Thesis for the Degree of Doctor of Philosophy

Geometry Assurance of Laser Processed Metal Components

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Cover: Image of the frame of reference highlighting the areas of relevance in this thesis. Chapter 2 provides more details on this figure.

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Abstract

The manufacturing industry largely contributes to the global economy. However, with the growing complexity of customer demands, stringent environmental norms, and requirements for shorter product development lead times, the industry continues to seek alternatives to address these challenges. Laser based manufacturing techniques are among the popular alternatives to address the challenges, mainly for their precision focusing abilities. Specifically, two laser assisted manufacturing techniques, namely the selective laser heat treatment of sheet metals and the selective laser melting of metal powders, have garnered attention for their ability to produce complex, and near net-shaped products that caters to the needs of industries such as the automotive and the aerospace industry.

While great progress has been made in understanding their process capabilities, shortfalls remain in the area of geometric quality. Specifically, addressing the effect of local heating and local melting on geometric variation is scarce due to the novelty of the aforementioned manufacturing processes. As a result, the methods and tools in practice today may not be readily applicable to analysing and minimizing the effect of local heating and local melting on geometric variation. Thus, this thesis aims at developing knowledge to provide insights into the effect of the aforementioned manufacturing processes on geometric variation and, thereby, assist in establishing methods and tools for the geometry assurance process.

To this end, literature studies were performed to map the significant factors influencing geometric variation and a robust design framework was established as the first step. The focus was then directed towards analysing a set of factors that could be optimized in the early design stages. Specific to the selective laser heat treatment of boron steels, the effect of factors such as the laser heat treatment grid pattern dimension, laser heat treatment grid pattern position, and laser heat treatment scanning path sequence on geometric variation were analysed. Meanwhile, in the selective laser melting of 316L stainless steel powder, the effect of factors such as particle size distribution and powder layer thickness on geometric variation were analysed.

The results highlight the significance of considering the effect of the specified set of factors on geometric variation in the early product development stages and offer solutions to minimize the effect on geometric variation. Moreover, simulation techniques are presented that enable accurate decision making and demonstrate integration into the virtual product development setup. In summary, this thesis demonstrates the application of a robust design approach and the significance of considering geometry assurance in the product development process of laser processed metal components.

Keywords: Geometry assurance, geometric variation, robust design, selective laser heat treatment, selective laser melting

Acknowledgements

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Vaishak Ramesh Sagar
Gothenburg, May 2021

Appended Publications

Paper A
Ramesh Sagar, V., Wärmefjord, K. and Söderberg, R., 2018. Geometrical Variation from Selective Laser Heat Treatment of Boron Steels. Procedia CIRP 75, 409-414. Milan, Italy

Paper B
Ramesh Sagar, V., Wärmefjord, K. and Söderberg, R. 2019. Influence of Selective Laser Heat Treatment Pattern Position on Geometrical Variation. Journal of Manufacturing Science and Engineering, 141 (4).

Paper C
Ramesh Sagar, V., Wärmefjord, K. and Söderberg, R., 2021. Effect of Selective Laser Heat Treatment on Geometrical Variation in Boron Steel Components: An Experimental Investigation. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 235(1-2), pp.54-64.

Paper D
Ramesh Sagar, V.,Lorin, S., Wärmefjord, K. and Söderberg, R., 2021. A Robust Design Perspective on Factors Influencing Geometric Quality in Metal Additive Manufacturing. Journal of Manufacturing Science and Engineering, 143(7), p.071011.

Paper E
Ramesh Sagar, V., Lorin, S., Göhl, J., Quist, J., Cromvik, C., Mark, A., Jareteg, K., Edelvik, F., Wärmefjord, K. and Söderberg, R., 2020, November. Investigating the Sensitivity of Particle Size Distribution on Part Geometry in Additive Manufacturing. In ASME International Mechanical Engineering Congress and Exposition (Vol. 84492, p. V02BT02A064). American Society of Mechanical Engineers.
Also submitted to the ASME Journal of Manufacturing Science and Engineering under the title - *A Simulation Study on the Effect of Particle Size Distribution on the Printed Geometry in Selective Laser Melting*.

Paper F
Ramesh Sagar, V.,Lorin, S., Wärmefjord, K. and Söderberg, R., 2021. A Simulation Study on the Effect of Layer Thickness Variation on the Printed Geometry in Selective Laser Melting.
Submitted to the ASME Journal of Manufacturing Science and Engineering.

Work Distribution

Paper A
Ramesh Sagar initiated the idea and wrote the paper. Experiments were performed at the industrial partner site. Ramesh Sagar collected and analysed the data, and presented the results. Wärmefjord and Söderberg contributed as reviewers.

Paper B
Ramesh Sagar initiated the idea and wrote the paper. Experiments were performed at the industrial partner site. Data from the experiments were collected and analysed by Ramesh Sagar. Wärmefjord and Söderberg contributed as reviewers.

Paper C
Ramesh Sagar initiated the idea and wrote the paper. Ramesh Sagar performed the literature studies, collected data from the experiments and conducted spot weld simulations. Wärmefjord and Söderberg contributed as reviewers.

Paper D
Ramesh Sagar initiated the idea, performed the literature studies, and wrote the paper. Lorin supported with the Robust Design Framework. Wärmefjord and Söderberg contributed as reviewers.

Paper E
Ramesh Sagar and Lorin initiated the idea. Ramesh Sagar performed literature studies and finalized the DoE with inputs from Lorin and Quist. Quist and Jareteg conducted the DEM simulations, Göhl conducted the CFD simulations, and Lorin conducted the structural mechanics simulations. Ramesh Sagar collected and analysed the data from the all the simulations, and wrote the paper. The remaining authors contributed as reviewers.

Paper F
Ramesh Sagar and Lorin initiated the idea. Ramesh Sagar presented the method while Lorin implemented the method and performed the simulations. Ramesh Sagar analysed the data and wrote the paper. Wärmefjord and Söderberg contributed as reviewers.

Contents

List of Acronyms

AM	Additive Manufacturing
CAT	Computer Aided Tolerancing
CFD	Computational Fluid Dynamics
CMM	Coordinate Measuring Machine
DED	Directed Energy Deposition
DEM	Discrete Element Method
DfAM	Design for Additive Manufacturing
DFM	Design for Manufacturing
DoE	Design of Experiments
DoF	Degrees of Freedom
DRM	Design Research Methodology
FCC	Fraunhofer Chalmers Centre
FEM	Finite Element Method
L-PBF	Laser Powder Bed Fusion
MC	Monte Carlo
PBF	Powder Bed Fusion
PSD	Particle Size Distribution
SLHT	Selective Laser Heat Treatment
SLM	Selective Laser Melting
STL	Standard Tessellation Language
THTB	Tailor Heat Treated Blanks
VED	Volumetric Energy Density

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CHAPTER 1

Introduction

This chapter provides an overview of the research topic. Moreover, the research goal and research questions are presented.

1.1 General introduction

The impact of global warming has prompted environmental policy makers to push for stricter regulations to curb carbon dioxide (CO_2) emissions. The manufacturing sector pertaining to the automotive and aerospace industries, which is one of the largest contributors to the global economy faces an uphill task as it is responsible for about one-fifth of the current global CO_2 emissions [OWID, 2020]. Furthermore, increase in transportation demands due to population growth and rise in per-capita income needs to be addressed while fulfilling the stringent emission targets. Thus, providing solutions that adhere to economic, social and environmental aspects of sustainability has become a strategic priority for the transportation industry.

As of today, improving engine efficiency to meet the emission targets is the main focus. A complete shift to electric powertrains is seen as a long-term solution to reduce vehicle emissions. However, a complete transition is estimated to take several decades. Therefore, adapting to lightweight materials, design optimization, and novel manufacturing techniques are seen crucial to reaching the set emission targets.

Among the novel manufacturing technique alternatives available, laser based manufacturing techniques such as the selective laser heat treatment of sheet metals and laser assisted additive manufacturing of metals have piqued the interest of the automotive and aerospace industries to fulfil their needs. These techniques have displayed great potential in producing light weight components and offer the designers more freedom. However, what remains less explored and of critical importance is the effect on geometric variation and its consequences. Geometric variation affects the functionality and aesthetics of the end product [Söderberg et al., 2016]. To utilize the aforementioned manufacturing techniques to their fullest potential, it is important to identify the influencing factors and minimize their effect on geometric variation. Doing so will enable a unique range of solutions without compromising on the geometric quality and cost of the end product.

Therefore, in this thesis, robust design methodology is employed to identify the influencing factors and propose solutions to minimize their effect on geometric variation. In the following sections, an overview of the laser-based manufacturing techniques considered in this study is given to provide the background on the basis of which the research gap and research questions are identified and positioned.

1.2 Laser based manufacturing techniques

Laser-based manufacturing techniques have played a significant role in shaping the automotive and aerospace industries. According to Ion [Ion, 2005], lasers have undergone a phase of technology push and industrial pull where the laser as a technology, was a solution looking for a problem at the same time that the industry was looking for solutions to its problems.

Lasers are capable of producing high-energy concentration due to their monochromatic, coherent and low-divergence characteristics. Such characteristics have allowed lasers to be used in applications requiring local heating, melting and vaporizing the materials. While laser based welding, cutting and drilling techniques have been well established, extending its application to novel processes such as the selective laser heat treatment of sheet metals and selective laser melting of metal powders has taken the potential of laser applications within the manufacturing industry to new heights. Figure 1.1 summarizes the requirements for various laser manufacturing techniques as a function of laser power density and interaction time.

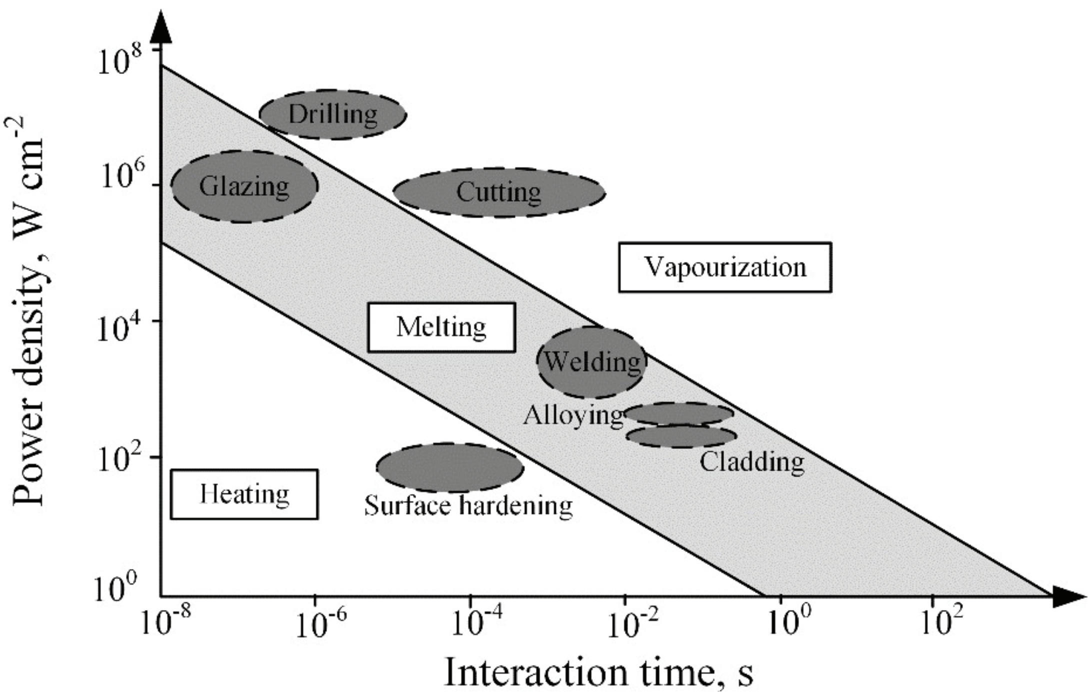

Figure 1.1: Power density and interaction time spectrum for laser material processing. Redrawn from [Santhanakrishnan and Dahotre, 2013]

1.2.1 Laser-based surface modification – Selective laser heat treatment of sheet metals

Selective laser heat treatment (SLHT) is a laser-based surface modification process capable of enhancing the forming behaviour of sheet metals and functionality of the final parts, specifically for lightweight materials such as high or ultra high strength steels or aluminium alloys [Merklein et al., 2014]. Commonly known as tailored heat treated blanks (THTB), they are processed by selectively heat treating pre-determined areas of the sheet metal blank that require modification by using laser as heat source (Figure 1.2). As a vehicle body consists of large number of sheet metal parts, this process is deemed most suited for the automotive industry.

1.2.2 Laser-based additive manufacturing – Selective laser melting of metal powders

Selective laser melting (SLM) also known as the laser powder bed fusion process (L-PBF), is an additive manufacturing (AM) process that uses a laser beam to selectively melt the metal powder, added layer by layer spread on a build platform. As opposed to traditional manufacturing techniques, it enables fabrication of complex geometry parts, provides more design freedom, and enables weight and cost savings for the automotive and aerospace industry.

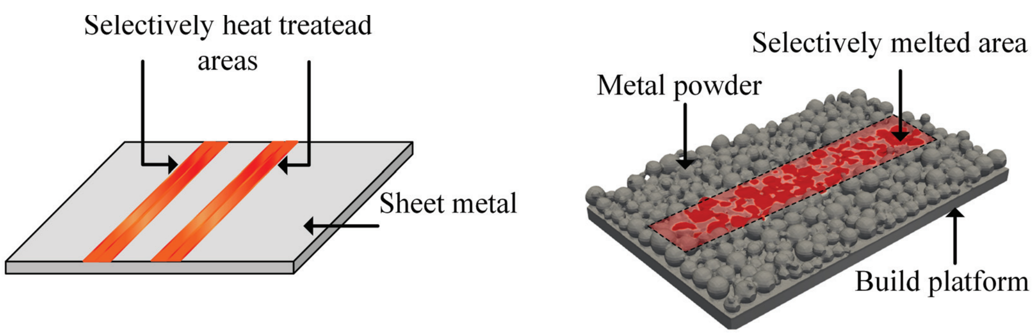

Figure 1.2: Concept of selective laser heat treatment (left) and selective laser melting (right) processes

As is evident in Figure 1.1, the SLHT and SLM processes lie under different spectrums of heating and melting, respectively. However, common among these two processes and what draw interest in this research are the similarities in terms of process design, i.e., the process parameters that influence the outcome. The processes are flexible enough to locally adjust the process parameters in accordance with the design and functionality requirements and produce products with tailored material properties.

1.3 Effect on geometric quality

In every manufacturing process, the part being manufactured varies from the intended nominal geometry. The nature of geometric variation, even if minimal at the part level, can have adverse effects when assembled to other sub-assemblies or parts. It affects the functionality and aesthetics of the final assembled product. Physical verification often carried out in the later stages of the product development process involves rework and repair and sometimes leads to scrapping, thereby affecting the overall product development time and cost. It is therefore necessary that the concerns related to geometric variation are dealt with in the early phases of the product development process.

In the product development process, the concept phase is considered crucial as different design concepts can be virtually evaluated instead of expensive physical prototypes. The ability to virtually evaluate the design concepts, however, depends on 1) awareness of phenomena relevant to the manufacturing techniques and the final product's operating environment, and 2) capability of the simulation tools to correctly depict the relevant phenomena.

Due to the novelty of the SLHT of sheet metals and SLM of metal powders, not all aspects that affect the geometric quality of the product have been explored to date. Thus, more research is needed to understand the various aspects of these processes that affect the product's geometric quality to enable accurate decision making in the early design stages.

1.4 Geometry assurance and robust design

Geometry assurance is a framework aimed at reducing the effect of geometric variation through a set of activities performed in different phases of the product development process, namely the concept phase, the verification phase, and the production phase [Söderberg et al., 2016]. Figure 1.3 depicts the activities performed in the geometry assurance framework with respect to the product development process. The work presented in this thesis is aimed at contributing to the activities in the concept phase of the product development loop.

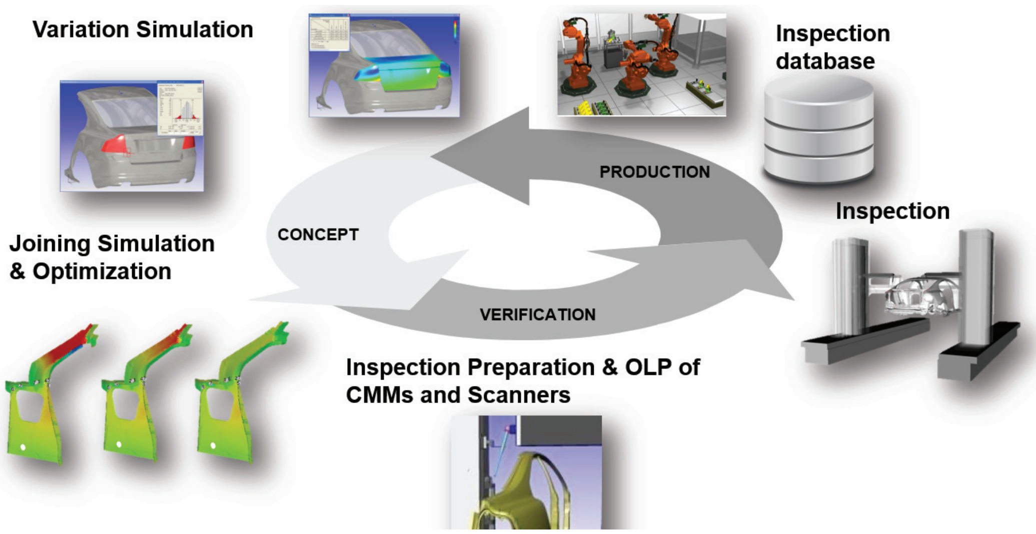

Figure 1.3: Geometry assurance activities [Söderberg et al., 2016]

The sources influencing geometric variation could be, for example, the manufacturing process, fixture design or a sensitive design concept. Variation sources, when discovered, are expensive to either eliminate or reduce. Instead, an alternative would be to make the design concept robust. Here, robustness can be defined as the ability of the product or process to function consistently as the surrounding uncontrollable factors vary [Chowdhury and Taguchi, 2016]. This can be achieved through robust design methodology. The fundamental principle of the methodology is to minimize the effect of the variation sources without eliminating them [Phadke, 1989], as discussed in detail in Section 2.2.

1.5 Research purpose

The research purpose has evolved during the course of this thesis. The purpose of this research was initially limited to geometry assurance of selective laser heat treatment of sheet metals as presented in appended papers A, B and C. Given the uniqueness of this manufacturing technique, the goal here was to understand how the laser heat treatment of selected areas impacted the geometric quality of the produced component. However, with similarities between the SLHT of sheet metals and SLM of metal powders, specifically in terms of process design, the purpose evolved into implementing the concept of robust design and laying the foundation for geometry assurance practices in the concept phase of developing laser-processed metal components.

Previous research efforts within geometry assurance have worked towards considering the effects of heating and melting on geometric variation. In addition, simulation techniques to virtually evaluate robustness by considering the effect of heating and melting have been proposed [Lorin, 2014]. However, these evaluations have mainly been limited to the assembly level. With novel processes such as the SLHT and SLM coming into foray, evaluating robustness at the part level has become imperative. While extensive research has been conducted on understanding the nuances of these manufacturing techniques and design for manufacturing (DFM) frameworks have been proposed in a broader sense, they have largely been based on the process constraints or their capabilities. Knowledge gaps remain concerning optimizing the product design and process design that accounts for the process variability effects.

Therefore, the purpose of this thesis is to develop knowledge, methods and tools to enable robustness evaluation and establish geometry assurance practices in the concept phase of developing laser-processed metal components, pertaining to the manufacturing processes considered in this research work.

1.6 Scientific goal

The scientific goal is to develop knowledge in regard to the challenges related to geometric quality when considering selective laser material processing by means of heat treatment and melting. The generated knowledge can then be used to develop methods and tools that enable robustness evaluation of selective laser-processed products produced by means of heat treatment and melting.

1.7 Industrial goal

The likes of the SLHT process and SLM process have garnered immense industrial interest and have been implemented to produce products for specific applications. However, the current industrial geometry assurance practices either do not account for or are not equipped with sufficient knowledge of the effects of SLHT or SLM on geometric quality. Thus, the industrial goal is to identify the issues related to geometric quality when implementing SLHT and SLM processes and consequently, to equip the industry with the means, through tools and methods, to address geometric quality issues in the early concept design stages of the product development process.

1.8 Research questions

Based on the research purpose and the previously described scientific and industrial goal, the following research questions have been formulated to govern this research.

RQ1: What are the sources of geometric variation stemming from the selective laser heat treatment process and the selective laser melting process?

The goal of this question is to identify and understand various sources that influence geometric variation. Here, the focus is on the sources that could be accounted for or controlled in the early design stages.

RQ2: How can the geometric variation from the selective laser heat treatment process and selective laser melting process be controlled?

Once sufficient knowledge on the sources that influence geometric variation is accumulated, the next step is to analyse how these identified sources can be adjusted to minimize their effects on geometric variation.

RQ3: How can simulation in product development be employed to predict geometric variation in the selective laser melting process?

In the concept phase of the product development process, simulation methods and tools aid in evaluating various design concepts. This question is thus formulated to examine and, thereby, demonstrate how the simulation tools and methods can be employed to evaluate robustness of design concepts in the early product development stages.

1.9 Delimitations

As this thesis has evolved during the course of the research, a set of delimitations are applicable. As can be observed from the research questions, the research was conducted considering two manufacturing processes, namely the SLHT of sheet metals and SLM of metal powders. The research project involving the SLHT process was conducted as a collaborative project between the Department of Industrial and Materials Science at Chalmers University of Technology and a components supplier in the automotive industry. Thus, vehicle body components made of sheet metals, specifically of boron steels were of interest.

The research project involving SLM of metal powders was conducted as a collaborative project between the Department of Industrial and Materials Science and the Centre for Additive Manufacture - Metal (CAM^2) based in Chalmers University of Technology. Here, 316L stainless steel was the material of choice in the simulation studies.

Though the research results are specific to the manufacturing processes and materials chosen, some aspects of the research outcomes could be made applicable to other laser-assisted manufacturing processes that are similar in nature. However, the nature and level of applicability are subject to similarities exhibited specifically in terms of process design.

Nevertheless, the main contribution is the application of robust design and establishing geometric assurance practices for laser-assisted selective heat treatment and selective melting of materials. Though the work touches upon other disciplines, such as the discrete element method, finite element method and computational fluid dynamics, the application of these disciplines within this research is only to support its contribution to the field of robust design and geometry assurance.

1.10 Structure of the thesis

This thesis is structured as follows:

- **Chapter 1** titled '**Introduction**' provides the background on the research topic.
- **Chapter 2** titled '**Frame of Reference**' discusses research areas pertaining to the research topic.
- **Chapter 3** titled '**Research Methodology**' discusses the research approach and methods followed in this research.
- **Chapter 4** titled '**Results**' presents and summarizes the results achieved in this research.
- **Chapter 5** titled '**Discussion**' discusses the results from the scientific publications with respect to the formulated research questions.
- **Chapter 6** titled '**Conclusion**' summarizes and concludes the research, and briefly discusses the future work.

CHAPTER 2

Frame of Reference

Breakthroughs in research transpire when interactions of different disciplines occur through the transfer of knowledge, ideas and methods [Blessing and Chakrabarti, 2009]. Therefore, when conducting research, it is vital to consider all the possible areas that could be relevant to the topic of interest. As mentioned in the introduction, the aim is to develop knowledge, methods and tools to effectively produce geometrically assured laser-processed metal components. Thus, this work can be positioned within the framework of geometry assurance. This chapter presents various topics that are relevant to this research and lays the theoretical foundation (Figure 2.1).

