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UTILIZATION OF DESIGN FOR ADDITIVE MANUFACTURING METHOLOGY IN L-PBF OF METAL SPARE PARTS

DFAM SUUNNITELUPERIAATTEEN KÄYTTÖ METALLISTEN VARAOSIEN L-PBF VALMISTUKSESSA

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DfAM suunnitteluperiaatteen käyttö metallisten varaosien L-PBF valmistuksessa
Kandidaatintyö

2021

43 sivua, 20 kuva ja 1 taulukko

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Tämän kandidaatin työn tarkoituksena oli tutkia DfAM suunnitteluperiaatteen mahdollisuuksia ja käyttöä metallisten varaosien tuotannossa soveltaen lisäävän valmistuksen jauhepetisulatustekniikkaa. Työ suoritettiin kirjallisuuskatsauksena, jonka tarkoituksena on selostaa lukijalle aiheen kehityksen nykytasoa, johtuen lisäävän valmistuksen nopeasta kehityksestä viime vuosien aikana.

Työ on kokoelma jauhepetisulatuksen rajoittavista tekijöistä, lisäävän valmistuksen eduista ja eritoten jauhepetisulatuksen soveltavuudesta varaosien tuotantoon. Näitä aspekteja huomioidaan suunnitteluperiaatteen käytännöllisyyden ja käyttökelpoisuuden arvioimisessa metallisten varaosien valmistuksessa teollisella tasolla.

Tutkimuksessa havaittiin, että rajoittavat tekijät ovat mm. jauhepetisulatuksessa aiheutuvat lämpöväärisTymät ja rajallinen kappaleen koko. Lisäävää valmistusta varten osat on usein suuniteltava uudestaan ja sen lisäksi optimoitava. Tulostuksen aikaiseen lämpökäyttäytymiseen ja ennakoimiseen voidaan soveltaa erilaisia simulaatiometodeja. Varaosien mallinnus ja simulaation laatu ovat saavuttamassa kasvavaa luotettavuutta, mutta kaipaavat oikeaoppista soveltamista ja jatkuvaa kehitystä. Lisäksi lisäävän valmistuksen avulla fysikaaliset kokeet voidaan tehdä luotettavasti ja nopeasti. Lisäävä valmistus tuottaa samanaikaisesti liudan räätälöityjä kappaleita, mikä nopeuttaa kappaleiden testausta.

ABSTRACT

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Utilization of Design for Additive Manufacturing methodology in L-PBF of metal spare parts

Bachelor's thesis

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43 pages, 20 figure and 1 table

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Keywords: Spare parts, Metal L-PBF, Additive Manufacturing, DfAM, 3D-printing

The purpose of this bachelor 's thesis was to investigate the possibilities and application of the DfAM design principle in the production of metal spare parts with additive manufacturing, especially powder bed fusion technology. The work was conducted as a literature review to explain to the reader the current state of development of the subject, due to the rapid development of incremental manufacturing in recent years.

The work is a collection of the limiting factors of powder bed fusion, the advantages of additive manufacturing and especially the applicability of powder bed fusion to the production of spare parts. These aspects are considered when assessing the practicality and applicability of the design principle in the manufacture of metal spare parts at the industrial level.

The study found that limiting factors are e.g. thermal distortions caused by powder bed fusion and limited part size. For additive manufacturing, parts often need to be redesigned and further optimized. Various simulation methods can be applied to thermal behavior and prediction during printing. Spare part modeling and simulation quality are gaining increasing reliability but need proper application and continuous improvement. In addition, with the help of additive manufacturing, physical experiments can be performed reliably and quickly. Additive manufacturing simultaneously produces custom batches of specimen, which speeds up piece testing.

ACKNOWLEDGEMENTS

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I would like to thank Ilkka Poutiainen, Marika Hirvimäki & Professor Heidi Piili for guiding and supporting me through this project.

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LIST OF SYMBOLS AND ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
AM	Additive Manufacturing
CAD	Computer Aided Design
CM	Conventional Manufacturing
DfAM	Design for Additive Manufacturing
L-PBF	Laser-based Powder Bed Fusion
PBF	Powder Bed Fusion
SC	Supply Chain
STL	STL file format

1. INTRODUCTION

Additive manufacturing (AM) is finding broader usage and utilization in manufacturing industries with its ability for mass customized productions and multitude of unique designs that cannot be replicated by other manufacturing means. Laser-based powder bed fusion (L-PBF) is in 2021 the most common AM technique. It has been finding growing general deployment in the industry due to its high-class properties and application possibilities while working with metals (Wohlers et al. 2018). It must also be noticed that AM improvements, advantages and specialization come with limits and known challenges. Education concerning AM L-PBF in general is required to optimize the utilization, tackle design related challenges and internal development of further applications (Diegel et al. 2019, s.121).

1.1 Background

Laser-based powder bed fusion is the most commonly used AM technique in industrial applications, because of its ability to simplify part complexity, freedom of design and application possibilities with industrial materials especially metals (Yang et al. 2017, p.63).

Compared to other AM techniques working with metals L-PBF superior properties can be achieved due to it being the most evolved in relation to other AM processes, achieving complicated designs with the best possible accuracy. Results are heavily influenced by designs and product parameters related to the produced parts volume (Gibson et al. 2015, p.51; Wohlers et al. 2019, p.173).

When AM is being utilized in the industry, production and research groups require deeper understanding of the technique, related properties and ways to achieve maximal benefits. Next to general lists of design rules exist an ever-expanding group of high-quality modelling and simulation software to further assist and verify design choices with model related limits (Diegel et al. 2019, s.121,).

L-PBF has a growing attraction in the fields of decentralized spare-part production, which reduces complicated logistics, eliminates large quantity storing and cuts loss of time due to maintenance delays. At the same time AM allows implementation of rapid prototyping in cooperation with redesigning of components with the goal of replacing outdated and failing parts with improved versions performing identical duties. On site and on demand replacement manufacturing can be effectively applied and organized due to the technology's mobile nature (Meisel et al. 2015; Montero et al. 2020, p. 313). In 2017 a study found out that the requested number of parts for tooling had seen an increase of reportedly more than 60 % in design modifications applied during the production phase, ever more demanding in innovation and development. This phenomenon has led to measurable delays in production time, while requiring further costs for extensive testing and research (Attaran 2017).

This development has led to an increasing interest and possibilities of AM, focusing on extensive education for personnel. At the same time growing requirements for more sophisticated simulation methods in combination with computer aided design tools referred to as CAD have also appeared. Prototype creation and testing phases can be performed simultaneously with the help of L-PBF's ability to produce multiple mass customized series of parts, while retaining a very cost-effective small volume manufacturing capability (Attaran 2017).

CAD related possibilities and effectiveness of L-PBF with a focus on printed L-PBF spare parts are presented in this thesis and frame the significant majority of the research topic. Simulation method's effectiveness, impact on design choices and feasibility for decentralized production are also taken into account in this study.

1.2 Objective and the framing of the research

Motivation for this thesis was to establish the relevance and relation in employment of simulation software’s to industrial environments producing spare parts manufactured with the use of L-PBF. As parts produced with L-PBF heavily rely on design and structures to avoid heat distortion and residual stress, it is necessary to evaluate and to investigate simulation software’s (Yang et al. 2017, p. 599).

The objective of this thesis is to answer the following research questions:

- How can spare part manufacture be optimized?
- Are simulation software’s feasible for L-PBF applications in the spare part industry?
- How can part failure through the use of DfAM be minimized?
- What are the current challenges L-PBF is facing?

A literature review forms the basis for this bachelor thesis, linking sources referring to applications utilizing L-PBF for the industrial manufacture of spart parts. Compared to conventional manufacturing, AM spare parts require substantial modifications to provide greater yield. This encourages the use of evolved design software, computer aided designs and simulation methods analyzing the spare part production. Accumulated information will be used to present L-PBF aspects and the impact of DfAM on the whole process.

2. FABRICATION OF SPARE PARTS BY L-PBF

Additive Manufacturing is defined by ISO/ASTM 52900 as a fabrication technique, that builds physical parts by solely fusing building material layer by layer. Parts built using this technique are based on 3D models created with computer animated design software (CAD). Additive manufacturing phases ignore all forming processes like forging, bending etc., in favor of only adding material during the building process. At the same time creation of excess material is avoided by removing the machining process from the manufacturing phase and purely relying on adding more building material. Removal of support structures and remaining metal powder are treated as a separate action. These procedures are still considered being part of the additive manufacturing process (SFS-EN ISO/ASTM 52900 2017). Additive manufacturing is able to utilize a big variety of materials most notable plastics, metals, composites and ceramic materials (SFS- EN ISO/ASTM 52900 2017, s. 16).

2.1 L-PBF

Powder bed fusion (PBF) is one of AM's major categories of which L-PBF is in this thesis's focus. In PBF, three-dimensional models are made by melting powdered material in layers to realize three-dimensional parts. Lasers are the core thermal energy source of L-PBF in comparison to other PBF processes, that for example utilize electron beams as their designated heat source. L-PBF can produce polymer, ceramic and metal parts, of which the metal parts have been selected as the sole research subject of this thesis, due to their widespread industrial capabilities (Wohlers et al. 2018 pp. 41–42).

Figure 1 shows a typical L-PBF 3D printer. It features EOS's best-selling AM device of 2020 model named M 290. This machine features a center closed chamber and a control panel for the operator located on the center structures right side of the 3D printer. With a average volume of 250 x 250 x325 mm printing capability compared to the current maximum size being around 500 x 500 x 500 mm commercially available, the M 290 enables flexible and cost-effective augmentation of parts directly from a STL file formats (Asnafi et al. 2019).

Figure 1. EOS’s M 290 which utilizes the L-PBF process (EOS 2020).

The manufacturing process starts with a 3D model created with CAD software. From the first design stage, it is very important to keep in mind that the piece in question will be fabricated by additive fabrication (Gibson et al. 2015, pages 4–5). Once this issue has been internalized and taken into account, then it is possible to design a compact and better functioning spare part. After 3D rendering, the file is converted to an STL file. The model is converted into 2D layers by STL’s slicing procedures. The thickness of these planes is typically between 20 micrometers and 60 micrometers, depending on the desired resolution and print speed. After conversion, the part model is installed in the optimal printing position. Printing orientation effects the support structures and can be utilized to minimize the need for additional support structures, preventing some possible distortion caused by the high thermal energy of the laser (Lefky et al., 2017). After these finishes, the model is ready to be transferred to a 3D printer.

