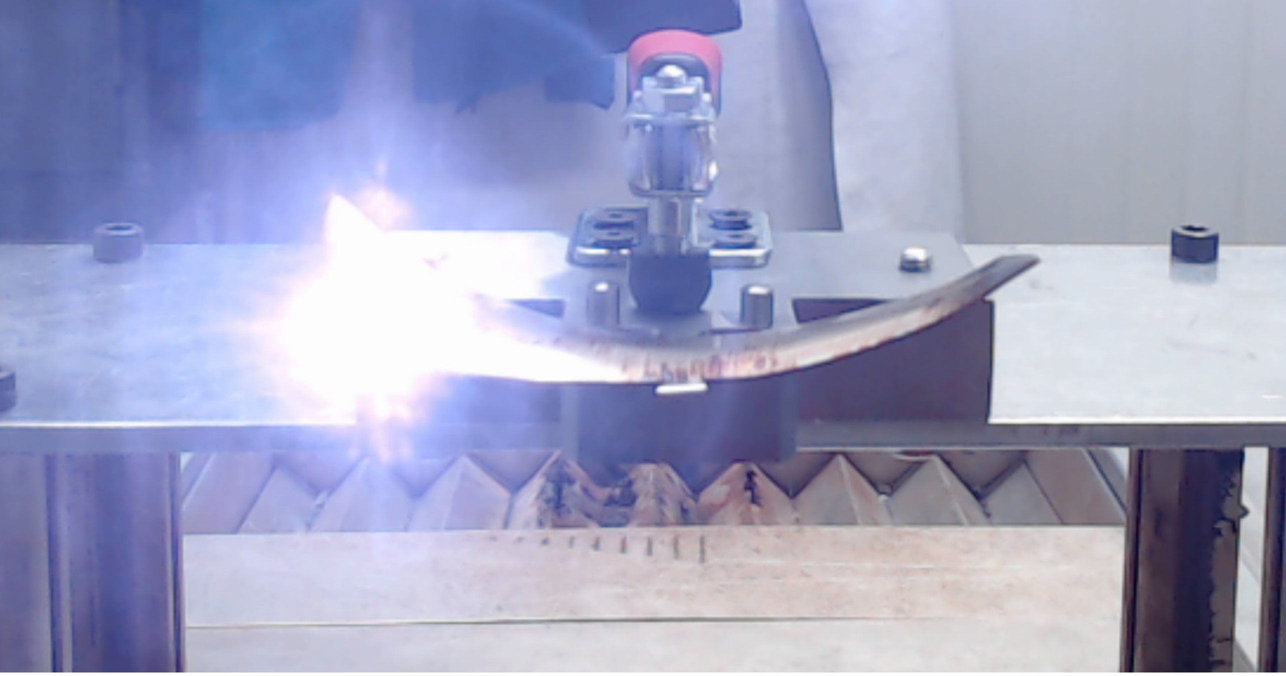
Laser Forming of Sheet metal

Thomsen, Anders Noel



LASER FORMING OF SHEET METAL

BY

ANDERS NOEL THOMSEN

DISSERTATION SUBMITTED 2020

AALBORG UNIVERSITY
DENMARK

Laser Forming of Sheet Metal

Ph.D. Dissertation

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Abstract

Laser forming of sheet metal is an innovate method for contact-less thermal forming. The process is based on using a laser as a heat source for introducing thermal based permanent stresses and strains in the workpiece. The process has been investigated in numerous scientific articles and boasts a large potential as a non-contact free forming method. However, its use and even awareness in industry is still severely lacking.

This thesis investigates the limitations and potentials of the process which forms the basis for introducing improvements. The investigation led to several different open problems for laser forming, which deserve further attention. However, one problem stood out as the primary driving force against the adaptation of the process; process control. Several factors constrain the use of process control. Firstly, the process is iterative, where each laser scan path introduced a small amount of the total deformation required; this creates a discrete multi-variable planning operation. Secondly, the process suffers from a relatively large degree of process variation, which when coupled with an iterative process causes variations to build up from each pass.

A framework for feedback control of laser forming was introduced and tested experimentally as part of this thesis. The framework is based on planning a part of the total process and measuring the surface. The measurements allow the framework to account for unwanted distortions and process variations. The framework shows that feedback control is possible, but further development is necessary before laser forming is competitive with traditional sheet metal forming. To improve the framework a theoretical study on the basis of discrete constrained non-linear multi-variable optimization of the process settings using analytical equations to predict the laser forming response was performed. The study shows promise but has not been experimentally tested yet.

The thesis has been funded by MADE Academy Denmark under the SPIR Work package 3 in conjunction with Terma A/S and by the Innovation Fund Denmark INTERLASE project. The results of the thesis are communicated as published and submitted peer reviewed papers.

Resumé

Laser formgivning af plade metal er en innovativ metode til kontaktløs termisk formgivning. Processen er baseret på at bruge en laser som varme kilde til at introducere permanente spændinger og tøjninger i et emne. Processen er blevet undersøgt i adskillige videnskabelige artikler og indebærer et stort potentiale som en kontaktløs fri formgivnings metode. Dog er brugen af laser formgivning og endda kendskab dertil stadig stærkt begrænset i industrien.

Denne afhandling undersøger begrænsninger og muligheder ved processen hvilket skaber et grundlag for at introducere forbedringer. Undersøgelsen leder til flere åbne problemstillinger som fortjener yderligere behandling. Dog er der et problem som fremstår som den primære drivkraft mod brugen af laser formgivning; proces styring. Adskillige faktorer komplicerer styringen. For det første er processen iterative, hvor hver laser sti introducerer en lille andel af den totale deformation. Dette skaber et diskret multi-variable planlægnings problem. For det andet er processen ramt af en relativ stor andel af proces variation som hober sig op over de iterative laser stier.

En ramme model for styringen af laser formgivning med en tilbagekoblingssløjfe er introduceret og testet eksperimentelt i denne afhandling. Ramme modellen er baseret på planlægning af en andel af den totale proces med efterfølgende opmåling af overfladen. Opmålingen tillader ramme modellen at tilpasse uønsket deformation og proces variation. Ramme modellen viser at styring med tilbagekoblingssløjfe er mulig, men yderligere udvikling er nødvendig for at processen bliver konkurrencedygtig med traditionel pladeformgivning. Et teoretisk studie er introduceret for at forbedre ramme modellen baseret på diskret, begrænset, ikke-lineær, multi-variable optimering af processen ved brug af analytiske ligninger til at forudsige responsen. Studiet har et potentiale men mangler at blive verificeret eksperimentelt.

Denne afhandling er en del af MADE Academy Denmark under SPIR arbejdspakke 3 i samarbejde med Terma A/S samt af IFD INTERLASE projektet. Resultaterne i afhandlingen er kommunikeret som udgivet og indsendte artikler.

To my girls:
Lad os så lege med dukkehus

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Preface

This thesis is submitted as a collection of papers to the Faculty of Engineering and Science at Aalborg University in partial fulfillment of the requirements for the degree of Doctor of Philosophy. The research presented in this thesis has been performed in the period August 2016 to August 2020 at the Department of Materials and Production.

The research has primarily been part of the MADE Academy Denmark as part of the SPIR work package 3 project in collaboration with Terma A/S. The final year of the research was supported by the Grand Solutions INTERLASE project (7050-00024B) from the Danish Innovation Foundation. Experimental equipment used in the thesis was funded by The Poul Due Jensen Foundation.

The thesis has been supervised by Associate Professor Benny Endelt and Associate Professor Morten Kristiansen. I would like to express my sincere gratitude to them for their time and effort in supporting me to grow as both a researcher and a person. I especially cherish the numerous discussions on research, life and politics, even if we disagreed on the latter.

I would like to thank Dr Stuart Edwardson and Professer Geoffrey Dearden at University of Liverpool for hosting my visit and engaging in interesting discussion on laser forming.

I would like to thank my former colleagues Ph.D. Erik Appel and Ph.D. Rathesan Ravendran for their valuable sparring and constant words of encouragements during the trying times that is a Ph.D. project. Furthermore I would like to thank Ph.D. Ewa Kristiansen for our successful collaboration on several projects. Similarly, I would like to acknowledge Ph.D. fellow Georgi Nikolov and Ph.D. fellow Anders Mikkelstrup for their time and input with the laser cell.

A special thanks goes to my sister Simone and my friend Lennart Kjær for answering silly questions on the topic of programming and offering distractions in times of need.

Lastly, I wish to thank my family and especially my girlfriend who suffered a stressed out PhD fellow while birthing two beautiful little girls. I owe you everything.

Anders Noel Thomsen
Aalborg University, August 20, 2020

Part I

Introduction

Chapter 1

Project background

> Every honest researcher I know admits he's just a professional amateur. He's doing whatever he's doing for the first time. That makes him an amateur. He has sense enough to know that he's going to have a lot of trouble, so that makes him a professional.
>
> *Charles Franklin Kettering*

This chapter contains the motivation for this thesis including the initial problem that was used as the onset of the work. This is followed by the methodology used to analyze the initial problem. The chapter is concluded with an overview of the thesis.

1.1 Motivation

The motivation for this thesis is based on the potential of using a laser for a free forming process of sheet metal known as laser forming. Laser forming is an incremental non-contact forming technique that allows tool and die free forming. This enables a high level of variation without changing the equipment setup. As a highly flexible process, it has a potential that is suited for the expected future manufacturing paradigm of industry 4.0 as an equivalent to 3D printing for sheet metal.

1.1.1 The laser forming process

The process uses a laser as a heat source to induce a thermal expansion of the sheet metal. The localized thermal expansion is restricted by the surrounding colder material which causes plastic compressive stresses in the heated area. As the material cools down, the thermal expansion is removed, but the plastic compressive stresses remain, causing a deformation of the sheet. While the deformation is relatively small per pass of the laser, multiple passes of the laser can be used to create larger deformations. The deformation is dependent on the heat input and the path of the laser:

Heat input: Controls the amount of deformation, which can be based on different mechanisms for bending and upsetting.

Laser scan path: Controls the directions of deformation as most of the deformation occurs perpendicular to the laser scan path.

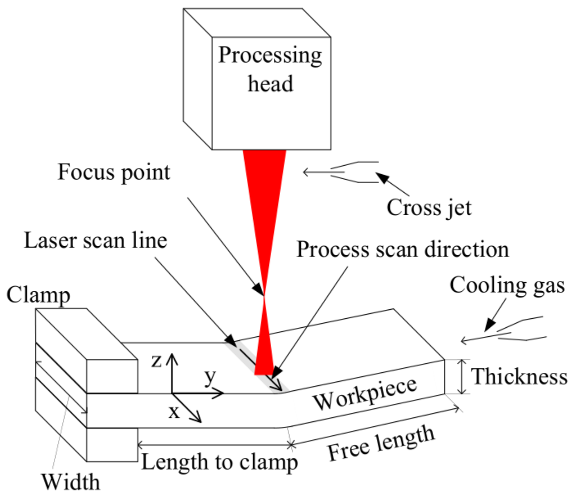


Fig. 1.1: A laser forming setup (Thomsen et al., 2019a).

The use of the laser enables a tool and die free forming, see figure 1.1, as different shapes can be made by changing the heat input and the laser scan paths. The process is incremental as each pass of the laser introduces a limited amount of deformation, however, each pass of the laser increases the total amount of deformation allowing the forming of complicated shapes, see figure 1.2.

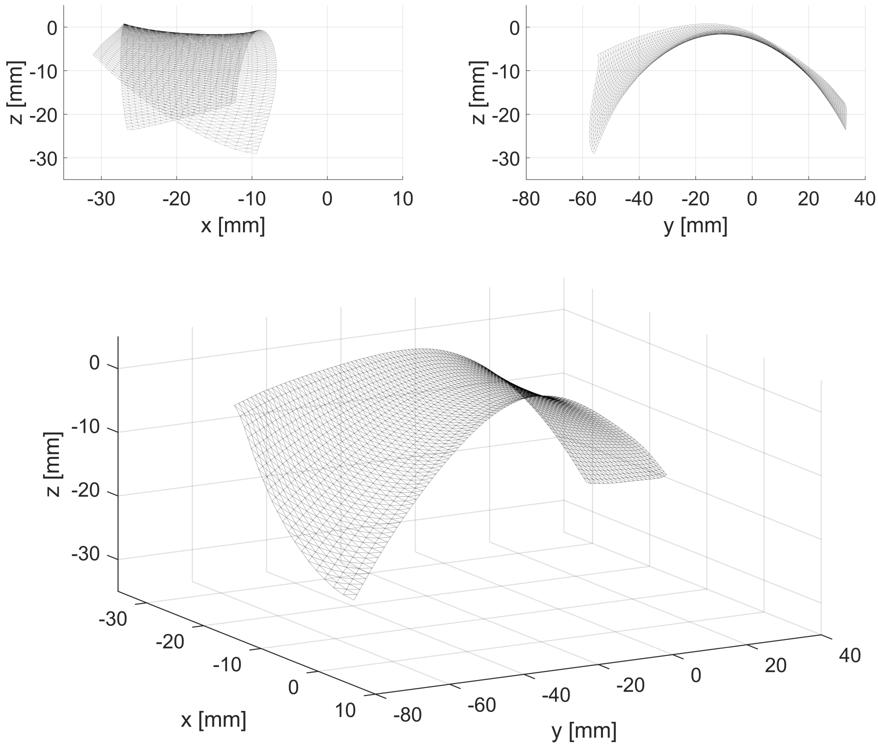


Fig. 1.2: Mesh of double curved blade seen from different angles (Paper A).

1.1.2 Initial problem

The process was introduced at a conference in 1985 (Namba, 1986; Shen and Vollertsen, 2009), however its use is still very limited, especially compared with 3D printing which originates in 1981 (Kodama, 1981). Laser forming boasts a similar potential and has been proclaimed for several different cases and industries:

Complex shapes: The forming of double curved sheet metal plates for various industries such as the aerospace, automobile and medicinal industry. (Geiger, 1994; Watkins et al., 2001; Cook et al., 2016).

Complex materials: The forming of specialized materials such as magnesium and titanium alloys which are difficult to manufacture (Watkins et al., 2001; Kant et al., 2013).

Flexible Manufacturing: As a flexible manufacturing process that could be used to produce spare parts for the military on their forward bases on earth (Lazarus and Smith, 2017, 2018), or in space (Namba, 1986).

Improvement of tolerances: Improvement of tolerances for micro electronics (Lazarus and Smith, 2018) and correction of weld distortion (Dowden, 2009).