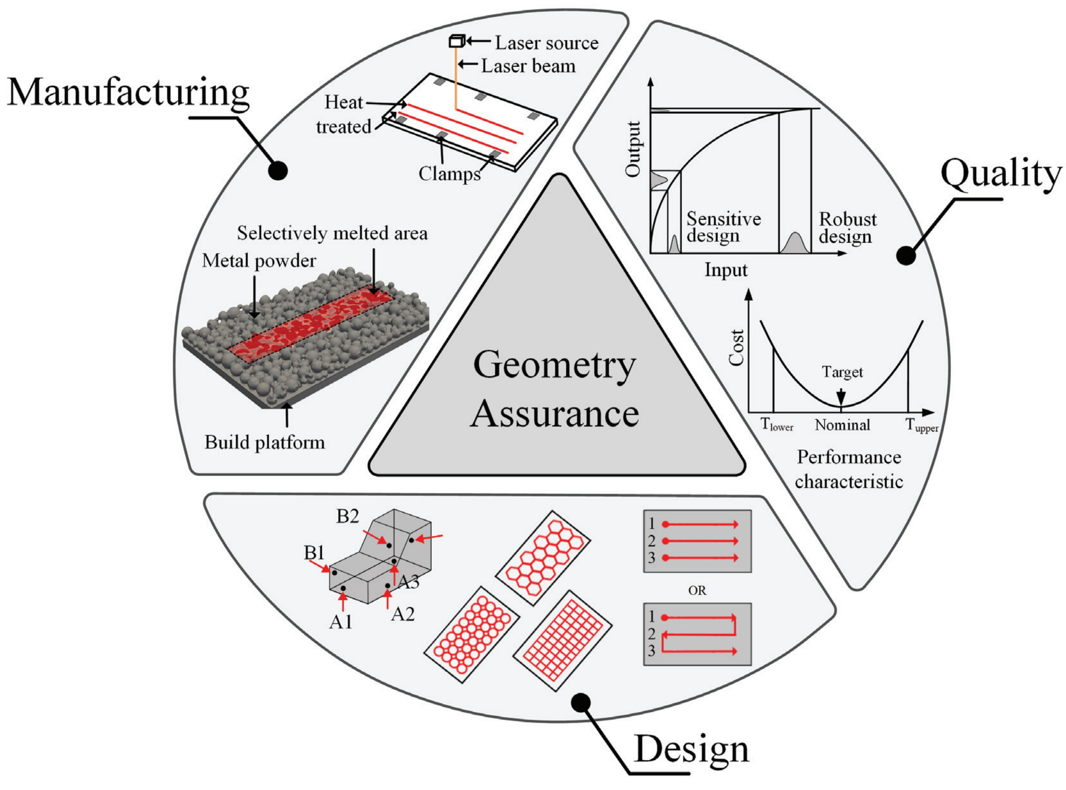

Figure 2.1: Frame of reference highlighting the areas of relevance in this thesis

2.1 Quality and its significance

The definition of the term 'Quality' varies based on the context. According to Garvin [Garvin, 1984], quality can be defined based on five different approaches, namely the transcendent approach of philosophy, the product-based approach, the user-based approach, the manufacturing-based approach, and value-based approach. In the product-based approach, quality is defined as a precise and measurable variable in which the difference in quality is measured by the difference in quantity of the product's attribute. According to the manufacturing-based approach, quality is defined based on meeting the established specifications, i.e., any deviation from the specifications characterises the quality outcome. Garvin further identified eight dimensions of quality: performance, features, reliability, conformance, durability, serviceability, aesthetics and perceived quality. Performance is regarded as the primary operating characteristics of a product. According to Garvin, the connection between performance and quality depends on the customer's perspective, where differences in performance can correspond to differences in product quality. Genichi Taguchi, who is considered one of the pioneers in the field of quality engineering, described quality based on the effect of the product on the end users. According to Taguchi, quality loss is the loss imparted to society from the time a product is shipped [Taguchi and Wu, 1980]. The desirability of the product increases when the loss imparted is lower. Thus, when the performance of the product is lower due to poor quality, it leads to societal loss. However, the total loss not only involves societal loss incurred after the product is sold but also involves loss that occurs during manufacturing of the product. Performance characteristics, which are the primary operating characteristics of the product, may vary due to the working environment that the product operates in, the wearing out of the product over time, and poor manufacturing. Taguchi related the deviation of the performance characteristic and its effect on the cost due to quality loss and represented it in the form of a quadratic approximation.

$$l(Y) = k(Y - T)^2 \tag{2.1}$$

where Y is the performance characteristic and the target value of Y set as T, l(Y) is loss in terms of cost due to deviation of Y from target value T, and k is considered to be an unknown constant. Representing the quality loss in the form of quadratic loss asserts the significance of continuously reducing performance variation. Here, the quadratic loss function considers that the performance characteristic is non-zero and displays the 'nominal the best' type characteristic. The quality loss is symmetrical as seen in Figure 2.2. Phadke [Phadke, 1989] presented more variations of this quadratic loss function, namely the 'smaller the better' type characteristic, 'larger the better' type characteristic, and asymmetric.

2.2 Robust design

The final quality and cost of a product is driven by its design and the manufacturing process used to produce it. Phadke demonstrated through the robust design concept how the quality loss and the total cost could be minimized. In

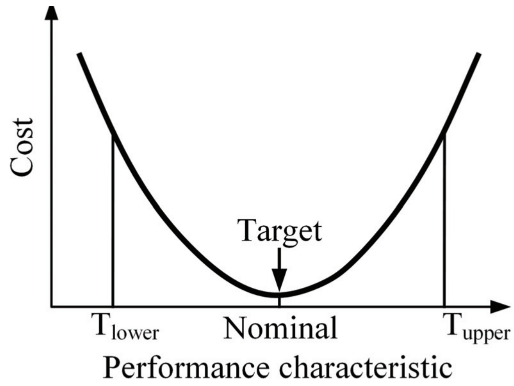

Figure 2.2: Quality loss [Phadke, 1989]

the concept of robust design, a product or process can be considered as a system, illustrated in Figure 2.3. Taking product as the example here, the response or output of the product is a certain performance characteristic and is denoted as y. The output of the product depends on the input signal factor (M) which could be influenced by some other factors, classified as noise factors (x) and control factors (z). The signal factor is the input and is based on the desired response from the product. Noise factors are uncontrollable parameters that cause deviations in the product's response and result in quality loss. Control factors are the parameters that could be adjusted to minimize the influence of noise factors and achieve the desired outcome. Noise factors affecting the response could be 1) some external factors, such as operating environment conditions or the load conditions that the product is subjected to; 2) wearing out of the product upon usage; or 3) inconsistency in the product's manufacturing process, which causes response variation between products. This inconsistency could be a result of inhomogeneity in the manufacturing environment conditions, variation in the raw materials, or operator errors among other things. Therefore, a product's engineering design and manufacturing process govern the final quality and cost associated with the product.

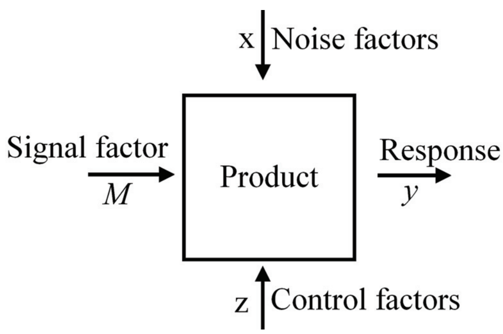

Figure 2.3: P-diagram [Phadke, 1989]

The fundamental principle of robust design is to improve the quality of the product by minimizing the effects of the causes of variation without eliminating those causes [Phadke, 1989]. A three-step approach to achieve robust design is proposed:

- ***Concept design***: Also known as system design, this is the first step.

It consists of applying scientific and engineering knowledge to scrutinize available alternatives. The best concepts out of the available alternatives are chosen, and a basic functional prototype design is made, which serves as the initial parameter settings for the product. Here, understanding of the customer's needs and the manufacturing environment is necessary.

- ***Parameter design***: This second step consists of optimizing the product parameter settings such that the product's performance is least sensitive to variation sources. As illustrated in Figure 2.4, moving the nominal value of the input (from sensitive design to robust design) results in an output that is less sensitive to variation. Parameter design is considered to be a highly cost-effective method of improving engineering design, as it reduces the influence of variation on performance instead of eliminating the variation sources altogether.

- ***Tolerance design***: Once the nominal product parameter values are set during the parameter design, tolerances can then be allocated, which forms the third step in this approach. Tight tolerance can affect the manufacturing cost or wide tolerance can increase performance variation. Thus, it involves a trade-off between the quality loss due to performance variation and the increase in manufacturing costs.

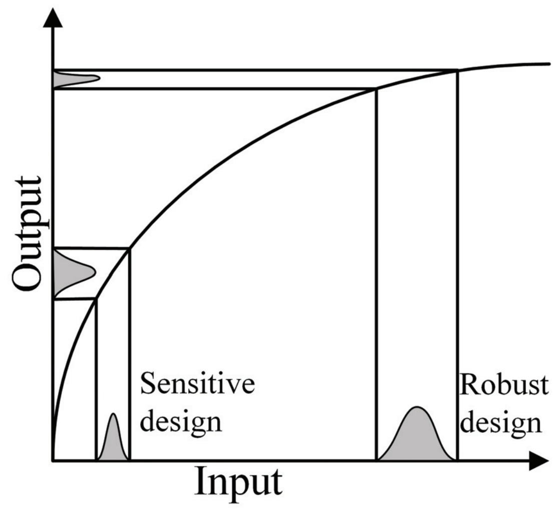

Figure 2.4: Parameter design to minimize sensitivity [Phadke, 1989]

In the product development process, product design is deemed the most ideal way to deal with all types of noise factors, as early evaluation of various design concepts can be made. However, when it comes to manufacturing process design, dealing with all types of noise factors is not possible. Since the manufacturing process design mainly deals with noise factors that affect the manufacturing process, only the product-to-product (unit-unit) variation can be reduced. Phadke [Phadke, 1989] summarizes the role of robust design during the product development stages in dealing with various noise factors, as shown in Table 2.1.

A modern perspective of robust design methodology is presented in [Hasenkamp et al. 2009], where the whys, the whats and the hows of robust design are decomposed as principles, practices and tools, respectively. Here, the main

Table 2.1: Role of robust design in product development stages

Product development stages	Activity	Can reduce effect of		
		External noise	Wear	Unit-Unit
Product design	Concept design	✓	✓	✓
	Parameter design	✓	✓	✓
	Tolerance design	✓	✓	✓
Manufacturing process design	Concept design	✗	✗	✓
	Parameter design	✗	✗	✓
	Tolerance design	✗	✗	✓

principle considered is insensitivity to noise factors, implemented through practice of exploiting the nonlinearities and interactions, with the help of experience and prior knowledge or by generating the requisite knowledge through, for example, design of experiments (DoE). Later, Göhler and Howard [Göhler and Howard, 2014] reviewed the robust design tools and methods and identified four facets, namely robust design guidance and principles, robustness evaluation, robustness optimization and robustness visualization, to classify the reviewed tools and methods. Furthermore, on the basis of reviewed tools, methods and identified facets, a robust design process was proposed to guide designers in the application of robust design methodology [Göhler et al., 2018]. A summary on the importance of implementing robust design in the industry can be found in [Krogstie et al., 2015, Eifler and Howard, 2018].

The robust design methodology has been extended to minimize the effect of variation and assure the product's geometry. The factors affecting geometric variation were expressed by means of an Ishikawa diagram that enabled categorizing the control and noise factors [Söderberg, 1998]. This work laid the foundation for developing the robustness evaluation toolbox and framework for virtual geometry assurance [Söderberg et al., 2016]. A framework for analysing geometrical robustness of plastic assemblies was proposed in [Lorin et al., 2010]. It was based on the notion proposed by Smith [Smith and Johan Clarkson, 2005], where robustness is regarded as the ability to break the connections between contextual, formal and functional variety. Moreover, Schleich [Schleich et al., 2015] presented a framework for sensitivity analysis in geometric variation management to support decision making during integrated product and process design. Thus, the concept of robust design continues to prevail and assist in geometry assurance to achieve the desired product quality.

2.3 Geometry assurance

The product being manufactured is prone to noise factors, and the intended response from the product may be affected. The sources of geometric variation can be classified with respect to part variation, assembly variation, and design concept (see Figure 2.5). Variation in the manufacturing process causes the shape and size of the part to vary and is classified under part variation. This variation could further aggravate during the assembly process due to variations in assembly techniques or in the equipment, or due to the application of external force through clamps and fixtures. The likelihood of the effect of these stated sources is higher if the design concept is sensitive to it.

As previously explained in robust design, the effect of noise factors can be minimized during the early design stages to assure the geometry is consistent with the functional and aesthetical requirements. Geometry assurance can be defined as a set of activities aimed at minimizing the effect of geometric variation on the final product. The set of activities can be found in all stages of the product development process (Figure 1.3).

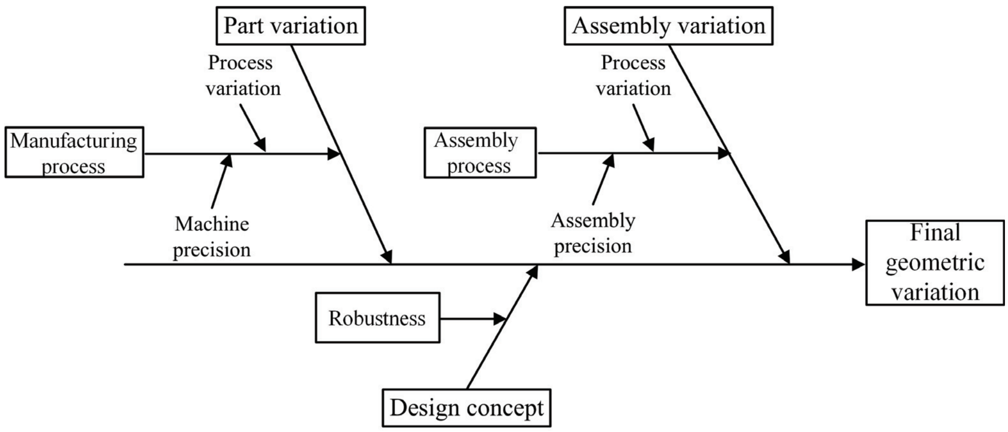

Figure 2.5: Geometric variation sources [Söderberg et al., 2006b]

In the *concept phase*, product and production concepts are analysed and optimized to resist the effect of manufacturing variation. The highlight of this phase is that the concept evaluation can be conducted virtually with respect to the available production data or the assumed production system. In the *verification phase*, the product and the production system are verified and adjustments made to prepare for full production. This phase assists in inspection planning. In the *production phase*, inspection data is monitored to detect errors and control the production.

In a robust geometry design, positioning of the locators, i.e., the locating scheme, is a way to suppress the effects from the variation sources. Simply put, a locating scheme can be seen as the transfer function between input and output variation and is considered the most important activity within the geometry assurance process [Söderberg et al., 2016].

2.3.1 Locating schemes and tolerances

The purpose of a locating scheme is to lock the part during the manufacturing, assembly or inspection process. With a robust locating scheme, the effect of variation sources can be minimized. A locating scheme is chosen to lock the parts based on required degrees of freedom (DoF). Typically, for rigid parts, a 3-2-1 locating scheme of orthogonal type is employed to lock the position (see Figure 2.6). Three locator points, A1, A2 and A3, lock three DoF; in other words, they lock translation along the z-axis and rotation along the x-axis and y-axis. Locator points B1 and B2 lock two DoF, i.e., translation along the x-axis and rotation along the z-axis, while the locating point C1 locks the remaining one DoF, i.e., translation along the y-axis. In the case of non-rigid parts or assemblies with irregular geometry, a six direction locating scheme could be used instead. Additional support points could be used wherever necessary. Having a robust design allows for wider tolerances on the part geometry features, which, in turn, results in lower manufacturing costs.

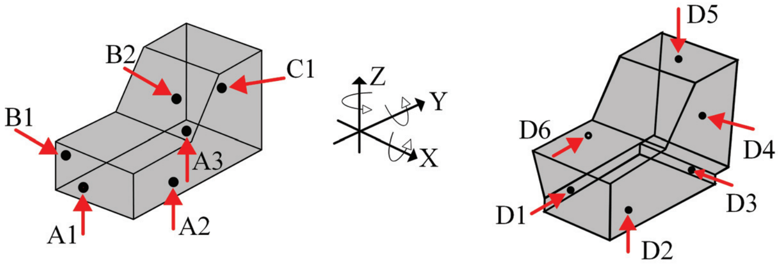

Figure 2.6: A three direction (left) locating scheme and a six (right) direction locating scheme [Söderberg et al., 2006a]

As geometric variation exists due to variation during the manufacturing and assembly process, it is equally important to consider how much variation is acceptable and does not affect the performance of the part. This is done by assigning tolerance limits. Tolerancing can be categorized into two types, parametric and geometric [Hong and Chang, 2002]. In parametric tolerancing, a critical set of parameters is identified. An upper and lower limit is assigned to it as a conventional plus/minus tolerancing type. Geometrical tolerancing consists of assigning values to certain attributes of a feature, such as form, orientation, location and runout. Tolerance allocation can be done through either a top-down approach or a bottom-up approach. In top-down approach, a tolerance requirement for the final assembled product is specified [Söderberg, 1994, Söderberg, 1995, Lööf and Söderberg, 2007]. It is then broken down to individual parts of the product. Contrary to this, in the bottom-up approach, a tolerance is specified for every individual part within the product. They then define the tolerance of the final assembled product.

2.4 Introduction to laser material processing

Laser material processing has gained popularity over traditional manufacturing processes for its ability to precisely deposit a large amount of energy into the material over a short time in a spatially confined region [Amuda and Akinlabi, 2016]. Laser material processing techniques can be classified based on the occurrence or absence of phase change (Figure 2.7). Laser surface hardening, laser bending and shock peening are some of the no phase change processing techniques, while processing techniques such as joining, surface cladding, rapid prototyping and machining involve phase change. The main difference between the two types is the amount of energy density required, as previously highlighted in Figure 1.1.

2.4.1 Selective laser heat treatment of sheet metal components

Laser heat treatment is a surface modification process that allows for modifying the microstructure of metals by means of controlled heating and cooling. Since the laser as a heat source enables heat treatment of discrete surface regions instead of the entire material, the process is commonly known as selective or

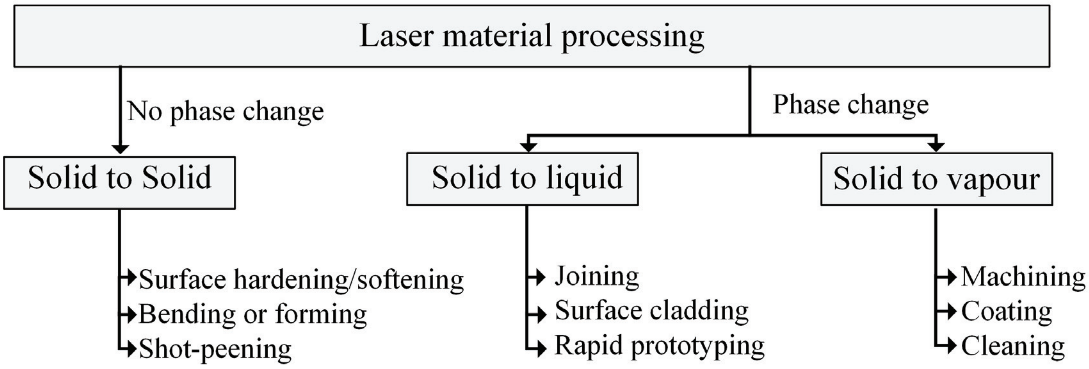

Figure 2.7: Laser material processing classification [Majumdar and Manna, 2003]

local laser heat treatment. The term 'surface modification' may suggest only modifying the characteristics of the surface; however, the material beneath the surface is also altered to a certain depth in the process.

The selective laser heat treatment (SLHT) process can be used for hardening- or softening of the material. A typical process setup is illustrated in Figure 2.8. The laser beam moves across the areas which require modification and heats up the area to the temperature in accordance with the end requirements, i.e., based on hardening or softening. In the case of laser hardening, when the temperature of the irradiated area crosses the transformation start temperature (Ac_1), transformation of the initial microstructure to austenite begins. It is completed when the temperature crosses the transformation of the microstructure, referred to as the Ac_3 temperature. The surrounding material which remains untreated acts as a heat sink, resulting in rapid cooling of the heat-treated area. This rapid cooling causes the heat-treated area to transform to martensite and results in hardening of the area. In the case of softening, the cooling process is rather controlled or slow, which softens the heat-treated area. However, the exact nature of hardening or softening, the respective final surface and the resulting mechanical properties depend on the initial microstructure, process parameters and thermophysical properties of the material.

The SLHT process has most commonly been used in the industry for applications requiring surface hardening. Surface hardening is mainly performed to increase wear resistance and to improve the fatigue life of the laser heat-treated part. Common examples of this process in the automotive industry include laser-hardened wear tracks for power steering housing, cam shafts, gear teeth, diesel cylinder liner bores and hardening the edges on press tools [Dutta Majumdar and Manna, 2011].

Selective laser heat treatment for sheet metals has largely been investigated to enhance the formability or crashworthiness of sheet metal components [Merklein et al., 2014]. Enhancing the formability or crashworthiness can mostly be done at the blank level prior to cold forming of the components. Known as tailored heat treated blanks (THTB), this approach is seen as a substitute to the hot forming process. The critical areas in the sheet metal blank that are required to be tailored to improve formability or for enhanced crash perfor-

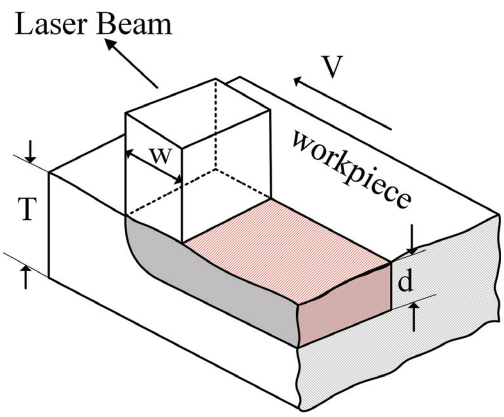

Figure 2.8: Laser heat treatment process setup. V is the laser beam traverse speed, T is the sheet metal thickness, W is the laser beam diameter or width, and d is the depth of the laser-hardened area. Redrawn from [Mazumder, 1983]

mance can be identified either through simulations or through historical data of similar components. The critical areas are selectively laser heat treated, and the heat-treated metal blank is then cold formed to the desired shape (Figure 2.9a). When the formed part is subjected to a crash, the softer areas crumble first in a controlled manner (Figure 2.9b) [Bambach et al., 2016, Conrads et al., 2017]. Selective laser heat treatment can also be conducted after the part is cold formed to facilitate subsequent joining operations such as riveting or hemming [Synergy, 2020] or to impart strength [Asnafi et al., 2016] for controlled crash behaviour.

