Laser Welding of Zinc Coated Steel Without a Pre-set Gap
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The research described in this thesis was performed in the department of Materials Science and Engineering, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands.
Laser Welding of Zinc Coated Steel
Without a Pre-set Gap

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Laser welding of zinc coated steel without a pre-set gap
PhD thesis Delft University of Technology, with summary in Dutch

Keywords: Laser welding, Zinc coated steel, Zinc vapour, Overlap configuration, Zero gap, Weld stability.

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# Nomenclature and symbols

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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$</td>
<td>material dependent constant</td>
<td>[K]</td>
</tr>
<tr>
<td>$A_g$</td>
<td>area of the argon gas escape channel</td>
<td>[m$^2$]</td>
</tr>
<tr>
<td>$A_n$</td>
<td>nozzle (vapour escape channel) area</td>
<td>[m$^2$]</td>
</tr>
<tr>
<td>$A_s$</td>
<td>area of the zinc vaporisation front</td>
<td>[m$^2$]</td>
</tr>
<tr>
<td>$B_0$</td>
<td>material dependent constant</td>
<td>[-]</td>
</tr>
<tr>
<td>$b$</td>
<td>width of liquid metal at the keyhole side wall</td>
<td>[m]</td>
</tr>
<tr>
<td>$b_1$, $b_2$</td>
<td>distances of vaporisation isotherm at different positions</td>
<td>[m]</td>
</tr>
<tr>
<td>$C$</td>
<td>material and incident laser power dependent constant</td>
<td>[s m$^{1/2}$]</td>
</tr>
<tr>
<td>$C_p$</td>
<td>heat capacity</td>
<td>[J kg$^{-1}$ K$^{-1}$]</td>
</tr>
<tr>
<td>$C_0$</td>
<td>material dependent constant</td>
<td>[K$^{-1}$]</td>
</tr>
<tr>
<td>$D_0$</td>
<td>material dependent constant</td>
<td>[-]</td>
</tr>
<tr>
<td>$D$</td>
<td>characteristic dimension of the nozzle exit</td>
<td>[m]</td>
</tr>
<tr>
<td>$d_1$, $d_2$</td>
<td>distance from reflected beams to keyhole centre line</td>
<td>[m]</td>
</tr>
<tr>
<td>$E$</td>
<td>energy per unit mass required to raise the substrate from one temperature to another</td>
<td>[J]</td>
</tr>
<tr>
<td>$E_{oh}$</td>
<td>energy required to melt a unit mass of steel</td>
<td>[J]</td>
</tr>
<tr>
<td>$E_{zm}$</td>
<td>energy required to melt a unit mass of zinc</td>
<td>[J]</td>
</tr>
<tr>
<td>$E_{zv}$</td>
<td>energy required to vaporize a unit mass of zinc</td>
<td>[J]</td>
</tr>
<tr>
<td>$g_{min}$</td>
<td>the minimum gap between the zinc coated sheets that allows a stable weld</td>
<td>[m]</td>
</tr>
<tr>
<td>$h$</td>
<td>height of the keyhole characteristic deviation</td>
<td>[m]</td>
</tr>
<tr>
<td>$h_p$</td>
<td>distance from the workpiece to power meter</td>
<td>[m]</td>
</tr>
<tr>
<td>$h_{top}$, $h_{root}$</td>
<td>heights of weld top and root reinforcements</td>
<td>[m]</td>
</tr>
<tr>
<td>$k_1$</td>
<td>Constant</td>
<td>[N s m$^{-3}$]</td>
</tr>
<tr>
<td>$l$</td>
<td>length of the keyhole front wall in a coaxial view</td>
<td>[m]</td>
</tr>
<tr>
<td>$L$</td>
<td>Latent heat</td>
<td>[J kg$^{-1}$]</td>
</tr>
<tr>
<td>$m$</td>
<td>mass of liquid steel melted per unit time</td>
<td>[kg s$^{-1}$]</td>
</tr>
</tbody>
</table>
$P$ incident laser power [W]

$P_a$ power required to melt the workpiece [W]

$P_b$ reflected power loss from the weld pool top face [W]

$P_c$ power dissipated during vaporisation [W]

$P_d$ combined convective and radiative losses [W]

$P_e$ dissipated from the weld zone by conduction [W]

$P_f$ direct transmission [W]

$P_g$ transmission after multiple reflections [W]

$P_j$ plasma absorption [W]

$p_0$ reservoir pressure [Pa]

$p_{d,l}$ hydrodynamic pressure of melt flow [Pa]

$p_{d,z}$ dynamic pressure of zinc vapour [Pa]

$p_i$ radiation pressure [Pa]

$p_s$ hydrostatic pressure [Pa]

$p_r$ vapour recoil pressure [Pa]

$p_z$ zinc vapour pressure on the keyhole rear wall [Pa]

$p_γ$ surface tension pressure [Pa]

$Q_0$ incident laser power [W]

$Q_i$ power absorbed by the workpiece [W]

$Re_c$ critical Reynolds number [-]

$r$ average keyhole radius [m]

$r_3$ radius of the power meter acceptance area [m$^2$]

$r_v$ radius of zinc vaporisation front [m]

$r_k$ radius of the keyhole top aperture [m]

$r_w$ radius of the melt pool [m]

$T$ temperature [K]

$T_{z,v}$ temperature of zinc vapour [K]

$t_p$ thickness of steel sheet [m]

$t_m$ thickness of zinc coating [m]

$u_v$ vapour velocity distribution along x direction [m s$^{-1}$]
\( V_a \) flow rate of argon gas \([\text{m}^3 \text{s}^{-1}]\)

\( V_{sm} \) the volume of steel that is melted during welding \([\text{m}^3]\)

\( V_{zv} \) the volume of zinc that is melted during welding \([\text{m}^3]\)

\( \dot{V}_{zv} \) volume of the zinc vapour generated per unit time \([\text{m}^3 \text{s}^{-1}]\)

\( \dot{V}_{key} \) volumetric flow escaping through the keyhole \([\text{m}^3 \text{s}^{-1}]\)

\( \dot{V}_{vent} \) volumetric flow venting through the weld pool \([\text{m}^3 \text{s}^{-1}]\)

\( v \) welding speed \([\text{m} \text{s}^{-1}]\)

\( v_{hump} \) hump velocity \([\text{m} \text{s}^{-1}]\)

\( v_{flow} \) flow velocity \([\text{m} \text{s}^{-1}]\)

\( v_{max} \) maximum liquid flow velocity around the keyhole \([\text{m} \text{s}^{-1}]\)

\( v_{min} \) minimum liquid flow velocity around the keyhole \([\text{m} \text{s}^{-1}]\)

\( v_{ph} \) phase velocity of the hump \([\text{m} \text{s}^{-1}]\)

\( v_v \) velocity of zinc vapour \([\text{m} \text{s}^{-1}]\)

\( w \) keyhole width \([\text{m}]\)

\( w_v \) vapour velocity distribution along x direction \([\text{m} \text{s}^{-1}]\)

\( X_0 \) characteristic distance \([\text{m}]\)

\( x \) coordinate · distance along the axis of zinc vapour jet \([\text{m}]\)

\( y \) coordinate \([\text{m}]\)

\( \alpha \) inclination angle of the keyhole front wall \([\degree]\)

\( \alpha_{thermal} \) coefficient of thermal expansion \([\text{K}^{-1}]\)

\( \gamma \) surface tension coefficient \([\text{N} \text{m}^{-1}]\)

\( \varepsilon \) thermal expansion \([\text{m}]\)

\( \eta_h \) heat transfer (process) efficiency \([-]\)

\( \eta_m \) melting efficiency \([-]\)

\( \mu_{z,v} \) dynamic viscosity of zinc vapour \([\text{kg} \text{m}^{-1} \text{s}^{-1}]\)

\( \rho_a \) density of argon gas \([\text{kg} \text{m}^{-3}]\)

\( \rho_{s,l} \) density of liquid steel \([\text{kg} \text{m}^{-3}]\)

\( \rho_{s,solid} \) density of solid steel \([\text{kg} \text{m}^{-3}]\)
\( \rho_{\text{liquid}} \)  
\( \rho_{\text{solid}} \)  
\( \rho_{\text{g.v}} \)  
\( \rho_{\text{g.v}}^0 \)  

<table>
<thead>
<tr>
<th>Constant</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g )</td>
<td>gravitational constant</td>
<td>9.81 [m s(^{-2})]</td>
</tr>
<tr>
<td>( M_z )</td>
<td>Atomic weight of zinc</td>
<td>65.38 [g mol(^{-1})]</td>
</tr>
<tr>
<td>( p_{\text{atm}} )</td>
<td>atmospheric pressure</td>
<td>1.01 \times 10^5 [Pa]</td>
</tr>
<tr>
<td>( R )</td>
<td>gas constant</td>
<td>8.314 [J mol(^{-1}) K(^{-1})]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW</td>
<td>continuous wave</td>
</tr>
<tr>
<td>EZ</td>
<td>electrogalvanized</td>
</tr>
<tr>
<td>GA</td>
<td>galvannealed</td>
</tr>
<tr>
<td>GI</td>
<td>hot dip galvanized</td>
</tr>
<tr>
<td>GDOES</td>
<td>glow discharge optical emission spectroscopy</td>
</tr>
<tr>
<td>GTAW</td>
<td>gas tungsten arc welding</td>
</tr>
<tr>
<td>PIV</td>
<td>particle image velocimetry</td>
</tr>
<tr>
<td>PTV</td>
<td>particle tracking velocimetry</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Research background

In the automotive industry, zinc coated sheet is commonly used as a result of consumer demands for improved corrosion resistance of the car body. Simultaneously the usage of laser welding in the automotive industry is steadily increasing due to the advantages of flexibility in manufacturing, low and local heat input and production of continuous welds obtained with high welding speed. As a consequence laser welding of zinc coated steels is under investigation with a strong emphasis on the overlap joint geometry, which is desirable in automotive constructions for its simplicity and tolerance. However, the production of consistent, high quality laser welds on zinc coated steels remains a challenge. An overlap joint without a channel between two sheets has been shown to be extremely detrimental to laser welding because the zinc vapour formed at the interface between the two sheets expands into the keyhole and disrupts fluid flow in the melt pool, which often leads to metal ejection. Many practical techniques have been developed to improve the process stability. Although successes have been reported, the additional procedural steps and precautionary measures required to apply these methods limit their application in industry. Research is on-going to obtain approaches to weld coated materials without any additional arrangement. Welds with acceptable quality have been reported, but the mechanism for these welds is still not fully understood.

1.2 Objective

The objective of this work is to develop an understanding of the material behaviour, particularly the zinc behaviour during laser welding of zinc coated steels in an overlap configuration without deliberately introducing a gap between the sheets. This includes the investigation of the influence of the zinc vaporization on the laser induced full penetration keyhole and the weld pool, and the resultant process stability. The specific subjects to be addressed in this thesis include:

- The influences of the zinc vapour on the keyhole and weld pool geometry and the oscillation of the keyhole rear wall.
Chapter 1. Introduction

- The investigation of the influence of the elongated keyhole on the power distribution during welding and the weld cross-sectional profile.

- The investigation of the evacuation of zinc vapour through the weld pool and the formation of instabilities.

- Weldability of Hot-dip galvanized (GI), electrogalvanized (EZ), galvanealed (GA) and Mg-Zn coated sheets with various coating thickness.

These investigations have been conducted mainly using experimental approaches, including welding tests and visual assessment of weld stability, high speed video imaging of the dynamics of the keyhole and surrounded weld pool and the measurement of power distribution. A simple analytical model has also been developed to describe the influence of zinc vapour on the keyhole length.

1.3 Outline of the thesis

This thesis continues in chapter 2 with a review of major phenomena in laser welding, problems encountered when welding zinc coated steels and techniques suggested to overcome these problems. Particular attention is paid to the literature reporting stable welds obtained when welding zinc coated sheets without any additional arrangement and the mechanisms suggested to understand the material behaviour.

A description of the materials and equipment used during the experimental work is given in chapter 3. The metallographic sample preparation and various tests methods employed to analyse the material behaviour during welding are also described.

Experimental results for welding of GI sheets are presented in chapter 4, including the influences of the coating thickness, welding speed and laser power on the process stability. In addition to the results of weld surface and cross-section examination, the outcomes of transient gap measurement and high speed video imaging are also presented. The zinc vapour evacuation through a channel on the keyhole front wall into the keyhole and the development of an elongated keyhole are considered. An analytical model describing the influence of zinc vapour on keyhole elongation is presented.

Chapter 5 deals with the power distribution during welding. Both uncoated and zinc coated steel are studied. The power absorbed by the workpiece and transmitted through the keyhole is measured calorimetrically and using a power meter respectively. The influence of the elongated keyhole on the power distribution and the subsequent influence on the weld pool dimensions are addressed.