Figure 2 shows a simplified L-PBF procedure by Vyas et al. The laser for the mainstream L-PBF method are generally fiber lasers which have replaced the CO2 laser, due to results with superior properties in printed parts, such as material density and accuracy. Layers are rapidly melted with powerful lasers in relation to high scanning speeds. For example, EOS’s M 290 featured in figure 1 can produce a maximal scanning speed of up to 7 meters per second. Scanning speed and other settings need to be optimized to achieve desired property ratios, while avoiding critical failure of parts due to thermal distortion and possible loss of mechanical properties (Aboutaleb et al. 2019). The key phases in figure 2 are proper deposition of building material on the center substrate with levelling roller, proper selective melting by the high-speed laser and solidification of molten material. While this system of high scanning speed with high energy deposition features overwhelming benefits in certain applications it also features a challenge to control and nullify the effects of the unavoidable nonuniform heat input. The result is residual stress within the printed structure due to rapid heating and cooling effects occurring simultaneously (Li et al. 2017).

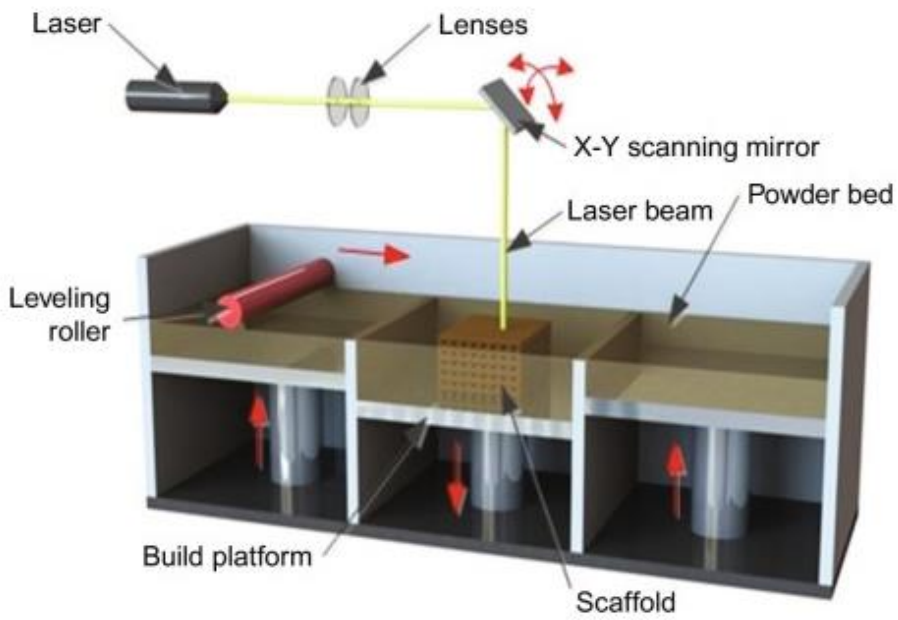

Figure 2. Internal process and components of L-PBF in theory (Vyas et al 2017).

Prior to the actual 3D printing process, the printing chamber of the device is filled with inert gas and heated to a suitable temperature to minimize the negative anomalies. Inert gases in question are generally composed of pure argon or nitrogen, which function as inhibitors between the molten material and possible foreign contaminations. Preheating the manufacturing chamber of the AM device and the building material reduces the presence of possible residual stresses in the AM output. The probability of residual stress in the printed part can also be reduced in a controlled manner with the help of trained design. After preparation, the machine applies a very thin layer of metal powder to the building platform. Layer thicknesses were previously defined in the STL model of the part when the model was converted from the original 3D model. The printing process begins with the device's fiber single laser or multiple lasers selectively fusing the material into a uniform manner according to the directive of given STL files.

2.2 L-PBF limitations

In L-PBF printed parts, one of the most significant factors is the surface quality of the print. The surface quality of the part is heavily influenced by the post-treatment methods used and their successful application. In order to achieve good surface quality in AM parts, there is a need to apply surface treatment methods that vary depending on the material and the designated purpose for the printed part. In some cases, the surface quality and properties of L-PBF prints can become problematic. For these cases surface treatment, coating, and machining have evolved into part of the AM process if the part is to achieve the desired dimensional standard accuracy. There may not be a need to apply after-treatment to parts where the improvement in surface quality does not affect the functionality of the part or in cases where the appearance is not significant when the part disappears inside the assembly. Yet the desired surface qualities require a workshop with the equipment on each production sight to fulfill these demands (Lefky et al. 2016)

In AM, support structures and the printing base are impractical needs in part construction because the number of support structures directly increases the complexity of the finishing process. These structures play an important role in prints because they act as fasteners for the piece. At the same time, supports reduce thermal distortion by conducting heat away from parts, as well as supporting larger extending components. Support structures play important roles during printing but can become problematic at the end of the process (Lefky et al. 2016). The substrate is critical to the fact that in L-PBF the print is practically welded to the substrate. Removal from the base in most cases requires some forms of cutting or breaking. Sufficient space must be reserved for the tool for a high-quality cut for the cutting process. This is accomplished by adding material between the substrate and the work piece. The shear surface quality becomes weaker, due to diminished properties of the shear surface.

The problem can be addressed by installing the model to be manufactured in a position where the cutting surface and the need for support structures are minimal. Figure 3 features an uncommon solution in which the substrate can be left as a permanent part of the final product. In this case the platform can be mounted onto its designated position as utilized as a fastener in its final application (Kokkonen et al 2016).

Figure 3. L-PBF print with integrated support structure and platform (Kokkonen et al. 2016).

The magnitude of the distortions was found to be directly related to the size and shapes of the pieces. As the size of the workpiece is increased, a similar phenomenon of distortion is observed. In this aspect, an increase in the parameters and size of the bodies results in a relatively increasing number of thermal distortions. Due to the increase in print size, proportionally deeper machining margins are required for larger pieces to correct for larger distortions (Kokkonen et al. 2016, p. 81). Figure 4 features the general process for correcting disfigured prints. Produced parts require enough allowance to be post-processed to perform the designated task. Amount of correction, excess material and the machining process are directly linked to the generated amount of thermal distortion produced by designs non-optimized for AM applications (Kokkonen et al 2016, p.80-84). This could be prevented with effective redesigning, supported with the utilization of simulation software.

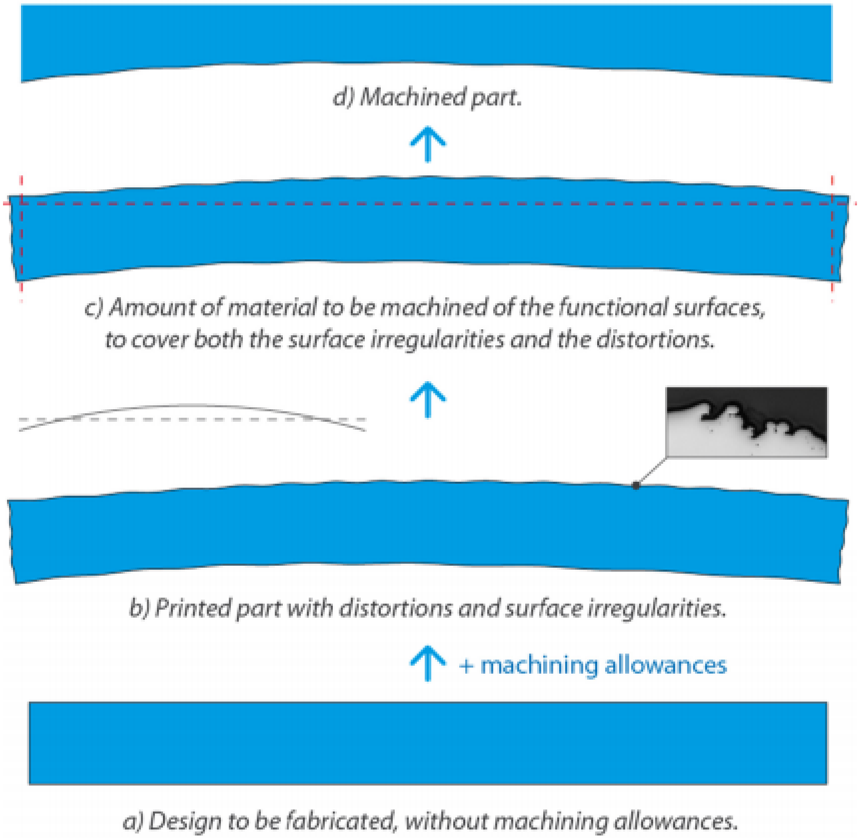

Figure 4. Examples of typical distortion and consequences of applying corrective machining for the L-PBF produced part (Kokkonen et al. 2016, p. 84).

A study commissioned by VTT studied guide values for a metal test piece model H-13, which were manufactured with L-PBF. The resulting values formed the minimum limits of the machining allowance in this study, which can be seen in Figures 5 and 6. The images show the effect of shapes and surface orientation on surface quality (Kokkonen et al. 2016, p. 80). Based on these guide values (see figure x), it is possible to compensate for distortions caused by thermal energy, possible inaccuracies in the device and taking into account other possible factors. Sufficient depth was obtained for the surface treatment, as shown in the figures 5 and 6. At the depth of 0.5 mm and deeper, the study points to densely fused material which after machining would leading to an acceptable surface quality (Kokkonen et al. 2016, p. 81).