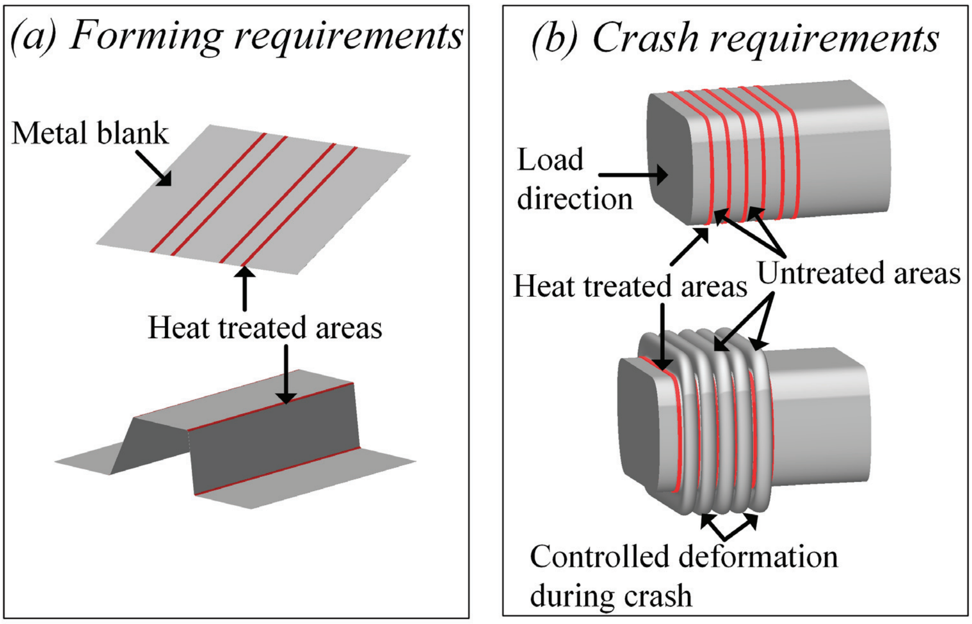

Figure 2.9: Selective laser heat treatment based on (a) forming requirements and (b) crash requirements

Based on the literature studies, an overview of the SLHT of sheet metal blanks is presented in Figure 2.10. The first step involves determining the forming requirements and crash requirements of the component to be manufactured. This provides an understanding of the critical areas that require local modification and aids in planning the next step. It serves as the input to decide on the SLHT process-based alternatives, such as the pattern type, pattern dimension and pattern position. A pattern is preferred when there are multiple areas in the metal blank that require local modification. Grid-based pattern and honeycomb-based (hexagon) pattern are some examples. They also add aesthetic characteristics to the component. Once the pattern-related aspects are chosen, various laser path sequence strategies can be simulated (Figure 2.10, step 2). The laser path sequence governs the stress distribution in the sheet metal blank, as well as the overall processing time. Therefore, it is beneficial to plan it in the early design stages. Simulation tools and methods play a crucial role as different alternatives can also be evaluated and optimized with respect to geometric variation. Information on the chosen pattern type, pattern size and sequence strategy serves as the input for the robot coupled laser equipment (Figure 2.10, step 3). After the laser heat treatment of sheet metal blanks, they are formed into the desired shape. The local heat treated and formed components can then be assembled with other components.

While the SLHT process seems highly promising, several gaps must be filled for the process to be fully mature and be ready for full-scale implementation in the manufacturing industry. Currently, the focus within research and industry is mainly on establishing material specific laser heat treatment process windows and their consequence on stamping. One of the gaps which must be concurrently addressed and is of concern in this thesis is the effect of the SLHT technique on the geometric quality of the produced component. There is a lack of sufficient knowledge on the effect of SLHT process parameters on geometric variation. Increased understanding will enable planning the SLHT process that accounts for geometric variation and will enable setting up simulation support for virtual evaluation in the early product development stages.

2.4.2 Introduction to boron steels - Heat treatment perspective

High-strength and ultra-high-strength steels are lightweight materials widely used in the automotive industry for vehicle body applications. They offer economical and weight-saving possibilities and are used for improving the impact energy-absorbing capacity (crashworthiness) of the vehicle body components. Among ultra-high-strength steels, boron steels are preferred.. Boron steels up to 40% of the total vehicle weight have been used to improve crashworthiness and to achieve substantial weight reduction [ArcelorMittal, 2015]. The presence of boron as an alloying element improves hardenability of steels. Boron content in the range of 0.001% weight to 0.003% weight provides maximum hardenability [Deva and Jha, 2014]. Due to this high hardness, boron steels have good wear resistance properties. The presence of boron delays transformation to other phases such as bainite, ferrite, and pearlite microstructures, which are softer. Hence, the microstructure transforms into martensite as a result of rapid quenching, thereby increasing the hardness of the material. The as-received yield strength in the range of 300-550 MPa can be increased to 1000-1300 MPa from the heat treatment process.

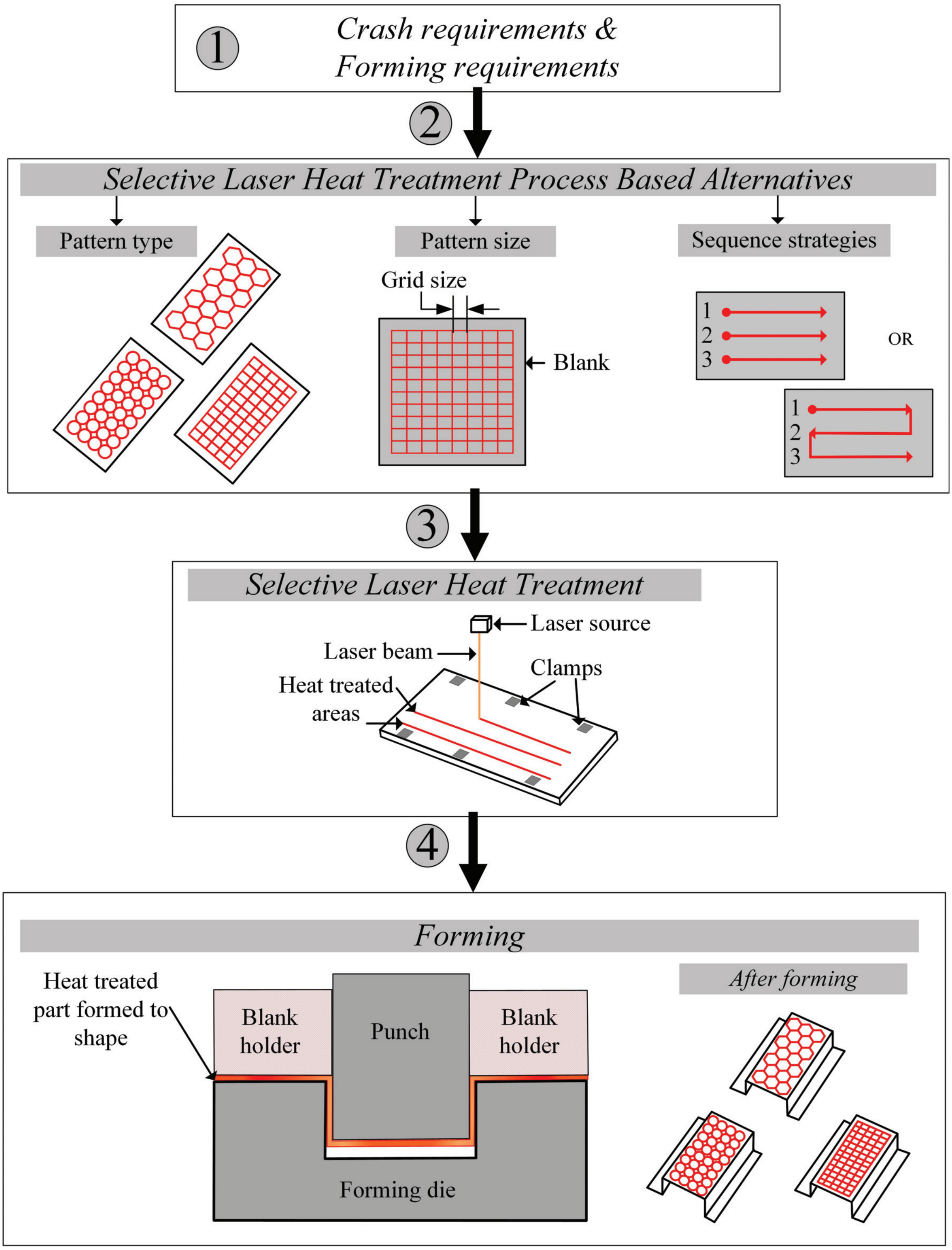

Figure 2.10: Process overview of selective laser heat treatment of sheet metal components

2.4.3 Introduction to metal additive manufacturing

Additive manufacturing (AM) is defined as a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies [ASTM International, 2015b]. The first AM technique was demonstrated in 1986 by [Deckard, 1986], and the technology has undergone tremendous development ever since. Various types of materials, such as metals, polymers, ceramics and composites can be processed. The process enables the production of complex parts and provides increased design freedom. There are various types of metal AM processes which could be classified in terms of heat source or the physical state of material. Figure 2.11 depicts a classification of some of the notable metal AM processes. Of the many listed processes, powder bed fusion (PBF) and directed energy deposition (DED) are two techniques that have received the greatest attention. In this thesis, the laser-powder bed fusion (L-PBF) technique is of particular interest.

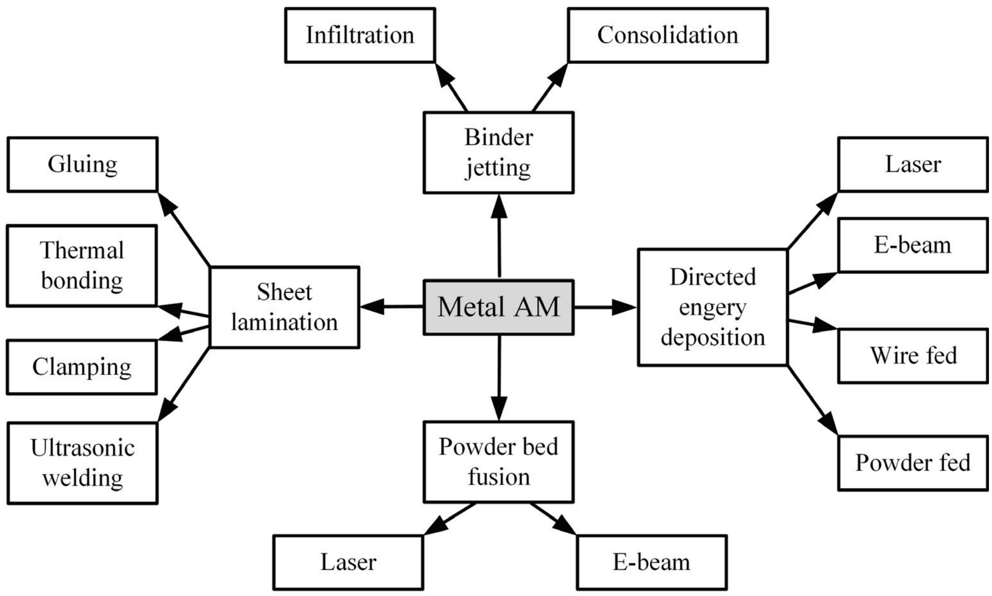

Figure 2.11: Classification of metal AM processes [ASTM International, 2015a]

2.4.3.1 Selective laser melting

Selective laser melting is an L-PBF type AM process. As the name suggests, the raw material is in the powder form and is spread over the build platform to form a powder bed layer. A laser is scanned over the powder bed in a pre-determined pattern and fuses the powder particles together. The build plate moves along the vertical axis as per the required layer thickness, and the recoater applies a new layer of powder material. The process is repeated layer upon layer to fabricate the 3D object. Figure 2.12 illustrates an overview of the SLM process.

The sequence of steps in producing a typical SLM part is explained in Figure 2.13. The first step involves designing and modelling the part that adheres to the process capabilities. Once the model is fixed, the next step is to tessellate the 3D model by converting it to STL file format, a de facto file format, and slicing the model into layers. The sliced STL file is then transferred to the

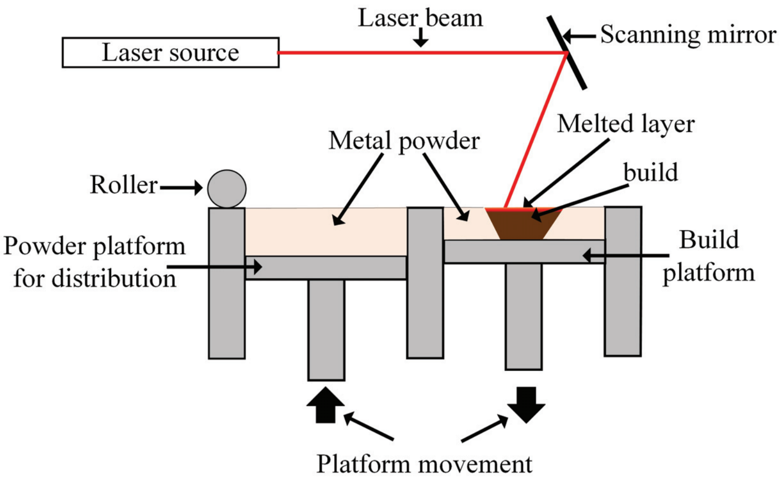

Figure 2.12: Selective laser melting process setup

AM machine through a customized machine software where factors such as the build orientation, position and scanning patterns are looked at. The part is built in the next step, which is mostly an automated process. Once the build is complete, the part is prepared for removal from the machine. Prior to that, the surrounding unused powder is to be removed, and the part should be brushed. Post-removal, the part is processed further to, for example, remove support structures, for heat treatment and surface finishing before it is ready for application.

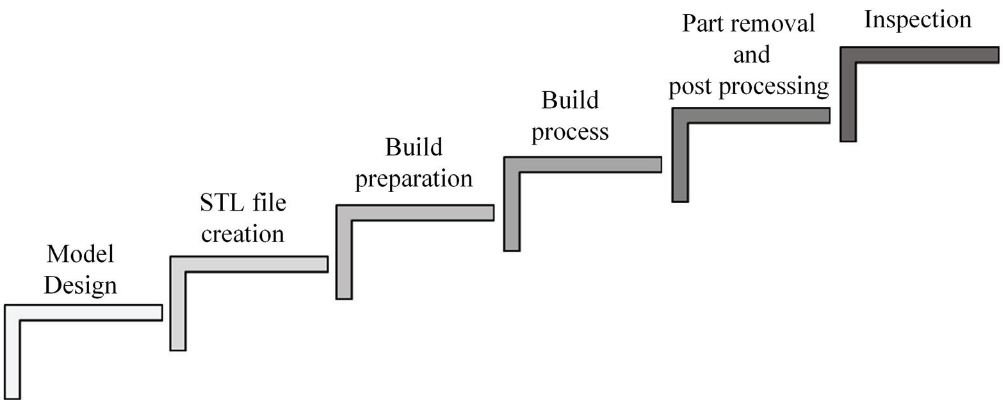

Figure 2.13: Sequence of steps in the AM process, from model design to inspection [Ian Gibson, 2015]

2.4.3.2 Design considerations

Additive manufacturing techniques in general offer unique flexibility in designing and fabricating complex shaped products. A design that is insensitive to the effect of process variation and fulfils the functionality of the end product is desirable. To achieve this, understanding of the process capabilities and constraints is necessary.

Some of the design considerations related to geometry that are critical in AM are minimum feature size, minimum spacing between the features, maximum aspect ratio, and maximum part size that can be produced by the machine used [ASTM International, 2018]. An ideal scenario would be a design that is least perturbed by the choice of process parameters used to fabricate the product. Often, this is not the case as the size and shape of the features considered in the design restrict the physical orientation of the part during manufacturing. Therefore, based on the features considered in the design and the build orientation of the part, the need for support structures may arise.

2.4.3.3 Powder material characteristics

The consistency of the powder material (feedstock) has a critical influence on the build properties. Key powder material characteristics include the particle shape, particle size distribution and chemical composition [Dawes et al., 2015].

Particle shape has a significant impact on the flow properties of powder. Spherically shaped powder particles have good flowability compared to irregularly shaped particles and stack more closely during the powder spreading process. Particle size distribution (PSD) can be a uni-modal, bi-modal or a multi-modal type distribution and governs the flowability and packing density of the powder bed on the build platform. The mean particle size and the distribution type are chosen with the aim to maximize particle contact with the least voids in the powder bed. Choice of particle size distribution affects particle-particle contact and the powder bed density. It causes porosity and variation in powder layer thickness, surface roughness and build geometry [Tan et al., 2017]. Typically, in a powder-based AM process, a large amount of powder material that is spread during the process goes unused. From an economical perspective, the unused powder is processed by sieving for reuse [43]. However, as the recycled powder is already exposed to a build cycle, it alters the particle size distribution on reuse [Tang et al., 2015].

The chemical composition of the powder material governs the mechanical and microstructural properties [Murgau, 2016]. Certain alloy elements are added to the composition to achieve specific outcomes in mechanical properties. Alteration of chemical composition alters the melt kinetics and, consequently, the mechanical properties of the build.

2.4.3.4 Process parameters

Process parameters in SLM are vital in achieving the required build. Plenty of research continues to investigate the role of process parameters and their effect on the build. Here, some of the critical identified process parameters are discussed.

- **Beam characteristics:** Laser spot size, or beam diameter, is an important parameter that influences the melt pool size and shape. Smaller beam diameter is chosen when fine resolution and surface finish is preferred. Along with spot size, the final microstructure and the mechanical properties of the build are governed by the beam modulation, whether continuous wave or pulsed wave [Demir et al., 2017]. The pulsed wave type has temperature variation and melt pool motion. However, it has advantages over the continuous wave type in terms of surface quality and refined microstructure.

- **Laser power and scan speed:** The laser power and scan speed, along with spot size, collectively determine the energy input to fuse the powder. Based on the beam power, the scan speed needs to be adjusted. For a fixed beam power, an increase in scan speed will cause irregular melting, leading to a balling effect [Yadroitsev et al., 2010], while slower scan speed can lead to excessive melting or key holing. This alters the cooling rate, thermal gradient, build time and residual stresses [Kruth et al., 2010]. Moreover, variation in porosity can occur [Zhong et al., 2015]. Typically, the laser power and speed are selected in a manner which allows a penetration depth of about 3-5 layers.

- **Powder layer thickness:** Powder layer thickness is a critical parameter as it governs the mechanical properties, productivity and surface quality [Sufiiarov et al., 2017]. Typically, in SLM, the layer thickness ranges from 20 -150 μm. Smaller layer thickness can result in better surface roughness compared to greater layer thickness. However, the advantage of using the latter is the faster build rate [Leicht et al., 2020a]. Powder particle size, particle shape and particle size distribution (PSD) are some of the important powder characteristics that influence the powder layer thickness. Any inhomogeneity in the powder layer thickness for the chosen beam power and beam speed can lead to non-uniform melting.

- **Build direction:** A part can be built in different directions (orientation), such as horizontal, vertical or angled, with respect to the build platform (Figure 2.14). Build direction is one of the most critical parameters, as it affects the surface quality and mechanical properties [Alsalla et al., 2018, Zhou and Ning, 2020]. Furthermore, the choice of build direction dictates the requirement of support structures.

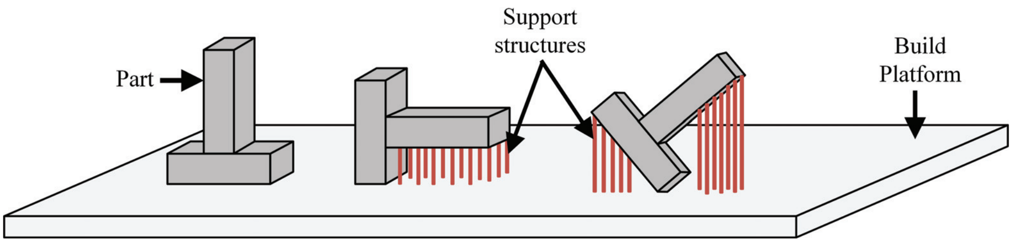

Figure 2.14: Examples of build direction and support structure strategies

- **Support structures:** When a part has overhang features, it is appropriate to consider support structures to support the overhang features. Support structures also act as a heat sink to dissipate the heat away from the processed layers. Some important aspects when considering support structures are the distance between support structures [Cloots et al., 2013], contact area between support structures and the melted layer of the build [Gan and Wong, 2016], strategies for removal of support structures, the overall processing time and accessibility during removal [Jiang et al., 2018].

- **Scanning strategy:** Scanning strategy is the path that the laser beam follows during the melting process. It is responsible for the resulting mechanical properties, residual stresses, surface roughness and distortion [Ali et al., 2018, Leicht et al., 2020b]. Thus, careful choice of scanning strategy is necessary. Scanning often occurs in two modes, the contour mode and the fill mode (Figure 2.15). The outline is first scanned during the contour mode and the inside of the contour is then filled in the form of a pattern during the fill mode. Having the contour mode allows for superior surface roughness and better build accuracy.

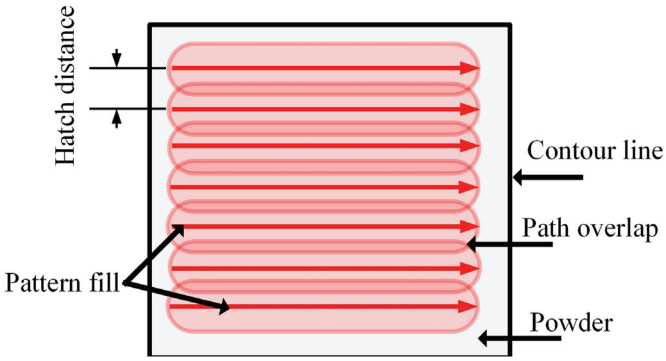

Figure 2.15: Scanning strategy setup

Some of the commonly used strategies are illustrated in Figure 2.16 (a-c). Uni-directional and bi-directional scanning are the mostly commonly used fill mode pattern types. The filling area can also be divided in the form of islands, and these islands are sequentially filled. The scanning strategy can be adjusted layer by layer by rotating the hatch pattern, as depicted in Figure 2.16 (d-f).

- **Hatch distance:** Hatch distance or hatch spacing is the distance between the centers of two adjacent tracks or paths (Figure 2.15). The hatch spacing is dependent on the laser spot size and the laser power, as a certain degree of overlap of the two adjacent paths is preferred for complete melting and fusion of the paths. The build rate could be enhanced by increasing the hatch spacing; however, an increase in hatch spacing can cause insufficient melting, porosity and surface quality issues [Xia et al., 2016, Louw and Pistorius, 2019].

It is evident that the energy density required for successful melting and for producing a useful build is dependent on various parameters. Determining the value of the required energy density by considering all of these factors is rather complex. Thus, a simple equation (Equation 2.2) is used to calculate the energy density.

$$VED = \frac{P}{V{*}H{*}T} \tag{2.2}$$

where the VED is the volumetric energy density J/mm^3, P is the laser power in watts (W), V is the scanning speed in mm/s, H is the hatch distance in mm, and T is the layer thickness in mm. In another approach, the laser beam diameter is used instead of hatch distance to calculate the VED. Even though characteristics such as powder absorptivity, heat of fusion, bed temperature and other important characteristics are not included, the above equation is considered sufficient to calculate the minimum applied energy density necessary to achieve adequate material fusion for the desired material properties.