In chapter 6, the focus is on the zinc vapour that vents through the melt pool and the resultant instabilities generated in the weld pool. The tendency of weld defects to appear on
the weld top or root face has been studied and related to the weld cross-sectional profiles. The generation of instabilities in the weld pool is monitored by means of high speed imaging. The influences of the coating thickness and welding speed on the amount of zinc vapour evacuated through the weld pool are discussed.

Weldability of steels with different coating types is studied in chapter 7, including hot dip galvanized (GI) sheets subject to a chemical etching to reduce the coating thickness, electrogalvanized (EZ), galvanealed (GA) and Mg-Zn coated sheets with various coating thicknesses. The results are discussed with focus on the influences of compositions and coating thickness on the weld stability, which provides supports to the mechanisms suggested in the previous chapters.

Finally, chapter 8 highlights the general conclusions of the research and provides some recommendations for further study.
Chapter 2

Background

Laser material interaction during a laser welding is a complex subject involving many physical effects; e.g., laser beam absorption by the material and fluid flow in a melt pool. In section 2.1 both conduction mode and keyhole mode laser welding are discussed with focus on the fluid flow in the melt pool and process efficiency when welding in the keyhole mode. The properties and types of zinc coated steels are given in section 2.2, where the application of coated steels in the automotive industry and the joining methods used are also addressed. The difficulties arising during laser welding of zinc coated steels in an overlap configuration and the techniques developed to improve the weld stability are presented in section 2.3, followed by a review of models suggested to understand the zinc behaviour and the influence this has on process stability during laser welding.

2.1 Laser material interaction

An important aspect in laser beam welding is the interaction of the laser beam with the material. This interaction is governed by a number of factors including laser power, intensity distribution, welding speed, material properties and shielding gas supply. Two fundamental modes of laser welding are conduction welding and keyhole welding, the main features of which are briefly described below.

2.1.1 Conduction mode welding

When the power density is insufficient to cause vaporisation of the workpiece, conduction welding occurs and the laser energy is absorbed at the surface of the workpiece by Fresnel absorption, whilst the energy absorbed by the vapour generated from surface evaporation (inverse Bremmstrahlung absorption) is negligible. The temperature-dependent absorption for polished metals has been theoretically obtained in earlier works as shown in table 2.1. It can be seen that the absorptivity of Nd:YAG lasers is about 3 times higher than that of CO\textsubscript{2} lasers, but the absorptivity of the metals for both Nd:YAG and CO\textsubscript{2} lasers is always less than 50%, even at the melting temperature. Therefore, the majority of the laser energy is reflected away from the weld pool surface during laser conduction welding. The absorbed energy is transported into the workpiece by
conduction and fluid convection, driven primarily by Marangoni forces resulting from the variation in surface tension with temperature.\textsuperscript{[1]} For most pure metals, as well as iron and steels with low oxygen and sulphur content, the surface tension decreases with increasing temperature, which results in a negative surface tension – temperature gradient ($d\gamma/dT$). In this case, the surface tension will be greatest in the cooler region at the edge of the weld pool inducing a radially outward surface flow, which carries hot metal to the edge of the pool. Hence in conduction mode welding the weld geometry is typically shallow and wide (Figure 2.1a).	extsuperscript{[4],[5]} The addition of surface active elements (Sulphur or oxygen) results in a positive $d\gamma/dT$ and causes an inward surface flow, which increases the depth to width ratio (Figure 2.1b).	extsuperscript{[3],[7]}

Table 2.1: Absorptive of polished metals at room and melting temperature.\textsuperscript{[3]}

<table>
<thead>
<tr>
<th></th>
<th>Room temperature</th>
<th>Melting temperature (liquid)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO$_2$</td>
<td>Nd:YAG</td>
</tr>
<tr>
<td>Aluminium</td>
<td>1.9%</td>
<td>5.9%</td>
</tr>
<tr>
<td>Copper</td>
<td>1.5%</td>
<td>4.9%</td>
</tr>
<tr>
<td>Iron</td>
<td>3.1%</td>
<td>9.7%</td>
</tr>
<tr>
<td>Nickel</td>
<td>4.7%</td>
<td>14.9%</td>
</tr>
<tr>
<td>Titanium</td>
<td>8.1%</td>
<td>25.7%</td>
</tr>
<tr>
<td>Carbon steel</td>
<td>2.7%</td>
<td>8.7%</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>9.7%</td>
<td>30.7%</td>
</tr>
</tbody>
</table>

Figure 2.1: Schematic diagram illustrating (a) outward, and (b) inward surface flows during laser conduction welding.\textsuperscript{[6]}
2.1.2 Keyhole mode welding

As the intensity of laser beam increases, the evaporation of the molten metal becomes strong. The recoil pressure of the vapour pushes the melt aside, creating a hole in the melt pool. This hole is known as a keyhole and can extend over the complete depth of the workpiece. The hot gas escaping from the keyhole forms a plasma or a plume above the workpiece, as shown schematically in Figure 2.2. The laser radiation enters the keyhole and is subject to multiple reflections before being able to escape. One important consequence is that a higher absorption is obtained (> 90% when welding steel).\textsuperscript{[1],[8]} The vapour above and inside the keyhole also absorbs laser radiation by inverse Bremmstrahlung, although for a Nd:YAG laser, this absorption mechanism is very weak compared with Fresnel absorption at the keyhole walls.\textsuperscript{[9],[11]} Since the energy is absorbed throughout the whole depth of the keyhole, welds with a high depth to width ratio are generally produced.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{keyhole.png}
\caption{Schematic of a keyhole and multiple reflections of a laser beam.}
\end{figure}

The dynamic behaviour of the keyhole is decisive for the welding process. Keyhole fluctuations, particularly those parallel to the welding direction, can stimulate weld pool oscillations. Conversely, large oscillation amplitudes of the melt pool may lead to a collapse of the keyhole and result in weld seam defects such as porosity and undercut.\textsuperscript{[12],[13]} To keep the keyhole open, the energy balance and the pressure balance at the keyhole wall must be satisfied. The energy flux absorbed by the keyhole wall has to balance the energy lost through heat flow into the material and evaporation of the material, whilst the evaporation pressure of the metal vapour inside the keyhole acts against the surface tension to keep the keyhole open.\textsuperscript{[14],[15]}
2.1.3 Melt flow

Inside the melt pool during a keyhole welding process, different types of melt flow can take place, driven by buoyancy, surface tension gradients and surface drag due to impinging gas flows or vaporisation.\textsuperscript{[16],[17]} The relative importance of the driving forces varies with operating conditions. Some major flow phenomena are illustrated in Figure 2.3. Marangoni convection driven by surface tension gradients (A in Figure 2.3) is dominant in keyhole mode welding at relatively low welding speeds.\textsuperscript{[5],[7]} This convection increases the lateral heat transport in the melt pool and therefore widens the top of a weld (and also the root when there is a full penetration keyhole) as shown in Figure 2.4a.\textsuperscript{[18],[19]} However, this convection has been reported to be less dominant with increasing welding speed, due to reduced time available for thermocapillary stirring;\textsuperscript{[20],[21]} or when a side gas jet is applied in which case the liquid flow on the melt pool surface is dominated by the gas pressure which causes molten metal to flow toward the rear of the melt pool.\textsuperscript{[21],[22]} Another major feature of the melt flow includes liquid transport around the keyhole (B).\textsuperscript{[15],[23]} The driving force for this motion is the evaporation recoil pressure at the front of the keyhole, controlled by the input laser power, power density and welding speed.\textsuperscript{[2],[23]} At lower welding speeds the melt pool between the keyhole and the melting isotherm is wide, resulting in a less constrained, low speed flow. At high welding speeds, a much higher flow speed is generated because the volume of metal melted per unit time increases and the distance between the leading edge of the keyhole and the melting isotherm is reduced.\textsuperscript{[2],[24]} This melt flows around the keyhole, collides with the slowly moving weld pool and is forced upwards (C), forming a weld bead shape with a central peak and undercut at either side (Figure 2.4b).\textsuperscript{[20],[26]} The excess evaporation recoil pressure causes vertical flow in the liquid film on the keyhole front wall (D). In full penetration welding, this downward vertical flow often leads to a root drop-out (Figure 2.4c). An interior eddy (E), possibly driven by vertical flow at the keyhole rear wall and redirected at the root of the melt pool was observed by high speed X-ray imaging using tracer particles.\textsuperscript{[22],[27]} This flow has a transportation effect on bubbles generated near the bottom of the keyhole, moving them to the top surface of the melt pool and is therefore helpful in improving weld quality.\textsuperscript{[22]}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2_3.png}
\caption{Some important melt flow phenomena during laser welding. A: Marangoni flow, B: melt flowing around the keyhole, C: upward flow due to accumulating melt, D: downward flow at the keyhole front wall, and E: inner eddy.\textsuperscript{[17]}}
\end{figure}
Figure 2.4: Weld profiles resulting from different melt flows during laser welding, (a) enlarged weld top and root,\textsuperscript{[19]} (b) a peak at the centre of the weld with undercut at the sides\textsuperscript{[25]} and (c) drop-out at the weld root.\textsuperscript{[28]}

2.1.4 Process efficiency in laser keyhole welding

Keyhole dynamics and fluid flow within the melt pool have substantial influences on energy absorption. The process efficiency of a laser keyhole weld is regarded as a complex subject that has resulted in considerable research effort. Both the heat transfer (process) efficiency and the melting efficiency are of interest.

The heat transfer (process) efficiency is defined as the ratio of the heat absorbed by the workpiece to the incident laser power. The heat absorbed by the workpiece has been evaluated based on calorimetric measurements,\textsuperscript{[29]-[31]} calculations from measured temperature profiles\textsuperscript{[12],[33]} or from weld bead areas.\textsuperscript{[29],[34]} As mentioned earlier, it is well known that a keyhole is effective in coupling a beam to the workpiece, as a result of multiple reflections. Additionally, it has also been shown that once a stable deep penetration keyhole is established, variations in travel speed do not affect the heat transfer (process) efficiency significantly, as illustrated in Figure 2.5.\textsuperscript{[29],[30]}

Melting efficiency is defined as the ratio of the heat required to just melt the fusion zone to the heat absorbed by the workpiece.\textsuperscript{[29]} An increase of melting efficiency with increasing welding speed has been reported\textsuperscript{[29],[30]} as a result of a reduction in lateral convective stirring in the melt.\textsuperscript{[29],[35]} The distribution of the laser power during CO\textsubscript{2} laser welding has been evaluated by Lampa \textit{et al.},\textsuperscript{[30],[36]} who showed that approximately one third of the input power is utilised in melting and the total power loss in terms of reflection, convection, radiation and plasma plume absorption is around 25% of the input power. The remaining power is dissipated by conduction in the workpiece.

The reported studies focus on deep penetration keyhole welding; there is only limited literature available on process performance on thin sheets with a full penetration (open) keyhole. A significant fraction of the incident laser power in full penetration keyhole welding can dissipate through the root aperture of a keyhole, either by direct transmission
or via one or more reflections. The power loss in this way has been measured by Krasnoperov et al.\cite{31} indicating losses ranging from 0% to 50%, dependent on input power, welding speed and sheet thickness. Similar results have been presented by Fabbro et al.\cite{9}

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure2.5.png}
\caption{Heat transfer (process) efficiency when welding stainless steel SS2333, as a function of welding speed.\cite{30}}
\end{figure}

### 2.2 Zinc coated steel

Zinc coatings are commonly used to improve the aqueous corrosion resistance of steel by two methods, barrier protection and galvanic protection.\cite{37} The barrier effect occurs because the steel surface is sealed off by the zinc coating which prevents moisture or oxygen from reaching the surface. 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 cut edges or scratches in the coating. Typical processing methods used in producing zinc coatings include hot dip galvanizing, electrogalvanizing, thermal spraying, scherardizing, mechanical coating and zinc painting.

Heating either a hot-dip or electrodeposited coated sheet to promote diffusion of the iron into the zinc coating will produce a coating with several intermetallic layers, including zeta, delta, and two gamma phases, according to the zinc-iron phase diagram shown in Figure 2.6. This alloying process is known as galvannealing and is normally accomplished in the hot dip process by immediately taking the zinc coated sheet, after it leaves the bath of molten zinc, into a heat treatment oven at a temperature in the range of 720 K to 870 K.\cite{37,38} However, it can also occur in a solid-state diffusion at a lower temperature; e.g., 570 K.\cite{39} This iron-zinc alloy layer is reported to have corrosion resistance as good as or better than pure zinc.\cite{37,40} The primary advantages of galvannealed (GA) steels are the improved resistance spot-welding and painting properties. However, a GA coating is more brittle than the relatively soft coating of hot-dip galvanizing and shows a greater tendency toward
'powdering' during forming.\textsuperscript{41-42} For this reason, galvanized (GI) sheet is more commonly used in the automotive industry where complex forming and deep drawing of sheet material are necessary.

