage]. [Referred 11.1.2019]. Available: https://cdn0.scrvt.com/eos/c88047245bff2c4b/2f494ef432d0/MS-MS1-M280_M290_400W_Material_data_sheet_05-14_en.pdf

EOS. 2019e. Material data sheet of EOS AlSi10Mg – M280 and M290. [EOS webpage]. [Referred 11.1.2019]. Available: https://cdn0.scrvt.com/eos/public/8837de942d78d3b3/4e099c3a857fdddca4be9d59fbb1cd74/EOS_Aluminum_AlSi10Mg_en.pdf

EOS. 2019f. Material data sheet of AlSi10Mg – M400. [EOS webpage]. [Referred 4.2.2019]. Available: https://cdn0.scrvt.com/eos/8b10a79e70834745/8101b7ed6758/AlSi10Mg_9011-0024_M400_Material_data_sheet_Flexline_03-18_en.pdf

EOS. 2019g. Material data sheet of EOS Ti64. [EOS webpage]. [Referred 11.1.2019]. Available: https://cdn.eos.info/a4eeb73865d54434/5926811b3739/Ti-Ti64_9011-0014_9011-0039_M290_Material_data_sheet_11-17_en.pdf

Finder. 2019a. 3Dstep Oy. [Finder webpage]. [Referred 23.1.2019]. Available: https://www.finder.fi/3D-suunnittelu+3D-mallinnus/3DStep+Oy/Yl%C3%B6j%C3%A4rvi/yhteystiedot/3122301

Finder. 2019b. AM Finland Oy. [Finder webpage]. [Referred 23.1.2019]. Available: https://www.finder.fi/3D-suunnittelu+3D-mallinnus/AM+Finland+Oy/Lahti/yhteystiedot/2769002

Finnish Constructional Steelwork Association. 2017. Ruostumattomien terästen käyttö kantavissa rakenteissa. Fourth edition. Helsinki: Finnish Constructional Steelwork Association. 230 p. [Design Manual for Structural Stainless Steel] (in Finnish)

Finnish Rapid Prototyping Association. 2019. Suomen AM-laitteet. [FIRPA webpage]. [Referred 23.1.2019]. Available: http://www.firpa.fi/AM_lista_viimeisin.pdf [AM systems in Finland] (in Finnish)

Fiocchi, J., Tuissi, A., Bassani, P. & Biffi, C. 2016. Low temperature annealing dedicated to AlSi10Mg selective laser melting products. Journal of Alloys and Compounds. Volume 695. 2017. Pp. 3402–3409.

Forbes. 2019. The World’s Billionares. [Forbes webpage]. [Referred 14.1.2019]. Available: https://www.forbes.com/billionaires/list/#version:static

Ganesh, P, Kaul, R., Sasikala, G., Kumar, H., Venugopal, S., Tiwari, P., Rai, S., Prasad, R. & Kukreja, M. 2014. Fatigue Crack Propagation and Fracture Toughness of Laser Rapid Manufactured Structures of AISI 316L Stainless Steel. Metallography, Microstructure, and Analysis. Volume 3(1). 2014 Pp. 36–45.

Gibson, I., Rosen, D. & Stucker, B. 2015. Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. Second Edition. New York: Springer. 498 p.

Gray, G., Livescu, V., Rigg, P., Trujillo, C., Cady, C., Chen, S., Carpenter, J., Lienert, T. & Fensin, S. 2017. Structure/property (constitutive and spallation response) of additively manufactured 316L stainless steel. Acta Materialia. Volume 138. 2017. Pp. 140–149.

Gu, D. 2015. Laser Additive Manufacturing of High-Performance Materials. Berlin: Springer. 311 p.

ISO. 2019. ISO/TC Additive manufacturing. [ISO webpage]. [Referred 23.1.2019]. Available: https://www.iso.org/committee/629086/x/catalogue/p/0/u/1/w/0/d/0

Halpenevat robotit lisäävät investointeja. 2019. Tekniikka & Talous 11.1.2019 (n:o 1), p. 12.

Hitsatut profiilit. 2000. Helsinki: Finnish Constructional Steelwork Association. 288 p. [Welded Profiles] (in Finnish)

King, W., Anderson, A., Ferencz, R., Hodge, N., Kamath, S., Khairallah, S. & Rubenchik, A. 2015. Laser powder bed fusion additive manufacturing of metals; physics, computational, and materials challenges. Applied Physics Reviews. Volume 2(4). 2015. Pp. 041304-1–26.

Koivisto, H. 2019. RE: Metallitulostimenne [private email]. Receiver: markus.korpela@lut.fi. Sent 16.1.2019 08:11 o’clock (GMT +0200).

Koivisto, K., Laitinen, E., Niinimäki, M., Tiainen, T., Tiilikka, P. & Tuomikoski, J. 2008. Konetekniikan materiaalioppi. Twelfth edition. Helsinki: Edita Prima Oy. 341 p. [Material Science in Mechanical Engineering] (in Finnish)

Koivisto, K. & Tuomikoski, J. 2008. [Chapter 5:] Terästen valmistus. In: Koivisto, K., Laitinen, E., Niinimäki, M., Tiainen, T., Tiilikka, P. & Tuomikoski, J. 2008. Konetekniikan materiaalioppi. Twelfth edition. Helsinki: Edita Prima Oy. Pp. 76–85. [Production of steels. In: Material Science in Mechanical Engineering] (in Finnish)

Koivisto, K. & Tuomikoski, J. 2008. [Chapter 7:] Teräkset. In: Koivisto, K., Laitinen, E., Niinimäki, M., Tiainen, T., Tiilikka, P. & Tuomikoski, J. 2008. Konetekniikan materiaalioppi. Twelfth edition. Helsinki: Edita Prima Oy. Pp. 128–148. [Steels. In: Material Science in Mechanical Engineering] (in Finnish)

Konepajojen sorveista on moneksi. 2018. Prometalli 4/2018, p. 32. [Versatile Lathes in Machine Shops] (in Finnish)

Korpela, M. 2016. Additive Manufacturing – costs, benefits and challenges [web document]. Rauma: May 2016 [Referred 24.1.2019]. Bachelor’s Thesis. Satakunta University of Applied Sciences, Degree Programme in mechanical and production engineering.74 p. + appendices 2 p. Available in PDF-file: http://urn.fi/URN:NBN:fi:amk-201605198759

Kotila, J. 2019. R&D Group Manager, Electro Optical Systems Finland Oy. Phone interview 31.01.2019. Interviewer Markus Korpela. Notes are occupied by the interviewer.

