THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Towards Geometry Assurance of Laser Processed Sheet Metal Components

VAISHAK RAMESH SAGAR

Department of Industrial and Materials Science

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2019

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VAISHAK RAMESH SAGAR

Report no. IMS-2019-7

Department of Industrial and Materials Science
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

vaishak@chalmers.se

Cover:
The cover image is author's perception of geometry assurance process activities that accounts for effects from selective laser heat treatment. See page 15 and 16 for details.

Printed by
Chalmers Reproservice
Gothenburg, Sweden 2019

To my Family

ABSTRACT

Stricter emission norms have propelled the automotive industry towards lightweight transportation solutions to reduce the environmental impact. The industry has adapted to cost effective lightweight sheet metal solutions to control the vehicle weight as well as maintain the safety standards of the vehicle. Also, the industry continues to explore for innovative manufacturing techniques to achieve further vehicle weight reduction. Novel laser processing techniques for sheet metals have slowly gained prominence in the automotive industry. Specifically, the selective laser heat treatment process has gained interest for its ability to locally modify material properties to enhance formability and strength. Consecutively, it widens the horizon for lightweight design. However, some challenges remain in order to utilize this process to its fullest. Geometrical variation related effects from local heating is an area of concern. Also, integrating them into the virtual product development setup is necessary to enable accurate decision making.

In every manufacturing process the component produced varies from the desired values. This is further affected by variation in fixtures and subsequent assembly processes. It affects aesthetical characteristics and functionality of the product in its operating environment. It is expensive to either make adjustments in the final stages of the production process or to totally eliminate the variation sources. This could be overcome by making the design insensitive to the effects of such variation through the concept of robust design. Implementing the robust design concept requires adequate understanding of geometrical variation related effects due to local heating, an area which remains scarce. As a result, this phenomena is unaccounted for in the methods and tools that are in practice today.

The goal of this research is to understand the phenomena and gain sufficient knowledge to develop methods and tools for geometrical variation simulation that considers selective laser heat treatment effects. In this thesis, boron steels are the material in focus. Through literature studies, the geometrical variation influencing factors are identified and further investigated through experimental studies for deeper understanding. Sufficient knowledge on the influencing factors are developed which forms the major outcome of this thesis. This lays the foundation for developing methods and tools to perform accurate robust design assessment for selective laser heat treated sheet metal components.

Keywords: Geometry assurance, geometrical variation, robust design, selective laser heat treatment, tailored heat treated blanks

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisor Professor Rikard Söderberg for giving me this opportunity. Your energy levels have always motivated me to give my best. I am forever indebted for the support you have given me. I would like to thank my co-supervisors Associate Professor Kristina Wärmefjord and Associate Professor Lars Lindkvist for always setting aside the time whenever I asked for support. I gratefully appreciate your patience and guidance.

My sincere thanks to VA Automotive for helping me with all the necessary resources to materialize the research activities. Special thanks to Jukka Rajalampi, Thomas Skåre at Swerea IVF and Jan Kvist at LaserTool, Olofström for allowing me to access the facilities and helping me with the experiments.

I wish to thank my colleagues Roham Sadeghi Tabar, Abolfazl Rezaei Aderiani, Soner Camuz, Julia Madrid, Konstantinos Stylidis, Julia Orlovska, Mohsen Bayani, Maria Siiskonen, Jakob Müller, Ilker Erdem, and Kanishk Bhadani for a stimulating and fun filled environment. Many thanks to Dr Samuel Lorin, FCC Chalmers for some thought provoking discussions. I extend my thanks to Hans Sjöberg, Per Nyqvist and Jonatan Berglund for helping me with the laser scanner equipments.

Last but not the least, I am deeply thankful to my parents for their unconditional support and sacrifices. I would not have made it this far without their encouragement. I would like to thank my wife, Manasa for being patient, understanding and being my pillar of strength.

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)**,** pp. 041016-041016-7. DOI:10.1115/1.4042831

Paper C
Ramesh Sagar, V., Wärmefjord, K. and Söderberg, R., 2018. Effect of Selective Laser Heat Treatment on Geometrical Variation in Boron Steel Components: An Experimental Investigation. *SAGE Journal of Engineering Manufacture (Submitted)*

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 analyzed the data, and presented the results. Wärmefjord and Söderberg contributed as reviewers.

Paper B

Ramesh Sagar initiated the idea and wrote the paper. Data from the experiments were collected and analyzed by Ramesh Sagar. Wärmefjord and Söderberg contributed as reviewers.

Paper C

Ramesh Sagar initiated the idea and wrote the paper. Ramesh Sagar collected data from the experiments and performed spot weld simulations. Wärmefjord and Söderberg contributed as reviewers.

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1 INTRODUCTION

This chapter provides an overview of the research topic. The research objective and the research questions are presented.

1.1 CURRENT SCENARIO IN THE AUTOMOTIVE INDUSTRY

The automotive industry is growing at a rapid pace with estimation of two billion vehicles by 2040 globally (WEF, 2016). Population growth, rise in per-capita income especially in the emerging markets, and surge in technology will lead to increase in ownership of vehicles. Energy consumption which is all time high is set to increase further (WEO, 2018). This has resulted in increase in greenhouse gas emissions contributing to global warming. It is estimated that transportation sector has a share of 22% in emitting greenhouse gases globally (Goldman Sachs, 2015). Specific to the European (EU) region, passenger cars are still responsible for 12% of total carbon dioxide (CO_2) emissions (EU Comission, 2018). This has resulted in policy makers pushing for stricter regulations and targets for CO_2 emissions. For passenger cars, the CO_2 emission target is set at 81 g/km by 2025 (ICCT, 2019). Such stringent emission norms have compelled the automotive industry to explore new strategies to counter the challenges.

As of today, the automotive industry has adopted various strategies such as improving the efficiency of the combustion engine or controlling the vehicle weight through lightweight materials and design. A complete shift to electric powertrains is seen as solution to control the emissions in the future. However, it will require additional systems in the vehicle thus reducing the total weight savings that could be achieved. Hence, controlling the vehicle weight through lightweight materials as well as structural modification through design is seen crucial in achieving the set emission targets. Along with weight reduction, lightweight materials and design should also fulfill the safety aspects of the vehicle.

Several material alternatives have been explored and are used in vehicles thus far. Materials such as carbon fiber, plastics, aluminum, high strength steels have been used based on the end application requirements. Carbon fiber, though the most potential of all the available options, is still seen as a distant alternative due to high manufacturing costs associated with it (McKinsey, 2012). Therefore, keeping the cost-weight savings and safety aspects in mind, materials such as aluminum, magnesium, high strength steels (HSS) and ultra high strength steels (UHSS) are currently employed (McKinsey, 2012). Specifically for vehicle body-in - white, HSS and UHSS are preferred more as they offer high strength to weight ratio. For the material choices available, manufacturing processes and strategies have a significant role to play in achieving weight reduction targets.

1.2. NOVEL MANUFACTURING TECHNOLOGIES FOR ACHIEVING LIGHT WEIGHT SOLUTIONS

A vehicle body consists of numerous sheet metal parts of different specifications which are processed in different ways and assembled together. Along with standard metal forming techniques that are largely in use today, novel advanced sheet metal processing techniques complementing the existing processes are being developed. Tailored blanks (Figure 1), a collective of semi-finished products have allowed combining of different sheet metals, of different sheet thicknesses and properties to achieve local modified properties which have further expanded the design freedom. Automotive industry has already employed some tailored blanks approaches such as tailor welded blanks (TWB, 2019, Zadpoor et al., 2007), tailor rolled blanks (Mubea, 2019, Kopp et al., 2005), patchwork blanks (Gestamp, 2019). They have allowed substantial weight savings in vehicle while maintaining the structural requirements intact. With growing complexity in customer demands and tougher emission requirements, the industry is looking for alternatives that could provide further weight reduction, meet the required safety standards, and be cost effective. Tailored heat treat blanks (THTB) achieved through selective laser heat treatment process is one such promising alternative that is capable of serving the automotive industry’s objectives. Through local modification of material properties using laser, enhancements in forming behavior as well as crash behavior are achievable. Forming issues due to inhomogeneous thickness or strength distribution encountered by some of the earlier mentioned processes (Figure 1 a, b, & c) can be avoided which has definitely caught the interest of the industry.

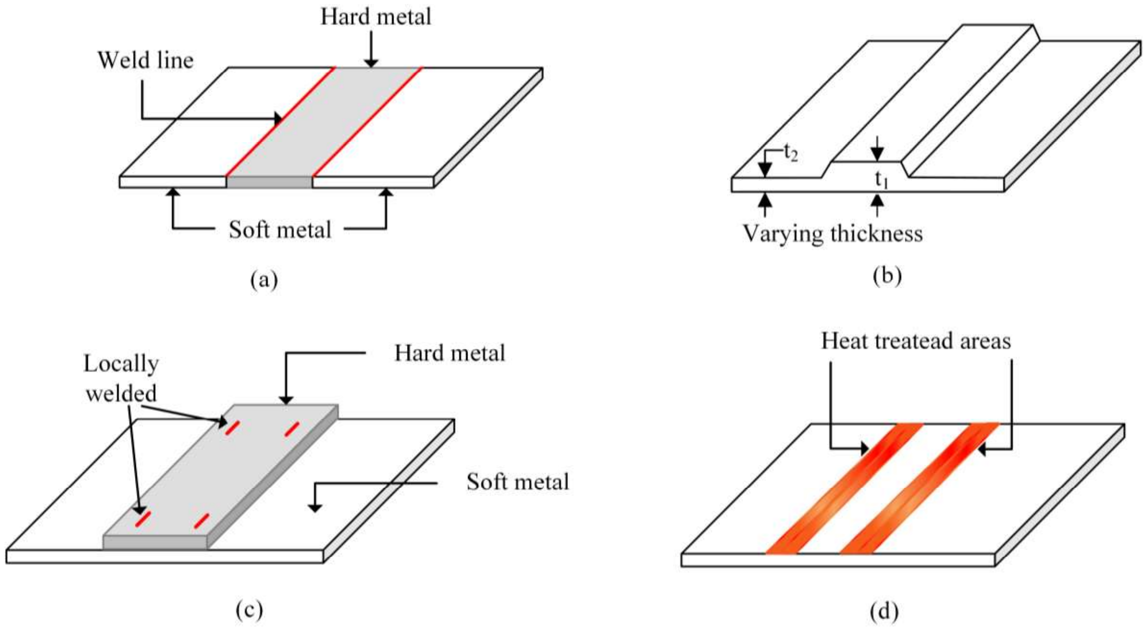

Figure 1 Tailored blanks. (a) Tailor welded blanks (b) Tailor rolled blanks (c) Patchwork blanks (d) Tailor heat treated blanks