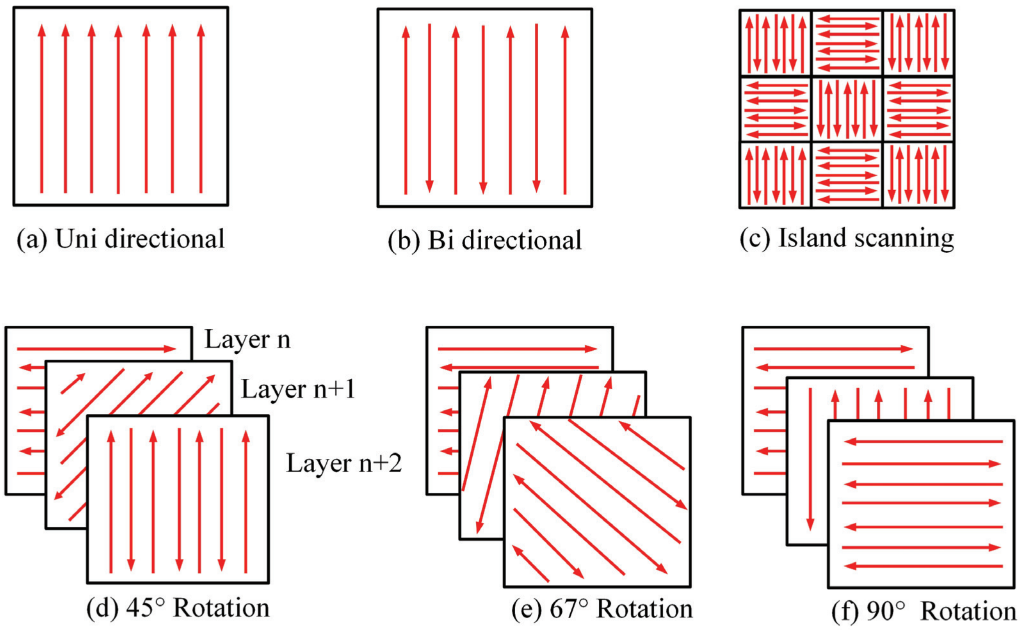

Figure 2.16: Scanning and hatch rotation strategies

2.4.4 316L stainless steel

316L is a low-carbon, austenitic steel preferred for its strength, toughness and corrosion resistance properties. The presence of small amounts of molybdenum enhances the corrosion resistance. Such properties of 316L makes it ideal for manufacturing parts such as rear-view mirror mounts, windshield wiper arms, fasteners, spacers and washers in the automotive industry [Samal and Newkirk, 2015]. Other popular areas of application include the oil and gas, marine and medical industries. 316L is also a widely considered powder material in metal AM research. Numerous physical and simulation based studies exist for this material, mostly focusing on its microstructural and mechanical properties [Tran and Lo, 2018, Cao, 2019, Leicht, 2020]. For these highlighted reasons, 316L was the material of choice in this research study related to the SLM process.

2.5 Effect on the geometry

As the SLHT and SLM processes continue to mature, several challenges remain. Thermal, metallurgical, and mechanical coupling effects (Figure 2.17) generate residual stresses and distort the material. In SLHT, the nature of distortion and magnitude of the residual stresses can vary from blank to blank, which may be due to noise factors such as incoming stress from prior blank processing steps, chemical composition variation and sheet thickness variation among the blanks within the same batch. The residual stress state may influence spring back after stamping and affect subsequent processing steps. In SLHT, the effects of microstructural phase changes may have minimal influence at the blank level. However, the final state of microstructure (hardness or softness) could influence the geometric variation after stamping.

In AM, distortion can occur when processing every layer due to repeated melting and cooling. Thermally induced residual stresses, as well as solidification shrinkage effects, are sufficiently large to distort the part. These may, however, be influenced by noise factors such as the powder size, particle size distribution and chemical composition causing build-build variation. It is therefore desirable to have a good understanding of the process parameters that are possible to control to mitigate the coupling effects on geometric variation.

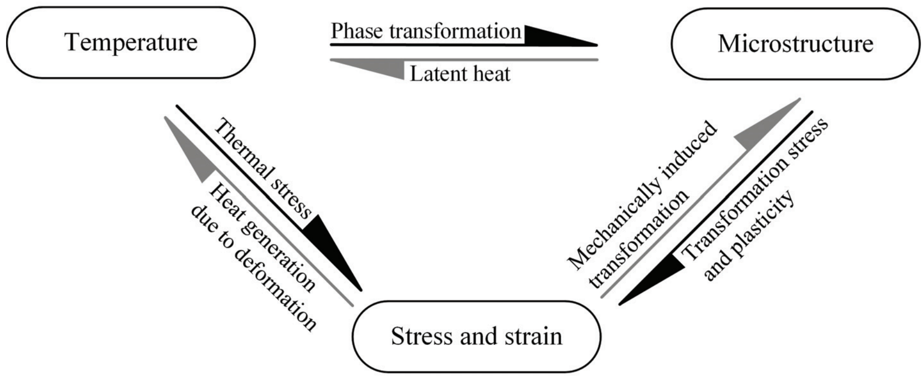

Figure 2.17: Coupling phenomena between temperature, microstructure, and stress and strain. Redrawn from [Inoue and Wang, 1985]

2.6 Design for manufacturing

Design for manufacturing (DFM) is a practice in which input from manufacturing is used in the early stages of design so that the parts can be produced economically and as consistent with the intended quality [Poli, 2001]. Use of DFM was prevalent as early as the 1960s, when manufacturing handbooks were maintained. It served the design engineers guidelines of available manufacturing techniques to ensure that the product specifications were met. Later, the concept to simultaneously consider the manufacturing constraints during design was adapted [Stoll, 1986]. Design for manufacturing explores the relationship between design and manufacturing and its impact on the design process and practices. It addresses topics such as material and process selection and concurrent engineering [Thompson et al., 2016].

Some of the notable examples of DFM guidelines are for well-established manufacturing processes such as injection moulding, casting, machining, and sheet metal forming [Kuo et al., 2001, Thompson et al., 2016]. As the laser-based manufacturing techniques such as SLHT of sheet metals and SLM of metal powders introduce unique design and manufacturing flexibility, the traditional DFM guidelines, tools and practices may not be directly applicable. It redefines the role of designers, requiring enhanced understanding of the process-specific capabilities to enable faster design decisions. Consequently, a new body of knowledge is required.

In the case of design for AM (DfAM), the focus on a macroscopic level has been - to identify opportunities and gaps [Thompson et al., 2016, Makes, A. and Collaborative, A.A.M.S, 2018] and to establish technical considerations [ASTM International, 2018, US Food and Drug Administration, 2018], frameworks and methodologies [Kumke et al., 2016, Diegel et al., 2019, Bikas et al., 2019, Vaneker et al., 2020] to assist in the design and manufacturing of AM products. The focus on a microscopic level has been based on the knowledge gaps identified regarding, for example, AM process characteristics, process capabilities, key process variables and their settings and process impacts on material properties. Process-specific and material- specific guidelines have been proposed [Kranz et al., 2015, Emmelmann et al., 2017, ASTM International, 2019]. The geometry-based design considerations have included minimum feature size, surface roughness, accuracy and precision, to name a few, while the process considerations have consisted of key process variables, such as laser power, scan speed, scan pattern, powder composition and powder size distribution. These guidelines are a step towards increased understanding of the processes and their capabilities. Work is under progress towards translating knowledge when designing complex parts.

Similar advancements have been made in the case of design for SLHT of sheet metals. The focus has been on identifying key process variables and their settings, as well as defining material specific process windows. However, most of these have been implemented on existing component designs. Though SLHT is seen as a highly promising technique, examples of components designed taking full advantage of the technique's uniqueness is limited within both research and industry. Much research effort is needed to establish comprehensive guidelines and frameworks to guide the designers.

In summary, extensive literature is available with a focus on defining process windows, guidelines, frameworks and methodologies which have augmented the concept of design for SLHT and DfAM. However, the sensitivity of SLHT and SLM components' geometry to the process's variability is an aspect that is unaccounted for within the framework. A framework with a set of activities within the broader design framework to optimize the geometric design and process design accounting for the process variability effects is, therefore, desirable.

2.7 Variation simulation

To predict and suppress the effects of possible sources of geometric variation in the early design stages, many methods have been developed over the years for both rigid and non-rigid models, as presented in [Chase and Parkinson, 1991, Nigam and Turner, 1995, Cai et al., 1996, Hu et al., 2001]. These methods have laid the foundation for several simulation tools. A methodology and a software tool called RD&T was developed for evaluating robustness and geometric stability and has evolved over the years [Söderberg et al., 2016]. This tool is based on Monte Carlo (MC) simulation and has finite element analysis (FEA) capability to enable non-rigid variation simulation. Monte Carlo simulation is based on running multiple iterations of the model as in random sampling. For each sample, random variates are generated on each input variable, and computations are run through the model, yielding random outcomes on each output variable. Since each input is random, the outcomes are random [Thomopoulos, 2012]. RD&T was used in current research to analyse geometric variation to a very brief extent. Therefore, before diving into a discussion considering the effect of heating and melting in variation simulation and the challenges associated with it, the fundamentals of analysis in RD&T are explained.

Stability analysis is the first step, which concerns evaluating the geometrical robustness of the chosen concept with respect to its locating scheme [Söderberg and Lindkvist, 1999]. A small variation is induced into the locator point, and its effect on the critical areas of the part geometry can been determined. The root sum square of variation in the locator points can be calculated and represented in colour-coded form. This colour coding provides information that could be used to make necessary changes in the locator positioning. The analysis can be re-run after the positioning changes to determine the differences in effects.

Once the robust locating scheme is selected based on the aforementioned analysis, tolerances can then be allocated. ***Variation analysis*** enables simulation of the effect of allocated tolerances for those locator points on the critical areas of the part geometry [Lindkvist and Söderberg, 1999]. Variation analysis performed based on Monte Carlo simulation allows one to check whether the effects of simulated variations are within the specified limits for the critical areas. If outside the limits, then ***contribution analysis*** can be performed to determine which locator points contribute to variation and where the tolerances could be tightened [Söderberg and Lindkvist, 1999].

2.7.1 Compliant variation simulation

Variation simulation has, thus far, been explained with the assumption that the parts are rigid. In the case of non-rigid parts, such as the sheet metal parts, the scenario is different. They may have to be constrained using extra locator points due to the compliant nature of the sheet metal parts. In reality, this is performed, for example, using clamps or weld joints, which could deform the sheet metal part, the effect of which should be considered in the variation simulation environment. Moreover, mating of adjoining parts needs be accurately replicated. Such considerations have been successfully demonstrated by combining FEA with MC simulations and method of influence coefficients (MIC) [Dahlström and Lindkvist, 2007, Wärmefjord et al., 2013, Lorin et al., 2014c]. Research has progressed further in optimizing the joining sequence [Lorin et al., 2018, Sadeghi Tabar et al., 2019] and selective assembly to match individual parts [Rezaei Aderiani et al., 2019], all towards mitigating the effect of incoming part variation on the assembly.

2.7.2 Thermal effects in variation simulation

Limited work towards considering the effect of temperature and heat in variation simulation has been conducted, mainly using the welding process as an example. Variation simulations and welding simulations were combined to consider the influence of heating and cooling processes on geometric variation in [Pahkamaa et al., 2012]. Here, the significance of considering non-nominal conditions was demonstrated, as the difference between deviation of nominal and non-nominal parts due to the influence of welding was found to be quite large. The study, however, had limited population of non-nominal parts, which would otherwise be computationally heavy. A relatively faster variation simulation approach for welded assemblies was demonstrated using a thermo-elastic finite element model in [Lorin et al., 2014a, Lorin et al., 2014b]. The approaches were made more robust by considering various factors [Lorin et al., 2014c, Lorin et al., 2015]. A summary of considering the effect of temperature with a focus on methods and tools to enable variation simulation can be found in [Lorin, 2014].

Extending the same approach to variation simulation of SLHT and SLM, however, is challenging. For example, most of the aforementioned studies have been for a single continuous weld path. Both of these processes (SLHT and SLM) have multiple heating and melting paths to be considered during variation simulation which would result in a large number of iterations and would be extremely computationally heavy. There is growing interest in recent years to create traceability of the effect of material-process-microstructure properties on geometric variation. Such predictions, however, would require coupling of different simulation environments. Thus, a clear need exists for simulation approaches that are flexible enough to provide different levels of accuracy based on the level of detailing required. Another significant challenge is knowledge of what factors to vary and how much to vary, to determine their influence on geometric quality. The decision could be based on user experience or made through trial-and-error practices. Having information on what unit disturbances to consider when performing the sensitivity analysis will equip the designers with sufficient knowledge to minimize the design's sensitivity to process variation.

2.8 Introduction to discrete element method

The discrete element method (DEM) is a numerical method based on Newtonian interactions of a system of particles where constitutive relations including contacts and collisions, heat transfer, inter-particle bonds and forces and reaction to external fields are resolved. The DEM is used for simulating large populations of particles such as powders, granules, and rock and ore particles, among many other materials. The DEM was originally proposed by Cundall and Strack [Cundall and Strack, 1979] in a series of publications and has since been further developed by a wide range of contributors spanning many different fields of engineering and science. The DEM has been applied to simulate AM powders in the SLM process in several works such as [Lee and Zhang, 2015, Meier et al., 2019]. In this thesis, the DEM simulation tool used is Demify™, developed at Fraunhofer-Chalmers Research Centre (FCC) for industrial mathematics. More information on the fundamentals of the DEM and the details of its applicability in AM can be found in [Jing and Stephansson, 2007, Steuben et al., 2016, Parteli and Pöschel, 2016].

2.9 Introduction to computational fluid dynamics

Computational fluid dynamics (CFD) can be defined as the analysis of systems involving fluid flow, heat transfer and associated phenomena by means of computer-based simulations [Versteeg and Malalasekera, 2007]. The technique has been widely used for various applications such as aircraft and vehicle aerodynamics analysis, turbomachinery flow analysis and chemical process engineering, to name a few. Today, CFD is extensively employed in research to study the melt pool dynamics in AM processes. The fundamentals of CFD lie in the governing equations of fluid dynamics, i.e., the continuity, momentum and energy equations.

In this thesis, CFD software called IPS IBOFlow®, developed at FCC, is used to simulate the melt pool dynamics of the SLM process. IBOFlow (Immersed Boundary Octree Flow Solver) is a finite, volume-based, incompressible, segregated Navier-Stokes solver based on unique immersed boundary methods and a Cartesian octree grid that can be dynamically refined and coarsened. The software has previously been used to simulate, for example, the additive manufacturing in bio printing [Göhl et al., 2018b] and surface tension- driven flows [Göhl et al., 2018a]. For more details on the theoretical aspects of the CFD, such as the finite volume method, see [Versteeg and Malalasekera, 2007, Wendt, 2008].

2.10 Introduction to finite element method

The finite element method (FEM) is a numerical method commonly used for solving complex engineering problems. The method was initially applied in the field of structural mechanics to analyse aircraft structures and later extended to problems related to heat conduction, fluid dynamics, and electric and magnetic fields, to name a few.

In this method, as the term FEM suggests, the geometry of the matter (continuum), be it solid, liquid or gas, is discretized into many small, interconnected regions called finite elements. The shape and size of elements during discretization depend on the geometry of the matter, required level of accuracy, and computation time. See Figure 2.18 for examples. The points of interconnection between these finite elements are considered nodal points or nodes. A simple function is used to approximate the variation of the field variables, such as the displacements, stress or temperature inside the continuum. The function, however, is defined in terms of the field variables at the nodal points, since the field variables inside the continuum are unknown. Thus, the field equations for the entire continuum are represented by the nodal values of the field variable. By solving the field equations, the nodal values of the field variable will be known. From there, the approximating functions define the field variable throughout the assemblage of elements. Further details on the application of FEM for a variety of problems can be found in [Rao, 2017, Zienkiewicz et al., 2005].

In this thesis, FEM is used to simulate how the solidified material distorts and to predict how the resulting strain and stress fields evolve as a result of heating, melting and solidification. The FEM approach for thermo-mechanical simulation of the AM process stems from welding simulation due to the many similarities between welding and metal AM simulations [Gouge and Michaleris, 2017]. A structural mechanics simulation tool developed at FCC is used to perform the thermo-mechanical simulations. The simulation tool includes a wide variety of material models for metals and polymers and allows analysis of beams, shells and volumes subject to large deformations and mechanical contacts [FCC, 2021].

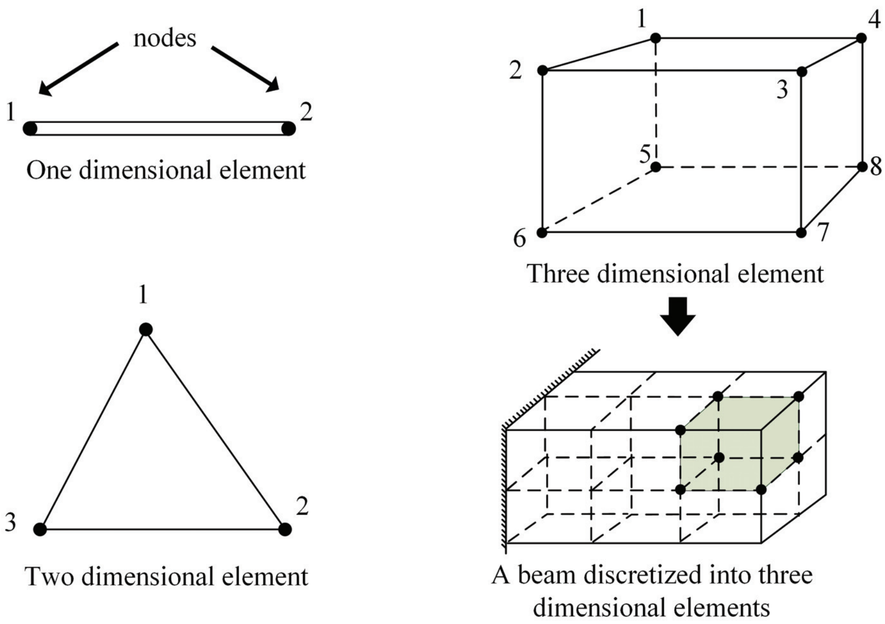

Figure 2.18: Types of elements that could be used in the discretization process [Rao, 2017]

2.11 Inspection

Inspection is the process of determining whether the manufactured product is within the desired specification or deviates from it [Kennedy et al., 1987, Newman and Jain, 1995]. Inspection techniques and procedures have played a vital role in the quest towards achieving high-quality,low- cost products. The coordinate measuring machine (CMM), a well-known contact-type inspection technology, has led the manufacturing industry in the quality control process. Due to its long history of usage in the industry, calibration processes and best practices are well established today. Contact type inspection techniques, though well-established, are disadvantageous due to high operating time when measuring large sets of points. Moreover, they show difficulties in measuring free-form surfaces. With growing complexity in the geometry of the products, as well as shorter development times, industry is shifting focus towards faster available inspection techniques.

Non-contact laser-based inspection techniques are extensively used in the manufacturing industry and will play a pivotal role in the concept of digital twin for real-time geometry assurance [Söderberg et al., 2017, Rezaei Aderiani, 2021]. Three dimensional laser scanning allows the acquisition of larger sets of measurement points in a shorter duration. They offer a high degree of precision and low cost in comparison to other non-contact measurement equipment. Most of the 3D laser scanners are based on the laser triangulation principle by means of a laser stripe [Ebrahim, 2015]. Typical laser-scanning equipment consists of a robotic arm equipped with a laser-scanner probe at the end of the arm. The laser probe consists of a projector that emits a laser beam on the surface. The laser beam in the form of laser stripe is incident on the object's surface and reflects back to the laser probe system consisting of cameras. The data from scanning is generated in the form of point cloud data consisting of X, Y and Z coordinate values for each measured point through image processing and triangulation.

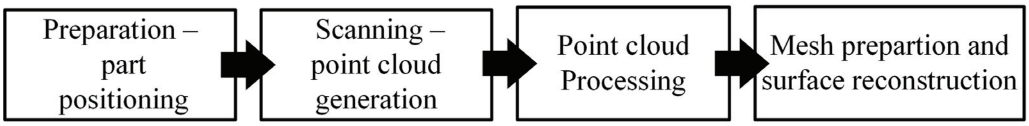

Figure 2.19: Sequence of steps in generating inspection data from 3D laser scanning

This point cloud data can be processed further to reconstruct into a mesh or a surface model using various commercially available reconstruction software such as CATIA, Geomagic, MeshLab and Rhino, to name a few. Hexagon [Hexagon, 2021], ATOS [GOM, 2021] and Faro [Faro, 2021] are some of the popular 3D laser scanners used in the industry. In this thesis, 3D laser scanning was employed to capture the point cloud data of laser heat-treated sheet metal blanks and components. Thus, the previous description is intended to provide a brief understanding of the 3D laser scanning process. The sequence of steps followed to capture the data is depticted in Figure 2.19.

CHAPTER 3

Research Approach

This chapter briefly presents different approaches for a scientific study and discusses the research approach employed in this work.

3.1 Background

Design research can be defined as a systematic inquiry aimed at obtaining knowledge of, or in, the embodiment of configuration, composition, structure, purpose, value and meaning in man-made things and systems [Archer, 1981]. The relation between design and research has evolved over the years. One of the main reasons has been the complexity of requirements which challenge the traditional practices followed. Ekeles [Eekels and Roozenburg, 1991] compared the structures of research and engineering design (Figure 3.1). The work stated that the outcome of the research process was knowledge in the form of theories, which belonged to realm of the mind in the factual world. While the outcome of the design process was the final design, which belonged to the realm of material reality, the interdependency between them was strongly acknowledged. In traditional practices, the design process was not regarded as an opportunity to learn and build knowledge. Hubka and Eder [Hubka and Eder, 1988] were instrumental in changing this notion about design science. According to them, design science consists of using scientific methods to analyse technical systems such as products and process, their relationship to other systems and the processes used in designing them. Horvath defined design research as generating knowledge about design and for design [Horvath, 2001]. Blessing and Chakrabarti [Blessing and Chakrabarti, 2009] described design research as the integration of two aspects of research: the development of understanding and the development of support. Better understanding of existing design and development of means of support can make design more effective and efficient.

