Title: Laser Welding of Overlap Zinc Coated Steel Sheets without any Preset Gap.

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Assignment

Mechanical, Maritime and Materials Engineering
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Clair Micron and Nano Engineering
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Internship and MSc Project combined
for Mr.
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Laser Welding of Overlap Zinc Coated Steel Sheets without any Preset Gap

Introduction:
Zinc coated steels are widely used in the automotive industry as corrosion resistant materials for improved durability of structures. Laser beam welding is now appearing as a good alternative of the resistance spot welding (RSW) for the welding of zinc coated steel sheets in a lap joint configuration. However the process is disturbed due to spattering of molten metal during welding. The reason for this spattering is related to the low melting temperature of zinc (419°C) compared to the melting point of steel (1530°C). Due to this temperature difference, the zinc coating vaporizes and expands during welding at the interface of two sheets. This causes spattering of molten metal and porosity in the fusion zone if the zinc vapor cannot be vented properly.

Many solutions have been proposed to avoid this problem. Welding without any preset gap between sheets appeared as a good alternative during research in the Materials Science and Engineering Department, TU Delft. To understand the process physics of this technique, it is required to examine the following factors:
- Effects of process parameters on the weld quality such as welding power, welding velocity and coating thickness.
- Effects of different zinc coatings on the weld quality.

Assignment:
Develop theoretical hypothesis on the basis of prior research carried out to understand the process physics by addressing the above mentioned factors. Validate these hypotheses by experiments. Report your findings, discuss the results, propose additional investigations, concepts for improvements and make necessary recommendations.

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Coaching: Yu Pan (Materials Science & Engineering)  
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Acknowledgement

This report describes the work that I have carried out during my master’s project being a student at Delft University of Technology. The M.Sc. thesis work has been performed at M.S.E Department, TU Delft where I started in November 2007. During the project, I have gained a lot of practical knowledge that will definitely help me in future. This master’s thesis is the final part of the Master of Science program at the faculty of Mechanical, Maritime and Materials Engineering at TU-Delft.

Guidance and assistance of this project have been given by a graduation committee.

The members of the graduation committee are:
Prof. dr. U. Staufer (PME Department, TU Delft)
Prof. dr. I. M. Richardson (MSE Department, TU Delft)
Ir. J.J.L. Neve (PME Department)
Y. Pan (MSE Department, TU Delft)

I would like to acknowledge the efforts of my colleagues from MSE Department for their support and co-operation. I am also grateful to Dr. Ir. A. C. Riemslag who has arranged the Erichsen test in Corus. I also want to express my regards to E. de Wit and Dr. T. van der veldt of Corus who have helped me in performing this test. I would also like to thank E.R. Peekstok and A. Murugaiyan who have guided me in microstructure inspections and micro-hardness measurements at the MSE Department.

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Finally, I would like to express my deepest appreciation to my family, who have supported and encouraged me throughout this work, and to my wife whose steadfast love and support has made all this possible.

Muhammad Fahad
Summary

The demand for zinc coated steels in the automotive industry has increased significantly due to their usage in durable cars. Resistance spot welding is used mainly for the welding of zinc coated sheets in the automotive industry, but application of laser beam welding is now emerging as a good alternative. Recent research in this area is focused on understanding the process physics and evaluating problems which appeared in practice. One problem which is still not understood clearly is spattering of molten metal during welding. The reason for this spattering is related to the low boiling temperature of zinc (907°C) compared to the melting point of steel (1530°C). Due to this temperature difference, at the interface between two sheets, the zinc coating vaporizes and expands during welding. The high vapor pressure causes spattering of the molten metal and porosity in the fusion zone if the zinc vapor cannot be vented properly. Many solutions have been proposed to avoid this problem. Welding without any preset gap between sheets appeared feasible during research in the Materials Science and Engineering Department, TU Delft.

This project forms part of a research programme carried out in the MSE department. The objective of this project is to investigate and understand the effects and process physics of different process parameter and coating types on the weld quality of laser welding of overlap zinc coated steel sheets without a preset gap. Experiments on different zinc coatings were performed on the basis of previous research with varying process parameters. The experimental work yield interesting results regarding the influence of process parameters on weld quality. It was found that the effects of welding speed and welding power are significant. Good quality welds can be made at intermediate speed ranges i.e. around 45 mm/s where mass loss and the number of holes per unit length are low. It was also found that thinner zinc coatings can produce better weld beads than thicker zinc coatings. This result is contrary to previous research carried out in the MSE department and Corus, according to which thicker coatings produce good quality welds; further investigation is therefore recommended. Different alloy elements present in the zinc coating also have considerable influence on the zinc vapor formation which ultimately defines the weld quality.

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1 Introduction

1.1 Background
Zinc coated steels are widely used in the automotive industry as corrosion resistant materials for improved durability of structures. Resistance spot welding (RSW) is used mainly for welding of these materials but the electrodes suffer shorter life times when compared to electrodes used on uncoated steels. Laser beam welding is now appearing as a good alternative for the welding of zinc coated steel sheets in a lap joint configuration. In this type of welding, less flange (overlap) material is required. One sided access is also one of the advantages of laser welding. The stiffness of a structure is improved in the case of laser welding as compared to RSW welding due to the presence of a continuous weld. Since the laser process is non-contact, no electrode wear occurs, reducing the time and cost of the process. Very high welding speeds can be achieved and the process is also capable of welding sheets with less distortion as compared to RSW.
Successful implementation of laser beam welding will result in a significant reduction of weight, manufacturing time and cost. However the process is disturbed due to spattering of molten metal during welding. The reason for this spattering is related to the low boiling temperature of zinc (907°C) compared to the melting point of steel (1530°C). Due to this temperature difference, the zinc coating vaporizes and expands during welding at the interface of two sheets. The high vapor pressure causes spattering of molten metal and porosity in the fusion zone if the zinc vapor cannot be vented properly.
Many solutions have been proposed to avoid this problem. Welding without any preset gap between sheets appeared feasible during research in the Materials Science and Engineering Department, TU Delft.

1.2 Objective of Present Work
This project forms part of a research programme carried out by Y. Pan in MSE department in collaboration with M2i (Materials Innovation Institute) and Corus (Europe’s second largest steel producer). The objective of this work is to investigate and
understand the influence and process physics of the different process parameters and zinc coatings on the weld quality of overlap zinc coated steel sheets in the case of laser welding without any preset gap. To compare the weldability of different zinc coatings, materials were obtained from Corus, including Sn-Zn and Mg-Zn coatings. As these coatings are new and not examined yet during the research programme, the results will help to form a comparison of behavior of different zinc coatings during laser welding. Along with welding experiments, microstructure inspections, micro-hardness measurements and strength tests (Erichsen test) were also carried out in this research project to compare the different zinc coating influences on the welded region.

1.3 Thesis outline

This thesis is divided into two parts, a literature review of the previous research carried out in this field (chapters 2 and 3) and experimental investigations, comparisons, results, discussion, conclusions and recommendations for the future work (chapter 4 to 7). Following the first chapter which explains the background of the problem and objective of the thesis project, Chapter 2 provides information about zinc coatings. Zinc coating application in the automotive industry is described and different types of coating processes are discussed. An overview of zinc coating types and their metallurgy is also given. Chapter 3 deals mainly with the laser welding of zinc coated steels. A description of zinc vapor eruption is given and research strategies carried out to solve this problem are reviewed. The effects of different process parameters on the quality of laser welding of zinc coated steels are also considered.

In the experimental part, experimental setup and procedures, results and discussion are given. Chapter 4 describes the Welding experiments which consist of procedures, result of the experimental work and discussion made on basis of the experimental results. Microstructure inspections, micro-hardness measurement and strength test (Erichsen test) are discussed in chapter 5. Procedures are given for each of the tests followed by the results and discussion.

Conclusions and recommendation made on the basis of the experimental results and discussion are given at the end of the report (chapters 6 and 7).
Part-I Literature Review

2 Zinc Coatings
In this chapter, an overview of zinc coatings is presented and the application of zinc coatings in the automotive industry is discussed. Different types of zinc coatings and their metallurgy are introduced and methods of application on substrate steel are also described. Different zinc coatings used in the laser welding of zinc coated steels are discussed at the end of the chapter.

2.1 Zinc Coatings Application in Automotive Industry
In the automotive industry, zinc coated steel sheets are mainly used to improve the product durability and aqueous corrosion of steel. There are two methods of corrosion resistance, barrier protection and galvanic protection. In barrier protection, the zinc coating will first corrode before the corrosive environment reaches the steel. In galvanic protection, zinc is less noble or anodic than iron under ambient conditions, and will sacrificially corrode to protect the substrate steel, even if some of the steel is exposed as in the case at cut edges or scratches in the coatings.

2.2 Types of Coating Process
Zinc coatings are generally applied to iron and steel by the six methods briefly outlined below.

2.2.1 Hot-dip Galvanizing
In this process cleaned steel sheet is immersed in a bath of molten zinc maintained at a temperature around 450-460°C. A metallurgical bond is formed between zinc and iron or steel. The rate of coating formation is related to the type of steel. Coatings with reasonably constant thickness can be obtained by varying the immersion time in the bath. There are several specific zinc/iron compounds produced during the reaction, which form layers in the coating such as zeta (ζ), delta (δ), Gamma1 (Γ1) and Gamma (Γ) phases.
Hot-dip galvanized coatings are widely used in automotive industry. More than 2 million tons of zinc is used in this method to coat about 40 million tons of steel each year. All mild steels and cast irons can be coated and nearly half of the steel coated is in the form of sheet and a quarter is fabricated work; the remainder is tube or wire².

