There is a strong industrial need for developing robust and flexible manufacturing methods for future light-weight design. In this study, focus has been on laser welding induced distortions for ultra-high strength steel (UHSS) where trials were performed on single hat and double hat beams simulating A-pillar and B-pillar structures. Furthermore, also laser welding induced porosity in cast magnesium alloy AM50 for interior parts were studied.

The results show that the total weld metal volume or the total energy input were good measures for predicting the distortions within one steel grade. For comparing different steel grades, the width of the hard zone should be used, corresponding to the martensitic area of the weld. Additionally, compared with continuous welds, stitching reduced the distortions.

For cast magnesium, two-pass (repeated parameters) welding with single-spot gave the lowest porosity of approximately 3%. However, two-pass welding is not considered production friendly. Twin-spot welding was done, where the first beam provided time for nucleation and some growth of pores while reheating by the second beam should provide time for pores to grow and escape. This gave a porosity of around 5%.

Independent on material, low energy input seems to generally minimize quality issues. Laser welding shows high potential regarding weld quality and other general aspects such as productivity in light-weight design for both high strength steel and cast magnesium.
Laser welding of ultra-high strength steel and a cast magnesium alloy for light-weight design

Karl Fahlström
Acknowledgements

The results within this work are a compilation of several projects and studies. The work within these studies has been financed by the member programme “Centre for Joining and Structures (CJS)” at Swerim as well as VINNOVA and participating companies of the project “LaserLight” and “CastMa”. The KK-foundation has been financing the research school of “SiCoMaP”.

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Karl Fahlström

Stockholm, 2019
Populärvetenskaplig Sammanfattning

**Nyckelord:** Lasersvetsning; höghållfasta stål; gjuten magnesium; kvalitetsproblem; lättviktskonstruktion; fordonsindustrin; distorsioner; porositet

För att kunna möta klimatmål med minskade utsläpp genom minskad bränsleförbrukning så måste dagens fordon bli lättare. Detta kan åstadkommas genom introduktion av nya material med ökad hållfasthet i förhållande till sin vikt. Flera material är lovande, däribland fiberförstärkta kompositer, aluminium, magnesium och höghållfasta stål liksom kombinationer av dessa.

För krockapplikationer är så kallat borstål det mest intressanta materialet. Borstål har hög hållfasthet och styvhet samt är både formbart och svetsbart. För interiöra komponenter så är pressgjutna magnesiumlegeringar av högt intresse på grund av hög hållfasthet i förhållande till sin vikt. Vid tillverkning av bilar så måste dessa material fogas både mot sig själv och mot andra material.

Traditionellt sett har motståndspunktsvetsning varit den mest använda metoden inom fordonsindustrin, men på senare tid har lasersvetsning blivit mer och mer populärt. Lasersvetsning ger fördelar så som hög produktivitet och ökad styvhet i förbanden.

För att kunna öka användandet av lättviktsmaterial och lasersvetsning inom fordonsindustrin så måste kvalitén hos svetsarna kunna säkerställas. I denna studie har tänkbara problem studerats som kan uppstå vid lasersvetsning av borstål samt gjuten magnesium.

Kvalitetsproblemen som studerats är geometriförändringar på komponenten samt porositet. Arbetet har inkluderat svetsförsök med olika uppställningar, samt analys av egenskaper och deformationer för att kartlägga och förstå inverkan av svetsningen.

Studien har resulterat i ökad kunskap om de vanligt förekommande kvalitetsproblemen. Även rekommendationer för hur dessa problem ska kunna undvikas har tagits fram.
Abstract

Title: Laser welding of ultra-high strength steel and a cast magnesium alloy for light-weight design

Keywords: Laser welding, ultra-high strength steel, cast magnesium alloy, light-weight design, automotive industry, distortion, porosity

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There is a strong industrial need for developing robust and flexible manufacturing methods for future light-weight design. Better performing, environmental friendly vehicles will gain competitive strength from using light-weight structures. In this study, focus has been on laser welding induced distortions for ultra-high strength steel (UHSS) where trials were performed on single hat and double hat beams simulating A-pillar and B-pillar structures. Furthermore, also laser welding induced porosity in cast magnesium alloy AM50 for interior parts were studied.

For UHSS, conventional laser welding was done in a fixture designed for research. For cast magnesium, single-spot and twin-spot welding were done. Measurements of final distortions and metallographic investigations have been performed.

The results show that the total weld metal volume or the total energy input were good measures for predicting the distortions within one steel grade. For comparing different steel grades, the width of the hard zone should be used. The relation between the width of the hard zone, corresponding to the martensitic area of the weld, and the distortions is almost linear. Additionally, compared with continuous welds, stitching reduced the distortions.

For cast magnesium, two-pass (repeated parameters) welding with single-spot gave the lowest porosity of approximately 3%. However, two-pass welding is not considered production friendly. Twin-spot welding was done, where the first beam provided time for nucleation and some growth of pores while reheating by the second beam should provide time for pores to grow and escape. This gave a porosity of around 5%.

Distortions and porosity are the main quality problems that occur while laser welding UHSS and cast magnesium, respectively. Low energy input seems to generally minimize quality issues. Laser welding shows high potential regarding weld quality and other general aspects such as productivity in light-weight design for both high strength steel and cast magnesium.
Appended Publications

**Paper A. Minimization of distortions during laser welding of ultra-high strength steel**

Published in “Journal of Laser Applications (JLA)” during 2015.

**Authors:** Karl Fahlström¹,², Oscar Andersson³,⁴, Urban Todal³, Arne Melander¹,⁴

The laser welding trials were done by me and Mr. Andersson with help from laser equipment operators at Volvo Cars. Evaluation and writing of the paper was done by me and Mr. Andersson. Mr. Andersson did the modelling and writing of the parts of the paper that considered modelling. I evaluated experiments and wrote the corresponding parts in the paper as well as the Introduction. The results were discussed between all authors.

**Paper B. Correlation between laser welding sequence and distortions for thin sheet structures**

Published in “Science and Technology of Welding and Joining” during 2016.

**Authors:** Karl Fahlström¹,², Oscar Andersson³,⁴, Arne Melander¹,⁴, Leif Karlsson² and Lars-Erik Svensson²

The laser welding trials were done by me and Mr. Andersson with help from laser equipment operators at Volvo Cars. Evaluation and writing of the paper was done by me. Discussing the results and editing of the text was done by me, Prof. Karlsson and Prof. Svensson.

**Paper C. Metallurgical effects and distortions in laser welding of thin sheet steels with variations in strength**

Published in “Science and Technology of Welding and Joining” during 2017.

**Authors:** Karl Fahlström¹,², Oscar Andersson³,⁴, Leif Karlsson² and Lars-Erik Svensson²

The laser welding trials were done by me and Mr. Andersson with help from laser equipment operators at Volvo Cars. Evaluation and writing of the paper was done by me. Discussing the results and editing of the text was done by me, Prof. Karlsson and Prof. Svensson.
Paper D. Effect of laser welding parameters on porosity of welds in cast magnesium alloy AM50

Published in “Modern approaches on Material Science (MAMS)” during 2019.

Authors: Karl Fahlström1,2, Jon Blackburn5, Leif Karlsson2 and Lars-Erik Svensson2

The laser welding trials were done by me with help from laser equipment operators at TWI Ltd. Planning of the trials were done by me and Dr. Blackburn. Evaluation and writing of the paper was done by me. Discussing the results was done by me, Prof. Karlsson and Prof. Svensson. Editing of the text was done by all authors.

Paper E. Low porosity in cast magnesium by advanced laser twin-spot welding

Published in “Material Sciences and Applications (MSA)” during 2019.

Authors: Karl Fahlström1,2, Jon Blackburn5, Leif Karlsson2 and Lars-Erik Svensson2

The laser welding trials were done by me with help from laser equipment operators at TWI Ltd. Planning of the trials were done by me and Dr. Blackburn. Evaluation and writing of the paper was done by me. Discussing the results were done by me, Prof. Karlsson and Prof. Svensson. Editing of the text was done by all authors.

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“Evaluation of laser weldability of 1800 and 1900 MPa boron steels”
Published in “Journal for Laser Applications (JLA)” during 2016.
Authors: Karl Fahlström¹,², Kjell-Arne Persson¹, Johnny K. Larsson³, Elisenda Vila Ferrer⁶

“Laser welding of 1900 MPa boron steel”
Published in “NOLAMP 14 – The 14th Nordic Laser Materials Processing Conference - Proceedings” during 2013.
Authors: Karl Fahlström¹,², Johnny K. Larsson³

”Distortion analysis in laser welding of ultra-high strength steel”
Published in the proceedings of “The sixth Swedish Production Symposium” during 2014
Authors: Karl Fahlström¹,², Oscar Andersson³,⁴, Urban Todal³, Arne Melander¹,⁴

“Experiments and efficient simulations of distortions of laser beam welded thin sheet closed beam steel structures”
Authors: Oscar Andersson³,⁴, Arne Melander¹,⁴, Karl Fahlström¹,²

“Verification and evaluation of simulation methods of laser beam welding of thin sheet steel structures”
Published in “Journal of Material Processing Technology” during 2017.
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List of abbreviations

AHSS = Advanced High Strength Steel
BIW = Body-in-White
CE = Carbon Equivalent (%)
CFRP = Carbon Fiber Reinforced Plastic
EDS = Energy Dispersive Spectrometry
HAZ = Heat Affected Zone
HPDC = High Pressure Die Casting
HSS = High Strength Steel
HV = Vickers Hardness
ISO = International Organisation for Standardisation
kJ = Kilo Joule
kW = Kilo Watt
Laser = Light Amplification by Stimulated Emission of Radiation
LBW = Laser Beam Welding
LOM = Light Optical Microscopy
MIG = Metal Inert Gas
MPa = Mega Pascal
RSW = Resistance Spot Welding
SEM = Scanning Electron Microscopy
TIG = Tungsten Inert Gas
UHSS = Ultra High Strength Steel
1 Introduction

Within the automotive industry, lighter weight of vehicles gives several performance benefits such as better handling and acceleration. However, the main driving force for reducing weight is to reduce energy consumption during use of the vehicle. In future vehicles, reduced energy consumption is a critical aspect since the environmental demands, in particular demands on reduced CO₂-emissions, become increasingly tougher [1-3].

A key enabler for reduced weight is material technology, introducing lightweight structures by using low density materials and materials with higher strength to weight ratio, i.e. specific strength. Several materials suitable for lightweight design are available today including innovative solutions with laminates of different materials or “hollow” sheet structures. Both the material itself and the use of the material are critical. An important research field within automotive industry is also how to combine different materials, i.e. mixed materials or multi materials. All of this can be considered as light-weight technology [2].

Laser beam welding has been in focus during the last two decades. Its potential for high volume production has the possibility to give a strong advantage compared to several other welding methods. However, it is important to have the process in full control since quality issues may occur.

This study will investigate laser welding of ultra-high strength steels and cast magnesium alloys. Both materials are considered solutions for future light-weight vehicles. However, high strength through ultra-high strength steel or low density through cast magnesium are two different ways to achieve light-weight and high strength to weight ratio.

Section “Background” will give information regarding ultra-high strength steel (UHSS), magnesium alloys, lasers, laser beam welding, as well as common quality issues that can occur in laser beam welding.

1.1 Scope

The work in this study is a response to a rather strong industrial need of developing robust and flexible manufacturing methods for future light-weight design. It is crucial to develop better performing, environmental friendly
vehicles by using light-weight structures. It is also of academic relevance to get a better understanding of laser welding of light-weight materials, such as ultra-high strength steels as well as cast magnesium alloys, and the quality problems occurring.

This work is on one hand considering ultra-high strength steel which is thought to be one of the most promising solutions today for crash performance applications. On the other hand, for interior parts, cast magnesium alloys are considered due to their excellent specific strength. These two materials are in focus throughout this study.

1.2 Research questions

Light-weight structures are of great importance for future vehicles. An increased understanding of how to design with and control the properties of new materials and promising joining processes is crucial. This study aims at contributing with further understanding in laser welding of ultra-high strength steels as well as cast magnesium alloys.

The overall objective is to find robust laser welding solutions that can be applied to production of future light-weight vehicles. This contains several topics and aspects. To be more specific about the present work, the general questions are:

- What quality problems occur while laser welding?
- Why do the quality problems occur?
- How can these quality problems be understood and avoided?

Two different applications of light-weight structures have been studied with specific research questions:

- How can distortions be minimized for ultra-high strength steel structures during laser welding?
- How can porosity in cast magnesium alloys be minimized during laser welding?

1.3 Limitations

When studying light-weight design for the automotive industry the possibilities are many. There are several strategies including design, choice of materials, joining methods etc. This study is narrowed down to laser welding of ultra-high strength steels and cast magnesium alloys. It would be possible to include many other materials as well, such as aluminium alloys or carbon fiber reinforced plastics, but that would compromise the depth of the study. Also other joining
methods could have been included, e.g. mechanical joining, adhesive bonding, or spot welding, but these are excluded with the same motivation.

Simulation and FEM-modelling has been used to further understand the quality problems occurring. The work discussed in the thesis is however delimited to the experimental work.
2 Background

2.1 Ultra-high strength steel

In today’s models of road vehicles, e.g. cars, buses and trucks, one can find high strength materials. A widely shared philosophy is to increase the use of high strength material within the structural components of the car to lower the weight and increase the performance. Common components such as front and rear bumper beams, door reinforcements, windscreen upright reinforcements, B-pillar reinforcements, floor and roof reinforcements, and roof and dash panel cross members are often produced from high strength materials [1-6]. To further reduce the weight of vehicles, both new materials as well as design improvements need to be applied [2, 3].

With high strength materials, maintained performance with thinner and lighter material is possible. Implementation of ultra-high strength steels incorporates several benefits. Main driving forces are weight reduction, crash performance improvement, high strength, cost reduction and sustainability [1-3]. High strength steels (HSS) are available in different grades. According to the X-brand (a cooperative definition of HSS used by Ford of Europe, Volvo Cars, Jaguar and Land Rover) steel material definition HSS are steels with a yield strength higher than 180 MPa [7]. The complete definition of different HSS can be seen in Table 1.

Table 1 – HSS definitions used by Ford of Europe, Volvo Cars, Jaguar and Land Rover.

<table>
<thead>
<tr>
<th>Steel class</th>
<th>Abbreviation</th>
<th>Min yield strength, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel/forming grades</td>
<td>MS</td>
<td>&lt; 180</td>
</tr>
<tr>
<td>High strength steel</td>
<td>HSS</td>
<td>= 180 &lt; 280</td>
</tr>
<tr>
<td>Very high strength steels</td>
<td>VHSS</td>
<td>= 280 &lt; 380</td>
</tr>
<tr>
<td>Extra high strength steels</td>
<td>EHSS</td>
<td>= 380 &lt; 800</td>
</tr>
<tr>
<td>Ultra-high strength steels</td>
<td>UHSS</td>
<td>=&gt; 800</td>
</tr>
</tbody>
</table>

A common steel to use within thin sheet automotive applications are dual phase steels (DP-steels). The microstructure of DP-steels consists of a mixture of
ferrite and martensite. The martensite is formed as islands within the soft ferritic matrix giving high tensile strength (depending on grade, typical tensile strength of 450-1000 MPa) as well as good elongation and formability [2, 3, 8]. This is considered as a standard steel within the car body, Body-in-White (BIW).

Another type of steel that is increasing in use within the automotive industry is boron steels, the most common grade being 22MnB5. Boron steels are fully martensitic with a typical tensile strength of 1500 MPa. Characteristic properties are high hardness and high tensile strength [1, 2, 9].

Press-hardening, or hot-stamping and die quenching, is a method to produce ultra-high strength components for the automotive industry. The use of this technique has rapidly increased in the last decade [2, 9], and a great advantage is the decrease of spring-back compared to cold forming techniques. Typical components produced by the press-hardening process are structural parts, e.g. A- and B-pillar reinforcements, floor sills, cant rails, side impact door beams and bumper beams.

To enable the boron-alloyed steel material to be formed and further on cooled down to a fully martensitic structure, the material first has to be heated up to its austenitisation temperature at around 880-950°C. To achieve a fully martensitic structure, the cooling rate must exceed 25-30°C/s [1, 2]. A schematic continuous cooling transformation diagram is illustrated in Figure 1. The small amount of boron (~0.002 wt.%) is used to facilitate the quenching process by delaying the nucleation of ferrite at the austenite grain boundaries. This will prolong the time until ferrite starts to form during quenching [10].
To avoid oxidation of the steel during heating and quenching, and to prevent corrosion, it is common to use coatings on the steel. A conventional coating consists of a combination of aluminum and silicon (AlSi). Other coating variants are different mixtures of Al, Mg and Zn. Within the automotive industry both uncoated 22MnB5 and AlSi-coated 22MnB5 are common [1, 11].