1.3. EFFECT ON GEOMETRICAL QUALITY

As we foresee exciting times ahead with prospects of aforementioned technology being implemented on a larger scale in the automotive industry, many hurdles remain which should be taken care of. In every manufacturing process, the part being manufactured varies from the intended nominal geometry. In this case, application of heat in local areas results in distortion of the material and can have consequences on the subsequent stamping process. The nature of geometrical variation even if minimal at part level can have adverse effects at assembly level. This results in a poorly built vehicle affecting its overall performance. The crash behavior which is an essential requirement for structural components, can get compromised. It affects functionality, esthetics, and performance of the final assembled part. Sources could be the manufacturing process, fixtures, and most important of all, the design concept. Physical verification often carried out in the later stages of assembly process involves rework, repair, and sometimes scrapping of the part affecting the overall product development time and cost. Due to the novelty of the selective laser heat treatment process, not all aspects that affect the end quality of the product are explored yet. Hence, it is important to understand the various aspects that affect the product's geometrical quality to enable accurate decision making in the early design stages.

1.4. GEOMETRY ASSURANCE AND ROBUST DESIGN

The process of minimizing geometrical variation and its effects is addressed as geometry assurance. It consists of a set of activities performed in different phases of product realization process namely, the concept phase, the verification phase, and the production phase. Figure 2 shows activities performed in geometry assurance with respect to product realization process.

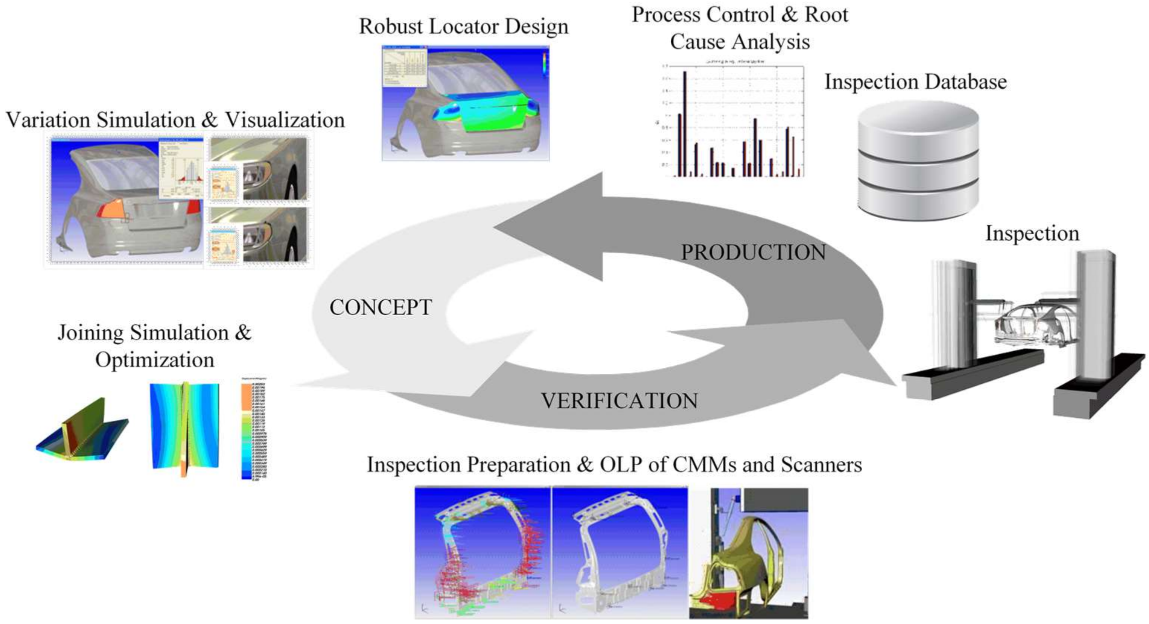

Figure 2 Geometry assurance activities (Söderberg et al., 2016)

Here, the concept phase is considered crucial as different design concepts are virtually assessed and a robust design concept that is insensitive to variation is chosen. In the verification phase, the chosen concept is physically built and tested. All necessary production requirements are undertaken and full production of the product begins. The process is monitored for any discrepancies as well as data is collected that could be useful for streamlining the geometry assurance further. The activities associated to different phases are allocating locating schemes, variation simulation and tolerance allocation, inspection preparation, root cause analysis, six sigma, some of which are described in the next chapter.

1.5. RESEARCH OBJECTIVE

Every manufacturing process is afflicted with variation due to which the manufactured part varies from the intended geometry, especially the sheet metal parts due to their compliant nature. There is sufficient knowledge available for the well-established manufacturing processes and standard practices are followed through experience to control the geometrical quality. However for novel manufacturing processes such as the one in this study that involves phenomena of selective laser heating, the knowledge that could aid in design and manufacturing of sheet metal products is inadequate. Also, the standard methods and tools that are used as of today for geometry assurance can become inefficient.

Therefore, the objective of this research is to gain sufficient knowledge involving selective laser heat treatment and its effect on geometrical variation. An increased understanding of its effects and ways of minimizing it will enable in developing methods and tools to produce geometry assured products.

1.6. SCIENTIFIC GOAL

The concept of selective laser heat treatment of sheet metals has been a topic of research for some time. The main objective so far has been to explore the various aspects of the process for different materials and define process windows for manufacturing a part without failure. However, very few investigations focusing on the influence of selective laser heat treatment on geometrical variation exists. As a result, there is limited knowledge on how to account for the influencing factors from selective laser heat treatment in the early design stages. Hence the scientific goal is to have increased understanding and develop knowledge about the various factors from selective laser heat treatment process that affect geometrical variation.

1.7. INDUSTRIAL GOAL

Though selective laser heat treatment is seen as a potential process by the automotive industry, its implementation in the industry remains minimal. The industrial goal is to provide more clarity on design and manufacturing of selective laser heat treated components based on the knowledge developed. The current practices within the industry can be improved to support design and optimization in early phases, and produce geometrically assured products.

1.8. RESEARCH QUESTIONS

Based on the research objective, scientific and industrial goal highlighted earlier, the following research questions were formulated.

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

This question is framed to understand the selective laser heat treatment process and identify various sources that influence geometrical variation. Here, the focus has been on the sources that could be accounted for in the early design stages.

RQ2: How does the geometrical variation stemming from the selective laser heat treatment process affect subsequent processes?

A product is usually produced through a combination of different manufacturing processes. This question is framed to understand the effect of geometrical variation resulting from selective laser heat treatment on the subsequent manufacturing processes at part level as well as at assembly level.

RQ3: How can the sources of geometrical variation stemming from the selective laser heat treatment process be controlled?

This question is framed to understand how the sources that influence geometrical variation can be adjusted to minimize their effects.

1.9. DELIMITATIONS

In this research work, only selective laser heat treatment of boron steels is investigated. With respect to RQ3, no optimization of the identified sources is carried out yet in this research to show how exactly the sources could be controlled. However, a possibility of controlling the effects of such sources on geometrical variation is demonstrated through the experiments. The research results are mostly relevant to the automotive industry. However, it could be possible to extend the concept to other industries where weight savings and safety are of paramount importance.

1.10. STRUCTURE OF THE THESIS

The thesis is structured with chapter one providing background on the research topic. The research gap is highlighted and research questions are presented. In chapter two, research areas pertaining to the research topic are discussed. Chapter three discusses the research approach and methods followed in this research. Chapter four presents and summarizes the results achieved in this research thus far. Chapter five discusses the results from the scientific publications with respect to the research questions formulated. Chapter six concludes the research and briefly discusses the future work.

2 FRAME OF REFERENCE

Breakthroughs in research transpire when interaction of different disciplines occur through transfer of knowledge, ideas and methods (Blessing and Chakrabarti, 2009). Therefore when performing research, it is important to consider all the possible areas that could be relevant to the topic of interest. As per the description in the introduction chapter, the aim is to develop knowledge and methods in order to effectively produce geometrically assured products. Hence, this work can be positioned within the framework of geometry assurance. This chapter presents various topics that are associated with this research and lays the theoretical foundation.

2.1. QUALITY AND ITS SIGNIFICANCE

The definition of the term "Quality" varies based on the context it is being looked at. According to Garvin (Garvin, 1984), quality could be defined based on five different approaches, namely; the transcendent approach of philosophy, the product based approach, the used based approach, the manufacturing based approach, and value based approach. As per the product based approach, quality is defined as a precise and measureable variable. As per the manufacturing based approach, quality is defined based on meeting the established specifications, i.e. any deviation from the specifications characterizes the quality outcome. Garvin further identified eight dimensions of quality such as performance, features, reliability, conformance, durability, serviceability, aesthetics, and perceived quality. Performance is considered as the primary operating characteristics of a product. According to him, connection between performance and quality is dependent on the customer's perspective where difference in performance can correspond to difference in quality of the product.

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. As per Taguchi, quality loss is the loss imparted to the society from the time a product is shipped (Taguchi and Wu, 1980). The desirability for the product grows higher when the loss imparted is lower. So 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, due to the wearing out of the product over time, and also when the products are poorly manufactured. 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

$$l(Y) = k(Y - T)^2$$

where Y is the performance characteristic and the target value of Y is set as T, $l(Y)$ is loss in terms of cost due to deviation of Y from target value T, k is the 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 nonzero and displays nominal-the best type characteristic. The quality loss is symmetrical as seen in Figure 3. Phadke (Phadke, 1989) presented more variations of this quadratic loss function namely, smaller-the better type characteristic, larger the better type characteristic, and asymmetric.