2.2.2 Electroplated coating
Pure zinc in the form of zinc salt solution is electrolytically deposited to form a layer on a steel surface. This process gives a bright and smooth finish, and is sometimes termed “electrogalvanizing” which is misleading, because the main feature of galvanizing is the formation of metallurgical bond at the zinc-iron interface and this does not happen in electroplating. Electroplated zinc is very ductile and extensively used for the plating of articles where severe deformation is required. These coatings are also used for decorative effect and to protect delicate objects where rough or uneven finishes cannot be tolerated (in instrument parts) and for articles that cannot withstand the pretreatment or temperatures required in other coating processes².

2.2.3 Mechanical Coating
This process involves agitating the parts to be coated with an appropriate mixture of nonmetallic impactors (e.g. glass beads), zinc powder, a chemical promoter and water. All types of steel can be coated in this process. The process has a limitation for parts heavier than about 250 g due to tumbling process which reduces the coating thickness at edges. The coating does not have an alloy layer between zinc and steel. Mechanical coating is particularly suitable for wrapping pipes and exposed steel bars or for touch-up purpose².

2.2.4 Sherardized Coatings
Steel sheets are tumbled in a barrel which contains zinc dust at a temperature just below its melting point, typically around 380°C. A diffusion process takes place between zinc and steel which creates a hard, even coating of zinc-iron compounds. Sherardized coating is useful for complicated shapes such as nuts and bolts due to its uniformity and abrasion resistance².

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2.2.5 Thermally Sprayed Coatings
Zinc wire or powder is melted by gas or electric heating and then ejected from a gun onto the workpiece. The droplets of semi-molten zinc coalesce and some zinc oxide is present at the interface of the droplets. Voids are present between coalesced particles, typically around 10%. Thermally sprayed coatings are used for local repair of zinc coatings that have been damaged and when local removal has occurred through machining. It is also used to protect high strength aluminum alloys\(^2\).

2.2.6 Coatings Containing Zinc Dust or Flake
In zinc paints, very fine dust and/or flake of zinc is suspended in an organic or inorganic medium. The dry paint film must be capable of conducting electricity to get the benefits of zinc cathodic protection. To ensure a good contact, the steel should be shot- or grit-basted before application of zinc dust paints. A barrier effect for corrosion resistance is provided by blocking the pores of zinc paint. Zinc painting is also termed cold galvanizing. This term is also misleading because there is no chemical bond developed at the zinc-steel interface. Zinc dust paints may be used alone for protection or as a primer followed by conventional top coats. Zinc dust paints are used as prefabrication primers. These paints are also used to repair damage caused by corrosion, welding, or mechanical damage to other types of zinc coatings\(^2\).

2.3 Types and Metallurgy of Alloy Coatings
There are four main types of zinc coatings. These alloy coatings are categorized principally on the basis of the percentage of the aluminum particles present in the alloy coating. These alloy coatings have been developed to reduce the cost of coating materials and to increase the lives of zinc coated products. An overview of these alloy coatings is given in this section.

2.3.1 Galvanized (<1 wt% Al)
Aluminum is used as an alloying element added to the hot-dip galvanizing bath to produce different properties in the bath\(^3\). The grain structure of hot-dip galvanized coating is usually termed as spangles. These structures are basically very large grains as shown in Fig. [2.1]. Spangle size is dependent on the cooling condition during
solidification. As mentioned before, intermetallic layers are formed at the interface of zinc and steel. These intermetallic layers are

![Image](image_url)

Figure 2-1 Typical spangles structure of a galvanized coating (Scale not found)$^1$.

- **Zeta (ζ) phase**
  The iron content in zeta (ζ) phase, FeZn$_{13}$ ranges from 5.0-6.0 wt% and the phase develops from the peritectic reaction between the delta (δ) phase and liquid zinc at 530±10°C. The unit cell of zeta (ζ) phase is monoclinic. It has an atomic structure which consists of an iron atom and zinc atom bounded by 12 zinc atoms at the vertices of a slightly distorted icosahedron. These icosahedra links form chains these linked chains are packed jointly in a hexagonal array$^4$.

- **Delta (δ) phase**
  The iron composition ranges from 7.0-11.5 wt% in the delta (δ) phase, FeZn$_{10}$ which has a hexagonal unit cell. This phase is the result of another peritectic reaction between gamma (Γ) and liquid at 665°C$^5$.
• Gamma$_1$ (Γ$_1$) phase
The lattice structure of Gamma$_1$ (Γ$_1$) phase, Fe$_3$Zn$_{21}$ is face centered cubic and contains iron contents of 17-19.5 wt% at 450°C. It is the result of a peritectoid reaction between the gamma (Γ) and delta (δ) phases. It appears as an uninterrupted layer between the gamma (Γ) and delta (δ) layers and can be formed upon heating at low temperatures over long periods of time$^6$.

• Gamma (Γ) phase
The iron content in the Gamma (Γ) phase, Fe$_3$Zn$_{10}$ is 23.5-28.0 wt% at 450°C. This phase has a body centered cubic structure and is produced as a result of a peritectic reaction between α iron and liquid zinc at 782°C$^7$.

Figure 2.2 Microstructure of Zn coating. (1) gamma (Γ) phase, (2) delta (δ) phase (3) zeta (ζ) phase$^1$.

2.3.2 Galfan (5 wt% Al-Zn)
Galfan is a Zn-alloy which contains 5% of Al. A Galfan coating has a two-phase microstructure i.e. a zinc-rich eta(η) proeutectoid phase bounded by a eutectic type phase
consisting of beta (β) aluminum and eta (η) zinc lamellae as shown in Fig. 1.3. The microstructure of Galfan can be varied depending upon cooling rate. It is reported by Makimattila and Ristolainen that there is no visible intermetallic layer or at least an extremely thin layer (<0.5μm) at the interface between the steel substrate and the overlay coating at normal bath temperatures of 420-440°C.

![Figure 2.3 Planar view of the lamellar microstructure of a Galfan coating](image)

**2.3.3 Galvalume (55 wt% Al-Zn)**

A Galvalume alloy coating contains 55% Al and 1.5% Si as alloying elements. Si is used to prevent an exothermic reaction at the coating overlay/substrate steel interface. An interfacial Fe-Al-Zn intermetallic alloy forms during the coating process at the interface between the steel substrate and the overlay coating. The Galvalume coating surface contains typical spangles that consist of aluminum dendrites as shown in Fig. 2.4.
2.3.4 Galvanneal

Galvanneal coatings are basically diffusion coatings which are produced by heat treatment of either hot-dip or electro-galvanized coatings. In this process zinc galvanized steels are exposed to an annealing temperature around 500°C to produce a fully alloyed coating containing Fe-Zn intermetallic phases. Good process control is required to produce desired galvanneal microstructures and properties because the variables involved are complex. The important process parameters include heating rate, hold temperature and time, cooling rate, bath chemistry and substrate composition\(^1\). Galvanneal coating microstructures have been classified by Jordan and Marder\(^2\) as follows:

- Type 0 contains an underalloyed coating consisting of predominantly zeta (\(\zeta\)) phase.
- Type 1 consist of an optimum alloyed coating with less than a 1 µm interfacial gamma (\(\Gamma\)) layer and an overlay containing delta (\(\delta\)) phase interspersed with a small amount of zeta (\(\zeta\)) phase.
Type 2 contains an overlaid coating with a gamma layer >1µm and an overlay containing of a delta (δ) phase with basal plane cracks perpendicular to the coating/substrate interface and an occasional top layer of zeta (ζ) phase.

Figure 2.5 Morphology of galvanneal coatings: (a) type 0, (b) type 1, and (c) type 2.
2.4 **Zinc Coatings used in Laser Welding of Zinc Coated Steel**

Mostly researches on laser welding of zinc coated steel sheets in an overlap joint configuration are done with hot-dip galvanized, electrogalvanized and galvanneal coatings. The effect of alloy coating types on laser weld quality is not significant as reported in\textsuperscript{[13-14]}. However as mentioned in\textsuperscript{[15-16]} weldability of galvanized coatings are better than the galvannealed coating. It is interesting to mention that galvanneal alloy coatings are especially developed to improve the welding properties of zinc coated steel for the resistance spot welding. The possible reason for this behavior in the case of laser welding could be the different coating melting temperatures. A coating molten zone is developed at the sheet/sheet interface just in front of the keyhole. A wider molten zone as in the case of galvanized coating due to its lower melting temperature may enable a consistent and uniform liquid coating thickness which would minimize the effect of any irregular changes in the coating characteristics\textsuperscript{16}. It is observed from the literature review that the effect of different zinc coatings on the quality of laser welding of zinc coated steel sheets is not well understood. Therefore a detailed study is required to examine the effect of alloy coating composition on welding quality.
2.5 References

3 Laser Welding of Zinc Coated Steel

In this chapter laser welding of zinc coated steels in an overlap configuration is discussed, the problem of zinc vapor expulsion is described and consequences are mentioned. Existing techniques which are used in laser welding of zinc coated steels are introduced and effects of different process parameters on laser welding are addressed. A novel ZnMg coating is described at the end of the chapter and laser welding of this new coating is also discussed.