The trigger for action in the form of research arises from either the current state of the subject of interest or the expected future state of it. This research work is no different. This work was carried out in Wingquist Laboratory (Section 3.4) where it began due to an industrial need as well as a research gap. The work was conducted in close collaboration with an industrial partner. The objective of this research work was to generate knowledge and develop support that could aid in making better design decisions. The main contribution of this

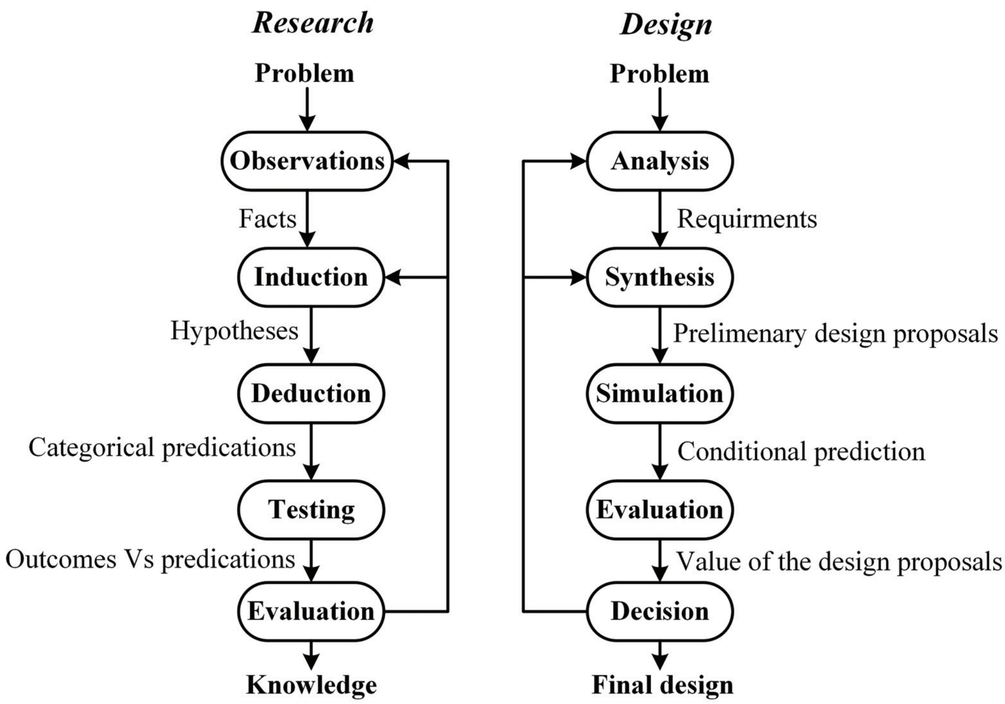

Figure 3.1: Research and Design process comparison redrawn from [Eekels and Roozenburg, 1991]

research is to design science. The research topic is in the area of geometry assurance and involves developing knowledge on managing manufacturing variation, which otherwise affects the quality of the end product. Access to substantial manufacturing process knowledge allows designers to reduce downstream production costs to produce robust design concepts that are insensitive to manufacturing variation. However, to develop knowledge and support which could aid in mitigating geometric variation effects through robust design concepts, understanding the manufacturing process and geometric variation contributors is vital.

3.2 Research frameworks

A significant characteristic of research is that it is methodologically well executed. Addressing the research gap and industrial needs will involve multiple stages. Thus, using a structured methodology becomes necessary. Design methodology is a concrete course of action for the design of technical systems that derives its knowledge from design science and cognitive psychology and from practical experience in different domains [Pahl et al., 2007]. Many methodologies have been proposed thus far to perform design research: the Mitroff model [Mitroff et al., 1974], theory of technical systems [Hubka and Eder, 1988], axiomatic design [Suh, 1998], logic of design [Roozenburg and Eekels, 1995], and framework for modeling of synthesis [Takeda et al., 2001]. However, most of the approaches lack clarity on how they could be implemented based on the nature of the problem at hand. This work employs the design research methodology (DRM) presented in [Blessing and Chakrabarti, 2009] that follows a more rigorous approach to make design research more effective and efficient.

3.3 Design research methodology

Design research methodology (DRM) is defined as an approach and a set of supporting methods and guidelines to be used as a framework for conducting design research. It is a generic methodology that links the research questions together and provides support to address them in a systematic manner.

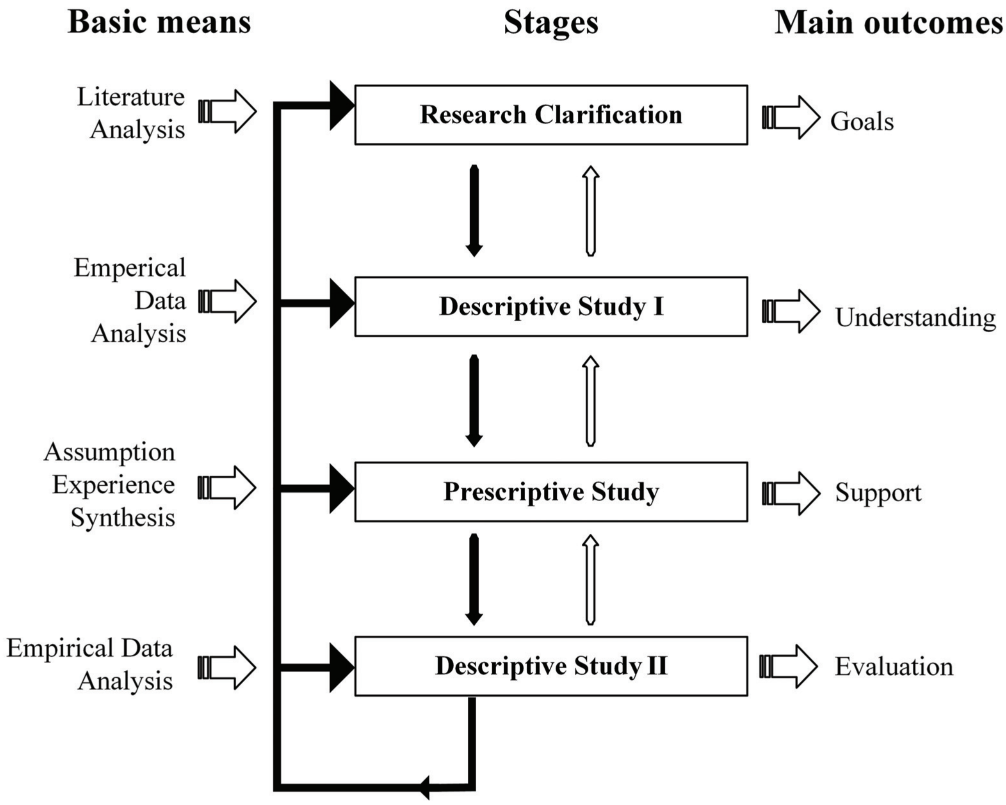

Figure 3.2: DRM framework redrawn from [Blessing and Chakrabarti, 2009]

This methodology is divided into four stages: research clarification (RC), descriptive study I (DS-I), prescriptive study (PS) and descriptive study II (DS-II) as shown in Figure 3.2. To obtain successful results from design research, it is curcial to have information available from past research and to formulate research goals [Edelson, 2002]. The first stage of research clarification involves understanding the problem situation to gain more clarity with the objective to establish the research goal and identify the preliminary success criteria. This is often done by performing literature studies. Collecting available information allows the researcher to describe the problem and the desired solution to an extent. Quite often, not all information is readily available. More knowledge must be acquired to gain more clarity and elaborate on the problem to be addressed. This leads to the second stage of the methodology, DS-I. In DS-I, the objective is to gain more information to form a detailed description and highlight the factors that must be addressed to solve the problem situation. More knowledge can be obtained through observation of the process associated with the problem, experimental investigation and interviewing stakeholders such as designers or manufacturing engineers. Based on the understanding gained in this step, the success criteria can be clearly defined.

Concrete evidence may not be possible at DS-I but it provides sufficient information on the factors that influence the nature of the problem, as well as the final research goal. The third stage, PS, consists of developing support in the form of methods and tools to address the research goal. Preliminary investigations are performed to demonstrate the nature the problem and explore possible ways to solve the problem. The fourth stage, DS-II, consists of evaluating the effect of support and the degree of its effect in achieving the desired goal. If the effect of support is to be improved, the DRM process can be iterated. It is not necessary to follow a particular sequence of steps in the process. Based on the level of maturity of the problem at hand, the appropriate stage in the DRM process could be chosen.

3.4 Wingquist Laboratory research and implementation process

As described in the introduction chapter, the research gap was identified from an industrial need. The Wingquist Laboratory process follows a similar practice as the DRM (Figure 3.3). The first step in the framework is to further understand the research gap that arises from the industrial requirements and to define the research goal. More clarity about the problem is gained, and the factors influencing the goal are established. This is similar to the research clarification and DS-I in the DRM process. The next step is to develop a prototype or a working procedure that addresses the goal. This could be in the form of a software demonstrator as well. Following this, the prototype undergoes evaluation by the industry. This is similar to the PS and DS-II steps in the DRM process.

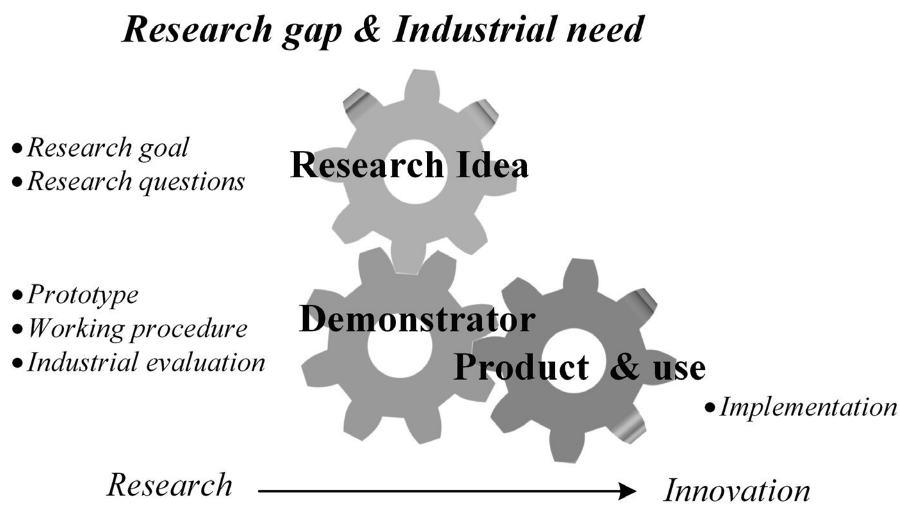

Figure 3.3: The Wingquist Laboratory research and implementation process

3.5 Research approach applied in this work

Planning of the research process requires holistic thinking and an end to end perspective. For this reason, DRM was chosen to follow a systematic approach in the planning of this research work. Implementation of each step from the DRM process is explained in the following sections.

3.5.1 Research clarification

Obtaining a thorough understanding of the existing situation is crucial. The research process began with discussions among the stakeholders, i.e., the industrial stakeholder, the research group and the researcher, to identify the most important problems and questions and to clarify the boundaries of the research topic. From the preliminary discussions, it was clear that due to the novelty of the manufacturing processes considered in the study, the effect of SLHT and SLM on the geometric quality needed to be well understood. Identifying the relevant aspects and influencing factors would consequently enable the establishment of strategies to perform geometry assurance of SLHT-and SLM-produced products, specifically in the early design stages.

This enabled defining the success criterion and measurable success criterion for the research. The *success criterion* was to have geometry assured laser-processed metal components produced from the SLHT and SLM processes. However, given the vastness of the subject at hand and considering the time frame of the research project, it would not be possible to fully demonstrate the success criterion. Instead, a measurable success criterion is presented, which is linked to the success criterion and acts as a proxy to it. The *measurable success criterion* in this thesis was to capture the effects of a set of identified influencing factors on geometric quality and demonstrate how to account for their effects. A reference model, in which the SLHT and SLM-based factors that influence geometric quality are presented, was developed to understand the existing situation (see Figure 3.4).

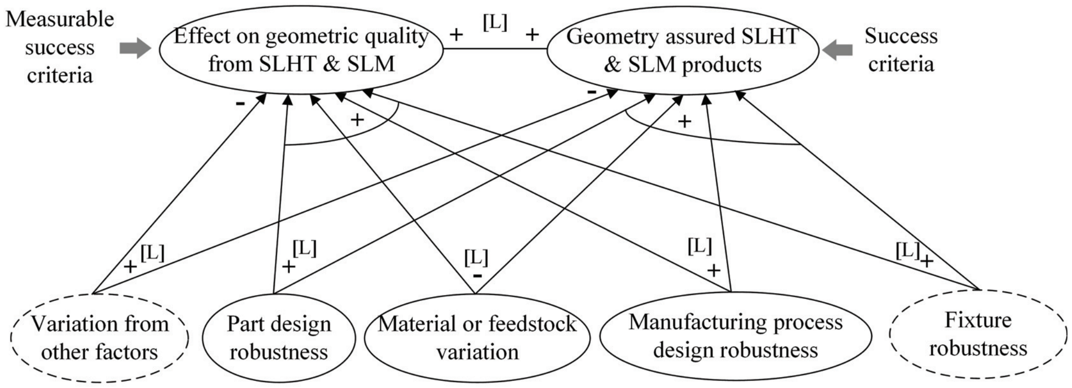

Figure 3.4: Reference model

The figure can be interpreted as follows. The influencing factors, such as the part design robustness and manufacturing process design robustness, are aspects of the existing situation that affects the geometric quality of the SLHT-or SLM-produced products. Each of the listed influencing factors is formulated as an attribute of an element that is considered relevant and can be measured. For example, the manufacturing process design is the element while the robustness is its attribute. Each factor is linked to the success criterion and measurable success criterion. The link defines the relation between them. The '+' and '-' signs at the ends of a link denote how the attribute's value at one end relates to the attribute's value at the other end. For example, a robust manufacturing process design (+) has a positive effect on the geometric quality (+) of the SLHT or SLM produced products. The arrows indicate causal links between the influencing factors (cause) and the criteria (effect). When several links towards a criterion have the same effect, then it is collectively represented by an arc.

The factors that are marked in discontinuous lines mean that they are outside the scope of this research project; however, based on evidence found in the literature studies, they are expected to influence the selected criteria. As shown in the figure, fixture robustness and variation from other factors are beyond the scope of this thesis. The links connecting the factors are labelled with the source of information connected to it within brackets. If there are any literature studies that discuss the link between factors to some extent, the literature references can be cited in the brackets to provide the source of information. The links between the factors and criteria in Figure 3.4 are mostly based on the literature evidence that has already been highlighted and discussed in the previous chapter. Thus, these links have been labelled as 'L' instead of citing the specific literature references to maintain legibility and to avoid overcrowding of the figure.

On the basis of the reference model, an impact model was developed that includes the desired outcome and as well as the supports that could help in achieving the desired outcome. The supports are represented as hexagonal elements as illustrated in Figure 3.5. These supports are connected by a causal link with a positive effect (+) towards their respective 'key' factors but without any sign at the support end. This implies that the details of the support are unknown at this stage, but it is assumed to have a positive effect on the outcome. The label in brackets, 'A', means that the relation is assumed to exist. The support elements in this thesis that are assumed to help in achieving the measurable success criterion are shown in Figure 3.5. Based on the reference model and the impact model, research questions presented in the introduction chapter have been formulated.

It is worth mentioning again that this thesis had evolved from first being limited to only the SLHT process and later being extended to the SLM process. Regardless, due to the commonality between the two processes in some aspects and the common measurable success criteria, the reference model and the impact model continued to be applicable with minimal modifications.

Based on the reference model and the impact model, the research questions presented in the introduction chapter were formulated. The first research question was formulated to clarify various sources related to the highlighted influencing factors that affect geometric quality, as pertains to SLHT and SLM. The second research question was formulated to focus on how some of the most relevant sources identified through the first research question can be adjusted to minimize the effect on geometric quality. Since the intention within the geometry assurance framework is to assist in the early design stages where virtual development is most favoured, the third research question was formulated to illustrate how simulation support could be utilized in predicting the effect on geometric quality and assist in the decision making. This question is however limited to the SLM process.

In the DRM process, each of the four stages can be conducted in the form of a review based study, a comprehensive study or an initial study. A review-based study mainly consists of a literature review of the problem. A comprehensive

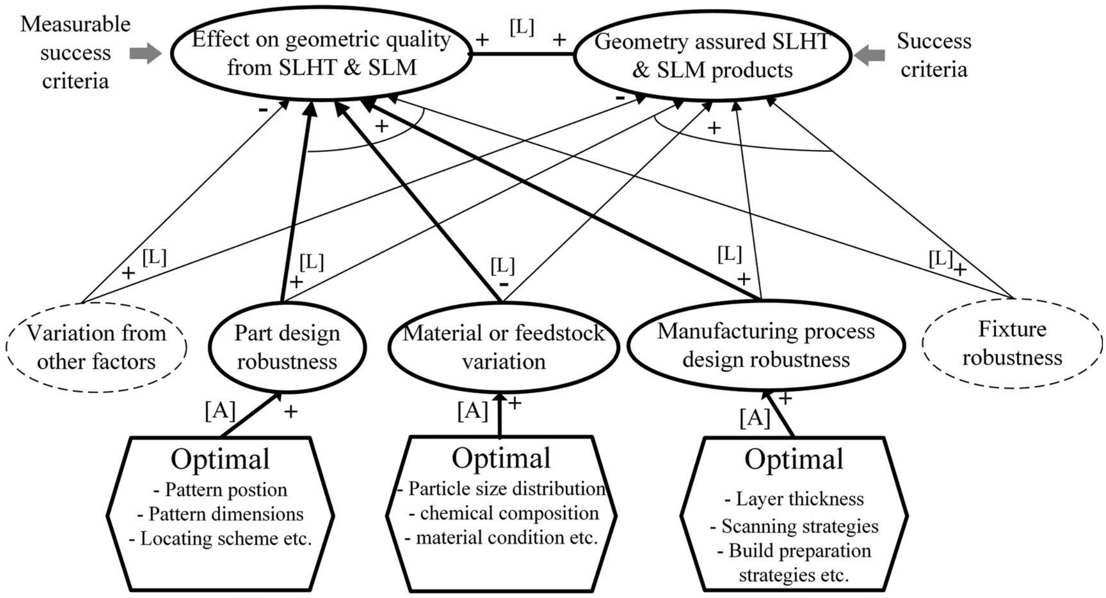

Figure 3.5: Impact model

study is pursued when there is insufficient evidence from the review study. The initial study is often chosen to close a project where the knowledge gained from the comprehensive study is demonstrated to an extent. In this thesis, a review-based study at the RC stage, a comprehensive study at the DS-I stage, and an initial study at the PS stage to close the project were undertaken. No DS-II study was undertaken in this thesis due to the nature of the research problem and the time limitations of the project.

3.5.2 Descriptive study I

A comprehensive DS-I consists of performing a detailed literature review, identifying the research gaps, determining the research focus, planning and performing empirical studies to address the gaps, and, finally, drawing necessary conclusions. The literature study conducted in the RC stage to establish the reference model and the impact model was also extended for a comprehensive DS-I review study. The next step was to gain a better understanding of the current situation by clarifying the significant factors that influence the success criteria. This laid the foundation for the empirical studies. Empirical studies were then performed to study the assumptions of the link between the supports and the key factors presented in the impact model. Since the objective of the research was to apply the concept of robust design and lay the foundation for geometry assurance, the review study first focused on identifying the sources of geometric variation, which included factors that are controllable and uncontrollable or, rather, deemed expensive to control. The study resulted in identifying a set of significant factors linked to the supports (hexagonal elements) of part design, process design, and feedstock, as presented in Paper C and Paper D. This helped in answering the first research question (RQ1). From here, some of the controllable factors that have the potential to minimize the effect of SLHT and SLM on geometric variation were considered for further empirical studies. Papers A, B, E and F were all based on empirical studies that facilitated a deeper understanding of the considered significant factors and their effect on geometric variation. This helped in answering RQ2.

3.5.3 Prescriptive study

Prescriptive study (PS) involves utilizing the information gained from the DS-I stage to develop methods and tools that address the research gaps and the success criteria. In the early stages of the product development process, simulation support in the form of methods and tools that enable analysing various concepts to assure the product's geometry is desirable. This motivated the studies in Papers E and F, where some of the existing simulation tools were utilized and new methods were proposed to support the geometry assurance process. This helped in answering RQ3. Thus, the thesis concluded with this initial PS to demonstrate the consequences of the results and illustrate, to an extent, how the understanding gained can be used towards the geometry assurance of SLHT- and SLM-based products.

Publication of scientific papers was the outcome of the research conducted. The summary of the publications, their affiliation to the research questions and the level of contribution to different stages of the DRM process are summarized in Table 3.1.

Table 3.1: Research results as per the DRM framework. Symbol used is 'laser beam'.

Papers	RQ	RC	DS I	PS	DS II
Paper A	RQ 1, RQ 2				
Paper B	RQ 1, RQ 2				
Paper C	RQ 1				
Paper D	RQ 1				
Paper E	RQ 2, RQ 3				
Paper F	RQ 2, RQ 3				
Low contribution: 			High contribution: 		

3.6 Methods employed

Each stage in the DRM process is propelled by different study methods. In this thesis, literature studies and empirical studies were the two main study methods used to gather necessary knowledge and develop a deeper understanding of the research topic.

3.6.1 Literature studies

Literature studies were mainly conducted to understand the existing knowledge in the areas concerned with this research topic. These studies mostly involved collecting information from scientific publications and experiences from the industrial stakeholder. The results of these literatures studies have been presented in the previous chapter.

3.6.2 Empirical studies

In empirical studies, it is generally better to have a deep understanding of a few factors than a shallow understanding of a large number of factors [Blessing and Chakrabarti, 2009]. Physical and computer-based experiments were used during the course of this thesis to study various factors and collect the data. The data from the physical experiments were collected using the laser scanning inspection techniques. The data collected in the form of point cloud were processed further using point cloud processing software and analysed using RD&T software. Design of experiments was used when analyzing factors in the studies involving computer experiments (Paper E and Paper F). Here, simulation tools based on DEM, CFD and FEM platforms were utilized to conduct the experiments. Every step in the empirical studies was documented to continuously reflect on the data collection process.

CHAPTER 4

Results

The learnings from the research conducted thus far have resulted in six publications that are appended with this thesis. This section summarizes of the appended publications. The sequence of the papers is based on the order of their publication.

4.1 Paper A: Geometrical variation from selective laser heat treatment of boron steels

Background: Literature studies were performed in the early stages of the research to understand the SLHT process and explore the possible sources of geometric variation. Based on the available information from literature studies and inputs from the industrial stakeholder's experiences, possible sources of variation that influence the geometric quality of sheet metal components when subjected to SLHT were identified and mapped. This is discussed in detail in Paper C. The criterion when identifying the sources of variation was to consider sources that could be optimized in the early design concept stage in accordance with the geometry assurance process. In this paper, two such sources, namely ***the laser heat treatment pattern dimension and the laser heating direction sequence***, were chosen to understand their influence on the geometric variation outcome. The laser heat treatment pattern dimension is of particular interest as, based on the dimensions of the pattern, the percentage of heat treatment on the blank varies. Laser heating direction sequence is of particular interest as the chosen heat treatment pattern can be applied in many possible laser heating direction sequence strategies. The heat treatment pattern when planning for the application of SLHT of sheet metal blanks is decided based on two criteria, namely 1) ***Forming requirements***: The objective of locally modifying the material properties is solely to aid in the cold forming process and 2) ***Structural requirements***: The objective is to locally modify the material properties to impart certain strength in the desired area, mainly to enhance the crash performance. Sometimes, the objective could be to fulfil both requirements. The choice of local areas is either known through previous history of the part or through information from forming simulations and crash simulations.

Method: Through a set of physical experiments, different strategies were tested by varying the laser heating direction sequence and heat treatment pattern dimensions. Specifically, a square grid heat treatment pattern was chosen, and two grid dimensions were considered. Three heating direction sequence strategies (scanning paths) were applied, meaning three heating direction sequences for each grid dimension type were tested. The position of the heat treatment pattern was fixed and was chosen based on the results from earlier industrial and literature studies. In terms of robust design concept, the heating direction sequence strategy was the control factor for a given input pattern dimension. The incoming variations in the sheet metal in the form of, for example, chemical composition variation and initial stress state were considered uncontrollable noise factors. The scanning strategy here was a process design factor, while the pattern dimension wass a part design factor.