Despite these cases, the process appears to see very limited use by industry today. Considering that the use of laser processing is becoming more widespread with the use of laser welding, laser cutting and more recently; laser sintering for additive manufacturing. The use of laser forming is lacking with few publications describing actual industrial applications. As laser forming does not require additional expensive tools or added equipment, one is left to wonder why it has found limited use? Two readily available answers often occur in these situations;

- It does not work
- No proper solution has been found yet

Unfortunately, there is no simple answer to this question. To examine it further, the potential and limitations of the process must be better understood. Therefore, the initial problem which is used as the onset of the problem analysis is given as:

What is laser forming of sheet metal and what are the limitations and potentials of the process?

The methodology of using a problem analysis based on an initial problem is elaborated in greater detail in the following section.

1.2 Project methodology

The methodology for the project is inspired by the problem based learning at AAU (Holgaard et al., 2014), using a problem driven approach to the thesis. An overview of the methodology can be seen in figure 1.3.

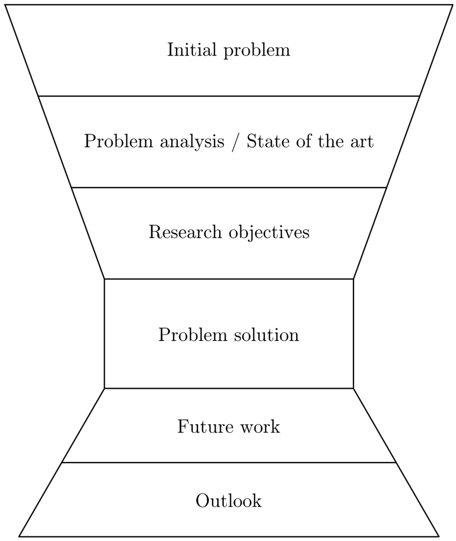


Fig. 1.3: The working methodology for this thesis based on the problem based learning at AAU (Holgaard et al., 2014).

The project is initiated by an initial problem which is intentionally broad in scope. This is a deliberate choice as the initial problem is used as the onset of the work and used to find a relevant research objective. This is important in a small and relatively new field such as laser forming, where a multitude of problems exist due to the fields infancy. As such, there are multiple interesting problems, which are almost irrelevant as other problems may inhibit the growth or even success of the technology.

The initial problem is examined using a problem analysis. The purpose of the problem analysis is twofold.

1. To revisit the assumptions that led to the initial problem, to ensure that the perceived problem at the onset of the work and the actual problem are aligned. This is to ensure that a found solution will have a positive impact on the problem which initiated the project.

2. To gather information necessary for the solution stage of the project,

similarly to a state of the art.

The problem analysis is used to formulate the research objective, which consists of both hypotheses and research questions.

Hypotheses: The hypotheses are examined using the method of conjectures and refutations wherein a refutation of the hypothesis is sought. Here it is important to note that a failure to refute the hypothesis does not prove the hypothesis, it only adds credibility to its correctness.

Research questions: The research questions are examined in a broader scope. This is to allow the formulation of hypotheses in future works.

The solution stage is based on the formulation and acceptance of peer-reviewed papers.

1.3 Thesis overview

An overview of this thesis is given in the following:

Part I: Introduction

Chapter 1 Project Background

Part II: Problem analysis

Chapter 2 Laser forming
The chapter covers the laser forming mechanisms along with the process parameters. The chapter also considers the literature on mechanical and corrosive properties of laser formed components. Furthermore, edge effects are examined.

Chapter 3 Laser forming models
The chapter discusses the analytical, numerical and empirical approaches to modeling of laser forming. On this basis, the guidelines for numerical modeling of laser forming are examined further.

Chapter 4 Process control
The chapter covers different process control schemes for single and double curved sheet metal.

Chapter 5 Discussion of scope
The chapter presents a discussion of the observations that arose from the problem analysis. The discussion leads to a choice of research objectives which consist of research questions and hypotheses for this thesis.

Part III: Conclusion

Chapter 6 **Summary of papers**
The papers from part IV are summarized along with the contributions of this thesis as an answer to the research objectives.

Part IV: Papers

Paper A **Feedback control of laser forming: a recipe**
This paper is a description of a generalized feedback control system for laser forming. The paper introduces the different steps that are necessary for feedback control and discusses possible solutions for each step. The chosen approach is examined experimentally by laser forming two different shapes.

Paper B **Online measurement of the surface during laser forming**
This paper measures the dynamic response of a v-bend during laser forming. This can be used to further the understanding of the dynamic response and improve verification of numerical models.

Paper C **Influence of cooling on edge effects in laser forming**
This paper attempts to reduce edge effects using active cooling. The effects of cooling on edge effects are investigated both numerically and experimentally.

Paper D **Investigation of the profile of laser bends with variable scan distance**
This paper examines the influence of the distance between paths on the curvature for v-bends.

Part V: Additional papers

Paper E **A new method for calculating the error term used in 2D feedback control of laser forming**
This paper numerically examines the use of feedback control for 2D bends using a mapping of the curvature along with a gain controller for determining the process parameters.

Paper F **Feedback control of laser forming using fattening simulations for error determination**
This paper uses an expansion of the mapping to 3D surfaces from Paper A, with a strain definition and a gain controller for feedback control. The approach is examined numerically.

Part VI: Working paper

Paper G **Discrete Constrained Non-Linear Multi-Variable Optimization of 2D Laser Forming Including Feedback Control**
This working paper contains a theoretical description of a methodology for finding the process settings using optimization and analytical expressions.

Part II

Problem analysis

Chapter 2

Laser forming

Science may be described as the
art of systematic
over-simplification

Karl Popper

This chapter will cover the laser forming mechanisms, followed by the literature describing the effect of different process parameters. Studies on the mechanical and corrosive properties are examined. Lastly the phenomenon known in the laser forming community as edge effects is described. The chapter is finished by a summary of some of the observations that arose during this literature study.

2.1 Laser forming mechanisms

Laser forming is commonly associated with three principle forming mechanisms; the temperature gradient mechanism (TGM), the upsetting mechanism (UM) and the buckling mechanism (BM). Although there are some that consider a fourth mechanism (Shi et al., 2006); the coupling mechanism as a combination of TGM and UM.

2.1.1 Temperature gradient mechanism

The temperature gradient mechanism (TGM) was introduced in 1993 by Geiger and Vollertsen (1993) and is defined by inducing a temperature gradient through the thickness of the material. The mechanism can be described in two stages, see figure 2.1, the first is the heating stage, at which heat is introduced at the surface using a laser.

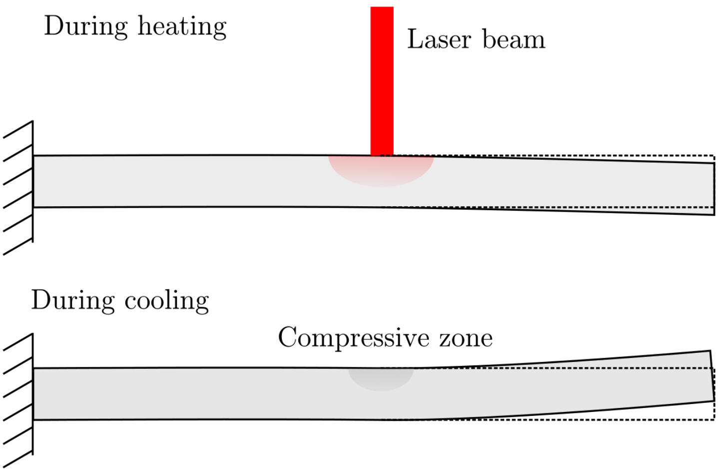


Fig. 2.1: The two stages of the temperature gradient mechanism (TGM).

Heating phase: A localized expansion of the material at the top of the surface is caused by the laser. The localized expansion creates a bending of the sheet away from the laser termed counter bending. The localized expansion is resisted by the surrounding colder material. This resistance creates plastic compressive strains in the heated area.

Cooling phase: As the laser is removed, the material begins to cool down. The localized expansion contracts, yet the plastic compressive state remains causing the sheet to bend toward the laser.

A key note of the temperature gradient mechanism is the temperature gradient that exists through the thickness during the heating phase.

2.1.2 Upsetting mechanism

The upsetting mechanism (UM) was introduced in 1993 by Geiger and Vollertsen (1993) and is defined by having no temperature gradient through the thickness of the material. The two stages of the mechanism are otherwise similar to TGM, see figure 2.2:

Heating phase: A small localized expansion through the thickness of the material. The localized expansion is resisted by the surrounding colder material. This resistance creates uniform plastic compressive strains through the thickness.

Cooling phase: As the laser is removed, the material begins to cool down. The localized expansion contracts, yet the plastic compressive state remains causing the sheet to upset (shorten).

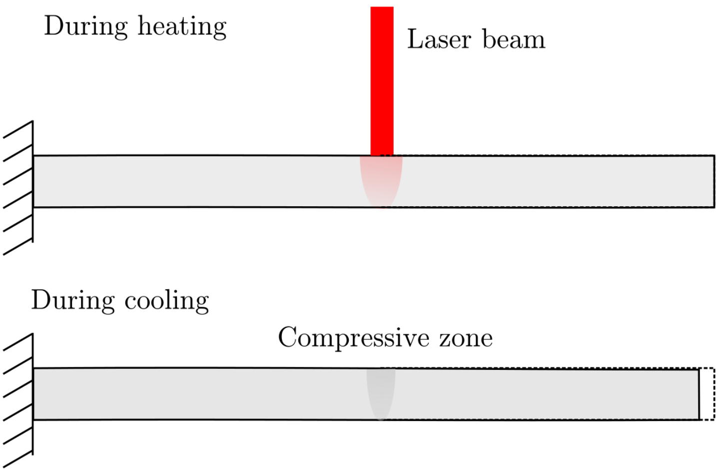


Fig. 2.2: The two stages of the upsetting mechanism (UM).

As it is impossible to avoid a temperature gradient in practice using a single laser heat source, this mechanism will always result in a small amount of bending. Shi et al. (2012) proposed heating both upper and lower surface with identical settings to create a more uniform deformation through the thickness.

2.1.3 Buckling mechanism

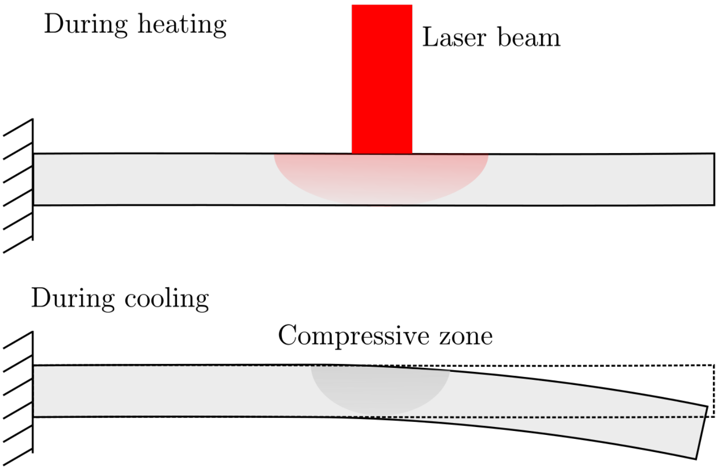


Fig. 2.3: The two stages of the buckling mechanism (BM).

The buckling mechanism (BM) was introduced in 1993 by Geiger and Vollertsen (1993) and is an instability version of UM. By creating a larger heated zone, a buckling instability occurs due to the shortening effect. This can cause bending towards or away from the laser (Vollertsen et al., 1995), see figure 2.3.

Heating phase: A larger localized expansion through the thickness of the material. The localized expansion is resisted by the surrounding colder material. This resistance creates through the thickness plastic compressive strains in the heated area.

Cooling phase: As the laser is removed, the material begins to cool down. The expansion contracts, yet the plastic compressive state remains. Due to the larger compressive zone, a buckling instability can occur, which can cause bending both toward and away from the laser (Vollertsen et al., 1995).

2.1.4 Coupling mechanism

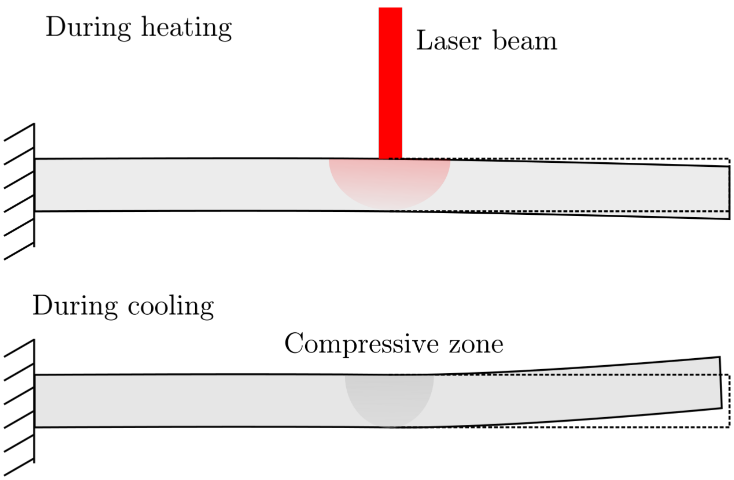


Fig. 2.4: The two stages of the coupling mechanism (CM).

The coupling mechanism (CM) was introduced in 2006 by Shi et al. (2006), and is defined by a combination of UM and TGM. The coupling mechanisms is a special mechanism as it is a combination of two idealized mechanisms. It can be argued that it is not possible to achieve pure TGM and UM under typical conditions.

Heating phase: A localized expansion through the thickness of the material. The localized expansion is largest at the surface but occurs through the thickness as well. The expansion is resisted by the surrounding colder material. The resistance creates plastic compressive strains in the heated area.

Cooling phase: As the laser is removed, the material begins to cool down. The expansion contracts, yet the plastic compressive state remains. Due to the larger temperature at the surface, bending occurs towards the laser. As there is also a compressive state at the bottom, upsetting is also achieved.

The mechanisms are dependent on the type of process parameters used, and some attempts have been made to predict which mechanism will be dominant under certain process settings. The Fourier's number appears to be the most popular.

2.1.5 Fourier's number

The Fourier's number is used for differentiating between TGM and UM or BM (Shi et al., 2006; Chakraborty et al., 2015b). Note that it cannot differentiate between BM or UM by itself, however the laser beam diameter can be used as a rule of thumb to differentiate between UM and BM (Shi et al., 2006). The Fourier's number, for continuous laser mode, is given by Shi et al. (2006); Chakraborty et al. (2015b) as:

$$F_0 = \frac{\kappa d}{t^2 v} \tag{2.1}$$

Where κ, d, t and v are the thermal diffusivity, the laser beam diameter, the thickness of the sheet and the laser scan speed. The Fourier's number is used in the following way:

- TGM is dominant when $F_0 < 1$ (Chakraborty et al., 2015b)
- UM or BM dominates when $F_0 > 1$. (Chakraborty et al., 2015b)
  - BM is dominant for larger laser beam diameters (Li and Yao, 2001b; Chakraborty et al., 2015a)
  - UM is dominant when the diameter is approximately the thickness of the sheet ($d \leq t$) (Kant et al., 2016)

From equation (2.1), the effect of achieving a specific mechanism with either the laser scan speed or laser scan diameter can be deduced. Increasing the laser scan diameter increases Fourier's number, while increasing the laser scan speed decreases it.