3.1 Problem Description
The vaporizing temperature of zinc (907°C) is much lower than the melting temperature of steel (1530°C). When the two zinc coated sheets are welded in a lap joint configuration without any preset gap, the zinc at the interface vaporizes and expands violently. The possible exit way of the zinc vapor is through the keyhole and weld pool. Due to the high dynamic pressure of zinc vapor, the keyhole stability is disturbed and a large amount of liquid steel is blown away from the weld pool. This phenomenon causes spattering, cavities and blow holes in the weld seam. The corrosion resistance, the strength and the aesthetics of the weld seam are disturbed by these defects.

3.2 Existing Techniques to Solve the Problem of Zinc Vapor Eruption
Various approaches have been investigated to prevent the weld pool from being destroyed by zinc vapor. These approaches are mainly divided into two categories: mechanical control and physical-chemical control. In mechanical control, zinc vapor is vented by introducing a preset gap at the interface or enlarging the keyhole by means of a dual beam. Physical or chemical methods of suppressing vapor discharge involve adding another substance to the welding environment to absorb, dissolve or react with the zinc. These approaches are discussed briefly in the following sections.

3.2.1 Removal of zinc coating from the interface
In this approach the zinc coating is removed from the interface of two sheets as proposed in [3-5]. Another technique is patented by Pennington in which zinc is removed from the weld area and replaced with a nickel coating. The vaporization of the nickel coating is not
significant at the steel fusion temperature, and still provides corrosion protection. However, these techniques have the disadvantage of additional processing cost and in general are not practical for industrial applications.

3.2.2 Formation of Zinc Alloy by Foil Insertion
In physical-chemical methods of managing Zn vapor, the vapor pressure may be reduced by combining Zn with another substance. Initially copper has been suggested as an interfacial addition for this activity [7-9]. It is observed that while copper could reduce the interfacial zinc activity by in-situ formation of a liquid brass alloy, its actual effectiveness should be low because its melting temperature of 1083°C is too far above the boiling point of zinc. Copper addition also enhances solidification cracking of steel [10]. Some researchers [2,11] used aluminum as an alloying element due to its advantages as a process stabilizing additive. Its low melting temperature facilitates rapid interaction with liquid zinc. It also has a complete liquid solubility for zinc. The very high vaporizing temperature (2450 °C) of aluminum minimizes the vapor pressure of liquid Al-Zn solution. Experiments performed on galvannealed coatings showed improvement in weld quality, as shown in Fig. 3.1.a and 3.1.b.

Figure 3.1.a Surface of a lap weld without Al foil.
Figure 3.1.b Surface of a lap weld with Al foil\(^2\).

As explained by Li et al\(^2\) aluminum foil was inserted between strips of galvannealed sheets as shown in Fig. 3.2. Good quality welds are found with this technique but tight clamping is one of the process requirements. As automotive weldments are typically much larger, more complex in shape and variable in terms of component fit up than the laboratory weldments, improved ways of applying Al are required. Therefore cold spray coating of Al was also investigated. The results were again satisfactory with hot-dip galvanized and galvannealed coated sheets. It is also discovered that tight clamping was not required in this case, which increased the process productivity by reducing the clamping time\(^2\).

Figure 3.2 Schematic diagram of weld coupon assembly for lap welding\(^2\).
3.2.3 Welding with preset gap

Laser welding of zinc coated steel with a preset gap is the most successful method to achieve good quality welds. This method provides space for the escape of the zinc vapor from the interface of two sheets. A model has been developed by Akhter and Steen to predict the range of gap sizes which will permit CO₂ laser seam welds of acceptable quality to be produced. According to this model, the required gap is a function of welding speed, zinc coating thickness, and sheet thickness. Generally, the zinc vapor pressure must be higher than the static pressure in the gap between the sheets, but lower than the ferrostatic pressure in the liquid metal at the sheet interface, for the escape of zinc vapor through the gap. Therefore, on the basis of this pressure balance, the minimum gap required to exhaust the zinc vapor between the sheets was given by the equation.

\[ G = \frac{AVt_{Zn}}{t_p^{1/2}} \]

where \( G \) is the measured gap between the sheets [m], \( V \) is the welding speed [m/s], \( t_{Zn} \) is the thickness of zinc coating of each sheet at the interface [m], \( t_p \) is the sheet thickness [m] and \( A \) is a material constant [\( \text{sm}^{-1/2} \)]

\[ A = \frac{\rho_s}{2(2.\rho_v\rho_l/g_g)^{1/2}} \]

where \( \rho_s \) is the density of solid zinc [kg/m\(^3\)], \( \rho_v \) is the density of zinc vapor [kg/m\(^3\)], \( \rho_l \) is the density of liquid iron [kg/m\(^3\)] and \( g_g \) is the acceleration due to gravity [m/s\(^2\)]. It can be observed from the above formula that the value of \( A \) depends on the densities of coating and substrate steel. Initially the value of \( A \) (18.25sm\(^{-1/2}\)) was found experimentally by Akhter. But latter, the value of \( A \) was re-calculated from his above mentioned formula with the values of \( \rho_s \) (7135kg/m\(^3\)), \( \rho_v \) (21.87kg/m\(^3\)), \( \rho_l \) (7320 kg/m\(^3\)) and \( g_g \) (9.8 m/s\(^2\)) and found 2sm\(^{-1/2}\).

The maximum gap to avoid the excessive drop-through was subjectively defined by Akhter and Steen to be 35% of the sheet thickness. This model was used by Graham for the galvanized and galvannealed sheet steels. Experimental results were compared with the model suggested by Akhter and plotted between \( AVt_{Zn}/(t_p)^{3/2} \) and \( g/Tp \) as plotted in Fig. 3.3.a and 3.3.b, respectively. The maximum gap above which drop-through occurred was consistent with the model, but the limit was slightly lower than the model.
The reason for this divergence was possibly due to the difference in the subjective interpretation of excessive drop-through. The optimized gap found by experiments is 0.1 mm [11-12,19].

Figure 3.3.a Operating regimes and results for laser seam welding of galvanized sheet steel with various gaps and welding speeds\textsuperscript{12}.

Figure 3.3.b Operating regimes and results for laser seam welding of galvannealed sheet steel with various gaps and welding speeds\textsuperscript{12}.
There are three methods to produce gap at the sheet interface.

- Gap produced by shims or spacers\textsuperscript{12}.
- Gap produced by burl sheet metal\textsuperscript{20}.
- Gap produced by radius in sheets\textsuperscript{21}.

The schematic views of these techniques are shown in Fig. 3.4.a, 3.4.b and 3.4.c. It has been shown during research under laboratory and industrial conditions that good quality welds are possible with a preset gap. However the implementations of these techniques are costly and require control in maintaining the gap.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig3_4_a.png}
\caption{Figure 3.4.a Gap produced by shims\textsuperscript{12}.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig3_4_b.png}
\caption{Figure 3.4.b Gap produced by burl sheet metal\textsuperscript{20}.}
\end{figure}
3.2.4 Laser-Arc Hybrid Welding

As discussed above, the optimized value of preset gap in the case of laser welding of zinc coated steel sheets is 0.1 mm. The requirement of controlling this gap is quite strict because if the gap is wide, burn-through occurs, and if the gap is excessive, the two sheets cannot be welded together. Laser-arc hybrid welding has been used to solve the problem of strict gap control. The combination of YAG laser welding and arc welding, facilitates a larger gap between lapped sheets than in laser welding, and produces less blowholes. In this technique, an arc-welding electrode is positioned behind the YAG laser radiation point as shown in Fig. 3.5.

The gap tolerance for hybrid lap welding is significantly greater than that for laser welding because the filler wire used in hybrid welding provides sufficient weld metal to fill the gap. In the case of laser welding, underfill or burn-through is observed because
there is no filler material available in this situation and the amount of molten metal tends to be insufficient to fill the gap. The strength of welded joints is also high because the bead width is wider than that in laser welding. The formation of blowholes is also restrained significantly compared with laser welding, even when the gap is 0 mm.

3.2.5 Dual Beam Laser Welding
The dual beam technique is used to extend the beam keyhole and increase the time available for vapor to diffuse through the weld under less violent conditions compared to single beam welding. For this purpose two beams with the same source or two beams with different sources are used. The reason that this technique is successful is that it keeps the rear wall of the keyhole away from the source of zinc vapor, preventing a collision which causes spatters or material expulsion during welding. The quality of dual beam welding is excellent with zero gap present between the sheets\textsuperscript{23}.

In some of the numerical simulation results, it was observed that when the two beams separate too far, the rear beam will generate a concavity in the rear keyhole wall as shown in Fig 3.6 which is not a stable structure for the liquid metal in the weld pool at the rear key wall. This causes spattering and porosity in the welds due to non-steady fluid flow. These numerical results were verified by the welding tests\textsuperscript{24}.