During the last years new upgraded versions of boron steel have been developed by several steel producers. ThyssenKrupp Steel Europe AG has developed the steel MBW 1900 which contains around 0.34-0.38 wt-% carbon which gives a tensile strength of $R_m = 1900$ MPa. The carbon equivalent (CE) is approximately 0.57 for MBW 1900 which is higher than for conventional boron steel (typically around 0.47) [12]. SSAB has released Docol 1800 Bor which also is a hardenable boron steel with a higher amount of carbon (0.27-0.33 wt-% instead of $\sim 0.23$ wt-%) than conventional boron steel. With a high cooling rate this gives a tensile strength of $R_m = 1845$ MPa after water quenching [8].

There is an almost linear relationship between the carbon content, hardness and tensile strength as illustrated in Figure 2 [13]. The higher hardness and tensile strength of these new grades gives further possibilities to produce light-weight components with thin sheet design compared to conventional boron steels [14].

Figure 1 – A schematic CCT-diagram (continuous cooling transformation). The martensite is formed through quenching of the steel [10].
2.2 Magnesium alloys

Similar to high strength steel and aluminium, magnesium alloys provide possibilities to reduce the weight of a structure due to the good strength-to-weight ratio. Cast magnesium alloys are found in many applications such as chain saw bodies, computer components, camera bodies, and certain portable tools and equipment. Furthermore, sand cast magnesium alloys are used extensively in aerospace components. However, the tensile strength of these alloys has a rather low range of 190-310 MPa, which limits suitable applications within the automotive industry to e.g. seat frames, steering wheels or structural dashboard cross beams [15-18].

Magnesium is the third most-commonly used structural metal, following steel and aluminum. The density is about one-fourth (1.74 g/m$^3$) of steel and two-thirds of aluminum. Magnesium is considered the lightest structural metal, and hence offers significant opportunities for automotive light-weight applications. As an example, magnesium castings are increasingly being used by major automotive companies including GM, Ford, Volkswagen and Toyota [19].

A common engineering magnesium alloy is the AM50 alloy (Mg + 4.4-5.5 wt% Al and 0.26-0.6 wt% Mn, according to ISO 16220(00)). The advantages of AM50 compared with most other magnesium alloys are its higher strength, higher hardness, high elongation and excellent castability, which makes it a good candidate for light-weight structures.
One way to utilize the properties of magnesium is to cast the alloy into complex shapes with high pressure die casting (HPDC) [20-23]. However, casting of large and complex details requires a huge effort and expensive and large machines [23]. An alternative is to cast less complicated parts and join them by welding, commonly by tungsten inert gas (TIG) or metal inert gas (MIG) welding [16].

There are several commercial magnesium alloys available for casting, some of them are; AM20, AM50, AM60, AZ81 and AZ91. The letters and numbers (according to ASTM) indicate the two main alloying elements e.g. the AZ91 alloy is a magnesium base alloy with around nine percent aluminium and one percent zinc or less [24]. The Aluminium-Manganese (AM) series of Magnesium alloys are increasing in popularity as they are more ductile in comparison to the Aluminium-Zinc alloys. The AM50 alloy has a ductility of 6-10 percent in comparison to AZ91 which has a ductility below two percent [25].

The alloy investigated in this study is the AM50 alloy. The microstructure of AM50 consists of mainly a matrix of $\alpha$-Mg dendrites with dissolved aluminium and a small fraction of divorced eutectic, consisting of $\alpha$-Mg and brittle $\beta$-Mg$_{17}$Al$_{12}$ particles. In addition, micro-porosity and segregated bands can be present [25-27]. In the HPDC process a small fraction of the melt can begin to solidify before being shot into the cast chamber. As the casting speed is high, the pre-solidified phase can become almost spherical due to the high shear force [28]. The melt solidifies dendritically, causing the remaining melt to be enriched in aluminium. As the eutectic reaction starts, the remaining melt solidifies as $\alpha$-Mg while the $\beta$-Mg$_{17}$Al$_{12}$ phase is precipitated at the grain boundaries [27]. There can also be a small number of Al-Mn particles present in the AM50 such as Al$_8$Mn$_5$ or Al$_4$Mn [26].

### 2.3 Laser welding

Laser welding is a common joining method within the automotive industry. The method is also used in several other industries such as aerospace, medical, component and construction industry. Traditionally resistance spot welding (RSW) has been the main method used within automotive production. To compete with RSW a new upcoming method has to challenge spot welding within the rather conservative industry regarding production speed, quality assurance, robustness, final properties and running and investment costs. Some of these properties are still of benefit for RSW, but laser welding has shown great potential when it comes to production speed, final properties, quality assurance and robustness [3]. To give a greater understanding regarding the potential benefits of the laser process, some background knowledge is given below.
2.3.1 Laser as a tool

Laser is an abbreviation of Light Amplification by Stimulated Emission of Radiation. Traditionally CO₂-lasers have been used, but today solid state lasers, such as disk, fiber or diode lasers, are more common within the automotive industry. These have several advantages such as high efficiency and compact design of equipment. Common solid state lasers for laser welding have a wavelength around 1 μm which enables flexible design of equipment where the laser beam is transported through a bendable fiber to the optics focusing the beam at the work piece surface. The optics can be designed in several ways resulting in different focal lengths, number of spots or beam profiles, used for different purposes.

2.3.2 Welding modes

When laser welding, the laser beam is aimed at the materials to be welded causing the materials to melt and fuse together. There are two common welding modes: conduction and keyhole welding of which the most common mode is keyhole welding (see Figure 3). In this case, the laser beam produces a thin but deep vapor cavity in the material, known as a keyhole. The keyhole is formed by vaporization of the metal. The keyhole remains stable as long as equilibrium exists between vapor pressure and forces due to molten material surrounding the keyhole. The size of the keyhole is approximately the same as the beam diameter, typically 0.6 mm [29].

![Figure 3 – Keyhole formed during laser welding [30]](image-url)
2.3.3 Welding optics

Laser welding optics can be designed in several ways. Often they are modularized which offers flexibility and makes it possible to change the system depending on what laser beam is desired. Basic components in a welding optics system for solid state lasers would be a collimator lens for aligning the beam and a focusing lens for focusing the beam onto the material to be welded. However, of course commercial systems are much more complex including several add-ons such as cover slides, temperature measurement, cameras etc. [31].

2.3.3.1 Twin-spot optics

Conventional laser welding is done by focusing the beam into one spot (hereafter single-spot) which heats the material. For different purposes such as change in weld pool dynamics, process stability or pre- or post-heating, one can use a beam splitter to create two welding spots (hereafter twin-spot) from one laser beam. This is done by either dividing the beam into two after collimating the beam, or by dividing the beam into two before collimating. The second option would require two optic systems for collimating and focusing, but will on the other hand give the degree of freedom to focus the beams separately which in some cases can be beneficial [31].

2.3.4 Process parameters

The most important process parameters in laser welding are covered in the following sections. Filler material will not be considered since that is seldom used in laser welding of boron steels or cast magnesium alloys.

2.3.4.1 Laser power

Conventional laser sources used for laser welding within the automotive industry have around 4-10 kW of power to use. The power is set to create enough penetration in the material. Too much power will cause excessive metal to melt and solidify at the root side of the weld, i.e. dropout welds. The parameter window for proper penetration is dependent on material, sheet thickness and welding speed. Since high welding speed is wanted, the highest power usually is set and then the welding speed is adapted to get a stable process giving the desired weld profile and penetration. In most cases the power is set close to the upper limit within the parameter window in order to allow for high welding speed but also some variations with maintained results [32].

Another aspect of welding power is the delivery mode; both a continuous laser power and pulsed laser power can be used. Pulsed power can be used when
energy input should be minimized. However continuous power is better from an efficiency perspective and also the most common delivery mode [32].

### 2.3.4.2 Welding speed

Welding speed (travel speed) is the speed at which the welding process travels. The welding speed [mm/s] together with laser power [kW] determines the heat input [kJ/mm] according to equation 1. Lack of penetration or dropout will occur if welding speed together with power are not optimized [29].

\[
\text{Heat input} (Q) = \frac{\text{Laser power} (P)}{\text{travel speed} (v)} \quad (1)
\]

With varying welding speed the weld pool shape and size changes. Lower speed increases the width of the weld pool and the risk of dropout increases. Higher welding speeds, on the other hand, increase the risk for the weld pool not to have enough time to redistribute and form a smooth joint. A high welding speed will in that case lead to undercut instead [32].

### 2.3.4.3 Focus positioning

The focal position relative to the sheet surface has effects on the local shape of the weld and penetration depth. Studies have shown that depending on beam diameter and focal length, the optimum focus position for maximum penetration is approximately 1 mm below the sheet surface for thin sheet applications. The reason is that the heat generation is optimized to form and maintain the keyhole inside the work piece [29, 33].

### 2.3.4.4 Process gases

Process gases are applied in or close to the molten material in order to change the atmosphere around the melt. In laser beam welding, process gases have three functions; shielding the weld pool, suppression of the plasma plume (ionized metal vapor originating from the keyhole [34]) and protection of the optics.

The shielding of the weld pool (from both sides of the work piece) may be necessary to prevent oxidation and contamination. Furthermore, at high welding power and low welding speeds plasma formation is higher, which will defocus the beam and reduce the heat absorbed by the weld. By using a gas jet the plasma can be removed from the critical zone and suppress the unbenefficial effects. Thirdly, weld spatter from the process may damage surrounding equipment, especially sensitive glass within the optics. A gas jet can direct the weld spatter in a certain direction and prevent such damages [32, 33, 35-37].
When selecting process gas several parameters must be considered. The most important are plasma suppression ability, density, ionization potential and cost. A common choice is helium, which is optimal in many aspects but may be expensive. Alternatives include argon (sometimes combined with small amounts of oxygen or carbon dioxide), nitrogen or pure carbon dioxide depending on application and weld property priority. However, within “non-corrosive” applications, the effect of gas shielding the weld pool is relatively small, and often thin sheet automotive applications are welded without shielding gas [32].

2.4 Quality issues in laser welding

During laser welding of common materials in light-weight design (aluminum, magnesium, HSS, etc.), different defects can form. For a specific component the defects will be considered as quality issues that need to be controlled depending on the level of occurrence. The aspects that need to be considered are strongly depending on material type, main alloying elements, surface condition etc. that are present. Despite this, there are some quality issues that are common in laser welding of most thin sheet materials. These issues are normally considered as critical for the construction and the lowest level of occurrence is wanted, independent of industry.

For thin sheet structures the most critical quality issues can be divided into four categories as illustrated in Figure 4.

Figure 4 – The four categories of most critical quality issues for thin sheet structures.
Below the common quality issues are described in more detail. As already mentioned, the issues are depending on several factors, and therefore only a generalization will be made to give further background knowledge of the phenomena occurring.

### 2.4.1 Imperfections

Imperfections can be disastrous for the joint properties. A small crack or cavity can be the initiation point for a complete failure of the weld in service. When laser welding, the most critical imperfections causing lowered strength are cracks and porosity/cavities.

#### 2.4.1.1 Porosity and cavities

Porosity can occur for different reasons. Usually pores are caused by instabilities within the keyhole or insufficient gas shielding. Porosity can also be enhanced by contamination or oxides that are vaporized creating gas bubbles that are trapped within the melt at solidification. Cavities can occur either by large pores merging or by growth from the interface between the sheets when welding surfaces with high amount of contamination/surface oxide [38].

Porosity in welded magnesium alloys has been the subject of a number of previous investigations [16, 39-44]. In these studies, a range of different factors have been found to cause pore formation, including: hydrogen/water, an unstable keyhole, pre-existing pores from the die-cast process, surface condition, gas entrapment, and alloying elements with a low vaporisation temperature. In studies by Zhao et al. [44] and Wahba et al. [40] porosity in laser welded AM60B (Mg-alloy with 5.5-6.5 wt.% Al and 0.24-0.6 wt.% Mn) was investigated. Pre-existing pores in the base metal coalesced and expanded in the weld metal during welding resulting in large pores. Harooni et al. [45] presented three solutions to avoid porosity; specifically, removing the oxide layer with a separate plasma arc before welding, use of dual laser beam welding or using a two-pass laser welding procedure. The best results were obtained using a two-pass welding, with a pre-heating configuration for the first laser pass.

The high pore content of die-castings is usually due to turbulent flow and rapid cooling experienced in the die-casting process. Hence, the weldability of magnesium die-castings greatly depends on the initial gas porosity in the base material [46].

Summarizing, porosity affects both static and fatigue strength of the welded structure and hence it is important to minimize porosity [16, 39].
2.4.1.2 Hot cracking

There are several types of hot cracks that could occur during thin sheet welding. Solidification cracking refers to the formation of shrinkage cracks during the solidification of weld metal. Furthermore, hot cracking can also refer to liquation cracking which occurs in the partially melted zone.

Solidification cracks can appear in several locations, and orientations, but most common for thin sheet structures are longitudinal centerline cracks. These occur at the intersection where the grains from opposite sides of the weld meet during solidification. Cracking occurs when the available supply of liquid weld metal is insufficient to fill the spaces between solidifying weld metal, which are opened by shrinkage strains [47]. Liquation cracking, on the other hand, does not necessarily occur in the center, but rather in the partially melted zone [48].

To prevent solidification cracking, three principal factors need to be controlled: weld metal composition, weld solidification pattern and strain on the solidifying weld metal.

Weld metal composition affects solidification cracking since the composition corresponds to a specific solidification temperature range. Since the composition varies (micro segregation) at different positions within the weld metal, also the solidification temperature varies. Several elements that increase the risk of solidification cracking have been identified such as sulphur and phosphorus. Generally, these are elements which form a second phase or impurities that get concentrated at the solidification front. The segregation will finally be seen in the center of the weld, which causes sensitivity to weld constraint [47].

In thin sheet applications the weld bead shape dictates the solidification pattern and is influenced largely by the welding parameters. Selection of appropriate welding parameters and fit-up give welds that solidify in an upward, rather than inward, direction, i.e. those that have a proper width and depth reduces the risk of solidification cracking. However, if the weld bead is too wide in thin sheet applications, solidification cracking may still occur. It is important to achieve good control over weld shape; a width-to-depth ratio of about 0.5 is usually best for resistance to solidification cracking [47].

Hot cracks have been reported to be one of the main welding defects for magnesium alloys [61]. An increase in number of alloying elements will generally increase the solidification temperature range. There are several parameters that affect hot cracking in magnesium alloys: the large temperature range, large solidification shrinkage, high coefficient of thermal expansion, and low melting
point intermetallic constituents. All of these make magnesium alloys susceptible to heat affected zone liquation cracking and solidification cracking in fusion zones [46].

### 2.4.1.3 Cold cracking

Ultra-high strength steels are quite highly alloyed with carbon to get the desired hardening of the steel after quenching. For conventional boron steel the level of carbon is around 0.24 wt.% (0.34-0.38 wt-% in MBW 1900 and 0.27-0.33 wt-% in Docol 1800 Bor). There are several formulas for calculating the carbon equivalent (CE). International institute of welding have presented a general CE formula according to the following equation (values in wt.%):

\[
CE = C + \frac{Mn}{6} + \frac{Cu+Ni}{15} + \frac{Cr+Mo+V}{5}
\]  
(2)

The CE is used for understanding how the alloying elements affect the hardness of the material. This is then directly related to the risk of hydrogen induced cold cracking. A higher value for the CE is related to an increased risk for cracking. As understood by the name, hydrogen induced cold cracking occurs at relatively low temperatures compared to hot cracking, usually below 200°C. The cracks can arise both directly after the welding, as well as several hours later. They can be found in the heat affected zone (HAZ) and in the weld metal and are promoted by high stresses, a high hardness and presence of hydrogen.

No literature has been found for welding induced cold cracking in magnesium alloys.

### 2.4.2 Local geometry

Several parameters are influencing the local geometry of the weld. The exterior of the weld can easily be evaluated. Undercut or sunk weld metal, depending on improper joint geometry or excess power, can be an issue. Although for thin sheet structures the laser welding process is usually quite stable if using a proper power. In this case, a small melt pool and rapid cooling is beneficial for reducing both undercut and sunk weld metal. Exterior geometry is often a larger problem for fatigue loaded structures (due to crack initiation points created by unbeneficial geometry or defects) of thicker sheets when a larger melt pool is used (e.g. MIG/MAG welding). For crash components within the automotive industry, high static strength and high energy absorption is dimensioning, and for interior parts only static strength.

An important quality issue that is harder to control is the cross-sectional shape of the weld. Strength of the weld is mainly controlled by the bonded area.
between the sheets, depending on joint type. In an overlap configuration the weld usually gets an hourglass shape resulting in a narrower bonding between the sheets than the weld width at the surface. To control the sheet interface weld width at the center, influencing parameters must be understood. In literature it has been reported that heat input and focal position are the main parameters influencing the sheet interface weld width [49].

### 2.4.3 Global geometry

Components that should be mounted to each other within e.g. an assembly line of course need to have the correct dimensions. When exposing material to heat the material expands and when lowering the temperature the material shrinks. If the heat isn’t applied homogeneously, expansion and shrinking occurs differently at different positions within the structure. The welding scenario including expansion and shrinkage of welds can result in built-in stresses, or a distorted geometry [50]. Some main welding induced distortions are visualized below in Figure 5.