Understanding the laser forming mechanisms, and the effect of the process parameters, the process parameters can be considered more in depth.

2.2 Process parameters

Laser forming, being an iterative process, offers a relatively large process window. A notion that is underlined by the fact that the laser forming literature has historically been divided into single and multi-pass laser forming for whether a single pass or multiple passes of the laser was used. Single pass laser forming being considered mainly to reduce the number of variables. Single pass TGM typically involves a bending angle of around 1-3°, too low to be of use in most applications. This work will therefore only consider multi-pass laser forming and denote it simply by laser forming.

The process parameters are given below. The list is divided into four separate parts. The first parts regards the heat input. The second part is about the laser scan path. The third part is the component specific parameters and the fourth part contains the equipment constants.

Heat input: Controls the amount of deformation and must be set to ensure that no melting of the surface occurs. The heat input controls which mechanism is active.

- **Laser scan power:** The laser scan power is directly related to the amount of deformation, by increasing the overall temperature. As it does not affect Fourier's number, see section 2.1.5, it should not affect which mechanism is active.

- **Laser scan velocity:** The laser scan velocity is perhaps the most dominant process parameter as it affects the amount of deformation and the mechanism, while being relatively simple to control.

- **Continuous or pulsed laser mode:** The difference between continuous and pulsed laser forming is less understood. Using a pulsed laser to achieve the same total temperature requires more intense pulses which increases the risk of burning the surface during the pulse. Several authors investigate the use of pulsed laser beam (Lee and Lin, 2002; Hsieh and Lin, 2004b,a; Yang et al., 2010a; Gollo et al., 2011). However, no comparison of pulsed laser forming compared to continuous laser forming was offered. Maji et al. (2013a) finds that pulsed laser forming has a larger bending angle for equal line energy (For line energy, see section 2.2.1, page 20).

- **Laser beam spot geometry:** The laser beam spot geometry is usually circular with a Gaussian distribution of the intensity but can be different shapes which affects the heat distribution over the surface. Lee and Lin (2002) used an elliptic laser spot, which was wider than the workpiece for a stationary laser beam. Shen et al.

(2006b) simulated two circular spots and found a higher deformation per pass. Edwardson et al. (2006) showed how the deformation of the plate affects the incident plane to reduce the amount of deformation per pass.

Dwell time: The dwell time is the wait time between passes to allow the material to cool. Shen et al. (2006a) numerically investigated the dwell time between two sequent scans. Lambiase et al. (2016) investigated the productivity of laser forming. The authors most notably found that the optimization of the dwell time was a "major concern", following that the maximization of bend angle per pass did not necessarily result in highest productivity defined as bend angle over time.

Cooling: Active cooling can be used to reduce the time it takes for the material to cool down naturally. Cheng and Yao (2001) investigated the use of active cooling both numerically and experimentally. Lambiase et al. (2013) investigated the use of partially submerged water cooling and found in their work of Lambiase et al. (2016) an increase of productivity of a factor of 10. Shen et al. (2014) investigated fully submerged water cooling.

Laser scan path: Controls the directions of deformation as most of the deformation occurs perpendicular to the laser scan path. Sistaninia et al. (2009) investigated the use of rotating and dithering beams instead of straight lines using numerical models. The authors found an increased bending angle due to a larger and more uniform plastic zone.

Component: The component affects the amount of deformation per pass of the laser. However, a reduction in deformation can easily be solved with multiple passes of the laser. To the authors knowledge there are no studies on the limitations of the component such as maximum sizes.

Dimensions of component: Studies have been performed to determine the effect on the bend angle when increasing the length, width or thickness of the component. Except for the thickness these studies are at best uninteresting, as the dimensions are related to the desired shape, see figure 1.1. Comparisons are difficult; an example is the work of Chen et al. (2004) who found an increase in bend angle with increasing width, while Cheng et al. (2005) found a decrease in bend angle with increasing width. The other settings were not constant between the two studies, which shows that their results can not be generalized.

Material: The material must have a response that allows for the use of the mechanisms described in section 2.3. This requires a thermal expansion of the material when heated and decreasing yield strength with increasing temperature without degradation of the material. A list of laser formed materials from literature is given in table 2.1.

Coating: Coating is used to increase the absorptivity of the surface. This can be done for reflective materials such as aluminium or titanium (Shidid et al., 2013) or to increase productivity. Adding a coating also adds two extra parts to the process, application and removal of the coating.

Equipment constants: The equipment used affects the process. However, to the authors knowledge, there have been no studies which compare the use of different equipment. Most research appears based on the availability in the laboratory.

Clamping: The clamping affects the mechanical response as it restricts the thermal expansion as well as the resulting deformation. Lazarus and Smith (2018) used a roller and cut the desired sheet with joints that served as clamps.

Laser: The type of laser affects the absorptivity of the material as well as the quality of the beam. A poor absorptivity can be remedied by using a coating. A good beam quality is necessary if beam shaping is to be used.

2.2.1 Note on line energy

Several works use the notion of line heating as the achieved total temperature is a close coupling between the laser power and the laser scan velocity. This has led some authors to use a combination given as line energy, see equation (2.2) (Li and Yao, 2001a; Knupfer et al., 2010; Mjali and Botes, 2018).

$$L = \frac{P}{v} \tag{2.2}$$

where L is the line energy given as J/m, P is the laser scan power in W and v is the laser scan speed in m/s (Li and Yao, 2001a). It is important to note that constant line energy does not result in constant deformation (Bao and Yao, 2001; Mjali and Botes, 2018), and will also influence which mechanism is dominant.

The usefulness of the line energy concept beyond creating an obscurity is therefore slightly lost on this author. Its use is rather restricted when considering that it does not account for the laser scan spot shape or size.

Table 2.1: A list of materials that have been laser formed. The list should not be considered exhaustive.

Metals	**References**
Steel	Knupfer and Moore (2010)
Aluminium	Watkins et al. (2001); Knupfer and Moore (2010)
Titanium	Watkins et al. (2001); Shidid et al. (2013); Mjali and Botes (2018)
Maginesium	Kant and Joshi (2016); Kant et al. (2013)
Ceramics	
Borosilicate glass	Wu et al. (2010)
Alumina (Al_2O_3)	Wu et al. (2010)
Silicon	Wu et al. (2010); Wang et al. (2011)
Polymers	
High density polyethylene	Okamoto et al. (2004)
Composites	
Bi-layer Fe/Al	Gollo and Kalkhoran (2017)
Sandwich panel with metal foam core	Bucher et al. (2018)
SUS430/C11000/SUS430 laminate	Seyedkashi et al. (2016)
Cement coated steel	Fetene et al. (2017)
Open cell aluminium foam	Quadrini et al. (2010)

2.3 Mechanical properties

The mechanical properties of laser formed parts depend on the material and the thermal history prior to and during laser forming. The heat affected zone (HAZ) is formed over several iterations. The iterative heating of laser forming causes a discontinuous thermal history, where precipitation, growth and phase transformations may occur over several passes of the laser. Due to the non-unique nature of laser forming, it is possible to cause two similar shapes with different thermal histories. This allows designing the thermal history to a certain extent based on the material used. Unlike welding and cutting, laser forming has a much larger process window. Therefore it is difficult to generalize the mechanical properties of laser formed parts.

Shen and Yao (2009) examines the monotonic tensile behavior of low carbon steel under different laser forming parameters. Unfortunately, only a single sample was tested per setting, but the found variation between samples was small. Knupfer and Moore (2010) investigated the mechanical properties for low carbon steel and aluminium alloy. Again, only a single sample was tested per sample with varying laser scan speed and number of scans. Knupfer and Moore (2010) conclude a decrease in strain at break for the low carbon steel, while a decrease in ultimate tensile strength (UTS) was reported for the aluminium alloy.

2.3.1 Residual properties

Knupfer et al. (2012) measured the residual stress and strains using neutron diffraction. By measuring the lattice distance as a result of varying laser scan speed and number of scans they estimated the residual strains and stresses. The residual strains and stresses were found to be tensile and largest in the direction of the laser scan path, while compressive strains where visible in the normal and perpendicular direction, with the latter being largest. The results show that the laser scan speed has an effect on the size of the residual state while the number of scans does not appear to alter the residual state. This suggests that the laser scan speed can be used to design the residual state with laser forming.

2.3.2 Fatigue properties

For the following discussion it is important to note that fatigue life is notoriously difficult to quantify and requires much larger data sets than found in the literature presented here.

McGrath and Hughes (2007) investigated the fatigue life of laser formed and mechanically deformed samples compared to bulk material of C2 steel, a high strength low alloy steel. The samples were tested using a bending test (Avery Model 7303 fatigue machine) and cut perpendicular to the bend. The results showed improvements up to 75% compared to bulk and 171% compared to mechanically deformed in number of cycles before break when loaded to approximately 80% of yield strength (McGrath and Hughes, 2007). McGrath and Hughes (2007) argues that the improvement in fatigue life is from two different factors:

- Hardening of the surface using the laser hardening mechanism resulting in a martensitic-ferritic phase transformation. This phase transformation requires temperatures above approximately 1200°C. On a study on the laser hardening mechanism, unrelated to laser forming, Cerny et al. (1998) finds that laser hardening can improve fatigue life, but is very sensitive to process parameters, and may be detrimental for some settings.
- Compressive residual stresses from the laser forming process. Although the authors quantify compressive residual stresses, there is no mention of methodology. Knupfer et al. (2012) did find compressive residual strains and small compressive residual stresses perpendicular to the laser scan path. Residual compressive stresses would likely improve fatigue life under tensile loading.

Shen and Yao (2009) examined the low cycle fatigue of laser formed components of low carbon steel (St12, with 0.1 wt% carbon) cut in the longitudinal direction. The results showed slightly improved fatigue life in the order of 10-20% (with 3-5 samples per setting, with five different settings and one reference). The authors examined the fracture surface, and found that crack initiation occurred on the non-laser scanned surface. This was believed to be a result of compressive residual strains in the longitudinal direction as found by numerical simulation.

From Knupfer et al. (2012) whom measured the residual strains, found that the residual strains should be tensile in the longitudinal direction. Furthermore, results determined by Zhang et al. (2005) found, using the low carbon steel, AISI1010, a decrease of about 20% for the laser formed components compared to the bulk material. Zhang et al. (2005) determined that cracks initiated at the laser irradiated surface. As different materials and settings were used in all these studies, this may fit the results of Cerny et al. (1998); That it is possible to design the process for improved fatigue life, but a wrong design can lead to detrimental effects.

2.4 Corrosion properties

The corrosion properties are, like the mechanical properties, dependent on the material and process history.

Yang et al. (2010a) investigated the corrosion resistance of the HAZ under pulsed laser forming. The authors found for austinitic stainless steel (1Cr18Ni9), an increased corrosion resistance compared to the matrix material. The authors attributed this to two effects:

- Smaller grain size in the HAZ increasing the inter-crystalline binding force.
- Martensite and bainite transformation in the HAZ.

Sami Yilbas et al. (2011) found pit formation due to an increased surface roughness on the irradiated surface. However, the authors report a melting pattern on the surface, which explains the increased surface roughness, and may thus be avoided by lowering the heat input.

2.4.1 Sensitization

Sensitization is the formation of chromium carbides, a combination of carbon and chromium. The carbides form at temperatures between 400-800°C, depending on composition (Lima et al., 2005). The carbides precipitate to the grain boundary causing a chromium depletion in the vicinity of the grain boundary which weakens the chromium oxide layer protecting stainless steels.

Walczak et al. (2010) finds sensitization of AISI 302 as a result of elevated temperatures. The effect of three different rasterization widths are considered with constant laser scan power and laser scan speed. However, Walczak et al. (2010) do not consider if it is possible to laser form outside the temperature range which causes sensitization. Furthermore, the authors correctly note that it may be preferable to use AISI 304 instead due to its lower carbon content. The lower carbon content reduces the risk of sensitization (Lima et al., 2005). Thereby it can only be concluded that sensitization is a risk for laser forming of stainless steel with a high carbon content. It may be possible to reduce or avoid it with proper process control. Another possibility is to use a post heat treatment.

2.4.2 Restoration of corrosion properties

Liu et al. (2009) showed, for AA 7075-T6, that while laser forming may change the corrosion properties, post heat treatment can restore the corrosion properties. It may be important to note that post heat treatment should not remove the deformation introduced by laser forming, but can cause slight deformation due to relaxation of residual stresses.

2.5 Edge effects

During laser forming, the primary deformation occurs perpendicular to the laser scan path, however a small amount of deformation may occur along the laser scan path. The effect is most pronounced at the edges of the sheet, thereby the term ’edge effects’. The edge effects are commonly defined by a variation in the bending angle along the laser scan path(Shen et al., 2010a; Kant et al., 2013), see Fig. 2.5. The variation in bending angle is undesirable and should be minimized.

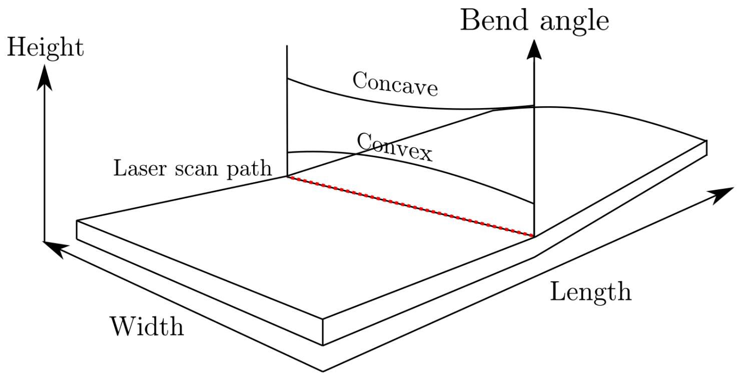


Fig. 2.5: Schematic representation of a v-bend with a concave bending angle along the laser scan path (the dotted line). Bao and Yao (1999) and Bao and Yao (2001) found that the edge effects were defined by a concave shape when BM was used for the bending and a convex shape for TGM.

Jha et al. (2008) found that the entire surface is curved and the bending angle and inherently the bending angle variation is depending on the distance from the laser scan line. Jha et al. (2008) denoted this phenomena as a multi-curvature effect. It is likely that the multi-curvature effect and the edge effects describe the same phenomena. The edge effects are then merely a single observation of the multi-curvature effect. However, this would require further investigation.