Kousa, J. 2018. RE: Rauten metal AM -nimikkeet [private email]. Receiver: markus.korpela@lut.fi. Sent 11.12.2018 21:47 o’clock (GMT +0200).

Kurzynowski, T., Gruber, K., Stopyra, W., Kuźnicka, B. & Chlebus, E. 2018. Correlation between process parameters, microstructure and properties of 316 L stainless steel processed by selective laser melting. Materials Science and Engineering: A. Volume 718. 2018. Pp. 64–73.

Kyröläinen, A. & Lukkari, J. 2002. Ruostumattomat teräkset ja niiden hitsaus. Second edition. Tampere: Metalliteollisuuden Keskusliitto, MET. 526 p. MET-julkaisuja nro 14/2002. [Stainless Steels and their weldability] (in Finnish)

Ladec. 2019. Materflow: Teollisuuden 3D-tulostaja. [Ladec webpage]. [Referred 23.1.2019]. Available: https://base.ladec.fi/filebank/10359-Metallin-3D-tulostus_TimoPeltonen_Materflow_27-11-2018.pdf

Leary, M. 2017. [Chapter 4:] Surface roughness optimization for selective laser metling (SLM): accommodating relevant and irrelevant surface. In: Brandt, M. 2017. Laser additive manufacturing: Materials, design, technologies, and applications. Amsterdam: Elsevier. Pp. 99–116.

Li, W., Li, S., Liu, J., Zhang, A., Zhou, Y., Wei, Q., Yan, C. & Shi, Y. 2016. Effect of heat treatment on AlSi10Mg alloy fabricated by selective laser melting: Microstructure evolution, mechanical properties and fracture mechanism. Materials Science and Engineering: A. Volume 663. 2016. Pp. 116–125.

Lindqvist, M. 2019. Chief Technology Officer, Delva Oy. Internet video call interview 1.2.2019. Interviewer Markus Korpela. Notes are occupied by the interviewer.

Lukkari, J., Kyröläinen, A. & Kauppi, T. 2016. Hitsauksen materiaalioppi: Osa 1, Metalliopin perusteet, terästen luokittelu ja valmistus, rakenneterästen käyttäytyminen hitsauksessa, murtuminen ja korroosio. Helsinki: Suomen Hitsausteknillinen Yhdistys r.y. 188 p. [Material Science in Welding: Part 1, basics of metallurgy, grading and production of steels, performance of structural steels in welding, cracking and corrosion] (in Finnish)

LUT University. 2019. LUTissa tarjolla maksutonta koulutusta metallien 3D-tulostuksessa. [LUT University webpage]. Updated January 1, 2019. [Referred 23.1.2019]. Available: https://www.lut.fi/uutiset//asset_publisher/h33vOeufOQWn/content/lutissa-tarjolla-maksutonta-koulutusta-metallien-3d-tulostuksessa

Materflow. 2019. [Materflow webpage]. [Referred 27.1.2019]. Available: https://www.materflow.com/

Milewski, J. 2017. Additive Manufacturing of Metals: From Fundamental Technology to Rocket Nozzles, Medical Implants, and Custom Jewelry. Cham: Springer. 343 p.

Moilanen, T. 2019. RE: Metallitulostimenne [private email]. Receiver: markus.korpela@lut.fi. Sent 9.1.2019 17:09 o'clock (GMT +0200).

Mower, M. & Long, M. 2015. Mechanical behavior of additive manufactured, powder-bed laser-fused materials. Materials Science and Engineering: A. Volume 651. 2016. Pp. 198–213.

Official Statistics of Finland. 2018. Structural business and financial statement statistics [web document]. Helsinki: Statistics Finland. [Referred 24.1.2019]. Available: http://www.stat.fi/til/yrti/2017/yrti_2017_2018-12-18_tie_001_en.html

Oulupmc. 2019. EOSINT M270. [Oulupmc webpage]. [Referred 23.1.2019]. Available: http://www.oulupmc.com/palvelut/valmistuspalvelut/eosint-m270.html

Pace, M., Guarnaccio, A., Dolce, P., Mollica, D., Parisi, G., Lettino, A., Medici, L., Summa, V., Ciancio, R. & Santagata, A. 2017. 3D additive manufactured 316L components microstructural features and changes induced by working life cycles. Applied Surface Science. Volume 418(PB). 2017. Pp. 437–445.

Pere, A. 2003. Teknisen piirustuksen perusteet: Oppi- ja harjoituskirja ammattiopetukseen. Sixth edition. Espoo: Kirpe Oy. 252 p. [Basics of Technical Drawing: Textbook and workbook for vocational training] (in Finnish)

Pere, A. 2012. Koneenpiirustus 1 & 2. Eleventh edition. Espoo: Kirpe Oy. 757 p. [Mechanical Drawing] (in Finnish)

Piili, H. 2017. R&D Engineer, EOS Finland Oy. Metallien lisäävä valmistus (eli 3D-tulostus) teollisessa tuotannossa. Tampere: Tulevaisuuden tehdas 2017 14.11.2017.

Pham, M., Dovgyy, B. & Hooper, P. 2017. Twinning induced plasticity in austenitic stainless steel 316L made by additive manufacturing. Materials Science and Engineering: A. Volume 704. 2017. Pp. 102–111.

Raaka-ainekäsikirja 1: Muokatut teräkset. 2001. 3rd edition. Helsinki: Metalliteollisuuden Keskusliitto, MET. 361 p. Raaka-ainekäsikirja -sarja. MET-julkaisuja nro 3/2001. [Handbook of Raw Materials 1: Wrought steels] (in Finnish)

Raaka-ainekäsikirja 5: Alumiinit. 2002. Tampere: Metalliteollisuuden Keskusliitto, MET. 235 p. Raaka-ainekäsikirja -sarja. MET-julkaisuja nro 13/2002. [Handbook of Raw Materials 5: Aluminums] (in Finnish)

Raukola, J. 2019. Additive Manufacturing Engineer, Wärtsilä Finland Oy. Messaging application interview 31.1.2019. Interviewer Markus Korpela. Notes are occupied by the interviewer.

Renishaw. 2019a. RenAM 500Q. [Renishaw webpage]. [Referred 23.1.2019]. Available: https://www.renishaw.com/en/renam-500q--42781

Renishaw. 2019b. Data sheets – Additive manufacturing. [Renishaw webpage]. [Referred 23.1.2019]. Available: https://www.renishaw.com/en/data-sheets-additive-manufacturing--17862

Riemer, A., Richard, H., Brüggemann, J. & Wesendahl, J. 2015. Fatigue crack growth in additive manufactured products. Frattura ed Integritá Strutturale. Volume 34. 2015. Pp. 437–446.