![Figure 5](image.png)

Figure 5 – Schematic figure with three common welding induced distortions; transverse shrinkage, longitudinal shrinkage and angular distortion [51].

### 2.4.4 Strength reduction

During laser welding of HSS the rapid cooling rate in general creates a hard and brittle martensitic structure in the weld metal and parts of the HAZ where the temperature has reached the austenitisation temperature (where complete austenitisation takes place) [52].

In the HAZ closest to the weld metal, the temperature is high enough for complete transformation to austenite. The structure will be completely martensitic after cooling and no softening will take place. In the outmost parts of the HAZ the temperature never exceeds the temperature where transformation to austenite starts, but annealing can take place [52]. Parts of the HAZ in between these two areas are exposed to temperatures only slightly
above the starting temperature for austenite transformation but where transformation is not complete. In these parts, after cooling, some ferrite will remain together with carbides resulting in a zone with lower hardness [52].

Within RSW a too small area of soft material is thought to be the major contributing factor for the sensitivity to the undesired interfacial fracture of UHSS. For both RSW and laser welding the softer area in the HAZ is called the soft zone and has lower hardness and strength than the weld zone as well as the hard and brittle parts of the HAZ. The soft zone could be wanted, especially within RSW, to control the fracture propagation path [53].

Within cast magnesium, compared with the initial structure, the rapid cooling experienced during laser welding leads to very fine grain in the weld metal. For as-cast alloys, there is an increase in hardness of the weld metal (compared to base metal) but only a small change in hardness in the HAZ. Laser welding of die-cast AM60B alloy showed that the average hardness in the weld metal was approximately 63 HV as compared with a hardness of 53 HV in base material. In the fusion boundary region, however, a lower average hardness of approximately 47 HV was observed. As mentioned, the increase in hardness of the weld metal was probably due to its finer microstructure, but also a higher volume fraction of intermetallics such as Mg17Al12. Hardness in the weld metal was found to increase almost linearly with welding speed, because higher welding speeds lead to lower heat input which gives more rapid solidification resulting in a microstructure with fine grains [46].
3 Experimental

Experimental work has been done to study the different quality issues mentioned in section 2.4. Weldability, imperfections and geometry have been hot topics over the years and the methods for evaluation of these are many. The methods used within this work are described below.

3.1 Ultra-high strength steel

3.1.1 Material

In the present study steel of three different strength levels were welded. The mild steel Docol 200 (Rm=280 MPa) and the high strength steel Docol 800 DP (Rm=800 MPa, referred to as DP800) are uncoated cold formed steels, while MBW 1500+AS (Rm=1500 MPa) is a hot formed ultra-high strength steel with a 25 μm thick AlSi-coating. For composition of the steels, see Table 2.

The steels were cold (Docol 200 and DP800) or hot (MBW1500) formed into a U-beam-geometry and then welded to either a flat sheet, to generate one geometry, or to another U-beam, to generate a second geometry. The two geometries were chosen to generate two different distortion modes. One beam should give possibility to asymmetric deformation when joining a hat-profile with a flat sheet (hereafter named “single hat”), and the other symmetric deformation along the neutral plane of the geometry when joining two hat-profiles (hereafter named “double hat”). The two cases were chosen as simplified models to simulate A- and B-pillars, see Figure 6. The thickness of the materials was 1.0 mm with a beam length of 700 mm.

Table 2 – Chemical composition of steels (weight-%).

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>Nb</th>
<th>Ti</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Docol 200</td>
<td>0.037</td>
<td>0.067</td>
<td>0.300</td>
<td>0.008</td>
<td>0.012</td>
<td>0.044</td>
<td>0.013</td>
<td>0.03</td>
<td>-</td>
</tr>
<tr>
<td>DP800</td>
<td>0.110</td>
<td>0.190</td>
<td>1.580</td>
<td>0.012</td>
<td>0.003</td>
<td>0.044</td>
<td>0.020</td>
<td>0.019</td>
<td>-</td>
</tr>
<tr>
<td>MBW 1500</td>
<td>0.230</td>
<td>0.240</td>
<td>1.270</td>
<td>0.015</td>
<td>0.001</td>
<td>0.028</td>
<td>0.002</td>
<td>0.018</td>
<td>0.0023</td>
</tr>
</tbody>
</table>
3.1.2 Welding equipment

In this study, both laser welding and resistance spot welding was used. Laser welding was done with a Trumpf HL4006D Nd:YAG laser with a spot size of 0.6 mm focused perpendicular at the upper surface of the top sheet. Optics from Permanova were used with a collimator and focusing lens of both 200 mm. Compressed air with a lateral flow of 25 l/min was used as process gas.

For the resistance spot welded beam, an Aro welding gun and a Bosch 6000 PSI power source with 16/6 mm ISO B-caps were used. Two welding pulses applied from production parameters were used, see Table 3.

Table 3 Parameters used for resistance spot welding. The applied parameters are from production.

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Weld time</th>
<th>Force</th>
<th>Hold time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st pulse</td>
<td>5.0 kA</td>
<td>40 ms</td>
<td>3.4 kN</td>
<td>40 ms</td>
</tr>
<tr>
<td>2nd pulse</td>
<td>6.6 kA</td>
<td>270 ms</td>
<td>3.4 kN</td>
<td>160 ms</td>
</tr>
</tbody>
</table>

3.1.3 Welding sequence

The profiles were mounted in a pneumatically controlled fixture, shown in Figure 7. The fixture is designed for research, allowing precise control of
clamping forces and position. The clamping force was set individually for each clamp. In the fixture, the beam flange edges were resting on a wall, which hindered downward vertical displacement. Furthermore, five pneumatic clamps, 40 mm wide, were used on each flange to fix the profiles without gaps. The clamping range was 3 mm in from the flange edge. The welding was done at the center of the flange.

The pneumatic clamping pressure was fixed to 4 bars to ensure sufficient force holding the beams. If choosing a lower clamping force the beams would distort resulting in cutting effects from the laser beam.

Clamps R5 and L5 were released 180 s after welding was finished. After another 10 s the clamp pairs R4/L4-R2/L2 were released sequentially. Finally, R1 and L1 were released after 30 s. (see Table 4).

Table 4 – The welding and unclamping sequence used during distortion studies.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Time and details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding</td>
<td>Varies with welding speed</td>
</tr>
<tr>
<td>Cooling</td>
<td>180 sec</td>
</tr>
<tr>
<td>Unclamping R5</td>
<td>Pair R5 + L5</td>
</tr>
<tr>
<td>Unclamping R4</td>
<td>Pair R4 + L4 after 10 sec</td>
</tr>
<tr>
<td>Unclamping R3</td>
<td>Pair R3 + L3 after 10 sec</td>
</tr>
<tr>
<td>Unclamping R2</td>
<td>Pair R2 + L2 after 10 sec</td>
</tr>
<tr>
<td>Unclamping R1</td>
<td>Pair R1 + L1 after 30 sec</td>
</tr>
</tbody>
</table>

Figure 7 – Welding fixture with double hat profile and clamps (L1-L5 and R1-R5). (Figure from paper B, used with permission).

In the reference case (sequence A, Figure 8), the beams were welded in a U-shaped pattern (from R1 to R5 and then from L5 to L1), starting and finishing in the same end of the beam. The total laser weld length per flange was 690 mm.
leaving 5 mm at each end of the beam. To study the influence of energy input three welding speeds were used; 1.5 m/min, 3.5 m/min or 7.5 m/min all at a laser power of 4000 W. This resulted in energy inputs of 32 J/mm, 69 J/mm or 160 J/mm.

In addition to the reference case described as sequence A (Figure 8), different welding sequences were tested to study the influence on distortions. In total five welding sequences were tested whereas four were welded with laser and one with RSW (see sequence A-E in Figure 8). For sequences B and C, a welding speed of 3.5 m/min and a laser power of 4000 W was used, giving a energy input of 69 J/mm, was used.

Stitching (sequence D) was done with 8 stitch welds on each flange with a length of 46 mm each, starting and finishing at the same position as the continuous welds. The distance between the stitch welds were also 46 mm, and the welding speed 3.5 m/min giving a energy input of 69 J/mm.

Resistance spot welded beams were used as another reference. The spot welds were done with a center-to-center distance of 20 mm, starting with a spot weld in one corner moving onwards similar to sequence A, resulting in 35 spot welds on each flange. In this case the beam was only clamped by the welding gun, i.e. the electrode force. The spot welds were centered on the beam flanges.
3.1.4 Measurement of distortions

The beam geometry was measured after the welding sequence, cooling and unclamping. For single hat beams, the total height and width of the beam was measured at three different locations, at each end of the beam and in the middle. For double hat, transversal distortions were in focus (widening and narrowing of the beam width) and measured using a digital caliper at both ends (W\text{End} and W\text{Start}) and at the beam center (W\text{Middle}) comparing dimensions before welding and after unclamping after welding (Figure 9). Each welding case was repeated three times. The upper and lower sheet was measured separately and then the average widening and narrowing was calculated to avoid influences from possible misalignment.
The optical measurement system Move Inspect by Aicon 3D Systems was used for more advanced measurement of distortions. Move Inspect consists of three cameras placed at a distance of approximately 2 m from the beam. The system recognizes measurement points (small circular stickers, shown in Figure 10) placed on the beam, and records the position with x-, y-, and z- coordinates at 2 Hz. One great benefit of this method is that the recording can be done dynamically during the whole welding sequence, including cooling and unclamping. This will give an understanding of where and when the distortions occur during the sequence.

In total nine measurement points were placed on the beam. Five were evenly distributed on the top surface of the beam (at positions 70, 210, 350, 490 and 630 mm) and four on one of the sides of the upper beam (at positions 140, 280, 420 and 460 mm), see Figure 7.
3.1.5 Metallography and hardness

Cross-sections of the welds were prepared and studied by light optical microscopy (LOM) after polishing and etching with 2% Nital. Specimens for microstructural studies by scanning electron microscopy (SEM) were prepared by vibration polishing.

Three cross-sections (start, middle and end of the first flange of the beam) from each welding scenario were analyzed with the software Image J, an open source Java-based image processing software [54]. The width of the weld metal at the interface between the two sheets was measured. For the laser welds, the volume of the weld metal was estimated from the average area of the weld metal within the three cross-sections multiplied with the length of the welds. For RSW the
volume of weld metal within one spot weld was multiplied with the number of welds.

Hardness measurements (Vickers) were done with a load of 0.5 kg across the weld with a distance of 0.15 mm in the mid thickness of the upper and lower sheets.
3.2 Cast magnesium alloy

3.2.1 Material

In the present study 3 mm thick sheets of high pressure die cast magnesium alloy AM50 were welded. The sheets had the dimension 100 x 170 mm. The specification of AM50 according to ISO 16220(00) and the composition of the actual sheet used, measured with glow-discharge optical emission spectroscopy, are given in Table 5.

Table 5 Alloaying elements of AM50 magnesium alloy in wt-%. ISO 16220(00) specification and measured values are shown.

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Mn</th>
<th>Zn</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO 16220(00)</td>
<td>4.4-5.5</td>
<td>0.26-0.6</td>
<td>&lt;0.2</td>
<td>&lt;0.1</td>
<td>&lt;0.004</td>
<td>&lt;0.01</td>
<td>&lt;0.002</td>
</tr>
<tr>
<td>Measured</td>
<td>4.9</td>
<td>0.48</td>
<td>0.2</td>
<td>0.04</td>
<td>&lt;0.001</td>
<td>&lt;0.008</td>
<td>0.001</td>
</tr>
</tbody>
</table>

3.2.2 Welding

Bead-on-plate welds were produced with 100 mm length across the sheet. Argon gas with a purity >99.99% (gas type I1 according to ISO 14175:2008) was used as shielding gas both at the top side and at the root side, with a flow rate of 40 l/min and 5 l/min, respectively. On the top side a trailing gas shielding was used with a “panpipe” design to distribute the gas. The root gas was applied through a 10 mm gap in the fixture along the weld line (Figure 11).

Welding was done with an IPG 5 kW (with a 150 μm fiber, for twin-spot) or 10 kW (with a 200 μm fiber, for single-spot) fiber laser. The fiber laser was equipped with one (for single-spot and twin-spot with beam splitter) or two optics (for twin-spot with primary and secondary optics). The primary optics was aligned perpendicular to the sheet to be welded, while the secondary optics had a 12 degree angle (see Figure 11). Laser welding parameters and optics setup were varied to study their influence on porosity. When using two optics, both optics had identical lenses. The welding parameters varied were power, welding speed and focus position (see Table 6-Table 8).

Both single-spot and twin-spot optics were used with different focus and collimator lenses. Twin-spot welding was performed in two ways, either with a beam splitter in the primary optics resulting in two identical laser beams perpendicular to the surface, or by using two separate optics. In the case with two separate optics the primary optics is perpendicular to the sheet surface,
while the secondary is placed in front of the process, but at a small angle (12 degrees). The laser power is equally divided between the two optics.

Both optic solutions had the focus position placed on the surface of the material as the standard setup.

Figure 11  – Schematic image of the laser welding setup with single- (only primary) and twin-spot optics. The primary optics was aligned perpendicular to the sheet to be welded, while the secondary optics had a 12 degree angle. A trailing gas shielding was used on the top side with a “panpipe” design to distribute the gas. The root gas was applied through a 10 mm gap in the fixture along the weld line. (Figure from paper E, used with permission).

Surface conditions were also varied to study the influence on porosity formation. The surface condition was varied through different cleaning procedures, namely wire brushing (Br), acetone degreasing (A) and grit blasting (Bl).

In addition, single or two-pass welding was used (Table 6-Table 8). Full penetration welds were attained from both passes during two-pass welding, i.e. not a pre- or post-heating setup.
Table 6 – Parameters and optics setup for single-spot laser welds. Specimens W07 and W08 were welded with two passes. For W07, loose welding soot was removed with a soft brush between the passes.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Power [W]</th>
<th>Welding speed [m/min]</th>
<th>Focus pos. relative surface [mm]</th>
<th>Optics [type, focus/collimator]</th>
<th>Spot size [mm]</th>
<th>Distance between spots, cc [mm]</th>
<th>Cleaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>W01</td>
<td>2200</td>
<td>3</td>
<td>0</td>
<td>Single, 120/400</td>
<td>0.66</td>
<td>-</td>
<td>Br+A</td>
</tr>
<tr>
<td>W02</td>
<td>2200</td>
<td>3</td>
<td>+3</td>
<td>Single, 120/400</td>
<td>0.66</td>
<td>-</td>
<td>Br+A</td>
</tr>
<tr>
<td>W03</td>
<td>2200</td>
<td>3</td>
<td>-3</td>
<td>Single, 120/400</td>
<td>0.66</td>
<td>-</td>
<td>Br+A</td>
</tr>
<tr>
<td>W04</td>
<td>1100</td>
<td>1.5</td>
<td>0</td>
<td>Single, 120/400</td>
<td>0.66</td>
<td>-</td>
<td>Br+A</td>
</tr>
<tr>
<td>W05</td>
<td>1100</td>
<td>3</td>
<td>0</td>
<td>Single, 120/400</td>
<td>0.66</td>
<td>-</td>
<td>Br+A</td>
</tr>
<tr>
<td>W06</td>
<td>3400</td>
<td>3</td>
<td>0</td>
<td>Single, 120/400</td>
<td>0.66</td>
<td>-</td>
<td>Br+A</td>
</tr>
<tr>
<td>W07</td>
<td>2200</td>
<td>3</td>
<td>0</td>
<td>Single, two-pass, 120/400</td>
<td>0.66</td>
<td>-</td>
<td>Br+A (+brushing)</td>
</tr>
<tr>
<td>W08</td>
<td>2200</td>
<td>3</td>
<td>0</td>
<td>Single, two-pass, 120/400</td>
<td>0.66</td>
<td>-</td>
<td>Br+A</td>
</tr>
<tr>
<td>W09</td>
<td>2200</td>
<td>3</td>
<td>0</td>
<td>Single, 120/400</td>
<td>0.66</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>W10</td>
<td>2200</td>
<td>2</td>
<td>0</td>
<td>Single, 120/400</td>
<td>0.66</td>
<td>-</td>
<td>Br+A</td>
</tr>
<tr>
<td>W11</td>
<td>2200</td>
<td>4</td>
<td>0</td>
<td>Single, 120/400</td>
<td>0.66</td>
<td>-</td>
<td>Br+A</td>
</tr>
<tr>
<td>W12</td>
<td>2200</td>
<td>3</td>
<td>0</td>
<td>Single, 120/400</td>
<td>0.66</td>
<td>-</td>
<td>A</td>
</tr>
<tr>
<td>W13</td>
<td>2200</td>
<td>3</td>
<td>0</td>
<td>Single, 120/400</td>
<td>0.66</td>
<td>-</td>
<td>Bl+A</td>
</tr>
</tbody>
</table>