Dahotre and Harimkar (2008) summarize (based on Magee et al. (1997); Bao and Yao (2001)) three different reasons for the edge effects:

1. Differences in temperature along the laser scan path.

2. Differences in mechanical constraints along the laser scan path.

3. Contraction of the material in the direction of the laser scan path.

The focus on edge effects have been primarily for v-bends, and therefore it is unclear how double curved shapes will be affected. Different strategies have been employed to counteract the edge effects. This overview will use three different categories to describe the different strategies;

Process parameter studies: These studies find a set of optimum process settings to reduce edge effects. The studies are based on a strategy to utilize a quantitative approach to investigate the edge effects.

Variable process settings: These studies use variable process settings over the laser scan path to counteract the varying bending angle. The underlying strategy is done to utilize differences in temperature along the laser scan path (Reason 1 in Dahotre and Harimkar (2008)).

Different clamping strategies: These studies use different clamping strategies to change the differences in mechanical constraints along the laser scan path (Reason 2 in Dahotre and Harimkar (2008)).

2.5.1 Process parameter studies

Several attempts to reduce the edge effects through process parameter optimization have been made (Bao and Yao, 1999, 2001; Jha et al., 2008; Kant et al., 2013; Zahrani and Marasi, 2013). The results largely agree that the effect of laser scan power, laser scan speed and laser beam diameter are important for reducing the edge effects.

Fauzi et al. (2019) investigated numerically the influence of using a non-circular laser beam shape on the edge effects. A triangular shape pattern was found to reduce the bending angle variation along the bend.

Most interesting is the results of Cheng and Yao (2001), whom found using numerical simulations, that cooling could be used to reduce the edge effects. As cooling has other beneficial components, see section 2.2, this would only add to its usefulness. The reduced edge effects were explained by a reduced difference in longitudinal and tangential plastic strains with respect to the laser scan path direction. Considering the reasons summarized by Dahotre and Harimkar (2008), an explanation for the effect of the cooling, could be given by considering the first reason; If active cooling is introduced as a dominant cooling mechanism, the influence of the geometrical differences in the natural cooling due to the edge compared to the bulk material would be reduced. However, Shen et al. (2010a) simulated the use of forced water cooling as a method for cooling, and found no impact on the edge effects. As both of these results were reported based on numerical results, it cannot be entirely concluded that cooling has no effect.

2.5.2 Variable process settings

Magee et al. (1997) used differences in laser scan speed to change the heat input over the laser scan path. A pattern of 20-40-28 mm/s was compared to a constant of 30 mm/s and showed improved results (Magee et al., 1997)(Dahotre and Harimkar, 2008). Shen et al. (2010b) tested six different patterns and found that a similar strategy with different start and end velocities were preferable, see figure 2.6. The purpose of the pattern is specifically designed for a concave edge effect, where the bending angle is smaller at the edges. By reducing the laser scan speed near the edges, more deformation occurs which reduces the differences in bending angle. The discrepancy between the start and end laser scan speed is to utilize heat buildup along the laser scan path.

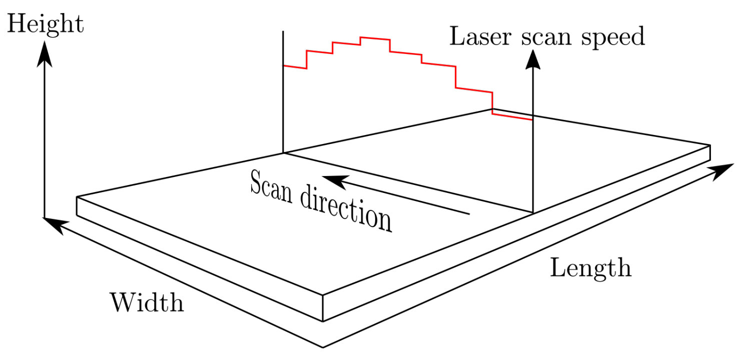
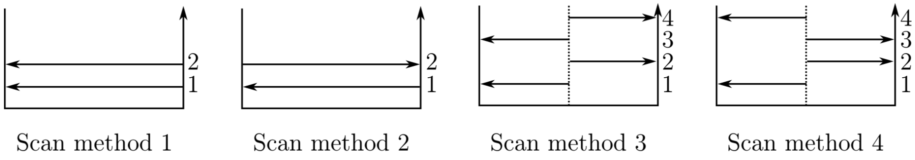


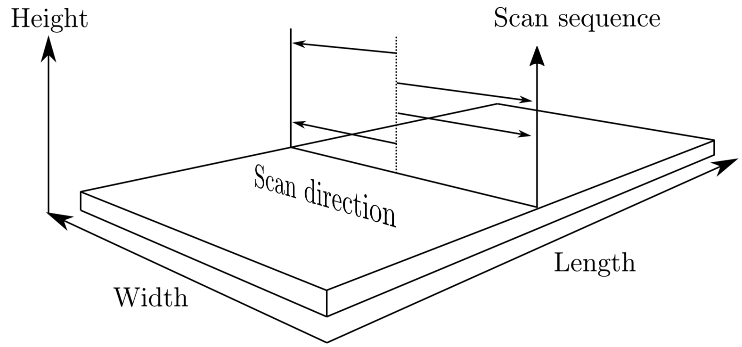
Fig. 2.6: A schematic of the variable speed increments employed by Shen et al. (2010b) for reducing edge effects.

To test the influence of differences in thickness along the laser scan path, Safari and Farzin (2014) used tailor machined blanks. The blanks changed thickness halfway along the bend, from 1 to 2 mm. Different irradiation schemes were tested that allowed for varying the laser scan speed, the laser scan power and the laser beam diameter. The results showed that the varying laser scan speed was preferable followed by the varying laser scan power.

Four different scan paths were examined by Shi et al. (2013), see figure 2.7. The authors found that it was better to reverse the direction of consecutive scans, rather than always going in the same direction. Furthermore, the results showed that scan method 3 and 4 were better, with scan method 4, achieving the best final results.



(a) Four different methods proposed by Shi et al. (2013)



(b) Schematic representation using scan method 4

Fig. 2.7: The (a) four different scan methods proposed by Shi et al. (2013) with (b) a schematic representation using method 4.

2.5.3 Different clamping strategies

Hu et al. (2013) and Shen and Hu (2013) investigated the use of changing the clamping, see figure 2.8. Instead of clamping one end, the authors attempt clamping at the edges of the laser scan path. The results show reduced edge effects due to the difference in mechanical constraints. While the results are better and could be useful for simple v-bends, it may be difficult to expand to other shapes.

2.6 Observations

Based on the literature studied in this chapter, some observations have been established. These observations serve to create ideas for the research objective and will be discussed further in chapter 5. Three observations will be introduced in the following;

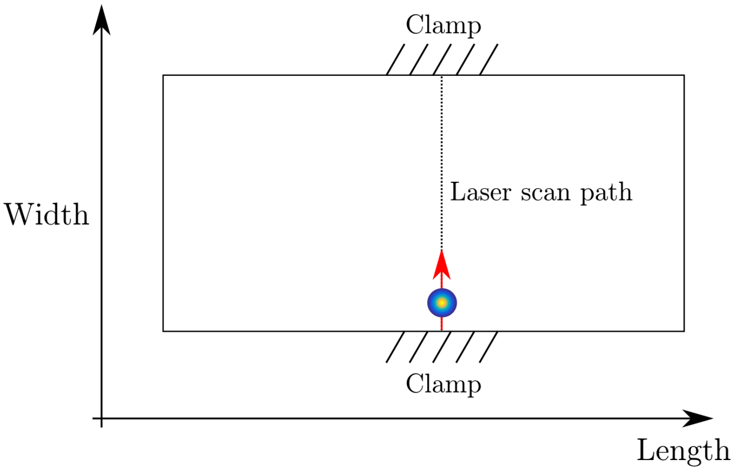


Fig. 2.8: Instead of clamping one end of the v-bend, the authors of Hu et al. (2013) and Shen and Hu (2013) clamp the sides of the laser scan path.

- Design of laser formed properties and the very one-sided focus on maximizing the bend angle
- The use of flexible clamping
- Reducing edge effects

2.6.1 Laser formed properties

There appears to exist a very one-sided focus on maximizing the bend angle per pass and use fewer passes of the laser. Coming from a traditional forming perspective, this makes sense, as large bend angles most resembles traditional forming in an attempt to create large deformations. However, this does not utilize the relatively large process window of laser forming. As has been discussed in section 2.3 and 2.4, there may be a reason to focus on choosing process parameters based on other considerations beside the bend angle:

Mechanical properties: It appears plausible, based on the literature study, that the thermal history can be designed so as to change the mechanical properties. This may even create improved properties compared to bulk material in certain cases.

Corrosion resistance: Similar to the mechanical properties. The specific material may benefit from having a designed thermal history that either avoids or induces certain precipitations or transformations during processing.

Total process time: Even considering the total process time, maximizing the bend angle, is not guaranteed to yield the lowest total process time, due to increases in necessary dwell time, see section 2.2.

To design the process parameters based on material properties rather than the bend angle is, however, more difficult. It requires a greater understanding of the material composition and its possible phases at different temperatures as well as an understanding of the effect of these phases on the desired properties. Furthermore, it requires a general understanding of the residual properties after forming. This raises the following questions:

1. Is it possible to alter the resulting properties using different laser forming parameters?
2. Is it feasible?
3. What are the possible negative effects of ignoring it?

The answer to the first question can be assumed to be yes, but still requires further confirmation. The second and third questions are related but still kept separate as they can involve different cases. The second question is related to the added cost for optimizing a high-end component. The third question is related to the possible tolerances expected of the average laser formed component compared to the bulk material. To answer these questions, a larger theoretical and experimental study is required.

2.6.2 Flexible clamping

Flexible clamping is required to fit the flexible manufacturing of laser forming. Considering the setup used by Lazarus and Smith (2018), where the parts are cut with a laser from a larger sheet, this allows designing flexible joints. Instead of adding typical clamping at one end of a v-bend it becomes easier to introduce joints at specific positions, for example at the ends of the bends to reduce edge effects similar to Hu et al. (2013); Shen and Hu (2013).

Similar joints can be made for a double curved shapes with a form of spring like joints that can deform with the part, see figure 2.9. Similar solutions are being used within deep drawing to hold the part between operations. Positioning and sizing of such joints becomes an optimization problem, that must be correlated with the expected laser forming parameters to determine where the restrictions of deformation can be beneficial. This requires a larger theoretical study.

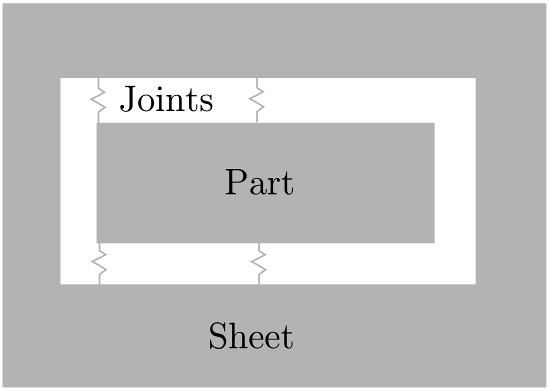


Fig. 2.9: Using a laser to cut the initial blank from a larger sheet allows designing specific joints that may affect the process to reduce undesirable deformation such as edge effects.

2.6.3 Edge effects

The edge effects are clearly a problem that will affect the possible tolerances that can be achieved with laser forming. Despite this, many of the proposals to reduce edge effects are difficult to generalize; Even if an optimum set of conditions are found, they will only work for a specific set of parameters. This type of optimization can be used in case of large scale manufacturing, where optimization of a single component is worthwhile. Two other solutions appear more favorable.

Active cooling: The first possibility was introduced by Cheng and Yao (2001), where active cooling was found to reduce edge effects. Unfortunately Shen et al. (2010a) was unable to verify these results. However, the possibility of using active cooling would be extremely advantageous and therefore deserves to be revisited. This would be a much simpler solution compared to some of the other solutions that have been proposed. Considering that both Cheng and Yao (2001) and Shen et al. (2010a) have been based on numerical work, it would be very beneficial to do an experimental study on this phenomenon.

Laser forming : The second possibility is to use the laser forming process itself to make corrections, this has not yet been explored in literature. However, laser forming has been used to make micro-adjustments for electronic components (Lazarus and Smith, 2018) which shows that it may be possible to reduce these distortion with laser forming itself. However, this requires a way to measure the system and predict the necessary settings to reduce the distortions.

2.7 Partial analysis

This chapter initializes the answer to the first part of the problem statement; laser forming is a thermal incremental forming technique that can be used to iteratively form a variety of materials as long as the material follow certain behavior at elevated temperatures. A list of possibilities and limitations was also found and are summarized in the following:

Possibilities:

- Free forming process with a large process window due to a large number of process variables.
- Works with a variety of different metals and even some other materials.
- Possibility of tailoring mechanical and corrosive properties due to thermal treatment during processing.

Limitations:

- Less understood due to being a relatively new technology.
- Only allows compression to form the parts.
- Unwanted distortion in the direction of the laser scan path increases process complexity.

The second limitation is a major difference compared with other and more traditional forming technologies. While traditional forming is based largely on stretching with a small amount of compression, laser forming is based entirely on compression. This makes it difficult to predict the design limitations, since it is unknown how much the material will compress considering the heating continuously changes the micro structure of the material. Furthermore, it means that the design process of the parts must be different to account for the lack of stretching. Determining the initial flat shape or blank problem to create the laser formed part from will be elaborated in section 4.5.

The initial question was largely based on understanding the restricted use of laser forming, and the limitations summarized here do not account for limited use of laser forming. While there are currently limitations to the understanding of laser forming, this is to be expected of a relatively new and small field. Therefore, on this basis, there is no reason to suggest that the laser forming process itself has reached its potential, rather there are plentiful of open questions left to examine that open new possibilities.

Chapter 3

Laser forming models

> All models are wrong, but some are useful.
>
> *George Box*

This chapter contains a description of the modelling of laser forming. It describes the literature on numerical process modeling of laser forming. Lastly, the observations that arose are covered.

3.1 Modelling of laser forming

Modeling of laser forming has received some interest due to the desire to predict the deformation based on a set of input process parameters. However, there are numerous limitations that must be considered when modeling laser forming. As with most other models, the primary concerns are the speed and accuracy of the models. Both of which are difficult to satisfy.

Laser forming is a weakly coupled thermal and mechanical process. The thermal load affects the mechanical response, however the effect of the mechanical load on the thermal can be considered negligible. Each pass of the laser affects the following passes by changing the material and surface properties. This means that the multiple passes should be handled in sequence.