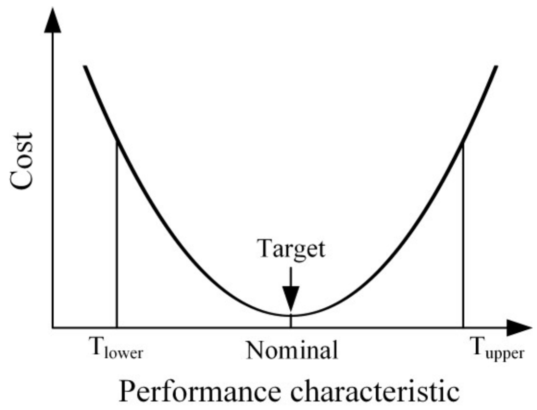

Figure 3 Quality loss (Phadke, 1989)

2.2. ROBUST DESIGN

The final quality and the cost of a product is driven by its design and the manufacturing process used to produce it. Phadke (Phadke, 1989) demonstrated through the robust design concept how the quality loss and the total cost could be minimized. In the concept, a product or a process can be considered as system as shown in Figure 4. Taking product as the example here, the response or the output of the product is a certain performance characteristic and is denoted as y. The output of the product depends on the input factors which could be influenced by some other factors. They are classified as signal factors (M), noise factors (x), and control factors (z). Signal factors represent the desired outcome from the product. Control factors are the parameters that could be adjusted to minimize the influence of noise factors and achieve the desired outcome. While, noise factors are uncontrollable parameters and cause deviation in the product's response thereby resulting in quality loss. The noise factors affecting the response could be some external factors such as operating condition environment, or wearing out of the product on usage, or inconsistency in the manufacturing process leading to variation in the response from product to product. Hence, product's engineering design and the manufacturing process govern the final quality and cost associated to the product.

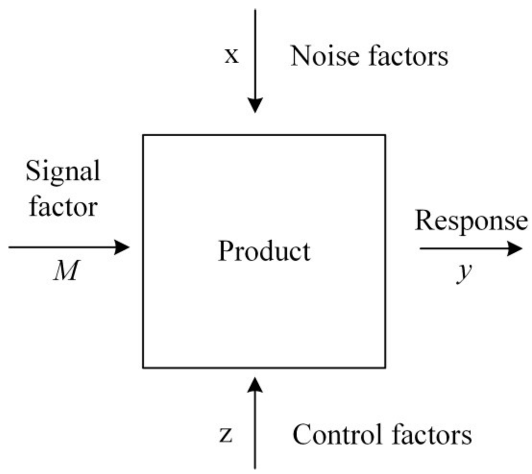

Figure 4 Block diagram (Phadke, 1989)

The fundamental principle of Robust Design is to improve the quality of the product by minimizing the effect of the causes of variation without eliminating the causes (Phadke, 1989). A three step approach to achieve robust design is proposed:

- ***Concept design***: It is also known as system design and is the first step. It consists of applying scientific and engineering knowledge to scrutinize available alternatives. Best out of the available alternatives is chosen and a basic functional prototype design is made which serves as the initial parameter settings for the product. In order to do so, understanding of the customer's needs and the manufacturing environment is necessary.
- ***Parameter design***: It is the second step which consists of optimizing the product parameter settings such that the product's performance is least sensitive to variation sources. As shown in Figure 5, moving the nominal value of the input (from sensitive design to robust design) results in output that is less sensitive to the input variation.

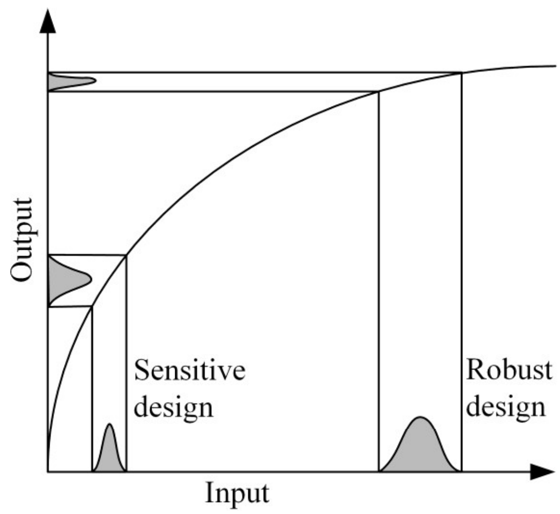

Figure 5 Parameter design to minimize the sensitivity (Phadke, 1989)

Parameter design is deemed as a very cost effective method of improving engineering design as it reduces the influence of variation on performance instead of eliminating the variation sources all together.

- ***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. Too tight tolerance can affect the manufacturing cost or too wider tolerance can increase performance variation. Hence it involves a trade-off between the quality loss due to performance variation and the increase in manufacturing cost.

2.3. GEOMETRY ASSURANCE

Geometry of the product being manufactured is prone to noise factors as a result of which the intended response from the product is affected. Geometry related quality issues are often discovered during assembly stages. This has huge cost implications as the product has to be either repaired or scrapped. Söderberg (Söderberg et al., 2006c) classified the sources of geometrical variation into part variation, assembly variation, and design concept variation. 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 variation in assembly techniques or in the equipment, or from application of external force through clamps and fixtures. The likelihood of the effect of the above said sources is higher if the design concept is sensitive towards it. Taguchi and Phadke (Taguchi and Wu, 1980, Phadke, 1989) underlined that the effect of noise factors on the product's response could be greatly minimized during early design stages of the product, i.e., by choosing a robust design concept. In robust geometry design, positioning of the locators i.e., the locating scheme is a way to suppress the effects from the variation sources.

2.3.1. LOCATING SCHEMES AND TOLERANCES

The purpose of the locating scheme is to lock the part during manufacturing, assembly or inspection. By having 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 is employed (Figure 6) to lock the position and is of orthogonal type (Söderberg et al., 2006b). Three locating points A1, A2, A3 lock three DoF, locating points B1 and B2 lock two DoF, while the locating point C1 locks the remaining one DoF. In case of non-rigid parts or assemblies with irregular geometry, a 6 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 cost (Söderberg et al., 2006c).

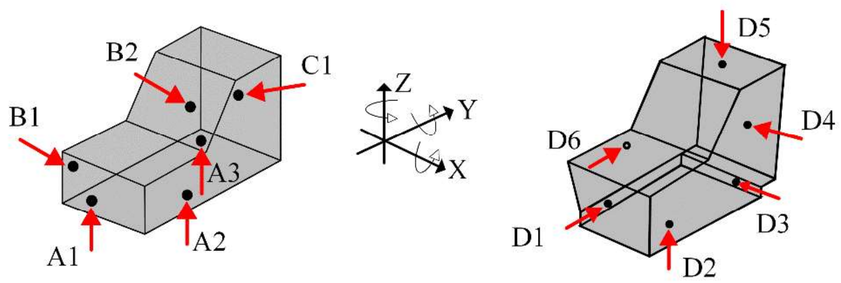

Figure 6 Orthogonal (left) and Non-Orthogonal (right) positioning scheme

As geometrical variation exists due to variation during manufacturing and assembly process, it is equally important to consider how much variation is acceptable and that 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, critical set of parameters are identified. An upper and lower limit is assigned to it. This is a conventional plus/minus tolerancing type. Geometrical tolerancing consists of assigning values to certain attributes of a feature such as form, orientation, location, runout etc. Tolerance allocation can be done either through top down approach or bottom up approach. In top down approach, tolerance requirement for the final assembled product is specified (Söderberg, 1994, Lööf and Söderberg, 2007, Söderberg, 1995). It is then broken down to individual parts of the product. Contrary to this, in bottom up approach the tolerance is specified to every individual part within the product. They then define the tolerance of the final assembled product.

2.3.2. VARIATION SIMULATION

In order to predict and suppress the effect of possible sources of geometrical variation in the early design stages, many methods have been developed over the years for both rigid and non-rigid models (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 software tools. A methodology and a software named RD&T were developed for evaluating robustness and geometrical stability and have evolved over the years (Söderberg and Lindkvist, 1999a, Söderberg et al., 2006a, Söderberg et al., 2016). RD&T has been used in this research work to analyze geometrical variation and hence various types of analyses in it are described with respect to the geometry assurance framework.

Stability analysis is the first step which is about evaluating the geometrical robustness of the chosen concept with respect to its locating scheme (Söderberg and Carlson, 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 color-coded form. The color 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 notice the differences in effects.

Once the robust locating scheme is selected based on the above analysis, tolerances can then be allocated. ***Variation analysis*** allows simulating 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 to check if the effect of simulated variations are within the specified limits for the critical areas. If outside the limits, then ***Contribution analysis*** can be performed to check which locator points contribute towards variation and where the tolerances could be tightened (Söderberg and Lindkvist, 1999b).

2.3.3. COMPLIANT VARIATION SIMULATION

Variation simulation explained so far is with the assumption that the parts are rigid. In 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 (Cai et al., 1996). In reality, this is performed for example using clamps which could deform the sheet metal part; the effect of which should be considered in the variation simulation environment. By combining Finite Element Method (FEM) with Monte Carlo simulation, variation simulation considering different input variables can be performed as shown in (Dahlström et al., 2002, Dahlström et al., 2007). FEM combined with method of influence coefficients as proposed in (Liu and Hu, 1997) is an alternative to the above said method were larger number iterations and faster simulations could be performed as demonstrated in (Dahlström and Lindkvist, 2007, Lorin et al., 2014d, Wärmefjord et al., 2013).

In case of variation simulation of assemblies considering joining process such as spot welding, the adjoining parts are first required to be positioned in the assembly fixture such that all degrees of freedom are locked. Spot welding can then be performed in the preferred sequence to join the parts together. Once the joining process is complete, the assembly is unclamped. Unclamping causes the assembly to springback (Figure 7). The extent of the assembly springback is influenced by factors such as the springback and locating scheme of the formed part, the assembly joining process, stiffness of the assembly, or the assembly may be over constrained.