In the automotive industry, zinc coated sheets are mostly welded by means of resistance spot welding. The major problem with this process is the relatively rapid degradation of a Cu electrode by deformation and chemical reaction with the zinc.\textsuperscript{43-45} The non-contact laser welding process was introduced and is increasingly used in body-in-white applications for the welding of tailored blanks due to the high level of precision, automation and productivity achievable.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.png}
\caption{Zinc rich corner of the Fe-Zn binary phase diagram.\textsuperscript{40}}
\end{figure}

\section{2.3 Laser welding of zinc coated steel}

\subsection{2.3.1 Welding defects}

Overlap (stake) welds are commonly employed in the assembly of cars. The main difficulty that arises when laser welding zinc coated sheets is associated with the vaporization temperature of zinc (1180 K), which is much lower than the melting temperature of steel (1800 K). In an overlap configuration, the zinc vapour produced between the sheets during welding will vent through the keyhole or melt pool, particularly when no gap is present between the overlapping sheets. This causes unstable fluid flow and molten metal is often ejected from the pool, resulting in the formation of pores and severe undercut. Krageler \textit{et al.}\textsuperscript{46} analysed different types of process instabilities caused by zinc
vapour; these are shown in table 2.2. Some typical defects on weld seams, including porosity, undercut and blow holes, are shown in Figure 2.7.

Table 2.2: Different types of process instabilities and defects.\textsuperscript{[46]}

<table>
<thead>
<tr>
<th>Defect</th>
<th>Origin</th>
<th>Caused by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small spatter</td>
<td>Keyhole wall</td>
<td>Vapour plume out of keyhole</td>
</tr>
<tr>
<td>Small spatter</td>
<td>Melt pool</td>
<td>Process dynamics, surface waves</td>
</tr>
<tr>
<td>Big Spatter</td>
<td>Keyhole wall</td>
<td>Zinc vapour evacuation through the keyhole</td>
</tr>
<tr>
<td>Big spatter</td>
<td>Melt pool</td>
<td>Zinc vapour expands into the upper part of melt pool</td>
</tr>
<tr>
<td>Explosion</td>
<td>Keyhole</td>
<td>Keyhole collapse</td>
</tr>
<tr>
<td>Explosion</td>
<td>Melt pool</td>
<td>Zinc evacuation through the melt pool</td>
</tr>
</tbody>
</table>

Figure 2.7: Typical defects (a) porosity, (b) undercut and (c) blow holes in laser welding of zinc coated sheets without a gap at the interface.\textsuperscript{[47],[49]}

2.3.2 Welding with a gap at the interface

One of the first methods introduced and still in use today to overcome process stability problems is to set a gap between the sheets prior to welding, usually in the range of 0.1 to 0.2 mm, which provides a channel for escape of the zinc vapour.\textsuperscript{[50],[57]} Various methods
have been used to produce this gap: using special clamping or roller systems,[58] inserting shims at the joint interface[52][53][56] or using pre-stamped sheets.[54][55][57]

A model was developed by Akhter et al.[52][59] to calculate the appropriate gap size for CO₂ laser welding of coated sheets. The model was derived from the volume rate balance of zinc vapour generated around the weld pool and escaping through the gap. An estimate of the pre-set gap size is

$$g_{\text{min}} = \frac{C \cdot v \cdot t_{\text{zn}}}{t_{p}^{3/2}},$$  \hspace{1cm} (2.1)

where $g_{\text{min}}$ is the minimum gap, $v$ is the welding speed, $t_{\text{zn}}$ is the thickness of zinc coating, $t_{p}$ is the thickness of the sheet and $C$ is a material constant depending on laser power. Another criterion suggested was that the maximum gap preventing excessive drop-through is 35% of the sheet thickness.[52] A verification of the model was given by Graham et al.[50] using a 2 kW Nd:YAG laser applied to the welding of GI and GA sheets. Comparisons between calculation and experimental values are shown in Figure 2.8. It can be seen that the experimental limit of maximum gap is slightly lower than the calculated limit, whilst welds with good quality can be produced at faster welding speeds than predicted; an effect which becomes more pronounced at smaller gaps. The difference of spot size and coupling efficiencies with the Nd:YAG laser, which would result in different values of $C$, was suggested to explain this divergence.

![Figure 2.8: Processing window for welding (a) GI sheets (5 μm coating thickness) and (b) GA sheets (4 μm coating thickness) with various gaps and welding speeds.[50]](image-url)
Chapter 2. Background

A model derived from the same idea of volume rate balance of zinc vapour was given by Ono et al.\(^\text{[60]}\) to express the minimum gap size \(g_{\text{min}}\) as

\[
g_{\text{min}} = \left( \frac{2}{\pi} \right)^{1/2} \frac{w \cdot t_{\text{w}} \cdot \rho_{z,v}}{\sqrt{2 \cdot p_0 \cdot \rho_{z,v}}},
\]

where \(\rho\) is density and subscripts \(z\), \(v\) and \(s\) refer to zinc and vapour and solid states respectively, \(p_0\) is the reservoir pressure. This model shares the same disadvantage as the one suggested by Akhter et al.\(^\text{[52],[59]}\) that the calculations are dependent on the selection of material property data. It was reported that the use of inappropriate material property data could lead to significant errors (up to 5 times greater than the minimum gap determined from experiments).

Despite the uncertainties in prediction of an optimum gap size, introducing a gap has proved successful when an appropriate gap is found experimentally for specific sheets and is well controlled during welding.\(^\text{[50],[57]}\) However, under production conditions involving large pressed steel sheets, controlling the gap size is difficult. The uncertainty of the optimised gap size depending on substrate and coating thickness, welding speed, types of lasers, surface roughness and distortion during welding is also undesirable in industrial production. These disadvantages limit the application of this method in industry.

Another approach to generate a zinc vapour evacuation channel prior to welding involves employing an extra laser to cut a slot along the weld line, thus making an exit path for the zinc vapour as schematically illustrated in Figure 2.9.\(^\text{[61],[63]}\). While promising experimental results were reported, the drawback of this method is that the slot results in severe undercut of the final weld bead, which reduces the weld strength.

**Figure 2.9: Schematic showing laser welding over a pre-cut slot.**\(^\text{[61]}\)

2.3.3 **Welding with an elongated keyhole**

Much of the zinc vapour produced at the interface between sheets was observed to evacuate through the keyhole,\(^\text{[61],[63]}\) and process instabilities were believed to arise due to the zinc vapour hitting the rear wall of the keyhole.\(^\text{[63],[66]}\) An elongated keyhole was therefore suggested, leaving sufficient time for zinc vapour to evacuate. This technique was
Laser welding of zinc coated steel

studied extensively and many successful results were reported. Forrest et al.\textsuperscript{[67]-[69]} modelled keyhole geometries varying with respect to welding speed and inter-beam distance, when welding zinc coated sheets with dual beams. It was shown that welds with good quality can be obtained when the leading beam makes a full penetration keyhole and the trailing beam maintains the position of the keyhole rear wall, avoiding too steep and severe concavity, as shown in Figures 2.10 and 2.11.

**Figure 2.10**: Keyhole geometries when welding sheets with a 7 μm zinc coating thickness, with the dual beam technique. The processing parameters are: power 4 kW, power distribution 72% leading : 28% trailing, inter-beam distance 0.53mm and welding speeds (a) 1.3 m min\(^{-1}\), (b) 2.2 m min\(^{-1}\) and (c) 3.0 m min\(^{-1}\)\textsuperscript{[67]}

**Figure 2.11**: Keyhole geometries when welding sheets with a 7 μm zinc coating thickness, with the dual beam technique. The processing parameters are: power 4 kW, power distribution 72% leading : 28% trailing, welding speed 2.2 m min\(^{-1}\) and inter-beam distance (a) 0.41 mm (b) 0.55mm and (c) 0.70 mm\textsuperscript{[67]}
The elongated keyhole can also be produced using an elongated beam spot or a tilted laser beam, which apply the same principle as the dual beam method; i.e., enlarge the keyhole. For the tilted laser beams, there is a contradiction in the literature with respect to the trailing or leading poison of the beam, as illustrated in Figure 2.12. It was noted by Bergmann et al. that good results were produced with the leading configuration because in this configuration the laser beam is not likely to be blocked by the vapour plume. However, it was reported by Gu et al. that a good weld was made with a trailing beam configuration, ascribed to the preheating of the material by conduction. Although good results have been reported with beam manipulation, the reproducibility of this process remains limited. Naeem et al. conducted experiments with a 4 kW Nd:YAG laser with various power distributions and inter-beam distances. The results showed that when the samples were clamped tightly, there was no improvement in the weld quality with the dual beam technique. Xie et al. also suggested that this process was heavily dependent on some critical parameters; e.g., coating thickness or coating types.

2.3.4 Pulsed laser welding

Pulsed laser welding has been adopted to limit the power input and thus minimize the amount of zinc vapour. Tzeng showed that gap free welding with visually sound surfaces was achieved by a careful control of pulse energy, pulse duration, peak power density, mean power and welding speed. Stable keyhole dynamics and adequate spot overlap are two key aspects that contributed to a stable weld. The first allows zinc vapour to escape smoothly, while the second permits pulses to refill the pores formed during the previous pulse. However, the visually sound welds still contained unavoidable inner pores. By control of the heat input (peak power, duty cycle, welding speed) these defects can be minimized but cannot be eliminated. Figure 2.13 illustrates porosity distributions at various welding speeds. High speeds produced large wormholes and low welding speeds produced smaller and more spherical pores (bubbles). This observation was explained with the aid of a numerical simulation developed by Zhou et al. The defect formation mechanisms and porosity of all sizes developed when pulsed laser welding GI stainless steel sheets were
Large, irregular pores were suggested to be formed due to the quick solidification of liquid metal before the keyhole can be completely filled when welding with a lower beam power, whilst smaller bubbles formed because of the entrapment of zinc vapour, which is sealed and compressed by the liquid metal (Figure 2.14). It was also suggested that in the latter case, zinc vapour trapped in the bubble was dissolved in the surrounding liquid metal. This is in agreement with the metallurgical investigation made by Katayama et al.\cite{66} which showed a zinc enriched layer covering the surface of the pores.

Figure 2.13: Evolution of porosity distribution during pulsed laser welding at a peak power 1800 W, base power of 0 W, duty cycle ratio 0.9, frequency 300 Hz and welding speed (a) 21 mm s\(^{-1}\), (b) 20 mm s\(^{-1}\), (c) 17.5 mm s\(^{-1}\) and (d) 15 mm s\(^{-1}\)\cite{75}
Chapter 2. Background

Figure 2.14: The laser pulse used in modelling and the corresponding defects generated, namely (a) large voids and (b) small bubbles.\textsuperscript{78}

Attempts have also been made to control the oscillation of a keyhole rear wall by means of applying an external, frequency-modulated signal to the laser power.\textsuperscript{46,64} It was shown that it is possible to stabilize the oscillation of a keyhole. However, vaporization of zinc resulted in a high pressure gradient inside the keyhole and the melt pool, which often outweighed the stabilizing effect of the power modulation and led to instabilities.
2.3.5 Hybrid welding

Laser-arc hybrid welding was employed to solve the stability problem when welding zinc coated sheets in an overlap configuration. Welds with improved quality were reported when the arc torch was placed behind the laser beam. \(^{[80],[42]}\) It was found that a strict control of the gap between two sheets was not necessary because the filler wire used in hybrid welding supplied enough weld metal to fill any weld drop through. Another benefit for a laser leading configuration is that the arc weld performed after laser welding results in a longer time before the solidification of the molten metal. This provides more time for the zinc vapour to escape from the molten metal. Yang et al.\(^{[83],[84]}\) performed tests with gas tungsten arc welding (GTAW) preheating followed by a laser weld. Virtually defect-free welds were produced with this configuration, which were attributed to the formation of metal oxides on both the sample top surface and on the interface between two sheets. The zinc and other metal oxides formed on the top surface enhanced the coupling of laser energy, which aids the opening of a keyhole and is reported to provide a stable venting channel for zinc vapour. Additionally, the zinc oxide at the interface has a higher melting temperature \((2248 \, \text{K} \text{ for ZnO})\) than that of zinc \((693 \, \text{K})\), which also helped to stabilize the welding process.\(^{[85]}\) Unlike the laser beam leading configuration, where the arc needs to be close to the laser to heat the melt pool, in the arc leading configuration, welds with good quality can only be produced when the distance between the torch and laser is above some threshold value. A distance of 180 mm was suggested when welding at a laser power 3 kW and a welding speed of 1.8 m min\(^{-1}\).\(^{[84]}\)

2.3.6 Metal film insert

While seeking the solutions that can vent zinc vapour effectively, a physical – chemical control method was developed to reduce the amount of zinc vapour by dissolving it in another material. Zhou et al.\(^{[49],[86]}\) selected aluminium as the solvent since it has a high boiling temperature and even lower melting temperature than zinc. A thin layer of aluminium \((0.025 \, \text{mm})\) at the interface between two sheets was made by either inserting a foil or by applying a cold spray technique. The results show that the presence of aluminium suppresses the defects, and welds with good quality can be produced. Aluminium rich residues were found in the gap adjacent to the weld bead, as shown in Figure 2.15. Excessive dissolution of Al into the steel weld beads was observed and this dissolution may have negative effects on weld properties (e.g., making the weld brittle) and should be avoided.\(^{[49],[84]}\)
Due to the good alloying characteristics of zinc with copper, Cu foil or powder have also been used to trap the zinc at the interface by forming brass when the temperature reaches the melting temperature of copper, 1356 K. Elemental mapping made on a weld cross-section showed that very little zinc was left in the weld and most zinc was found mixed with copper in the form of brass (table 2.3). A computational model was developed by Dasgupta et al. to describe the generation of zinc vapour and its influence on the melt flow. It has been shown both experimentally and by modelling that the addition of copper reduces the vaporization of zinc and therefore stabilizes the process. It should be noted that the introduction of copper in the molten steels can lead to new problems with respect to hot cracking or decreased corrosion resistance of the fused region.