Salminen, A. 2018. Professor of Laser Materials Processing, LUT University. Lappeenranta, LUT University. Discussion 1.9.2018.

SFS. 2019a. Standardization worldwide. [SFS webpage]. [Referred 15.1.2019]. Available: https://www.sfs.fi/en/standardization/what_is_standardization/standardization_worldwide

SFS. 2019b. Standardization. [SFS webpage]. [Referred 15.1.2019]. Available: https://www.sfs.fi/en/standardization

SFS. 2019c. [SFS webpage]. [Referred 15.1.2019]. Available: https://www.sfs.fi/

SFS-EN 485-2:2016+A1:2018:en. 2018. Aluminum and aluminum alloys. Sheet, strip and plate. Part 2: Mechanical properties. Helsinki: Finnish Standards Association SFS. 97 p.

SFS-EN 515. 2017. Alumiini ja alumiiniseokset. Muokatut tuotteet. Tilojen tunnukset. 2nd edition. Helsinki: Finnish Standards Association SFS. 45 p. Confirmed and published in English.

SFS-EN 573-1. 2005. Alumiini ja alumiiniseokset. Muokattujen tuotteiden kemiallinen koostumus ja tuotemuodot. Osa 1: Numeerinen nimikejärjestelmä. 2nd edition. Helsinki: Finnish Standards Association SFS. 12 p. Confirmed and published in English.

SFS-EN 755-2. 2016. Alumiini ja alumiiniseokset. Pursotetut tangot, putket ja profiilit. Osa 2: Mekaaniset ominaisuudet. 4th edition. Helsinki: Finnish Standards Association SFS. 113 p. Confirmed and published in English.

SFS-EN 1706. 2010. Alumiini ja alumiiniseokset. Valut. Kemiallinen koostumus ja mekaaniset ominaisuudet. 2nd edition. Helsinki: Finnish Standards Association SFS. 42 p. Confirmed and published in English.

SFS-EN 1780-1. 2003. Alumiini ja alumiiniseokset. Uudelleen sulatettavien harkkojen, esiseosten ja valujen nimikkeet: Osa 1: Numeerinen nimikejärjestelmä. 2nd edition. Helsinki: Finnish Standards Association SFS. 9 p. Confirmed and published in English.

SFS-EN 10020. 2000. Teräslajien määritelmät ja luokittelu. 2nd edition. Helsinki: Finnish Standards Association SFS. 15 p. Confirmed and published in English.

SFS-EN 10027-1. 2016. Terästen nimikejärjestelmät. Osa 1: Terästen nimikkeet. 3rd edition. Helsinki: Finnish Standards Association SFS. 50 p. Confirmed and published in English.

SFS-EN 10027-2. 2016. Terästen nimikejärjestelmät. Osa 2: Numeerinen järjestelmä. 2nd edition. Helsinki: Finnish Standards Association SFS. 25 p. Confirmed and published in English.

SFS-EN 10088-1. 2014. Ruostumattomat teräkset. Osa 1: Ruostumattomien terästen luettelo. 3rd edition. Helsinki: Finnish Standards Association SFS. 127 p. Confirmed and published in English.

SFS-EN 10088-2. 2014. Ruostumattomat teräkset. Osa 2: Yleiseen käyttöön tarkoitetut korroosionkestävät levyt ja nauhat. Tekniset toimitustiedot. 3rd edition. Helsinki: Finnish Standards Association SFS. 106 p. Confirmed and published in English.

SFS-EN ISO 4957. 2018. Työkaluteräkset. 2nd edition. Helsinki: Finnish Standards Association SFS. 76 p. Confirmed and published in English.

SFS-EN ISO/ASTM 52900:en. 2017. Additive manufacturing. General principles. Terminology (ISO/ASTM 52900:2015). Helsinki: Finnish Standards Association SFS. 25 p.

Seppälä, M. 2018. Chief executive officer, HT Laser Oy. Stockholm, 3Dverkstan: Nordic AM Group 4.12.2018.

SLM. 2019a. SLM$^{®}$800. [SLM webpage]. [Referred 11.1.2019]. Available: https://slm-solutions.com/en/products/machines/slmr800/

SLM. 2019b. Machines. [SLM webpage]. [Referred 11.1.2019]. Available: https://slm-solutions.com/en/products/machines/selectivelasermeltingmachines/

SLM. 2019c. 3D Metals. [SLM webpage]. [Referred 11.1.2019]. Available: https://slm-solutions.com/fileadmin/user_upload/downloads/en/201en171023-01-001-powder_web.pdf

Sorsa, J. 2015. Materiaalitekniikka. Helsinki: Sanoma Pro. 252 p. [Material Science] (in Finnish)

Subcontracting 2018 Fair Catalogue. 2019. [AMT webpage]. [Referred 16.1.2019]. Available: https://amt.fi/en/publication/59/keywords#16070545

Subcontracting Trade Fair. 2019. [Subcontracting Trade Fair webpage]. [Referred 16.1.2019]. Available: https://www.alihankinta.fi/en/

Sun, S., Brandt, M. & Easton, M. 2017. [Chapter 2:] Powder bed fusion processes: an overview. In: Brandt, M. 2017. Laser additive manufacturing: Materials, design, technologies, and applications. Amsterdam: Elsevier. Pp. 55–79.

Technology Industries of Finland. 2018a. Lehdistötilaisuuden 26.4.2018 kalvot [web document]. Technology Industries of Finland. [Referred 24.1.2019]. Available: https://teknologiateollisuus.fi/sites/default/files/file_attachments/lehdistotilaisuus_26.4.2018_1.pptx

Technology Industries of Finland. 2018b. Economic Outlook 3/208 [web document]. [Referred 24.1.2019]. Avaibale: https://teknologiateollisuus.fi/sites/default/files/file_attachments/t_talousnakymat_3-2018_fi_digi_02.pdf

Tekniikka & Talous. 2018. Metso toimitti ensimmäiset metallista tulostetut komponentit [web document]. Published 27.12.2018 [Referred 28.12.2018]. Available: https://www.tekniikkatalous.fi/tekniikka/metalli/metso-toimitti-ensimmaiset-metallista-tulostetut-komponentit-3d-tulostus-on-tullut-jaadakseen-6753556?fbclid=IwAR3W3LmjxWOH4N3lksqJqaz5O7h2Uq2rkQmY5OB0nFlts554Hg_S8OAp2dU

Thijs, L., Kempen, K., Kruth, J. & Humbeeck, J. 2012. Fine-structured aluminum products with controllable texture by selective laser melting of pre-alloyed AlSi10Mg powder. Acta Materialia. Volume 61(5). 2013. Pp. 1809–1819.