Three different strategies have been attempted to solve the modeling of laser forming, analytical, numerical and empirical. The three review articles, Shen and Vollertsen (2009); Ablat and Qattawi (2017); Das and Biswas (2018) cover most of the contributions within modeling since the inception of laser forming. A summary of the three different strategies is given in the following:

Analytical models The analytical models are fast, but their use is often limited to 2D bends, being used primarily to predict the bending angle using TGM. To be used in double curved bends, accounting for the geometry and the thermal and mechanical history, limits the possibility of handling all the variables analytically without very crude assumptions.

Numerical models The numerical models are favored by their versatility and can better handle the limitations in accuracy of the other models. The cost comes in the form of calculation time. Creating a model which can handle a single laser scan pass often requires a calculation time measured in hours. Laser forming applications requires tens, if not hundreds of passes of the laser.

Emperical models The empirical models, are quite frequently used as part of databases for process control, see chapter 4. They often require extensive experimental or numerical work to prepare, and only work for interpolation within the specific material investigated. Furthermore, the models often make assumptions regarding independence between adjacent laser scan paths to reduce the number of variables. This imposes a rather strict limit on the number of possibilities while increasing the risk of introducing a discontinuous deformation field.

Of the three strategies, only the numerical models hold the promise for accurately predicting the result of laser forming of complex geometries. The literature on numerical models will therefore be examined more closely in this chapter. For a larger review on all three types and for a more general introduction to the numerical models, the reader is referred to Shen and Vollertsen (2009); Ablat and Qattawi (2017); Das and Biswas (2018).

3.2 Numerical models

This section considers the process modeling of laser forming using numerical methods. This is meant to examine the literature for input to increase the accuracy and reduce the total processing time of laser forming models. Therefore a general overview of the finite element method and the governing equations are left to the numerous other works on the topic.

Heat input: Models the heat flux from the laser. Hu et al. (2001); Shi et al. (2006) used a Gaussian distribution given by equation (3.1).

$$I = \frac{2AP}{\pi r_b^2} exp(-\frac{2r^2}{r_b^2}) \tag{3.1}$$

Where I is the heat flux, A is the absorption, P is the laser power, r_b is the radius of the laser beam corresponding to a diameter defined at $1/e^2$, r is the distance from the center of the laser beam.

Mesh: Zhang et al. (2004) found that at least two elements per radius of a circular beam were necessary to capture the Gaussian distribution of the flux. They furthermore determined that three elements through the thickness should be used. Yu et al. (2001) used a re-meshing method to refine the mesh around the laser beam, to achieve a reduction of a factor of 2 in total calculation time.

Time step: Chen and Xu (2001) writes that the time step must be set low enough to capture the continuous movement of the laser beam. Chen and Xu (2001) use a maximum change of temperature between time steps of 20°C. Zhang et al. (2004) introduces equation (3.2) instead. Note that the two different strategies may result in vastly different time steps.

$$\delta = \frac{r}{4v} \tag{3.2}$$

Where δ is the time step, r is the radius of a Gaussian beam, v is the laser scan speed.

Boundary conditions: Modeling of laser forming requires both thermal and mechanical boundary conditions:

Mechanical: The mechanical boundary conditions are usually given by fully clamped nodes (Hu et al., 2013; Shen and Hu, 2013).

Thermal: The thermal boundary conditions include convection and radiation, but Shen et al. (2007) found that the effect of radiation could be considered negligible due to the relatively low peak temperature compared with welding or cutting (Shen and Vollertsen, 2009).

Material: Laser forming being a temperature dependent process requires temperature dependent material properties. These are rarely easily available and can be difficult to determine due to the equipment required. Chen and Xu (2001) state that their material properties used for the simulations are gathered from similar materials and using room temperature values for their Poisson's ratio as they were unable to determine temperature dependent values. It is likely a fair assumption that this is relatively common, though rarely explicitly stated.

Verification: Verification of the models is commonly completed by comparison with the final bend angle achieved using a v-bend (Hu et al., 2013; Song et al., 2015; Kant and Joshi, 2016; Fauzi et al., 2019). The only exception appears to be Reeves et al. (2003), who measures the dynamic response during laser forming.

3.3 Observations

Based on the literature study in this chapter, only a single observation will be discussed further:

- A need for better verification

3.3.1 Verification

Considering that different laser forming settings can lead to the same bending angle, it is worrisome that the primary method of verification is the final static results. An argument can be made, that if the physics are modeled, then the chance of a false positive happening is limited. But the counter argument is that modeling of laser forming is based on numerous assumptions to reduce calculation time that are ultimately a simplification or fitting of more complex behavior. To consider the words of Professor Jesper Hattel, DTU:

A model is not a model without a few fitting parameters.
Professor Jesper Hattel[1]

For laser forming, and possible laser processing, an obvious fitting parameter is the absorbance coefficient. It is tricky to measure, changes with passes of the laser, and far easier to estimate based on the results.

The process may reach the same bending angle for different process parameters, however, it is not likely to have the same thermal and mechanical history. For multiple passes of the laser, the variation is bound to increase with each pass of the laser.

By measuring the dynamic response, a far better verification of the model would be possible. Using the dynamic response, increases the credibility that the appropriate physics and behavior is captured by the model. Unfortunately, this requires the possibility to measure the process during laser forming, which may explain why it is rarely used.

[1] Said at Rathesan Ravendran's public PhD Defense, November 23, 2018, Aalborg, Denmark

3.4 Partial analysis

It would likely be hubris to consider the laser forming modeling capabilities at their pinnacle, due to the relative low attention towards laser forming as a field. That is to say that there is possibilities for improvements in both accuracy and speed. The limitations of the models described in this chapter, are arguably a limitation for laser forming as it makes it more difficult to examine the process.

This raises the questions about whether the effort of improving the laser forming models is worth the time at the current stage of development. Considering the quote by George Box at the beginning of this chapter. The purpose of the models must be considered in relation to the effort in developing them. The advantages of a numerical model can be discussed as follows:

Faster and cheaper result: A shorter development time is usually expected from a numerical model, due to the possibility of testing before parts are manufactured. However, the laser forming process remarks itself by being a tool and die free process. The advantage of laser forming as a free forming process negates some of the advantages of a model.

Additional information: The model can add information such as temperature, stresses and strains which are valuable to understand the process. However, if the results takes weeks to compute to achieve a sensible accuracy, it becomes faster and cheaper to examine the microstructure following a real experiment.

That is not to say, that numerical models hold no value for laser forming. Only to consider that the advantages normally associated with modeling of metal forming are reduced for laser forming.

Chapter 4

Process control

Chalk mark	1 $
Knowing where to put mark	9,999 $
Total	10,000 $

The Handyman's Invoice (Snopes staff, 2001)

This chapter contains the literature study on process control of laser forming of sheet metal. The chapter also contains a section on line heating from the ship building industry and a section on finding the initial shape. Finally the observations made throughout the literature study are examined.

4.1 Process control of laser forming

The laser forming process remarks itself by its free forming and incremental forming, however, these aspects which add freedom becomes more difficult to handle from a process control perspective. The numerous options makes the problem ill-posed, as a single shape can be achieved with a variety of input parameters.

The literature is largely fragmented with little comparison between contributions. Most contributions establish their own cases, which may resemble v-bends, domes and saddle shapes, but they vary in material and overall dimensions. This variation in cases means that direct comparison between shapes is difficult at best. As such there exists no benchmark for the comparison of strategies. The lack of comparison makes evaluation of the strategies difficult.

Reproduction is unfortunately not simple either, as the strategies require significant effort to reproduce. Pseudo code is rare and even then, there are excluded details. Therefore, a discussion on the different strategies is performed based on a higher abstraction level.

The contributions in literature, will be split by two categories to simplify their respective solutions. The first category relates to the type of control system, treating the surface as two dimensional (2D) or three dimensional (3D). The 2D simplification is commonly used for surfaces with single curvatures, see figure 4.1, and can be solved using only TGM, while a 3D surface commonly involves double curvatures and therefore requires UM. The second category denotes the type of control as either open or closed loop. Open loop control, is defined by planning the entire process before it starts. Closed loop (also denoted as feedback control) requires monitored the process so that corrections can be made while the process is occurring.

The following terminology is used to describe some key stages of the shape during laser processing.

Target shape The ideal shape for the laser forming process to achieve. Literature notations may include desired shape or reference shape.

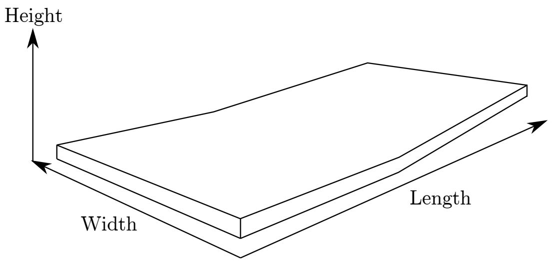
Initial shape The starting shape before any laser forming has been conducted. Literature notations may include blank.

Current shape An intermediate shape between the initial and target shape. For a closed loop process, monitoring includes measurement of the current shape.

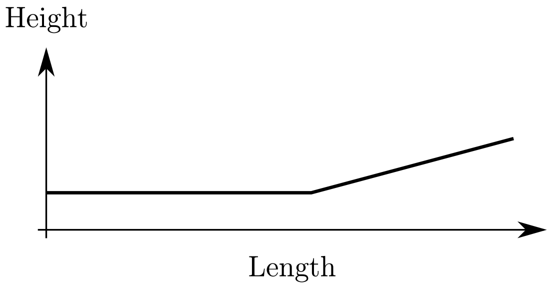
Final shape The final shape reached using the laser forming process. As the target shape is an ideal shape, the final shape is the achieved shape from a particular strategy.

4.2 2D

The 2D surface is related to the formation of v-bends, see figure 4.1. These type of shapes are commonly made using traditional mechanical bending machines. While laser forming is not likely to replace traditional mechanical bending machines, much can be gained by laser forming simple v-bends. The evaluation of v-bends is simpler and can often be reduced to comparison of



(a) The v-bend as seen from a 3D perspective



(b) 2D simplification

Fig. 4.1: A 2D simplification of the v-bend by assuming that any variation over the width is insignificant. This simplifies the path planning by only considering lines perpendicular to the length of the sample with a constant laser scan length equal to the width of the sample.

the bend angle. Thereby it is easier to study the laser forming process using simple v-bends.

The process control is vastly simpler as the laser scan paths can be simplified to straight lines from side to side. The degrees of freedom for a 2D control strategy is given by:

- Distance between adjacent paths
- Number of laser scans over each path
- Heat input

The following contains a summary of the different strategies presented in the literature.

4.2.1 Open loop

Response surface. Liu and Yao (2002) used a response surface to determine the laser scan paths and heat input. The authors used their approach for both v-bends and circular domes. The dome problem was simplified to a 2D problem, by considering a polar coordinate system with straight radial lines. This approach requires multiple experiments to determine the response surface, which can limit its use.

Difference in angle or height algorithm. Kim and Na (2003) developed two algorithm to determine the distance between laser scan paths based on offsets in height or angle. Changing the offset, changed the distance between the paths. The heat input was found using a database.

Genetic algorithm. Cheng and Yao (2004) used a genetic algorithm for a class of v-bend shapes. The process variables were the number of scan paths, the distance between paths and the laser scan speed and power, however, fewer were often chosen to reduce the number of variables. It was assumed that the parallel scan lines do not have any coupling. An empirical database to predict the bending angle based on input parameters were used to evaluate the fitness function. Similarly, the authors of Maji et al. (2013b) compared two variations of a genetic algorithm for the analysis and synthesis of laser forming of the bend angle of a v-bend.

Probability function based on radius of curvature Shen et al. (2016b) optimized the total production time of 2D laser formed parts. Heating lines were optimized to reduce the total processing time. To determine the heating lines a weight function based on the radius of curvature and a set of rules was used. The processing time was determined from a database of processing parameters. The dwell time does not appear to be included in the optimization, even though the dwell time is responsible for the majority of the total processing time.

4.2.2 Closed loop

Single deflection feedback. Thomson and Pridham (1997) where the first to recognize the need for feedback control in laser forming. They created a single input, single output control system, meaning the laser scan path was kept constant. The input was the deflection and the output was the laser scan speed. A rule system was used to determine the laser scan speed in increments depending on the deflection error. They suggested using fuzzy logic and artificial intelligence to improve the rule system.

Difference in angle or height algorithm Kim and Na (2005) modified their approach from Kim and Na (2003) to allow for feedback. The algorithm was based on adjusting the forming points based on the deviation between the expected angle and the achieved angle.

4.3 3D

3D surfaces are characterized by double curvatures. 3D Laser forming has traditionally been investigating dome and saddle shapes, see figure 4.2, as they form the basic possibilities for a double curved surface; The dome is a double curved shape that is defined by a positive Gaussian curvature, while a saddle shape has a negative Guassian curvature. The Gaussian curvature is given by

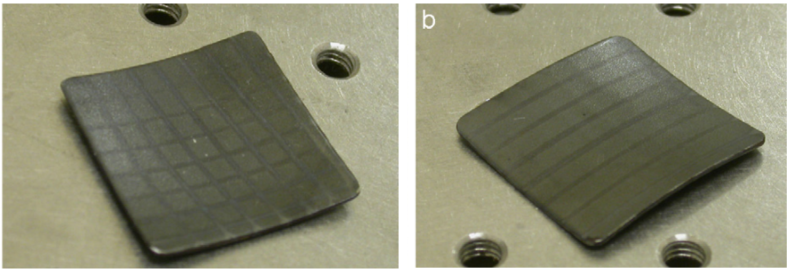
$$K = k_1 k_2 \tag{4.1}$$

where K is the Gaussian curvature, k_1 and k_2 are the principle curvatures. If K is zero, it is either a flat surface or a single curved surface. The argument is therefore that if dome and saddle shapes can be laser formed, then all other surfaces are simply a combination of single curved, dome and saddle parts.

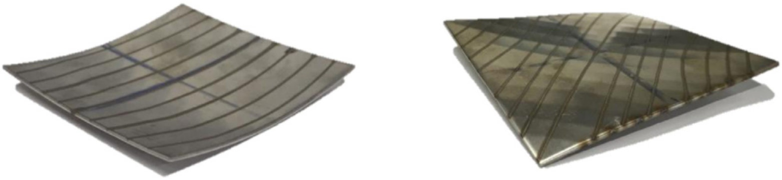
The most important aspect of double curved geometries for laser forming is that they are non-developable. Developable surfaces are surfaces that can be made from a flat surface without stretching or compression, while non-developable surfaces require either stretching or compression. Note that laser forming does not have a stretching mechanism, only compression is possible.