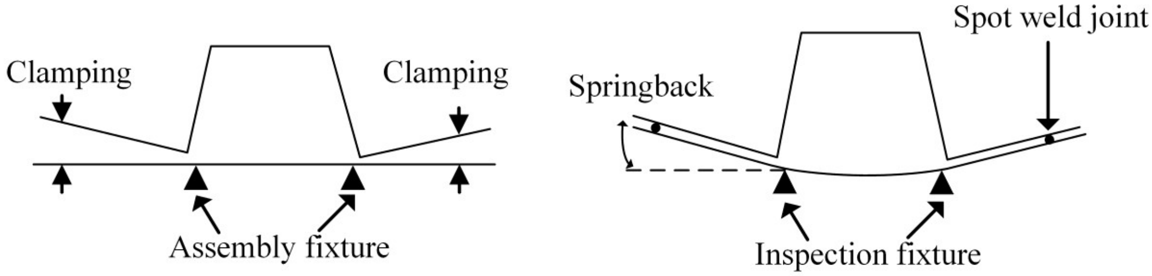

Figure 7 Example of springback due to unclamping in spot welding

2.3.4. THERMAL EFFECTS IN VARIATION SIMULATION

Several works on considering the effect of temperature and heat in variation simulation have 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 geometrical variation in (Pahkamaa et al., 2012). A faster variation simulation approach for welded assemblies was demonstrated by using a thermo-elastic finite element model in (Lorin et al., 2014b, Lorin et al., 2014c). The approaches were made more robust by considering various factors in (Lorin et al., 2014a, Lorin et al., 2015). A summary of including the effect of temperature with focus on methods and tools to enable variation simulation can be found in (Lorin, 2014).

Simulation support exists for manufacturing applications that involves heating and melting. However in order to have a robust design concept when employing manufacturing applications such as the one in this research work (selective laser heat treatment), information about how to define the end requirements by considering the effects of temperature and heat on geometrical variation is necessary. Understanding of what parameters to consider during the design stages is vital. Optimal choice of design parameters along with robust locating scheme will suppress the effect of geometrical variation and make the final assembly robust. From an industrial perspective, a demonstrator (simulation tool) and design guidelines based on the knowledge gained in this research could aid the design engineer in choosing a robust design concept.

2.4. INTRODUCTION TO LASER MATERIAL PROCESSING

Since the first publication of the concept of laser in the late 1950s, and its first working concept by Theodore Harold in 1960, the application of lasers in material processing has progressed (Steen and Mazumder, 2010). As per Ion (Ion, 2005a), it has undergone the phase of technology push and the industrial pull where laser as a technology was as solution looking for a problem at the same time when the industry was looking for solutions to its problems.

Laser beam acts as the heat source in laser materials processing because of its ability to produce high energy concentrations due to the monochromatic, coherent, and low divergence characteristics (Kannatey-Asibu Jr, 2009). Such characteristics allow lasers to be used in applications that require heating, melting and vaporizing the materials. Some early applications of laser in material processing were in welding, machining as well as for surface modification such as heat treatment. With advancements made in other areas within manufacturing, its applications have extended to processes such as laser forming, shock peening, micromachining, and nano processing. Figure 8 (Power density vs Interaction time) summarizes the requirements for various laser material processing techniques.

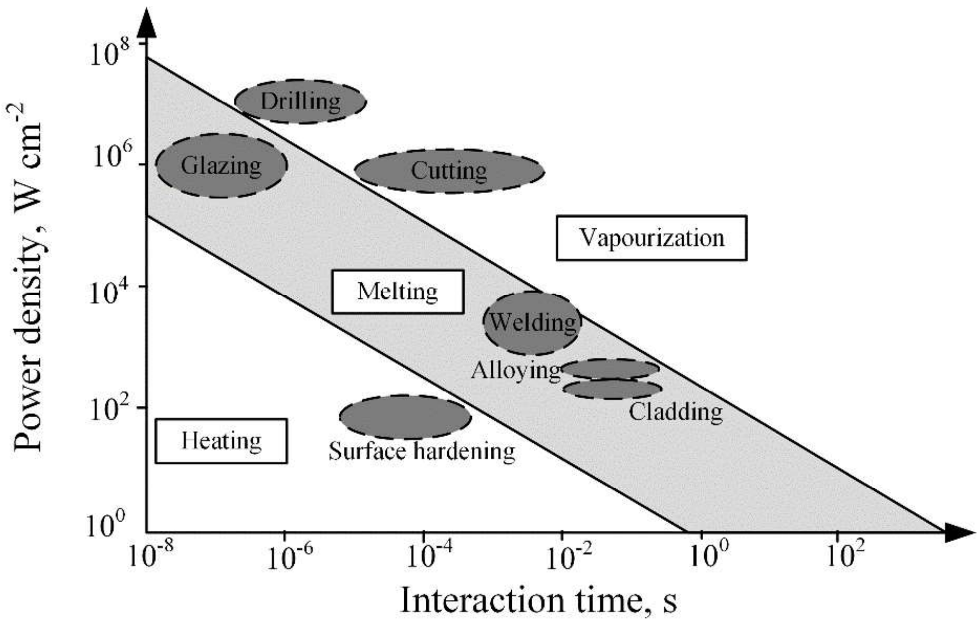

Figure 8 Power density and interaction time spectrum for laser material processing. Redrawn from (Santhanakrishnan and Dahotre, 2013)

In laser material processing, the most significant parameters to achieve the desired outcome are the power density and interaction time. Power density is defined by the input power when the laser is incident on the interaction surface of the material and the size of the laser beam (Kannatey-Asibu Jr, 2009). The interaction time for a continuous process is defined as the time taken for the incident laser spot to move one diameter relative to the material (Chen et al., 1994). For a pulsed process, the interaction time is the pulse duration itself. The specific energy delivered to the material to undergo required changes is the product of power density and interaction time.

2.4.1. SELECTIVE LASER HEAT TREATMENT OF SHEET METAL BLANKS

Selective laser heat treatment belongs to the laser surface modification category also known as laser transformation surface hardening. Ion (Ion, 2005c) defines it as an autogenous method of producing wear-resistant patterns on discrete surface regions of components. The process involves modifying the surface composition or the microstructural properties of the material locally by using laser as a heat source (Figure 9). Contrary to conventional heat treatment practices where the entire part undergoes heating, only areas requiring modifications are to be heated in this process instead of the entire part. The laser beam moves across the areas which require modification and heats up the area above the transformation temperatures.

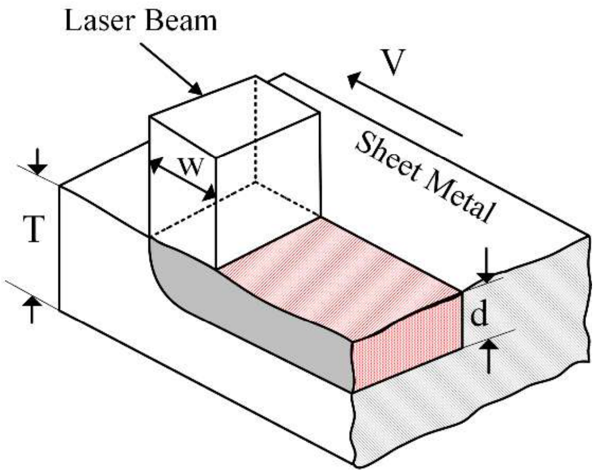

Figure 9 Laser heat treatment process setup. V is laser beam traverse speed, T is sheet metal thickness, W is laser beam diameter or width, d is the depth of laser hardened area. Redrawn from (Mazumder, 1983)

The surrounding material which remains untreated act as heat sink resulting in rapid cooling of the heat treated area. The material does not melt and transformation occurs in solid state condition instead. It is mainly performed to increase wear resistance or induce compressive residual stresses to improve 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 surface hardening of mill rollers (Kannatey-Asibu Jr, 2009, Ion, 2005b).

Some of the current manufacturing processes though have substantially contributed in achieving the goal of weight savings, poor formability aspects of the lightweight materials such as high strength steels and aluminium alloys restrict in achieving further weight savings (Geiger and Merklein, 2007). Hence, the concept of selective laser heat treatment was further extended to sheet metal blanks with the intention to locally modify material properties prior to the forming process to enhance formability and impart strength into the material. Selective laser heat treatment of the blanks is planned based on the forming requirements as well as the crash requirements as shown in Figure 10. The critical areas in the sheet metal blank which are prone to failure during the forming process or during crash can be identified either through simulations or through experience from similar parts. As per Figure 10a, the areas critical for the forming process are locally laser heated and the heat treated metal blank is then formed to the desired

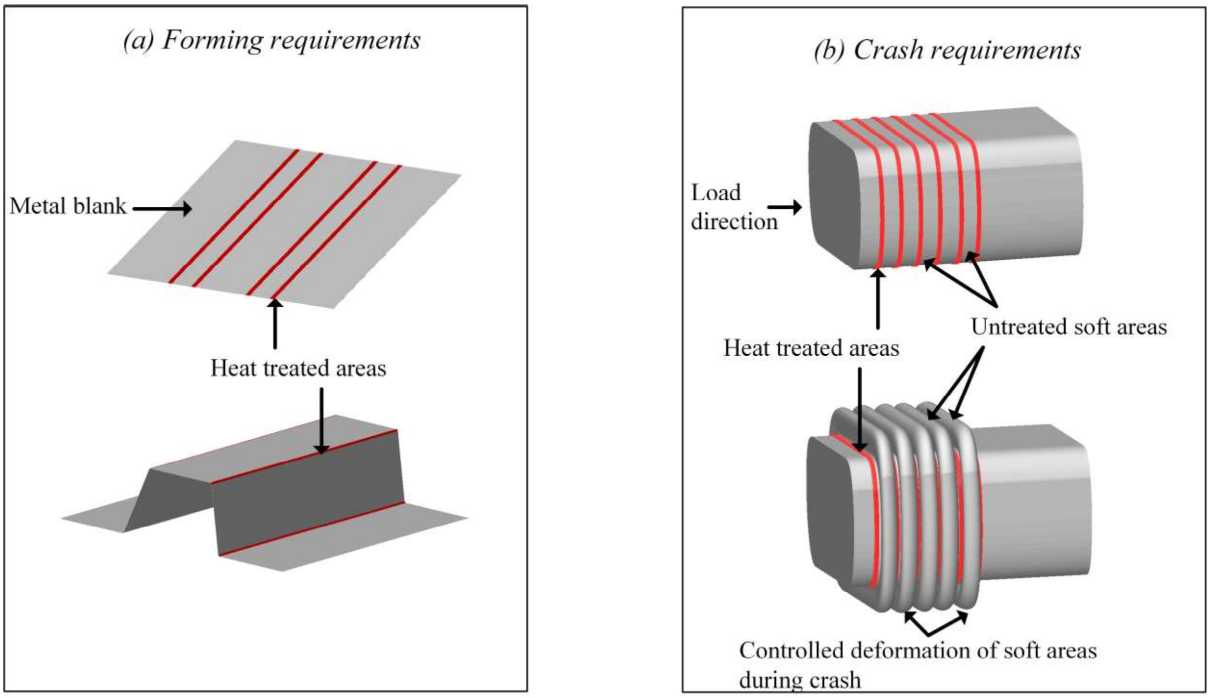

Figure 10 Selective laser heat treatment based on (a) Forming requirements (b) Crash requirements

shape. The process sometimes does not directly enhance the formability of the material by softening due to heating. It is the interaction of hard and soft areas that lead to improved material flow when the blanks are subjected to forming (Merklein et al., 2014). As per Figure 10b, the critical areas for the required crash behavior are locally laser heat treated at the blank stage and then formed to the desired shape. When the formed part is subjected to crash, the softer areas between the local laser heat-treated areas crumble first in a controlled manner. Based on the literature studies, an overview of the selective laser heat treatment of sheet metal components is presented in Figure 11.