* Br=Wire brushing, A=Acetone, Bl=Grit blasting
### Table 7 – Parameters and optics setup for single-spot and twin-spot welding with beam splitter.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Power [W]</th>
<th>Welding speed [m/min]</th>
<th>Focus pos. relative surface [mm]</th>
<th>Optics [type, focus/collimator]</th>
<th>Spot size [mm]</th>
<th>Distance between spots, cc [mm]</th>
<th>Cleaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-spot and twin-spot with beam splitter</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>W16</td>
<td>1700</td>
<td>3</td>
<td>0</td>
<td>Single, 120/500</td>
<td>0.625</td>
<td>-</td>
<td>Br+A</td>
</tr>
<tr>
<td>W17</td>
<td>1700</td>
<td>2</td>
<td>0</td>
<td>Twin, beam split, 120/500</td>
<td>0.625</td>
<td>1</td>
<td>Br+A</td>
</tr>
<tr>
<td>W18</td>
<td>1100</td>
<td>3</td>
<td>0</td>
<td>Twin, beam split, 120/500</td>
<td>0.625</td>
<td>1</td>
<td>Br+A</td>
</tr>
<tr>
<td>W19</td>
<td>1700</td>
<td>3</td>
<td>0</td>
<td>Twin, beam split, 120/500</td>
<td>0.625</td>
<td>1</td>
<td>Br+A</td>
</tr>
<tr>
<td>W20</td>
<td>2300</td>
<td>3</td>
<td>0</td>
<td>Twin, beam split, 120/500</td>
<td>0.625</td>
<td>1</td>
<td>Br+A</td>
</tr>
<tr>
<td>W21</td>
<td>1700</td>
<td>4</td>
<td>0</td>
<td>Twin, beam split, 120/500</td>
<td>0.625</td>
<td>1</td>
<td>Br+A</td>
</tr>
<tr>
<td>W22</td>
<td>1700</td>
<td>3</td>
<td>0</td>
<td>Single, 120/160</td>
<td>0.2</td>
<td>-</td>
<td>Br+A</td>
</tr>
<tr>
<td>W23</td>
<td>1700</td>
<td>2</td>
<td>0</td>
<td>Twin, beam split, 120/160</td>
<td>0.2</td>
<td>0.32</td>
<td>Br+A</td>
</tr>
<tr>
<td>W24</td>
<td>1100</td>
<td>3</td>
<td>0</td>
<td>Twin, beam split, 120/160</td>
<td>0.2</td>
<td>0.32</td>
<td>Br+A</td>
</tr>
<tr>
<td>W25</td>
<td>1700</td>
<td>3</td>
<td>0</td>
<td>Twin, beam split, 120/160</td>
<td>0.2</td>
<td>0.32</td>
<td>Br+A</td>
</tr>
<tr>
<td>W26</td>
<td>2300</td>
<td>3</td>
<td>0</td>
<td>Twin, beam split, 120/160</td>
<td>0.2</td>
<td>0.32</td>
<td>Br+A</td>
</tr>
<tr>
<td>W27</td>
<td>1700</td>
<td>4</td>
<td>0</td>
<td>Twin, beam split, 120/160</td>
<td>0.2</td>
<td>0.32</td>
<td>Br+A</td>
</tr>
</tbody>
</table>

* Br=Wire brushing, A=Acetone, Bl=Grit blasting
### Table 8 – Parameters and optics setup for twin-spot welding with primary and secondary optics.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Power [W]</th>
<th>Welding speed [m/min]</th>
<th>Focus pos. relative surface [mm]</th>
<th>Optics [type, focus/collimator]</th>
<th>Spot size [mm]</th>
<th>Distance between spots, cc [mm]</th>
<th>Cleaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>W28</td>
<td>2000</td>
<td>2</td>
<td>0/0</td>
<td>Twin, Prim. and sec., 120/500</td>
<td>0.625</td>
<td>1</td>
<td>Br+A</td>
</tr>
<tr>
<td>W29</td>
<td>1700</td>
<td>2</td>
<td>0/0</td>
<td>Twin, Prim. and sec., 120/500</td>
<td>0.625</td>
<td>2.5</td>
<td>Br+A</td>
</tr>
<tr>
<td>W30</td>
<td>2000</td>
<td>2</td>
<td>0/0</td>
<td>Twin, Prim. and sec., 120/500</td>
<td>0.625</td>
<td>5</td>
<td>Br+A</td>
</tr>
<tr>
<td>W31</td>
<td>2000</td>
<td>3</td>
<td>0/0</td>
<td>Twin, Prim. and sec., 120/500</td>
<td>0.625</td>
<td>5</td>
<td>Br+A</td>
</tr>
<tr>
<td>W32</td>
<td>2000</td>
<td>2</td>
<td>0/+5</td>
<td>Twin, Prim. and sec., 120/500</td>
<td>0.625</td>
<td>1</td>
<td>Br+A</td>
</tr>
<tr>
<td>W33</td>
<td>2000</td>
<td>2</td>
<td>0/+20</td>
<td>Twin, Prim. and sec., 120/500</td>
<td>0.625</td>
<td>1</td>
<td>Br+A</td>
</tr>
<tr>
<td>W34</td>
<td>2000</td>
<td>2</td>
<td>0/-5</td>
<td>Twin, Prim. and sec., 120/500</td>
<td>0.625</td>
<td>1</td>
<td>Br+A</td>
</tr>
<tr>
<td>W35</td>
<td>2000</td>
<td>3</td>
<td>0/+20</td>
<td>Twin, Prim. and sec., 120/500</td>
<td>0.625</td>
<td>1</td>
<td>Br+A</td>
</tr>
<tr>
<td>W36</td>
<td>2000</td>
<td>2</td>
<td>+10/0</td>
<td>Twin, Prim. and sec., 120/500</td>
<td>0.625</td>
<td>1</td>
<td>Br+A</td>
</tr>
<tr>
<td>W37</td>
<td>2000</td>
<td>3</td>
<td>+10/0</td>
<td>Twin, Prim. and sec., 120/500</td>
<td>0.625</td>
<td>1</td>
<td>Br+A</td>
</tr>
</tbody>
</table>

* Br=Wire brushing, A=Acetone, Bl=Grit blasting

#### 3.2.3 Metallography

Metallographic cross-sections, both transverse and longitudinal to the welding direction were prepared to study the resulting microstructure and porosity of the welds. The longitudinal sections were cut from the center of the weld with a length of 20 mm. All sections were ground with 4000 grit paper, and polished with either a 6 or 1 μm diamond suspension slurry for the LOM (Light Optical Microscopy) evaluation and the SEM (Scanning Electron Microscopy) evaluation, respectively. No etching was used.
When performing LOM, an external ring shaped light source (directed from the sides onto the sample) was used to provide additional illumination and increase visibility of the pores. This yielded a high contrast image suitable for image analysis using ‘Image J’. A JEOL JSM-7001F field emission SEM equipped with a back-scatter detector and an Oxford Instruments EDS (Energy Dispersive Spectrometry) detector was used for microstructure studies and phase analysis.
4 Results

The objective of this work was to examine laser welding of candidate materials for use in future light-weight vehicles. Therefore, in this case, ultra-high strength steels and cast magnesium alloys have been evaluated. Structures and sheet material simulating components for light-weight vehicles have been welded considering both weld quality and structural geometry. Several quality issues have been identified and controlled.

In the following section results from the welding trials are presented. The section includes the main results from the appended papers. More details can be found in each paper.

4.1 Ultra-high strength steel

In this section results from the papers focusing on distortions in laser welding of ultra-high strength steel are included: Paper A - “Minimization of distortions during laser welding of ultra-high strength steel”, Paper B - “Correlation between laser welding sequence and distortions for thin sheet structures” and Paper C - “Metallurgical effects and distortions in laser welding of thin sheet steels with variations in strength”.

4.1.1 Microstructure

The microstructures of the base materials are shown in Figure 12. Docol 200 had a ferritic microstructure, DP800 a ferritic-martensitic microstructure and MBW1500 a martensitic microstructure.
Figure 12 – Microstructures in the base material of Docol 200 (A), DP800 (B) and MBW1500 (C). Images were taken with a backscattered detector in SEM. For Docol 200 a ferritic microstructure can be seen, for DP800 a ferritic-martensitic microstructure and for MBW1500 a martensitic microstructure. (Figure from paper C, used with permission).

Weld metal and heat affected zone in the higher tensile strength steels were mainly martensitic and decreased energy input resulted in more martensite. For energy inputs of 32 or 69 J/mm the microstructure for the weld metal in Docol 200 was interpreted as consisting of martensite with some bainite. However, for 160 J/mm the weld microstructure appeared to be bainitic.

4.1.2 Hardness

Hardness curves for the three material grades welded with 69 J/mm can be seen in Figure 13. For all energy inputs in MBW1500, soft areas occurred in the heat affected zone, with a hardness reduction from approximately 500 HV to 300 HV. For all energy inputs in Docol 200 and DP800, the hardness increased in the weld metal and near weld HAZ compared with the base material. For Docol 200 the hardness increased from the range of 101-112 HV to 188-281 HV and for DP800 from 267-276 HV to 418-425 HV depending on energy input. For Docol 200 the average width (in the upper and lower sheet) of the hard zone was measured to 1.5, 2.2 and 3.1 mm with increasing energy input. DP800 had wider hard zones compared with Docol 200: 1.9, 2.4 and 3.3 mm with
increasing energy input. The widest hard zones were found in MBW1500: 2.0, 2.5 and 3.9 mm with increasing energy input.

Figure 13 – Hardness curves at mid thickness of the upper sheet for an energy input of 69 J/mm. MBW1500 gives a hardness of 500 HV in the weld metal similar to the martensitic base material. Docol 200 and DP800 show an increase in hardness in the weld metal compared with the base material. Location of fusion lines are marked with vertical dotted lines. (Figure from paper C, used with permission).

For Docol 200 the weld metal hardness decreased with increasing energy inputs (Figure 14) from 281 HV for 32 J/mm, to 247 HV at 69 J/mm and 188 HV at 160 J/mm.

Figure 14 – Hardness curves at mid thickness of the upper sheet for different energy inputs for Docol 200. The hardness in the weld metal decreased from 280 HV at the lowest energy input to 180 HV at the highest. Fusion lines are marked with vertical dotted lines. (Figure from paper C, used with permission).

Hardness results are summarized in Table 9. The values are averages of three measurements and the scatter is within the range of ±10 HV0.5 for all measuring points. As can be seen, hardness in the base material and the soft zones were constant for each material independent of energy input, but the hardness of the hard zone varied for Docol 200.
Table 9 – Hardness for base material, hard zone and soft zone for the three steel grades and energy inputs.

<table>
<thead>
<tr>
<th>Steel and energy input</th>
<th>Base material [HV0.5]</th>
<th>Hard zone [HV0.5]</th>
<th>Soft zone [HV0.5]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Docol 200</td>
<td>32 J/mm</td>
<td>101</td>
<td>145</td>
</tr>
<tr>
<td></td>
<td>69 J/mm</td>
<td>108</td>
<td>144</td>
</tr>
<tr>
<td></td>
<td>160 J/mm</td>
<td>112</td>
<td>132</td>
</tr>
<tr>
<td>DP800</td>
<td>32 J/mm</td>
<td>267</td>
<td>249</td>
</tr>
<tr>
<td></td>
<td>69 J/mm</td>
<td>268</td>
<td>242</td>
</tr>
<tr>
<td></td>
<td>160 J/mm</td>
<td>276</td>
<td>229</td>
</tr>
<tr>
<td>MBW1500</td>
<td>32 J/mm</td>
<td>502</td>
<td>303</td>
</tr>
<tr>
<td></td>
<td>69 J/mm</td>
<td>493</td>
<td>304</td>
</tr>
<tr>
<td></td>
<td>160 J/mm</td>
<td>498</td>
<td>293</td>
</tr>
</tbody>
</table>

4.1.3 Cross-sectional weld geometry

The difference in cross-sectional weld geometry for the three different welding speeds in MBW1500 for sequence A is shown in Figure 15. A cross-section of a resistance spot weld is also shown. The width of this weld is much larger than the laser welds, so the magnification here is just half compared to the micrographs of the laser welds.

Figure 15 – Cross sections of MBW1500 showing the cross-sectional geometries of continuous welds (A1-A3) and RSW (E). Three different welding speeds were used, 1.5 m/min (A1), 3.5 m/min (A2) and 7.5 m/min (A3). (Figure from paper B, used with permission).
The heat affected zone as well as the width of the weld in the interface between the sheets in the macro cross-section differ between the grades, even when the same energy input was used (Figure 16). The white bands seen in Figure 16 correlate with the soft zone measured in hardness testing.

In Docol 200 and DP800 the lowest energy input (32 J/mm) resulted in only partial penetration. The MBW1500 at 160 J/mm weld suffered from sunken weld metal.

![Figure 16](image)

Figure 16 – Light optical micrographs showing cross-sections of laser welds. The yellow contour shows the weld metal boundary. Red lines show measurements of width of the weld metal. In Docol 200 and DP800 the lowest energy input (32 J/mm) resulted in partial penetration. The MBW1500 at 160 J/mm weld suffered from sunken weld metal. (Figure from paper C, used with permission).

The width of the weld was fairly constant at 0.8 – 1.1 mm, measured at the center of the welds. The only deviation here is for Docol 200, welded at 160 J/mm, where a fairly broad weld was found. Increasing energy input resulted in increasing weld metal volume for each steel grade, while it was difficult to see any trends when comparing the different steels for the same energy input.

### 4.1.4 Distortion sequence

Distortions during the complete sequence including welding, cooling and unclamping was recorded with optical measurements. The total welding time
varied between the beams since different welding speeds were used. Optical measurements recorded distortions in all measurement points during welding, although after welding the distortions almost completely withdrew due to the strong clamping. During cooling, very low distortions were recorded compared to during welding. When the unclamping began, distortions increased stepwise, resulting in the final distorted geometry. A schematic figure of the full sequence is illustrated in Figure 17.

![Schematic figure of the distortions (deformation) occurring during welding, cooling and unclamping. The different curves represent different measurement points. (Figure from paper A, used with permission).](image)

**4.1.5 Geometry changes due to distortions**

In general, two different characteristic distortion modes occurred for the two geometries welded, see Figure 18. The single hat beam suffered from transverse shrinkage of the gap between the “legs” of the profile. This resulted in a small height change at the ends of the beam. The reason for the height change is that the heat from the process increased along the flange. Something that also was noted was an occasionally low weld quality between the clamps. In these areas the profile has risen from the flat sheet giving a gap resulting in cutting with the laser process.

The double hat beam suffered from larger distortions than the single hat beam. This is due to that the flat sheet in the single hat geometry hindered transverse distortion. For double hat, the geometrical change was in the transverse direction with an hourglass looking shape. Due to the geometrical symmetry of
the beam before welding the distortion did not result in a longitudinal bending mode as for single hat but instead expansion of the cross-section width. The flat sheet in single hat gave a lower bending stiffness around the y-axis (transverse) compared to the double hat geometry.

Figure 18 – Schematic figure of the distortions (deformation) occurring after the complete welding sequence. Dominant geometrical distortions for single hat (upper) and double hat (lower). Black line represents original geometry and red dotted line represents dominant geometry change. (Figure from paper A, used with permission).

The final state of the distortion was measured with a digital caliper. The results can be seen in Figure 19. For the single hat beam the distortions were small, with a maximum value of around 1.0 mm. For the double hat beam the distortions were much larger, with a maximum around 9.3 mm. For the double hat beam it was clear that a higher energy input resulted in a larger distortion.
Measurements of final distortions with the optical measurement technique were carried out for double hat beams. In Figure 20, graphs with distortions in y-direction (width) as well as z-direction (height) can be seen. The maximum remaining distortions are approximately 2.0 mm for vertical deformation (z) and 3.5 mm for transverse deformation (y). Note that the last clamping pair (R1+L1) was still mounted during recording of these values.
In conclusion, for the single hat geometry the distortions are generally smaller compared to the double hat geometry. In addition, the results show that welding speed significantly affects the magnitudes of distortions in the double hat geometry.

### 4.1.6 Influence of welding procedure

As seen in Table 10 a higher welding speed and hence a lower energy input resulted in a smaller distortion, both as a widening at the two ends of the beam, but also as a narrowing in the middle. Scatter was small with a variation between the repetitions within each sequence of less than 0.5 mm.

**Table 10** – Distortions in MBW1500. Widening at the ends and narrowing at the center of the beam after welding presented as the change in width. Welding sequence A shows that an increased energy input gives a larger distortion. There is no clear difference between welding sequences A, B and C for the same welding speed. Stitching and RSW gave the lowest distortion.
Table 10 shows that stitch welding gave a lower distortion than the continuous laser welds. The distortion was close to half compared to the continuous weld A2 (3.5 m/min).