Tiainen, T. & Laitinen, E. 2008. [Chapter 17:] Konstruktiomateriaalien käytön kehitys. In: Koivisto, K., Laitinen, E., Niinimäki, M., Tiainen, T., Tiilikka, P. & Tuomikoski, J. 2008. Konetekniikan materiaalioppi. Twelfth edition. Helsinki: Edita Prima Oy. Pp. 260–266. [Development of Use of Construction Materials. In: Material Science in Mechanical Engineering] (in Finnish)

Tiilikka, P. 2008. [Chapter 2:] Materiaalien käyttöominaisuudet. In: Koivisto, K., Laitinen, E., Niinimäki, M., Tiainen, T., Tiilikka, P. & Tuomikoski, J. 2008. Konetekniikan materiaalioppi. Twelfth edition. Helsinki: Edita Prima Oy. Pp. 9–37. [Performances of Materials. In: Material Science in Mechanical Engineering] (in Finnish)

Voisin, T., Calta, N., Khairallah, S., Forien, J., Balogh, L., Cunningham, R., Rollett, A. & Wang, M. 2018. Defects-dictated tensile properties of selective laser melted Ti-6Al-4V. Materials & Design. Volume 158. 2018. Pp. 113–126.

Vossi Group. 2015. Asiakastarina: VTT. [Vossi Group webpage]. [Referred 5.1.2019] Available: https://www.vossi.fi/asiakas/vtt/

Vossi Group. 2016. Asiakastarina: SASKY Municipal Education and Training Consortium. [Vossi Group webpage]. [Referred 5.1.2019] Available: https://www.vossi.fi/asiakas/sasky-koulutuskuntayhtyma/

Vossi Group. 2018. Asiakastarina: V.A.V GROUP OY. [Vossi Group webpage]. [Referred 5.1.2019] Available: https://www.vossi.fi/asiakas/v-a-v-group-oy/

Wei, P., Wei, Z., Chen, Z., Du, J., He, Y., Li, J. & Zhou, Y. 2017. The AlSi10Mg samples produced by selective laser melting: single track, densification, microstructure and mechanical behavior. Applied Surface Science. Volume 408. 2017. Pp. 38–50.

Wu, J., Wang, X., Wang, W., Attallah, A. & Loretto, M. 2016. Microstructure and strength of selectively laser melted AlSi10Mg. Acta Materilia. Volume 117. 2016. Pp. 311–320.

Yang, L., Hsu, K., Baughman, B., Godfrey, D., Medina, F., Menon, M. & Wiener, S. 2017. Additive Manufacturing of Metals: The Technology, Materials, Design and Production. Cham: Springer. 168 p.

Yrittäjät. 2018. Yrittäjyys Suomessa. [Yrittäjät webpage]. Updated March 23, 2018. [Referred: 24.1.2019]. Available: https://www.yrittajat.fi/suomen-yrittajat/yrittajyys-suomessa-316363

Xjet. 2019. Technology. [Xjet webpage]. [Referred 16.1.2019]. Available: https://xjet3d.com/technology/

Zhang, M., Sun, C., Zhang, X., Goh, P., Wei, J., Hardacre, D. & Li, H. 2017. Fatigue and fracture behaviour of laser powder bed fusion stainless steel 316L: Influence of processing parameters. Materials Science & Engineering: A. Volume 703. 2017. Pp. 251–261.

APPENDIX I

Boundary between non alloy and alloy steels (Mod. SFS-EN 10020 2000, p. 9).

Specified element	Limit value % by mass
Al	0.30
B	0.0008
Bi	0.10
Co	0.30
Cr	0.30
Cu	0.40
La	0.10
Mn	1.65*
Mo	0.08
Nb	0.06
Ni	0.30
Pb	0.40
Se	0.10
Si	0.60
Te	0.10
Ti	0.05
V	0.10
W	0.30
Zr	0.05
Others (except C, P, S, N (each))	0.10
* Where manganese is specified only as a maximum the limit value is 1.80 % and the 70 % rule of chapter 3.1.2 of EN 10020 does not apply	

APPENDIX II

Designations of the second of the five figures in designation of aluminum alloys according to SFS-EN 1780-1 (SFS-EN 1780-1 2003, p. 7).

The second number	Indication of the alloy group
2$\boxed{1}$XXX	Al Cu
4$\boxed{1}$XXX	Al SiMgTi
4$\boxed{2}$XXX	Al Si7Mg
4$\boxed{3}$XXX	Al Si10Mg
4$\boxed{4}$XXX	Al Si
4$\boxed{5}$XXX	Al Si5Cu
4$\boxed{6}$XXX	Al Si9Cu
4$\boxed{7}$XXX	Al Si(Cu)
4$\boxed{8}$XXX	Al SiCuNiMg
5$\boxed{1}$XXX	Al Mg
7$\boxed{1}$XXX	Al ZnMg

Designation of wrought aluminum alloys based on main alloying elements (Raaka-ainekäsikirja 5: Alumiinit 2002, p. 66; SFS-EN 515 2017, pp. 34-37).

Designation	Main alloying elements
1070A	Al99.7
1050A	Al99.5
1350	E-Al99.5
1200	Al99.0
2011	AlCuBiPb
2014	AlCu4SiMg
3103	AlMn1
3003	AlMn1Cu
3005	AlMn1Mg0.5
3004	AlMn1Mg1
4015	AlSi2Mn
4045	AlSi10
5005	AlMg1
5049	AlMg2Mn0.8
5052	AlMg2.5
5754	AlMg3
5083	AlMg4.5Mn
6060	AlMgSi
6063	AlMg0.7Si
6061	AlMg1SiCu
6005	AlSiMg
6082	AlSi1MgMn
7020	AlZn4.5Mg1
7021	AlZn5.5Mg1.5
7075	AlZn5.5MgCu
Temper designations: O=annealed - products achieving the required annealed properties after hot forming processes may be designated as O temper	

H18=strain-hardened- 4/4 hard (fully hardened)
T6=solution heat-treated and then artificially aged
H16=strain-hardened - 3/4 hard
T62=solution heat-treated and then artificially aged. Applies to test material heat-treated from annealed or as-fabricated temper or to products heat-treated from any temper by the user

APPENDIX IV, 1

ASTM & ISO standards of additive manufacturing (ASTM International 2019; ISO 2019).