The degrees of freedom for a 3D surface is as follows:

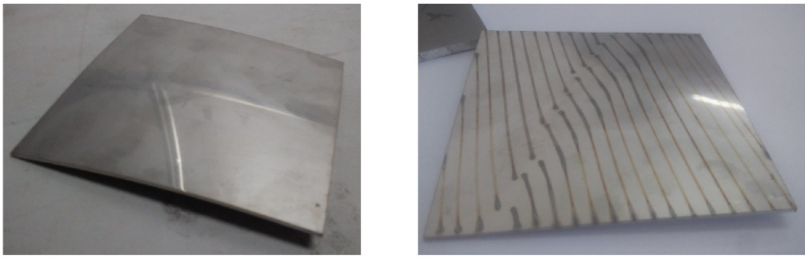
- Position of the paths



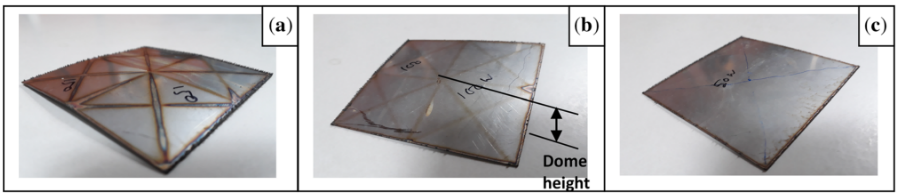
(a) Dome and saddle shape, respectively, by Kim and Na (2009)



(b) Dome and saddle shape, respectively, by Shen et al. (2018b)



(c) Dome and saddle shape, respectively, by Shen et al. (2018a)



(d) Dome shape under three different conditions, by Maji et al. (2020)

Fig. 4.2: Examples of cases for dome and saddle shapes in the more recent literature.

- Number of scans over each path
- Heat input

The following contains a summary of the different strategies presented in the literature.

4.3.1 Open loop

Strain field from curvature Liu et al. (2004) calculated the in-plane strain field from the curvature using planar development. First the curvature is calculated which is used in an optimization approach to minimize the total strain energy required for planar development. A constraint is used to ensure that all strains are compressive when going from the planar case to the target shape. The laser forming settings were calculated using a database.

Strain field from flattening Cheng and Yao (2004), Liu and Yao (2005) and Cheng et al. (2006) used a FEM model to calculate the flattening of the target shape. The flattening of the target shape resulted in the strain field required to develop the initial blank shape into the target shape. The strain field is decomposed into a bending and membrane component. The bending and membrane components are used with a database and the CM. The same method was examined by Gao et al. (2016) and Gao et al. (2017), which looked into different scan paths.

Strain field from inverse model Shen et al. (2016a, 2018b,a) developed an inverse solver which computed the strain field directly. The approach is based on ignoring the time dependencies and only computing the strain field from the initial shape to the target shape. As the intermediate steps are not computed, the results are much faster, although they are also more simplistic. The laser forming parameters where determined from a database.

Geometric patch matching. Carlone et al. (2008) created an inverse model based on a database approach. A database of patches were created numerically, but can be created experimentally. The target shape was divided into a set of 16 point patches which were matched with the database to find the laser forming settings and passes required to create each patch. The authors show a set of shapes and the corresponding laser forming paths, but do not show the final shapes achieved by following the strategy.

Difference in angle or height algorithm Kim and Na (2009) expanded their method from Kim and Na (2003) to 3D. First a series of patches are created using the method from Kim and Na (2003). The patches are then transformed to a 2D plane surface, a set of virtual springs are used to determine the amount of stretching required to create a continuous surface. The stretching is equivalent to the amount of shrinkage required by laser forming. The amount of bending and shrinkage is compared to a database to determine the laser forming settings.

Manual design templates Several authors have attempted to create specific laser scan path templates to develop specific shapes. There are numerous limitations to these, as each template has a limited design range, usually fitting only for a dome or a saddle. However, they have gained some popularity in the scientific literature as they avoid the entire problem with process control. It is unlikely that they can ever fulfill more than a scientific curiosity.

Concentric circular pattern. Creates saddle shapes (Watkins et al., 2001).

Spiral. Creates a saddle shape (Safari and Farzin, 2015) or a dome shape (Gollo et al., 2015).

Cross spider. Creates a dome shape (Yang et al., 2010b; Maji et al., 2014).

Machine learning Maji et al. (2020) trained a neural network to find the process settings of preplanned paths for creating a dome shape. The American company Energyn Tech boasts a neural network for both laser forming and line heating, capable of fully planning the approach called LITS-Form. Unfortunately the available information is scarce.

4.3.2 Closed loop

Lines of constant angles Abed et al. (2007) used lines of constant angles to calculate the laser scan path. The heat input was controlled using a variable speed which was found using a database. It is not entirely clear how the projections between surface was performed. The authors use only TGM, and therefore only consider shapes that although 3D, have very small Gaussian curvatures.

4.4 Line heating

The PhD thesis by Clausen (2000) considers laser forming as part of a broader field called line heating. Line heating, as defined by Clausen (2000), is a method of incremental heating with different heat sources: gas torch, induction and lasers. However, it would appear that laser forming and line heating have developed independently. Considering the number of hits in the different scientific databases, Web of Science, Scopus and Google Scholar, see table

4.1.

Table 4.1: Number of hits, comparing laser forming and line heating for three different scientific databases. Queries performed on August 23, 2019 using quotation marks to ensure relevant results. Searching line heating using Google Scholar without the quotation marks results in about 3,950,000 hits.

Search term	Google Scholar	Web of Science	Scopus
"Laser forming"	8,250	534	750
"Line heating"	8,470	206	371

There are several interesting consequences of this, an example is that an article on line heating will not denote the mechanisms of deformation as TGM, UM and BM (Park et al., 2016b), although the governing effects are described similarly. The reason appears to be that TGM, UM and BM are described in the laser forming literature (Geiger and Vollertsen, 1993). Instead, Park et al. (2016b) considers line heating and triangle heating as a bending and upsetting method, respectively.

Interestingly, this also means that automation of line heating and laser forming, albeit similar, have been developing in parallel with very limited overlap. Furthermore, it appears that line heating has more advanced closed loop control strategies that have been tested in industry. Two different systems have been found in the literature.

Tango et al. (2011) describes an industrial system used for line-heating with gas torch for the shipbuilding industry. The system is not explained in detail, and is limited in the amount of curvature it can handle, it is not clear if this is due to limitations in methodology or equipment. The system is an iteration of a former open loop control system.

Park et al. (2016b) describes a (semi-)automated feedback control system as a summary of their work in Park et al. (2007, 2008, 2016a). The system is based on induction heating and is introduced as automatic. However, the feedback loop is stopped when 80% of the shape is within a set tolerance level and manually formed from there. The system is based on a database of heating information. It is also worth noting that the methodology is the result of numerous works from 2007 to 2016 (Park et al., 2007, 2008, 2016a,b).

It is worth mentioning that neither Tango et al. (2011) nor Park et al. (2016b) mention any of the references listed in section 4.2 or 4.3. As a result, these works were only discovered late in this work. Due to the late discovery, these works could not be included in the overall analysis. They are included here to ease future studies.

An example of the disparity between fields, the review article by Das and Biswas (2018) actually cites both line heating and laser forming work such as Clausen (2000); Cheng and Yao (2001); Vollertsen (1994); Shen et al. (2006a) and uses a mixed terminology from both line heating and laser forming. However, they do not reference any of the works by Park et al. (2007, 2008, 2016a,b) or Tango et al. (2011). Instead they summarize as part of the future work for line heating:

Research work related to proper planning of automation of line heating process is lacking in the published literature.
(Das and Biswas, 2018)

Which could still be considered valid as Park et al. (2016b) are also dependent on final manual adjustments.

4.5 Blank shape problem

The initial shape, sometimes denoted as the blank, has been discussed in the previous as a given, however in the case of non-developable shapes this is far from reality. The target shape is the one designed for manufacturing, and relating a desired target shape to an initial shape is an ill-posed problem due the possibility of several solutions. Finding the initial shape from a target shape is sometimes referred to as an inverse problem (Guo et al., 1990).

The primary consideration for laser formed components is if they are non-developable. For laser forming only compression is possible, which must be included in the analysis to find the initial shape.

The inverse problem can be solved using two different methods. The first method is based on adjusting the size of the blank shape based on the process response. An initial guess is made, and optimized following the results attained from the process using this guess. The process can be experimental or numerical. This can be time consuming and requires several full iterations.

This has led to the development of one-step solvers (Guo et al., 1990). These one-step solvers directly calculate the initial shape from the target shape, under several assumptions. The consequence is that the direct solvers are very simplified in their response compared to the actual system. This can create unreasonable estimates depending on the algorithm used (Liu et al., 2013). Some of these algorithms have been adapted for line heating.

Yu et al. (2000) used a constrained non-linear optimization solver to find the minimum strain field required to form an initial shape to the target shape using line heating. Ryu and Shin (2006) uses constrained non-linear optimization based on deformation theory for line heating. Ryu and Kim (2008) expanded the method from Ryu and Shin (2006).

4.6 Observations

Based on the literature study in this chapter, some observations have been made. The following three observations will be discussed in this section:

- The need for better process control
- The need for benchmark tests
- The focus on databases; the classical control system is not really considered, even by Thomson and Pridham (1997).

4.6.1 Improved process control

During the literature review of laser forming, it becomes apparent that the process control of laser forming is not at an acceptable level for industrial or even scientific level yet. The result is that the field is less explored as the lack of process control increases the barrier to begin using the process.

A comparison can be made with 3D printing, which is comparatively more widely available and even used by hobby enthusiasts who have built their own setups. A part of what has made this possible is the availability of the slicing software, that helps turn a complex 3D structure into a series of 2D surfaces that can be printed. While the slicing software can be improved, this has still served to reduce the barrier to start working on the different parts of the 3D printer to where even hobby enthusiasts can follow.

As process control is a key part, most laser forming articles limit themselves to simple 2D bends or using the manual 3D schematics and investigating process parameters. Unfortunately, these process parameter studies do not reduce the barrier towards process control, as the problem lies within the software. The usual progress of the incremental research approach, where smaller studies combine to advance the field thereby falls short as it requires a substantial effort to reduce the barrier.

A sign of the required effort can be found using the case of Park et al. (2016b), which has taken an effort over 9 years and at least 4 journal papers to produce a system capable of forming to 80% using line heating. This supports the conjecture that laser forming is severely hindered by a lack of process control and remedying this will require a significant effort.

4.6.2 Benchmark test

As mentioned in the beginning of this chapter, a lack of reproducibility and benchmark tests makes it difficult to compare different strategies. The problem of reproducibility is affecting all fields of science and is therefore less interesting in this work. The subject of a benchmark case is, however, more relevant as the case(s) needs to be specific for laser forming.

Until now, testing has resolved to standard shapes such as v-bends for 2D bending and domes and saddles for 3D forming. These three shapes do resemble all shapes, as mentioned previously, as they represent the three different Gaussian curvatures that can arise in a plate; zero, negative or positive. However, as size, thickness, material and reported parameter choices varies, the results cannot be directly compared. Therefore there needs to be a commonly accepted benchmark test. The requirements of such cases can be summarized in the following:

- Relatively easy to use
- Simple to quantify and compare well defined parameters
- Highlight known problems such as edge effects

It must be relatively easy to use and compare benchmark tests, otherwise the test itself will loose its applicability. The last point of highlighting known problems is to allow comparison of different strategies by comparing their result on difficult problems. The results is that setting up a good benchmark case is not as simple as it seems as it requires experience to determine an adequate case. Establishing a benchmark case is therefore both relatively simple, but attaching a userbase requires a direct value for its users.

4.6.3 Database control

All of the process control strategies found in this work, used a database to determine the process settings. These can be created numerically or experimentally but always seek to solve the same problem, create a model between the desired output and input parameters.

The advantage is that they are fairly simple to create, as it requires trying a set of different process data and measuring the response. Interpolation can be used to determine the process settings between tested values. A limitation is that they are material dependent and require a database for each material. Furthermore, variation between samples due to noise factors result in difference between expected and actual response of the material.

A slightly different problem is a common assumption of independence of the individual paths when using databases (Liu et al., 2004; Liu and Yao, 2005). The purpose of this assumption is to reduce the number of variables in the database. However, the implication of this assumption is less understood. A conjecture can be attempted;

If the paths are truly independent, then there would be no overlap between the heat affected zones of each pass. This would also hold for the laser forming induced strains. Assuming a Gaussian structure, as seen by Knupfer et al. (2010), would yield a discontinuous strain field as seen in figure 4.3. Such a strain field would yield a discontinuous curvature which would yield a surface structured from a series of straight lines and bends, rather than one continuous bend.

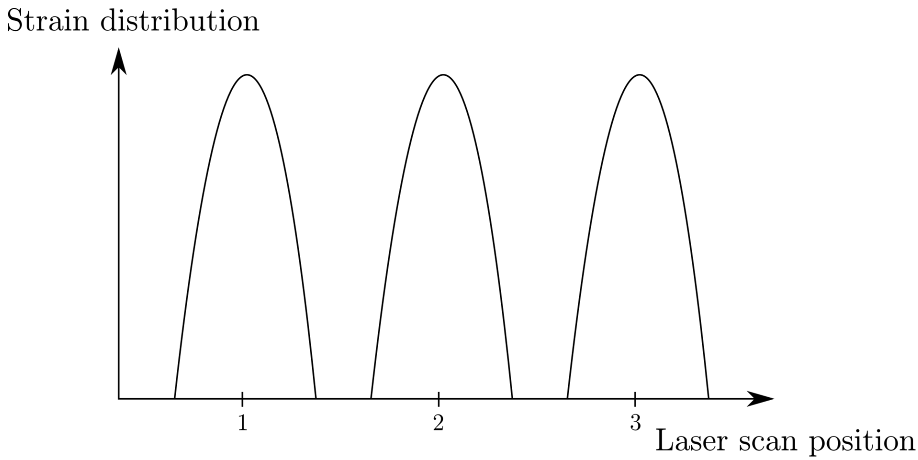


Fig. 4.3: The strain distribution, assuming a Gaussian distribution as found by Knupfer et al. (2010), given independence between paths.

This could become relevant for laser forming, precisely because it allows very localized deformation due to the focusing of the heat. This deserves further investigation as to whether this affects only the microscopic or also the macroscopic appearance of a component.

Alternative control strategy

As the databases are material dependent, while still not being able to fully predict the actual response of laser forming, it seems viable to examine other options. A consideration could be the more classical feedback controller, where a series of proportional, integral and derivative terms determine the process settings.

This would require a method for determining the terms of the controller, using a simpler method than creating a database. It seems worth investigation if the necessary equations or rules could be derived from some of the analytical expressions presented in literature, such as the Fourier number, see equation (2.1) on page 17. This would require a study of whether a feedback controller is even viable and derivation of such equations for planning.

4.7 Partial analysis

Considering the initial problem in chapter 1, it appears that process control can be considered the primary limitation of laser forming. A total of 24 articles were presented in section 4.2 and 4.3, yet no accepted solution exists. That so many attempts have been made without significant progress reveals a difficulty to the problem.