Comparing welding sequence A2 (3.5 m/min), with sequences B (In to out) and C (Out to in), there was no significant difference between the maximum widening at the two ends for the different welding directions. A small difference can be seen comparing the narrowing in the middle of the beam, where sequence A2 (3.5 m/min) gave a somewhat larger (~0.5 mm) distortion.

For the complete beam 70 resistance spot welds were done, corresponding to 35 on each flange. As can be seen from Table 10, the widening of the beams was lower than for the continuous laser welded beams but the narrowing in the

<table>
<thead>
<tr>
<th>Welding sequence</th>
<th>Heat input [J/mm]</th>
<th>Distortions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>W_{Start} [mm]</td>
</tr>
<tr>
<td>A1 - 1.5 m/min</td>
<td>160</td>
<td>9.2</td>
</tr>
<tr>
<td>A1 - 1.5 m/min</td>
<td>160</td>
<td>9.3</td>
</tr>
<tr>
<td>A1 - 1.5 m/min</td>
<td>160</td>
<td>9.2</td>
</tr>
<tr>
<td>A2 - 3.5 m/min</td>
<td>69</td>
<td>5.6</td>
</tr>
<tr>
<td>A2 - 3.5 m/min</td>
<td>69</td>
<td>6.0</td>
</tr>
<tr>
<td>A2 - 3.5 m/min</td>
<td>69</td>
<td>6.0</td>
</tr>
<tr>
<td>A3 - 7.5 m/min</td>
<td>32</td>
<td>4.8</td>
</tr>
<tr>
<td>A3 - 7.5 m/min</td>
<td>32</td>
<td>4.5</td>
</tr>
<tr>
<td>A3 - 7.5 m/min</td>
<td>32</td>
<td>4.2</td>
</tr>
<tr>
<td>B - In to out</td>
<td>69</td>
<td>6.0</td>
</tr>
<tr>
<td>B - In to out</td>
<td>69</td>
<td>5.9</td>
</tr>
<tr>
<td>B - In to out</td>
<td>69</td>
<td>6.0</td>
</tr>
<tr>
<td>C - Out to in</td>
<td>69</td>
<td>6.4</td>
</tr>
<tr>
<td>C - Out to in</td>
<td>69</td>
<td>5.9</td>
</tr>
<tr>
<td>C - Out to in</td>
<td>69</td>
<td>6.3</td>
</tr>
<tr>
<td>D – Stitch</td>
<td>69</td>
<td>3.7</td>
</tr>
<tr>
<td>D – Stitch</td>
<td>69</td>
<td>3.8</td>
</tr>
<tr>
<td>D – Stitch</td>
<td>69</td>
<td>3.6</td>
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<tr>
<td>E – RSW</td>
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<td>2.8</td>
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<td>E – RSW</td>
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<td>3.0</td>
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<tr>
<td>E – RSW</td>
<td>-</td>
<td>2.79</td>
</tr>
</tbody>
</table>
middle was similar to that of weld sequence A3 (7.5 m/min). The widening at the ends for RSW was similar to stitching but the narrowing in the middle was much larger for RSW.

4.1.7 Influence of steel grade

The measured distortion, weld width, width of hard zone and weld metal volume for each steel grade are summarized in Table 11. As previously seen for the double hat geometry, welding induced distortion, independent of steel grade, resulted in an hour glass shape of the profiles with the main distortion being a symmetrical increase of the width at both ends. In this case, only transverse distortion (widening) at the ends of the beam (average value of the two ends) has been chosen as critical value for the distortion. This was motivated by that the largest distortion occurs at the ends of the beam, and hence the distortion at the middle of the beam can be neglected.

When studying different steel grades, sequence A was used with varying energy input. A higher energy input resulted in a larger distortion and the distortion was larger for higher steel strengths. The only deviation here was at 69 J/mm, where Docol 200 had a transverse distortion of 4.3 mm, while DP800 had a somewhat smaller distortion of 3.9 mm.

Table 11 - The distortion, weld width, width of hard zone, weld metal volume and total energy input measured for the three material grades and different energy inputs.

<table>
<thead>
<tr>
<th>Steel and energy input</th>
<th>Energy input per flange [kJ]</th>
<th>Transverse distortion [mm]</th>
<th>Weld width [mm]</th>
<th>Width of hard zone [mm]</th>
<th>Weld metal volume [mm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Docol 200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32 J/mm</td>
<td>22</td>
<td>1.6±0.3</td>
<td>0.8±0.1</td>
<td>1.5±0.1</td>
<td>860±70</td>
</tr>
<tr>
<td>69 J/mm</td>
<td>47</td>
<td>4.3±0.4</td>
<td>1.1±0.1</td>
<td>2.2±0.3</td>
<td>1850±110</td>
</tr>
<tr>
<td>160 J/mm</td>
<td>110</td>
<td>4.9±0.2</td>
<td>2.1±0.2</td>
<td>3.1±0.2</td>
<td>2970±190</td>
</tr>
<tr>
<td>DP800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32 J/mm</td>
<td>22</td>
<td>2.8±0.8</td>
<td>0.9±0.1</td>
<td>1.9±0.2</td>
<td>1450±90</td>
</tr>
<tr>
<td>69 J/mm</td>
<td>47</td>
<td>3.9±0.5</td>
<td>0.9±0.2</td>
<td>2.4±0.3</td>
<td>1590±100</td>
</tr>
<tr>
<td>160 J/mm</td>
<td>110</td>
<td>6.0±0.4</td>
<td>1.1±01</td>
<td>3.3±0.3</td>
<td>2190±130</td>
</tr>
<tr>
<td>MBW1500</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>32 J/mm</td>
<td>22</td>
<td>4.3±0.5</td>
<td>0.9±0.1</td>
<td>2.0±0.2</td>
<td>1320±60</td>
</tr>
<tr>
<td>69 J/mm</td>
<td>47</td>
<td>5.8±0.4</td>
<td>0.7±0.1</td>
<td>2.5±0.3</td>
<td>1460±110</td>
</tr>
<tr>
<td>160 J/mm</td>
<td>110</td>
<td>9.2±0.1</td>
<td>1.1±0.1</td>
<td>3.9±0.3</td>
<td>2370±210</td>
</tr>
</tbody>
</table>
4.2 Cast magnesium alloy

In this section, results from the papers focusing on porosity in laser welding of the cast magnesium alloy AM50 are summarized: Paper D - “Effect of laser welding parameters on porosity of welds in cast magnesium alloy AM50” and Paper E - “Low porosity in cast magnesium by advanced laser twin-spot welding”.

4.2.1 Microstructure

EDS analysis showed that the matrix of the as-received AM50 sheet material contained a Mg-Al phase (corresponding to \(\beta\)-Mg\(_7\)Al\(_{12}\) according to literature [55]), particles of Al-Mn (typically Al\(_8\)Mn\(_5\) [55]) and Mg-Al oxides (Figure 21). Also, occasional cavities were found in the base material. These are most likely shrinkage pores from the high pressure die-casting process.

Secondary phases (white areas) were found to be evenly distributed and smaller in size in the fusion zone. Larger spherical pores occurred with varying sizes (Figure 21).

![Figure 21](image)

Figure 21 – Cross section images of AM50 weld obtained using the back scattered detector in SEM showing (a) base material and (b) fusion zone. White areas are Mg-Al and Al-Mn phases. Black areas are shrinkage pores from die-casting (1), Mg-Al oxides (2) or pores from welding (3). (Figure from paper D, used with permission).
4.2.2 Porosity occurrence

The porosity analysis was performed using images of cross-sections taken transverse to the welding direction. Longitudinal section images (Figure 22) were also analyzed to verify that the transverse cross-sectional images were representative of the full length of the weld.

![Figure 22 – LOM micrograph of a longitudinal section of W01. (Figure from paper D, used with permission).](image)

Table 12 details the number of pores, including the percentage of the fusion zone cross-sectional area covered by pores (hereafter ‘area fraction of pores’). The porosity counts in the transverse cross-sections show a good correlation with the porosity counts in the longitudinal cross-sections, suggesting that cross-sectional porosity is representative and can be used for evaluation.

Table 12 – Transverse and longitudinal cross-section porosity content, including number of pores in the section as well as area fraction.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Number of pores in the transverse cross-section</th>
<th>Area fraction of pores in the fusion zone, transverse cross-section (%)</th>
<th>Number of pores in the longitudinal cross-section</th>
<th>Area fraction of pores in the fusion zone, longitudinal cross-section (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W01</td>
<td>1013</td>
<td>8.7</td>
<td>2440</td>
<td>10.6</td>
</tr>
<tr>
<td>W02</td>
<td>408</td>
<td>14.7</td>
<td>1811</td>
<td>12.3</td>
</tr>
<tr>
<td>W04</td>
<td>151</td>
<td>9.3</td>
<td>2055</td>
<td>10.6</td>
</tr>
<tr>
<td>W07</td>
<td>152</td>
<td>2.9</td>
<td>1251</td>
<td>4.3</td>
</tr>
<tr>
<td>W12</td>
<td>394</td>
<td>5.4</td>
<td>1842</td>
<td>6.4</td>
</tr>
</tbody>
</table>

The size distribution (Figure 23) of pores was analysed for samples welded at three different welding speeds (keeping all other parameters constant); 2 m/min (W10), 3 m/min (W01) and 4 m/min (W11). Most pores had a radius in the range 10-40 μm, independent of welding speed. However, for the lowest
welding speed (2 m/min) some pores exceeded 100 μm in radius. Smaller pores than 10 μm could have been present, but weren’t detectable with the software Image J.

Figure 23 – Size distribution of pores for three welding speeds: 2 m/min (W10) 3 m/min (W01) and 4 m/min (W11). Most pores were in the size of 10-40 μm. Welding speed 2 m/min had some large pores with a radius >100 μm. (Figure from paper D, used with permission).

### 4.2.3 Effect of welding procedure on porosity

#### 4.2.3.1 Surface condition

Several different surface cleaning procedures were evaluated, including grit blasting and cleaning with acetone (W13), cleaning with acetone (W12), no cleaning (W09) and brushing and cleaning with acetone (W01). The area fraction of pores for grit blasted (W13) and brushed samples (W01) was ~8-10% (Figure 24), compared with 5-7% for samples either degreased with acetone or subjected to no cleaning (W12 and W09); suggesting that cleaning without a mechanically abrading process was most favourable. The number of pores per mm² was 78 for grit blasting (W13) compared with 58 for cleaning with acetone (W12), 85 for no cleaning (W09) and 147 for brushing and subsequent cleaning with acetone (W01).
4.2.3.2 Power
The laser power was varied in three steps, 1100 W (W05), 2200 W (W01) and 3400 W (W06), while keeping other parameters constant. Both the fusion zone area and the area fraction of pores were nearly doubled when increasing the power from 1100 to 3400 W (Figure 25). The number of pores per mm² was 99 for a power of 1100 W (W05), compared with 147 for a power of 2200 W (W01) and 100 for a power of 3400 W (W06). No clear correlation between the number of pores and the laser power can be seen.

4.2.3.3 Welding speed
Three different welding speeds were evaluated; 2 m/min (W10), 3 m/min (W01) and 4 m/min (W11) keeping all other parameters constant. The area fraction of pores was reduced significantly as the welding speed increased (Figure 26). The number of pores per mm² was 71 for a welding speed of 2 m/min (W10), compared with 147 for a welding speed of 3 m/min (W01) and 47 for a welding speed of 4 m/min (W11). No clear correlation between the number of pores and welding speed can be seen.
4.2.3.4 Focus position

The focus position of the laser beam was varied in three steps; 3 mm (-3) below the top surface of the work piece (W03), on the top surface of the work piece (0) (W01), and 3 mm (+3) above the top surface of the work piece (W02). The lowest area fraction of pores was achieved with a focus position on the top surface of the work piece material (0). The amount of porosity did not change significantly when moving the focus position into the work piece (i.e. -3), although, positioning the focus above the surface (i.e. +3) almost doubled the percentage of pores. The number of pores per mm² was 80 for -3 mm (W03), compared with 147 for 0 mm (W01), and 58 for +3 mm (W02).

4.2.3.5 Single- and two-pass welding

Single-pass welding with two welding parameter combinations of nominally identical energy input (J/mm) was evaluated. Welds were produced with a welding speed of 3 m/min and a laser power of 2200 W (W01), and also with a welding speed of 1.5 m/min but with a laser power of 1100 W (W04). Both single-pass welds were brushed and acetone degreased prior to welding. Two-pass welding was performed with two repetitions of the W01 parameters, with two different interpass cleaning procedures evaluated - brushing (W07) and no cleaning (W08). Both two-pass welds were brushed and acetone degreased prior to welding.

Both single-pass welded samples had an area fraction of pores of approximately ~8-10%, whilst for the two-pass welds it was 2-4%, independent of the interpass cleaning procedure (Figure 27). The number of pores per mm² was 147 for a single-pass weld made with a welding speed of 3 m/min and a laser power of 2200 W (W01) compared with 28 pores per mm² for a welding speed of 1.5 m/min and a laser power of 1100 W (W04). These numbers suggest that the lower welding speed and lower power for W04 results in fewer but larger pores compared to W01. For the two-pass welding process, 26 pores per mm² were found when a brushing interpass cleaning procedure was used (W07), and 35 with no interpass cleaning (W08).
Figure 27 – LOM images showing porosity content of single-pass with 3 m/min and 2200 W (W01), single-pass with 1.5 m/min and 1100 W (W04), two pass with 3 m/min and 2200 W using brushing between passes (W07) as well as two-pass with 3 m/min and 2200 W without cleaning (W08). The yellow contour shows the fusion zone. The area fraction of pores clearly decreased when using two-pass welding. (Figure from paper D, used with permission).

4.2.3.6 Summary of porosity in cross-sections

For an overview of the results from single-spot welding the porosity measurements are summarized in Table 13.

Table 13 – Cross-sectional porosity content including number of pores in the section, percentage of area in the section covered with pores and number of pores/mm².

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Sample explanation</th>
<th>Number of pores in the transverse cross-section</th>
<th>Area fraction of pores in the fusion zone, transverse cross-section [%]</th>
<th>Cross-sectional weld area [mm²]</th>
<th>Number of pores/mm² for weld cross-section</th>
</tr>
</thead>
<tbody>
<tr>
<td>W01</td>
<td>Ref.</td>
<td>1013</td>
<td>8.7</td>
<td>6.9</td>
<td>147</td>
</tr>
<tr>
<td>W02</td>
<td>Focus +</td>
<td>408</td>
<td>14.7</td>
<td>7.0</td>
<td>58</td>
</tr>
<tr>
<td>W03</td>
<td>Focus -</td>
<td>456</td>
<td>9.6</td>
<td>5.7</td>
<td>80</td>
</tr>
<tr>
<td>W04</td>
<td>Half power and speed</td>
<td>151</td>
<td>9.3</td>
<td>5.4</td>
<td>28</td>
</tr>
<tr>
<td>W05</td>
<td>Low power</td>
<td>415</td>
<td>7.1</td>
<td>4.2</td>
<td>99</td>
</tr>
<tr>
<td>W06</td>
<td>High power</td>
<td>748</td>
<td>14.0</td>
<td>7.5</td>
<td>100</td>
</tr>
<tr>
<td>W07</td>
<td>Two-pass + brushing</td>
<td>152</td>
<td>2.9</td>
<td>5.9</td>
<td>26</td>
</tr>
<tr>
<td>W08</td>
<td>Two-pass</td>
<td>200</td>
<td>3.5</td>
<td>5.7</td>
<td>35</td>
</tr>
<tr>
<td>W09</td>
<td>No cleaning</td>
<td>440</td>
<td>6.2</td>
<td>5.2</td>
<td>85</td>
</tr>
<tr>
<td>W10</td>
<td>Low speed</td>
<td>404</td>
<td>10.5</td>
<td>5.7</td>
<td>71</td>
</tr>
<tr>
<td>W11</td>
<td>High speed</td>
<td>234</td>
<td>3.3</td>
<td>5.0</td>
<td>47</td>
</tr>
<tr>
<td>W12</td>
<td>Only acetone</td>
<td>394</td>
<td>5.4</td>
<td>6.8</td>
<td>58</td>
</tr>
<tr>
<td>W13</td>
<td>Grit blasting</td>
<td>454</td>
<td>9.6</td>
<td>5.8</td>
<td>78</td>
</tr>
</tbody>
</table>
4.2.4 Effect of twin-spot welding on porosity

The weld metal cross-sectional geometry clearly varies between the different setups, e.g. a small spot size with narrow weld geometry and high porosity content (Figure 28, W25), a large spot size with wide weld geometry and high porosity content (Figure 28, W28), and a large spot size with medium weld geometry and low porosity content (Figure 28, W35).