Designation	Title
ISO / ASTM52915 - 16	Standard Specification for Additive Manufacturing File Format (AMF) Version 1.2
ISO / ASTM52910 - 18	Additive manufacturing — Design — Requirements, guidelines and recommendations
F2924 - 14	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion
F3001 - 14	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion
F3049 - 14	Standard Guide for Characterizing Properties of Metal Powders Used for Additive Manufacturing Processes
F3055 - 14a	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion
F3056 - 14e1	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N06625) with Powder Bed Fusion
F3091 / F3091M - 14	Standard Specification for Powder Bed Fusion of Plastic Materials
F3184 - 16	Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion
F3187 - 16	Standard Guide for Directed Energy Deposition of Metals
F3213 - 17	Standard for Additive Manufacturing – Finished Part Properties – Standard Specification for Cobalt-28 Chromium-6 Molybdenum via Powder Bed Fusion
F3301 - 18a	Standard for Additive Manufacturing – Post Processing Methods – Standard Specification for Thermal Post-Processing Metal Parts Made Via Powder Bed Fusion

F3302 - 18	Standard for Additive Manufacturing – Finished Part Properties – Standard Specification for Titanium Alloys via Powder Bed Fusion
F3303 - 18	Standard for Additive Manufacturing – Process Characteristics and Performance: Practice for Metal Powder Bed Fusion Process to Meet Critical Applications
F3318 - 18	Standard for Additive Manufacturing – Finished Part Properties – Specification for AlSi10Mg with Powder Bed Fusion – Laser Beam
ISO / ASTM52901 - 16	Standard Guide for Additive Manufacturing – General Principles – Requirements for Purchased AM Parts
ISO / ASTM52900 - 15	Standard Terminology for Additive Manufacturing – General Principles – Terminology
F2971 - 13	Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing
F3122 - 14	Standard Guide for Evaluating Mechanical Properties of Metal Materials Made via Additive Manufacturing Processes
ISO / ASTM52921 - 13	Standard Terminology for Additive Manufacturing-Coordinate Systems and Test Methodologies
ISO 17296-2:2015	Additive manufacturing -- General principles -- Part 2: Overview of process categories and feedstock
ISO 17296-3:2014	Additive manufacturing -- General principles -- Part 3: Main characteristics and corresponding test methods
ISO 17296-4:2014	Additive manufacturing -- General principles -- Part 4: Overview of data processing
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

APPENDIX V

Chemical compounds of EOS MaragingSteel MS1 and SLM Tool Steel 1.2709 (EOS 2019d; SLM 2019c).

Element	EOS MaragingSteel MS1	SLM Tool Steel 1.2709
Fe	balance	balance
C	≤0.03	0.03
Ni	17.0-19.0	18.0-19.0
Co	8.50-9.50	8.50-9.50
Mo	4.50-5.20	4.70-5.20
Ti	0.60-0.80	0.50-0.80
Al	0.05-0.15	0.05-0.15
Mn	≤0.10	0.10
P	≤0.01	0.01
S	≤0.01	0.01
Cr	≤0.50	N/A
Cu	≤0.50	N/A
Si	≤0.10	N/A

Main mechanical properties of EOS MaragingSteel MS1 and SLM Tool Steel 1.2709.

Yield strengths of EOS MaragingSteel MS1 and SLM Tool Steel 1.2709 (EOS 2019d; SLM 2019c).

Yield strength test method	EOS MaragingSteel MS1 [MPa]	SLM Tool Steel 1.2709 [MPa]
1	1100 ± 100*	N/A
2	930 ± 150*	N/A
3	N/A	987 ± 15
4	N/A	1920 ± 12

1=Yield strength $R_{p0.2,}$ ISO 6892-1:2009, horizontal (XY), as built, 20 µm
2=Yield strength $R_{p0.2}$, ISO 6892-1:2009, vertical (Z), as built, 20 µm
3=Offset yield stress $R_{p0.2}$, standard N/A, direction N/A, as built, 50 µm
4=Offset yield stress $R_{p0.2}$, standard N/A, direction N/A, heat treated, 50 µm
*typical

Tensile strengths of EOS MaragingSteel MS1 and SLM Tool Steel 1.2709 (EOS 2019d; SLM 2019c).

Tensile strength test method	EOS MaragingSteel MS1 [MPa]	SLM Tool Steel 1.2709 [MPa]
1	1200 ± 100*	
2	1100± 150*	
3		1135 ± 29
4		1784 ± 313

1=Ultimate tensile strength, ISO 6892-1:2009, horizontal (XY), as built, 20 µm
2=Ultimate tensile strength, ISO 6892-1:2009, vertical (Z), as built, 20 µm
3=Tensile strength, standard N/A, direction N/A, as built, 50 µm
4=Tensile strength, standard N/A, direction N/A, heat treated, 50 µm
*typical

Elongation values of EOS MaragingSteel MS1 and SLM Tool Steel 1.2709 (EOS 2019d; SLM 2019c).

Elongation test method	EOS MaragingSteel MS1 [%]	SLM Tool Steel 1.2709 [%]
1	12 ± 4*	N/A
2	N/A	11 ± 1
3	N/A	44 ± 2
4	N/A	3 ± 1
5	N/A	10 ± 0

1=Elongation at break, ISO 6892-1:2009, horizontal (XY), as built, 20 µm
2=Break strain A, standard N/A, direction N/A, as built, 50 µm
3=Reduction of area Z, standard N/A, direction N/A, as built, 50 µm
4=Break strain A, standard N/A, direction N/A, heat treated, 50 µm
5=Reduction of area Z, standard N/A, direction N/A, heat treated, 50 µm
*typical

Hardness values of EOS MaragingSteel MS1 and SLM Tool Steel 1.2709 (EOS 2019d; SLM 2019c).

Hardness test method	EOS MaragingSteel MS1	SLM Tool Steel 1.2709
1	33-37*	N/A
2	50	N/A
3	N/A	373 ± 2

1=Rockwell hardness C (HRC), EN ISO 6508-1, polished surface, as built
2=Rockwell Hardness C (HRC) standard N/A, surface N/A, heat treated
3=Vickers hardness (HV10), standard N/A, surface N/A, as built
*typical

Young’s modulus values of EOS MaragingSteel MS1 and SLM Tool Steel 1.2709 (EOS 2019d; SLM 2019c).