![Diagram of keyhole geometry](image)

Figure 3.6 Longitudinal keyhole geometry as derived from numerical simulation\textsuperscript{24}.
In order to improve the process, a new idea was suggested in which the trailing beam is tilted to certain angle as shown in Fig. 3.7. The intention for tilting the trailing beam was to align the beam with the rear keyhole wall formed by the leading beam to solve the problem caused by formation of concavity in the rear keyhole wall. Good quality welds were found with this configuration with a wide range of different welding parameters.\(^{24}\)

![Figure 2.7 Dual beams with tilted trailing beam.\(^{24}\)](image)

3.2.6 Laser Welding of Zinc Coated Steel Sheets with Zero Gap

Although, different methods discussed above to solve the problem of zinc vapor expulsion during laser welding of zinc coated steel showed promising results, their application in an industrial environment is not generally feasible due to technical and economical restrictions. Continuous wave, single spot, gap free welding of zinc coated steel was investigated by different researchers\(^{25\text{-}29}\). The main challenge in this approach is still zinc vapor expulsion from the weld pool which causes porosity, blowholes and spattering. However, successful implementation of this technique was reported by Pieters\(^{25}\). He also proposed the mechanism of transient gap formation at the sheet interface to explain the process dynamics.\(^{26}\) Pan\(^{28\text{-}29}\) also mentioned satisfactory results with different zinc coating thickness and clamping systems. In the next sections, these results are explained in detail because gap free welding of zinc coated steel is the main scope this project.

3.3 Zinc Transport Mechanism in Gap Free Laser Welding

Pieters\(^{26}\) suggested a possible mechanism for the transport of the zinc during the laser welding process of zinc coated steel, where it is assumed that the zinc at the interface of two sheets vaporizes, which is the main cause of the blowholes and porosity in the welds. This happens because zinc vaporizes before the melting of steel, causing a high pressure
between the steel sheets immediately in front of the weld pool. This high pressure is released by ejection of vapor through the weld pool when the weld pool penetrates the first sheet and the molten pool is ejected. Pieters proposed that the liquid zinc transportation is a much more effective way of removing the zinc from the weld area in comparison with zinc vapor venting since the volume to be removed is 2000 times smaller in the liquid state. A large amount of molten zinc is present between the sheets at the same time when the evaporation temperature is reached. The evaporated zinc pushes the liquid zinc away from the weld region in front of the weld as well as outward, like a bow wave. A balance is expected between speed of the bow wave, welding speed and evaporation rate of the liquid zinc. This defines the boundary between good welds and welds with blowholes and porosities.

It was noticed that the zinc coating was found in contact with the fusion zone after weld solidification which indicates that the zinc was liquid after the weld pool solidified and the zinc was transported back to the weld pool as a liquid. It is assumed that this must have happened close to the zinc melting temperature. It would be expected that at high temperature, the high vapor pressure of zinc would have created a gap between the weld pool and the zinc layer.

It was also observed that there were discontinuities in the zinc coating at a consistent distance from the weld pool as shown in Fig. 3.8. During the welding process, the zinc was molten close to the weld region. The zinc vapor pressure transported some of the zinc away from weld pool. The zinc flows back after weld pool solidification but the viscosity of liquid zinc increases with decreasing temperature and it increased the distance of liquid zinc from the weld pool. The viscosity of the liquid zinc becomes too high at some distance from the weld pool and as a result the flow of liquid is obstructed. This leaves a gap behind in the zinc coating after solidification.
3.4 Effect of Different Process Parameters on Weld Quality

In this section effect of different process parameters such as zinc coating thickness, shielding gases and different clamping systems are discussed.

3.4.1 Zinc Coating Thickness

In the research of Pieters\textsuperscript{26} and Pan\textsuperscript{2929}, laser welding on zinc coated sheets of different coating thicknesses was performed. A mechanism of transient gap formation was suggested according to which when the sheets are heated by the laser beam, a transient gap is thought to be produced due to local thermal deformation. The lower sheet tends to deform downward whilst the upper sheet tends to hump up due to thermal expansion. This causes an out of plane deformation, as clamping limits the possibility for planar movement. A large amount of zinc is present between the sheets which is pushed away by the zinc vapor pressure from the weld region in front the weld as well as outward like a wave. Sufficient zinc vapor is available in the case of thicker zinc coating to provide a stable pressure which pushes away the liquid zinc from the weld area. In contrast, the zinc vapor at the interface is not sufficient in the case of thinner zinc coating in helping a gap or pushing the liquid zinc away from the fusion zone. This reduces the additional space required for the zinc vapor to escape from the interface. Therefore the process is more stable and fewer weld defects are observed in the case of thicker zinc coating compared to thinner zinc coatings.

In the case of thicker zinc coating, uniform zinc coating was observed as compared to thinner zinc coating which showed irregular appearance of zinc at the interface. This happens because from the thicker zinc coating, molten zinc exists in between the sheets which flows back and wets the weld zone after the latter has solidified. This does not occurred with thinner zinc coating because the mechanism of transient gap and liquid zinc is not working well in this case as discussed above.
3.4.2 Clamping System
The effect of clamping system on the laser welding of zinc coated steel was investigated by Pan\textsuperscript{28}. Three types of clamping systems were used during the research. A schematic view of the clamping systems is given in Fig. 3.9.a. The difference between the three is the air gap widths of 16, 8 and 4 mm as show in Fig. 3.9.b.

![Clamping force diagram](image)

Figure 3.9.a Schematic illustration of the clamping system\textsuperscript{28}.

![Clamping system illustration](image)

Figure 3.9.b Schematic illustration of the different clamping system (a) air gap width of 16mm and (b) air gap width of 8mm\textsuperscript{28}.

Defects such as blowholes and surface breaking porosities are observed mainly on the top surface in the case of 16mm air gap width as shown in Fig 3.10. However, the bottom surface showed better weld quality and the weld seam width is uniform as shown in Fig.3.10.
Figure 3.10 Laser welded zinc coated steel sheets with a 16mm air gap underneath\textsuperscript{28}.

In the case of the 8mm air gap width, fusion defects were observed on both sides and the weld seam root width also varied from 1.3 to 1.7 mm as shown in Fig.3.11. With a 4mm air gap width, the top surface showed a good quality weld, but the bottom surface showed severe instability. Blowholes and porosities were observed throughout the weld seam and width of seam was also inconsistent, varying from 1.5 to 2 mm as shown in Fig 3.12.

Figure 3.11 Laser welded zinc coated steel sheets with a 8 mm air gap underneath\textsuperscript{28}.

Figure 3.12 Laser welded zinc coated steel sheets with a 4 mm air gap underneath\textsuperscript{28}.

The influence of clamping system was explained with the transient gap mechanism suggested by Pieters\textsuperscript{26}. With smaller air gap width under the sheet, the possibility of
downward deformation is less and the transient gap created between the sheets is reduced. Due to this reason, it is expected that the heat transfer between two sheets and the keyhole dynamics will be modified. More heat might be transferred to the lower sheet because the distance between two sheets is reduced due to a smaller transient gap. This broadens the weld seam root width in the case of smaller air gap width. Due to an increase in heat input to the lower sheet, more zinc is evaporated which will intensify the disturbance of the melt pool. More fusion defects are found on the weld at the bottom side with smaller air gap because the time left for the weld pool to heal defects by means of fluid flow is less. This happens due to heat removal from the bottom sides of the sheets by the bars underneath.

As mentioned by Fabbro, the laser keyhole is supposed to be an important channel for zinc escaping when there is no gap between the sheets. This function dominates as compared to transient gap which also provides a space for a certain amount of zinc, especially when zinc vapor production is excessive. The disturbance to the upper sheet is less severe in the case of smaller air gap width as described in the phenomena mentioned above that due to the heat loss from the bottom sides of the sheets to the clamps, less time is left for the weld pool to heal itself. Hence, the melt pool fails to heal following zinc vapor disturbance and lower aperture of the keyhole remains open for the zinc vapor escape. The zinc vapor tends to escape through the lower sheet leaving a lot of blowholes behind. Therefore the quality of the upper weld surface is good even though an extremely bad quality weld is found at the lower surface. In contrast, when the heat loss to the clamp is less severe, as in the case of larger air gap width, the bottom side weld is able to heal itself and the lower aperture of the keyhole tends to close earlier than the upper aperture. Therefore, zinc vapor tends to escape through the upper sheet, resulting in more top side fusion defects.

3.4.3 Shielding Gases
Effect of different shielding gases was investigated by Graham. It was observed that the type of shielding gas used had little effect on laser weld quality. In the case of preset gap of 0.15 mm, use of different gases showed slight changes in weld shape. Welds produced in a zero gap condition showed some changes in penetration with shielding gas. Gases

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like nitrogen, M5 (93%Ar+2%O₂+5%CO₂)³⁰, and argon shielding produced distinctly deeper welds. M5 gas exhibited the smoothest top surface. It is also reported that the increase in shielding gas flow produced deeper penetration but the stability of the weld pool surface decreased.
3.5 References


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13 P. Denney and J. Xie, The welding of galvanized steel, ICALEO 2000, Laser applications in the automotive industry, 2000, West Bloomfield, MI, USA.
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Part-II Experimental Work

The major tasks in this thesis are to study the effects of different welding parameters and coating types on the weld quality of the laser welded zinc coated steel sheets. It was observed from the previous research that the main process parameters of laser welding are welding speed and welding power, which need to be investigated in order to understand their effects on the welding quality. The parameters relating to zinc coating are coating thickness and alloying elements which may change the weld quality. Welding experiments were carried out to study these effects. These experiments were followed by microstructure inspection, micro-hardness measurements and strength (Erichsen) test to investigate and compare the changes in microstructure and weld strength for different zinc coated steel sheets.