![LOM images showing porosity content for different welding scenarios: single-spot welding (W01), single-spot with double pass (W08), beam splitter 120/500 (W19), beam splitter 120/160 (W25), twin optics with both in focus and 1 mm distance (W28), twin optics with both in focus and 5 mm distance (W31), twin optics with defocused secondary optics (W35) and twin optics with defocused primary optics (W37). The lowest porosity content was found in (W08) and (W35). The yellow contour shows the fusion zone. (Figure from paper E, used with permission).](image)

The area fraction of pores has been calculated, see Figure 29. In the figure it is clear that twin-spot welding with a beam splitter does not give a lower porosity amount (area fraction of pores 9-15%) compared to single-spot welding (area fraction of pores of roughly 9%). More lens setup variations than presented in Figure 29 were tested with (focus/collimator, in mm) 120/400, 120/300 and 120/250 combinations. However, the results from these tests were in line with the 120/500 and 120/160 setups, and are hence not presented in detail.

The same high porosity amount (area fraction of pores 8-31%) was seen for twin-spot with two optics when both optics had the focus position at the surface. Even higher was the porosity amount (area fraction of pores 29-32%) when the primary optics was defocused to +10 mm above the sheet surface. However, good results (area fraction of pores 4-6%) were achieved when the secondary optics was defocused ranging from -5 to +20 mm. This result is comparable with the two-pass welding.
When using twin-spot welding, no clear relation between porosity and power or welding speed could be seen.

Figure 29 – Area fraction of pores with welded samples grouped according to welding setup. Twin-spot welding with primary and secondary optics with a defocused secondary optics (W32-W35) gives the lowest porosity of around 5%. The highest porosity of around 30% was seen in twin-spot welding with primary and secondary optics with a defocused primary optics (W36-W37). (Figure from paper E, used with permission).
5 Discussion

Light-weight design has been a trend in the automotive industry for several years to reduce the environmental impact of products. Numerous materials, such as variants of high strength steels or low density metals, have therefore been introduced in the car body, in order to reduce weight without renouncing important properties such as strength, stiffness and crashworthiness [56].

Laser welding is a common joining method within the automotive as well as several other industries. Traditionally resistance spot welding (RSW) has been the main method used within automotive production. To compete with RSW, laser welding has to challenge spot welding regarding production speed, quality assurance, robustness, final properties and running and investment costs. Some of these properties are still of benefit for RSW, but laser welding has shown great potential when it comes to productivity, final properties (continuous joint), quality assurance and robustness [3] [57].

Several quality issues can occur during laser welding in light-weight design. As found in the present study, the main quality issues are different for different materials. They also vary depending on factors such as process setup, parameters, surface condition etc., and it is hence difficult to give general recommendations for avoiding.

In this work, distortions after laser welding of thin sheet ultra-high strength steel structures, as well as laser welding induced porosity of cast magnesium alloy AM50 were shown to be the major quality issues.

The presented results are discussed in the following sections. The results will be discussed with respect to light-weight design in general, design with ultra-high strength steels and cast magnesium alloy respectively, as well as laser welding in light-weight design.

Studies included are distortion analysis in ultra-high strength steels (Publications: Paper A - “Minimization of distortions during laser welding of ultra-high strength steel”, Paper B - “Correlation between laser welding sequence and distortions for thin sheet structures” and Paper C - “Metallurgical effects and distortions in laser welding of thin sheet steels with variations in strength”) as well as porosity study in cast magnesium alloy AM50 (Publications: Paper D - “Effect of laser welding parameters on porosity of welds
5.1 Quality issues in light-weight design

As seen in the results section, distortions and porosity are the main quality issues found in this study when welding UHSS and cast magnesium, respectively.

As for welding in general, independent of material, the local heating during laser welding introduces a highly non-uniform temperature distribution around the joint. Thermal expansion and contraction during heating and subsequent cooling as well as plastic deformation at elevated temperatures result in inevitable distortions and residual stresses in the weld metal, heat affected zone and base materials [58]. From a product point of view the thermal effects result in distortion or bad fit-up and are not desirable.

In paper A, B and C it is explained that the understanding of geometrical distortions is limited when it comes to thin sheet structures, independent of material type. The connection between distortion and parameters such as energy input, resulting microstructure in weld metal and HAZ, weld width and hardness is not clear. It has been claimed, though, that the energy density distribution of the heat source [59], the cross-sectional geometry and microstructure [60-63], volume change due to phase changes [64] and heat affected zone microstructure [65] are all factors that influence the distortions.

There are several ways to reduce the geometrical distortion induced by welding. According to literature the key is to control how much and where the energy is inserted into the material [66]. Obviously, less energy affects the material less. Furthermore, different welding sequences are also one solution that has traditionally been used to reduce residual stress and distortion. By welding with a controlled sequence the resulting expansion and shrinkage could counteract each other to reduce the final geometrical distortion [67, 68].

There are several studies focusing on geometrical distortions and residual stresses [58, 67, 69-78]. Most of these focus on either aluminium or thicker material within industries like ship building or pipe welding. There is very limited literature describing the prediction and measurement of welding induced deformation in thin steel sheet welded structures especially for a sheet thickness of less than 3 mm. Only a few studies have been found for automotive applications [78, 79]. In an article by Thater et al. [80] a complete car door has been studied, looking at different welding sequences to minimize distortions. For remote laser welding, various welding sequences, weld lengths and positions
Another aspect during laser welding in light-weight design is imperfections. As presented in the results chapter as well as in paper D and E, porosity is inevitable for cast magnesium, in a similar way as for e.g. aluminium. Nevertheless, magnesium alloys may exhibit many other processing problems and weld discontinuities, such as an unstable weld pool, spatter, drop-through, sagging, undercut, cracking, and oxide inclusions. A number of studies have been made focusing on weld quality of laser welded cast magnesium [16, 39-44, 46]. Pores are reported to be one of the main issues when welding cast magnesium. Therefore, it is important to understand the pore formation mechanisms and find procedures that could be used to reduce pore formation [16, 39]. As mentioned, pores in the weld metal lower especially the tensile strength. However, if compared with cracks, pores are usually allowed in the weld metal but to a limited extent.

From the results section, and from all appended papers, it can be seen that both laser welding in ultra-high strength steel as well as cast magnesium alloy AM50 show promising results when it comes to light-weight design. However, it is of great importance to have enough knowledge about how to control the laser welding process. It can be seen that welding induced distortions or porosity can vary from low and acceptable values, to extremely high and unacceptable values, depending on the settings for the laser welding process.

What clearly could be generalized from the results was that a high energy input was seldom of benefit. Independent of which quality issue to avoid, a high energy input compared to a low energy input resulted in several magnitudes larger distortions or amounts of porosity. The drawback with a lower energy input could be the risk of insufficient penetration depth for the laser beam, resulting in a low quality weld or a weld that is difficult to inspect.

### 5.2 Ultra-high strength steel

In this section, the results from laser welding of ultra-high strength steel are discussed in depth. Results are discussed in the following order: distortion mode, influence of energy input, influence of welding sequence, weld cross-section geometry, metallurgical effects and finally some concluding remarks.

#### 5.2.1 Distortion mode

In paper A, B and C, distortions due to laser welding of UHSS hat profiles were analysed. The experiments were performed to simulate laser welding of flanges...
at A- and B-pillar structures, a common application in automotive design. The two chosen geometries, single and double hat profiles, gave two different dominant distortion modes.

For single hat beams the transverse shrinking results in bending of the beam, as explained in paper A. The distortion modes that occurred resulted in an asymmetrical shape along the length of the beam. The magnitude of bending was quite small as the flat sheet was preventing large distortion. As seen in the double hat beam both profiles deform in the transverse direction resulting in an hourglass shape. The longer the weld is the more distortions will occur. In this case nothing is limiting the distortion resulting in large shape changes (transverse widening at ends of the beam) up to 9.3 mm. Such distortions are unacceptable for large scale automotive production.

In order to analyse the distortions accurately and effectively, the experiments were performed in idealized laboratory conditions. The geometries were simplified compared to actual pillars. Therefore more complex distortions or combinations of distortion modes may occur in actual A- and B-pillars.

Long et al. [58] stated that, in general, the highest longitudinal tensile residual stresses were predicted in the weld, which caused shrinkage. For the double hat, the resulting hourglass shape could therefore be understood in terms of that a longitudinal bending distortion mode was created due to axial shrinkage along the weld. As the welds were on the neutral plane of the cross-section of the beam, and since the cross section was symmetrical, the bending moments from each U-beam were working towards each other. As a result, the welded flanges bended outwards due to the shrinkage. This resulted in widening of the beam ends, and narrowing in the center of the beam. The distortion mode did not seem dependent on how the energy was delivered, rather the shape of the beams. However, comparison with other beam geometries needs to be done to confirm this hypothesis.

From the discussion in paper A, and as seen in the results section, there is a difference between optical measurements and measurements with digital caliper. However, a hypothesis is that measurements done with optical equipment only demonstrate geometry changes from half of the profile, since measurement points are only placed on one side of the beam. If distortions from optical measurements would be doubled, this would result in about 7.0 mm compared with 9.3 mm measured with digital caliper. Furthermore, the distortions from optical measurements are expected to increase when the last clamping from the beam fixture is removed, which still was in place during measurements. This could explain the somewhat smaller value for optical measurements compared to the measurements from digital caliper.
5.2.2 Influence of energy input

A common method of mitigating welding distortions is by reducing the energy input. In general terms, a lower energy input creates smaller distortions but increases the risk of reduced weld strength due to too low weld penetration at the faying interface. A full penetration weld is also desirable from a verification point of view since the weld penetration can be observed visually at the bottom surface.

As seen in Table 11 the total energy input for laser welding of a flange has been calculated accordingly:

\[
\text{Total energy input (kJ per flange)} = \frac{W}{v} \times \text{weld length}
\]

where \( W \) is the laser power in kW and \( v \) is the travel speed in mm/s. This energy input is the theoretical energy per unit length and does not consider loss of energy from reflections, absorption of laser light within the plume, etc.

For stitch welding (welding sequence D) the same formula was used but with a reduced weld length, giving 25 kJ. For resistance spot welds, the theoretically used energy from the Bosch 6000 PSI software was used; 3.74 kJ per spot weld. The energy per spot weld was multiplied with the number of spot welds on each flange (35) resulting in 131 kJ. The high energy input recorded from the spot welding process most likely differs from the actual deposited energy input to the material. Also, the resistance spot welding process transfers energy into the material in a different way compared to laser welding and hence the energy inputs are not directly comparable. Furthermore, the RSW energy input is calculated from the output of the power source and does not take into account losses due to resistance within the welding gun, current flow etc.

Welding sequences A (reference), B (in to out) and C (out to in) resulted in similar distortions for MBW1500. For the continuous welds (A1-A3), the energy input was almost linearly related to the distortion (see Figure 30). This supports the argument that with a higher energy input a larger zone (weld metal + heat affected zone) gets affected by thermally induced stresses leading to plasticity and creates the final distortions as explained above. This is in good agreement with Long et al. [58] who found that when the welding speed was reduced at a constant power, the longitudinal shrinkage of the weld was increasing considerably.
As discussed in paper B, and from these experiments, it is clear that the linear relation between the energy input and distortion does not apply to RSW and stitch welding. The distortion is believed to be caused mainly by the axial shrinkage and hence stitching and RSW results in lower shrinkage due to the shorter weld length. The stitch welding distortions do not decrease in proportion to the lowered energy input. An explanation could be that the axial shrinkage is roughly half since the welded length is close to half, but the stitch welded beam has un-deformed sections between the welds which do not contribute to the final distortion and act as mechanical constraints.

Spot welding also gives a lower distortion than continuous laser welds. For each individual spot weld the shrinkage should be symmetrical due to the circular shape of the weld. The transverse shrinkage does not have a large influence on
the final shape of the complete structure, but the combined axial shrinkage for all the spot welds do.

Since the axial shrinkage is believed to be the main reason for distortions, the volume of the weld metal for one flange was calculated, giving to 2374 mm$^3$ for continuous welds at welding speed 1.5 m/min (A1), 1456 mm$^3$ for welding speed 3.5 m/min (A2, B and C), 1318 mm$^3$ for 7.5 m/min (A3), 776 mm$^3$ for stitching (D), and 720 mm$^3$ for RSW (E). The relation between the volume of weld metal on each flange and maximum distortion at both ends and middle of the beam is presented in Figure 31 and the volume of weld metal is approximately proportional to the distortion. A hypothesis is that the shrinkage of the weld metal is the main contributing factor to the distortion, and hence the amount of weld metal controls the amount of distortions.

Figure 31 – Volume of weld metal per flange vs. distortion at ends (upper figure) and middle (lower figure) of the double hat MBW1500 beams. Widening at ends is presented as the average value of the two ends. There is nearly a linear relationship between the volume of weld metal and the distortion. (Figure from paper B, used with permission).
5.2.3 Influence of welding sequence

The most suitable welding sequence, process and parameters for the beam should be chosen not only with respect to distortion, but also productivity as well as strength and stiffness of the welded structure. A continuous weld in general results in a stiffer and stronger structure, and laser welding compared with RSW usually needs shorter time for the complete welding sequence.

As seen in paper B, the distortions are clearly reduced by changing the welding sequence to stitching, or by changing welding method to RSW. One thing to keep in mind is that the clamping was different for RSW, where only the welding gun, i.e. the electrode force, was used for clamping. It is not clear how this affects the distortion.

As described previously, the distortion is believed to be caused mainly by the axial shrinkage and hence stitching and RSW results in lower shrinkage due to the shorter total weld length. During this study, no significant influence of the welding directions on distortion could be seen. Comparing with literature, Kadivar et al. [68] saw a clear effect on distortions when changing the welding sequence while studying a circular patch. They divided the circular patch into eight parts and welded the parts in different orders (welding sequences). Their results do not correspond with the present study where the different welding sequences A2 (3.5 m/min), B and C all produced similar distortions. A hypothesis is therefore that the effect of varying the welding direction is too small to give a clear measurable effect on the thin sheet beams, compared with the distortion induced by the shrinkage of the weld metal that occurs independent of the welding sequence. Hence, the distortion in this study seems to be dependent mainly on the volume of weld metal and not on the welding direction. The difference between findings in the study by Kadivar et al. [68] and the present can most likely be understood in terms of geometrical factors such as linear versus circular welds, symmetrical versus non-symmetrical cross sections, and different sheet thicknesses. Another aspect is the distortion mode; the radial displacement from Kadivar et al. compared with longitudinal shrinkage in the present study. The effect of weld sequencing most likely differs for different dominating distortion modes.

5.2.4 Weld cross-section geometry

As discussed in paper C, and as seen in Figure 16, the shape of the weld metal cross-section differs between the different steels, which affects the bonding area between the sheets (weld width at the interface). The variation of weld metal cross-sectional shape most likely differs due to parameters such as heat flow, laser coupling or laser beam divergence.
Docol 200 has more parallel fusion boundaries while MBW1500 has a narrowing at the middle. A linear regression analysis shows poor correlation between weld width and distortion resulting in an $R^2$-value of 0.053. Hence, weld width is not a good measure for estimating distortions for different steel grades.

In Figure 32 the relation between weld metal volume and distortion is shown. No clear relation can be seen with an $R^2$-value of 0.39 for all steels. However, considering only Docol 200 the $R^2$-value is 0.86, for DP800 0.97 and for MBW1500 0.96, suggesting that weld metal volume is a good measure when steel grades are evaluated separately. When comparing different steel grades there are several properties most likely influencing distortion such as the microstructure, volume change during cooling [64], absorption of laser energy [81] and steel strength influencing the degree of restraint thereby making the effect of weld metal volume alone a poor measure.

![Figure 32](image_url)

**Figure 32** – Graph showing the limited correlation between distortion and weld metal volume for double hat beams in different steel grades. (Figure from paper C, used with permission).

### 5.2.5 Metallurgical effects

In paper C, the magnitude of distortions was also compared for different steel grades. When comparing different steel grades using welding sequence A (reference), a linear regression analysis was done to see how total energy input and distortion are related. Regression analysis for MBW1500 gave an $R^2$-value of 0.999 and for DP800 an $R^2$-value of 0.996. However, a rather poor correlation was found for Docol 200 with an $R^2$-value of 0.686. The $R^2$-value was 0.556 when including all steel grades, which indicates a poor general correlation.
Mochizuki et al. [59] used computational simulations to study the effects of welding conditions on microstructures and distortion. In the study, 25 mm thick steel was multi-pass welded with laser using filler material. The authors stated that the distribution of the energy affects weld distortion, because the temperature distribution and temperature history change. In the present study three steels with different surface conditions (coated and uncoated) have been welded. Different surfaces absorb unequal amounts of radiation from the laser [82]. This is likely to result in that the amount of energy absorbed in Docol 200, DP800 and MBW1500 differs, and hence the energy input is not suitable for predicting distortions when comparing different steels or even the same steel with different surface conditions.

Another hypothesis for the low correlation in Docol 200 is that the welding induced distortions locally deform the material plastically around the welds at higher energy input, and hence global distortions are reduced. This would happen to a reduced degree for DP800 and MBW1500 due to their higher strength, i.e. resistance to deformation. However, local deformation has not been seen during visual inspection of the welded structures.

The relation between the distortion and width of the hard zone is illustrated in Figure 33. Regression analysis gives an $R^2$-value of 0.84 which suggests a good correlation.