The first step involves determining the forming requirements and crash requirements of the component to be manufactured. This gives 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 selective laser heat treatment process based alternatives such as the pattern type, the 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, honey comb based (hexagon) pattern are some of the examples. They also add aesthetical characteristics to the component. Once the pattern related aspects are chosen, various laser heat treatment sequence strategies can be simulated. The laser heat treatment sequence governs the stress distribution in the sheet metal blank as well as the overall processing time. Therefore, these are to be planned in the early design stages. Simulation tools play a crucial role as different alternatives can also be evaluated with respect to geometrical variation and optimized. Information of the chosen pattern type, pattern size and sequence strategy serves as the input for the robot coupled selective laser heat treatment equipment (Figure 11, step 3). After laser heat treatment of sheet metal blanks, they are formed into the desired shape. The local heat treated – formed components can then be assembled with other components.

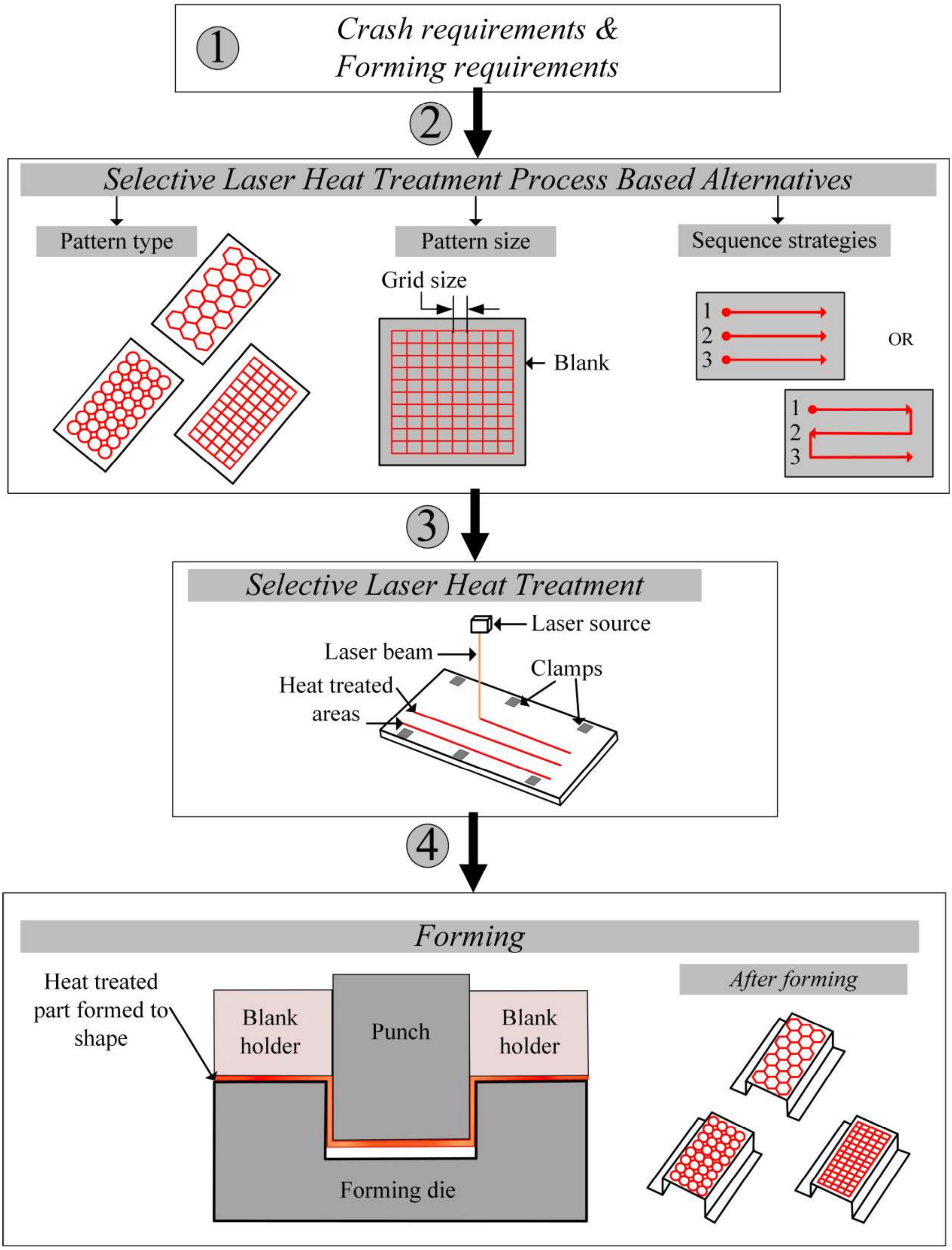

Figure 11 Process overview of selective laser heat treatment of sheet metal components

Plenty of research has been undertaken in this area to study aluminium and high strength steels to show great possibilities of enhancing formability as well as imparting strength into the material. Process windows have been proposed for some of the materials. A summary can be found in (Merklein et al., 2014) (Mäntyjärvi et al., 2007) (Bergweiler et al., 2010, Asnafi et al., 2016).

Even though the results look promising, the thermal, metallurgical, and mechanical coupling effects (Figure 12) generate residual stresses and distort the part**.** It affects the subsequent processes both at part level and assembly level. This variation in the geometry affects the intended functionality and performance of the part. Hence, the quality of the part being manufactured is compromised. The focus of establishing material specific process windows have mainly been on how to successfully perform laser heat treatment. As the understanding of selective laser heat treatment process is still in the nascent stages, not much information is available on the effect of design concept on the quality of the part manufactured through selective laser heat treatment process. This research tries to investigate the effect of some of the design concept decisions on the geometrical variation.

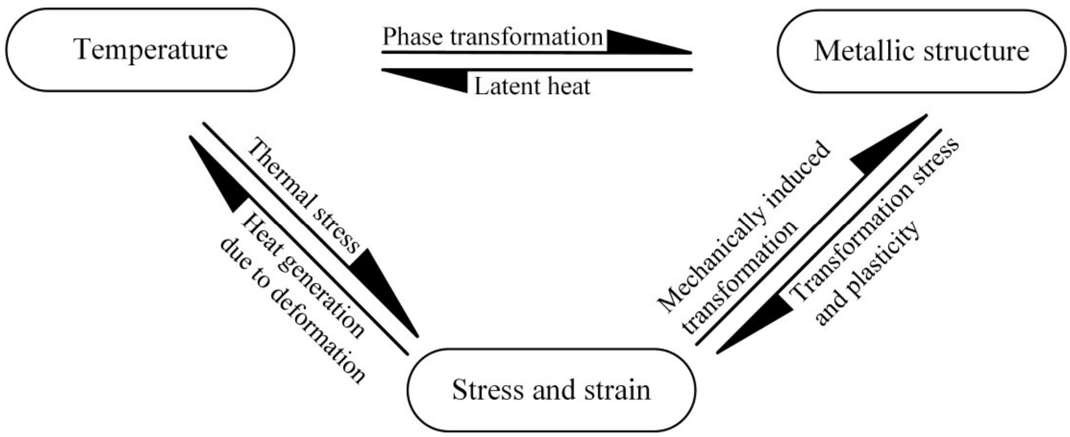

Figure 12 Coupling phenomena between temperature, metallic structure, and stress and strain. Redrawn from (Inoue and Wang, 1985)

The sources of variation from selective laser heat treatment process is classified based on part variation, assembly variation, and design concept variation. Figure 13 provides the details of the classification.

- ***Part Variation*****:** As described earlier, part variation is associated to the size and form variation in the geometry due to variation in the manufacturing process parameters, material condition and processing conditions.