4 Laser Welding Experiments

In this chapter the materials used in the welding experiments are introduced. The laser welding experimental arrangements and procedures are described and results are presented and discussed.

4.1 Laser Welding Arrangement and Procedures

4.1.1 Sheet Materials

Comparison of weldability of different overlap zinc coated sheet steels in the case of laser welding without any preset gap is studied in this Masters project. To compare different zinc coated steel sheets, it was planned to perform laser welding experiments on different types and thickness of zinc coatings. For this purpose, different types of zinc coated steel sheets were obtained from the Corus. The list of the materials examined and their description is given in table 4.1.
<table>
<thead>
<tr>
<th>Serial #</th>
<th>Type of Zinc Coating</th>
<th>Thickness of Base Metal (mm)</th>
<th>Thickness of Zinc Coating (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Electrogalvanized (EG) Coating</td>
<td>0.7</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Hot-Dip galvanized (GI) Coating</td>
<td>0.8</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>Sn-Zn Coating (Sn-Zn)</td>
<td>0.8</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>Mg-Zn Coating (6 μm)</td>
<td>0.8</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>Mg-Zn Coating (12 μm)</td>
<td>0.8</td>
<td>12</td>
</tr>
</tbody>
</table>

The compositions of the substrate steels are given in table 4.2. The substrate steels for the Mg-Zn coating is DX54D while the substrate steels for hot-dip galvanized and Sn-Zn sheets is the same. The melting and boiling temperatures of major alloying elements present in the zinc coating layers are given in table 4.3.
Table 4.2 The compositions in weight percent of the substrate steels measured with XRF (X-Ray Fluorescence Spectroscopy).

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>C</th>
<th>Cr</th>
<th>Mn</th>
<th>Si</th>
<th>Al</th>
<th>Cu</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>No1 EG</td>
<td>Bal.</td>
<td>0.0136</td>
<td>0.0161</td>
<td>0.16</td>
<td>0.108</td>
<td>0.0853</td>
<td>0.0099</td>
<td>0.0359</td>
</tr>
<tr>
<td>No 2,3 GI, Sn-Zn</td>
<td>Bal.</td>
<td>0.0271</td>
<td>0.0176</td>
<td>0.146</td>
<td>-</td>
<td>0.334</td>
<td>0.0187</td>
<td>0.0207</td>
</tr>
<tr>
<td>No 4,5</td>
<td>Bal.</td>
<td>0.002</td>
<td>0.022</td>
<td>0.171</td>
<td>0.007</td>
<td>0.033</td>
<td>0.015</td>
<td>0.026</td>
</tr>
<tr>
<td>Mg-Zn (6 μm),</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg-Zn (12 μm)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Ti</th>
<th>P</th>
<th>Zn</th>
<th>V</th>
<th>Mo</th>
<th>S</th>
<th>N [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No1 EZ</td>
<td>0.0584</td>
<td>0.12</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.0148</td>
<td>-</td>
</tr>
<tr>
<td>No 2,3 GI, Sn-Zn</td>
<td>0.0423</td>
<td>0.224</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.0159</td>
<td>-</td>
</tr>
<tr>
<td>No 4,5</td>
<td>0.045</td>
<td>0.008</td>
<td>0.014</td>
<td>0.001</td>
<td>0.005</td>
<td>0.007</td>
<td>21</td>
</tr>
<tr>
<td>Mg-Zn (6 μm),</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg-Zn (12 μm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3 Melting and boiling temperatures of alloying elements.

<table>
<thead>
<tr>
<th>Alloying Element</th>
<th>Melting temperature °C</th>
<th>Boiling Temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc (Zn)</td>
<td>419</td>
<td>907</td>
</tr>
<tr>
<td>Aluminum (Al)</td>
<td>660</td>
<td>2467</td>
</tr>
<tr>
<td>Magnesium (Mg)</td>
<td>648</td>
<td>1090</td>
</tr>
<tr>
<td>Tin (Sn)</td>
<td>231</td>
<td>2602</td>
</tr>
</tbody>
</table>
A brief description and application of each type of the coated steel sheet is given in the following sections:

4.1.1.1 Mg-Zn (12 μm)
Mg-Zn (12 μm) coatings has been developed by Corus. The percentage of Mg in the zinc coating is around 1–2 wt%. This product can be used for two applications namely building and construction as well as automobiles. For automobiles, it can be used for the future replacement of hot-dip galvanized i.e. GI (12 μm) coatings, which is presently used in the inner parts with the idea to increase perforation corrosion guarantees and to reduce costs in the car manufacturing (waxing, sealing, replacement corrosion primer). For building and construction, it is meant to replace present thick GI (22 μm) coatings contributing to zinc reduction while maintaining and even improving the corrosion resistance.

4.1.1.2 Mg-Zn (6 μm)
Mg-Zn (6 μm) is developed by Corus for future automobile applications and to replace presently used GI (7 μm), and GI (12 μm) zinc coatings. The percentage of Mg in the zinc coating is the same as in the case of Mg-Zn (12 μm).

4.1.1.3 GI (6 μm)
GI (6 μm) is a cold rolled hot dip galvanized low carbon steel sheet. The material was produced for typical automotive applications that require good formability and corrosion resistance as well high surface quality. The material was produced at Corus IJmuiden (The Netherlands).

4.1.1.4 Sn-Zn (4 μm)
The 4 μm thick SnZn coating contains 8 wt% Zn. The material is used to manufacture fuel tanks. The coating was developed as a replacement for lead containing coatings that are not acceptable anymore due to health and safety regulations. The material was produced at Corus’Cookley Works (UK).

4.1.1.5 EG (4 μm)
EG (4 μm) is used for the electrical household applications and already discussed in section 2.2.2.

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4.1.2 Welding Rig Equipment

The laser welding equipment consists of a clamping table that moves 1-dimensionally with respect to the laser head as shown in fig. 4-1.b. The clamping table consists of a 420 x 300 x 20 mm steel backing plate that is mounted on the x-axis of the transverse system. An 8 mm wide by 10 mm deep efflux channel exists along the centerline of the backing plate. The sheets were vertically clamped on the clamping table with the efflux channel in the middle where the weld was to be made. A schematic view of the clamping system is shown in Fig. 4-1.a. Mechanical forces were applied on the clamping bars by using toggle clamps with 9 clamps per side to ensure that the sheets were held tightly and evenly as shown in Fig. 4-1.b.

Different clamping systems were available in the laser welding lab but the above mentioned arrangement was used in this research to obtain consistency in the results. The effect of different clamping system has already been investigated in the MSE lab by Y. Pan and discussed in section 3.4.2. This clamping system was designed and developed by R. Pieters. This arrangement was especially designed for the research in the MSE lab and its results could be different from the arrangement used in the industry.

Figure 4-1 A schematic illustration of the clamping system.¹
Figure 4-1.b Laser Welding clamp arrangement.

The traverse system is controlled by a three-axis digital motion controller (DMC). The weld speed and direction is defined by the clamping table’s movement along the x-axis, while movement along the y axis defines the clamping table’s lateral placement. The z-axis defines the laser head height with respect to the clamping table. The clamping table moves during welding while the laser head is at a fixed position.

4.1.3 Sample Preparation

Sheets were cut into the sizes (50x100 mm) in such a way that samples can be clamped tightly to ensure the absence of a gap between the sheets. Samples were cleaned with acetone prior to welding to remove dust and any residual passive layer such as oil contamination from the surface.

4.1.4 Welding Parameters

Laser welding parameters i.e. laser power, welding speed and weld length were controlled with a Labview program which was developed in the MSE department. Different combinations of laser power and welding speed have been used to examine the effects of these parameters. Welding lengths (100-120 mm) were set in such a way that steady state processing conditions were obtained.
4.1.5 Laser Welding Process

A Nd:YAG (Trumpf HL3006D) laser with a nominal power of 3kW was used to perform the experiments. The laser light was transported through a 600 μm glass fibre to focusing lenses and the distance of the focusing lenses was 150 mm. The laser beam was focused to a single spot of 450 μm perpendicularly at the top sheet surface. Argon gas was used as the shielding gas to protect the hot sheet steels against oxidation. A coaxially nozzle was used with a flow rate of 30 l/min. A cross jet was placed just below the protection lens to blow away the spatter produced during welding. All laser welding experiments were repeated three times in different days to get repeatability in the results.

4.1.6 Process Recording with a High Speed Camera

A CMOS high-speed camera (Phantom V5) was used in the experiments to capture the plume behavior during welding. To shoot the videos of the top and bottom sides of the specimen, modifications were made in the clamping arrangement. Welded specimens clamped from one side were used for this purpose as it is not possible to capture the videos with specimens clamped on two sides. Therefore only the un-welded side of the specimen was clamped and welded side remained unclamped so that there was no gap at the interface as shown in fig 4-2.a. The camera was set horizontal to the specimen to observe both the top and bottom of the sample. To capture a video of the weldpool, the camera was set at an angle of 35° relative to the sample as shown in fig. 4-2.b. The welding experiments were carried out only once with the high speed camera to get the images of the weldpool and plume during welding.
4.2 Welding Quality Assessment
Welding quality is assessed in two ways during this study. The first is by correlation with the mass loss of the molten metal per unit weld length. Welded sheets were weighted before and after the weld and then the difference between the initial and final weight was divided by the actual welding length in order to calculate the mass loss.
In the second method, the number of holes at the top and bottom surfaces of the welded sheets were counted and then divided by the weld length. In this way the numbers of holes at the top and bottom sheets per unit length were obtained.