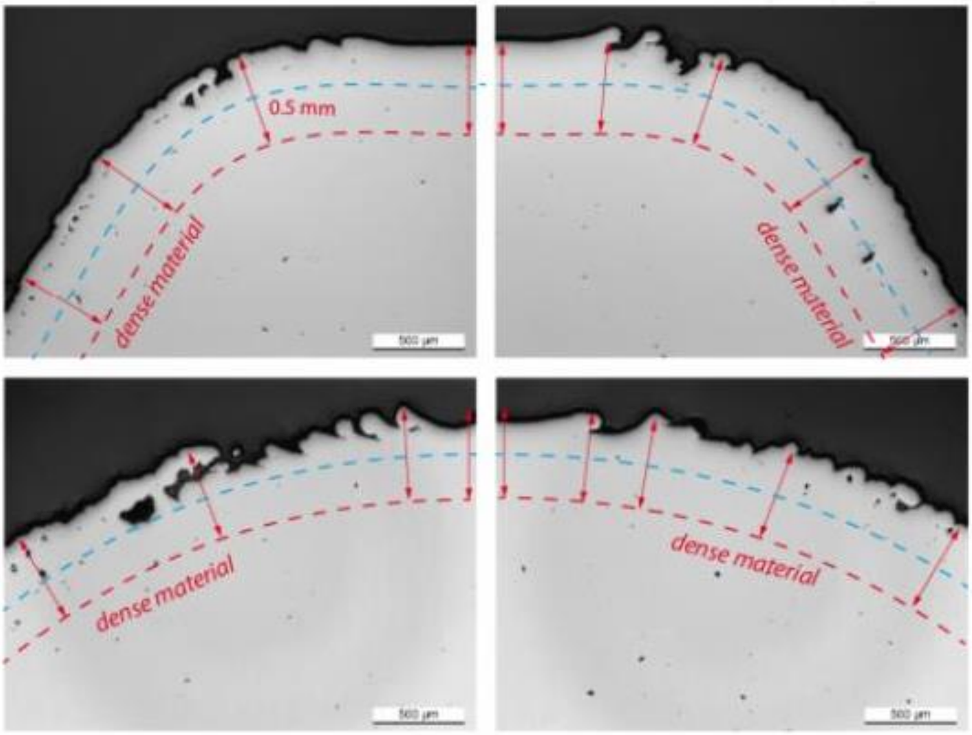

Figure 5. Location and surface of rounding's (Fillet) on a microscopic level (Kokkonen et al. 2016, p. 81).

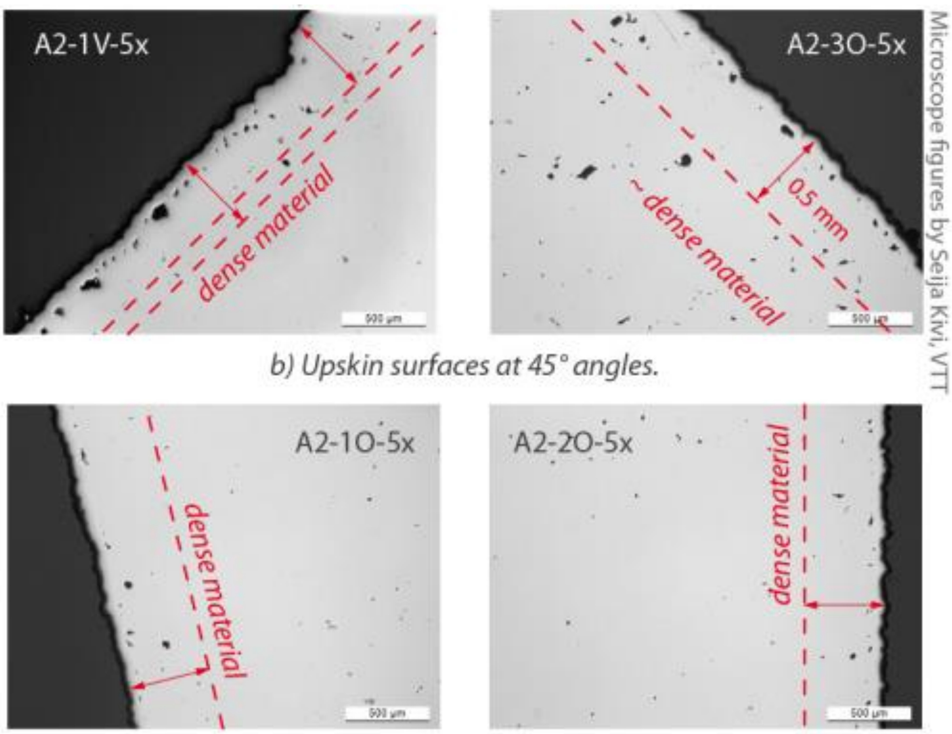

Figure 6. Microscopic images of vertical sections and nearly vertical specimens highlighting the surface-dense border (Kokkonen et al. 2016, p. 82).

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2.3 Spare part orientation of L-PBF industry

Figure 7 is a processing model established by Montero and Weber et al featuring the 5 general phases of L-PBF as an industrial application in 2 different sites. While the deployed facility is responsible for providing essential information related to the designated spare part, it is the central (local) facility in which a concentrated design team redesigns, optimizes, simulate and test set part. Montero and Weber discovered that pure 3D CAD models delivered to the deployment AM facilities for printing failed to provide designated parts due to differences in operational settings between facilities in reoccurring scenarios. Montero and Weber suggest that complete build files are to be delivered to inhibit problems due to AM experts only seeing deployment in the local facility. The effectiveness of AM application relies mostly on the design teams and operator to produce viable designs sufficient to pass testing phases. This arguably requires in challenging cases a majority of the time for supplying worksites with valid replacements (Montero & Weber et al. 2020).

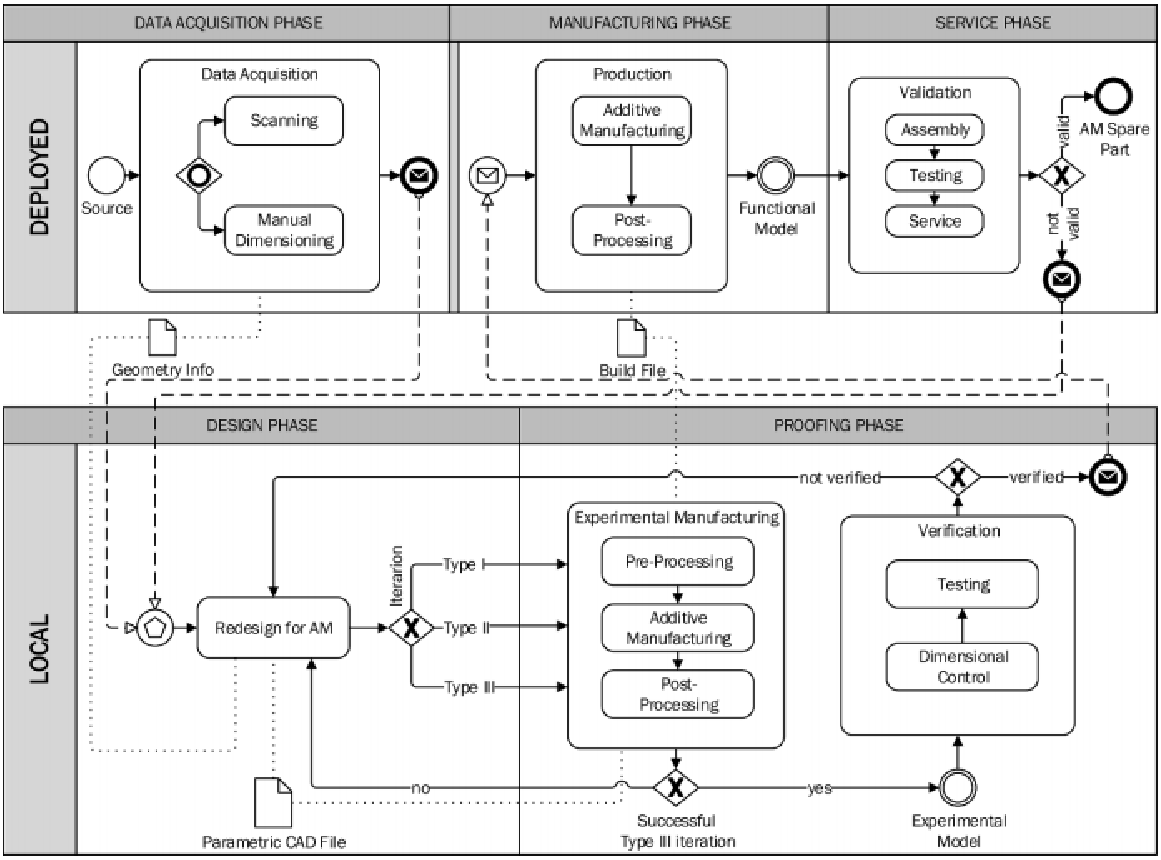


Figure 7. Segregation of the "local" design HQ and the deployed AM manufacturing on a key production site (Montero & Weber et al. 2020).

It is a general policy for any company that spare parts with high rates of requirement are to be stored in close proximity to compensate for more regular and irregular breakdowns. The same can be said about custom made parts that aren't available in production site regions, due to the likely complexity and general scarcity of specific spares. Spare parts have to be requested from the producer which is financially unfeasible for organizations situated in isolated locations, while Deployed AM machinery can provide requested replacements on site in relatively short time (Montero & Weber et al. 2020).

Typically, the deployment of AM is chosen because of its operational advantages, such as weight reduction and significantly shorter delivery time. However, the consequences of maintaining machinery and equipment are not so well understood, as the assembly of components causes replacement of larger parts in the event of a breakdown or makes them considerably more difficult to repair. Spare parts management benefits from shorter delivery times for AM parts and building material but may suffer from having to store more expensive as well as substantial parts on site. This situation would be due to machine parts, which are much more likely to be needed in the most stressed components of machines and require more frequent maintenance and replacement (Knofius et al. 2019).

L-PBFs application provides results to a multitude of challenges as can be seen in table 1. While decentralized production of small batch spare parts in unprecedented short delivery times is featured as its main attraction, it must be noticed that not only does AM enable a relatively cost-effective supply of expensive parts, but it also enables a universally feasible procedure to recreate obsolete parts that are no longer available as can be seen in figure 8 (Siemens 2019; Montero & Weber et al. 2020).