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition at a centre spot in weld (wt.%</th>
<th>Composition at a spot near Cu-Steel interface (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>93.27</td>
<td>24.30</td>
</tr>
<tr>
<td>Cu</td>
<td>4.80</td>
<td>65.28</td>
</tr>
<tr>
<td>Zn</td>
<td>1.92</td>
<td>10.41</td>
</tr>
</tbody>
</table>

### 2.3.7 Welding without additional control measures

Apart from the methods mentioned in previous subsections, other techniques have also been suggested including removing the zinc coating from the interface or combinations of several techniques. However they all share the disadvantage that additional procedural steps...
or precautionary measures are required. Research is on-going to obtain approaches to weld these materials without any special arrangements. Pieters et al.\cite{91-93} reported stable welds obtained in GI sheets with a coating thickness of 20 μm, without using a predefined gap or any other pre-treatment. As shown in Figure 2.16, the zinc coating on both sheets was fused together and wetted the weld, whilst at a small distance from the weld (between 0.5 and 1 mm), discontinuities in the zinc layer were observed. A mechanism indicating the generation of a transient gap and liquid zinc transportation was proposed to explain the good weld obtained. It was suggested that a gap was likely to be opened during welding due to heat induced distortion. The zinc was removed from the weld zone in the liquid state through this gap, possibly as a result of the vapour pressure. A simple calculation was performed to show the feasibility of this mechanism.\cite{92} Assuming a gap of 10 μm at the interface between two coated sheets with coating thickness of 50 μm, a distance of 3.3 mm from the weld fusion line was calculated to be required to transport all zinc from the fusion zone in a liquid state. This transportation was expected to occur within 0.044 s, which was the time between the melting and vaporization of zinc at the interface. The zinc at the interface wetting the weld also suggests that liquid zinc flows during weld solidification; however, the generation of a transient gap and the removal of liquid zinc from weld zone are unproven.

![Discontinuity in zinc layer](image)

\textit{Figure 2.16: Cross-section of a weld made at 2500 W and 55 mm s}^{-1\textit{}} with magnifications of the gap adjacent to the weld, which was filled by fused zinc.\cite{93}

Goebels et al.\cite{65} performed studies on welding of zinc coated sheets with both CO\textsubscript{2} and Nd:YAG lasers. It was found that with a full penetration keyhole with a clearly opened lower aperture, stable welds can be obtained using a continuous wave (CW) Nd:YAG laser without any gap or special beam setting. The lower aperture of a keyhole was suggested to be the main channel for zinc vapour escape, because more violent spatter splashing was observed at the weld root face (Figure 2.17). A dynamic keyhole model was introduced by Fabbro et al.\cite{94,95} to interpret the results, which showed that for a top-hat beam power profile, a characteristic keyhole shape was obtained that allowed zinc vapour to be reflected downwards to escape through keyhole root aperture. A clear aperture at the keyhole root and a low level of keyhole fluctuation on the rear wall are critical conditions for achieving a stable process. The model describing the interaction between the zinc vapour and the keyhole rear wall will be discussed in section 2.4.
2.3.8 Weldability of sheets with different types of coatings

The majority of the literature addressing laser welding of coated steels refers welds made with GI sheets, whilst electrogalvanized (EZ) and GA sheets are generally believed to have similar weldability. It was shown by Xie \textit{et al.}\cite{57,74} that conventional CW laser welds with acceptable quality could not be produced in all three types of coated sheets when there was no gap at the interface between the two sheets. Conversely whilst using the dual spot technique, all of the materials were successfully welded. Lu and Forrest suggested that GI sheets have a better weldability compared with GA sheets due to the lower melting point of the GI coating, which promotes the forming of a keyhole due to enhanced coupling of laser energy into the workpiece.\cite{68} Nevertheless, it was generally agreed that GI, EZ and GA sheets have the same problem of vaporization of zinc during welding and appropriate arrangements or configurations are necessary to make stable welds.\cite{50,72,80,96}

Another zinc coating with a small fraction of magnesium has been developed to improve the corrosion resistance. The weldability of this material was studied by Koll \textit{et al.}\cite{97} It was found that the addition of a small amount of Mg did not influence the process stability when laser welding coated sheets. A significant improvement of weld quality was observed when the coating thickness (for both zinc and Mg-Zn coating) was reduced below 3.5 μm.

2.4 Modelling of zinc behaviour

While there have been numerous reports concerning the weldability of zinc coated steel and process instabilities that occur in practice, studies on modelling the mechanisms of the zinc vapour, keyhole and melt pool interactions are limited.
Zhou et al.\textsuperscript{[78],[79]} suggested a two-dimensional model for pulsed laser welding of zinc coated steels. The formation and escaping processes of the zinc vapour are described together with the influence on the transient keyhole shape, weld pool shape, and velocity and temperature distributions both in the weld pool and in the vapour. Before the zinc vapour escapes into the keyhole, it is assumed that there is no vapour flow in the keyhole. When the keyhole bottom reaches the coating at the interface between the two sheets, the high pressure vapour will escape into the keyhole. Here the zinc vapour flow is considered to be incompressible and viscous and is described by following governing equations,

\begin{align}
\frac{\partial}{\partial t}(\rho_{z,v}) + \nabla \cdot (\rho_{z,v} v_z) &= 0, \quad (2.3) \\
\frac{\partial}{\partial t}(\rho_{z,v} u_z) + \nabla \cdot (\rho_{z,v} v_z u_z) &= -\frac{\partial p_z}{\partial x} + \nabla \cdot (\mu_{z,v} \nabla u_z) \\
\frac{\partial}{\partial t}(\rho_{z,v} w_z) + \nabla \cdot (\rho_{z,v} v_z w_z) &= -\frac{\partial p_z}{\partial y} + \nabla \cdot (\mu_{z,v} \nabla w_z), \quad (2.4)
\end{align}

where $\rho_{z,v}$ and $\mu_{z,v}$ represent the density and viscosity of zinc vapour, $v_z$ is the velocity vector of zinc vapour and $u_z$ and $w_z$ are the velocity distribution along $x$ and $y$ coordinates and $p_z$ is the zinc vapour pressure.

The inlet boundary conditions for zinc vapour into the keyhole are given as

\begin{align}
&u_z = 0; \quad w_z = \frac{2\rho_{z,l} g t_z}{\rho_{z,v}}, \quad (2.5) \\
p_z = \exp(A_0 T_{z,v}^{-1} + B_0 \log(T_{z,v}) + C_0 T_{z,v} + D_0),
\end{align}

where $\rho_{z,l} = \frac{M_z p_z}{RT_{z,v}}$. \quad (2.6)

Here $\rho_{z,l}$ is the density of liquid steel, $t_z$ is sheet thickness, $A_0$, $B_0$, $C_0$ and $D_0$ are material dependent constants, $T_{z,v}$ is the temperature of zinc vapour, $M_z$ is the atomic weight of zinc, $g$ and $R$ are the gravitational constant and gas constant respectively.

The results of the model simulating the formation of porosity were discussed in section 2.3.4. The model indicates that interaction between the zinc vapour and the weld pool is strong and by controlling the laser energy and pulse time, the vapour can be vented through the keyhole effectively avoiding many welding defects.
Another model for zinc vapour evacuation through a partial penetration keyhole was given by Dasgupta et al.\[^9\] The influence of zinc vapour was incorporated in a three-dimensional laser welding model, which solves the thermal, velocity and pressure fields together with the transient evolution of the keyhole. It has been assumed that a mixture of zinc and iron vapour exists in the keyhole, which behaves like an ideal gas and follows the law of partial pressures, where the effective vapour pressure depends on the mole fraction of each element. This pressure and the resulting force on the liquid-vapour interface are used to simulate the physics when welding zinc coated steels. The results show that the presence of zinc vapour increases the pressure in the keyhole by 30%. Consequently, the liquid velocity at the weld pool top surface is increased as shown in table 2.4 and the predicted average liquid velocity at the melt surface is in agreement with experimental observations.

**Table 2.4: Experimental and modelling results for CO\textsubscript{2} laser welding of galvanized steel.\[^9\]**

<table>
<thead>
<tr>
<th>Welding parameters</th>
<th>Experimental results</th>
<th>Modelling results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc coated sheets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Without zinc</td>
<td>1.58 × 10\textsuperscript{3}</td>
<td>1.06 × 10\textsuperscript{3}</td>
</tr>
<tr>
<td>With zinc vapour</td>
<td>1.30 × 10\textsuperscript{3}</td>
<td></td>
</tr>
</tbody>
</table>

A three-dimensional model based on continuity equations, the heat conduction equation and the Navier-Stokes equation was developed by Geiger.\[^9\] This model was used to investigate the influence of a gap at the interface when welding two sheets in an overlap configuration. The simulation shows that with a gap of 50 ~ 100 µm, the liquid metal does not completely close the interface between the two sheets (Figure 2.18a). The zinc vapour can easily escape into the keyhole. It is therefore helpful to minimize the disturbance caused by the zinc vapour on keyhole and melt pool (Figure 2.18b and c).
Figure 2.18: (a) simulation results showing an open channel connecting the interface with the keyhole when welding with a 100 µm gap, and schematic diagrams showing zinc evacuation through the keyhole when welding with (b) zero gap and (c) with a 100 µm gap.\cite{101}

Fabbro et al.\cite{94,95} developed a model to describe the interaction between the zinc vapour flow and the rear keyhole wall. The keyhole profile was modelled by a ray tracing technique, which determines the local energy and momentum balances at each point of the keyhole wall.\cite{94,99} The calculated keyhole geometries when welding with both CO$_2$ and Nd:YAG lasers are shown in Figure 2.19. The important feature in the case of a Nd:YAG laser is the characteristic deviation at the keyhole rear wall, located roughly at the middle of the sheets, resulting from the reflected beam on the front keyhole wall.
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Since the above model was built only to describe the keyhole profile without considering the hydrodynamics of the weld pool, the effect on the keyhole geometry is limited to the effect of zinc vapour pressure. The pressure of the zinc vapour was estimated by a simplified description of a free jet theory for a flow emitted from a nozzle,\[^{[100],[101]}\]

which is located on the keyhole front wall as illustrated in Figure 2.19. The dynamic pressure of zinc vapour on the axis of the jet is estimated by

\[
p_{x,z}(x) = p_0 \cdot \left(\frac{X_0}{x}\right)^2,
\]

where \(x\) is the distance along the axis of the jet from the exit of the nozzle (keyhole length here), \(p_0\) is the reservoir pressure that feeds the jet and \(X_0\) is a characteristic distance for the decrease of the velocity field of the emitted flow that depends on the Reynolds number. The effect of this vapour pressure on the keyhole profiles for different welding speeds is shown in Figure 2.20. At low welding speed, (a) and (d), it appears that the height \(h\) is greater than the sheet thickness \(t_p\), therefore, the zinc vapour hitting the keyhole rear wall forms a concave surface and becomes trapped in the melt pool. For an intermediate speed (b) and (e), \(h \approx t_p\), the zinc vapour is reflected from the lower part of keyhole wall and escapes through the keyhole root aperture; therefore welds with good quality can be achieved. At high welding velocity, (c) and (f), as \(h < t_p\), good quality should also be expected. However, fluctuations on the lower part of the keyhole rear wall become significant with increasing welding speed, hence increasing the instability.

Figure 2.19: Keyhole geometries generated by a (a) top-hat (Nd:YAG) and (b) Gaussian (CO\(_2\)) intensity profile, with incident power 4 kW and welding speed of 2 m min\(^{-1}\). Different calculated profiles are shown in an interval of 5 ms for visualizing the fluctuations.\[^{[95]}\]
Summary

2.5 Summary

The difficulty that arises in laser welding of zinc coated steels in an overlap configuration occurs due to the zinc vapour generated at the interface between the two sheets. Many approaches including the introduction of a channel for zinc vapour escape, using an enlarged keyhole, manipulating a laser pulse or reducing the amount of vapour by inserting Al or Cu films have been suggested to overcome this problem. Although these methods have been shown to be effective to improve the weld quality, they all require additional treatments or measurements, which increase the cost in industrial production.