This, along with the findings of the other chapters are discussed in the next chapter, which is used to determine a research objective for this thesis.

Chapter 5

Discussion of scope

I have many bad ideas and make many bad decisions. I can only hope a good idea is followed by a good decision.

Benny Endelt
Translated from its original Danish.

This chapter will start with an introduction to the scoring system used to rate the identified problems. This is followed by an overview of identified problems. Lastly the chosen research objectives of this thesis will be presented.

5.1 Overview of identified problems

This section is a summary of the problems identified during the problem analysis, see chapters 2 to 4. To identify the relevant problems for the research objective for this thesis, an overview is given here as a summary of the problem analysis. To help compare different problems, a predicted impact score and predicted resource score is introduced. They can be described as given in the following:

Predicted impact This is an estimate of the predicted impact of a solution. Impact is meant to encapsulate both the relevance for industrial applications and scientific relevance. A scale is used from + to ++++ to signify the impact, given with the following description:

- **+** A smaller improvement that does not directly affect the usability or understanding of the technology.

- **++** A larger improvement that affects the use or understanding of the technology.
- **+++** Solves a larger problem hindering the technology or enables new opportunities.
- **++++** Fundamentally changes the way the technology is used or understood.

Predicted resources This is an estimate of the predicted resources required to find a solution to the problem. A scale is used from + to ++++ to signify the resources required, given with the following description:

- **+** A smaller study involving a few experiments or simulations.
- **++** A study involving several experiments and simulations.
- **+++** A larger project, similar in size to the PhD project.
- **++++** A significant effort requiring multiple collaborators over several years.

It should become apparent that the scale is both subjective and exponential. The scale is subjective because it depends on the user and will differ between users. The scale is exponential as the step from + to ++ is smaller compared to the step from ++ to +++. In general + or ++ can be described by the common contributions found in literature, which adds an incremental understanding or use of the process.

Based on these scores, a set of problems were chosen. The chosen problems will be presented first with the remaining problems listed afterward for future reference.

The 'Predicted' term is shortened to P. in the following overview of the problems. If the predicted resources have dependencies, the dependencies are accounted for by adding extra + in a parenthesis.

5.1.1 Chosen problems

Process control

Subsection: 4.6.1
P. Impact: ++++
P. Resources: ++++

Process control appears to be the primary barrier for laser forming gaining a wider use, both scientifically and industrial. In other words; Laser forming will not become useful in an industrial scope, unless process control can be improved greatly. Considering that multiple attempts have been made without gaining any traction, it appears that the required resources are significant. While it appears to be ambitious to attempt improving process control during this thesis, it is also the only problem that really matters for laser forming at its current stage.

Process control is chosen as it is arguably the biggest problem for laser forming. Due to the significant resources required, the expectation is not to create a fully automatic setup by the end, but rather to understand the necessary steps in formulating a feedback control loop for 3D laser forming.

To help improve the understanding of laser forming and ensure progression of the thesis, other smaller problems are also chosen alongside the investigation into process control:

Cooling and edge effects

Subsection: 2.6.3
P. Impact: ++
P. Resources: +

The work of Cheng and Yao (2001) argues that active cooling reduces edge effects, while Shen et al. (2010a) argues that it has no effect. Both of these studies are based on numerical results. There is a theoretical basis for why active cooling could reduce edge effects. Furthermore, the use of active cooling is already a consideration for process speedup of laser forming, which means that reducing edge effects would be a bonus effect. Using cooling could be considered a simple and elegant method for reducing edge effects. Due to the opposing claims made by Cheng and Yao (2001); Shen et al. (2010a), it seems worthwhile to perform a smaller experimental study to investigate this further.

Independent paths

Subsection: 4.6.3 *P. Impact:* + *P. Resources:* +	The assumed independence between paths is a result of simplifying the use of databases for process control. While this is a common assumption, the effects of it have not been investigated further. It only requires a smaller experimental study to investigate if the curvature field will become discontinuous from a set of independent laser scan paths. The impact will not negate the use of databases, but will require them to be more advanced to account for coupling between the paths.

Verification of laser forming models

Subsection: 3.3.1 *P. Impact:* ++ *P. Resources:* ++	Using the static response of laser forming for verification can be problematic. Using the dynamic response requires more complicated measurements, however, it can also lend greater insight into the process. As the experimental setup at AAU allows for dynamic measurement, it has been chosen to make an exploratory study with the purpose of measuring and examining the dynamic response of laser forming.

Cooling as a method for reducing edge effects is chosen as it could help simplify the process control by reducing unwanted distortion. Furthermore the independence between paths is investigated as it affects the current methods for determining the process parameters. As a last point, the dynamic measurements of laser forming are performed to increase the understanding of laser forming and enable better verification to increase confidence in the models.

5.1.2 Remaining problems

The remaining problems are not part of the solution part of this thesis. However, they are relevant for laser forming and summarised here for future reference.

Laser formed properties

Subsection: 2.6.1 *P. Impact:* +++ *P. Resources:* +++	Controlling the laser forming settings to potentially improve the mechanical and corrosive properties could be beneficial. But it is unknown how much control freedom exists. This could allow for some interesting new opportunities for laser forming by optimizing the process for process time or certain properties. However, this requires a greater study into how large the process window is, and how the properties can be affected.

Flexible clamping

Subsection: 2.6.2 *P. Impact:* +++ *P. Resources:* +++(+)	Flexible clamping could be used to assist control of the mechanical response of laser forming. Furthermore, it is possible that certain shapes can only be formed by specific design of the clamps. However, the optimization of the clamps require significant effort to be able to evaluate different options, including a working laser forming control strategy.

Laser forming edge effects

Subsection: 2.6.3 *P. Impact:* ++ *P. Resources:* ++(++)	The laser forming process could potentially be used to reduce or even remove edge effects after they have formed. While this could be used to improve the tolerances, this is a less desired option. It would be better to avoid the formation of edge effects as subsequent laser forming to reduce them would increase process time. Furthermore, using laser forming itself to reduce edge effects requires much better feedback control strategies.

Benchmark

Subsection: 4.6.2 *P. Impact:* + *P. Resources:* +(+++)	Creating benchmarks would help compare different control strategies. The development of a benchmark is by itself relatively easy, as each case ever presented can be considered for a benchmark. To become a benchmark however, it must be a commonly accepted method for testing different strategies. This is best achieved by using it for testing several strategies so its is simple to make comparisons for others. However, as the current strategies are difficult to reproduce, this can more easily be done for new strategies.

Design of controller

Subsection: 4.6.3	Depending on the results of the independent paths, it may increase the required complexity of database approaches. The alternative use of a controller, requires generalization of the methods for designing the controller for laser forming. This requires a larger study into how the controller affects the feedback control strategy which can be used to develop design rules. If a controller could be designed from common material constants available in a datasheet, it would be an improvement over the current database approaches as it would be simpler to switch materials.
P. Impact: +++	
P. Resources: ++(++)	

5.2 Research objectives

From the overview of identified problems, one problem was chosen as the main focus of the thesis, with additional problems to support the main focus. To find a solution to these problems, they must be reformulated as research questions and preferably hypotheses.

5.2.1 Research question I - Generalized process control

From the literature study, it is apparent that some form of feedback control is required. It is too difficult to predict the response of laser forming which is required for open loop solutions.

As it has already been stated that process control is an ambitious subject, it is not the intention to create a fully optimized feedback control system. Instead the goal is to create a working feedback control system with identified generalized parts. These parts can then allow for individual optimization without affecting the entire system. This allows for continued incremental improvements that are necessary to develop the field of laser forming. Thereby the research question becomes:

How can a generalized feedback control system be created for controlling 3D laser forming of sheet metal?

This question is examined in Paper A.

5.2.2 Research question II - Measurement of the dynamic response

The dynamic response of laser forming could allow better verification of laser forming models. The setup at AAU allows the measurement of the surface during the process. However, it requires further understanding of how well this measurement can be used to examine the surface. Therefore the second research question becomes:

How can the dynamic response of the surface be measured for verification of laser forming models?

This question is examined in Paper B, Thomsen et al. (2020).

5.2.3 Hypothesis I - Effect of active cooling on edge effects

Cheng and Yao (2001) and Shen et al. (2010a) examined if there exists a causality between active cooling and the formation of edge effects. As their studies were numerical and had opposing results, the hypothesis cannot be said to be completely refuted as their models may have been the cause for the effect. The hypothesis can be stated as follows:

Active cooling reduces the formation of edge effects during laser forming.

This hypothesis is tested in Paper C, Thomsen et al. (2018).

5.2.4 Hypothesis II - Effect of path independence on curvature

The use of database approaches often assumes independence between paths (Liu et al., 2004; Liu and Yao, 2005). The effect of the independence on the paths on the curvature have not been examined. However, it can be argued that it is likely to have an affect. The hypothesis can be stated as follows:

The distance between paths affect the continuity of the curvature when laser forming.

This hypothesis is tested in Paper D, Thomsen et al. (2019a).

This concludes the problem analysis. The results are given in papers A-D, see part IV. A summary and conclusion are given in part III.

Part III

Concluding remarks

Chapter 6

Summary

No book can ever be finished. While working on it we learn just enough to find it immature the moment we turn away from it

Karl Popper

This chapter contains a summary of the papers as a result of working with the research objectives. This is followed by the conclusion, the future work and a section on the outlook of the technology as an answer to the initial problem.

6.1 Research question I - Generalized process control

The research question was determined in section 5.2 as:

How can a generalized feedback control system be created for controlling 3D laser forming of sheet metal?

To answer this research question, the necessary stages in a generalized feedback control system were examined in paper A, with the result seen in figure 6.1. Each stage is the result of a sub-problem which can be handled separately with a given interface between the other stages. This is shown to be necessary as creating a feedback control loop requires a multidisciplinary effort. For each stage an introductory literature review is made, with a single solution explained in greater detail. This is to help readers create their own feedback control system using this framework.

The framework itself is developed for TGM, with the underlying groundwork ready for including UM as well. The framework is verified experimentally by laser forming a v-bend and an impeller blade, see figure 6.2. The shapes achieved a difference of between 5.5 and 14.0 % for the v-bends and 25 % for the the impeller blade.

The achieved tolerances were compared with the literature and were found to be similar in size. The control strategy used to calculate the heat input did not result in the desired stability of the feedback loop but instead caused localized under- and overshooting. The method for calculating the heat input was based on a controller design with a gain factor, rather than a database. The results show that the strategy of using such a control design itself has merit, but the implementation needs to be improved.

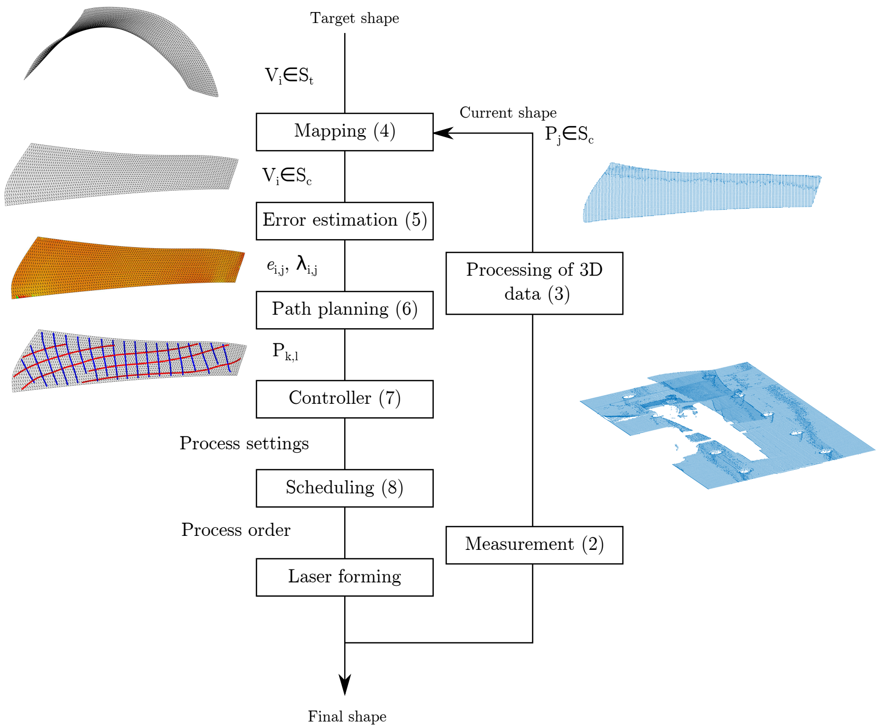
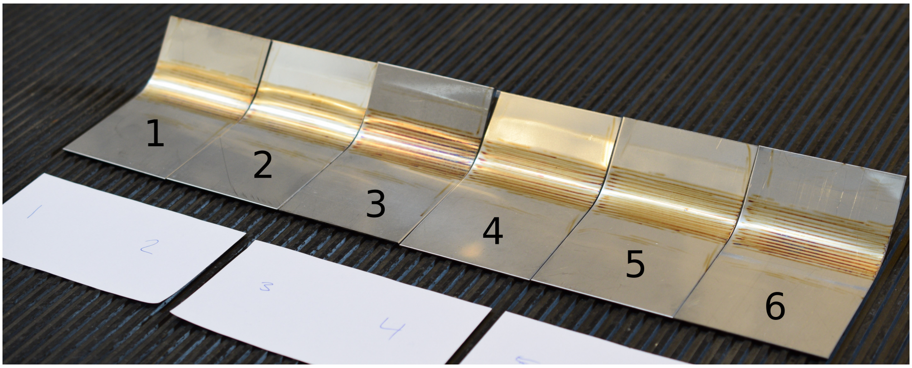


Fig. 6.1: A graphical representation of the feedback control framework presented in paper A. [Paper A]

The work in paper A, has led to an idea for improving process control using optimization combined with analytical solutions. The idea is described



(a) Six v-bends [Paper A].

(b) The impeller blade.

Fig. 6.2: (a) the six v-bends laser forming using the framework presented in paper A and (b) the impeller blade laser formed with the same framework.

in the working paper G, see part VI. Unfortunately, due to time constraints as the idea was conceived towards the ending of the PhD, the idea could not be examined beyond a theoretical study. The introduced methodology promises fully automatic process control of all important process settings:

- Laser scan power
- Laser scan speed
- Laser beam diameter
- Laser scan position
- The number of laser scan paths

In comparison, to simplify the process control in paper A, the laser scan speed and laser beam diameter was kept constant.

The method presented in Paper G uses simplified analytical equations to reduce the calculation time required by the optimization to counteract the deviation between the actual response and the one predicted by the simplified analytical equations, feedback control is used to introduce calibration of the analytical solutions between iterations. This, and more can be seen in the working paper G, see part VI.

6.2 Research question II - Measurement of the dynamic response

The research question was determined in section 5.2 as:

How can the dynamic response of the surface be measured for verification of laser forming models?