Siemens produced a spart part in figure 8 the gearbox of a century old Ruston Hornsby car within 5 days utilizing reverse engineering and L-PBF technology. This feat shows that L-PBF has evolved clearly enough for utilization in a broader spectrum of industrial applications. While the replacement had been printed successfully using L-PBF the design was not optimized for AM.

Figure 8. A reproduction of an original Roston Hornsby A1 model 1920 car gear box by Siemens. In comparison the original worn out part shown on the left had been machined from a solid metal block.

An extensive list covering all major advantages is featured by Attaran in table 1 concerning the application of AM's and thus L-PBF manufacturing over CM. Many advantages are directly intertwined with each other and reflect a strong drive towards spare part manufacturing with the application AM (Attaran 2017).

Table 1. L-PBF's advantages over conventional manufacturing (Attaran 2017).

Areas of Application	Advantages
Rapid Prototyping	Reduce time to market by accelerating prototyping Reduce the cost involved in product development Making companies more efficient and competitive at innovation

Production of Spare Parts	Reduce repair times Reduce labor cost Avoid costly warehousing
Small Volume Manufacturing	Small batches can be produced cost-efficiently Eliminate the investment in tooling
Customized Unique Items	Enable mass customization at low cost Quick production of exact and customized replacement parts on site Eliminate penalty for redesign
Very Complex Work Pieces	Produce very complex work pieces at low cost
Machine Tool Manufacturing	Reduce labor cost Avoid costly warehousing Enables mass customization at low cost
Rapid Manufacturing	Directly manufacturing finished components Relatively inexpensive production of small numbers of parts
Component Manufacturing	Enable mass customization at low cost Improve quality Shorten supply chain Reduce the cost involved in development Help eliminate excess parts
On Site and On-Demand Manufacturing of Customized Replacement Parts	Eliminate storage and transportation costs Save money by preventing downtimes Reduces repair costs considerably Shorten supply chain The need for large inventory is reduced Allow product lifecycle leverage
Rapid Repair	Significant reduction in repair time Opportunity to modify repaired components to the latest design

According to all sources L-PBF is cost-efficient mainly for cases in which out of service time, unconventional design and AM production cost outweigh long supply lines for non-generic parts, while for businesses reduction of warehousing in combination with reduced material usage may already achieve superficial savings. Instead of replacing entire production lines it has been deemed essential to combine AM and CM, focusing on specific advantages provided by both approaches (Attaran 2017; Montaro & Weber et al. 2020; Meisel et al. 2015; Knofius et al. 2019).

3. DFAM OF L-PBF

All the important aspects of these simulation challenges are linked to their time consumption values and respective accuracies. With one of L-PBFs major advantage being the ability to provide replacements in relatively short time compared to CM, it is apparent to uphold and maximize the main benefits interlinked with AM applications in deployed production sites. Extensive long term time-consuming DfAM methods are unfeasible for AM and specially the L-PBF's adaption in the manufacturing industry for negating the economic gains which it is trying to accomplish. Gouge et al 2018 states that thermo-mechanical tests are being currently performed through costly physical prototyping manner in time dependent replacement situations rather than CAD simulations, which are seen as situationally unfeasible in high priority replacement cases due to their present time-consuming nature outweighing possible benefits achieved (Gouge et al. 2018; Bugatti & Semeraro 2018).

3.1 Heat behavior and residual stress

In Li et al (2017) research concerning the predictive model of thermal distortion and residual stress, a cantilever was the selected as a test subject. Figure 9 presents analyzed CAD data featuring different states and related temperature during metal printing process. Phase (b) and (c) are specially related with new molten layers reverting previous layer partially back into a liquid state as part of the fusion process. Heating and cooling cycles are conducted in a rapid manner. Li’s model in figure 9 calculated a heat exposure time of 0.4 milliseconds, while cooling time between layers was set to 10 seconds. These temperature change cycles linked with non-uniform heat input create notable residual stress ultimately resulting in figure e. cantilevers structural deformation.

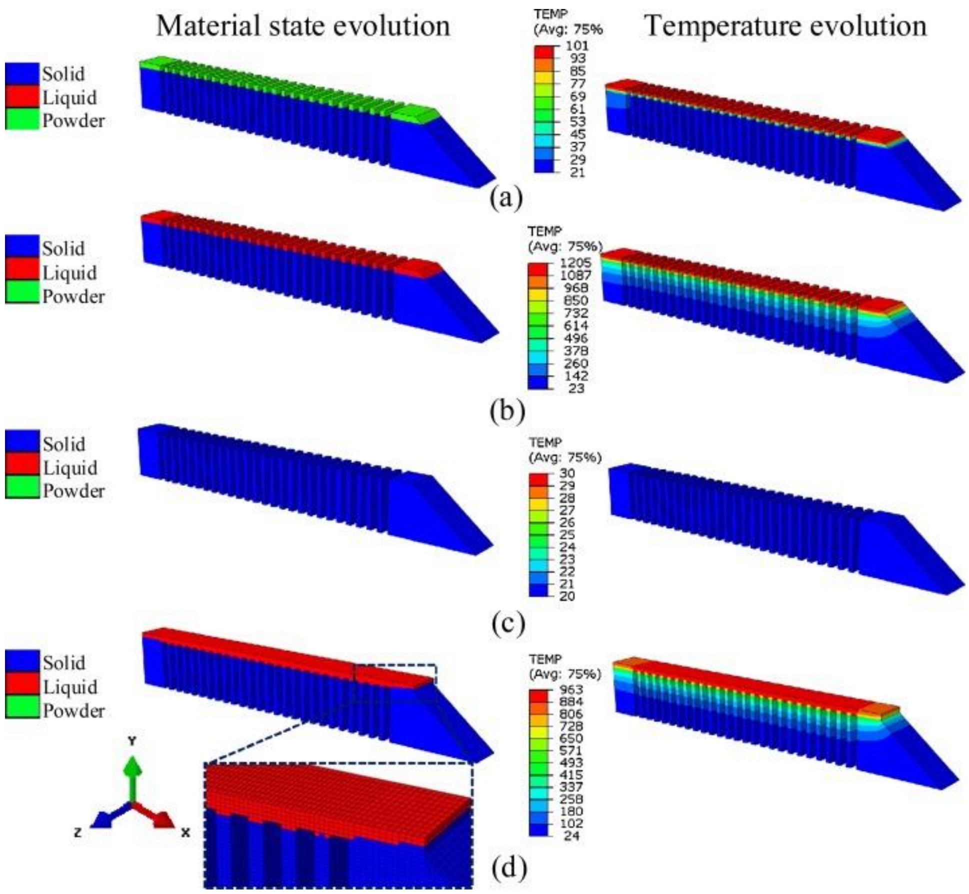


Figure 9. Table featuring material state in relation to layer temperature during a printing process: (a) deposited layer in a powder state, (b) powder layer has been liquified, (c) molten layer has reached solid state, (d) application of a new layer has reversed some of the previous layer into liquid state (Li et al. 2017)

Figure 10 cantilevers distortion (c), resulting from the disconnection of the substrate can be explained by the materials uncontrolled behavior. The phenomenon can be defined utilizing the temperature gradient mechanism. Building material expands naturally while being converted into the molten state under the influence of lasers heat energy. With the materials solidification process during cooling metal naturally contracts itself. The interaction and restriction between metal layers leads to thermal stress. Expanding and retracting material is constricted by surrounding solid material. Residual stress is relative to the parts geometry and size, while gradually dependable on the number of layers, since increases in volume naturally result in increasing thermal distortion (Kokkonen et al. 2016; Li et al. 2015; Wu et al. 2017; Yang et al. 2019).

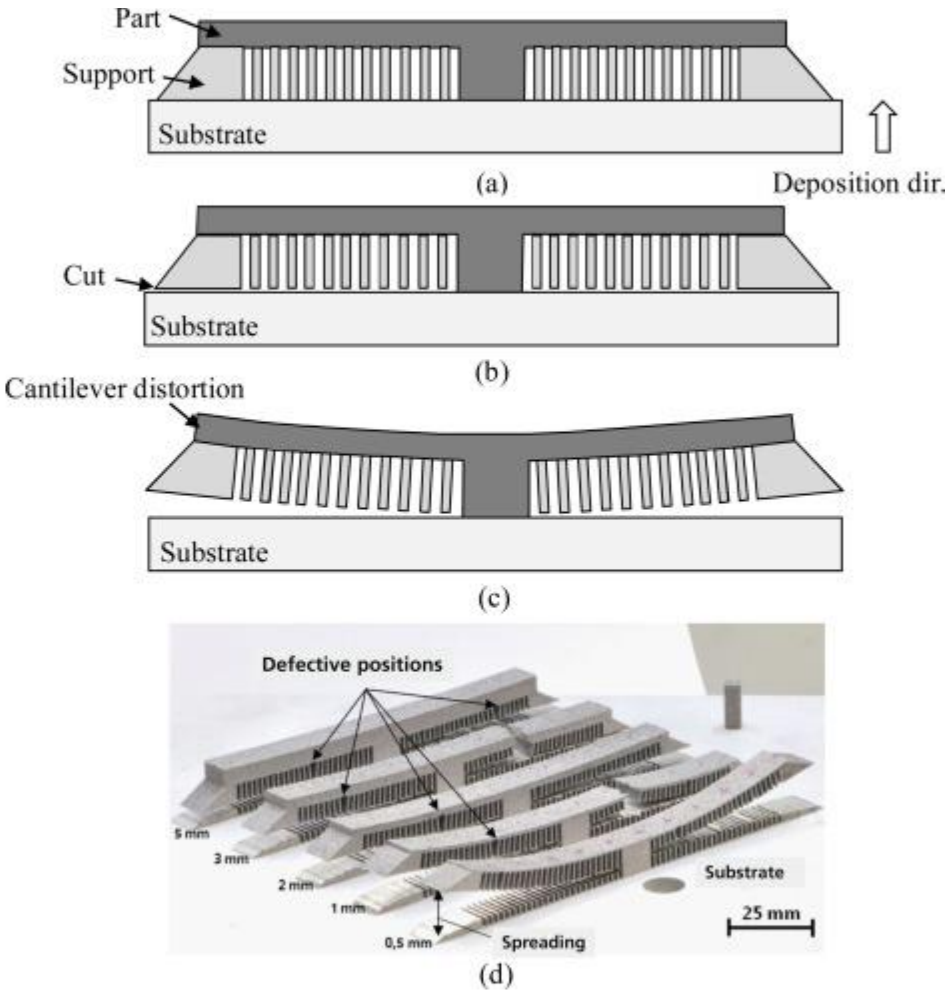


Figure 10. Schematic presenting a cantilever distortion after disconnection from the substrate and supports, highlighting structural distortion caused by residual stress (Li et al. 2017).