4.3 Background for Welding Experiments
It was observed from the previous research on laser welding of zinc coated steel sheets that welding speed has a significant influence on the weld quality. More fusion defects are expected at the bottom surface than the top surface during welding at lower speed as mentioned by Pan1. Opposite results were observed at the higher speed. However the observations were made for only two welding speeds and therefore it is required to perform more experiments with different welding speeds.

The effect of varying the welding power on the keyhole geometry and zinc vapor escape through it is rarely discussed in the previous research for laser welding of zinc coated steel sheets. However it is well known that the keyhole is wider in the case of high laser power which may facilitate the escape of zinc vapor from the interface of two sheets. It is therefore required to perform welding experiments with different welding powers. The maximum power available in the laser welding lab at the MSE department is 3 kW. Therefore it is only possible to check the welding quality at 2.5 kW to 3 kW because laser powers lower than 2.5 kW are not acceptable in the industry due to low productivity.

The influence of alloying elements present in the zinc coating is discussed in section 3.1.1.2. It was noted that addition of alloying elements of higher boiling point in the zinc coating may minimize the zinc vapor pressure by increasing the boiling temperature of the solution of the zinc and the alloying element. Hence the better quality welds can be obtained. However the experiments were performed with the Cu or Al foil inserted between two sheets. Zinc coatings with different alloying elements have not yet been examined. Recently new zinc coatings like Mg-Zn and Sn-Zn have been produced by Corus. Laser welding on these coatings could provide more information about the effect of alloying elements; hence welding experiments have been performed on these materials along with traditional zinc coatings like hot-dip galvanized (GI) and electrogalvanized (EG) coatings.
4.4 Results

4.4.1 Experiments with Varying Welding Speed

The influence of welding speed on the welding quality in terms of mass loss is given in fig 4-3. The welding power was kept constant at 3 kW in all the experiments. It is observed that welding speed has a significant effect on the weld quality especially for thicker coatings. For thinner coatings like Sn-Zn (4 μm) and EG (4 μm) coatings, the mass loss decreases with the increase in welding speed. In the case of thicker coatings i.e. Mg-Zn (12 μm), Mg-Zn (6μm) and GI (6μm) coatings, the mass loss increases at lower and higher speed. Minimum mass loss is observed around an intermediate speed (45 mm/s) for these three types of zinc coated sheets.

For Mg-Zn (6 μm) and Mg-Zn (12 μm) coatings, a dip was observed around 45 mm/s. To investigate this behavior, more experiments were carried out around this region (at 40, 42.5, 47.5 and 50 mm/s). It was noted that mass loss and the number of holes per unit length decreased when welding speed increased from 40 mm/s to 45 mm/s and after 45 mm/s mass loss and the number of holes per unit length increased. This shows that there is a narrow region of welding speed around which good quality welds can be obtained.

![Influence of Welding Speed on Weld Quality](image)

**Figure 4-3 Influence of varying welding speed on weld quality (mass loss).**

The effect of varying welding speed on the weld quality in terms of the number of holes at the top and bottom surfaces is shown in fig.4-4.a and 4-4.b. It is observed from the fig.
that at lower speed ranges (35 mm/s), the number of holes at the top surface is smaller than in the to higher speed range. Fig. 4-4.b shows the opposite results for the bottom surface with a higher number of holes observed at lower speed (35 mm/s). It is also noted that for thinner coatings like Sn-Zn (4 μm) and EG (4 μm), the number of holes produced at the top and bottom of the sheets are almost negligible. The top and bottom surfaces of welded sheets at lower speed are shown in fig. 4-5.a and 4-5.b, and at higher speed ranges are shown in fig. 4-6.a and 4-6.b. More results of the different zinc coated steel specimens are given in Appendix A-D.
Figure 4-4 (a) Influence of varying welding speed on weld quality (Number of holes at top surface).
(b) Influence of varying welding speed on weld quality (Number of holes at bottom surface).
Figure 4-5.a Weld Quality of top surface at lower speed. (Mg-Zn (6 μm) coating, Welding speed=35 mm/s, Welding Power=3 kW)

Figure 4-5.b Weld Quality of bottom surface at lower speed. (Mg-Zn (6 μm) coating, Welding speed=35 mm/s, Welding Power=3 kW)

Figure 4-6.a Weld Quality of top surface at higher speed. (Mg-Zn (6 μm) coating, Welding speed=65 mm/s, Welding Power=3 kW)

Figure 4-6.b Weld Quality of top surface at higher speed. (Mg-Zn (6 μm) coating, Welding speed=65 mm/s, Welding Power=3 kW)
High speed camera images were also taken with the resolution of 20,000 Hz to study the behavior of weld pool and plume during welding. To study the plume behavior, the camera was set horizontal to the sheet to capture the images of top and bottom plume. In order to capture the images of weld pool from the top side, camera was set at an angle of 35° with respect to the sheet surface.

It was found that at higher speeds i.e. 65 mm/s, the plume was mostly visible at the center above the top sheet throughout the weld length. The stability of weld pool was also disturbed, as a result severe expulsion of molten metal from the weld pool was observed from the top sheet as shown in fig. 4-7.

At lower speed i.e. 35 mm/s, the plume was not visible at the center and changing its position quite rapidly from right to left and left to right directions at the top side. More expulsion was observed from the bottom side in this case.

The weld pool was quite stable at 45 mm/s as compared to 65 mm/s as shown in fig. 4-8 and little expulsion of molten metal was observed at this speed.
4.4.2 Experiments with Varying Welding Power

The influence of Welding power on the weld quality is shown in fig. 4-9. Experiments were performed at 2.5 and 3 kW on Mg-Zn (12 μm) coated steel sheets. It is observed
that mass loss is higher in the case of low welding power (2.5 kW) for all speed ranges as compared to high welding power (3 kW).

Figure 4-9 Influence of varying welding power on weld quality (mass loss).

4.4.3 Experiments with Varying Coating Thickness
Welding experiments were performed on Mg-Zn (6 μm) and Mg-Zn (12 μm) to study the effect of coating thickness on weld quality. The welding power was kept constant at 3 kW for these experiments. The results are given in Fig. 4-10. The mass loss is higher in the case of the thicker zinc coating for all welding speeds. The weld quality was also good for the thinner zinc coating and fewer holes and spatters were observed in this case as compared to the weld made on the material with the thicker coating.

Figure 4-10 Influence of coating thickness on weld quality (mass loss).
4.4.4 Experiments with Different Zinc Coatings

Welding experiments were performed on different zinc coatings with the same process parameters to study the influence of zinc coating type. The results are given in fig. 4-11. The mass loss is high in the case of GI (6 μm) coating compared with the Mg-Zn (6 μm) coating. A greater number of holes and spatters were also observed with GI (6 μm) coatings.

![Influence of coating type on welding quality](image)

Figure 4-11 Influence of coating type on weld quality (mass loss).

4.5 Discussion

4.5.1 Influence of Welding Speed on Weld Quality

It was observed from fig. 4-4.a and fig. 4-4.b that, for thicker coatings, in the lower speed range (~35 mm/s) more fusion defects were present at the bottom surface compared with the top surface. Good quality welds were obtained at intermediate speeds i.e. around 45 mm/s. A higher number of holes and spatters were observed at the top surface compared with the bottom surface in the higher speed range (~55-65 mm/s). The process physics of this behavior can be explained as follows:

A downward zinc vapor escape from the clear aperture at the bottom keyhole is necessary condition for good quality welds, as mentioned by by Fabbro\(^2\). A schematic view of the keyhole produced during laser welding is shown in fig. 4-12.
Figure 4-12 Schematic view of the keyhole\textsuperscript{3}.

In this figure, ‘h’ represent the upper part of the rear keyhole front, ‘D’ represent keyhole length, ‘a’ represent the clear aperture at the bottom of the keyhole, ‘d’ represent the keyhole bottom, angle ‘α’ represents the inclination of the front keyhole wall and ‘2α’ represent the total thickness of the two sheets. The lower part of the rear keyhole front has an inclination twice as large as the front keyhole inclination indicated by 2α.

At lower welding speed the length ‘h’ is greater than the sheet thickness ‘e’ as shown in fig. 4-13.a. Therefore it is expected that the size of the clear aperture ‘a’ and bottom keyhole ‘d’ decrease and as a result zinc vapor cannot escape freely from the rear melt pool and then the weld quality will be bad at the bottom surface.

For an intermediate welding speed, the length ‘h’ is equal to the sheet thickness ‘e’ as shown in fig 4-13.b. In this case the size of the clear aperture ‘a’ and bottom keyhole ‘d’ is large enough that the zinc vapor can escape more easily and therefore good weld seam quality should result.