Paper B, Thomsen et al. (2020), examines the measurement of the dynamic response. The methodology is based on the use of a 2D laser line scanner and scanning multiple samples. By scanning a line perpendicular to the bend line, the dynamics of a single line can be determined. By scanning multiple lines in small increments along the bend line by using multiple samples, a surface can be approximated.

A total of 105 samples were laser formed with five passes of the process laser (responsible for the heat input). The 2D laser line scanner was used at 21 positions along the bend line and five samples were used per position. By averaging the five samples and combining all the averages, the surface is approximated, see figure 6.3. The resulting data was put in a public repository

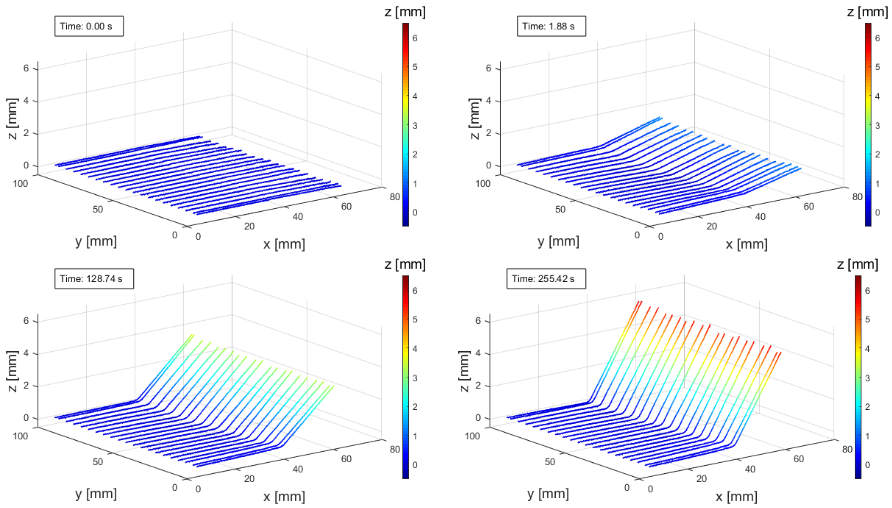


Fig. 6.3: The surfaces given by the data at Thomsen et al. (2019b).

at Thomsen et al. (2019b).

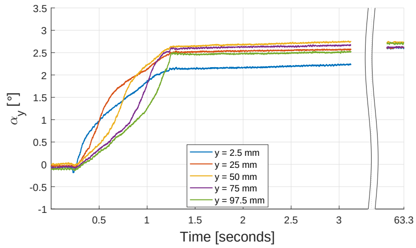
Paper B presented an analysis on the first pass of the process laser. It was found that the plate deforms significantly in front and behind of the process laser spot. This creates cold deformation of the plate in the leading edge before it is heated by the process laser. These results may change the understanding of the process as a new hypothesis was made:

> *The thermal expanded area is restricted not only by the surrounding material but also by the deformation caused by the already laser formed part of the laser scan path.* Paper B (Thomsen et al., 2020)

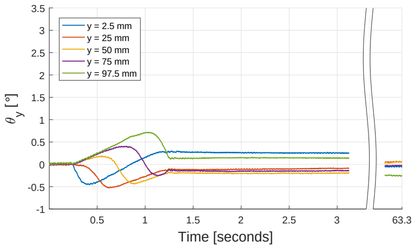
This changes the understanding of the way the plate deforms along the laser scan path. Two different angles, before (θ_y) and after (α_y) the bend line are introduced, and it is shown for both that they vary systematically along the bend line. These angles were compared with a numerical model with good results, see figure 6.4.

6.3 Hypothesis I - Effect of active cooling on edge effects

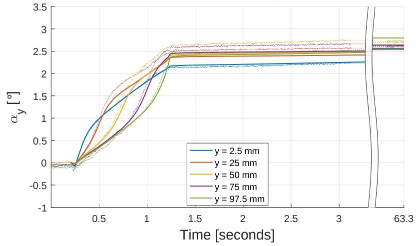
Paper C, Thomsen et al. (2018), examines the effect of active cooling on the edge effects numerically and experimentally. The numerical model was based on increasing the convection from 10 to 10,000 W/m^{2}K as a form of simplified



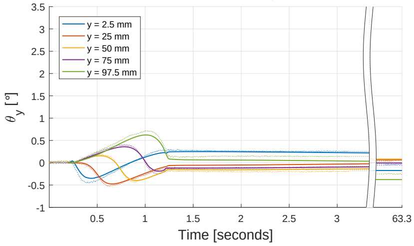
(a) Experimental α_y angle



(b) Experimental θ_y angle



(c) Simulated α_y angle



(d) Simulated θ_y angle

Fig. 6.4: The measured and simulated angles determined at five points along the bend line (Thomsen et al., 2020). (c-d) also show the experimental results in the dotted lines. The definition of the angles can be found in Fig 5a in Thomsen et al. (2020).

virtual cooling. The experimental results were based on using both forced air at 2.5 and 5 bar and CO_2. The experimental results had 3 repetitions per sample.

Neither the numerical or experimental results showed any improvements in edge effects with increased levels of cooling compared to the reference. It should be noted that the level of CO_2 cooling could unfortunately not be quantified, however the level of cooling should approach most, realistic upper bounds, see figure 6.5. Thereby it can be said that the hypothesis should be considered rejected:

Active cooling reduces the formation of edge effects during laser forming.

Rejected

6.4 Hypothesis II - Effect of path independence on curvature

Paper D, Thomsen et al. (2019a), examines the effect of the distance between paths on the curvature experimentally. The results were evaluated using

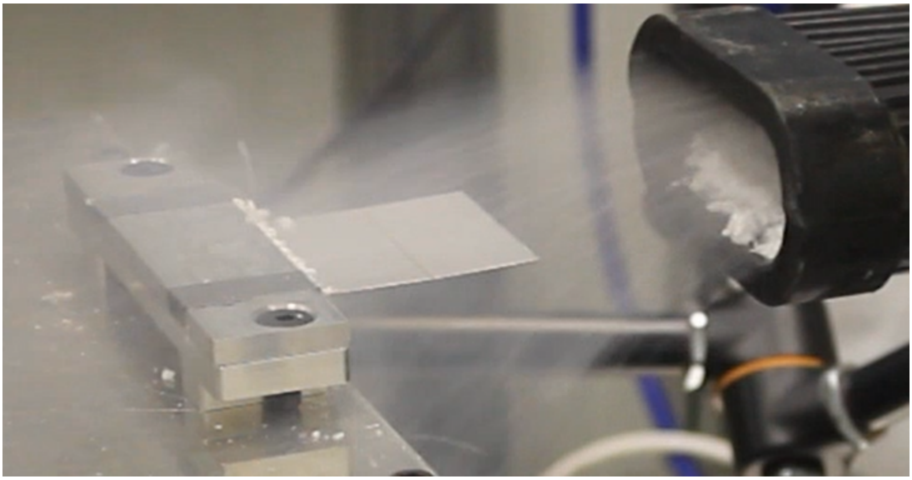


Fig. 6.5: CO_2 was used as a method for active cooling in an attempt to reduce edge effects.

three different methods; The curvature was calculated, the roundness tolerance of the bend was calculated and a manual examination of the bend was performed. The results agreed that the distance between the paths affected the continuity of the bend. In the worst cases, even a visual inspection is enough, see Fig 6.6. Thereby it can be said that the hypothesis failed rejection:

The distance between paths affect the continuity of the curvature when laser forming.

Failed rejection

The results also found that despite the same heat input, the total bending angle varied with distance between paths, see Fig 6.6. The effect was argued to be a result of two factors;

1. Each increment of the laser scan path uses new virgin material which increases the amount of deformation
2. The incrementation reduces the laser beam diameter distortion found by Edwardson et al. (2006)

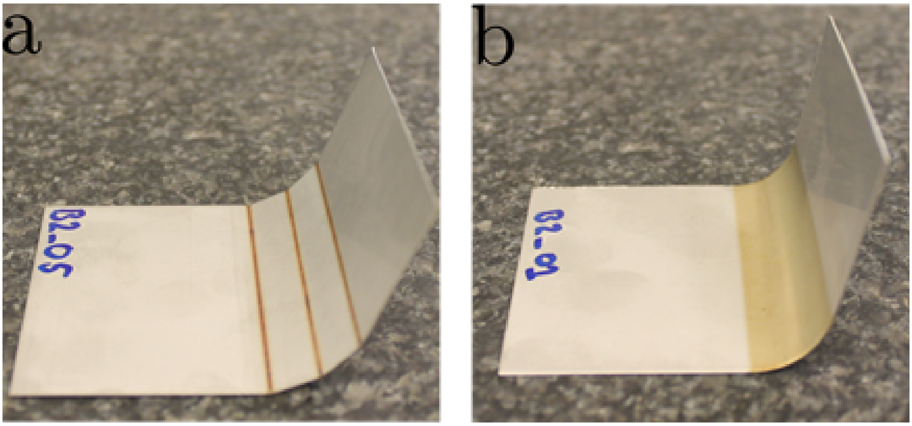


Fig. 6.6: Two shapes made with the same heat input with different scan line positions (Thomsen et al., 2019a). (a) has 3 laser scan lines with 15 repetitions over each line while (b) has 45 laser scan lines with 1 repetitions.

6.5 Conclusion

The primary focus of this thesis was to investigate why laser forming found limited use and how to improve it. Through the use of a problem analysis the primary cause was found to be a lack of automated process control. A research objective was therefore formulated around the research question on how to improve process control by creating a generalized feedback control system. A second research question as well as two other hypotheses were also formulated and investigated to support the purpose of improving laser forming.

The contributions towards the research objectives can be summarized as follows:

Research question I: A generalized feedback control loop was presented that included methods to incorporate different solutions to ensure generalization. This should reduce the barrier to investigate and improve laser forming as a process. A new method for determining the process settings were developed theoretically and deserves further experimental examination.

Research question II: The dynamic behavior of the surface during laser forming was measured. This can be used to better verify numerical models. Furthermore, the results were used to establish a new hypothesis about the dynamic behavior of laser forming.

Hypothesis I: The hypothesis that active cooling could be used to reduce edge effects was rejected. This result finalizes the discussion of cooling and edge effects and allows other areas to reduce edge effects to be further explored instead.

Hypothesis II: The hypothesis that independent paths affected the continuity of the curvature failed rejection. This is valuable for process control, as it rejects the assumption that the paths can be assumed to be independent as that will affect the curvature of the surface.

6.6 Future work

To consider future work, the overview of identified problems from section 5.1 is valuable. The most important work was and remains the introduction of process planning using feedback control. Laser forming will not convert from research into industrial use until process control using feedback control has been fully developed. Paper A has introduced a framework for feedback control as the first step towards fully automatic process control. The working paper G, shows the next logical progression on that journey.

Furthermore, the new aspects found during the solution stage of this thesis can be considered:

Further investigation into the dynamic response Paper B presents several possibilities for future work, two of which are highlighted here due to their influence on the understanding of the laser forming process and how it is used.

Better measurements The results showed significant noise when examining the rate of change in the defined angles. By working to reduce the amount of noise in the equipment and the setup, these rates could be examined more closely. This could be used to examine the hypothesis presented in section 6.2, because it is interesting and research should be.

Effect of greatly increased scan velocity The paper found a systematic change in the deformation along the bend line due to the movement of the laser. It would be interesting if, by applying a much faster scan velocity and scanning back and forth, if this effect could be eliminated, to reduce or even remove this variation.

Laser formed properties The laser formed properties were discussed in subsection 2.6.1. The idea is to design the laser forming parameters to achieve specific thermal histories to promote or negate specific transformations during laser processing. This could open new opportunities for both research and industrial applications, which could lead to an increased interest in the process.

6.7 Outlook

To consider the outlook of the technology, it may be prudent to reconsider the original answers to the question of why laser forming has found limited use, given in subsection 1.1.2. To reiterate them here;

- It does not work
- No proper solution has been found yet

The generalized feedback control strategy presented in this thesis is a definite step in the direction of finding a proper solution. However, significantly more work is required before it can realize the potential described in the introduction, see chapter 1. There are still numerous problems within feedback control of laser forming that require substantial progress.

Laser forming may fit well into the new manufacturing paradigms such as Reconfigurable Manufacturing System (Bi et al., 2008), pop-up factories and industry 4.0 in general. However, the focus of these new paradigms is mainly on 3D printing. As a result, the effort required for laser forming to perform may not be a given.

As a consequence, developing laser forming requires a continuous and supported approach over multiple years rather than treating the process as a scientific curiosity for investigating the effect of various process parameters on the bending angle.

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Part IV

Papers

Paper A

Feedback Control of Laser Forming: A Recipe

Anders Noel Thomsen
Anders Faarbæk Mikkelstrup
Benny Endelt
Morten Kristiansen

The paper is under review

Paper B

Online measurement of the surface during laser forming

Anders Noel Thomsen
Morten Kristiansen
Ewa Kristiansen
Benny Endelt

The paper has been published in
The International Journal of Advanced Manufacturing Technology Vol. 107,
pp. 1569–1579, 2020.
DOI: https://doi.org/10.1007/s00170-020-04950-6

Paper C

Influence of cooling on edge effects in laser forming

Anders Noel Thomsen
Ewa Kristiansen
Morten Kristiansen
Benny Endelt

The paper has been published in the
Procedia CIRP Vol. 74, pp. 394–397, 2018.
DOI: https://doi.org/10.1016/j.procir.2018.08.155

Paper D

Investigation of the Profile of Laser Bends with Variable Scan Distance

Anders Noel Thomsen
Ewa Kristiansen
Morten Kristiansen
Benny Endelt

The paper has been published in the
Procedia Manufacturing Vol. 36, pp. 192–199, 2019.
DOI: https://doi.org/10.1016/j.promfg.2019.08.025

Part V

Additional papers

Paper E

A new method for calculating the error term used in 2D feedback control of laser forming

Anders Noel Thomsen
Benny Endelt
Morten Kristiansen

The paper has been published in the
Physcics Procedia Vol. 89, pp. 148–155, 2017.
DOI: https://doi.org/10.1016/j.phpro.2017.08.003

Paper F

Feedback control of laser forming using flattening simulations for error determination

Anders Noel Thomsen
Benny Endelt
Morten Kristiansen

The paper has been published in the
IOP Conf. Series: Materials Science and Engineering Vol. 651, 2019.
DOI: https://doi.org/10.1088/1757-899X/651/1/012093

Part VI

Working paper

Paper G

Discrete Constrained Non-Linear Multi-Variable Optimization of 2D Laser Forming Including Feedback Control

Anders Noel Thomsen

This is a very early working paper.
It only contains a theoretical description of the idea.

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