![Figure 33](image)

Figure 33 – Correlation between distortion and width of the hard zone. A good correlation can be seen independent of material grade. (Figure from paper C, used with permission).

The hard zone corresponds to the weld metal and the predominantly martensitic area in the heat affected zone adjacent to the fusion boundary. The steels have different compositions, and hence they form martensite and bainite at different temperatures during cooling after welding. The temperatures in Celsius for start
of martensite ($M_s$) and bainite ($B_s$) transformation have been calculated from the chemical composition (wt.%) according to [82]:

$$M_s = 539 - 423 \times C - 30 \times Mn - 11 \times Si - 12 \times Cr - 18 \times Ni - 7 \times Mo$$

$$B_s = 830 - 270 \times C - 90 \times Mn - 70 \times Cr - 37 \times Ni - 83 \times Mo$$

It can be seen that the higher strength steels have lower transformation temperatures (Table 14), which in this study was connected to larger distortions.

Table 14 – Calculated martensite ($M_s$) and bainite ($B_s$) start temperatures.

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>$M_s$ ($^\circ$C)</th>
<th>$B_s$ ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Docol 200</td>
<td>514</td>
<td>793</td>
</tr>
<tr>
<td>DP800</td>
<td>443</td>
<td>658</td>
</tr>
<tr>
<td>MBW 1500</td>
<td>401</td>
<td>654</td>
</tr>
</tbody>
</table>

If the distortion is believed to be affected by martensite formation during cooling, several parameters would affect the final distortion: the martensite transformation temperature, strength of surrounding material (restraint), amount of material transformed into martensite and the volume increase on martensite formation (affected primarily by the carbon content). How much each of these parameters affects the distortion needs to be studied further.

In a study by Deng [64], effects of volume change due to austenite-martensite transformation on the final residual stress and the welding distortion were examined. Simulation results revealed that the final residual stress and the welding distortion in low carbon steel (0.15 wt-% C) do not seem to be influenced by the solid-state phase transformation. However, for medium carbon (0.44 wt-% C) steel, the final residual stresses and the welding distortion seem to be affected significantly. The difference was explained in terms of a relatively smaller expansion due to martensitic transformation and a relatively high transformation temperature range for the low carbon steel and larger expansion taking place at a lower temperature for higher carbon contents. The conclusions correlate well with the present study where higher distortion correlates with the higher carbon content of MBW1500 and DP800 compared to Docol 200 (Table 1) and hence larger volume change from the martensitic transformation.

**5.2.6 Concluding remarks**

The overall objective of this study is to find laser welding solutions that can be applied to production of future light-weight vehicles. For UHSS, laser welding induced distortions were considered one of the major hinders for increased
usage within BIW. A research question was therefore presented in the introduction chapter:

- How can distortions be minimized for ultra-high strength steel structures during laser welding?

According to the present study, distortions are heavily dependent on welding sequence and welding parameters. One easily recorded parameter that showed the best correlation with the distortion, for all steel grades, was the width of the hard zone. The width of the hard zone is dependent on steel grade and welding parameters and could hence be minimized by choosing welding parameters accordingly. In this study, energy input, which is controlled by laser welding power and welding speed, had a clear effect on the width of the hard zone for each grade and should hence be the parameter to control for minimizing distortions. Furthermore, the width of the hard zone can be expected to correlate well with the degree of distortion for any combination of steel and cooling rate resulting in a predominantly martensitic weld metal.

If one should predict the distortion within only one steel grade, the weld metal volume would also be a good parameter choice. This is also valid for different welding sequences including resistance spot welding.

For industrial use, the final geometrical shape change of a structure after welding could hence be predicted by measuring the width of the hard zone in a representative cross-section, or calculating the weld metal volume. Benefits are especially seen for computational modelling when predicting distortions for a specific component. However, to more extensively use these correlations, future work should include further component geometries to see the influence of other distortion modes.

The present geometries, single hat and double hat, mainly experience longitudinal bending and transverse widening. It can be seen that the geometry of the structure clearly influences the magnitude of distortion but also the distortion mode. The largest distortion was found for the double-hat profile whereas the single-hat profile exhibited much less distortion. One way of minimizing the distortion could be to find the most beneficial geometry. The design of critical components that experience a global geometry change during welding could also be adapted to compensate for the distortions or minimize transverse expansion and shrinking as well as longitudinal bending.

Within production of BIW, UHSS is mounted and welded in a framework design. This is normally done in hardened condition. If a large fitting issue would be present from distortions of longitudinal welding of flanges, the stiff
structure would most likely result in either gap problems or low quality welds. This is a complication as the laser welding process is known to be sensitive to gaps and requires small tolerances [83]. From a practical point of view, laser welded single hat profiles in UHSS could probably be used in a car body due to the small distortions, without special precautions. However a flat sheet is most likely not suitable within an A- or B-pillar. The double hat geometry suffered from distortions up to maximum 9.3 mm which most likely is too much from a production point of view.

If distortions cannot be prevented, techniques exist that could correct a distorted component. What has been used historically within other industry sectors for larger structures that can’t be straightened mechanically is counteracting heating [70, 84, 85]. The component is heated locally at certain points to retract to the wanted geometry. The released heat creates new internal stresses within the material causing controlled expansion and shrinkage. However, this is not used within the automotive industry and for boron steels this would most likely create a softening effect which makes it less suitable. Furthermore, it is also more beneficial if component geometry and welding parameters can be adapted to avoid large distortions, instead of using post-weld treatments for correcting them.
5.3 Cast magnesium

In this section porosity in cast magnesium alloy AM50 is discussed. The section is divided into two major parts dealing with results for single-spot optics and twin-spot optics.

5.3.1 Single-spot: Pore formation in the weld metal

The main consequence of porosity in the weld metal is the lowered strength of the joint [16, 39, 40]. With respect to strength, the pore volume should be the most useful measure to determine the quality of the weld from this study. The number of pores could also be critical due to possible initiation points for fatigue or crack growth. However, the application for cast magnesium alloys is rarely load carrying structures and hence static strength is most relevant. Therefore, the area fraction of porosity in the fusion zone cross-section is considered the most important measure in this study.

From paper D, and from the present experiments, there is no clear correlation between the number of pores and the area fraction of pores in the cross-section. This can be understood from Figure 23 showing that the size distribution of the pores depends on, for example, the welding speed. It can be seen that welds produced with a speed of 2 m/min (W10) resulted in 47 pores/mm² and 10.5 % of area fraction of pores while welds produced with a speed of 3 m/min (W01) resulted in 147 pores/mm² but only 8.7 % of area fraction of pores. In this case, a lower welding speed resulted in a lower number of pores, but with more pores with a radius > 100 μm. This suggests that the size of the pores increased with higher power rather than the number of pores. Large pores can form directly as a result of the welding process, or when several smaller pre-existing pores in the cast material coalesce [16].

Three major reasons for porosity are detailed in the existing literature: pre-existing pores from the die-casting process, pores formed by nucleation and growth of gas (most likely hydrogen/water) in the molten material, and porosity originating from process instabilities [46].

One explanation in agreement with the results of the present study is that gases entrapped in pre-existing shrinkage pores grow when the solid material becomes molten during welding [40, 41, 44]. These relatively large pores have difficulties to escape the molten pool due to the rapid solidification in laser welding.

This suggests that a higher heat input, giving a larger volume of molten material and allowing more entrapped gas to grow to larger pores, should result in a
larger pore volume. From literature it is also claimed that a higher welding speed reduces the available time to form and grow pores, resulting in fewer pores in the weld bead [44]. In line with this Zhao et al. [44] found that the porosity increased with increased heat input, i.e. an increase in laser power and/or a decrease in welding speed. This corresponds well with results from the present study since the welds that had above 10% area fraction of pores had parameter settings giving the highest heat input or most defocused laser beam (W02, W06 and W10). The welds with the lowest area fraction of pores of around 3% had parameter settings with the highest welding speed or were two-pass welds (W07, W08 and W11). The effects of the heat input, welding speed and power are illustrated in Figure 34 and Figure 35. The black line corresponds to the best fit with linear regression.

Figure 34 – Area fraction of pores as a function of heat input. A higher heat input results in more porosity. (Figure from paper D, used with permission).
5.3.2 Single spot: Surface cleaning

As seen in paper D, unexpectedly brushing (area fraction of pores 8.7%) or grit blasting (area fraction of pores 9.6%) resulted in more porosity than no cleaning (area fraction of pores 6.2%) and cleaning only with acetone (area fraction of pores 5.4%) (Table 13). This suggests that cleaning has a negative impact on porosity, which is not the common understanding when welding magnesium or aluminium alloys [86]. It is usually suggested to clean the surface prior to welding due to the oxide film (MgO) which is a result of the high reactivity with oxygen [46].

A consideration should be the laser beam absorption. The absorption of the laser beam depends on the surface condition and thereby the cleaning procedure [16]. The higher porosity content in the cleaned samples could therefore possibly be due to a lower absorption of the laser beam and hence a resulting unstable welding process. An unstable keyhole could be one explanation for pore formation [46], however, this is more common when welding aluminium than magnesium due to the lower vapor pressure and higher surface tension causing the keyhole to collapse.

In a study by Cao et al. [46] a CO₂-laser was used while investigating the absorbivity of the Mg-surface. Magnesium oxide (MgO) was found to have a very high energy absorptivity of 93–98% (90–99% for Al₂O₃) suggesting that the oxide increased the absorptivity of the laser beam. It was assumed that the high
absorption will result in high heat input and melt, or even evaporate, the oxides present in the weld pool, leading to the decrease of oxide inclusions and the purification of weld metal. This is considered to be a possible explanation, however, nothing that can be confirmed by the present study.

Harooni et al. [16] stated that the surface oxide on magnesium alloys was one of the causes of pore formation. When welding a lap joint where the oxide layer had been mechanically removed almost no porosity was found, while welding with as-received surfaces produced porosity at the faying surface of the two overlapping sheets. The explanation was that the oxide layer bonds moisture forming magnesium hydroxide. As a result of heating during welding water molecules were released from the hydroxide and trapped in the molten metal thereby forming pores. Lower porosity content when plasma arc pre-heating was explained by degassing of the oxide layer.

In the present study there were no faying interfaces for the bead-on-plate samples, why porosity formation cannot readily be explained by moisture being released from surface oxides. This suggests cleaning of the surface would not have a major effect.

5.3.3 Single-spot: Two-pass welding

The lowest amount of porosity was achieved with two-pass welding with 2.9% (W07) and 3.5% (W08). The porosity decreased roughly 5%-units when applying the second pass, as described in paper D. Obviously, pores formed in the first pass, while the second pass had a degassing effect removing in particular the large pores. A higher heat input in a single-pass could be thought to have the same effect, however, more material becomes molten and hence more porosity forms. The two-pass welding only melts a small volume of material, but two times. The second pass will not heat a larger volume of material compared with the first pass, and hence no new pores are expected to be formed by the second pass. What is believed to cause a reduction of porosity from the second pass is the extra time to degas.

Another example where two-pass laser welding has been applied is in another study by Harooni et al. [87]. In that case, two-pass laser welding was done for AZ31B magnesium alloy in a lap-joint configuration. In the study, the origin of the pores was concluded to be the oxide layers at the faying interface between the two sheets. It was found that the first welding pass decomposed the magnesium hydroxide into magnesium oxide and water while the second pass helped the vaporized water to escape, and thereby produced a pore free weld.
Two-pass welding is however not considered production friendly due to the lower productivity (double process time).

### 5.3.4 Twin-spot: Pore formation in the weld metal

As shown in paper D, a lower heat input in single-spot welding gave lower porosity content. The welding speed had the largest effect, i.e. a higher welding speed reduced the porosity. However, as discussed in paper E, for twin-spot welding no clear relationship between heat input and area fraction of pores could be seen (see Figure 36). This suggests that several parameters influence the porosity when using twin-spot, not only heat input.

![Figure 36](image.png)

Figure 36 – The area fraction of pores in relation to heat input for twin-spot welding with beam splitter (upper figure) and twin-spot welding with primary and secondary optics (lower figure). No clear relationship between the heat input and the area fraction of pores can be seen. (Figure from paper E, used with permission).
Several mechanisms for porosity formation in the weld metal have been suggested in literature. As mentioned earlier, one explanation [40, 41, 44] is that pores already existing in the base material grow when remelted during welding. The gas expands to form bubbles in the liquid metal resulting in larger pores during solidification. The bubbles have little time to escape from the molten pool because of the rapid solidification in laser welding. This could be one explanation of the pore behavior for single-spot welding, but it’s not the full explanation for twin-spot welding.

An alternative explanation, in line with the findings from Haboudou et al. [88], who performed twin-spot welding of cast aluminium, is that the keyhole is stabilized. They stated that a twin-spot stabilizes the weld pool and keyhole dynamics that reduces the porosity amount to below 2%. If the keyhole is stable and somewhat larger when using twin-spot, the degassing of large pores should occur to a larger extent. This could be part of the explanation, but since several setups with twin-spot welding do have a large amount of porosity in the present study, at least one other factor does influence as well.

Harooni et al. [89] studied twin-spot laser welding of an AZ31B magnesium alloy. The aim of the study was to decrease the amount of porosity caused by the oxide layer at the faying interface between the sheets. They found that pre-heating with the first beam provided a lower amount of porosity, and hence a twin-spot setup was beneficial from a weld quality point of view. However, Harooni et al. studied overlap joints, which differ from the bead-on-plate welds in this study.

In Figure 37, which can be found in paper E, a hypothesis for the observed porosity occurrence is suggested. Some of the existing inclusions (oxides, precipitates etc.) (1) in the material will remain undissolved and are distributed in the molten material during welding together with remainders of the broken-up surface oxide (2). Most of the gas in the pores from (1) is dissolved in the melt due to higher solubility in the liquid state. During cooling of the melt the inclusions can act as nucleation points (3) for new pores. The higher the density of inclusions is, the more nucleation points. While still in the liquid state, during subsequent heating, either as an effect of the energy input from the first beam or by the second beam (by beam splitter, or the second optics), the nucleated pores grow (4) due to that dissolved gas is diffusing to pores and increase volume and/or that small pores coalesce.
Figure 37 – Suggested mechanism for porosity formation and degassing. Solid material with inclusions and small pores (1) is molten by the first laser beam resulting in a melt with a distribution of inclusions (2). The inclusions then act as nucleation points (3). When the second beam heats the material, the nucleated pores grow by diffusion of dissolved gas or coalescence of smaller pores (4). The second beam gives the pores enough time to reach the surface of the melt resulting in degassing (5). (Figure from paper E, used with permission).

Depending on how the twin-spot procedure is designed, a degassing effect (5) is achieved with the second beam. If the energy input into the material, in this case controlled by defocusing, (more defocusing – less energy into the material) from the first beam is too high the molten material will have little time to cool between the two beams and pores will not form until the final cooling of the melt and hence little degassing will take place. However, if the energy input from the first beam is well balanced, there will be time for nucleation and some growth before reheating by the second beam. The second beam then heats the melt and allows the pores to grow and also escape from the molten material. For illustration, see Figure 38.
Figure 38 – A schematic description of porosity formation, growth and degassing during the heat cycle of twin-spot laser welding. The blue dots represent the nucleation of pores. (Figure from paper E, used with permission).

The effect of defocusing on the porosity amount for the twin optics solution is explained in Figure 39. For (a) both beams are in focus. The energy input from the first beam is high, resulting in a small temperature reduction between the beams, hence little nucleation of pores occurs on cooling after passing of the first beam. Consequently few pores will exist that can grow in size making degassing unlikely when the melt pool is heated by the second beam. Furthermore, nucleation and growth will occur on cooling after passing of the second beam, leaving a weld with high porosity content (e.g. Figure 28, W19/W25/W28). A similar scenario can be envisaged for (b) where the first beam is in focus, but the second beam is defocused. This results in a long cooling time which is unbeneeficial from a porosity point of view resulting in nucleation and growth at the end of the sequence and little degassing (see Figure 28, W37). Looking at (c), the pores can nucleate on cooling after the first defocused beam has passed (as explained in Figure 38), since the energy input is relatively low. The second beam then provides the heating required for growth of the pores and time for degassing (see Figure 28 W35).
Figure 39 – Explanation of how porosity content varies with different setups of the twin-spot optics. (a) and (b) will result in extensive porosity, while (c) allows degassing to occur, and hence a low porosity content. The blue dots represent the nucleation of porosity. (Figure from paper E, used with permission).

5.3.5 Concluding remarks

As discussed in the previous section, laser welding of cast magnesium alloy AM50 seems promising if done in the right way. Porosity in the weld metal is considered one of the major hindrances for increased usage of cast magnesium in interior automotive components. The research question presented in the introduction chapter was:

- How can porosity in cast magnesium alloys be minimized during laser welding?