Continuous wave laser welding of zinc coated steel with relatively stable welds have been reported without any additional treatment or arrangement. Some mechanisms have been proposed including the opening of a transient gap and enlargement of the lower aperture of a keyhole. A clear understanding of the interaction between zinc vapour and keyhole and melt pool is still missing. Several types of process instabilities and the corresponding defects have been presented in the literature. However, a detailed description
of the evolution of these instabilities and the generation of defects is required, in order to understand the behaviour of the zinc vapour. In addition, although the influence of zinc vapour on keyhole geometry has been presented, the subsequent effect of this modification on the process stability, energy distribution and weld cross-sectional profile is not yet reported.

In this research, the way in which the zinc vapour impinges on the weld pool and the subsequent influence on both keyhole and melt pool geometries and process stability are studied. The evolution of process instabilities and the generation of defects are examined by means of high speed imaging. The absorbed and transmitted powers are also measured to evaluate the influence of zinc vaporization on the power distribution during laser welding with a full penetration keyhole.
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69. M.G. Forrest, L. Feng and W. A. Marttila, Process development for dual beam laser welding of zinc-coated steel sheets in lap joint configuration without gap control at the interface, IIW 2005, Advances in automotive joining technologies workshop, 1-9,


Chapter 3

Equipment and Methods

The main materials, equipment and methods used throughout the course of this work are described in this chapter. The chemical composition of the coated sheets including the substrate and the coating layer (only for GI coating) are given, followed by a description of the laser welding arrangement and specimen preparation and microscopy. The arrangements for transient gap measurement, high speed imaging, calorimetric and transmitted power measurement and temperature measurement are also presented.

3.1 Zinc coated sheets

The majority of experiments were conducted on 0.8 mm thick hot dip galvanized (GI) sheets with 7 (Sample No.1) and 20 μm (Sample No.2 and 3) nominal zinc coating thicknesses. The chemical composition of the base steel is shown in table 3.1. The thickness and main compositions of the coating were examined using Glow Discharge Optical Emission Spectroscopy (GDOES), the results of which are shown in Figure 3.1. All three samples show an enrichment of Al at the Zn-Fe interface, which serves as a barrier to prevent the formation of Zn-Fe alloy during hot dipping. However, alloy layers were still present and were more pronounced in the case of 20 μm coating thicknesses.

Other materials used in this research including EZ sheets with 4 and 7 μm coating thicknesses (substrate thickness 0.7 and 0.8 mm respectively) and 0.8 mm thick Mg-Zn coated sheets with coating thicknesses of 5 μm and 10 μm, containing 1~2 wt.% Mg. The chemical compositions of the substrate steels are shown in table 3.2.

<table>
<thead>
<tr>
<th>Sample</th>
<th>C</th>
<th>Si</th>
<th>Al</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>P</th>
<th>S</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td>&lt;0.001</td>
<td>0.002</td>
<td>0.019</td>
<td>0.131</td>
<td>0.016</td>
<td>0.055</td>
<td>0.011</td>
<td>0.005</td>
<td>0.031</td>
</tr>
<tr>
<td>No.2</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>0.026</td>
<td>0.104</td>
<td>0.018</td>
<td>0.052</td>
<td>0.012</td>
<td>0.005</td>
<td>0.030</td>
</tr>
<tr>
<td>No.3</td>
<td>0.011</td>
<td>0.007</td>
<td>0.020</td>
<td>0.180</td>
<td>0.014</td>
<td>0.053</td>
<td>0.008</td>
<td>0.005</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>
Chapter 3. Equipment and Methods

Figure 3.1: Zn, Fe and Al profiles across the coating layers of three GI sheets.

Table 3.2: Chemical compositions of the base steel (in wt%) of the EZ and Mg-Zn coated sheets examined.

<table>
<thead>
<tr>
<th>Sample</th>
<th>C</th>
<th>Si</th>
<th>Al</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>P</th>
<th>S</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>EZ</td>
<td>0.014</td>
<td>0.108</td>
<td>0.085</td>
<td>0.160</td>
<td>0.016</td>
<td>0.036</td>
<td>0.120</td>
<td>0.015</td>
<td>0.058</td>
</tr>
<tr>
<td>Mg-Zn</td>
<td>0.002</td>
<td>0.007</td>
<td>0.033</td>
<td>0.171</td>
<td>0.022</td>
<td>0.026</td>
<td>0.008</td>
<td>0.007</td>
<td>0.045</td>
</tr>
</tbody>
</table>
3.2 Laser welding

3.2.1 Laser source and optics

During the course of this work, most of the welds were made at TU Delft using a HAAS HL3006D lamp pumped Nd:YAG laser with a nominal power of 3 kW, whilst at Tata a Trumpf HLD 4506 diode pumped Nd:YAG laser with a nominal power of 4.5 kW was used to check the reproducibility of the process and to determine the processing window at higher powers.

Both lasers have a fibre delivery system with a fibre diameter of 0.6 mm. The focal length was 150 mm, projecting the laser beam to a spot of 0.45 μm diameter. The laser beam was focused on the top surface of the sheet with the beam perpendicular to the surface. A camera was used to determine the focus plane, which has a focus adjusted to coincide with that of the laser beam.

3.2.2 Manipulation and clamping systems

The manipulation system is shown in Figure 3.2, which consists of a table that moves orthogonally with respect to the welding head (x-axis) and laser beam optics mounted on a gantry, which allow it to move in the y and z-direction. Technical details of the system are given in table 3.3. A Labview program was developed to control the processing parameters namely: laser power, welding speed and weld length.

Two clamping systems were used; they are clamp 1 (Figure 3.3a ) consisting of a 220 × 330 × 30 mm steel backing plate with an efflux channel of 8 mm wide by 10 mm deep, and clamp 2 (Figure 3.3b) consisting of a 255 × 500 × 85 mm aluminium backing plate with an efflux channel of 15 mm wide by 65 mm deep. The majority of the work was performed on clamp 1. Welding using both clamps was performed to examine the influence of the clamping system on process stability, which is discussed in section 4.1. The workpiece was clamped by means of toggle clamps and “C” cross-section profile aluminium plates were used to distribute the clamping pressure evenly along the workpiece.
Table 3.3: Technical specifications of the manipulation system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>x-axis</th>
<th>y-axis</th>
<th>z-axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stroke</td>
<td>1200 mm</td>
<td>500 mm</td>
<td>500 mm</td>
</tr>
<tr>
<td>Max. velocity</td>
<td>11 m min⁻¹</td>
<td>15 m min⁻¹</td>
<td>15 m min⁻¹</td>
</tr>
<tr>
<td>Repeat accuracy</td>
<td>0.01 mm</td>
<td>0.01 mm</td>
<td>0.01 mm</td>
</tr>
<tr>
<td>Positioning accuracy</td>
<td>0.03 mm</td>
<td>0.03 mm</td>
<td>0.03 mm</td>
</tr>
<tr>
<td>Controller</td>
<td>Galil DMC1000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.2: Laser welding manipulator.

Figure 3.3: Laser welding clamp arrangements, (a) the steel rig with a smaller efflux channel and (b) the aluminium rig with a bigger efflux channel.
3.3 Specimen preparation and examination

3.3.1 Assessment of welds

All steel sheets were cut to dimensions of 120 × 50 mm, cleaned with ethanol and mounted on the traverse table. After welding, the welds were checked visually. The quality was quantified by a length fraction, defined by the length of the weld seam without any surface breaking pores or severe undercut divided by the total length of the seam. The average length fractions were determined for 3 welds per parameter set.

3.3.2 Grinding and polishing

After welding, the welds of interest were sectioned by means of a cooled cutting wheel and then mounted in a hot curing epoxy. The mounted samples were ground and polished using a Struers Rotopol automatic polishing machine in successive steps from a 500 grit silicon carbide to a 1 μm diamond finish. Between steps, the specimens were cleaned with a cotton pad saturated in ethanol. Ethanol was also used as the lubricant during grinding and polishing. Water was avoided because it was found that it severely stained the coating.\[1\]

3.3.3 Etching

The polished weld cross-sections were etched in 4% picric acid with a few drops of 5% nitric acid to reveal the weld profile. The specimens were immersed in the etchant for 8-9 minutes and rinsed and cleaned with ethanol and cotton, then dried with hot air.

3.3.4 Microscopy

Prior to sectioning, the welds of interest were photographed using an Olympus BX60M optical microscope to check the zinc fusion line at the weld end position. After polishing, but prior to etching welds were photographed with the same microscope to observe the zinc around the weld bead. The weld longitudinal sections indicating the porosity contained in the weld were also photographed without any etching. The etched weld cross-sections were again photographed for the weld profiles and the widths of the welds at the interface were measured. It is necessary to photograph as soon as possible after etching because etchant tends to remain in the gaps between the sheets or in pores in the welds, despite careful cleaning and drying, causing staining of the surfaces.
3.4 Transient gap measurement

Linear variable differential transformers (LVDT) were used to measure the displacement of the sheets in the vertical direction relative to the sheets surface plane. The LVDTs have a range of 35 mm and repeat accuracy of 1.5 μm. Since the working temperature of the LVDT is only up to 393 K, a measuring system was developed for measuring positions close to the weld zone. This arrangement is shown in Figure 3.4. During welding, any displacement of the position measured was sensed by probes made from fused quartz (thermal expansion coefficient $6 \times 10^{-7} \text{ K}^{-1}$) and transmitted to the LVDT by aluminium arms of 600 mm length. A clamp with a groove in the steel backing plate was made to conduct the measurement from both top and root faces of the sheets. The movement of the push rod of the LVDT was transformed into a voltage signal, monitored by a high frequency Yokogawa (DL 750 Scopecorder) oscilloscope. The length of the arms and probes were carefully measured to calculate the displacement of the sheets.

![Figure 3.4: Schematic of the arrangement for transient gap measurement.](image)

3.5 High speed video

The dynamic behaviour of the keyhole and melt pool was filmed with a Phantom v5.0 CMOS camera. Depending on the phenomena of interest the camera was placed at three different positions as shown in Figure 3.5. Position 1 is coaxial with the laser beam and images of the top surface of the keyhole and melt pool were captured at a sampling rate of 30,000 frames per second (fps). The exposure time was 10 μs and the resolution was $256 \times 64$ pixels. From position 2, the laser induced vapour plume and ejections of spatter from both top and root faces were visualized at a sampling rate of 10,000 fps and exposure time...
Energy measurement

3.6 Energy measurement

3.6.1 Calorimetric measurement

Calorimetric measurements were conducted using a Seebeck envelop calorimeter. This apparatus works on the gradient layer principle where a voltage output is produced that is proportional to the heat flux through the calorimeter walls. Prior to the measurements, the system was calibrated using a Joule heating method as detailed by Geidt et al.\textsuperscript{[2]}

A schematic of the measuring arrangement is presented in Figure 3.6. The test specimens were mounted on a clamping unit. A removable bar under the specimen was
designed to absorb the energy that passes through the keyhole during welding. The bar is surrounded by insulating materials to minimize the heat loss to the clamping unit.

![Figure 3.6: Schematic illustration of calorimetric measurement.](image)

The measurement procedure consisted of the following steps: i) placing the workpiece in the calorimeter and keeping the calorimeter closed until the output signal reaches equilibrium; ii) opening the calorimeter and performing the weld; iii) immediately after welding closing the calorimeter and monitoring the output signals until equilibrium is again obtained when the mass inside the calorimeter reaches the temperature of the incoming cooling water.

The output voltage of the calorimeter was recorded and subsequently integrated over the measuring time to obtain the power absorbed by the workpiece $Q_i$. The heat transfer (process) efficiency ($\eta_h$) can be calculated as

$$\eta_h = \frac{Q_i}{Q_0},$$

(3.1)

where $Q_0$ is the incident laser power, which was measured with a calibrated power meter. The actual power was found to be 2808 W with a nominal laser power of 3 kW. This measured value was adopted in calculation of heat transfer efficiency. The heat loss due to ejected droplets was accounted for by calculating the energy required to melt the lost mass, which was determined by weighing the workpiece before and after welding. The mean value of the mass loss was obtained for three measurements per parameter set.

### 3.6.2 Transmitted power measurements

The fraction of incident laser power that transmits through the keyhole during the welding process was measured with a PRIMES 70iCu power meter. The experimental
Energy measurement

arrangement for these measurements is shown in Figure 3.7. The power meter was placed directly below the keyhole and a cross jet and shielding sheet with a circular hole in the middle were used to avoid damage from any ejected droplet. In contrast to the calorimetric technique, which measures the total power dissipated through the keyhole, the transmitted power measurement indicates the fraction of the power transmitted through the keyhole without reflection.

Figure 3.7: Schematic illustration of transmitted power measurement.