  - ***Manufacturing process (selective laser heat treatment)***
    - *Laser Beam Properties*: Laser beam diameter or the spot size along with the traverse speed and the laser power determine the heat input during the laser beam-material interaction. The heat input controls the laser heat treatment process. The type of laser, continuous or pulsed, is also an influencing factor.
    - *Traverse Speed*: Laser traverse speed or the scanning speed governs the laser beam- material interaction time. The scanning speed and laser power collectively

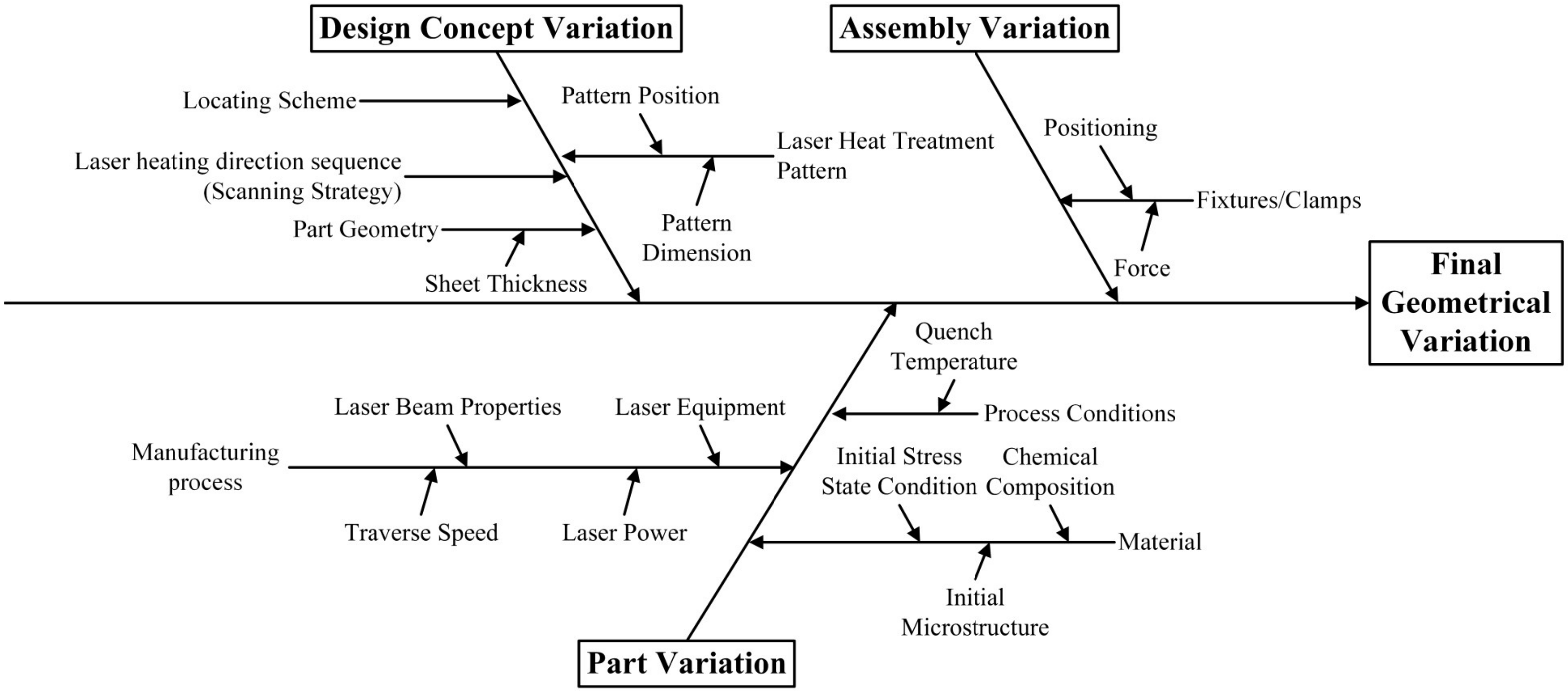

Figure 13 Geometrical variation contributors in selective laser heat treatment process

determine the hardness depth. The chosen scanning speed also affects the total processing time and has cost implications.

- *Laser Power*: It is decided based on the required temperature and the hardness depth. Variation in laser power can lead to insufficient heating, overheating or melting.
- *Laser Equipment*: The accuracy of the laser equipment also contributes to variation in the process. Any variation in the robot on which the laser equipment is mounted influences the end results.

➢ ***Process Conditions***: The environment in which the selective laser heat treatment process is conducted affects the quench temperature. It aids in rapid cooling for desired microstructure transformation and hardness. Change in microstructure is related to volumetric changes as well as transformation stress.

➢ ***Material***

- *Initial Microstructure*: The initial microstructure distribution influences the transformation stress and eventually the distortion.
- *Initial stress state condition*: The initial stress state of the sheet metal from the previous manufacturing steps also influences the final outcome.
- *Chemical Composition*: Phase transformation is governed by the chemical composition. Variation in chemical composition affects the phase transformation behavior which in turn affects the stress distribution.

- ***Design concept variation*:**

➢ ***Part geometry***

- *Sheet thickness*: Part geometry is important as the heat distribution is dependent on it. Sheet thickness governs the hardness depth. The corresponding laser power and laser traverse speed to achieve the hardness depth is then chosen.

➢ ***Laser heat treatment pattern***

- *Pattern position and pattern dimension*: The pattern design (pattern type) and its position is chosen according to the part geometry, forming requirements and functionality requirements. The pattern dimension is chosen accordingly. Pattern dimension governs the heat treatment percentage applied to the sheet metal. The stress state after laser heat treatment varies based on the pattern dimension and pattern position.

➢ ***Locating Scheme***: The choice of locating scheme to perform the selective laser heat treatment process can influence geometrical variation. Optimal locating scheme to position the sheet metal blank can minimize the effect of variation in the subsequent processes.

➢***Laser heating direction sequence***: Also known as scanning strategy, it influences the distortion shape, the stress distribution and also dictates the total processing time.

- ***Assembly variation*:** When assembling the parts together, any variation in fixtures and clamping tools influences the contact between the parts thereby influencing the geometrical variation at assembly level. Wear out of the equipments over time, or force exerted on the parts could be some of the reasons influencing assembly variation.

2.5. INTRODUCTION TO STEELS – HEAT TREATMENT PERSPECTIVE

High strength and ultra high strength steels are the widely used lightweight materials in the automotive industry for vehicle body applications. They offer economical and high weight-saving possibilities. They are used for improving impact energy absorbing capacity of the vehicle body components. Among ultra high strength steels, boron steels are the more preferred ones. Boron steels up to 40% of total vehicle weight have been used to improve crashworthiness as well as achieve substantial weight reduction (ArcelorMittal, 2015). Presence of boron as an alloying element improves hardenability in steels. Boron content in the range of 0.001% weight to 0.003% weight provides maximum hardenability (Anjana Deva and Jha, 2014). Due to this high hardness, boron steels have good wear resistance properties. Presence of boron delays transformation to other phases such as bainite, ferrite, and pearlite microstructures which are much softer (Anjana Deva and Jha, 2014, Total Materia, 2007). Hence, the microstructure transforms to 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.

2.6. INSPECTION

Inspection is the process of determining if the manufactured product is within the desired specification or deviates from it (Newman and Jain, 1995, Kennedy et al., 1987). Inspection techniques and procedures have played a vital role in the quest towards achieving high quality-low cost products. Coordinate measuring machine, a well-known contact type inspection technology has lead 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 because of high operating time when measuring large set of points. Also, they show difficulties in measuring free-form surfaces (Lee and Park, 2000). With growing complexity in geometry of the products as well as shorter development times, industry is shifting focus towards faster available inspection techniques.

Noncontact laser based inspection techniques have gained popularity over the years. They have been mostly used in reverse engineering applications (Varady et al., 1997) and will play a pivotal role in the concept of Digital Twin for real time geometry assurance (Söderberg et al., 2017). Laser scanning allows acquisition of larger set of measurement points in shorter duration (Sokovic and Kopac, 2006). Most of the laser scanning equipments used are based on laser triangulation by means of a laser stripe (Martínez et al., 2010). They are of higher precision and low cost in comparison to other noncontact equipments. A typical laser scanning equipment consists of a robotic arm equipped with a laser-scanner probe at the end of the robotic arm. The laser probe consists of a projector that emits 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 X, Y, Z coordinate values for each measured point through image processing and triangulation. This point cloud data can be processed further to reconstruct into a mesh or a surface model using many commercially available reconstruction softwares such as CATIA, Geomagic (Martínez et al., 2010), MeshLab (Cignoni et al., 2008) to name a few.

3 RESEARCH APPROACH

This chapter briefly presents the research approach and justifies the choice of research methodology employed in this work.

3.1. BACKGROUND

The process of obtaining knowledge of whatever is unknown can be termed as research. Research is not only an activity that is restricted to obtaining knowledge to understand a task but it also extends to making improvements in it. Kothari (Kothari, 2004) refers to research as a systematic method of enunciating the problem, formulating a hypothesis, collecting and analyzing the data and reaching conclusions in the form of solutions to the problem or in the form of general conclusions for theoretical formulation.

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 14). 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. However, 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 analyze 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) describe design research as integration of two aspects of research, namely development of understanding and 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 either from current state of the subject of interest or the expected future state of it. This research work is no different. This work has been carried out in Wingquist Laboratory where it began due to an industrial need as well as a

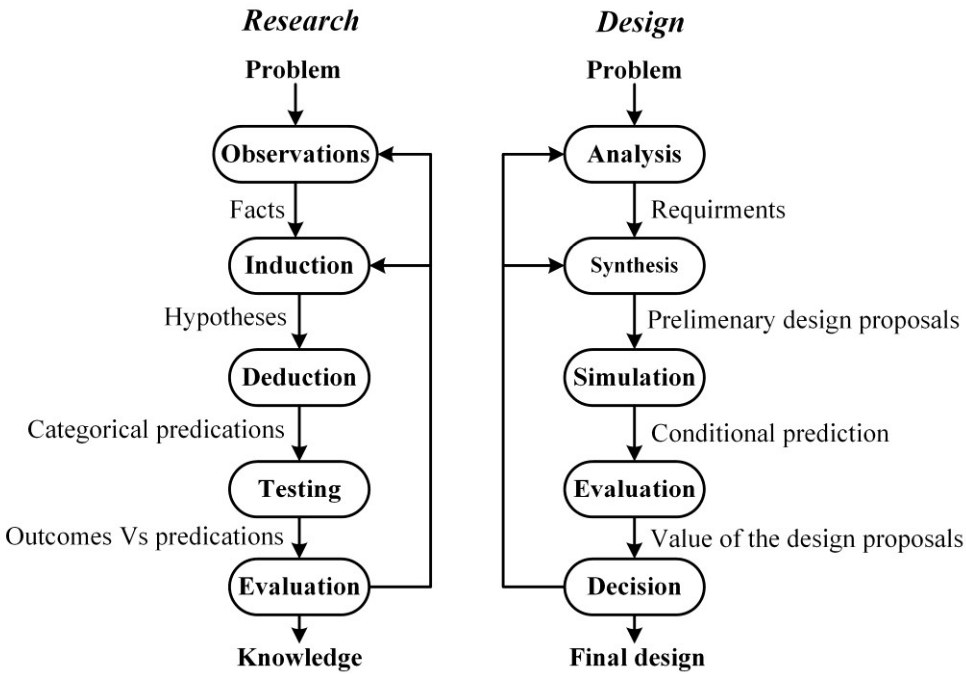

Figure 14 Research and Design process comparison redrawn from (Eekels and Roozenburg, 1991)

research gap. The work was conducted in close collaboration with an industrial partner. The objective of this research work is to generate knowledge and develop support that could aid in making better design decisions. The main contribution of this research is towards 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. It allows them to produce robust design concepts that are insensitive to manufacturing variation. But in order to develop knowledge and support which could aid in mitigating geometrical variation effects through robust design concepts, understanding the manufacturing process and geometrical variation contributors is vital.