Outcome: The results showed that for a given heat treatment pattern dimension, altering the laser heat treatment sequence altered the geometric variation outcome at blank level (see Figure 4.1). The magnitude of the geometric variation outcome differed among the two heat treatment pattern dimensions chosen in the study. An explanation to the effect of altering the laser heat treatment scanning sequence strategy on the geometric variation was pursued. During the laser heat treatment process, superposition of microstructural transformation stresses and thermal stresses occur due to a thermal gradient across the sheet metal. As the stresses generated exceed the yield stress of the material, plastic deformation occurs, which is further influenced by the application of external forces such as fixtures and clamps. The resulting distortion varies for example, when there is variation in chemical composition or residual stresses from previous manufacturing process steps. The stress distribution varies from blank to blank, as does the shape of the blank due to distortion.

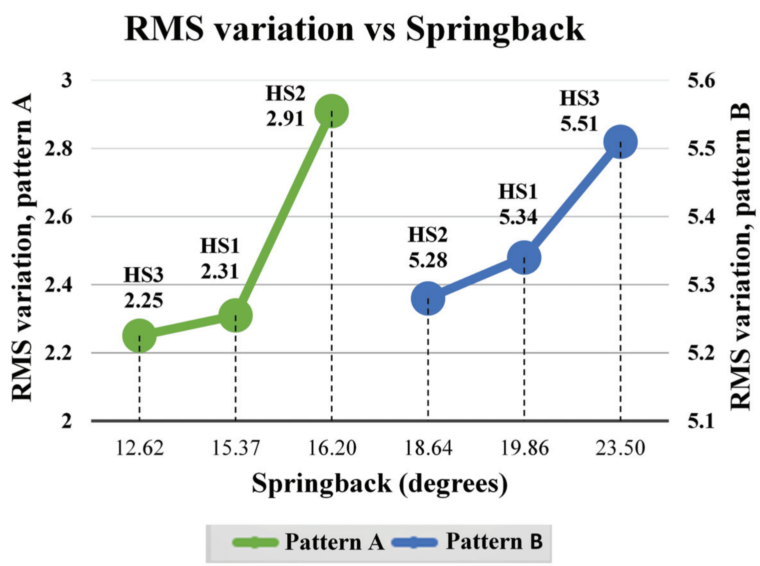

Figure 4.1: Geometric variation and springback results due to change in scanning sequence strategy for heat treatment pattern A (left) and pattern B (right)

For a given heat treatment pattern dimension, the effect of laser heat treatment sequence strategy of the blanks also affected the outcome from the subsequent stamping process as illustrated in Figure 4.1. Laser heat treatment sequence is a vital parameter because based, on the choice of sequence, the total processing time for performing SLHT varies. This will have cost implications on the end product. However, it should be noted that in this study, only a single laser source was employed. If multiple laser sources are employed, then the scanning sequence strategy can be optimized in a manner that negates the issue of processing time. That will, however, bring in new set of complexities in terms of robot path planning to avoid clash and still be able achieve the desired material properties.

Some general conclusions from the results are that the laser heating direction sequence strategy that influences the final outcome could be adjusted to minimize the effect on geometric variation. Moreover, the adjustment of laser heating direction sequence depends on the heat treatment pattern, its dimensions which are mainly decided on the manufacturing or functional aspects of the product.

4.2 Paper B: Influence of selective laser heat treatment pattern position on geometrical variation

Background: Most of the research conducted concerning SLHT has been about material specific process windows, mainly to demonstrate the formability and strength enhancement possibilities. Therefore, another aspect from the literature studies that required investigation was the importance of heat treatment pattern position and its effect on the geometric variation. As previously mentioned, heat treatment patterns and dimensions are decided based on the local areas on the sheet metal blank that require modification either for ease of manufacturing or for crash performance requirements. Various concepts could be explored by adjusting the position of the heat treatment pattern on the sheet metal blank. Heat treatment pattern dimension implies a certain percentage of heat treatment applied on the metal blank. Thus, varying the pattern position for the same percentage of heat treatment is of interest. The effect due to change in pattern position could be further altered due to variations in fixture locators or clamping tools. In addition, performing this study was of interest to consider possible positioning errors of the sheet metal blank during the SLHT setup that could trigger a change in originally intended pattern position to be applied on the blank.

Method: Through physical experiments, square grid patterns with two different dimensions were considered. An initial nominal pattern position and the adjusted pattern position were chosen based on the results from earlier industrial and literature studies.

Outcome: The results showed that a change in pattern position unfavourably affected the geometric variation, as well as the springback outcome (Table 4.1). However, the results were based on the initial and offset positions considered in this test case. The nominal position of heat treatment patterns A and B was chosen such that the entire pattern was positioned at the centre of the blank. It was positioned equidistant from all edges of the blank. After offsetting the pattern position, an increased effect on geometric variation was observed. However, if the offset position were initially considered to be the 'nominal position' to begin with, the nominal position considered in this test case would then become the new 'offset' position. As a result, offsetting the pattern would, in fact, minimize the effect on geometric variation and springback from the process.

Table 4.1: RMS deviation of laser heat-treated blanks and formed parts

Trials	RMS batch deviation - nominal pattern position		RMS batch deviation - offset pattern position	
	Pattern A	Pattern B	Pattern A	Pattern B
Laser heat-treated blanks	2.31	4.53	3.13	5.46
Formed parts	4.29	5.00	4.54	6.41

Some general conclusions from the results are that the positioning of the entire pattern or a part of it (heat treatment areas of the pattern) influences geometric variation. It can impact the assembly process and final product performance. The magnitude of the influence on geometric variation is further based on the percentage of laser heat treatment, which is based on the pattern dimensions. Even if the entire pattern is not required to be moved, but only some grid lines are to be moved, it could still be of interest to assess the effect of such adjustments on the geometric variation.

4.3 Paper C: Effect of selective laser heat treatment on geometrical variation in boron steel components: An experimental investigation

Background: This paper could be considered a precursor to Papers A and B. This is because this paper summarizes the outcomes from the literature studies and the initial descriptive study performed that laid the foundation to assess the specific set of factors discussed in Paper A and paper B. This paper gives an account of the effect of the SLHT process and how it impacts the subsequent forming and the assembly process. Unlike previous papers, the focus here was to study the geometric variation outcome for a fixed set of parameters.
Method: First, a literature study was performed to gather necessary information. Later, physical experiments were performed to demonstrate the effect at the part level, i.e., up to the cold forming process. The scanned data of the cold-formed parts were collected, and the propagation of incoming part variation at the assembly level was studied by performing spot welding computer simulations.
Outcome: A step-by-step account of geometric variation from part level to assembly level was outlined (Figure 4.2). Sources of variation that could be considered in the design for the manufacturing of tailored laser heat-treated blanks were presented (see Figure 4.3).

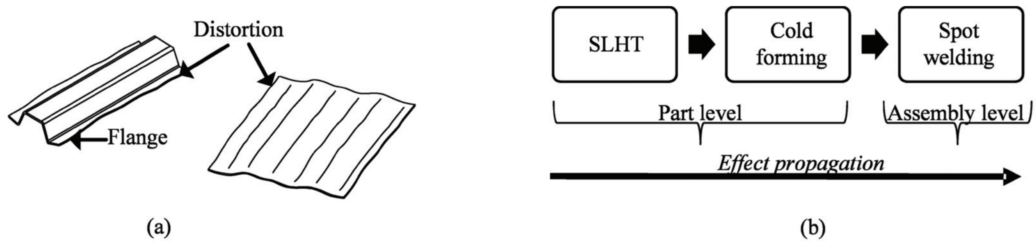

Figure 4.2: (a) Propagation of distortion from blank to cold-formed part (b) SLHT process effect propagation from part level to assembly level.

4.4 Paper D: A robust design perspective on factors influencing geometric quality in metal additive manufacturing

Background: The thesis and the research goal at this research stage evolved with the inclusion of metal AM, specifically the SLM process. The literature review revealed a clear need for a framework that accounts for geometric variation at different fabrication levels of metal AM products. Based on the experiences and learnings from the research conducted thus far on the SLHT process, and having observed commonality in the area of process design between SLHT and SLM, a more systematic approach was employed in performing the literature studies and applying the robust design thinking in the case of metal AM. Although the objective was to construct a framework considering the SLM process, the intent was to have a framework that could be more generic in nature, be it for SLM, SLHT or other similar selective laser processing techniques.

Method: A literature study was performed to collect necessary information on the significant product and process design factors related to the SLM process. The geometric variation contributors were classified into design concept, part level and assembly level. They were further organized using the block diagram (P-diagram) at each level (see Figure 4.4). Based on the sorting of these contributors from a robust design perspective, a framework for geometric robustness analysis of AM products was formulated by consolidating the block diagram (P-diagram) of each level. The process of constructing this framework was inspired and adapted from the framework of plastics design presented in [Lorin et al., 2010].

Outcome: As mentioned, this study resulted in the framework presented in Figure 4.5, which is adapted from the framework for geometric robustness in plastics design presented in [Lorin et al., 2010]. The framework was constructed from the block diagrams presented in Figure 4.4. In the presented framework, geometric robustness analysis of metal AM products is divided into part robustness, assembly robustness and functional robustness. The interconnection between different stages of robustness is presented together with the associated design activities. This framework forms the basis for developing methods and tools that could aid in geometric robustness analysis at the part level, assembly level and functional level. In addition, several potential gaps in the area of simulation support and lack of methods to utilize available simulation tools in the early design stages were identified through the literature studies.

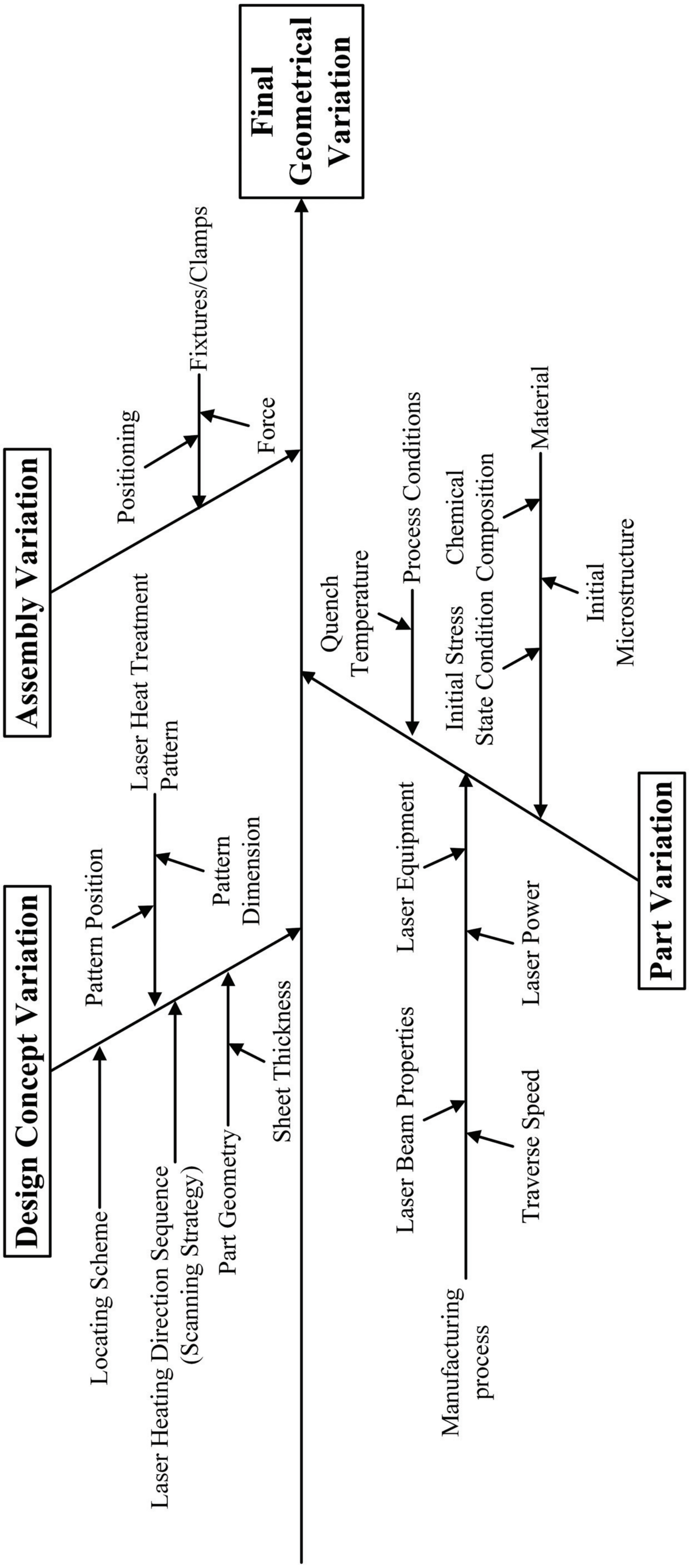

Figure 4.3: Geometric variation contributors in selective laser heat treatment process

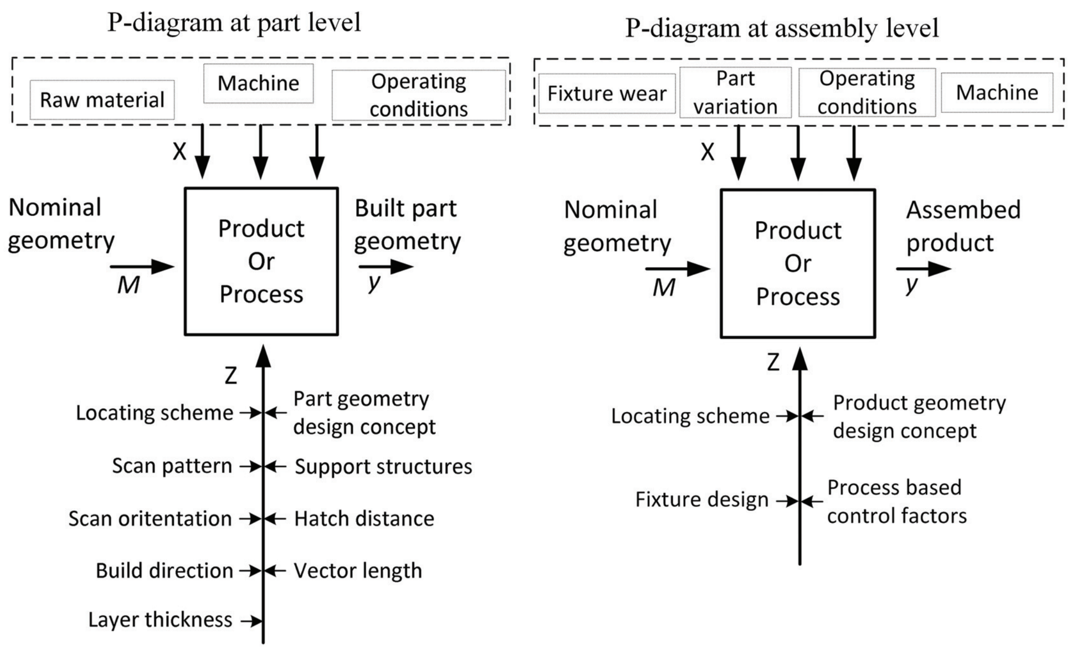

Figure 4.4: P- diagram at part level (left) and P-diagram at assembly level (right).

4.5 Paper E: A simulation study on the effect of particle size distribution on the printed geometry in selective laser melting

Background: From the literature studies for the papers published thus far, it was discovered that there are several simulation tools that have the potential to assist in making early design decisions. However, what seems lacking are the relevant methods to do so. The existing methods used to assess the effect on geometric quality for traditional manufacturing processes may not be directly applicable for novel processes considered in this study, specifically the SLM process. Given the complexity of this process due to the interaction of various factors, the need to capture the multi-physics of the process to gauge their effect on the geometric quality was evident. Hence, this study was directed towards the aforementioned research gap.

The SLM process consists of melting the raw material in powder form. This is unlike the sheet metal blanks, where the form of raw material differs and is therefore challenging. The powder bed is generated by spreading the powder on the build platform as per the pre-determined powder layer thickness. Here, particle size distribution (PSD) is an important powder material characteristic as the distribution of the powder on the build platform is dependent on it. Therefore, the effect of the stochastic nature of PSD on the printed geometry was studied in this paper.

Method: The design of experiments (DoE) approach was employed to investigate the effect of PSD on the build geometry. A full factorial design with four parameters and two levels was considered, leading to a total of 16 runs. Three in-house simulation tools built at FCC based on the discrete element method

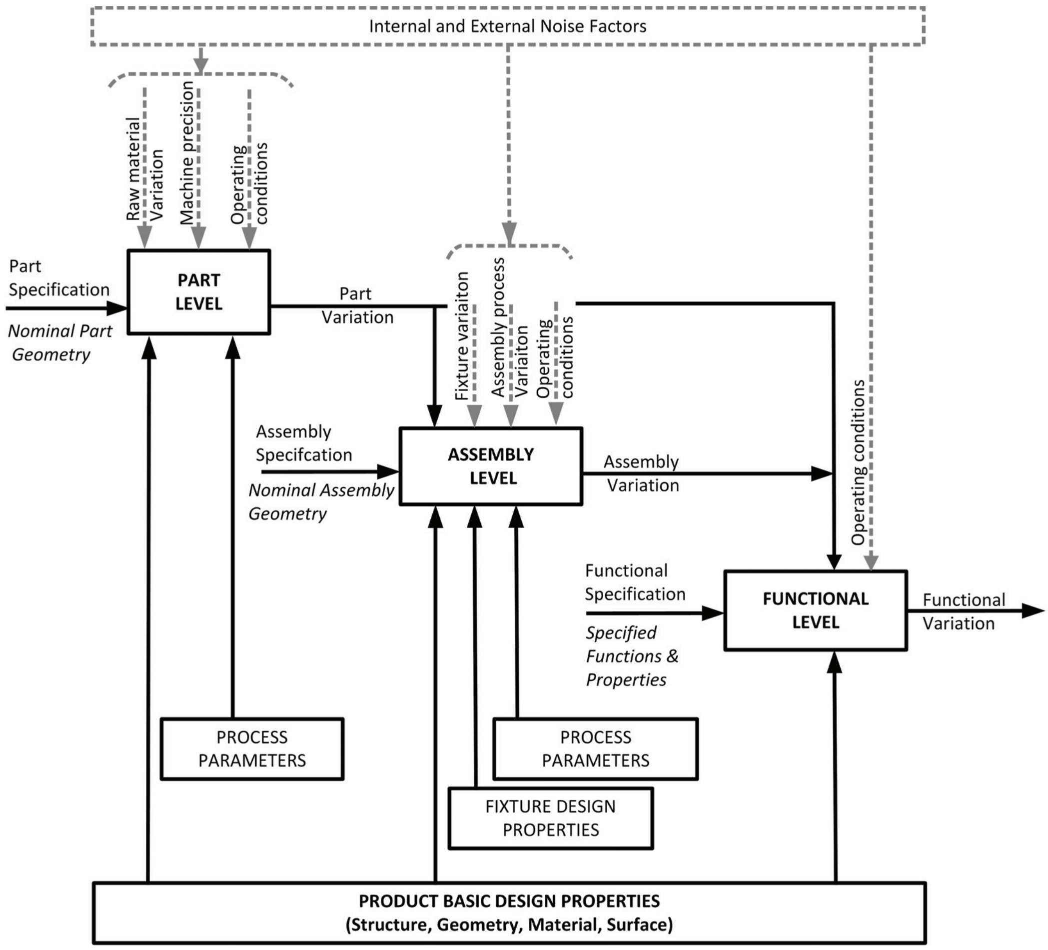

Figure 4.5: Framework for geometric robustness analysis of metal additive manufactured products.

(DEM), computational fluid dynamics (CFD) and structural mechanics were employed to generate the powder distribution, heat transfer and displacement, respectively. Powder beds with a single layer consisting of two melt tracks were simulated in this study. Packing density, powder layer thickness, melt pool layer thickness, layer displacement and final layer thickness after displacement were the responses measured from the simulations. See Figure 4.6 for the method summary.

Outcome: The results suggest that the mean particle size in the PSD greatly influenced the printed geometry. Specifically, smaller mean particle size and smaller standard deviation produced final layer thickness closest to the preset nominal layer thickness. This is an important observation because having the knowledge of final layer thickness or the final build geometry can help in compensating the 3D model or in model preparation when the slicing of the 3D model takes place. Moreover, the choice of PSD can contribute to the nature of residual stress, which, in-turn, could affect geometric variation. The learnings from this study will serve in setting up modelling and simulation to investigate multilayer-multitrack builds. The approach of combining three simulation tools establishes a way to calculate the effect of various aspects of the SLM process on the build geometry that could be used in scenarios that require detailed simulation accuracy.

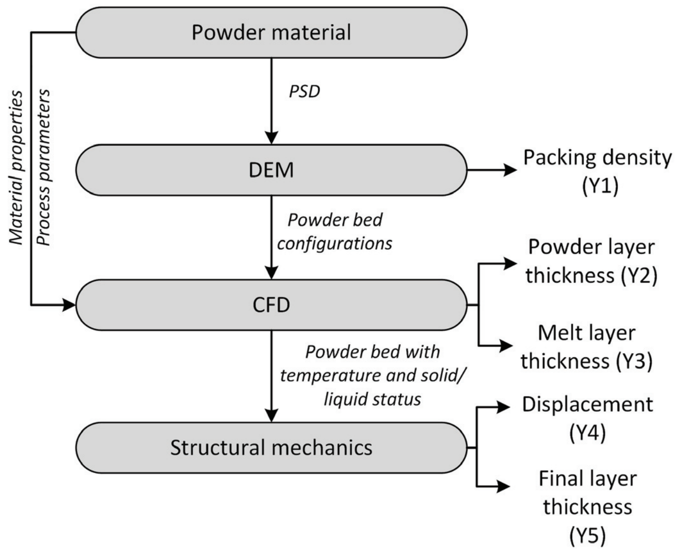

Figure 4.6: Method to integrate the simulation tools considered in the study. The responses measured at each stage are mentioned on the right.

4.6 Paper F: A simulation study on the effect of layer thickness variation on the printed geometry in selective laser melting

Background: This paper is set up based on the results achieved from the previous paper (Paper E). The objective was to extend the previous study to multiple layers and propose a faster simulation method that could assist in predicting the effect of layer thickness variation on geometric quality in early design stages.

From the previous study, it was observed that the PSD had an influence on the resulting layer thickness, which deviates from the nominal layer thickness. One general practice suggested in research to deal with this issue when fabricating SLM parts is to compensate for the deviation by adjusting the dimensions of the part in the 3D model. The knowledge on compensation is acquired by either running test builds or simulating the conditions. Running test builds is both time consuming and has cost implications. Moreover, the majority of simulation support available today considers nominal layer thickness settings when simulating the conditions. However, in reality, the layer thickness deviates from the desired nominal layer thickness. In addition, the layer thickness varies in the initial layers until it stabilizes at a certain layer thickness which, nevertheless, deviates from the desired nominal layer thickness. The data from the previous study revealed that for a fixed nominal layer thickness (67.4 μm), the shrinkage percentage varied due to the type of PSD. This observation triggered the curiosity to study such effects when extended to multiple layers. In the context of robust design, choosing a nominal layer thickness that is least sensitive to the PSD (noise) would be an ideal solution. Another perspective for looking at the problem is analysing what range of PSD would be optimal for a layer thickness value.

Method: From the results of the 16 runs in Paper E, runs that produced the highest melt layer thickness, the lowest melt layer thickness and the mean melt layer thickness were respectively considered as the upper limit case, lower limit case and mean case in this study. Figure 4.7 illustrates the method employed. The data on melt pool layer thickness of the 1^{st} layer produced in Paper E served as the starting point. The percentage difference between the mean melt pool layer thickness and the input nominal layer thickness was calculated. The percentage difference between the mean melt pool layer thickness and the nominal layer thickness calculated for the 1^{st} layer was assumed to remain the same for the subsequent layers, i.e., the percentage difference between melt pool layer thickness and the powder layer thickness of the 2^{nd} layer, and so on.