3.2 Optimization and redesigning of AM spares

Depending on the spare part that is to be reproduced, part design libraries may already feature existing CAD models that can be easily enhanced to adapt to L-PBF manufacturing processes in addition to resolving apparent problems with prior designs. Obsolete, outdated and restricted parts will in most cases feature no digital model at all, so recreation requires manual designing of 3D models or even reverse engineering in the form of 3D scanning to produce viable spare parts. In cases of worn-out parts, the reverse engineering method finds widespread usage in direct combination with PBF manufacturing processes underlining the impact on AM spare part production in the industry (López Milán 2020).

AM designs superiority is rooted in its ability to simplify part complexity, freedom of design and application possibilities. It is AM's freedom of design that is in no way restricted by conventional manufacturing techniques such as challenging processing efforts related to increasing production costs. The design process of metal L-PBF products are not limited by conventional machining processes, but instead by design choices influencing thermal behavior giving way to residual stress which must be repressed (Yang et al. 2017, p.63).

By combining the components of the assembly into single designs, it is possible to create new spare parts for faster production. This results in there being fewer components in the assembly and post processing procedures, but thus increasingly complex assembly designs. Although complex parts are in many cases difficult to manufacture with conventional manufacturing techniques (CM), the high design freedom of incremental manufacturing, frankly, recommends strongly the combination of parts (Knofius et al. 2019).

The designing of the 3D-model is an import phase and more significant if parts are needed in larger quantity and with possible variations. The design of the L-PBF part directly dictates the time required for the manufacturing, availability, time to production and for commercial cases time to reach the market. Figure 11 features an optimized U-bending tool which results in shorter manufacturing time and savings in building material while also achieving a substantial weight reduction of 45 % (Asnafi et al. 2019).

Any AM parts volume directly impacts the production parameters. The application of AM's high degree of freedom strongly encourages the application of design software featuring topology optimization abilities to directly combat the excessive use of unessential material, which is in many cases are linked to the former production limitations set by industrial CM capabilities. As shown in Figure 11 it removes unessential parts saving material, cutting production time and tremendously reducing costs. Topology optimized designs can easily be further enhanced to meet specific requirements set by the operator (Wohlers et al. 2019, p. 216).

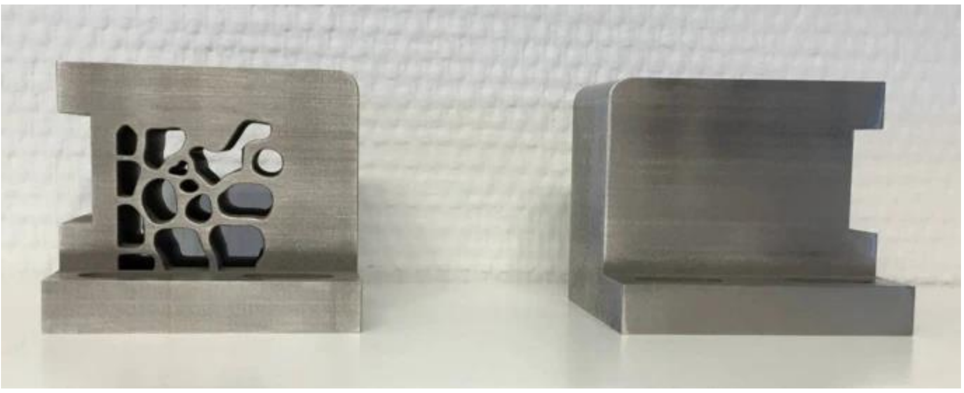


Figure 11. Two 3D-prints of the same U-bending tool. The right design has been optimized with topology featuring volume and weight reduction of 45 % (Asnafi et al. 2019).

The topological system in any design software featuring it relies on the finite element process to divide the designated design into elements that are graded by the system depending on their structural and property related factors called density values, becoming either essential or nonessential elements. The result can be guided to certain attributes by the operator, which will eventually influence the topological procedures outcome. This can be seen best in mass customized parts with differing structural properties. As Figure 12 shows a simplified principle of topological optimization it becomes clear that the software purely focuses on maximizing structural attributes which sets shapes of parts to lesser importance. Not only does topology enhance designs as seen in figure R part a, but it also features the ability to partially redesign structures to maximize set properties (Saadlaoui et al. 2017; Yang et al. 2017, Pp. 122–127).

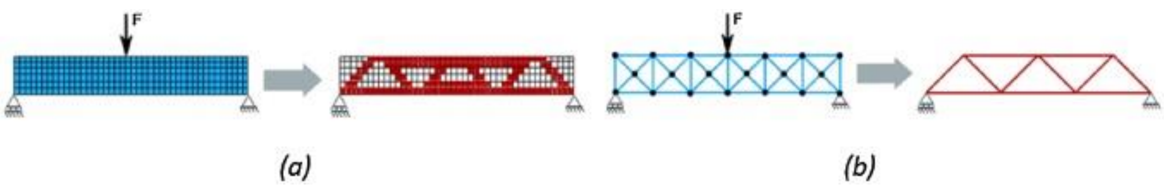


Figure 12. Simplified 2D view of topological optimization results (Saadlaoui et al. 2017).

With the development of L-PBF in the industry there has been a growing desire to produce functional parts and spares, while eliminating highly expensive testing phases and failures completely. Highly developed simulation software's would neutralize excess cost and extended production time caused due to physical testing. Simulation software's drive towards providing reasonably accurate results, that are rich in detail. These could then deliver estimates from detail related costs up to specific information essential for the operator. Currently validation processes are done with physical testing bearing a high cost, yet mandatory for the optimization of essential parts produced with L-PBF. Testing is performed in this physical prototyping manner, because the results produced have proven to be the most accurate in 2018 (Bugatti & Semeraro 2018).

Gouge et al 2018 stated that all simulation software must overcome the following listed major challenges for a successful modelling of any AM printing process to utilize AM’s accuracy in creating models to its maximum:

- Interaction of layers and added material layers
- Modeling of the heat input
- Accurate simulation of thermal loss for the duration of the process
- Elasto-plastic stress and strain projection
- Connectivity between thermo-mechanical behavior
- Accurate accounting of material specific property in relation to the temperature dependency from the beginning for the entirety of the process

Next to the listed primary concerns Gouge mentions further aspects that may require monitoring and addressing for the reason of validating AM process models:

- Changes in the parts microstructure
- Changes in the parts material property
- Anisotropy in thermo-mechanical material property
- Phase transformation effects

3.3 Thermo mechanical finite element method

The thermo-mechanical method is governed by an accurately accounted heat equilibrium and the entire process’s thermal history on which's behavior the mechanical aspect is predicted on. This is due to each building materials unique behavior under constantly changing temperatures and variating states of form. Temperature dependent material properties are studied under the thermo-mechanical method to predict and recognize patterns in their mechanical nature. A thorough thermal history is essential to produce accurate results concerning the estimation of mechanical properties for an additively manufactured object Yang et al. 2019). Temperature dependent properties that are of relevance to the thermo-mechanical method include:

- Thermal conductivity
- Coefficient of thermal expansion
- Poisson’s ratio
- Young’s modulus
- Specific heat capacitance

The thermo-mechanical finite element method functionality is based on the link between accounted thermal behavior effecting mechanical behavior during the AM process. While the thermal analysis allows a one-sided inspection of behavior of mechanical properties, one must understand that the weakly coupled model is a unidirectional phenomenon, meaning that the model only allows the inspection of mechanical properties through results achieved in analyzing thermal history. For time saving aspects the decoupled or weakly coupled model is commonly applied in AM, for its impact in decreasing the simulation software's computational period significantly in providing results. Gouge states that the weakly coupled analysis model while having its benefits is also fragile. In cases of distortion effecting boundary conditions the complete model becomes utterly useless. This is, because any changes resulting in the manufactured parts heavily altered geometry and properties inhibit the use of any information relating to the original simulation data (Gouge et al. 2018, p. 20).

The thermo-mechanic finite element method utilizes and provides thermal data specifically for each node in a mesh. Based on the commonly weakly coupled principle the quasi-static equilibrium is converted from a thermal equation into a mechanical model. The finite element mesh can be adjusted to simplify the finite element methods relation numeric implementation. Gouge et al 2017 presented a mesh pattern in figures 13 and 14 which have been adjusted for elements to accurately correspond to the added layers deposition thickness, while surface elements respond to lasers radial surface measures (Gouge et al. 2018, pp. 21, 25-27, 45-46).