Young’s modulus test method	EOS MaragingSteel MS1 [GPa]	SLM Tool Steel 1.2709 [Gpa]
1	150 ± 25*	N/A
2	140 ± 25*	N/A
3	N/A	113 ± 8
4	N/A	125 ± 5
1=manufacturing in horizontal direction (XY), as built 2=in manufacturing vertical direction (Z), as built 3=manufacturing direction N/A, as built 4=manufacturing direction N/A, heat treated *typical		

Hardness values of EOS MaragingSteel MS1 and SLM Tool Steel 1.2709 (EOS 2019d; SLM 2019c).

Surface roughness, as built	EOS MaragingSteel MS1 [µm]	SLM Tool Steel 1.2709 [µm]
R_a	5 or 9*	9 ± 1
R_z	28 or 50*	67 ± 5
*depends on layer thickness (40 or 50 µm)		

APPENDIX VII, 1

Chemical compound and main material properties of EOS Titanium Ti64 (EOS 2019f).

Element	EOS Titanium Ti64
Ti	balance
Al [w%]	5.50–6.75
V [w%]	3.50–4.50
O [w%]	≤0.20
N [w%]	≤0.05
C [w%]	≤0.08
H [w%]	≤0.015
Fe [w%]	≤0.30
Y [w%]	≤0.005
Other elements, each	≤0.10
Other elements, total	≤0.40
Yield strength test method	
1	945 MPa
2	965 MPa
Tensile strength test method	
3	1055 MPa
4	1075 MPa
Elongation test method	
5	13 %
6	14 %
7	>25 %
8	>25 %
Young’s modulus	N/A
Hardness *HV5*	ca. 320
Surface roughness test method	
R_a	5-9 µm
R_z	20-50 µm
Density	4.41 g/cm^3

1=Yield strength $R_{p0.2}$, ISO 6892-1 A14, heat treated, horizontal, 30 µm
2=Yield strength $R_{p0.2}$, ISO 6892-1 A14, heat treated, vertical, 30 µm
3=Tensile strength, ISO 6892-1 A14, heat treated, horizontal, 30 µm
4=Tensile strength, ISO 6892-1 A14, heat treated, vertical, 30 µm
5=Elongation at break A, ISO 6892-1 A14, heat treated, horizontal, 30 µm
6=Elongation at break A, ISO 6892-1 A14, heat treated, vertical, 30 µm
7=Reduction of area Z, ISO 6892-1 A14, heat treated, horizontal, 30 µm
8=Reduction of area Z, ISO 6892-1 A14, heat treated, vertical 30, µm
9=*HV5* EN ISO 6507-1 (5 kg)
10=after shot peening, ISO 4287

APPENDIX VIII, 1

Chemical compound and main material properties of remanium star® CL (Concept Laser 2019e).

Element	remanium® star CL
Co [w%]	60.5
Cr [w%]	28.0
W [w%]	9.00
Si [w%]	1.50
Mn [w%]	<1.00
N [w%]	<1.00
Nb [w%]	<1.00
Fe [w%]	<1.00
Yield strength test method	
1	792 ± 24
2	822 ± 14
3	835 ± 44
Tensile strength test method	
4	1136 ± 24
5	1200 ± 14
6	1156 ± 9
Young’s modulus test method	
7	230 Gpa
Elongation test method	
8	8 ± 3 %
9	8 ± 3 %
10	11 ± 1 %
Hardness	N/A
Surface roughness	N/A
Density	8.6 g/cm^3

1=Yield strength $Rp_{0,2}$, in line with DIN EN ISO 9693/DIN EN ISO 22674, 90° (horizontal), heat treated, µm N/A
2=Yield strength $Rp_{0,2}$, in line with DIN EN ISO 9693/DIN EN ISO 22674, 45° (polar angle), heat treated, µm N/A
3=Yield strength $Rp_{0,2}$, in line with DIN EN ISO 9693/DIN EN ISO 22674, 0° (upright), heat treated, µm N/A
4=Tensile Strength, in line with DIN EN ISO 9693/DIN EN ISO 22674, 90° (horizontal), heat treated, µm N/A
5=Tensile Strength, in line with DIN EN ISO 9693/DIN EN ISO 22674, 45° (polar angle), heat treated, µm N/A
6=Tensile Strength, in line with DIN EN ISO 9693/DIN EN ISO 22674, 0° (upright), heat treated, µm N/A
7=in line with DIN EN ISO 9693/DIN EN ISO 22674, 90°, 45°, 0°, (horizontal, polar angle and vertical), heat treated, µm N/A
8=Elongation at fracture A_5, in line with DIN EN ISO 9693/DIN EN ISO 22674, 90° (horizontal), heat treated, µm N/A
9=Elongation at fracture A_5, in line with DIN EN ISO 9693/DIN EN ISO 22674, 45° (polar angle), heat treated, µm N/A
10=Elongation at fracture A_5, in line with DIN EN ISO 9693/DIN EN ISO 22674, 0° (upright), heat treated, µm N/A

Original questions with answering options in Finnish language.

Information inside the brackets below was not seen by the respondents.

1. Onko yrityksenne Suomessa sijaitseva kone- ja/tai metallialan yritys?
    a. Kyllä (vaihtoehto johtaa kysymykseen 2)
    b. Ei (vaihtoehto päättää kyselyn)

2. Ammattinimikkeenne yrityksessä?
    ____

3. Työntekijöiden määrä yrityksessänne?
    a. <10
    b. 10-50
    c. 50-250
    d. >250

4. Yrityksenne sijainti?
    a. Uusimaa
    b. Varsinais-Suomi
    c. Satakunta
    d. Kanta-Häme
    e. Pirkanmaa
    f. Päijät-Häme
    g. Kymenlaakso
    h. Etelä-Karjala
    i. Etelä-Savo
    j. Pohjois-Savo
    k. Pohjois-Karjala
    l. Keski-Suomi
    m. Etelä-Pohjanmaa
    n. Pohjanmaa
    o. Keski-Pohjanmaa
    p. Pohjois-Pohjanmaa
    q. Kainuu
    r. Lappi

5. Arvioi suuruusjärjestyksessä, mitkä ovat kolme eniten käytettyä metallimateriaalia yrityksenne liiketoiminnassa? Pyri vastaamaan tarkemmin kuin "teräs" tai "alumiini". Esim. Niukkaseosteiset teräkset/7000-sarjan alumiinit/1.4404/Hardox
   a. Eniten käyttämänne metallimateriaali on: ______________________________________
   b. Toiseksi eniten käyttämänne metallimateriaali on: _______________________________
   c. Kolmanneksi eniten käyttämänne metallimateriaali on: ___________________________