At higher welding speed, the length ‘h’ is less than the sheet thickness as shown in fig 4-13.c. In this case, the zinc vapor evacuation could be temporarily impeded for two reasons. Firstly, in this case, the clear aperture ‘a’ of at the bottom of the keyhole is not present due to higher welding speed. Secondly, the high level of fluctuations that result, due to relatively low local laser intensity at higher welding speed, makes possible complete closure of the bottom keyhole by the rear keyhole wall. As a result, some melt ejection can occur from the upper keyhole and more fusion defects are produced at the top sheet.
4-13 (a) Keyhole profile at lower welding speed.
(b) Keyhole profile at intermediate welding speed.
(c) Keyhole profile at higher welding speed².

4.5.2 Influence of Welding Power on Weld Quality

As mentioned in section 4.2.2, higher mass loss was observed at 2.5 kW compared to 3kW. This happened because at higher welding power, the keyhole is wider which eases the zinc vapor escape from the interface of the two sheets, and less molten metal is ejected from the weld pool. At lower welding power, the keyhole is narrow and it impedes the zinc vapor escape from the interface. As a result, the pressure of zinc vapor increases which disturbs the keyhole stability and more molten metal is ejected from the weld pool.

4.5.3 Influence of Coating Thickness on Weld Quality

A high value of mass loss per unit length was observed in the case of thicker zinc coating steel sheets in comparison with thinner coating steel sheets. The weld beads also contain fewer holes and spatters in thinner zinc coated steel sheets. As the amount of zinc is high in thicker zinc coating, more zinc vapor is produced which increases the zinc vapor pressure at the interface of the two sheets. For the same welding power and welding speed, increased zinc vapor pressure disturbs the keyhole stability and more fusion defects are observed at the top and bottom sheets for the thicker zinc coated steel sheets.

These results are contrary to the previous research carried out on the GI coated steel sheets in the MSE department, TU Delft and Corus in which it was claimed that welding quality is better in the case of a thicker zinc coating, as mention in section 3.3.1.
Therefore detailed experiments are required with different coating thickness to understand the influence of coating thickness on the weld quality.

4.5.4 Influence of Coating Type on Weld Quality

In section 4.4.4, comparison was made between Mg-Zn (6 μm) and GI (6 μm) coated steel sheets. It was observed that Mg-Zn (6 μm) coated steel sheets have a low value of mass loss per unit length as compared to GI(6 μm) coated steel sheets and a lower number of holes and spatters are observed at the top and bottom surfaces. This may happen due to presence of magnesium in the zinc coating. Magnesium’s lower melting temperature (649 °C) facilitates its rapid reaction with liquid zinc and its higher boiling temperature (1090°C) minimizes the vapor pressure of liquid Mg-Zn solution by raising its boiling temperature. This results in a stable keyhole which facilitates the zinc vapor escape from the interface. Hence the amount of molten metal ejected from the weld pool is less and consistent weld bead is observed.

Welding experiments were also performed with Sn-Zn (4 μm) coated steel sheets and the results were shown in fig. 4-3 and fig. 4-4.a and fig. 4-4.b. It was observed that the mass loss was very low and weld beads without any fusion defects were achieved. Sn-Zn coating used in these experiments contains 92% Sn and only 8% Zn. The boiling temperature of Sn (2602°C) is very high as compared to zinc (907°C). As discussed above, the higher boiling temperature of Sn prevents the zinc vapor formation which results in a high quality weld.

Therefore it can be concluded that alloying elements in the zinc coatings have an influence on the weld quality of laser welded zinc coated steel sheets.
4.6 References


5 Microstructure Inspection, Micro-hardness and Strength (Erichsen test) Measurements

5.1 Microstructure Inspection

5.1.1 Sample Preparation

Five samples of each type of coated steel were made by cutting the welded sheets into slices to obtain cross-sections of the welded region for the microstructure inspection. These cross-sections have been subjected to the grinding and polishing procedure as shown in Table 5.1.

<table>
<thead>
<tr>
<th>Grit#</th>
<th>Time (sec)</th>
<th>Grinding</th>
<th>Polishing</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>220</td>
<td>120</td>
<td>9 microns</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>120</td>
<td>3 microns</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>120</td>
<td>1 micron</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>1200</td>
<td>120</td>
<td>Firch with 5% Nital</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>2400</td>
<td>300</td>
<td>Nitric Acid+ Alcohol</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5.1.2 Microstructure Inspection Procedure

Microstructure inspections of welded cross-sections were performed to study the changes in the microstructure of the welded regions for different types of zinc coatings and to compare them with substrate steel. Microstructure inspection of the cross-sections was carried out with an OLYMPUS BX60M optical light microscope. Micrographs were taken with a resolution of 50x, 100x and 200x to study the microstructure of the substrate steel, the fine and coarse grains heat affected zones (HAZ) and the fusion zone.

5.1.3 Results and Discussion

The micrograph of the welded region is shown in Fig. 5-1. The substrate steels consist of a ferritic microstructure in all types of zinc coated steel sheets used in these experiments,
as shown in fig. 5-2. The fusion zone of EG coated steel contains a few bainitic and widmanstatten microstructures along with the ferritic microstructure as shown in fig. 5.3. These phases were formed due to the higher percentage of Si content (0.108%) present in the substrate steel which facilitates in the formation of acicular products like bainite and widmanstatten phases in fusion zone.

![Figure 5-1 Micrograph of welded region.](image)

![Figure 5-2 Micrograph of substrate steel of GI (6 μm) coating.](image)
In all other types of zinc coated steel sheets, the fusion zone only contains ferrite phase because the percentage of carbon is very low in the substrate steel. The growth of the grains is columnar at the edges and equi-axed in the middle of the fusion zone as shown in fig. 5-4.

The microstructures of coarse and fine heat affected zones (HAZ) are also ferritic in all specimens. The grains in the coarse HAZ are larger as compared to fine HAZ and fusion zone because the sheet is heated in such a way that grain growth takes place during
welding, in this region, as shown in fig. 5-5. The micrographs of the different welded zinc coated steels specimens are given in Appendix E-I.

![Micrograph of fusion zone, coarse and fine HAZ in GI (6 μm) coated steel sheets.](image)

**Figure 5-5** Micrograph of fusion zone, coarse and fine HAZ in GI (6 μm) coated steel sheets.

## 5.2 Micro-Hardness Measurements

### 5.2.1 Micro-Hardness Measurement Procedure

Micro-Hardness profiles of the cross-sections of different un-welded and welded zinc coated steel sheets were measured to compare the micro-hardness of different zinc coatings. These tests were performed using standard Vickers micro-hardness testing equipment at TU-Delft. The profiles were made with a Vickers hardness tester. This test uses a square base pyramid to indent the steel surface with a certain load. The strength of the specimen is indicated by an HV number, which is defined as the load divided by the surface area of the indent. The test is described in ASTM Standard E92-72\(^1\).

The same cross-sections were used for the hardness measurements which were made for the microstructure inspection. The applied load for all measurements was 100 g. To get a smooth profile, 11 measurements have been taken through the weld bead, along the centers of the two sheets as shown in Fig. 5-6.
Figure 5-6 Microstructure of the welded region used for the micro-hardness measurements.

5.2.2 Results and Discussion

Average hardness values of different un-welded specimens are given in table 5.2.

Table 5.2. Hardness measurement of different un-welded zinc coated steel sheets.

<table>
<thead>
<tr>
<th>Type of Coating</th>
<th>SnZn (4 μm)</th>
<th>GI (6 μm)</th>
<th>MgZn (12 μm)</th>
<th>MgZn (6μm)</th>
<th>EG (4 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness(HV)</td>
<td>114</td>
<td>115</td>
<td>102</td>
<td>109</td>
<td>101</td>
</tr>
</tbody>
</table>

Hardness profiles along the center of two welded sheets are given fig. 5-7.a and fig. 5-7.b.
Figure 5-7 (a) Micro-Hardness profile of top surface of different welded zinc coated steel sheets.

(b) Micro-Hardness profile of bottom surface of different welded zinc coated steel sheets.
It is observed from the fig. 5-6.a and fig. 5-6.b that the hardness of the fusion zone is higher than the coarse and fine grained HAZs, which is due to the refined ferrite structure. The hardness of the Sn-Zn (4 μm) Coating is high compared with the other coatings which is due to the solid solubility hardening of the Sn atom present in the weld pool. In general the hardness profile is almost similar in all cases for the top and bottom surfaces. The increase in micro-hardness of fusion zone was relatively small in all types of zinc coated steel sheets in comparison with substrate steel, which shows that the microstructure does not have hardening phases such as bainite or martensite.

5.3 Strength (Erichsen Test) Measurements

5.3.1 Sample Preparation
Samples were cut according to the sizes (70x100 mm) as described in ISO 20482^2. Tests were performed on un-welded and welded sheets to compare the strength of the different zinc coated steel sheets after welding. No un-welded sheets were available for the Mg-Zn Zn (12 μm) and Mg-Zn Zn (12 μm) coated steel sheets, due to shortage of material, therefore the strength of un-welded sheet was not measured for these coated steel sheets. The welding parameters used to weld the specimens are given in table 5.3:

<table>
<thead>
<tr>
<th>Welding Speed</th>
<th>Welding Power</th>
<th>Weld Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 mm/s</td>
<td>3 kW</td>
<td>90-110 mm</td>
</tr>
</tbody>
</table>

5.3.2 Testing Procedure
The test is used to find quantitative measures for the deep drawability of a metal sheet. In this test an indentation is formed by pressing a punch with a spherical end against a clamped test piece between a blank and a die until a through crack appears. The measured depth of indentation is the result of the test based on the movement of the punch i.e. the larger the depth of indentation, the larger the formability of the material for typical stretching process. The schematic view of the test arrangement is given in fig. 5-8. The
test is performed with Erichsen testing equipment (Model 102) and is described in ISO 20482. The test arrangement employed is shown in fig. 5-9.