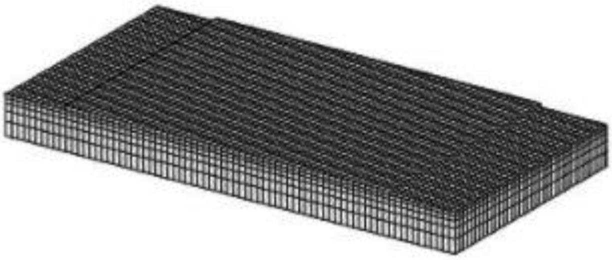


Figure 13. Mesh with adjusted elements according to layer and laser properties (Gouge et al .2018, p.46; originated from ASME The International Journal of AM Technology)

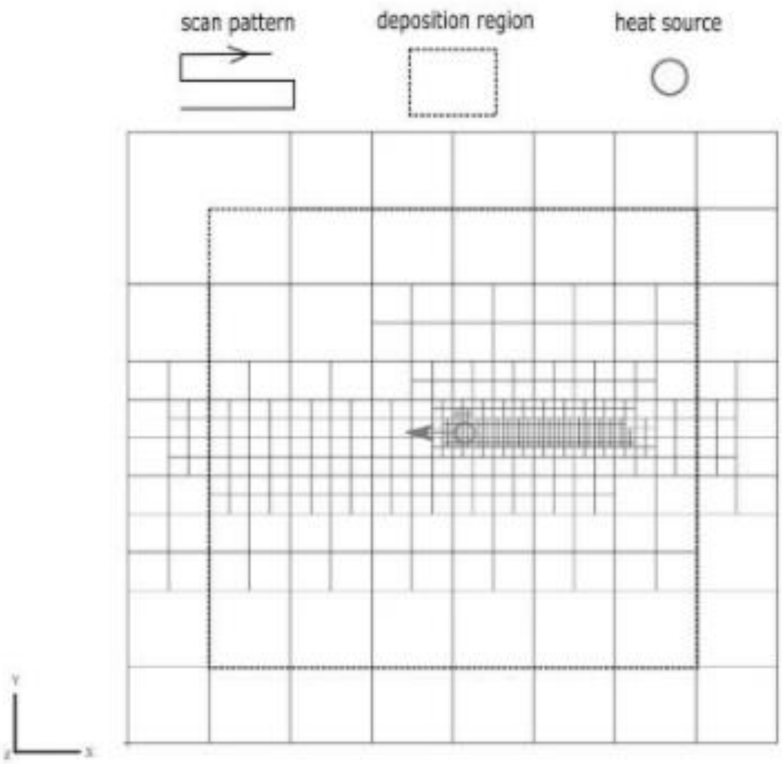


Figure 14. Mesh-pattern adjusted to the lasers surface width and length (Gouge et al. 2018).

3.4 Inherent strain method

The Inherent strain methods was originally developed by Ueda et al. 1975 for the application in simulating welding distortion and the related residual stress. Welding procedures and L-PBF are similar nature, while the unmodified inherent strain method can be used in observing residual stress in singular layers in both AM and Welding. The original inherent strain method based on single layer welding has been modified to be more suitable for AM purposes, because of the original weakness of not accounting for stress between multiple layer interactions. The modified Inherent strain method utilized has been adjusted for AM processes by Chen to take into account stress behavior between layers. The modified inherent strain method is referred to as the inherent strain method generally and in this study due to the original's inadequacy for AM process purposes. The Inherent strain method can be performed with values that have been received utilizing for example the thermo-mechanical finite element method or through physical measures from test objects. It doesn’t take into account thermal history and temperature and relies on purely mechanical aspects for its analysis of residual stress, reducing computational time due to data input reduction and its finite element structure. The inherent strain method functions based on the finite element method. Figure 15 presents the general framework conducted by Chen in which the inherent strain is received from singular elements and assigned to the structure that is to be analyzed (Ueda et al 1975; Chen et al. 2019).

The following data in this chapter refers to Chens et al 2019 research of the Inherent strain method revolving around the methods appearent challenges it features when analyzing different structures and models. Accuracy of residual stress values are compared with other methods. Models used in this study were printed by utilizing laser-based powder bed fusion (L-PBF). The system used was EOS M290 which is equipped with a 400 Watt Yb-fiber laser. The metal powder used for the experimental prints of both models was Inconel 718. The idea behind these two structurally quite different models as seen in figure 16 was to study each one’s experimental distortion values. These were received from multiple prints and directly compare to the simulation results. The parts had been produced prior to the tests to validate the simulation results accuracy gained through utilizing the applied inherent strain method.

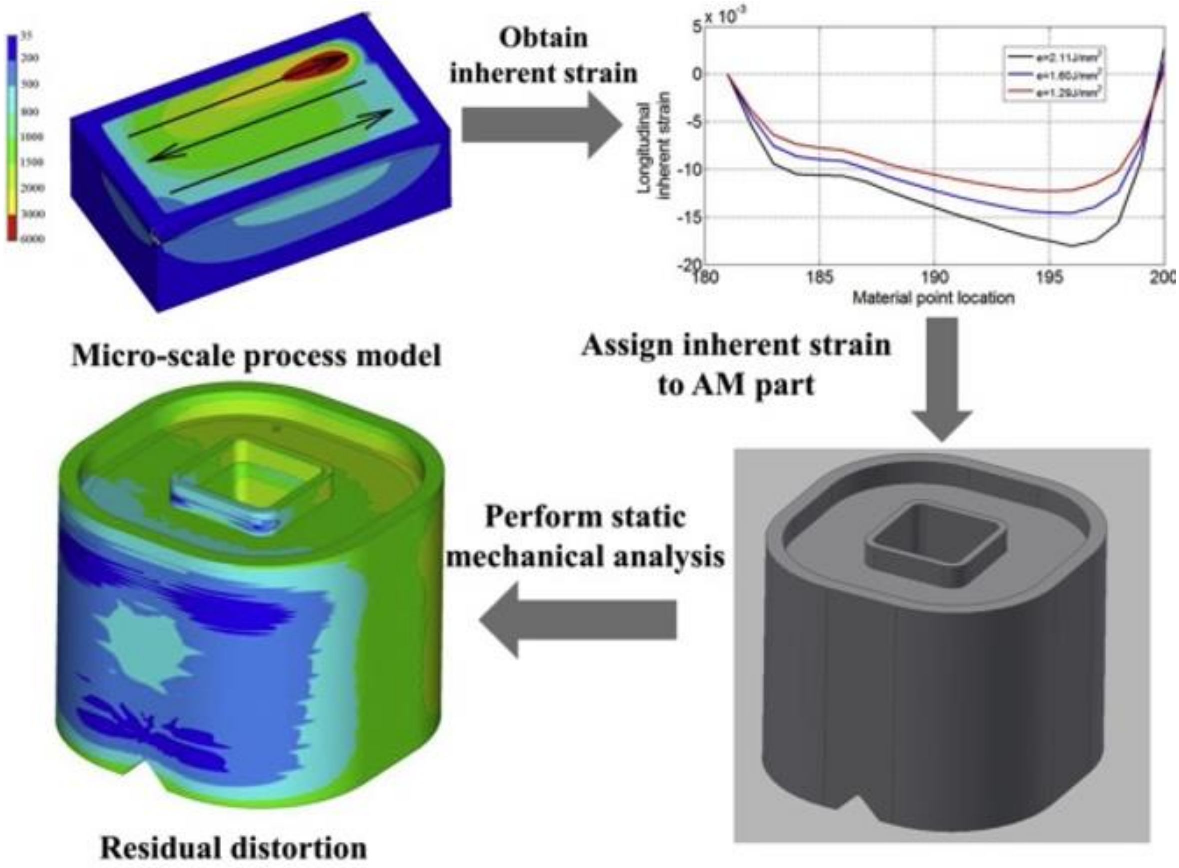


Figure 15. Inherent strain methods process framework (Chen et al. 2019).

Chen et al. (2019) studies two different digital models for laser powder bed fusion (L-PBF). This study is a direct continuation to a test series running the modified inherent strain version performed by the same author, for the purpose of evaluating distortion of new AM models. The digital models in figure 16. feature more delicate forms, complex internal structures and in the case of figure 16 b) integrated support structures. The first digital model in figure 16 a) was a square canonical part housing a complex internal structure and the second part in figure 16 b) a double cantilever beam (Chen et al. 2019).

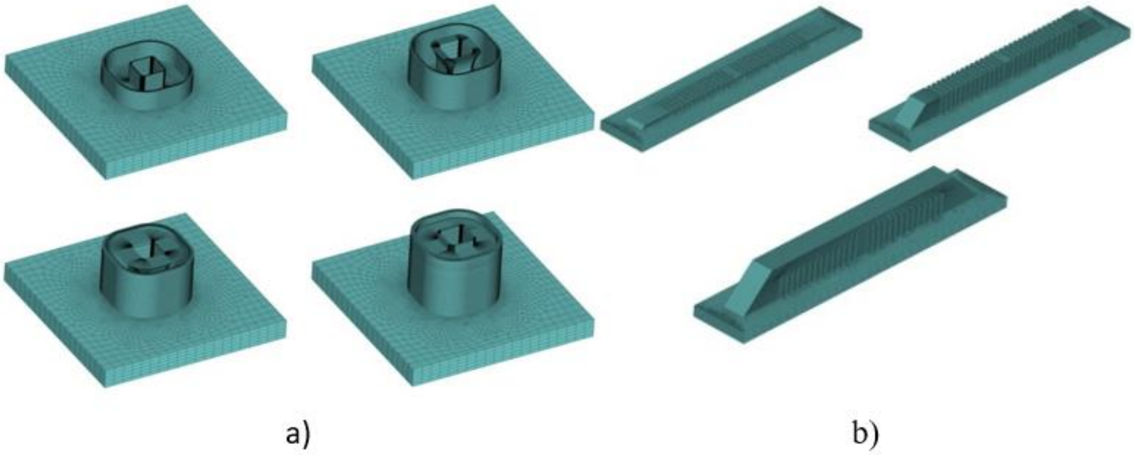
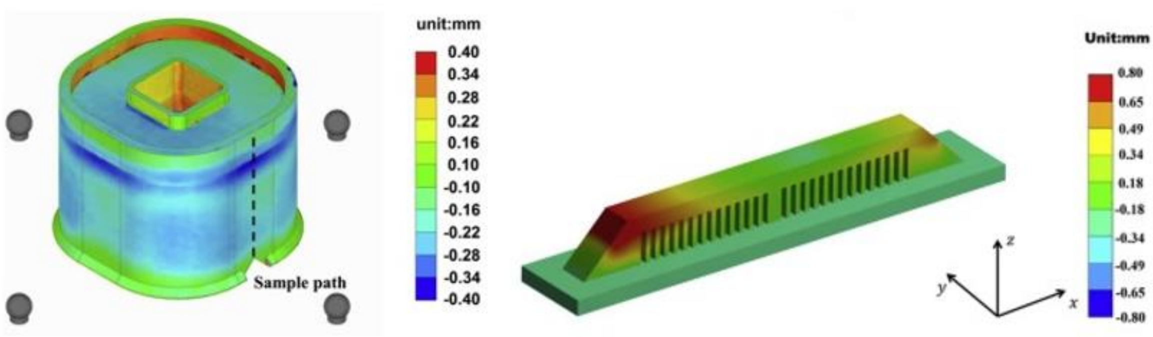


Figure 16. Models with their interior structural design a) a square canonical part with inner walls b) a double cantilever beam with integrated supports (Chen et al. 2019).