Single-spot welding with “standard parameters” results in a high porosity content of roughly 9%. Using two-pass welding the porosity content is reduced to 3%, which is considered low. However, two-pass welding is not production friendly in the aspect of process time. Twin-spot welding could be a good combination of a production friendly solution and high quality welding. Compared with single-spot optics, a twin-spot optic setup is more complex with more parameters to control; however, the porosity content is low (4-6%).

Summarizing, the optic setup is shown to be crucial when trying to minimize the porosity while laser welding cast magnesium. Harooni et al. [89] used twin-spot optics for minimizing pores originating from the oxide layer at the faying interface between the two sheets in a lap joint configuration. The present study shows that porosity also can be reduced in a butt joint configuration. Single-spot welding could give relatively low porosity welds, but degassing is limited when using single-pass welding. More effective degassing occurs when using twin-spot, which shows promising results. Future work should be directed towards further optimization of the twin-spot configuration, including power and welding speed, to have as low porosity as possible.
Furthermore, it is also worth mentioning that until today no published study has been found that correlates the amount of porosity in welded cast magnesium to the strength of the weld. Such a recommendation would be valuable as it would indicate which porosity content limit to aim for.
5.4 Laser welding in light-weight design

The choice of solution for achieving light-weight is not straightforward and the automotive producers seem to move in different directions. Nevertheless, it is important to understand the importance of light-weight. In a study done by Schubert et al. it is shown that by knowing the cost for an existing structure with a certain material it is possible to estimate the savings over the lifetime for the reduced fuel consumption due to the lower weight [90]. For a typical car this value is approximately 9.4 Euro/kg.

As mentioned in the introduction, there are several materials that are considered as light-weight materials including aluminum, magnesium, high strength steel and carbon fiber reinforced plastics (CFRP). CFRP has during the last years intensively been discussed as a solution [91]. To give further recommendations for light-weight design, aluminium and CFRP should be studied. Hence it would be valuable to complement this study with similar investigations for aluminium and CFRP.

If looking beyond that the different materials have different dominating quality issues while welding, the answer to achieving light-weight is most likely not the use of only one material, but a combination of several. The “right material at the right place” has been identified to be an enabler. This requires further studies of joining technologies for multi material design that is probably one of the most important topics within automotive BIW research today [9, 91, 92].

Laser welding has certain benefits in several applications. However, there are several aspects to understand, and several quality issues to avoid, when optimizing laser welding in light-weight design. In this study, laser welding of two light-weight materials have been investigated; ultra-high strength steel and cast magnesium alloy AM50. These materials are suitable for different applications in the automotive industry, ultra-high strength steel for so called crash components and cast magnesium for interior parts.

As stated, one way to achieve successful design and production of light-weight vehicles is to use boron steels due to their high strength-to-weight ratio. However, boron steels are mainly suitable in so called crash components due to their high strength. For joining, RSW has been used historically, but laser welding gives further possibilities of increased performance giving a higher stiffness through continuous welds, as well as a further reduced weight due to possibilities of having smaller flanges.

In a study by Bouaziz et al., high strength steels are considered to be a promising solution for “lightening” in BIW, which is referred to as the
reduction of weight of a component through the use of a thinner section of a steel with a higher yield or tensile strength [2]. In the conclusions of the study, weldability is considered to be one of three technology key areas for future optimizations.

In similar ways cast magnesium alloys such as AM50 show potential for further reduced weight. AM50 is not suitable for generic components in BIW, but rather interior parts where complex shapes and low weight is crucial. Traditionally, cast materials are avoided to be welded with other materials and hence the most common joining technique is bolting [93]. Welding is until today rarely used within the automotive industry due to the issue with high porosity content.

Considering the present study, three general research questions were presented in the introduction chapter:

- What quality problems occur while laser welding?
- Why do the quality problems occur?
- How can these quality problems be understood and avoided?

As mentioned, it can be seen that laser welding both in ultra-high strength steel as well as cast magnesium alloy AM50 show promising results when it comes to light-weight design. Control of the laser welding process is, however, crucial and needed also for the small tolerances given by the process itself due to the high power density. Quality issues, such as amount of porosity, can vary from low and acceptable values to extremely high and unacceptable values, depending on the settings for the laser welding process.

For the materials studied in this work, distortions are the main quality issue for ultra-high strength steel and porosity is the main issue for cast magnesium. Distortions are caused by the heat from laser welding, and correlate with the width of the hard zone in a cross-section of the weld. The width of the hard zone is dependent on steel grade and welding parameters and could hence be minimized by choosing welding parameters resulting in the smallest weld width. In this study, energy input, controlled by laser welding power and welding speed, had a clear effect on the width of the hard zone for each steel grade and should hence be the parameter to control for minimizing distortions.

Weld metal porosity is believed to be caused by growth of pre-existing pores, but also the formation of new pores by nucleation and growth. The weld metal porosity can be minimized by using a laser welding procedure allowing degassing of the porosity. This was found to be achievable in two ways, either by two-pass welding, or by twin-spot welding with a specific energy balance between the two beams.
In general, low energy input does seem to minimize the possible quality issues that can occur during welding of thin sheet structures in this study. Compared to other welding methods, this should be advantageous for laser welding which usually generates a low energy input.

As shown in this study, a high weld quality could be achieved and low component welding distortion and low weld metal porosity, were both results of a proper choice of welding sequence/parameters. Within the automotive industry a too large shape change after welding would result in expensive and complicated additional operations. Distortions could therefore be a stopper for the increased use of laser welding of UHSS. In a similar way, a high porosity content would risk the component strength. Hence, porosity could be a stopper for the increased use of cast magnesium.

Concluding, the results of the present study suggest that future light-weight design should allow both high strength steel and cast magnesium to be used more widely. Traditional joining processes (e.g. RSW or MIG) could be used, but laser welding as a manufacturing solution show high potential regarding weld quality and other general aspects such as productivity. However, this study also shows that process control and high process knowledge are key factors to enable successful application of laser welding for light-weight design.
6 Conclusions

Laser welding of ultra-high strength steels and the cast magnesium alloy AM50 for enabling light-weight design has been studied. The study included investigations of quality issues that could arise. Focus was on distortions for UHSS where trials were performed on single hat and double hat beams simulating laser welding of flanges at A- and B-pillar structures. Furthermore, also laser welding induced porosity in cast magnesium alloy AM50 for interior parts were studied. For UHSS, conventional laser welding was done in a specific fixture designed for research. For cast magnesium, single-spot and twin-spot welding was done bead-on-plate. Measurements of final distortions and metallographic investigations were performed. From the results and discussion the following could be concluded:

**Laser welding of ultra-high strength steel**

- Distortion modes occurring were mainly bending and transverse expansion, both were concluded to be caused by axial shrinkage of the weld.
- The single hat beam suffered from longitudinal bending due to its asymmetric geometry. The double hat suffered from transverse expansion resulting in an hourglass shape of the beam.
- For a weld length of 690 mm, the maximum single hat distortion was around 1.0 mm (increasing height in centre of beam) while the maximum double hat distortion reached 9.3 mm (widening at ends of beam).
- Distortions arose and retracted locally during the welding sequence. During cooling the material was fixed and hence no global distortions occurred. While unclamping, the global distortions increased stepwise with each clamp.
- The welding direction did not affect the geometrical distortions.
- Stitch welding in general reduced the distortions compared with continuous welding. Resistance spot welding reduced the distortions at the ends of the double hat beam, even more compared to stich welding, but the narrowing at the center was larger.
- Regression analysis of weld metal volume and total energy input showed a good correlation with distortion when comparing within one steel grade. When including all steel grades the correlation was poor.
- The correlation between the width of the hard zone and distortion was good. The hard zone corresponded to the martensitic area of the weld.
- Higher carbon steel resulted in larger distortions, most likely caused by a larger volume change during martensite formation.

**Laser welding of cast magnesium alloy AM50**

- The porosity content of the laser welded AM50 sheets varied between approximately 3 and 30%.
- An increased welding speed or a decreased welding power resulted in less porosity. The focus position did not influence the porosity.
- The lowest area fraction of porosity of 3% was achieved for 4 m/min with 2200 W and for two-pass welding at 3 m/min with 2200 W. Focus position was at the surface and the oxide was not removed.
- Low porosity in single-pass welds was achieved when pre-existing pores in the base metal didn’t have time to coalesce and expand.
- Low porosity in two-pass welds was due to degassing by the second pass removing, in particular, the large pores.
- Mechanical cleaning of the surface increased the amount of porosity.
- Twin-spot welding with a primary and a secondary optics using a defocused secondary optics gave the lowest porosity of around 5%.
- The amount of porosity will depend on the balance between the energy input of the first and second beams. For lowest porosity the first beam should provide time for nucleation and some growth of pores while reheating by the second beam should provide time for pores to grow and escape.
- Twin-spot welding is a promising combination of a production friendly solution and high quality welding.

**Laser welding for light-weight design**

- Distortions and porosity were the main quality problems that occurred while laser welding ultra-high strength steel and cast magnesium, respectively.
- Low energy input seemed to generally minimize quality issues during laser welding.
- A high weld quality was achieved and a low component welding distortion as well as low weld metal porosity, were both results of a proper choice of welding sequence/parameters.
- Laser welding shows high potential regarding weld quality and other general aspects such as productivity in light-weight design for both high strength steel and cast magnesium.
7 Future work

Further knowledge is needed to achieve light-weight design that fulfils the environmental demands of the future. Research needs to be focused on advanced materials, joining methods, properties and design. In this study ultra-high strength steel and a cast magnesium alloy have been studied. Future work could include design with other light-weight materials such as aluminium as well as carbon fibre reinforced plastics. Joining techniques for such materials should be compared for most successful results.

In this study, the geometry of the structure (beam) dictated which dominating distortion mode that occurred for ultra-high strength steel. Further geometries should be studied to verify that the width of the hard zone is a good measure for predicting distortions. Furthermore, several parameters most likely affect the final distortion of ultra-high strength steel: the martensite transition temperature, strength of surrounding material, amount of material transformed into martensite/bainite, and the final relative volume of the martensite (affected primarily by the carbon content). The individual contribution to distortion of these parameters must be further studied.

More production-like fixtures should be used for further learning. Also, in this study a certain clamping, welding direction and welding pattern was used. What should be further studied is how these influence the final geometry.

Residual stresses should be analysed to further understand the occurrence of distortions. Also it is of interest to further use simulations and modelling together with experiments to predict distortions.

For cast magnesium, more in-depth analysis of pre-existing porosity in the base metal should be done. Hydrogen content should be measured, both within the pores and solved in the base metal. Laser welding should be done on material with different hydrogen contents. This could give an indication on the effect of hydrogen for the susceptibility to pore formation.

Moreover, the effect of surface oxides should be further studied. In this study less cleaning of the surface was beneficial. This is in contradiction with the common understanding of how welding of magnesium and aluminium should be undertaken.
8 References


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9 Summary of appended papers

9.1 Minimization of distortions during laser welding of ultra-high strength steel

Ultra-high strength steels are frequently used within the automotive industry for several components. Welding of these components is traditionally done by resistance spot welding, but to get further productivity and increased strength, laser welding is introduced. Fusion welding is known to cause distortions due to built-in stresses in the material. The distortions result in geometrical issues during assembly which become the origin of low joint quality due to gaps and misfits.

U-beam structures of boron steel simulating B-pillars have been welded with laser along the flanges. Welding parameters and clamping have been varied to create different welding sequences and energy input generating a range of distortion levels. The distortions have been recorded with an optical measurement system during welding. In addition, distortions have been measured by a digital caliper. The combined measurements give the possibility to evaluate occurrence and magnitude of distortions with high accuracy. Furthermore, section cuts have been analyzed to assess joint geometry and metallurgy.

The results show that final distortions appear in the range of 0-8 mm. Distortions occur mainly transversely and longitudinally along the profile. Variations in energy input show clear correlation with the final geometry and joint quality. A higher energy input in general generates a higher level of distortion with the same clamping. Section cuts show that weld width and penetration are significantly affected by welding energy input.

The present study identifies parameters that significantly influence the magnitude and distribution of distortions. Also, effective measures to minimize distortions and maintain or improve joint quality have been proposed. Finally, transient FE simulations have been presented which show the behavior of the profiles during the welding and unclamping process.
9.2 Correlation between laser welding sequence and distortions for thin sheet structures

Thin ultra-high strength steel shaped as 700 mm long U-beams have been laser welded in overlap configuration to study the influence of welding sequence on distortions. Three different welding directions, three different energy inputs as well as stitch welding have been evaluated, using resistance spot welding as a reference. Transverse widening at the ends and narrowing at the center of the beam were measured. A clear correlation was found between the weld metal volume and distortion. For continuous welds there was also a nearly linear relationship between the energy input and the distortion. However, the amount of distortion was not affected by a change in welding direction. Stitching and resistance spot welding reduced distortion significantly compared to continuous laser welding.

9.3 Metallurgical effects and distortions in laser welding of thin sheet steels with variations in strength

Geometrical distortions occur while welding, but the understanding of how and why they occur and how to control them is limited. The relation between the weld width, weld metal volume, total energy input, width of the hard zone and distortions when laser welding three different thin sheet steels with varying strength has therefore been studied. Weld metal volume and total energy input show a good correlation with distortion for each steel individually. The best correlation when including all three steel grades was between the width of the hard zone composed of weld metal and the martensitic area in the heat affected zone.

9.4 Effect of laser welding parameters on porosity of welds in cast magnesium alloy AM50

Pores in the weld metal deteriorates the mechanical properties of the weld. It is therefore important to understand the pore formation mechanisms and find procedures that could reduce porosity. This study focused on laser welding of 3 mm thick magnesium alloy AM50, investigating how different parameters affect porosity formation. Low levels of porosity content were achieved by either
increasing the welding speed or using a two-pass welding approach. It was found that higher welding speeds did not allow pores, which were pre-existing from the die-casting process, to have sufficient time to coalesce and expand. In the two-pass welding technique, pores were removed as a result of a degassing process that occurred through the second pass.

### 9.5 Low porosity in cast magnesium by advanced laser twin-spot welding

Magnesium alloys are suitable for automotive and aerospace industry applications as their good strength-to-weight ratio provides possibilities to reduce the weight of a structure. However, porosity is reported to be a major issue when welding cast magnesium. Therefore, it is important to understand the pore formation mechanisms and find procedures that could be used to reduce porosity.

This study aims to investigate the possibility to use twin-spot optics for reducing the porosity in welding of cast magnesium. Two twin-spot welding setups were compared using either a beam splitter or twin-spot welding with primary and secondary (placed in front of the primary optic) optics. The results showed that welding with a two optics setup with a defocused secondary beam gave the lowest porosity of around 5%. The highest porosity of around 30% was seen with the same two optics setup but with a defocused primary beam. No clear relation between the level of porosity and power or welding speed was found.

It was concluded that the amount of porosity depends on the balance of the energy input (controlled by defocusing) between the two beams. The lowest amount of porosity will be achieved if the energy from the first beam will allow time for nucleation and some growth of pores. Reheating by the second beam should then allow the pores to grow and escape from the molten material without melting additional base material. Furthermore, twin-spot welding is shown to be a promising combination of a production friendly solution and high quality welding.
Tidigare avhandlingar – Produktionsteknik

PEIGANG LI Cold Lap Formation in Gas Metal Arc Welding of Steel An Experimental Study of Micro-lack of Fusion Defects, 2013:2.

NICHOLAS CURRY Design of Thermal Barrier Coatings, 2014:3.


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EBRAHIM HARATI Improving fatigue properties of welded high strength steels, 2017:11.


ESMAEIL SADEGHIRMERESHT High Temperature Corrosion of Ni-based Coatings, 2018:23.


MORGAN NILSEN Monitoring and control of laser beam butt joint welding, 2019:27. [Kommande]

ARBAB REHAN Effect of heat treatment on microstructure and mechanical properties of a 5 wt.% Cr cold work tool steel, 2019:28. [Kommande]
Laser welding of ultra-high strength steel and a cast magnesium alloy for light-weight design

There is a strong industrial need for developing robust and flexible manufacturing methods for future light-weight design. In this study, focus has been on laser welding induced distortions for ultra-high strength steel (UHSS) where trials were performed on single hat and double hat beams simulating A-pillar and B-pillar structures. Furthermore, also laser welding induced porosity in cast magnesium alloy AM50 for interior parts were studied.

The results show that the total weld metal volume or the total energy input were good measures for predicting the distortions within one steel grade. For comparing different steel grades, the width of the hard zone should be used, corresponding to the martensitic area of the weld. Additionally, compared with continuous welds, stitching reduced the distortions.

For cast magnesium, two-pass (repeated parameters) welding with single-spot gave the lowest porosity of approximately 3%. However, two-pass welding is not considered production friendly. Twin-spot welding was done, where the first beam provided time for nucleation and some growth of pores while reheating by the second beam should provide time for pores to grow and escape. This gave a porosity of around 5%.

Independent on material, low energy input seems to generally minimize quality issues. Laser welding shows high potential regarding weld quality and other general aspects such as productivity in light-weight design for both high strength steel and cast magnesium.

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