6. Oletteko hyödyntäneet tai yrittäneet hyödyntää METALLIEN 3D-tulostusta yrityksessänne?

a.	Kyllä, omalla laitteella ja alihankintana	(vaihtoehto johtaa kysymykseen 8)
b.	Kyllä, vain omalla laitteella	(vaihtoehto johtaa kysymykseen 8)
c.	Kyllä, vain alihankintana	(vaihtoehto johtaa kysymykseen 8)
d.	Ei, mutta aiomme lähitulevaisuudessa	(vaihtoehto johtaa kysymykseen 7)
e.	Ei	(vaihtoehto johtaa kysymykseen 11)
f.	En osaa sanoa	(vaihtoehto johtaa kysymykseen 9)

7. Arvioi, montako erilaista metallikappaletta pyritte tulostamaan itse tai tulostuttamaan alihankintana seuraavien 12 kuukauden aikana

a.	0	(vaihtoehto johtaa kysymykseen 11)
b.	1	(vaihtoehto johtaa kysymykseen 11)
c.	1-5	(vaihtoehto johtaa kysymykseen 11)
d.	5-20	(vaihtoehto johtaa kysymykseen 11)
e.	20-50	(vaihtoehto johtaa kysymykseen 11)
f.	>50	(vaihtoehto johtaa kysymykseen 11)
g.	En osaa sanoa	(vaihtoehto johtaa kysymykseen 11)

8. Arvioi, montako erilaista metallikappaletta olette tulostaneet itse tai tulostuttaneet alihankintana tähän mennessä

a.	1	(vaihtoehto johtaa kysymykseen 11)
b.	1-5	(vaihtoehto johtaa kysymykseen 11)
c.	5-20	(vaihtoehto johtaa kysymykseen 11)
d.	>50	(vaihtoehto johtaa kysymykseen 11)
e.	En osaa sanoa	(vaihtoehto johtaa kysymykseen 11)
f.	0	(vaihtoehto johtaa kysymykseen 11)

9. Voiko tämän kyselylomakkeen linkin lähettää jollekin muulle henkilölle, joka osaisi vastata edelliseen kysymykseen 3D-tulostamisen hyödyntämisestä yrityksessänne?
    a. Ei, päätä kysely (vaihtoehto päättää kyselyn)
    b. Kyllä (vaihtoehto johtaa kysymykseen 10)

10. Yrityksenne henkilö, joka osaa kertoa 3D-tulostamisen hyödyntämisestä yrityksessänne: (ammattinimike, yrityksen nimi & sähköpostiosoite)

    ________________________________ (vastaus päättää kyselyn)

11. Mikäli ette ole hyödyntäneet METALLIEN 3D-tulostusta tai olette joskus yrittäneet siinä onnistumatta, mitkä seuraavista vaihtoehdoista arvioisitte olevan/olleen syynä tähän:
    a. Ei tarvetta
    b. Liian korkea hinta
    c. Tietotaidon puute
    d. Laatuvaatimukset
    e. Liian pitkä toimitusaika
    f. Prosessi osoittautui liian hankalaksi
    g. 3D-tulostuksen rajallinen materiaalivalikoima
    h. 3D-tulostuksen rajoitteet kappaleen koon suhteen
    i. En osaa sanoa
    j. Olemme aina onnistuneet
    k. Muu:___________________

12. Oletteko törmänneet tilanteeseen, jossa olisitte halunneet hyödyntää METALLIEN 3D-tulostusta, mutta sopivaa materiaalia ei ollut saatavilla?
    a. Kyllä (vaihtoehto johtaa kysymykseen 13)
    b. Ei (vaihtoehto päättää kyselyn)
    c. En osaa sanoa (vaihtoehto johtaa kysymykseen 14)

13. Kun törmäsitte tilanteeseen, jossa olisitte halunneet hyödyntää 3D-tulostusta, mutta sopivaa materiaalia ei ollut saatavilla, mistä materiaalista/materiaaleista oli kyse?

    ____

14. Voitteko te tai joku muu yrityksenne henkilö tarvittaessa vastata toiseen, muutaman minuutin kestävään jatkokyselyyn metallien 3D-tulostukseen ja siinä käytettäviin materiaaleihin liittyen?
    a. Ei (vaihtoehto päättää kyselyn)

b. Kyllä (vaihtoehto johtaa kysymykseen 15)

15. Yrityksenne henkilö, joka voi tarvittaessa vastata toiseen, muutaman minuutin kestävään kyselyyn metallien 3D-tulostukseen ja siinä käytettäviin materiaaleihin liittyen: (ammattinimike, yrityksen nimi & sähköpostiosoite)

________________________________ (vastaus päättää kyselyn)

Questions of the survey translated to English.

Information inside the brackets below was not seen by the respondents.

1. Is your company a metal and/or mechanical engineering company and located to Finland?
    a. Yes (this option leads to question 2)
    b. No (this option ends the survey)

2. Your title in the company?

    ____

3. Number of employees in your company?
    a. <10
    b. 10-50
    c. 50-250
    d. >250

4. Location of your company?
    a. Uusimaa
    b. Varsinais-Suomi
    c. Satakunta
    d. Kanta-Häme
    e. Pirkanmaa
    f. Päijät-Häme
    g. Kymenlaakso
    h. South-Karelia
    i. Etelä-Savo
    j. Pohjois-Savo
    k. North Karelia
    l. Central Finland
    m. South Ostrobothnia
    n. Ostrobothnia
    o. Central Ostrobothnia
    p. North Ostrobothnia
    q. Kainuu
    r. Lapland

5. Please estimate, which are the three most used metal materials in your company? Strive to answer more accurate than ”steel” or ”aluminum”. For example, low-alloy steels/7000 series alumunium/1.4404/Hardox
   a. The most used material is: ____
   b. The second most used material is: _________________________________
   c. The third used material is: ____

6. Have you or have you ever tried to utilize metal additive manufacturing in your company?
   a. Yes, with our own machine and by subcontracting (this option leads to question 8)
   b. Yes, only with our own machine (this option leads to question 8)
   c. Yes, only by subcontracting (this option leads to question 8)
   d. No, but we are planning to do so in the near future (this option leads to question 7)
   e. No (this option leads to question 11)
   f. I don’t know (this option leads to question 9)