3.2. RESEARCH FRAMEWORKS

The significant characteristic of research is that it is methodologically well executed. Addressing the research gap and industrial needs will involve multiple stages. Hence, 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: Theory of Technical systems (Hubka and Eder, 1988), Axiomatic design (Suh, 1998), Framework for modeling of synthesis (Takeda et al., 1999, Takeda et al., 2001), Mitroff model (Mitroff et al., 1974), Logic of design (Roozenburg and Eekels, 1995). However, most of the approaches lack clarity on how they could be implemented based on the nature of the problem. They lack methodological rigor that could also aid in interpretation, validation and documentation of results. This work employs 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 as defined by the authors (Blessing and Chakrabarti, 2009) is an approach and a set of supporting methods and guidelines to be used as a framework for doing design research. It is a generic methodology that links the research questions together and provides support to address them in a systematic manner.

DRM is divided into four stages namely Research Clarification (RC), Descriptive study I (DS I), Prescriptive study (PS) and Descriptive study II as shown in Figure 15. In order to have successful results from design research, it is important to have information available from past research and also have research goals formulated (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 to describe the problem and the desired solution to an extent. Quite often, all information is not readily available. Some more knowledge has to be acquired to gain more clarity and elaborate 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 requires to be addressed to improve the problem situation. More knowledge can be attained through observation of the process associated with the problem, through experimental investigation, through interviewing stakeholders such as designers, or manufacturing engineers. Based on the understanding gained in his step, the success criteria can be clearly defined.

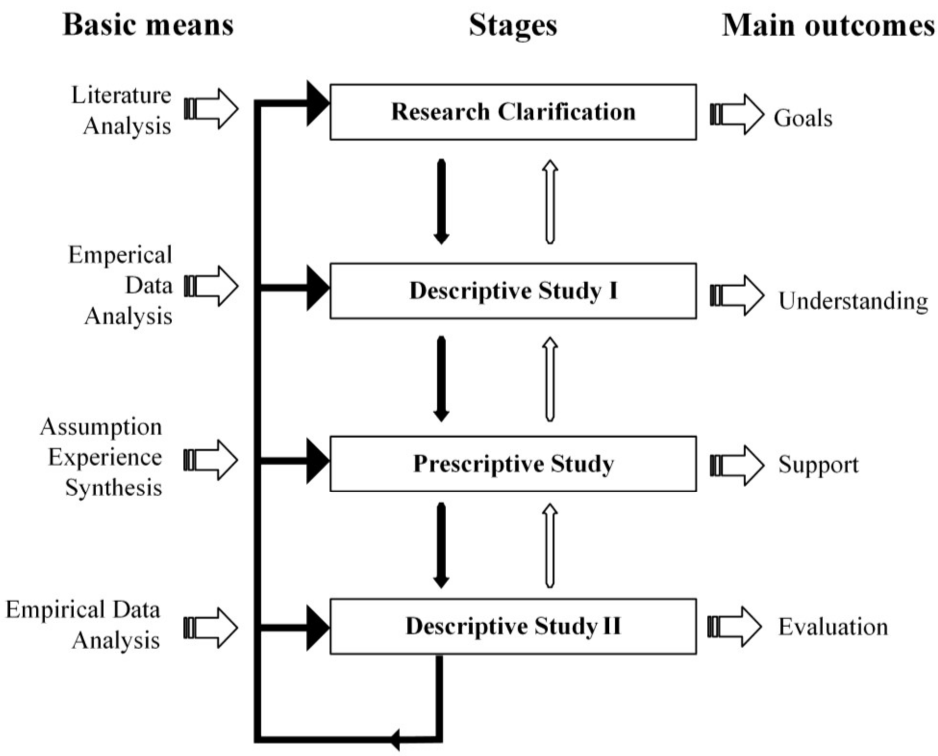

Figure 15 DRM framework redrawn from (Blessing and Chakrabarti, 2009)

Concrete evidence may not be possible at DS I but it provides sufficient enough information on the factors that influence the nature of the problem as well as the final research goal. In 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 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, appropriate stage in the DRM process could be chosen.

3.4. WINGQUIST LABORATORY RESEARCH AND IMPLEMENTATION PROCESS

As mentioned earlier, the research gap was identified from an industrial need. The Wingquist Laboratory process follows a similar practice as the DRM (Figure 16). The first step in the framework is to further understand the research gap that arises from the industrial requirements and 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 prescriptive study and descriptive study II steps in the DRM process.

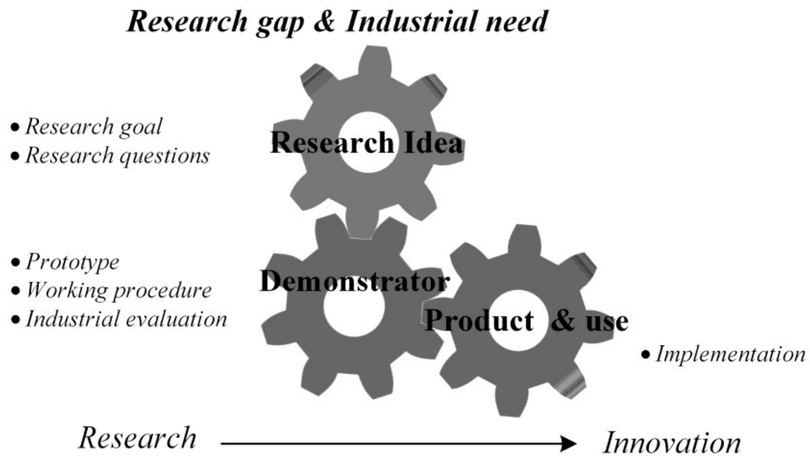

Figure 16 The Wingquist Laboratory research and implementation process

3.5. RESEARCH APPROACH APPLIED IN THIS WORK

Planning of the research process requires holistic thinking and a logic of end to end perspective. For this reason, Design Research Methodology (DRM) was chosen to follow a systematic approach in planning of this research work. The research process began with research clarification stage by performing literature studies. Based on the information gathered, research goal and the success criteria were formulated. The research goal is to have deeper understanding and generate knowledge that allows developing methods and tools to perform geometrical variation simulation for sheet metal components considering heat treatment effects. The ultimate goal or the success criteria for this research is to be able to perform accurate robust design assessment for sheet metal components that accounts for local heat treatment effects.

Through the literature studies, factors that contribute to the success criteria were identified. Three research questions have been formulated that govern the research. Lack of concreate information encouraged empirical studies to gain more understanding of the factors that influence the success criteria. This shaped the DS I of the DRM process. The research work conducted thus far has mainly contributed to the DS I. The objective in the DS I study was to gain better understanding of the current situation by identifying and clarifying the factors that influence the success criteria in detail. The research outcome achieved up to this stage lays the foundation for subsequent prescriptive study where the aim is to develop a method that could be demonstrated through a demonstrator such as the CAT tool RD&T. Once developed, the method will be validated before being implemented in the industry to address their needs.

Publication of scientific papers have been 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 (Figure 17).

	RQ	RC	DS I	PS	DS II
Paper A	RQ 1, RQ3				
Paper B	RQ1, RQ3				
Paper C	RQ2				
: Low contribution		: High contribution			

Figure 17 Research results as per the DRM framework

3.6. METHODS USED IN THE STUDY

A comprehensive DS-I study has been carried out involving a literature review and empirical studies. Literature studies were mainly done to understand the existing knowledge in the area concerned with this research topic and is presented in the previous chapter. The literature studies mostly involved collecting information from scientific publications and experiences from the industrial stakeholder.

In empirical studies it is generally better to have a deep understanding about a few factors, than a shallow understanding of a large number (Blessing and Chakrabarti, 2009). Experiments were performed to collect the data. All the research questions are dealt with from the information observed and data collected from the experiments. Every step in empirical study is documented to continuously reflect on the data collection process.

3.7. VERIFICATION AND VALIDATION

Verification and Validation are defined in various ways in different disciplines. As per (Blessing and Chakrabarti, 2009), validation is about doing the right thing while verification is about doing the thing right. As per Taylor (Taylor, 2013), validation is about questioning the validity of the outcome and is classified as *internal validity, external validity, construct validity, and statistical conclusion validity* (Cook et al., 2002, Yin, 2017). Internal validity is about if the relationship between variables under investigation is causal i.e., if 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 experiment (construct) setup up. Any unaccounted factor influencing the causal relationship between variables being investigated, researcher's bias, and conditions under which the studies are conducted are some of the 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 the two means of verification. As per logical verification, there should not be any conflicts between the elements outlined in the research and it should show *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. As per verification by acceptance, the established theory should be acceptable to experienced practitioners in the relevant field. Also, the models and methods that are developed based on the established theory should be accepted by the experienced practitioners within the field.

4 RESULTS

The learnings from the research conducted so far has resulted in three publications that are appended with this thesis. This section presents the summary 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 selective laser heat treatment process and explore the possible sources of geometrical variation. Based on the available information from literature studies and inputs from the industrial stakeholder's experiences, possible sources of variation that influence the geometrical quality in sheet metal components when subjected to selective laser heat treatment were identified. The criteria 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 geometrical variation outcome. 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 application of selective laser heat treatment is decided based on two criteria, 1) ***Forming requirements:*** The objective of locally modifying the material properties is solely to aid in the 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 fulfill both the requirements. The choice of local areas are 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 were applied. Meaning, three heating direction sequences for each grid dimension type were tested. The position of heat treatment pattern was fixed. It was chosen based on the results from earlier industrial and literature studies.