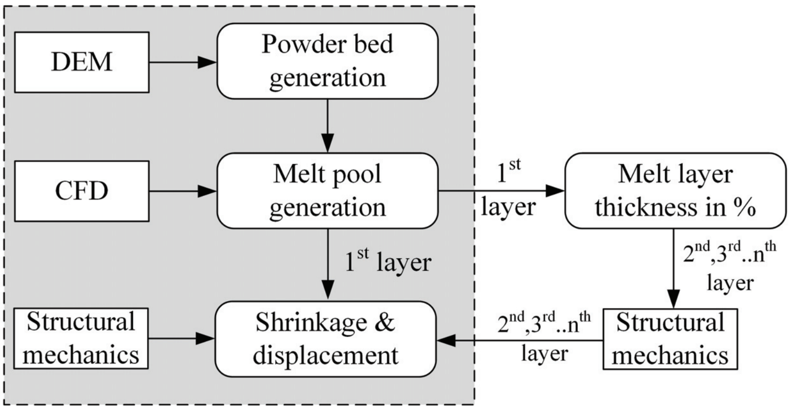

Figure 4.7: Proposed simulation method

Figure 4.8 illustrates the procedure using the example of the upper limit case. From Paper E, the melt layer thickness on the 1^{st} layer in % for upper limit case was found to be 68.8% (46.38 μm) with respect to the nominal layer thickness (67.4 μm). The displacement of this 1^{st} layer was analysed using the FEM solver. The mean layer thickness of the 1^{st} layer after displacement served as the input to estimate the melt pool thickness of the 2^{nd} layer as shown in Figure 4.8, Step 3. The FEM solver then calculated the displacement of the 2^{nd} layer. The same process was repeated for the subsequent layers. From the 2^{nd} layer onwards, only the structural mechanics solver was used instead of going through the iteration of detailed DEM and CFD based simulations, which is a time-consuming process. Therefore, this method is to be considered as an alternative to the method proposed in Paper E when considering simulation of multiple layers.

For the purpose of comparison, another nominal layer thickness setting (20 μm) was considered, and the same procedure was repeated from the 1^{st} layer using the same percentage differences observed in the initial nominal layer thickness settings (67.4 μm). For the initial nominal layer settings (67.4 μm), a 5-layer simulation was performed, while the study was extended to 10 layers for the 2^{nd} setting (20 μm) as the computational time was more affordable due to the layer thickness value used in the 2^{nd} setting. The results were compared with existing literature, which consisted of computer and physical experimental results.

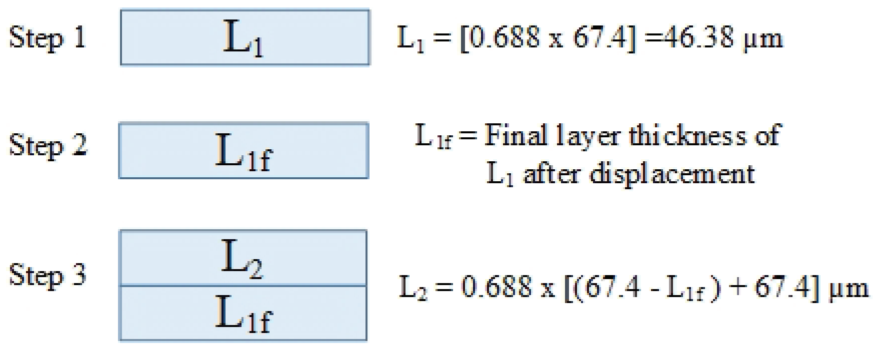

Figure 4.8: Illustration of the proposed layer thickness estimation method.

Outcome: The results of the three cases studied for both nominal layer thickness settings (67.4 μm 20 μm) showed that the effect of PSD due to the stochastic nature of the powder distribution caused variation in the build height. From the results, it was observed that setting 2, with a lower layer thickness value, would be an ideal layer thickness to achieve better geometric quality and is least sensitive to the PSD. However, productivity rate could be affected. A possible solution, then, could be to have hybrid layer thicknesses among different regions of a part. That is, areas in the part that are sensitive or have higher functional – aesthetic importance could be produced with lower layer thickness. Moreover, the build orientation could be strategized such that the support structures could be used in the areas where the geometry is expected to be affected, as the support structures are removed after the build.

From the 10-layer simulation cases for setting 2, the simulations showed that the layer thickness begin to homogenize around the 9^{th} layer. This observation is in line with the literature studies backed by physical experimental data, where the layer thickness homogenized approximately around 9^{th}-13^{th} layer.

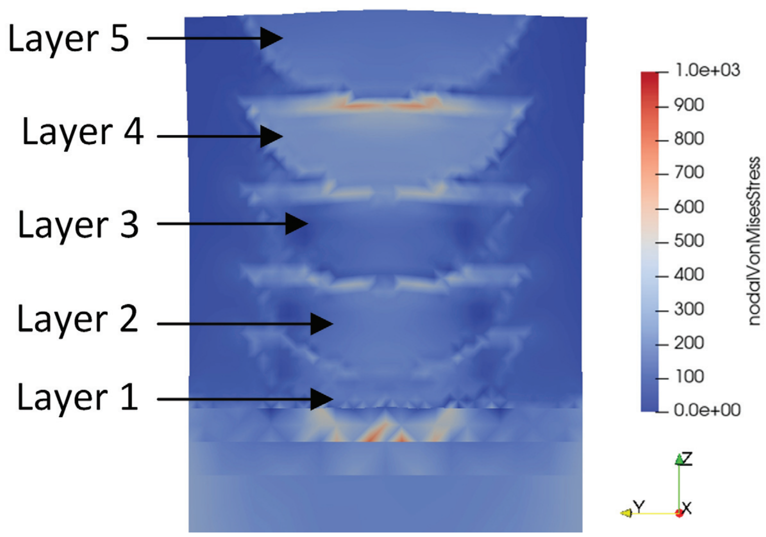

Figure 4.9: Simulation outcome of one of the cases studied

Even though other aspects of the build quality such as porosity may not be possible to detect, the cross section of the simulation model can reveal the depth of fusion of melt tracks, which can provide some valuable inputs in the early design stages. This, when coupled with microstructural simulations, can provide more intricate details that may enable capturing the 'design-material-microstructure-build quality' chain digitally, even before physically printing a part.

4.7 Unpublished results and attempts

Here, the author wishes to briefly mention some of the other works that have been carried out or attempted and the reasons for not pursuing them further during this thesis. Nevertheless, such experiences have enhanced the author's awareness of the subject and the challenges associated with it.

1. The laser heat-treated sheet metal blanks produced with different pattern dimensions during the investigation of the SLHT process were subjected to tensile tests by the industrial stakeholder in co-ordination with the author. Though a large amount of data is available, the analyses have not been conducted, as their outcome was not the primary objective in this thesis. Nevertheless, they could contribute substantially going forward when considering connecting the mechanical properties-geometry-functionality characteristics.

2. The laser heat-treated-cold stamped parts were subjected to 3- point bending tests, and the results were analysed by the industrial stakeholder. Due to resource limitations and the stakeholder's status, the results remain unprocessed in terms of connecting them to geometric quality.

3. Simulation studies concerning SLHT were made to combine MC simulations and thermo-mechanical simulations. The specific objective was to study the effect of scanning path (heat treatment pattern) position variation on the geometry of laser heat-treated blanks. Variation in the scanning path here means applying unit disturbance in the scanning path. Similarly, another idea was related to analysing the effect of chemical composition variation on the SLHT of blanks, and preliminary simulation investigations were conducted as well. The idea here was to observe the effect on residual stresses and, consequently, on the geometry. However, due to these problems being computationally heavy, the outcome remained inconclusive.

CHAPTER 5

Discussion

This section discusses the results presented in the previous section. The results are discussed in relation to the research questions and the research methodology framed at the beginning of the research. The scientific and industrial contributions and research quality criteria are discussed as well.

5.1 Answering the research questions

RQ1: *What are the sources of geometric variation stemming from the selective laser heat treatment process and the selective laser melting process?*

To answer this question, the first step was to conduct literature studies to gather information on the possible geometric variation contributors concerning the SLHT and SLM processes.

In Paper C concerning SLHT, the study was extended to a comprehensive descriptive study to gain further understanding on the geometric variation sources at the part level and their effects at the assembly level. The hypothesis here was that the geometric variation sources must indeed be addressed at the part level, i.e., when the blanks are laser heat treated instead of handling them at the assembly level. In Paper D concerning SLM, a large base of available literature provided the necessary information on the possible geometric variation sources that need further analysis.

The information gathered were mapped in the form of a fish-bone diagram and represented in the form of blocks of P-diagram. This was later shaped into a framework. Paper C and Paper D answer this question for SLHT and SLM, respectively. As the conclusion from the studies is to suppress the variation as early as possible, sources that could be adjusted during the product design or process design stages are pursued further in this thesis.

For dealing with geometric variation in SLHT, critical product and process design factors that were identified were the laser heat treatment pattern dimension, laser heat treatment pattern position, and the laser heating direction sequence (scanning sequence).

For dealing with geometric variation in SLM, one of the critical parameters that needed to be pursued was the powder layer thickness. Given the complexity of the SLM process, factors that influence the powder layer thickness required further probing. Hence, powder material characteristics such as the particle size, particle size distribution, scanning strategy aspects such as the scanning sequence, and the hatching spacing were identified for further analysis in this study.

RQ2: *How can the geometric variation from selective laser heat treatment process and selective laser melting process be controlled?*

As discussed in the previous question, the focus has been to consider the sources that could be possible to optimize in the early stages of the product development process.

Paper A and Paper B answer this question concerning SLHT, where the effects of adjusting the considered sources are shown. Three sources have been taken into account: laser heat treatment direction sequence, laser heat treatment pattern dimensions and laser heat treatment pattern position. Here, the laser heat treatment direction sequence (scanning strategy) is a process design parameter, while the pattern dimension and pattern position is a produce design parameter.

Based on the end requirements in terms of formability and strength, the heat treatment layout/pattern are to be planned accordingly. Positioning of the heat treatment pattern could affect geometric variation. The heat treatment pattern, in turn, defines the heat treatment direction sequences that could be of interest. In Paper A, it was shown that adjusting the laser heat treatment sequence strategy for a given pattern type and dimensions could minimize the effects. Paper B demonstrated that a robust pattern position on the metal blank could minimize the effects on geometric variation. Such adjustments had a consequential effect on the subsequent processes as well.

Paper E and Paper F answer this question concerning SLM. The studies revolved around layer thickness as a critical factor. Here, the influence of particle size distribution, hatch spacing, sequence strategies on the resulting layer thickness and residual stress was considered. The results revealed that opting for a particle size distribution with smaller mean particle size and standard deviation would help in achieving the layer thickness closest to the input nominal layer thickness considered in the system settings. Another option would be to opt for layer thickness which would be least sensitive to the nature of particle size distribution. This was observed in Paper F, where a lower layer thickness value was minimally affected by the nature of the particle size distribution. The third option would be to estimate the shrinkage that could be expected with the help of simulation support and compensate for the shrinkage in the 3D model.

RQ3:*How can simulation in product development be employed to predict ge-ometric variation in selective laser melting process?*

From the literature studies, the need for simulation support in analysing the effect on geometric variation in the early stages of product development was evident. Thus, the study discussed in Paper E and Paper F focused on methods that could support the virtual product development process. Through computer experiments, critical factors identified in Paper D were studied.

In Paper E, a method of integrating three different simulation tools that replicate the multi-physics aspects of the SLM process was considered. This method was employed to analyse the effect of particle size distribution on the layer thickness at a detailed level, as discussed in the previous research question.

From the simulation results, it was determined that for a nominal power layer thickness, the stochastic nature of the powder distribution on the build platform and the particle size distribution can lead to variation in the solidified layer thickness. This detailed study was, however, performed for a single layer.

Repeating this method for multiple layers, while possible, would be computationally heavy and time consuming. Thus, a method was proposed in Paper F which utilizes the result from Paper E and builds upon it for relatively faster prediction.

The results from Papers E and F using the proposed methods were in strong agreement with computer and physical experimental data found in the available literature, which boosts the confidence in the proposed methods.

5.2 Results in the context of DRM and geometry assurance

In the context of DRM and geometry assurance, the results can be summarized as follows:

- *Descriptive results*: The outcome of empirical studies led to findings that contribute to the design practice.
- *Prescriptive results*: Formulation of methods and demonstrating the potential of utilizing existing simulation tools that could assist in meeting the success criteria.
- *Knowledge of phenomenon connected to design*: The descriptive and prescriptive studies have led to several observations regarding the effect of local laser heat treatment and local laser melting of metals. Such observations could assist in capturing the digital foot print of the 'product design- material-microstructure-mechanical properties-geometric quality' chain when combined with other relevant simulation tools.

With the assistance of the DRM process, the research results presented in the previous chapter and the summary of the results discussed earlier in this chapter have enabled in realization of the measurable success criteria defined in Chapter 3 (Section 3.5.1).

5.3 Scientific and industrial contributions

The scientific contribution is in the form of addressing the research gaps identified in the initial stages of this research, while the industrial contribution is based on how the addressed research gaps could benefit the industry.

5.3.1 Scientific contribution

- New knowledge on variation sources from laser heat treatment and laser melting, specifically in the context of sheet metal and metal powders is presented in Papers C and D, respectively.

- A structured framework tailored for geometric robustness analysis of SLM products, which could also be applicable to robustness analysis of SLHT products, is presented in Paper D.
- A prescription of strategies to adjust a set of critical factors to minimize their effect on geometric variation is presented in Papers A, B, E and F.
- A number of gaps identified in the area of simulation support which are needed during the early product development stages are presented in Paper D.
- A developed method to evaluate robustness that provides simulation support required in the early product development stages is presented in Papers E and F.

5.3.2 Industrial contribution

Many of the research results presented here have been performed in close collaboration with the industrial partners, specifically the SLHT process. Some of the industrial contributions are highlighted below:

- A number of identified shortcomings and problems that could occur with respect to geometric quality based on the current established practices related to SLHT and SLM processes (Papers C and D).
- An increased understanding of the manufacturability aspects, i.e., about laser heat treatment of sheet metals and their influence on the subsequent forming process (Papers A and B).
- An increased understanding of the effect of local heat treatment and melting that can potentially assist in developing new product solutions while achieving the required geometric quality (Papers A, B, E and F).
- A framework and method that could assist in early decision making, minimizing the product lead time and the cost incurred (Papers E and F).

5.4 Research quality: Verification and validation

Verification and validation are defined in various ways in different disciplines. According to [Blessing and Chakrabarti, 2009], validation is about doing the right thing, while verification is about doing the thing right. As per [Taylor, 2013], validation is about questioning the validity of the outcome, classified as internal validity, external validity and construct validity. *Internal validity* concerns whether the relationship between variables under investigation is causal, i.e., whether they affect each other. *External validity* deals with generalizability of the results beyond the study settings undertaken. *Construct validity* is about generalizing the higher-order concepts or the constructs (theoretical concepts) based on the results. It relates to the quality of the investigation or experimental (construct) setup. Any unaccounted factor influencing the causal relationship between the variables being investigated, researcher bias, or conditions under which the studies are conducted are threats to these validity types that should be taken care of.

Verification involves making judgements about the credibility of the results. Buur [Buur, 1990] proposed *logical verification* and *verification by acceptance* as two means of verification. According to *logical verification*, there should not be any conflict between the elements outlined in the research, and it should demonstrate *consistency*. The research needs to be *complete* and should be able to explain or reject the observations made. The research should be *coherent*, and well-established approaches should be in agreement with the research. The research results should be able to elucidate specific problems. In *verification by acceptance*, the established theory should be acceptable to experienced practitioners in the relevant field. Furthermore, the models and methods that are developed based on the established theory should be accepted by the experienced practitioners within the field.

The research conducted in this thesis corresponds to the first three stages of the design research methodology, i.e., the RC, DS-I and PS stages. While the research has resulted in an increased understanding of the subject of interest, as well as knowledge and method development, the research results and the approach taken need to be evaluated. The described research quality measures are discussed with respect to the research conducted.

- **Internal validity** : This relates to whether the findings or results of the research relate to and are caused by the phenomena or the variables under investigation [Winter, 2000]. Many factors can affect internal validity. Internal validity was ensured by performing controlled experiments, and any threats in the form of unaccounted variables were eliminated. Repetition of the tests also helped in ensuring internal validity.

- **External validity**: This relates to whether the research results can be generalized to conditions other than those studied. The results observed when evaluating different factors are specific to the settings considered in the study and are not directly generalizable. However, cues can be drawn from the approach and results for similar processes and conditions.

- **Construct validity**: This refers to whether the research approach actually measures what it is intended to measure. Construct validity is demonstrated by performing different strategies and repeating the strategies for consistency. For the results presented in Papers E and F, the methods used in the study have constructs that are widely used in the field of research and have broad industrial application; DEM, CFD, FEM and DoE.

- **Verification**: The results presented in Chapter 4 are based on well-established methods that are widely accepted in the field of research and within the industry. Documentation was a regular activity at every stage of the research process. Regular meetings were conducted with the stakeholders to discuss and review the research progress to ensure the correctness of the research approach. Through literature studies, discussion with experienced practitioners, and experimental study of different cases, various aspects of logical verification were achieved. This research has been discussed with the industrial partner and practitioners within the relevant field who are in agreement with the results. The appended papers have been presented at conferences and journals, where they have undergone peer reviews by experts within the field of research. The results have also been presented and accepted at various forums consisting of many participants from the industry.

CHAPTER 6

Conclusion

This section summarizes and concludes the research presented in this thesis. The direction for future research is discussed under future work.

6.1 Conclusion

Focus on reducing the environmental impact has forced the manufacturing industry, including the automotive and aerospace industries, to adopt various weight-reduction strategies. The strategy of using lightweight materials and employing advanced material processing techniques is seen as the way forward. As new processing techniques emerge, integrating them into the current product development setup to enable efficient decision making is necessary. To this end, a greater understanding of advanced processing techniques such as the SLHT and SLM processes considered in this study is necessary.

The research objective has been to gain a better understanding of the aforementioned said processes and their effects on geometric quality and to utilize this knowledge to develop methods that could assist in the geometry assurance process. Literature studies were performed, and research questions in line with the research objective were formulated. In addition, descriptive and prescriptive studies were conducted to gain a deeper understanding of the subject and propose methods to answer the framed research questions. Based on the outlined results, it can be concluded that:

- The thermal, metallurgical and mechanical effects from the SLHT and SLM processes influence geometric variation.
- In SLHT of sheet metal blanks:
  - The heat treatment pattern dimension, the pattern position and the laser scanning strategy are critical factors that influence geometric quality and must be considered in the early product development stages.
  - The laser scanning strategy should be planned in accordance with the pattern dimension to minimize the effect on geometric variation. The significance of the laser scanning strategy increases with smaller heat treatment pattern dimensions.

- Adjusting the pattern position for functionality or formability requirements influences geometric variation, regardless of the pattern dimensions.

- In SLM of metals:
  - The mean particle size and the particle size distribution of the metal powder cause variation in layer thickness, consequently affecting the build's geometric quality. Thus, smaller mean particle size and particle size distribution is desirable to minimize variation in layer thickness.
  - A smaller layer thickness is suggested as it is least sensitive to variation in particle size distribution. However, productivity is compromised as the build time increases.
  - Simulation platforms based on the discrete element method, computational fluid dynamics and structural mechanics can be employed to replicate the SLM process and capture the effect of variation sources on the geometric quality.
  - Faster simulation prediction can be achieved for multi-layer simulation of SLM process. From the detailed DEM-CFD-FEM structural mechanics simulations, the effect on single layer build can be predicted. This can be used as an input to make faster predictions for the remaining multiple layers using the FEM structural mechanics simulation technique.

6.2 Future work

The research conducted thus far has laid the foundation for geometry assurance of laser-processed metal components, specifically pertaining to the SLHT and SLM processes. In addition to some of the points highlighted in Section 4.7, other potential areas that are worth pursuing are as follows:

- *Scanning strategy optimization*: Since every component to be produced using SLHT is designed specific to the product design and the end requirements, the scanning strategy will also be unique to it. Hence, optimization of scanning strategies could be pursued. In SLM processes, most of the machines have a pre-fixed, limited set of scanning strategies to choose from. However, optimization of other aspects of the scanning strategy, such as the hatch spacing and layer rotation could be pursued.

- *Variation simulation*: Methods to combine thermo-mechanical and Monte-Carlo simulation would enable faster predication with reasonable simulation accuracy to enable early design decision making.

- *Studies on other critical factors*: In SLM, studies on other critical factors such as support structure design and optimization and removal sequence could be pursued. In SLHT, virtual simulations to predict geometric variation in laser heat treated metal blanks could be combined with forming simulations and crash simulations to capture the complete chain effect for non-nominal settings as well.

- *Extension of results*: Future research should explore the possibilities of extending the learnings to other advanced manufacturing processes involving selective heating and selective melting.
- *Establishment of design guidelines*: Finally, future research should establish detailed design guidelines that assist in designing geometry assured products produced by means of selective heating and selective melting.

Bibliography

[Ali et al., 2018] Ali, H., Ghadbeigi, H., and Mumtaz, K. (2018). Effect of scanning strategies on residual stress and mechanical properties of selective laser melted Ti6Al4V. *Materials Science and Engineering: A*, 712:175–187.

[Alsalla et al., 2018] Alsalla, H. H., Smith, C., and Hao, L. (2018). Effect of build orientation on the surface quality, microstructure and mechanical properties of selective laser melting 316L stainless steel. *Rapid prototyping journal*.

[Amuda and Akinlabi, 2016] Amuda, M. O. H. and Akinlabi, E. T. (2016). Trend and development in laser surface modification for enhanced materials properties. In *Advanced Manufacturing Techniques Using Laser Material Processing*, pages 92–120. IGI Global.

[ArcelorMittal, 2015] ArcelorMittal (2015). Automotive R&D event (Accessed November 29, 2016). `https://europe.arcelormittal.com/newsandmedia/pressreleases/PR2015/PRAutomitiveInvestorEvent`.

[Archer, 1981] Archer, B. (1981). A view of the nature of the design research. In *R. Jacques and J. Powell (ed.) Design: Science: Method*. Guildford Westbury House.

[Asnafi et al., 2016] Asnafi, N., Andersson, R., Persson, M., and Liljengren, M. (2016). Tailored boron steel sheet component properties by selective laser heat treatment. In *IOP Conference Series: Materials Science and Engineering*, volume 159, page 012023. IOP Publishing.

[ASTM International, 2015a] ASTM International (2015a). ISO/ASTM52900-15 standard terminology for additive manufacturing - general principles - terminology. *ASTM International, West Conshohocken, PA*.

[ASTM International, 2015b] ASTM International (2015b). ASTM 52900-15 standard terminology for additive manufacturing—general principles—terminology. *ASTM International, West Conshohocken, PA*, 3(4):5.

[ASTM International, 2018] ASTM International (2018). ISO/ASTM 52910-18 Additive manufacturing — Design — Requirements, guidelines and recommendations. *ASTM International, West Conshohocken, PA*.