7. Please estimate, how many of different metal parts your company is going to print or print by subcontracting during the next 12 months?
   a. 0 (this option leads to question 11)
   b. 1 (this option leads to question 11)
   c. 1-5 (this option leads to question 11)
   d. 5-20 (this option leads to question 11)
   e. 20-50 (this option leads to question 11)
   f. >50 (this option leads to question 11)
   g. I don’t know (this option leads to question 11)

8. Please estimate, how many of different metal parts your company has printed or printed by subcontracting this far?
   a. 1 (this option leads to question 11)
   b. 1-5 (this option leads to question 11)
   c. 5-20 (this option leads to question 11)
   d. >50 (this option leads to question 11)
   e. I don’t know (this option leads to question 11)
   f. 0 (this option leads to question 11)

9. Would it be possible to send link for this survey to another person of your company who could answer previous question about utilizing of additive manufacturing in your company?
    a. No, end the survey (this option ends the survey)
    b. Yes (this option leads to question 10)

10. Details of the person who can answer to the question about utilization of additive manufacturing in your company (title, name of the company and email address)

    ___________________________________ (this option ends the survey)

11. Whether your company has not utilized metal additive manufacturing or it has without succeeding in it, which of the following options you would estimate to be reasons for that?
    a. No need
    b. Too high costs
    c. Lack of know-how
    d. Quality requirements
    e. Too long lead time
    f. The process turned out to be too hard
    g. Limited material repertoire of additive manufacturing
    h. Limited size of a part
    i. I don’t know
    j. We have always succeeded
    k. Other:_______________________

12. Has your company ever been in a situation where METAL additive manufacturing would have been wanted to utilize, but suitable material was not available?
    a. Yes (this option leads to question 13)
    b. No (this option ends the survey)
    c. I don’t know (this option leads to question 14)

13. When your company was in this situation, in which METAL additive manufacturing would have been wanted to use, but suitable material was not available, which material was it about?

    ____

14. If needed, could you or another person of your company answer to second survey that takes couple of minutes regarding to metal additive manufacturing and its materials?
    a. No (this option ends the survey)
    b. Yes (this option leads to question 15)

15. Details of the person who can answer to the second survey, that takes couple of minutes, regarding to metal additive manufacturing and its materials (title, name of the company and email address) ___________________________

    (this option ends the survey)

L-PBF system producers and their machine base prices. (Wohlers 2018 pp. 65–127).

System producer	System name	Base price (x1000 €*)	Max. building volume, liters
Realizer	SLM 50	120	0.31
Sentrol	SMJ80	442	0.40
Concept Laser	Mlab cusing	164	0.65
Concept Laser	Mlab cusing R	184	0.65
EOS	EOS M 100	200	0.75
Sisma	mysint 100	165	0.79
Trumpf	TruPrint 1000	170	0.79
Trumpf	TruPrint 1000 ML	225	0.79
Renishaw	ProX DMP 100	170	0.80
Renishaw	ProX 100 Dental	170	0.80
Eplus 3D	EP-M100	184	0.80
OR Laser	Orlas Creator	95	0.86
Concept Laser	Mlab cusing 200R	199	1.00
Farsoon	FS121M	168	1.44
SLM Solutions	SLM 125	195	1.95
Sisma	ProX DMP 200	332	2.09
Long Yuan	AFS-M120	159	2.88
Realizer	SLM 125	275	3.13
Brigh Laser Technologies	BLT-S200	241	4.50
Zrapid	SLM150	124	4.50
Sentrol	SM250	309	12.50
Concept Laser	M1 cusing	359	15.63

Huake 3D	HK M250	290	15.63
Zhuhai CTC	CTC Walnut SLM	137	17.58
Renishaw	AM400	381	18.75
Renishaw	AM400 HT	497	18.75
3DSystems	ProX DMP 300	552	18.75
Eplus 3D	EP-M250	351	18.75
ERMAKSAN	ENA 250	350	18.75
EOS	EOS M 290	480	20.31
Concept Laser	M2 cusing	479	21.88
Concept Laser	M2 cusing2 ML	599	21.88
Renishaw	RenAM 500M	462	21.88
Renishaw	RenAM 500D	583	21.88
Renishaw	RenAM 500Q	756	21.88
Long Yuan	AFS-M260	203	23.66
Farsoon	FS271M	353	24.20
Brigh Laser Technologies	BLT-S300	470	25.00
Zrapid	SLM280	159	26.25
Realizer	SLM 300i	420	27.00
Trumpf	TruPrint 3000	430	28.27
SLM Solutions	SLM 280	450	28.62
Sentrol	SM350	530	30.79
3DSystems	ProX DMP 320	507	31.76
Aspect	RaFaEl-HV 300F	966	36.00

AddUp	FormUp 350	730	42.88
SLM Solutions	SLM 500	700	51.10
EOS	EOS M 400	1250	64.00
EOS	EOS M 400-4	1420	64.00
Xery	Victory 400M	440–800	64.00
Concept Laser	M LINE Factory	1200	68.00
Additive Industries	MetalFAB1**	875	70.56
Additive Industries	MetalFAB1**	1100	7056
SLM Solutions	SLM 800	2000–3000	119.00
Concept Laser	X LINE 2000R	1575	160.00
*according to exchange rate of 25th Jan 2019 *development system			

APPENDIX XII

Basic mechanical properties of austenitic stainless steels 1.4301, 1.4307, 1.4306, 1.4401, 1.4436, 1.4432, 1.4404, and 1.4435 in rolled forms (Mod. Kyröläinen & Lukkari 2002, p. 36).

EN	ASTM	Form	$R_{p0.2}$ [MPa]	R_m [MPa]	Ultimate elongation *A80* (<3 mm) min. [%]	Ultimate elongation *A* (>3 mm) min. [%]
1.4307	304L	C	220	520–670	45	45
1.4307	304L	H	200	520–670	45	45
1.4306	304L	C	220	520–670	45	45
1.4306	304L	H	200	520–670	45	45
1.4301	304	C	230	540–750	45	45
1.4301	304	H	210	520–720	45	45
1.4404	316L	C	240	530–680	45	45
1.4404	316L	H	220	530–680	40	40
1.4432	316L	C	240	550–700	40	40
1.4432	316L	H	220	550–700	40	40
1.4435	316L	C	240	550–700	40	40
1.4435	316L	H	220	550–700	40	40
1.4401	316	C	240	530–680	40	40
1.4401	316	H	220	530–680	40	40
1.4436	316	C	240	550–700	40	40
1.4436	316	H	220	550–700	40	40
C=cold rolled strip, *t*=max. 6 mm H=hot rolled strip, *t*=max. 12 mm						