As it can be seen from figure 16, to begin with the simulation produces an accurate recreation of the printing process by systematically applying 2D layers from the models above. These layers form the basis for further analysis focusing on their respective effect of heat with each other. Figure 16 specifically has two models with very different forms to further study marginal accuracy of the modified inherent strain method in contrast to structural designs.

Digital model used in study of Chen et al. (2019) was chosen for this study, because this modified version of the inherent strain method had not been performed on more complex structures and thus far the methods reliance had not been validated on more complex parts. The modified variant of the inherent strain method is used for AM solely for one reason. The original inherent strain method is incapable to comprehend the effects of multiple layers building system applied by AM process simulations. This inability is due to the fact, that the unmodified inherent strain is designed to purely feature behavior within each isolated layer ignoring the impact of stress transmitted from other layers.

The process Chen et al. (2019) performed was collecting data of inherent strains from a simulation running a modified version and feeding the information gained into the FEA (finite element analysis). Software of Ansys and Simufact Additive 3.1 were used for the analyzation of the test models. According to Chen et al. (2019) combining the inherent strain data from the modified version with finite element analysis led to simulation times of roughly similar scale for Ansys and Simufact Additive 3.1, taking up to 30 minutes for the double cantilever part and roughly up to 3 hours for the more complex and sizeable square canonical structure. Using these simulation technique, feasible results can be achieved as seen in figure 17 in a relatively short time saving days or even weeks of time needed by other methods (Chen et al. 2019).



(a) (b)

Figure 17. Residual stress simulation results for a) the square canonical with inner walls and b) double cantilever beam with integrated supports structures (modified from Chen et al. 2019).

For example, one reference is made to the double ellipsoid heat source model of Goldak as featured in figure 18, which would have consumed an estimated 3 month in order to calibrate the thermal element model, due to the computational amount, if it had been applied on conventional and commercial software.

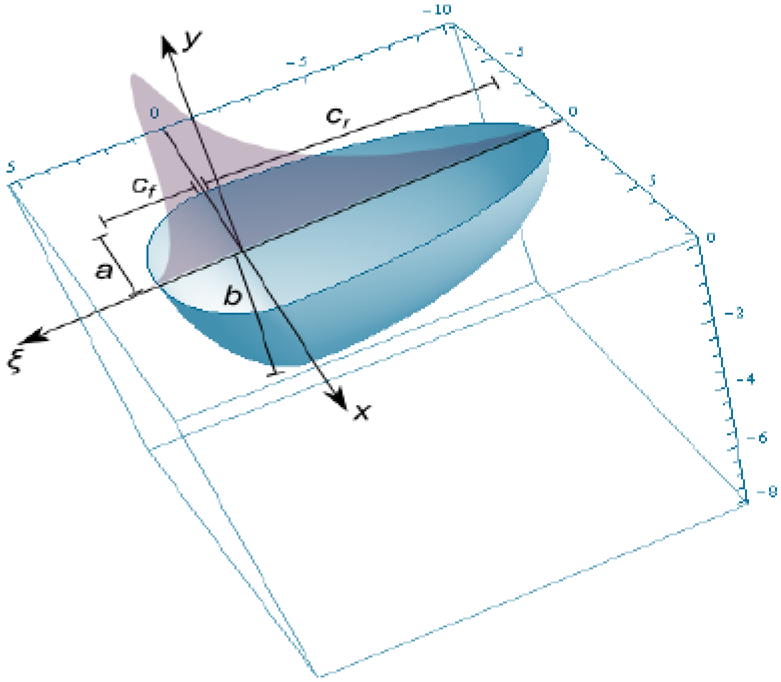


Figure 18. Goldak's Double ellipsoidal volumetric heat source model (Flint et al. 2013).

Chen et al. (2019) concluded in their study that simulation done with commercial software decreases the simulation time from days or even weeks to only a couple of hours. Accuracy of predictions in material behavior and areas of distortion also showed improvements, due to inherent strain methods simplified simulation structure. This gained accuracy depends more on technique and method used to analyze the targeted structural entity and not so much on the difference of calculations and simulation software's used to process the given information.

Chen et al. (2019) concluded in their study that when comparing simulation of digital models to additively manufactured parts, accuracy of simulation results correlated well with experimental result. Identical behavior in pattern, while base values require further adjustment figure 19 illustrates results of these simulations (Chen et al. 2019).

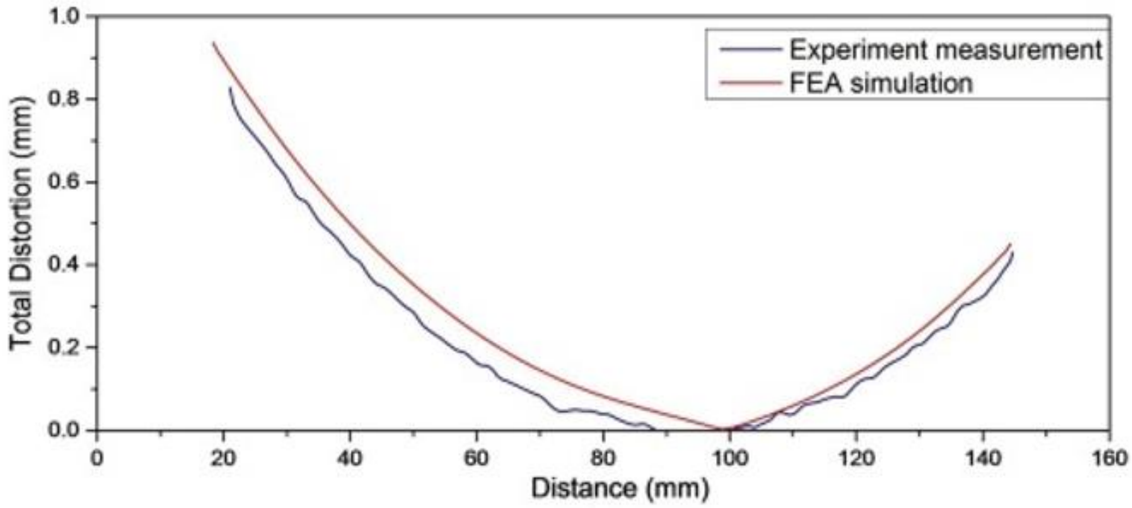


Figure 19. Test result comparison between the Finite element analysis and physical experimental measures (Chen et al.2019).

As it can be noticed from figure 19 simulations executed for the double cantilever beam structure from figure 16 b) showed a near identical behavior in comparison to the experimental measurements. Overpredicting the distortion and small differences are based on certain information possibly not taken into the account by the calculation method. Figure 20 shows simulation result of second model used in study of Chen et al. (2019). It can be noticed that in case of results produced for the square canonical seen in figure z, the distortion profile shows a similar behavior between performed measurements with the silver lining, that larger differences in measures are found. It can clearly confirm that the simulations are able to predict distortion peaks and their location with a high accuracy featuring the decisive distortion peaks.

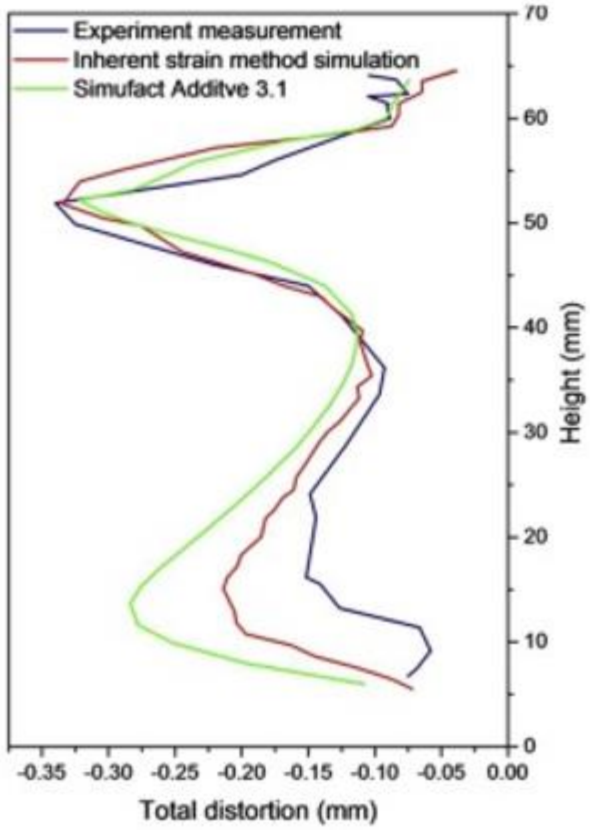


Figure 20. Comparison of distortion profiles for the square canonical part with inner walls (modified from Chen et al. 2019)

4. ANALYSIS

With more than 60% of spare parts being modified and redesigned during the production process, L-PBF's potential in the spare part industry has become immense. Existing models of spare parts can just be accessed and redesigned to suit L-PBF or frankly models can just be produced by utilizing reverse engineering, which finds increasing application in combination with L-PBF highlighted by examples like Siemens figure 8. L-PBF's potential to recreate obsolete and rare spares, which have the tendency to feature extremely high costs forcing customers usually to move onto modern tools and machinery on the basis of current spare part and service availability. L-PBF does not only excel by producing small batches of spare part cost-effectively but optimizing models to a modern level, flaw removal of original designs in combination with applying AM advantages from a multitude of categories presented table 1 by Attaran. L-PBF utilization for example in industries working with casting and stamping of metals yields high potential alone from the simplification of the manufacturing process.