[ASTM International, 2019] ASTM International (2019). ISO/ASTM 52911-1:2019Additive manufacturing - Design - part 1: Laser-based powder bed fusion of metals. *ASTM International, West Conshohocken, PA*.

[Bambach et al., 2016] Bambach, M., Conrads, L., Daamen, M., Güvenç, O., and Hirt, G. (2016). Enhancing the crashworthiness of high-manganese steel by strain-hardening engineering, and tailored folding by local heat-treatment. *Materials & Design*, 110:157–168.

[Bikas et al., 2019] Bikas, H., Lianos, A., and Stavropoulos, P. (2019). A design framework for additive manufacturing. *The International Journal of Advanced Manufacturing Technology*, 103(9):3769–3783.

[Blessing and Chakrabarti, 2009] Blessing and Chakrabarti (2009). *DRM, a design research methodology*. Springer Dordrecht.

[Buur, 1990] Buur, J. (1990). *A theoretical approach to mechatronics design*. Denmark: Institute for Engineering Design, Technical University of Denmark.

[Cai et al., 1996] Cai, W., Hu, S. J., and Yuan, J. (1996). Deformable sheet metal fixturing: principles, algorithms, and simulations. *Trans. ASME, J. Manufacturing Sci. Eng.*, 118:318–324.

[Cao, 2019] Cao, L. (2019). Numerical simulation of the impact of laying powder on selective laser melting single-pass formation. *International Journal of Heat and Mass Transfer*, 141:1036–1048.

[Chase and Parkinson, 1991] Chase, K. W. and Parkinson, A. R. (1991). A survey of research in the application of tolerance analysis to the design of mechanical assemblies. *Research in Engineering design*, 3(1):23–37.

[Chowdhury and Taguchi, 2016] Chowdhury, S. and Taguchi, S. (2016). *Robust Optimization: World's Best Practices for Developing Winning Vehicles*. John Wiley & Sons.

[Cloots et al., 2013] Cloots, M., Spierings, A., and Wegener, K. (2013). Assessing new support minimizing strategies for the additive manufacturing technology SLM. In *24th International SFF Symposium-An Additive Manufacturing Conference, Austin, USA, University of Texas at Austin*, pages 631–643.

[Conrads et al., 2017] Conrads, L., Liebsch, C., and Hirt, G. (2017). Increasing the energy absorption capacity of structural components made of low alloy steel by combining strain hardening and local heat treatment. *Procedia engineering*, 207:257–262.

[Cundall and Strack, 1979] Cundall, P. A. and Strack, O. D. (1979). A discrete numerical model for granular assemblies. *geotechnique*, 29(1):47–65.

[Dahlström and Lindkvist, 2007] Dahlström, S. and Lindkvist, L. (2007). Variation simulation of sheet metal assemblies using the method of influence coefficients with contact modeling.

[Dawes et al., 2015] Dawes, J., Bowerman, R., and Trepleton, R. (2015). Introduction to the additive manufacturing powder metallurgy supply chain. *Johnson Matthey Technology Review*, 59(3):243–256.

[Deckard, 1986] Deckard, C. (1986). Part generation by layer-wise selective laser sintering. *MS, Univeristy of Texas-Austin, Austin, TX.*

[Demir et al., 2017] Demir, A. G., Colombo, P., and Previtali, B. (2017). From pulsed to continuous wave emission in slm with contemporary fiber laser sources: effect of temporal and spatial pulse overlap in part quality. *The International Journal of Advanced Manufacturing Technology*, 91(5):2701–2714.

[Deva and Jha, 2014] Deva, A. and Jha, B. K. (2014). *Heat Treating of Boron Steels*, volume 4D. ASM Handbook.

[Diegel et al., 2019] Diegel, O., Nordin, A., and Motte, D. (2019). *A Practical Guide to Design for Additive Manufacturing*. Springer.

[Dutta Majumdar and Manna, 2011] Dutta Majumdar, J. and Manna, I. (2011). Laser material processing. *International materials reviews*, 56(5-6):341–388.

[Ebrahim, 2015] Ebrahim, M. A.-B. (2015). 3D laser scanners' techniques overview. *Int J Sci Res*, 4(10):323–331.

[Edelson, 2002] Edelson, D. C. (2002). Design research: What we learn when we engage in design. *The Journal of the Learning sciences*, 11(1):105–121.

[Eekels and Roozenburg, 1991] Eekels, J. and Roozenburg, N. F. (1991). A methodological comparison of the structures of scientific research and engineering design: their similarities and differences. *Design studies*, 12(4):197–203.

[Eifler and Howard, 2018] Eifler, T. and Howard, T. J. (2018). The importance of robust design methodology: case study of the infamous gm ignition switch recall. *Research in Engineering Design*, 29(1):39–53.

[Emmelmann et al., 2017] Emmelmann, C., Herzog, D., and Kranz, J. (2017). Design for laser additive manufacturing. In *Laser additive manufacturing*, pages 259–279. Elsevier.

[Faro, 2021] Faro (2021). Faro (Accessed January 28, 2021). `https://www.faro.com/industry/automotive`.

[FCC, 2021] FCC (2021). Computational structural mechanics (Accessed January 28, 2021). `http://www.fcc.chalmers.se/technologies/comp/computational-structural-dynamics/`.

[Gan and Wong, 2016] Gan, M. and Wong, C. (2016). Practical support structures for selective laser melting. *Journal of Materials Processing Technology*, 238:474–484.

[Garvin, 1984] Garvin, D. A. (1984). What does "product quality" really mean. *Sloan management review*, 25.

[Göhl et al., 2018a] Göhl, J., Mark, A., Sasic, S., and Edelvik, F. (2018a). An immersed boundary based dynamic contact angle framework for handling complex surfaces of mixed wettabilities. *International Journal of Multiphase Flow*, 109:164–177.

[Göhl et al., 2018b] Göhl, J., Markstedt, K., Mark, A., Håkansson, K., Gatenholm, P., and Edelvik, F. (2018b). Simulations of 3D bioprinting: predicting bioprintability of nanofibrillar inks. *Biofabrication*, 10(3):034105.

[Göhler et al., 2018] Göhler, S. M., Ebro, M., and Howard, T. J. (2018). Mechanisms and coherences of robust design methodology: a robust design process proposal. *Total Quality Management & Business Excellence*, 29(3-4):239–259.

[GOM, 2021] GOM (2021). GOM (Accessed on January 28, 2021). `https://www.capture3d.com/3d-metrology-solutions/3d-scanners`.

[Gouge and Michaleris, 2017] Gouge, M. and Michaleris, P. (2017). *Thermomechanical modeling of additive manufacturing*. Butterworth-Heinemann.

[Hexagon, 2021] Hexagon (2021). Hexagon (Accessed on January 28, 2021). `https://www.hexagonmi.com/products/3d-laser-scanners`.

[Hong and Chang, 2002] Hong, Y. and Chang, T. (2002). A comprehensive review of tolerancing research. *International Journal of Production Research*, 40(11):2425–2459.

[Horvath, 2001] Horvath, I. (2001). A contemporary survey of scientific research into engineering design. In *Proceedings of the International Conference on Engineering Design, ICED*, volume 1, pages 21–23. Citeseer.

[Hu et al., 2001] Hu, M., Lin, Z., Lai, X., and Ni, J. (2001). Simulation and analysis of assembly processes considering compliant, non-ideal parts and tooling variations. *International Journal of Machine Tools and Manufacture*, 41(15):2233–2243.

[Hubka and Eder, 1988] Hubka, V. and Eder, W. E. (1988). Theory of technical systems: A total concept theory for engineering design. *Berlin and New York*.

[Ian Gibson, 2015] Ian Gibson, I. G. (2015). Additive manufacturing technologies 3D printing, rapid prototyping, and direct digital manufacturing.

[Inoue and Wang, 1985] Inoue, T. and Wang, Z. (1985). Coupling between stress, temperature, and metallic structures during processes involving phase transformations. *Materials Science and Technology*, 1(10):845–850.

[Ion, 2005] Ion, J. (2005). *Laser processing of engineering materials: principles, procedure and industrial application*. Elsevier.

[Jiang et al., 2018] Jiang, J., Xu, X., and Stringer, J. (2018). Support structures for additive manufacturing: a review. *Journal of Manufacturing and Materials Processing*, 2(4):64.

[Jing and Stephansson, 2007] Jing, L. and Stephansson, O. (2007). *Fundamentals of discrete element methods for rock engineering: theory and applications*. Elsevier.

[Kranz et al., 2015] Kranz, J., Herzog, D., and Emmelmann, C. (2015). Design guidelines for laser additive manufacturing of lightweight structures in TiAl6V4. *Journal of Laser Applications*, 27(S1):S14001.

[Krogstie et al., 2015] Krogstie, L., Ebro, M., and Howard, T. J. (2015). How to implement and apply robust design: insights from industrial practice. *Total Quality Management & Business Excellence*, 26(11-12):1387–1405.

[Kruth et al., 2010] Kruth, J.-P., Badrossamay, M., Yasa, E., Deckers, J., Thijs, L., Van Humbeeck, J., et al. (2010). Part and material properties in selective laser melting of metals. In *Proceedings of the 16th international symposium on electromachining*, volume 16. Citeseer.

[Kumke et al., 2016] Kumke, M., Watschke, H., and Vietor, T. (2016). A new methodological framework for design for additive manufacturing. *Virtual and physical prototyping*, 11(1):3–19.

[Kuo et al., 2001] Kuo, T.-C., Huang, S. H., and Zhang, H.-C. (2001). Design for manufacture and design for 'x': concepts, applications, and perspectives. *Computers & industrial engineering*, 41(3):241–260.

[Lee and Zhang, 2015] Lee, Y. and Zhang, W. (2015). Mesoscopic simulation of heat transfer and fluid flow in laser powder bed additive manufacturing. In *International solid free form fabrication symposium, Austin*, pages 1154–1165.

[Leicht, 2020] Leicht, A. (2020). Laser powder bed fusion of 316L stainless steel.

[Leicht et al., 2020a] Leicht, A., Fischer, M., Klement, U., Nyborg, L., and Hryha, E. (2020a). Increasing the productivity of laser powder bed fusion for stainless steel 316L through increased layer thickness. *Journal of Materials Engineering and Performance*, pages 1–10.

[Leicht et al., 2020b] Leicht, A., Yu, C.-H., Luzin, V., Klement, U., and Hryha, E. (2020b). Effect of scan rotation on the microstructure development and mechanical properties of 316L parts produced by laser powder bed fusion. *Materials Characterization*, 163:110309.

[Lindkvist and Söderberg, 1999] Lindkvist, L. and Söderberg, R. (1999). Concurrent robust product and process design. In *Proceedings of the ASME Design Automation Conference*, pages 12–15.

[Lööf and Söderberg, 2007] Lööf, J. and Söderberg, R. (2007). Top-down decomposition of multi-product requirements onto locator tolerances. In *ASME International Mechanical Engineering Congress and Exposition*, volume 42975, pages 247–255.

[Lorin, 2014] Lorin, S. (2014). *Increased precision in variation simulation by considering effects from temperature and heat*. Chalmers University of Technology.

[Lorin et al., 2014a] Lorin, S., Cromvik, C., Edelvik, F., Lindkvist, L., and Söderberg, R. (2014a). Variation simulation of welded assemblies using a thermo-elastic finite element model. *Journal of computing and information science in engineering*, 14(3).

[Lorin et al., 2014b] Lorin, S., Cromvik, C., Edelvik, F., Lindkvist, L., Söderberg, R., and Wärmefjord, K. (2014b). Simulation of non-nominal welds by resolving the melted zone and its implication to variation simulation. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, volume 46353, page V004T06A018. American Society of Mechanical Engineers.

[Lorin et al., 2015] Lorin, S., Cromvik, C., Edelvik, F., and Söderberg, R. (2015). Welding simulation of non-nominal structures with clamps. *Journal of Computing and Information Science in Engineering*, 15(2).

[Lorin et al., 2010] Lorin, S., Forslund, K., and Söderberg, R. (2010). Investigating the role of simulation for robust plastic design. In *DS 61: Proceedings of NordDesign 2010, the 8th International NordDesign Conference, Göteborg, Sweden, 25.-27.08. 2010*, pages 185–194.

[Lorin et al., 2018] Lorin, S., Lindau, B., Sadeghi Tabar, R., Lindkvist, L., Wärmefjord, K., and Söderberg, R. (2018). Efficient variation simulation of spot-welded assemblies. In *ASME 2018 international mechanical engineering congress and exposition*. American Society of Mechanical Engineers Digital Collection.

[Lorin et al., 2014c] Lorin, S., Lindkvist, L., and Söderberg, R. (2014c). Variation simulation of stresses using the method of influence coefficients. *Journal of computing and information science in engineering*, 14(1).

[Louw and Pistorius, 2019] Louw, D. F. and Pistorius, P. (2019). The effect of scan speed and hatch distance on prior-beta grain size in laser powder bed fused ti-6al-4v. *The International Journal of Advanced Manufacturing Technology*, 103(5-8):2277–2286.

[Majumdar and Manna, 2003] Majumdar, J. D. and Manna, I. (2003). Laser processing of materials. *Sadhana*, 28(3-4):495–562.

[Makes, A. and Collaborative, A.A.M.S, 2018] Makes, A. and Collaborative, A.A.M.S (2018). Standardization roadmap for additive manufacturing.

[Mazumder, 1983] Mazumder, J. (1983). Laser heat treatment: the state of the art. *JOM*, 35(5):18–26.

[Meier et al., 2019] Meier, C., Weissbach, R., Weinberg, J., Wall, W. A., and Hart, A. J. (2019). Critical influences of particle size and adhesion on the powder layer uniformity in metal additive manufacturing. *Journal of Materials Processing Technology*, 266:484–501.

[Merklein et al., 2014] Merklein, M., Johannes, M., Lechner, M., and Kuppert, A. (2014). A review on tailored blanks—production, applications and evaluation. *Journal of Materials Processing Technology*, 214(2):151–164.

[Mitroff et al., 1974] Mitroff, I. I., Betz, F., Pondy, L. R., and Sagasti, F. (1974). On managing science in the systems age: two schemas for the study of science as a whole systems phenomenon. *Interfaces*, 4(3):46–58.

[Murgau, 2016] Murgau, C. C. (2016). *Microstructure model for Ti-6Al-4V used in simulation of additive manufacturing*. PhD thesis, Doctoral thesis, Luleå University of Technology.

[Nigam and Turner, 1995] Nigam, S. D. and Turner, J. U. (1995). Review of statistical approaches to tolerance analysis. *Computer-Aided Design*, 27(1):6–15.

[OWID, 2020] OWID (2020). Cars, planes, trains: where do CO2 emissions from transport come from?. (Accessed on January 8th 2021). `https://ourworldindata.org/co2-emissions-from-transport#licence`.

[Pahkamaa et al., 2012] Pahkamaa, A., Wärmefjord, K., Karlsson, L., Söderberg, R., and Goldak, J. (2012). Combining variation simulation with welding simulation for prediction of deformation and variation of a final assembly. *Journal of Computing and Information Science in Engineering*, 12(2).

[Pahl et al., 2007] Pahl, G., Beitz, W., Feldhusen, J., and Grote, K.-H. (2007). Engineering design a systematic approach.

[Parteli and Pöschel, 2016] Parteli, E. J. and Pöschel, T. (2016). Particle-based simulation of powder application in additive manufacturing. *Powder Technology*, 288:96–102.

[Phadke, 1989] Phadke, M. S. (1989). Quality engineering using robust design.

[Poli, 2001] Poli, C. (2001). *Design for manufacturing: a structured approach*. Butterworth-Heinemann.

[Rao, 2017] Rao, S. S. (2017). *The finite element method in engineering*. Butterworth-heinemann.

[Rezaei Aderiani et al., 2019] Rezaei Aderiani, A., Wärmefjord, K., Söderberg, R., and Lindkvist, L. (2019). Developing a selective assembly technique for sheet metal assemblies. *International Journal of Production Research*, 57(22):7174–7188.

[Roozenburg and Eekels, 1995] Roozenburg, N. F. and Eekels, J. (1995). Product design: fundamentals and methods.

[Sadeghi Tabar et al., 2019] Sadeghi Tabar, R., Wärmefjord, K., Söderberg, R., and Lindkvist, L. (2019). A novel rule-based method for individualized spot welding sequence optimization with respect to geometrical quality. *Journal of Manufacturing Science and Engineering*, 141(11).

[Samal and Newkirk, 2015] Samal, P. and Newkirk, J. (2015). Alloy classification and compositions. *ASM Handbook*, 7:415–420.

[Santhanakrishnan and Dahotre, 2013] Santhanakrishnan, S. and Dahotre, N. B. (2013). Laser surface hardening. *ASM Handbook*, 4:476–491.

[Schleich et al., 2015] Schleich, B., Wartzack, S., et al. (2015). A generic approach to sensitivity analysis in geometric variations management. In *DS 80-4 Proceedings of the 20th International Conference on Engineering Design (ICED 15) Vol 4: Design for X, Design to X, Milan, Italy, 27-30.07. 15*, pages 343–352.

[Söderberg, 1994] Söderberg, R. (1994). Robust design by tolerance allocation considering quality and manufacturing cost. *Advances in Design Automation*, 69(1):219–226.

[Söderberg, 1995] Söderberg, R. (1995). Optimal tolerance band and manufacturing target for monotonic loss functions with functional limits. In *Design engineering technical conferences*.

[Söderberg, 1998] Söderberg, R. (1998). Robust design by support of cat tools. In *Proceedings of the ASME Design Automation Conference, September 13-16, Atlanta, GA, USA DETC98/DAC-5633*.

[Söderberg and Lindkvist, 1999] Söderberg, R. and Lindkvist, L. (1999). Computer aided assembly robustness evaluation. *Journal of Engineering Design*, 10(2):165–181.

[Söderberg and Lindkvist, 1999] Söderberg, R. and Lindkvist, L. (1999). Two-step procedure for robust design using cat technology. In *Global Consistency of Tolerances*, pages 231–240. Springer.

[Söderberg et al., 2006a] Söderberg, R., Lindkvist, L., and Carlson, J. S. (2006a). Managing physical dependencies through location system design. *Journal of Engineering Design*, 17(4):325–346.

[Söderberg et al., 2006b] Söderberg, R., Lindkvist, L., and Dahlström, S. (2006b). Computer-aided robustness analysis for compliant assemblies. *Journal of Engineering Design*, 17(5):411–428.

[Söderberg et al., 2016] Söderberg, R., Lindkvist, L., Wärmefjord, K., and Carlson, J. S. (2016). Virtual geometry assurance process and toolbox. *Procedia Cirp*, 43:3–12.

[Steuben et al., 2016] Steuben, J. C., Iliopoulos, A. P., and Michopoulos, J. G. (2016). Discrete element modeling of particle-based additive manufacturing processes. *Computer Methods in Applied Mechanics and Engineering*, 305:537–561.

[Stoll, 1986] Stoll, H. W. (1986). Design for manufacture: an overview.

[Sufiiarov et al., 2017] Sufiiarov, V. S., Popovich, A., Borisov, E., Polozov, I., Masaylo, D., and Orlov, A. (2017). The effect of layer thickness at selective laser melting. *Procedia engineering*, 174:126–134.

[Suh, 1998] Suh, N. P. (1998). Axiomatic design as a basis for universal design theory. *Universal Design Theory*, pages 3–24.

[Synergy, 2020] Synergy, A. M. (2020). Laser sheet metal annealing (Accessed January 28, 2021). `https://synergyadditive.com/services/laser-sheet-metal-softening`.

[Taguchi and Wu, 1980] Taguchi, G. and Wu, Y.-I. (1980). Introduction to off-line quality control systems. *Central Japan QCA, Nagoyo*.

[Takeda et al., 2001] Takeda, H., Yoshioka, M., and Tomiyama, T. (2001). A general framework for modeling of synthesis–integration of theories of synthesis. In *13th International conference on engineering design–ICED*, volume 1, pages 307–314.

[Tan et al., 2017] Tan, J. H., Wong, W. L. E., and Dalgarno, K. W. (2017). An overview of powder granulometry on feedstock and part performance in the selective laser melting process. *Additive Manufacturing*, 18:228–255.

[Tang et al., 2015] Tang, H., Qian, M., Liu, N., Zhang, X., Yang, G., and Wang, J. (2015). Effect of powder reuse times on additive manufacturing of Ti-6Al-4V by selective electron beam melting. *Jom*, 67(3):555–563.

[Taylor, 2013] Taylor, C. S. (2013). *Validity and validation*. Oxford University Press.

[Thomopoulos, 2012] Thomopoulos, N. T. (2012). *Essentials of Monte Carlo simulation: Statistical methods for building simulation models*. Springer Science & Business Media.

[Thompson et al., 2016] Thompson, M. K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R. I., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B., et al. (2016). Design for additive manufacturing: Trends, opportunities, considerations, and constraints. *CIRP annals*, 65(2):737–760.

[Tran and Lo, 2018] Tran, H.-C. and Lo, Y.-L. (2018). Heat transfer simulations of selective laser melting process based on volumetric heat source with powder size consideration. *Journal of Materials Processing Technology*, 255:411–425.

[US Food and Drug Administration, 2018] US Food and Drug Administration (2018). Technical considerations for additive manufactured medical devices: guidance for industry and food and drug administration staff.

[Vaneker et al., 2020] Vaneker, T., Bernard, A., Moroni, G., Gibson, I., and Zhang, Y. (2020). Design for additive manufacturing: Framework and methodology. *CIRP Annals*, 69(2):578–599.

[Versteeg and Malalasekera, 2007] Versteeg, H. K. and Malalasekera, W. (2007). *An introduction to computational fluid dynamics: the finite volume method*. Pearson education.

[Wärmefjord et al., 2013] Wärmefjord, K., Söderberg, R., and Lindkvist, L. (2013). Simulation of the effect of geometrical variation on assembly and holding forces. *International Journal of Product Development*, 18(1):88–108.

[Wendt, 2008] Wendt, J. F. (2008). *Computational fluid dynamics: an introduction*. Springer Science & Business Media.

[Winter, 2000] Winter, G. (2000). A comparative discussion of the notion of validity in qualitative and quantitative research. *The qualitative report*, 4(3):1–14.

[Xia et al., 2016] Xia, M., Gu, D., Yu, G., Dai, D., Chen, H., and Shi, Q. (2016). Influence of hatch spacing on heat and mass transfer, thermodynamics and laser processability during additive manufacturing of inconel 718 alloy. *International Journal of Machine Tools and Manufacture*, 109:147–157.

[Yadroitsev et al., 2010] Yadroitsev, I., Gusarov, A., Yadroitsava, I., and Smurov, I. (2010). Single track formation in selective laser melting of metal powders. *Journal of Materials Processing Technology*, 210(12):1624–1631.

[Zhong et al., 2015] Zhong, C., Biermann, T., Gasser, A., and Poprawe, R. (2015). Experimental study of effects of main process parameters on porosity, track geometry, deposition rate, and powder efficiency for high deposition rate laser metal deposition. *Journal of Laser Applications*, 27(4):042003.

[Zhou and Ning, 2020] Zhou, Y. and Ning, F. (2020). Build orientation effect on geometric performance of curved-surface 316L stainless steel parts fabricated by selective laser melting. *Journal of Manufacturing Science and Engineering*, 142(12).

[Zienkiewicz et al., 2005] Zienkiewicz, O. C., Taylor, R. L., and Zhu, J. Z. (2005). *The finite element method: its basis and fundamentals.* Elsevier.