Figure 5-8 Schematic view of the Erichsen test set-up.

Figure 5-9 Erichsen test set-up
5.3.3 Results and Discussion

The results of the Erichsen test are given in table 5.4.

<table>
<thead>
<tr>
<th>Type of Coating</th>
<th>Force (kN) Un-welded specimens</th>
<th>Height of Indentation (mm) Un-welded Specimens</th>
<th>Force (kN) Welded specimens</th>
<th>Height of Indentation (mm) Welded Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mg-Zn (12μm)</td>
<td>13</td>
<td>12.1</td>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td>Mg-Zn (6μm)</td>
<td>11.5</td>
<td>12.3</td>
<td>22</td>
<td>9.6</td>
</tr>
<tr>
<td>GI (6μm)</td>
<td>11</td>
<td>11.5</td>
<td>24</td>
<td>9.7</td>
</tr>
<tr>
<td>Sn-Zn (4μm)</td>
<td>11</td>
<td>12.3</td>
<td>7</td>
<td>4.9</td>
</tr>
<tr>
<td>EG (4μm)</td>
<td>11</td>
<td>11.5</td>
<td>24</td>
<td>12.9</td>
</tr>
</tbody>
</table>

It is noted from the indentation height is high for the welded specimens than the un-welded specimens. It is also observed that that EG (4 μm) coating has a maximum value of height of indentation. The crack produced in this sample was circular and across the weld bead, which shows that the weld bead has more strength than the substrate steel as shown in fig. 5-10. Mg-Zn (6 μm) and GI (6 μm) coatings have same height of indentation. The cracks produced in these coatings are along, the weld bead which indicates that weld bead has less strength than the substrate steel as shown in fig. 5-11. This may happen because the spatters and holes were observed during welding. As a result, less metal is left in the bead comparing to the base steel. It is therefore reasonable to expect that the cracks are observed along the weld bead. The results of this test are not valid for Mg-Zn (12 μm) coating because of the holes present in the weld bead due to which, the weld bead deforms pre-maturely and it was not possible to measure the height of indentation properly. In the case of Sn-Zn coating, a low value of height of indentation is observed because a crack was produced just after the application of the load. Tin atoms make intermetallics with steel which are brittle in nature, causing the pre-mature cracking of the weld bead in the Sn-Zn coating welded sheets during Erichsen testing as shown in fig. 5-12.
Figure 5-10 Crack produced across the weld bead in Erichsen test in the EG (4 μm) coated steel sheets.

Figure 5-11 Crack produced along the weld bead during Erichsen test in Mg-Zn (6 μm) coated steel sheets.
Figure 5-12 Pre-mature Crack produced along the weld bead during Erichsen test in Sn-Zn (4 μm) coated steel sheets.

5.4 References

1. ASTM Standard E92-72
2. ISO 20482

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6 Conclusions

The overall aim of this thesis was to investigate and understand the effects of different process parameters and types of coating on the weld quality of laser welding of overlap zinc coated steel sheets without a preset gap. The main findings and conclusions are summarized below:

- Welding speed has a significant influence on weld quality. It was observed that for thicker coatings, welding quality is not good at lower (~35mm/s) and higher (~55m/s) speeds as more fusion defects are observed in both cases. Good quality weld can be obtained at intermediate speed range i.e. around 45 mm/s for thicker zinc coatings. For thinner coatings, good quality welds can be achieved at higher speeds.

- Higher welding power could produce better welds due to the higher heat input that enlarges the keyhole which eases the escape of zinc vapor from the interface of the two sheets.

- Welding quality is good in the case of thinner coatings as compared to thicker coatings due to less zinc vapor present at the interface, which develops less zinc vapor pressure. The vapor can escape easily from the keyhole without disturbing the weld pool.

- Alloying elements in the zinc coating may play an important role in improving the weld quality of zinc coated steel sheets. The addition of alloying elements which have higher boiling temperatures than the zinc may increases the boiling temperature of the solution at the interface. Hence the zinc vapor pressure reduces which improves the keyhole stability and zinc vapor escape from the interface of two sheets. As a result, the amount of molten metal ejected from the weldpool is reduced and good quality weld can be obtained.

- The microstructures of the coarse and fine HAZ and fusion zones were not changed significantly and mostly a ferrite microstructure was observed in all types of zinc coated steel sheets.
The micro-hardness of the fusion zone (~160 HV) was not increased considerably in all types of zinc coated steel sheets as compared to substrate steel (~110 HV) which show that the microstructure does not contain a hardening phase such as bainite or martensite. The increase in hardness of fusion zone in comparison to the substrate steel is due to the generation of refined ferritic microstructure.
7 Recommendations

Very interesting results are found in this thesis project, it is therefore recommended that following points should be considered for the future work:

- Investigate the effects of welding power on the weld quality with higher laser powers (i.e. 3.5, 4, 4.5 kW etc.).
- Study the keyhole and weld pool behavior using high speed camera and validate these results with a numerical model which should be developed to understand the dynamic behavior of the weld pool.
- Investigate the effects of zinc coating thickness extensively for thicker and thinner coatings to understand its impact on the welding process.
- Study the microstructure with different zinc coated steel sheets to investigate the diffusion of alloying elements present in the coatings into the fusion zone and their effects on the microstructure of the fusion zone.
- Repeat Erichsen tests on defect free samples to compare the deep drawability of the welded sheet with the substrate steel.
Appendix A

Weld pictures of the GI (6 μm) coated welded sheets

GI (6 μm) coated sheets, P=3 kW, v=35mm/s, top view.

GI (6 μm) coated sheets, P=3 kW, v=35mm/s, bottom view.

GI (6 μm) coated sheets, P=3 kW, v=45mm/s, top view.

GI (6 μm) coated sheets, P=3 kW, v=45mm/s, bottom view.
GI (6 μm) coated sheets, P=3 kW, v=55mm/s, top view.

GI (6 μm) coated sheets, P=3 kW, v=55mm/s, bottom view.
Appendix B

Weld pictures of the Mg-Zn (6 μm) coated sheets

Mg-Zn (6 μm) coated sheets, P=3 kW, v=45mm/s, top view.

Mg-Zn (6 μm) coated sheets, P=3 kW, v=45mm/s, bottom view.

Mg-Zn (6 μm) coated sheets, P=3 kW, v=55mm/s, top view.

Mg-Zn (6 μm) coated sheets, P=3 kW, v=55mm/s, bottom view.
Appendix C

Weld pictures of the Mg-Zn (12 μm) coated sheets

Mg-Zn (12 μm) coated sheets, P=3 kW, v=35mm/s, top view.

Mg-Zn (12 μm) coated sheets, P=3 kW, v=35mm/s, bottom view.

Mg-Zn (12 μm) coated sheets, P=3 kW, v=45mm/s, top view.

Mg-Zn (12 μm) coated sheets, P=3 kW, v=45mm/s, bottom view.
Mg-Zn (12 μm) coated sheets, P=3 kW, v=55mm/s, top view.

Mg-Zn (12 μm) coated sheets, P=3 kW, v=55mm/s, bottom view.

Mg-Zn (12 μm) coated sheets, P=3 kW, v=65mm/s, top view.

Mg-Zn (12 μm) coated sheets, P=3 kW, v=65mm/s, bottom view.
Appendix D

Weld pictures of the Sn-Zn (4 μm) coated sheets

Sn-Zn (4 μm) coated sheets, P=3 kW, v=35mm/s, top view.

Sn-Zn (4 μm) coated sheets, P=3 kW, v=35mm/s, bottom view.

Sn-Zn (4 μm) coated sheets, P=3 kW, v=45mm/s, top view.

Sn-Zn (4 μm) coated sheets, P=3 kW, v=45mm/s, bottom view.
Sn-Zn (4 μm) coated sheets, P=3 kW, v=55mm/s, top view.

Sn-Zn (4 μm) coated sheets, P=3 kW, v=55mm/s, bottom view.

Sn-Zn (4 μm) coated sheets, P=3 kW, v=65mm/s, top view.

Sn-Zn (4 μm) coated sheets, P=3 kW, v=65mm/s, bottom view.
Appendix E

Micrographs of the GI (6 μm) coated welded sheets

Fusion zone.

Fusion zone-coarse-fine HAZ.
Appendix F

Micrographs of the Mg-Zn (6 μm) coated welded sheets

Bottom fusion zone with porosity

Bottom fusion zone and Course HAZ

Top fusion zone

Top fusion zone, coarse and fine HAZ
Appendix G

Micrographs of the Mg-Zn (12 µm) coated welded sheets

Substrate steel and zinc coating

fusion zone

Bottom fusion zone with under cut

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Appendix H

Micrographs of the Sn-Zn (4 μm) coated welded sheets

Fusion zone

Fusion zone, Coarse and fine HAZ
Appendix I

Micrographs of the EG (4 µm) coated welded sheets

Fusion zone

Coarse HAZ

Fine HAZ