3.6.3 Melting efficiency assessment

After polishing and etching, the surface area of the cross-section, zinc fusion zone and zinc vaporization zone were measured using an optical microscope equipped with a digital analysis system. The mean value of each area was determined for three cross-sections per parameter set. The mean area was multiplied by the total weld length to determine the individual volumes of the melted substrate steel and the melted and vaporized zinc coating. The melting efficiency $\eta_m$ is

$$\eta_m = \left( \frac{1}{Q_i} \left( \rho_{s\rightarrow solid} V_{s\rightarrow melt} E_{s\rightarrow melt} + \rho_{z\rightarrow solid} V_{z\rightarrow melt} E_{z\rightarrow melt} + \rho_{z\rightarrow liquid} V_{z\rightarrow liquid} E_{z\rightarrow liquid} \right) v \right) l,$$

where $Q_i$ is the absorbed power, $v$ is the welding speed, $l$ is the weld length and

$$E = \int_{T_1}^{T_2} C_p(T) \, dT + L,$$

$C_p$ is the heat capacity at constant pressure, $\rho$ is the density, $V$ the volume and $L$ is the latent heat. $E$ represents the energy per unit mass required to raise the substrate from temperature $T_1$ to temperature $T_2$ and to effect a phase change. The subscripts $s$, $z$, $m$ and $v$ refer to steel,
Chapter 3. Equipment and Methods

zinc, melting and vaporizing respectively. Thus $E_{stm}$ and $E_{zim}$ represent the energy required to heat a unit mass of steel and zinc respectively from room temperature to the melting temperature and to melt the material, whilst $E_{zv}$ is the energy per unit mass required to heat zinc from its melting to its vaporisation temperature and to effect vaporisation. The material properties given in table 3.4 were used to calculate the melting efficiencies.

Table 3.4: Physical property of material used in melting efficiency calculations.

<table>
<thead>
<tr>
<th>Property</th>
<th>Steel</th>
<th>Zinc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquidus Temperature (K)</td>
<td>1809</td>
<td>692</td>
</tr>
<tr>
<td>Vaporization Temperature (K)</td>
<td>3133</td>
<td>1180</td>
</tr>
<tr>
<td>Melting enthalpy (J kg$^{-1}$)</td>
<td>$2.7 \times 10^{5}$</td>
<td>$1.0 \times 10^{5}$</td>
</tr>
<tr>
<td>Evaporation enthalpy (J kg$^{-1}$)</td>
<td>$6.1 \times 10^{6}$</td>
<td>$1.8 \times 10^{6}$</td>
</tr>
<tr>
<td>Density (kg m$^{-3}$)</td>
<td>$7.8 \times 10^{3}$</td>
<td>$7.1 \times 10^{3}$ Solid</td>
</tr>
<tr>
<td></td>
<td>$6.5 \times 10^{3}$</td>
<td>$6.4 \times 10^{3}$ Liquid</td>
</tr>
<tr>
<td>Specific heat (J kg$^{-1}$ K$^{-1}$)</td>
<td>650 Solid</td>
<td>0.1915 T + 329.05 Solid</td>
</tr>
<tr>
<td></td>
<td>805 Liquid</td>
<td>-0.0685 T + 554.1 Liquid</td>
</tr>
<tr>
<td>Thermal conductivity (W m$^{-1}$ K$^{-1}$)</td>
<td>41 Solid</td>
<td></td>
</tr>
<tr>
<td></td>
<td>44 Liquid</td>
<td></td>
</tr>
</tbody>
</table>

3.7 Temperature measurement

Temperature measurements were performed with standard 0.13 mm diameter K-type thermocouples to determine the position of the zinc boiling isotherm at the top surface and the interface between two sheets. The locations of the thermocouples are shown schematically in Figure 3.8. Thermocouples were attached on the cleaned surface along a line perpendicular to the welding direction. Small pieces of ceramic were used to isolate the individual thermocouple wires. The exact positions were measured after welding to determine the position where the maximum temperature approached the zinc boiling point, 1180 K.

![Figure 3.8: Temperature measurements on the surface and at the interface between two sheets.](image-url)
References


Chapter 4

Welding of Hot-dip Galvanized (GI) Steel

In this chapter an investigation of the weldability of GI steels with two coating thicknesses is reported. After the examination of surface profiles, the influences of the coating thickness, welding speed and laser power on the process stability and weld profiles are presented. To understand the mechanisms responsible for the welding results, measurements were made to determine whether a transient gap develops in between the two sheets when welding in an overlap configuration, and high speed videos were taken to observe keyhole and melt pool dynamics. Based on these results, the critical parameters leading to stable welds when welding sheets with a 20 μm zinc coating thickness are discussed. A mechanism based on the development of an elongated keyhole is suggested to explain different performances of sheets with 7 and 20 μm coating thicknesses. The interaction between the vaporized zinc, the keyhole and the melt pool is simulated by an argon jet injected into a channel in the interface between two sheets. The results obtained from this test provide additional support for the proposed mechanism. An analytical model is developed based on operating parameters (welding speed) and material properties (coating thickness, surface tension and density) to describe the influence of zinc vapour on keyhole geometry.

4.1 Experimental procedures

4.1.1 Preliminary tests

In order to verify the feasibility of welding zinc coated steel without any pre-set gap and to determine the parameters dominating process stability, a set of preliminary tests were carried out with the welding parameters shown in table 4.1.

Among the parameters examined, the influences of defocusing and shielding gas/backing gas on the process stability in terms of defects on the weld faces were found not to be significant. Welding with different clamping systems, with various efflux channel dimensions, also showed no substantial differences, although a bigger efflux channel can
reduce the instabilities on the weld root face at lower welding speeds. However, the size of the efflux channel does not alter the weldability of a material.

When welding sheets with a 20 μm coating thickness, it was observed that welds with acceptable quality can be obtained. The quality of the weld is dependent on welding speed to some extent, but relatively good welds can be made for all the speeds examined (25 to 45 mm s⁻¹) and these were reproducible for both of the base metal compositions examined (No. 2 and No. 3 in table 3.1) independent of the clamping configuration employed. Based on the results of the preliminary tests, the parameters shown in table 4.2 were chosen for the subsequent experimental study.

**Table 4.1: Trial laser welding parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (kW)</td>
<td>3</td>
</tr>
<tr>
<td>Focal length (mm)</td>
<td>150</td>
</tr>
<tr>
<td>Spot diameter (mm)</td>
<td>0.45</td>
</tr>
<tr>
<td>Shielding gas / Backing gas</td>
<td>Argon</td>
</tr>
<tr>
<td>Gas Flow rate of shielding gas (L min⁻¹)</td>
<td>30 (delivered coaxially)</td>
</tr>
<tr>
<td>Focal plane</td>
<td>From -0.5 to +0.5 mm from the sample top plane</td>
</tr>
<tr>
<td>Speed (mm s⁻¹)</td>
<td>25 ~ 45</td>
</tr>
<tr>
<td>Clamping arrangement</td>
<td>As described in section 3.2.2</td>
</tr>
<tr>
<td>Material</td>
<td>Three GI sheets with sheet thickness of 0.8 mm and coating thickness of 7 and 20 μm respectively (see table 3.1).</td>
</tr>
</tbody>
</table>

**Table 4.2: Laser welding parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (kW)</td>
<td>3</td>
</tr>
<tr>
<td>Focal length (mm)</td>
<td>150</td>
</tr>
<tr>
<td>Spot diameter (mm)</td>
<td>0.45</td>
</tr>
<tr>
<td>Shielding gas / Backing gas</td>
<td>No shielding or backing gas</td>
</tr>
<tr>
<td>Focal plane</td>
<td>Top surface of the sample</td>
</tr>
<tr>
<td>Speed (mm s⁻¹)</td>
<td>25 ~ 55</td>
</tr>
<tr>
<td>Clamping arrangement</td>
<td>Clamps No. 1</td>
</tr>
<tr>
<td>Material</td>
<td>No. 1 (with 7 μm coating ) and No. 2 (with 20 μm coating )</td>
</tr>
</tbody>
</table>
4.1.2 Other procedures

Linear welds of 100 mm length were made on uncoated steels and commercially produced GI sheets with nominal zinc coating thickness of 7 and 20 μm (No. 1 and 2 in table 3.1) with parameters given in table 4.2. The quality of the weld was assessed visually by fraction of acceptable weld length as defined in section 3.3.1. The welds of interest were sectioned, polished and photographed according to the procedures described in section 3.3.2 to 3.3.4.

To evaluate the magnitude of a transient gap, measurements using the arrangement described in section 3.4 were carried out at a welding speed of 45 mm s\(^{-1}\). The majority of measurements were performed at positions of 1.5 mm from the weld central line, whilst the transient gap at a further position of 2.1 mm from the weld central line was also measured to investigate the positional sensitivity.

The interaction between the vaporized zinc, the keyhole and the melt pool was monitored by a high speed camera mounted coaxially with the laser beam (position 1 as described in section 3.5). The spatter generated at both top and root faces was observed by the same high speed camera placed at the side of the sheets (position 2 as described in section 3.5).

To simulate the effect of vaporized zinc on the keyhole and melt pool dynamics, an argon gas jet was delivered from a capillary tube into a gap at the interface between two sheets. The details of the arrangement and the parameters employed in this test are given in section 4.5.

4.2 Welding results

4.2.1 Examination of surface profile

Prior to welding, the coated sheets were sectioned to examine the coating thickness and thickness variations. Measurements were performed at intervals of 1 mm along a 100 mm sample length. Results show a mean thickness of 21.4 μm for the nominal 20 μm thick coating, with a standard deviation of ±1.6 μm, and an average thickness of 8.7 μm for the 7 μm nominal coating thickness with a standard deviation of ±2.2 μm (Figure 4.1).

Measurements of the surface profiles reveal the coating of the 20 μm nominal thickness is more uniform compared to that of the 7 μm nominal thickness, as shown in Figure 4.2. It can be seen that in the case of the 7 μm coating thickness, the substrate surface is not completely covered by the zinc coating. This is consistent with the microscopy observations of the surfaces of these coated materials, which show incompletely coated areas in the case...
of the 7 μm nominal coating thickness compared to a sheet with a more uniform coating in the case of the 20 μm nominal coating thickness (Figure 4.3).

![Figure 4.1: Coating thickness variation of two GI coated steels.](image1)

![Figure 4.2: Surface profiles of two GI coated steels, measured using an optical 3D profiler. The colour bar represents the surface height.](image2)
4.2.2 Weld quality examination

The influence of welding speed on weld quality, quantified by a length fraction of acceptable weld, is shown in Figure 4.4. As it is observed that typically there is no severe spatter splashing during welding when a length fraction is greater than 90%, a weld with good quality is defined as a weld with a length fraction greater than 90%. It can be concluded that welds with good quality are obtained when welding sheets with a 20 μm coating thickness at welding speeds ranging from 25 to 45 mm s\(^{-1}\) and a combination of sheets with 7 and 20 μm coating thicknesses at 25 and 35 mm s\(^{-1}\). For all three cases, a common tendency is that increasing welding speed reduces the weld quality. Examples of the weld surfaces are shown in Figure 4.5. It is notable that the welds produced with the thinner coatings have significantly more defects. At the lower speed, the weld defects primarily appear at the root face in terms of blow holes and undercut and shift to both top and root faces (through holes) with increasing welding speed.
4.2.3 Cross-section examination

The effect of welding speed and coating thickness on weld profiles is illustrated by weld cross-sections as shown in Figure 4.6. A hyperbolic shaped weld profile, characterized by a relatively wide weld root is observed when welding uncoated steel sheets, whereas a parallel sided profile is formed when welding sheets with a 20 μm coating thickness. The
Welding results

Welds made with a 7 μm coating are more hyperbolic in shape at 25 mm s⁻¹ but more parallel in shape at the higher welding speed. The magnified view of the interface in between the sheets shows zinc filled gaps of 20 μm and 6.5 μm respectively. These sizes are smaller than the original total thicknesses of zinc coatings at the interfaces between the two sheets, which were 40 and 14 μm respectively. This is related to the shrinkage of a weld during solidifying. It is also notable that the welds made at a lower welding speed have a larger cross-sectional area. The average areas of three welds for each parameter combination are shown in Figure 4.7. A decrease of weld area with increasing welding speed is observed, being most pronounced with the uncoated steels.

Figure 4.6: Transverse cross-sections of welds made on sheets with various combined coating thicknesses at the interface, at two travel speeds.
4.2.4 Processing window for the sheets with a 20 μm coating thickness

The results shown above indicate (surprisingly) that sheets with a 20 μm coating thickness can be laser welded with minimal process instability. The processing window for such materials is summarized in Figure 4.8. Welds with good quality (> 90% acceptable length fraction) can be obtained with welding speeds lower than 45 mm s\(^{-1}\). Quality is insensitive to the input laser power provided a full penetration keyhole is formed. At a given welding speed, increasing input power has no significant effect on the weld cross-section in terms of width of a weld bead. Welds have a generally parallel profile, however, severe undercut appears when welding with higher powers (Figure 4.9). With increasing laser power, a decreasing inclination angle of the keyhole front wall is observed (Figure 4.10). These cross-sections of weld end craters also reveal that the liquid steel on the keyhole front wall is completely penetrated and liquid zinc has flowed through the resulting channel during solidification.
Figure 4.8: Processing window showing optimal combinations of power and speed for sheet with a 20 μm coating thickness.