Outcome: The results showed that altering the laser heat treatment sequence alters the geometrical variation outcome. The magnitude of the geometrical variation outcome was further dependent on the heat treatment pattern dimension. During the laser heat treatment process, superposition of microstructural transformation stresses as well as the thermal stresses occur due to 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 fixture and clamps. The resulting distortion varies for example, when there are variations in chemical composition or residual stresses from previous manufacturing process steps. The stress distribution varies from blank to blank and so does the shape of the blank due to deformation.

The effect of laser heat treatment of the blanks also affected the subsequent stamping process. Laser heat treatment sequence is a vital parameter as based on the choice of sequence, the total processing time for performing selective laser heat treatment varies. This will have cost implications on the end product.

Some general conclusions from the results are that laser heating direction sequence that influences the final outcome could be adjusted to minimize the effects. 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.

Research contribution: The main contribution from this paper is that new knowledge is acquired on parameters influencing geometrical variation that are interconnected. The need to consider them during variation simulation to include thermal effects for more accurate prediction is highlighted.

Industrial contribution: The main contribution from this paper is increased understanding of the manufacturing process by demonstrating the effect of percentage of heat treatment on the blank (pattern dimensions) and possibilities of optimizing the parameters (heating direction sequence) to improve geometrical quality and lower the costs.

4.2. PAPER B: INFLUENCE OF SELECTIVE LASER HEAT TREATMENT PATTERN POSITION ON GEOMETRICAL VARIATION

Background: Most of the research conducted concerning selective laser heat treatment has been about material specific process windows, mainly to show the formability and strength enhancement possibilities. Therefore, another aspect from the literature studies that required investigation was the importance of heat treatment pattern position. As briefly described earlier, 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. Hence, varying the pattern position for the same percentage of heat treatment is of interest. The sensitivity due to change in pattern position could further get altered due to variation in fixture locators or clamping tools.

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

Outcome: The results showed change in pattern position unfavorably affected the geometrical variation as well as the forming outcome. Some general conclusions from the results are that positioning of the entire pattern or a part of it (heat treatment areas of the pattern) influences geometrical variation. It can impact the assembly process and final product performance. The magnitude of the influence on geometrical variation is further based on the pattern dimension. The outcome also throws light on the need for considering geometrical variation in the early stages of product development when optimizing the pattern and its positioning based on end requirements.

Research contribution: The main contribution from this paper is that the significance of pattern positioning on robustness is highlighted. It could also mean trade-off between robustness and end requirements.

Industrial contribution: The main contribution from this paper is that it demonstrates the effect of pattern positioning on formability. Improved understanding on the manufacturability aspects i.e., about laser material processing and its influence on subsequent forming process is shown.

4.3. PAPER C: EFFECT OF SELECTIVE LASER HEAT TREATMENT ON GEOMETRICAL VARIATION IN BORON STEEL COMPONENTS: AN EXPERIMENTAL INVESTIGATION

Background: The focus of the first two papers was limited to part level which was subjected to two manufacturing processes, namely selective laser heat treatment and metal forming. In this paper, the objective was to take the assembly process into account to demonstrate geometrical variation effects propagating from part level to assembly level. This paper gives a more detailed account of the effect of the selective laser heat treatment process and how it impacts the subsequent forming as well as assembly process. Unlike previous papers, the focus here was to study the geometrical outcome for a fixed set of parameters. This paper hence could be considered as a precursor for paper A and paper B.

Method: In the first step, physical experiments were performed to show the effect at part level i.e., till the forming process. The scanned data of the formed parts were collected and the effect at assembly level was shown through computer simulations.

Outcome: A step by step account of geometrical variation from part level to assembly level was outlined. Sources of variation that could be considered in design for manufacturing of tailored heat treated blanks using laser were presented.

Research contribution: The main contribution from this paper is that the possible parameters that influence the geometrical quality and that should be accounted for in the early stages of product realization process are identified. Need for a structured method that considers those parameters to evaluate different concepts in early stages is highlighted.

Industrial contribution: The main contribution from this paper is that it demonstrates the shortcomings and problems that could occur with respect to geometrical quality at part level and assembly level based on the current established practices related to selective laser heat treatment.

5 DISCUSSION

This section discusses the results presented in the previous section. The results are discussed in relation to the research questions framed at the beginning of the research.

5.1. RESEARCH QUESTIONS

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

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 specifically answer this question where the effects of adjusting the considered sources are shown. Three possible sources of variation have been taken into account; laser heat treatment direction sequence, laser heat treatment pattern dimensions, laser heat treatment pattern position (Figure 13). The influence of laser heat treatment direction sequence is specifically highlighted in relation to heat treatment pattern dimensions in Paper A. Same type of laser sequence strategy produces contrasting results for different heat treatment pattern dimensions which highlights the influence of percentage of laser heat treatment applied on the blank. In paper B, the importance of positioning the heat treatment pattern on the blank and its influence on geometrical variation is shown. It also reveals how the effect differs based on the percentage of laser heat treatment that the blank undergoes. In both papers A and B, it is shown that the geometrical variation after selective laser heat treatment of blanks impacts the subsequent forming process, where the similar trend in geometrical variation continues. In paper C, the sources of variation mainly affecting at the heat treated blank level are mapped and briefly discussed.

RQ2: *How does the geometrical variation stemming from the selective laser heat treatment process affect subsequent processes?*

This question is mainly dealt in paper C where effect at different stages from part level to assembly level was captured. For a fixed set of parameters, the main focus has been to determine that it indeed affects at different stages which should be accounted for at part level itself. In paper A and paper B, the effects are demonstrated at part level where selective laser heat treatment and the subsequent forming process are of interest. As various parameters are tested in paper A and paper B, the effect of adjusting the parameters on the final outcome at part level was seen. In paper C, the heat treated formed part was further assembled and studied using spot welding variation simulation. The trend originating after selective laser heat treatment at blank level more or less continued up to the assembly level pointing towards the need to control the effects at part level.

A mapping of the sources of geometrical variation in paper C is provided. As the conclusions made from the work is to suppress the variation as early as possible, the sources are mapped with respect to geometrical variation at the first step i.e., at laser heat treated blank level. They are categorized into design concept variation, manufacturing process variation, and assembly variation. The laser heating direction sequence, heat treatment pattern, heat treatment pattern dimension are assigned under robustness within design concept variation. As laser heating direction sequence is decided after the heat treatment pattern is fixed, it can be argued that the laser heating direction sequence could be branched under the manufacturing process variation instead. The reason it is categorized under the design concept is by considering the possibilities of trade-off between heat treatment pattern sequences with respect to laser heat treatment pattern. Also, considering implication of heat treatment pattern sequences on cost due to processing time.

RQ3: *How can the geometrical variation stemming from the selective laser heat treatment process be controlled?*

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 can effect geometrical 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. In paper B, it was shown that a robust pattern position on the metal blank could minimize the effects

5.2. RESEARCH QUALITY: VERIFICATION AND VALIDATION

The research conducted so far corresponds to the first two stages of the design research methodology. The research results produced are mainly aimed at developing knowledge and have increased understanding of the subject of interest. The research results and the approach taken needs to be evaluated. The research quality described in section 3.7 are discussed with respect to the research conducted.

- **Internal validity :** It 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 the internal validity. Internal validity was ensured by performing controlled experiments and any threats in the form of any unaccounted variables was eliminated. The tests were repeated within each strategy.

- **External validity:** It relates to whether the research results can be generalized to conditions other than the one studied. The results are not directly generalizable to other settings or domains beyond the ones considered in this research.

- **Construct validity:** It relates to whether the research approach actually measures what it is intended to measure. The construct validity is demonstrated by performing different strategies and repeating the strategies for consistency.
- **Verification:** The research results presented earlier (Chapter 4) are based on well-established methods that are widely accepted in the field of research as well as accepted within the industry. Through literature studies, discussion with experienced practitioners as well as through experimental study of different cases various aspects of logical verification is achieved. The research results have been discussed with the industrial partner and practitioners within the relevant field who are in agreement with it. 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 automotive industry.

5.3. RESEARCH CONTRIBUTION

The research results achieved so far hold scientific as well as industrial relevance. The scientific and industrial contributions are listed below.

5.3.1. Scientific contribution

- Increased understanding on robust sheet metal design by considering local heat treatment effects
- Increased understanding on the influence of microstructure transformation and residual stress on the geometrical accuracy
- Increased knowledge on several control parameters that should be considered in the early stages of geometry assurance process
- The knowledge gained will allow establishing methods and guidelines for efficient utilization of the combined thermal-geometrical variation simulation setup

5.3.2.Industrial Contribution

- Increased knowledge that could enhance the current industrial practices to minimize geometrical variation in selective laser heat treated sheet metal components
- Increased understanding of combining the laser heat treatment process and the forming process
- Increased knowledge on the characteristics of specific material (boron steel) when subjected to selective laser heat treatment

6 CONCLUSION

This section summarizes the research conducted thus far. The next step in this research is presented under future work.

6.1. CONCLUSION

Focus on reducing the environmental impact has forced the automotive industry to adapt to various strategies to control the vehicle weight. Strategy of using lightweight materials and employing advanced processing techniques is seen as the way forward. As new processing techniques come into the foray, integrating them into the current product development setup to enable efficient decision making is necessary. In order to do so, greater understanding of advanced processing techniques such as the selective laser heat treatment process is necessary. The research objective has been to gain better understanding of the above said process and the effect of local heat treatment phenomena on geometrical quality. Literature studies were performed and research questions in line with the research objective were formulated. The research questions have been addressed in detail. Some conclusions from the studies so far are:

- The thermal, metallurgical and mechanical effects from the selective laser heat treatment process influence geometrical variation
- It also affects subsequent manufacturing processes at part level and assembly level
- Geometrical variation contributors that could be adjusted to minimize the effect on geometrical variation are demonstrated
- There is a need to establish a process map to consider the control parameters in the early stages of geometry assurance process

6.2. FUTURE WORK

The research conducted so far has laid the foundation for the future work to be carried out. Some planned studies that are of particular interest are:

- Simulation based optimization of laser heating direction sequence strategies for local heat treatment
- Combining it with thermal – geometrical variation simulation environment
- To explore the possibilities of extending this concept to other advanced manufacturing processes involving selective heating and selective melting
- Establish guidelines to design products including selective heating and selective melting

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