Montero's and Weber's 2020 study makes it quite clear that the strength of L-PBF in the spare parts industry is heavily intertwined with decentralized production methods. The elimination of heavy warehousing at every production site combined with design headquarters for the purpose of concentrating personnel with AM modelling expertise into one location was suggested. This serves the purpose of dividing design and manufacturing into specialized sections. The decentralized production strategy is based on maximal reduction of production time, while eliminating time lost waiting for replacement transportation. With the rapid developing state of AM and L-PBF it is suggested not hiring AM experts, but instead focusing on personnel with design skills, able to operate simulation software.

Spare parts current and future success is reliant on the manufacturing accuracy in relation to short production time. While the L-PBF process allows the production of a multitude of customized parts simultaneously, reducing cost and time consumption of rapid prototype development in comparison to CM. Due to L-PBF spare parts expensive nature combined with the aspect of physical testing, requirement for more reliable and capable DfAM methods and simulation software have been increasing. As stated by Montero and Weber the loss by downtime cannot be accurately measured and so financial loss is related to a multitude of factors. This makes AM spare parts highly desirable especially as replacement parts with high priority profiting massively from reduced production time.

L-PBF is able to create complex structures by redesigning the spare parts, that cannot be produced with CM to this day. L-PBF's capability to produce uniquely complex geometry has been one of its definitive advantages. Additional advantages over CM, like casting in the metal and the spare part industry, its growing commercial attraction has been widely contributed to L-PBF's ability to apply significant weight reduction, building time reduction and modification opportunities for already existing spare part models. L-PBF's recent successes remain limited due to challenges restricting its proper utilization in the industry.

In comparison to CM, AM’s overwhelming freedom of design relies on DfAM and simulation software to optimize and validate L-PBF spare parts. Validation and monitoring of mechanical properties are often mandatory for ensuring spare parts with proper dynamic functions, while spares with static functions do not necessarily feature high requirements for surface and mechanical properties.

While L-PBF is the most evolved and promising manufacturing method of all AM processes, it is still being classified as juvenile. Thermal distortion interlinked with residual stresses limit the size and geometry of any spare part that can be produced with L-PBF, while effecting each parts mechanical properties in unreliable ways (Asnafi et al.2019; Wu et al. 2017; Yang et al. 2019, pp.294-296). Thermal distortion and residual stress are directly connected to the geometry and height of printed parts, with anomalies growing in relation to the number of added layers.

The inherent strain method and thermo-mechanical finite element method featured in this thesis represent the most evolved and examined means to simulate stress behavior in L-PBF printing processes to this date. Both simulation methods currently account for relatively high accuracy and focus on computational time reduction. These two methods are to some extent in addition to topological optimization and are featured in most analysis software's which highlights the current level of simulation capabilities of commercially available systems.

AM’s implementation is not as straight forwards at producing notable gains as it is commonly advertised with the manufacturing and design processes requiring a lot of optimizations to utilize AM and in specific L-PBF to its fullest potential. Unoptimized processes can feature extensive time consumption and failure rates of printed objects, neutralizing the benefits it is meant to provide especially for the rapid spare part production. Failures in the print require a redo of the entire design and testing process. This can make the entire implementation of AM in the manufacturing process unfeasible and that is why AM’s research and development is currently focused on achieving usable parts on the first try. While DfAM is utilized for the very reason of inhibiting undesirable occurrences in L-PBF and playing the core role in the successful AM application. DfAM processes are shown to be essential for the success and cost-effectiveness of producing optimized 3D-models, which ensure preemptive detection of thermal distortion and to a large extent the materials mechanic properties as featured in the thermo-mechanical finite element method and the inherent strain method.

5. CONCLUSION

With prediction methods and sophisticated simulation programs having reached a reliable level in their accuracy concerning the general analysis of stress behavior, L-PBF has reach a general acceptance on the industrial level. More than 60% of spare parts in the tooling industry are being subjected to modifications and redesign during the production process (Attaran 2017). This highlights the need and potential for simulation methods to produce optimized and cost-effective models with validated information on thermal behavior and possible predictive mechanical properties.

L-PBF has immense potential for the spare part industry, due to its ability to cost-effectively recreate spare parts for machinery that is no longer available. Even more potential is the yield from possible customers that would in many cases of CM have no feasible access to spare parts and can now be supplied through a decentralized production system as suggested by Montero and Weber 2020.

Widespread implementation of L-PBF for spare parts will require a more sophisticated simulation method to produce parts directly without failure. While promising simulation methods of thermal and mechanical behavior already exist and have already been commonly utilized, it is still suggested that the simulation methods should be developed to account for future challenges and a lack of personnel familiar with this technology. Challenges include the weakness of L-PBF and simulation methods to compensate the growing inaccuracy caused by thermal distortion in printed parts with increasing size.

This weakness sets a straight limit to the production of spare parts above a certain volume and geometry. Larger L-PBF printers are in theory unfeasible for the same reason. While 3D-printers can produce more units of smaller parts, larger parts are commercially unfeasible. Simulation methods and printed parts are directly more accurate in relation to their respected size. This represents a direct obstacle to the entire technology while inhibiting the production of large-scale spare parts with L-PBF.

LIST OF REFERENCES

Aboutaleb, A., Mahtabi, M., Tschopp, M. & Bian, L. 2019. Multi-objective accelerated process optimization of mechanical properties in laser-based additive manufacturing: Case study on Selective Laser Melting (SLM) Ti-6Al-4V. Journal of Manufacturing Processes, Volume 38. Pp. 432-444.

Asnafi, N., Shams, T. & Aspenberg, D. 2019. 3D Metal Printing from an Industrial Perspective. Product Design, Production and Business Models. BHM Berg Hüttenmännische Monatshefte, Volume 164. Pp. 91–100.

Attaran, M. 2017. The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. Business Horizons, Volume 60. Pp. 677-688.

Bugatti, M. & Semeraro, Q. 2018. Limitations of the inherent strain method in simulating powder bed fusion processes. Additive Manufacturing, Volume 23. Pp. 329-346.

Chen, Q., Liang, X., Hayduke, D., Liu, J., Cheng, L., Oskin, J., Whitmore, R. & To, A. 2019. An inherent strain based multiscale modeling framework for simulating part-scale residual deformation for direct metal laser sintering, Additive Manufacturing, Volume 28. Pp. 406-418.

Dunbar, A., Denlinger, E., Gouge, M., Simpson, T., Michaleris P. 2017. Comparisons of laser powder bed fusion additive manufacturing builds through experimental in situ distortion and temperature measurements. Additive Manufacturing, Volume 15. Pp. 57–65.

EOS 2020. M 290. Available: https://www.3dnatives.com/en/3D-compare/imprimante/eos-m-290#!

Flint, T., Francis, J. & Yates, R. 2013. Analytical solutions of the transient thermal field induced in finite bodies with insulating and convective boundary conditions subjected to a welding heat source. SMiRT-22.

Gibson, I., Rosen, D. & Stucker, B. 2015. Additive Manufacturing Technologies. 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. 2. Edition. Pp. 4,5,51.

Gouge, M., Michaleris, p: Denlinger, E. & Irwin, J. 2018. The Finite Element method for the Thermo-mechanical Modeling of Additive Manufacuring Processes. Thermo-mechanical Modeling of Additive Manufacuring Processes, Chapter 2. Pp. 19-46.

Kokkonen, P., Salonen, L., Virta, J., Hemming, B., Laukkanen, P., Savolainen, M., Komi, E., Junttila, J., Ruusuvuori, K., Varjus, S., Vaajoki, A., Kivi, S. & Welling, J. 2016. Design guide for additive manufacturing of metal components by SLM process. Research Report VTT. Pp. 80-84.

Knofius, N., van der Heijden, M. & Zijm, W. 2019. Consolidating spare parts for asset maintenance with additive manufacturing. International Journal of Production Economics, Volume 208. Pp. 269-280.

Lefky, C., Hildreth, O., Nassar, A. & Simpson, T. 2016. Dissolvable Metal Supports for Printed Metal Parts. Solid Freeform Fabrication, 27th International Symposium. Pp. 1604-1610.

Li, C., Liu, J., Fang, X. & Guo, Y., 2017. Efficient predictive model of part distortion and residual stress in selective laser melting. Additive Manufacturing, Volume 17. Pp 157-168.

Meisel, N., & Williams, C. 2015. An Investigation of Key Design for Additive Manufacturing Constraints in Multimaterial Three-Dimensional Printing. Journal of Mechanical Design, Volume 137.

Montero, J., Weber, S., Bleckmann, M., & Paetzold, K. 2020. A methodology for the decentralized design and production of additive manufactured spare parts. Production & Manufacturing Research, Volume 8. Pp. 313-334.

Nyamekye, P., Unt, A., Salminen, A. & Piili, H. 2020. Integration of Simulation Driven DfAM and LCC Analysis for Decision Making in L-PBF. Metals 2020. Number 9.

Saadloui, Y., Milan, J-L., Rossi, J-M. & Chabrand, P. 2017. Topology optimization and additive manufacturing: Comparison of conception methods using industrial codes. Journal of Manufacturing Systems, Vol: 43. Pp. 178-186.

López Milán, J. (2020). Reverse engineering methodology development for part reconstruction with laser powder-bed fusion additive manufacturing technology. Universitat Politècnica de València.

Ueda, Y., Fukuda, K., Nakacho, K. & Endo, S. 1975. A new measuring method of residual stresses with the aid of finite element method and reliability of estimated values. Pp. 499-507

Wohlers, T., Campbell, I., Diegel, O. & Kowen, J. 2018. Wohlers Report 2018: 3D Printing and Additive Manufacturing State of the Industry Annual Worldwide Progress Report. Pp. 41, 42.

Wohlers, T., Bourell, D., Campbell, I., Diegel, O., Hugg, R., Ismail, F. & Kowen, J. 2019. Wohlers Report 2019. 3D printing and additive manufacturing state of the industry. Pp. 173, 216.

Wu, J., Wang, L. & An, X. 2017. Numerical analysis of residual stress evolution of AlSi10Mg manufactured by selective laser melting. Optik, Volume 137. Pp. 65-78.

Yang, Y., Allen, M., London, T. & Oancea, V. 2019. Residual Strain Predictions for a Powder Bed Fusion Inconel 625 Single cantilever Part. Integr Mater Manuf Innov 8. Pp. 294-304.