Figure 4.9: Transverse cross-sections for welds made on sheets with a 20 μm coating thickness, with various laser powers and constant welding speed of 45 mm s\(^{-1}\).
4.3 Transient gap measurement results

The mechanism of transient gaps has been suggested to explain the results obtained when welding GI coated steel. According to this mechanism, adequate opening of a gap is required to contain the liquid zinc transported from the weld zone. The sheet deformations in the steel surface normal directions were therefore measured and some results are given in Figure 4.11 as examples. Since the measured data is subject to a scatter, a curve representing a moving average of 100 data points has been plotted to illustrate the evolution of sheet deformation.

In all measurements, the top sheets always show upward deformation during welding. The deformation measured 1.5mm from the weld central line begins to increase from the moment that welding starts and reaches a peak when the laser spot passes close to the measuring position. Afterward the deformation amplitude declines and this reduction can continue after welding finishes. In contrast, the lower sheets show nearly no deformation during welding. An average difference and the maximal difference of deformations of top and lower sheets are obtained as shown in Figure 4.11a. The thermal expansion of the sheet is subtracted from these differences to evaluate the magnitude of a potential transient gap in between the two sheets. The total thermal expansion of both sheets is given by

$$\varepsilon = 2t_p \cdot \alpha_{\text{thermal}} \cdot \Delta T,$$

(4.1)

where $\varepsilon$ is the total thermal expansion, $t_p$ is the sheet thickness, $\alpha_{\text{thermal}}$ is the coefficient of thermal expansion and $\Delta T$ is the change of the temperature at the measuring point during
Transient gap measurement results

the process. Given that the coefficient of thermal expansion of steel is $1.2 \times 10^{-5} \text{ K}^{-1}$,[3] and using a temperature difference of 450 K, which is determined by the temperature measurement made at the same point at which the transient gap was measured, the total expansion is estimated to be of the order 9 μm. The average and maximum differences of deformations of top and lower sheets and the corresponding magnitudes of the transient gaps are given in table 4.3. Since the maximum size of a transient gap is of interest, only the maximum values of 3–4 measurements for each material are shown here. Measurements indicated that a gap of no greater than 15.2 μm formed during welding.

<table>
<thead>
<tr>
<th>Material</th>
<th>Ave. difference (μm)</th>
<th>Transient gap (μm)</th>
<th>Max. difference (μm)</th>
<th>Transient gap (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncoated steel</td>
<td>13.0</td>
<td>4.0</td>
<td>22.5</td>
<td>13.5</td>
</tr>
<tr>
<td>7 μm coated</td>
<td>13.2</td>
<td>4.2</td>
<td>25.1</td>
<td>15.1</td>
</tr>
<tr>
<td>20 μm coated</td>
<td>12.7</td>
<td>3.7</td>
<td>25.2</td>
<td>15.2</td>
</tr>
</tbody>
</table>
Figure 4.11: Deformations of top and lower sheets when welding (a) uncoated steels (b) 7 \( \mu \text{m} \) coated and (c) 20 \( \mu \text{m} \) coated steels with a welding speed of 45 mm s\(^{-1}\).
4.4 Results of high speed video imaging

4.4.1 Effect of the vaporized zinc on the welding process

A weld was made on a sheet with a 20 μm zinc coating thickness over half of its length and no coating on the other half as illustrated in Figure 4.12a and b. The smaller weld obtained when welding zinc coated steels, which has been shown in Figure 4.6 and 4.7, is confirmed by the results shown in Figure 4.12b, where both top and root bead widths decrease on the transit from the uncoated to the coated section. High speed video images (Figure 4.12c and d) illustrate an elongated keyhole and a smaller weld pool obtained when welding the zinc coated section. The generation of a droplet ejection at the moment of transition is illustrated in Figure 4.12e. This ejection is generated at the keyhole rear wall and an enlarged keyhole is formed as a result.

Videos were taken (Figure 4.13) by placing a digital camera at the side of the specimen to monitor the development of spatter. It can be seen that when welding uncoated steel, the majority of the spatter is ejected from the root face of the specimen and directed in the welding direction, whereas when welding sheets with a 20 μm coating, there is more spatter directed opposite to the welding direction, generated from both top and root faces. Lateral observations made with high speed imaging shows a typical vapour plume on the top face with a direction normal to the sheets when welding uncoated sheets (Figure 4.14a). In addition, a liquid drop is formed at the front part of the keyhole lower aperture, due to the recoil force of evaporation and the gravitational force, and spatter is generated at this location. In contrast, when welding sheets with a 20 μm coating, the vapour plume is deflected from normal to 35° to the plate surface and the droplet at the keyhole root aperture is absent (Figure 4.14b).
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Figure 4.12: The influence of vaporized zinc on keyhole and melt pool geometries and weld bead size at a welding speed of 25 mm s\(^{-1}\). The interval between images shown in (e) is 1ms and weld pool boundaries are indicated by dotted lines.

Figure 4.13: Photos showing the spatter generated during the welding of uncoated and 20 μm coated sheets at a welding speed of 25 mm s\(^{-1}\).
Results of high speed video imaging

Figure 4.14: High speed video images showing the influence of vaporized zinc on the direction of the top face vapour plume and spatter generation when welding (a) uncoated sheets and (b) coated sheets with a 20 µm coating thickness at a speed of 25 mm s⁻¹. The spatter directed rearwards when welding the coated steel is marked by white circles.

4.4.2 Keyhole dynamics

Based on coaxial views of the keyhole opening, the keyhole geometry can be approximately reconstructed (Figure 4.15), with respect to the inclination of the keyhole front wall and the shape of the keyhole top aperture. The grey scale at any given position on an image represents a combination of both laser and radiative intensities. The bright zone on the images indicates the material directly exposed to the laser beam. The dark area in the centre of a keyhole indicates that the sheets have been fully penetrated. At these locations the laser beam travels through the keyhole without any significant reflection or refraction. It is found that the keyhole widths are virtually constant, being defined by the incident focal spot dimensions. In contrast, the keyhole length increases when welding zinc coated sheets and is more pronounced in the case of the 20 µm zinc coating thickness. It is also notable that a longer keyhole is obtained when welding with a higher speed. A dark line in the middle of the keyhole front wall is observed when welding coated steels, corresponding to a channel opened on the keyhole front wall. This indicates that the zinc vapour penetrates the liquid film at this location and escapes into the keyhole.

In Figure 4.15, the length of the keyhole front wall (\(l\)), which is directly irradiated by the laser beam, can be measured from the images. As sheet thickness is known, the inclination of the front keyhole wall (\(\alpha\)) can be determined. A continuous sequence of 10,240 images (representing a time period of 0.34 s) for steady state welding was analysed for each parameter combination and the results are shown in Figure 4.16. It can be seen that inclination angles increase quite linearly with the welding speed (in the range examined). The mean angles measured for sheets with a 20 µm thick coating are slightly smaller than
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those of the other two cases; however the difference is relatively small compared with the deviation, which arises from keyhole front wall oscillations. Hence, it is reasonable to use an overall mean value to represent all three cases.

![Figure 4.15: Coaxial views of the keyhole opening and schematics of corresponding keyhole profiles.](image)

---

64
Figure 4.16: The mean inclination angle of the keyhole front wall as a function of welding speed.

The mean keyhole lengths over a continuous sequence of 10,240 images were determined for each parameter combination and the results are shown in Figure 4.17. The keyholes obtained when welding coated steels are longer than those observed in the cases of uncoated steels. Welding speed has little influence on keyhole length when welding the uncoated steel, whilst keyhole lengths increase with welding speed when welding the zinc coated steels, the effect being more pronounced with the thicker coating. The deviations shown in the figure arise from the oscillations of the keyhole rear walls. It is notable that the keyholes produced when welding uncoated steels show relative small amplitude oscillations. Although large fluctuation amplitudes are observed for both coated materials, different modes of the keyhole fluctuation are noted when observing the keyhole evolution over a time period, as shown in Figure 4.18. In the case of the 20 μm coating thickness, less fluctuation is observed and the keyhole mostly oscillates in a narrow range with occasional large excursions. This contrasts with the case of the thinner coating, where the keyhole continuously oscillates over a large amplitude and some peaks are even higher than those produced with the 20 μm coating.
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Figure 4.17: Average keyhole lengths for various welding speeds and coating thicknesses, obtained from high speed images. The error bars represent the standard deviation of 10,240 measurements.

Figure 4.18: Evolution of the keyhole lengths over 0.2 s, welding at a speed of 45 mm s\(^{-1}\).

4.5 Results of welding with an injected argon jet

An argon gas jet was injected into a gap at the interface between the two sheets to simulate the effect of the vaporized zinc, as shown in Figure 4.19. The gap is 40 μm high.
and 3 mm wide and was created by removing the zinc coating from a sheet with a 20 μm coating thickness. The tests were performed at welding speeds of 25 and 45 mm s⁻¹. The flow rate of the argon gas jet was varied in the range of 1.8 to 3.3 L min⁻¹, corresponding to flow velocities of 250 and 460 m s⁻¹ respectively (assuming no change in gas temperature). The Reynolds number lies in the range 370 to 690, indicating that the flow is turbulent with respect to the critical Reynolds number of 40, which characterises the laminar to turbulent transition for free jet flows.¹⁴,¹⁵

![Diagram showing the arrangement of the argon gas supply into a gap at the interface between the two sheets.](image)

**Figure 4.19:** The arrangement of the argon gas supply into a gap at the interface between the two sheets.

When an argon jet is applied, the keyhole length is found to increase linearly with increasing argon flow rate (Figure 4.20). The average lengths are calculated from 5,012 successive images and the error bars represent the standard deviation of measurements. Relatively narrow melt pools are present when the flow rate ranges from 2.3 to 3.3 L min⁻¹, whereas at a flow rate of 1.8 L min⁻¹, a nearly circular keyhole is obtained and correspondingly a larger melt pool appears. This observation is similar to results obtained when welding uncoated and zinc coated steels as shown in Figure 4.12. In addition, it is notable that the development of elongated keyholes is insensitive to the welding speed when an external gas is supplied.

Since the gap between the sheets was made by etching the zinc coating, there is a risk that the coating of the sides of the gap can evaporate and affect the keyhole dynamics. This factor has been examined by checking the position of the zinc coating after welding without additional gas. In Figure 4.21a, it is shown that the gap in the zinc coating after welding is larger than 3 mm, indicating that part of the coating has evaporated during welding. However, its effect on the elongation of the keyhole is minor since no keyhole elongation is observed in the high speed images when welding without an applied argon flow (Figure 4.21a). To confirm this, a gap of 0.1 mm high and 3 mm wide was made by inserting aluminium foils in between two sheets and the keyhole dynamics during welding of these sheets with an argon flow rate of 6 L min⁻¹ was filmed. The influence of zinc vapour is completely excluded and the elongation of the keyhole during welding is only due to the argon jet applied (Figure 4.21b). This indicates that the dynamic pressure of the argon jet is
the dominant factor in the development of elongated keyholes and the influence from any additional evaporated zinc coating is small.

The weld profiles made with or without an argon jet also show similarity to the welds obtained when welding uncoated or zinc coated steels (Figure 4.22). A hyperbolic shaped weld profile is formed when welding without the jet (Figure 4.22a), whereas a parallel profile is formed when a jet (with a flow rate of 2.8 L min\(^{-1}\)) is applied, and a smaller weld cross-sectional area is obtained (Figure 4.22b).

**Figure 4.20:** Keyhole lengths measured when welding with an argon jet.

**Figure 4.21:** Widths of gaps after welding and the corresponding keyhole geometries, (a) when welding with a 40 μm gap at the interface and (b) when welding with a 0.1 mm gap at the interface and with an argon jet injected into the gap (at an argon flow rate of 6 L min\(^{-1}\) and a welding speed of 25 mm s\(^{-1}\)).
4.6 Discussion

4.6.1 The transient gap hypothesis

According to the mechanism suggested by Pieters et al.\textsuperscript{[1],[2]}, the welds with acceptable quality are associated with a zinc transport away from the weld pool in a liquid state, driven by vapour pressure, through a transient gap that is produced primarily due to the thermal expansion of the sheets and the pressure of the zinc vapour. In section 4.3, measurements showed that a gap with the maximum opening of 15.2 μm appeared in between the sheets during welding. In the calculation undertaken by Pieters et al.,\textsuperscript{[2]} a flow distance of 3.3 mm from the weld was suggested to be necessary to remove all the liquid zinc from the fusion zone in the case of a 20 μm coating thickness, with the assumption that there is a constant separation (transient gap) of 10 μm in between two sheets. However, the magnitude of a gap, formed due to the thermal expansion, is strongly dependent on the local temperature. In laser welding, the temperature gradient with distance is large, resulting in a reduction of the gap with increasing distance from the weld fusion boundary. Evidence for this is shown in Figure 4.23 where the transient gap measured at a position 2.1 mm away from the weld central line gives a much smaller gap with a maximum of 5 μm. Hence, it is unlikely that a constant gap with adequate size can be formed to provide sufficient space to contain displaced liquid zinc.

Additionally, if the liquid zinc can be completely transported before gross vaporization, it can be expected that the process will be more stable in the case of a thinner coating, because less zinc need be removed through the gap, which has the same size as that produced when welding the sheets with the thicker coating, as shown in Figure 4.11 and table 4.3. This obviously conflicts with the welding results shown in Figure 4.4 and 4.5, and fails to explain why a relatively stable process can be obtained when welding sheets with a 20 μm coating thickness.

Figure 4.22: Weld profiles when welding (a) without and (b) with an argon jet. The welds were made at a welding speed of 25 mm s\textsuperscript{-1}.
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The transient gap is therefore unlikely to function as a container of liquid zinc to avoid vaporization. Observations indicate that the vaporization of zinc occurs and the vapour expands into the keyhole and/or melt pool. The interaction between the vaporized zinc and the keyhole and melt pool is the key to understand the mechanism responsible for the stable process when welding with a 20 μm coating thickness.

4.6.2 Process parameters

Coating thickness

According to the results shown in section 4.2, the thickness of zinc layers and the welding speed appear to be the dominant parameters with respect to the weld stability when welding zinc coated sheets. There is no doubt that the vaporization of zinc causes process instabilities during laser welding of coated materials without the introduction of a pre-set gap. It may be expected that an increasing zinc coating thickness should result in greater instability due to larger volume of zinc vapour produced per unit length of weld. However, for all welding speeds examined, welds with better quality were obtained with the thicker coating (Figure 4.4, 4.5). As an alternative to the transient gap hypothesis, the current results suggest that the welding process is stable provided a dynamic balance is maintained between zinc vapour entering the keyhole, the keyhole itself and the surrounding weld pool. A constant or consistent supply of zinc vapour into the keyhole is needed to avoid the generation of severe keyhole and weld pool oscillations, which result in process instability and poor weld quality.

Figure 4.23: Deformation of the top and lower sheets, measured at a position of 2.1 mm away from the weld central line, when welding sheets with a 20 μm coating thickness at a welding speed of 45 mm s⁻¹.
Observation of constant keyhole widths when welding sheets with both 7 and 20 μm coating thicknesses, as shown in Figure 4.15, indicates that the zinc vaporization isotherms will be in approximately the same position with respect to the fusion boundary ahead of the keyhole, independent of the coating thickness. Indirect evidence for this is found from molten zinc region measurements in front of keyholes at the weld end position, as shown in Figure 4.24. In Figure 4.1 - 4.3 it was shown that the thickness of the 20 μm coating was more uniform than that of the 7 μm coating. Therefore a more consistent vapour pressure at the interface in front of the keyhole can be expected when welding the sheets with the thicker zinc coating. The effect of the zinc vapour evacuation through the keyhole on the process stability is linked to the development of an elongated keyhole, which is discussed in section 4.6.3.

Figure 4.24: Zinc fusion line in front of the weld end crater when welding sheets with a 20 and 7 μm coating thicknesses.

Welding speed

It is observed that the welding process is more stable when welding at the lower speed of 25 mm s⁻¹; this is understandable because there is more time available for heat conduction ahead of the keyhole and consequently a larger area over which zinc vaporization occurs in front of the keyhole. Larger vaporization areas are desirable because they reduce the effect of any sporadic change in the coating characteristics and consequently provide a more consistent supply of zinc vapour into the keyhole. The hypothesis of a larger vaporization
area is supported by evidence of a large zinc fusion area when welding at the lower speed, as shown in Figure 4.24.

**Laser power**

When welding sheets with a 20 μm coating thickness, it has been shown that the laser power does not influence the process stability significantly (Figure 4.8). An increase of the incident power will vaporize more material, leading to a steeper keyhole front wall (Figure 4.10) and will also result in the more severe undercut (Figure 4.9). Similar widths and profiles of the weld cross-sections (Figure 4.9) suggest any modification of the position of zinc vaporization and fusion isotherms is unlikely to be significant. This means that similar zinc vaporization characteristics can be expected with different incident laser powers, as illustrated in Figure 4.25, which shows similar sizes of the keyhole and melt pool when welding with laser powers of 2 and 3 kW. Subsequently, with the similar zinc vaporization and evacuation characteristics, consistent weld stability is obtained.

![Figure 4.25: High speed images showing the top faces of keyholes and melt pools produced when welding GI coated sheets with a 20 μm coating thickness at 25 mm s\(^{-1}\) and incident beam powers of 2 and 3 kW.](image)

**4.6.3 Keyhole dynamics**

**Zinc vapour evacuation through the keyhole front wall**

In the numerical simulation presented by Geiger et al.\(^6\) it was shown that as the gap at the interface between two uncoated sheets welded in an overlap configuration increases to 0.05 – 0.1 mm, the liquid metal on the keyhole front wall tends to separate; *i.e.*, a channel opens connecting the interface gap to the keyhole. It is reasonable to expect that this will
Discussion

occur at smaller gaps when a pressure gradient exists between the interface and the keyhole, caused for example by the evolution of zinc vapour. This is confirmed by the observations of the channels on the keyhole front wall, as shown in Figure 4.15. With a thick coating, a more consistent zinc vapour evacuation channel will open. This is partly because of the consistent generation of zinc vapour pressure as discussed earlier, but also because a larger gap already exists after the vaporisation of the 40 μm zinc coating at the interface. The visible presence of a zinc vapour evacuation channel was analysed to give the percentage of images showing the channel. For the 20 μm coating thickness, 94.6% show the presence of a channel at a welding speed of 25 mm s⁻¹ and 92% at 45 mm s⁻¹, compared with 63.9% and 61.0% for 7 μm coating thickness. The disappearance of a channel means no zinc vapour can expand into the keyhole. For example, in Figure 4.26 a separation region appears at the fusion boundary without penetrating into the keyhole. At the next moment, when zinc vapour penetrates through the liquid on the keyhole front wall again, instability will occur as illustrated in Figure 4.12. This explains the unstable process when welding sheets with thinner coatings, which is associated with a smaller percentage of time over which the zinc evacuation channel is open and the discontinuous nature of the pressure exerted on the keyhole rear wall by the emitted zinc vapour.

![Figure 4.26: Longitudinal cross-section of weld end crater showing zinc trapped by the keyhole wall when welding with a 7 μm coating thickness at a welding speed of 45 mm s⁻¹.](image)

**Keyhole elongation behaviour during welding**

The keyholes with modified shapes shown in Figure 4.15 are similar to those reported by Fabbro *et al.*[7] and Schimidt[8],[9] which show that the keyhole shape is strongly influenced by the dynamic pressure of the zinc vapour. In Figures 4.17, the elongation of the keyhole is evident when welding zinc coated steels and it increases with increasing coating thickness and welding speed. The results obtained when welding with an argon jet, including the development of an elongated keyhole, smaller melt pool (Figure 4.20) and modification on weld profile (Figure 4.22) show similar trends to those obtained when welding coated steels with a 20 μm coating thickness. These results confirm that the
dynamic pressure of the vaporized zinc escaping from the interface at the front keyhole wall is responsible for the elongated keyhole. The difference between the coated and argon jet configurations is that the elongation behaviour shows welding speed dependency when welding the zinc coated steels but not in the tests with an argon jet. This is because in the former case, the vapour pressure arises from the vaporized zinc, the volume of which is related to the welding speed, as discussed in the previous section; but in the latter case, the argon jet is delivered at a constant flow rate, independent of the welding speed.

As discussed in section 4.6.2, the zinc vaporization isotherms adopt an approximately constant position ahead of the keyhole for both coating thicknesses at a given welding speed. This suggests that a higher mass flow rate is required to evacuate the zinc vapour in the case of the thicker coating. Hence a higher vapour dynamic pressure at a given position in the keyhole can be expected, which explains the longer keyhole obtained with the thicker coating.

For a given coating thickness, it is observed that when the welding speed increases from 25 to 45 mm s\(^{-1}\) (a factor of 1.8), the cross-sectional area decreases. For the 20 μm coating thickness for example, the area decreases by a factor of 1.1. Since parallel sided weld profiles are obtained (as shown in Figure 4.6), the width of the weld waist also decreases by a factor of 1.1. Assuming that the zinc in the weld area is vaporized and leaves through the keyhole, the volume of the vapour expanding into the keyhole per unit time increases by a factor of 1.6 when welding speed rises from 25 to 45 mm s\(^{-1}\). Thus a higher mass flow rate is produced when welding at the higher welding speed, leading to a higher vapour pressure at a given position in the keyhole. This explains the longer keyholes obtained when welding at higher speeds.

### 4.6.4 Analytical model for keyhole elongation

In order to evacuate the vapour produced when welding steels with zinc coatings, zinc vapour flow will arise and dynamic pressure develops. The influence of zinc vapour evolution on keyhole elongation may be explained from an analysis of the pressure balance at the keyhole wall. For a stationary keyhole with a high aspect ratio, the following pressure balance is given by Duley\(^{[12]}\)

\[
p_v + p_i = p_x + p_r + p_d,l,
\]

where \(p_v\) is the vapour recoil pressure, \(p_i\) is the radiation pressure, \(p_d,l\) is the hydrodynamic pressure due to a melt flow, \(p_x\) is the hydrostatic pressure and \(p_r\) is the pressure due to surface tension. Orders of magnitude of the different pressure terms are given in table 4.4.\(^{[12]}\) It appears that \(p_i\) and \(p_r\) are small compared with other terms and for the purpose of the present discussion, can be neglected. According to Duley\(^{[12]}\) \(p_v, p_i\) and \(p_d,l\) act to keep the keyhole open, whilst \(P_x\) and \(P_r\) have the opposite effect.
The hydrodynamic pressure term \( p_{d,l} \) has been estimated from the Navier-Stokes equation by Beck et al.\(^{[13]} \) under the assumption of low welding speed where viscous forces can be neglected

\[
p_{d,l} = \frac{1}{2} \rho_s \left( v_{\text{max}}^2 - v_{\text{min}}^2 \right).
\]

(4.3)

Here \( \rho_s \) is the steel liquid density and \( v_{\text{max}} \) and \( v_{\text{min}} \) are liquid flow velocities around the keyhole. Viscous flow effects are known to be important and even to dominate at high flow velocities under the conditions of small keyhole radius to keyhole length ratio; i.e., deep keyholes.\(^{[14]} \) Conversely, at the ends of the keyhole, surface tension effects play an important role. For the full penetration welds in relatively thin materials studied in this work, this inviscid expression is adopted, primarily for simplicity. The choice may be defended to some extent on the grounds that the keyhole radius to length ratio is of the order 1:3 to 1:4 and those keyholes showing stable elongation are subject to little through thickness variation in pressure or radius. Nevertheless, the validity of this approximation remains open to question.\(^{[14,15]} \)

It is notable that \( p_{d,l} \) is negative (\( v_{\text{max}} > v_{\text{min}} \)) in the formulation of Duley\(^{[12]} \), Aalderink et al.\(^{[22]} \) and Beck et al.\(^{[13]} \) and has been regarded as a pressure acting to retain the keyhole (Duley states this explicitly), whilst in much of the literature \( p_{d,l} \) is assumed to act to collapse the keyhole,\(^{[10,11]} \) is ignored\(^{[7,10,13,16]} \) or is addressed by a more complex model formulation including viscous hydrodynamic terms.\(^{[14,15]} \) For welds made in uncoated steels, the minimum velocity \( v_{\text{min}} \) is assumed to be the welding speed \( v \) and the maximum velocity \( v_{\text{max}} \) is calculated to be between 2 and 4 times the welding speed for welding speeds of 25 mm s\(^{-1} \) to 100 mm s\(^{-1} \).\(^{[17]-[19]} \) Hence this term is also negligibly small (<0.1 kPa) at low to moderate welding speeds. For a cylindrical keyhole, a good first order description of the pressure balance can be written as

\[
p_{r} \approx p_{r}. \tag{4.4}
\]

The surface tension pressure term is

\[
p_{r} = \frac{\gamma}{r}, \tag{4.5}
\]

where \( \gamma \) is the surface tension coefficient \( \gamma = 1.6 \text{ N m}^{-1} \) (typical for the range of mean pool surface temperatures experienced)\(^{[20][22]} \) and \( r \) is the average keyhole radius determined from camera images to be \( \sim 0.26 \text{ mm} \). The surface tension pressure \( p_{r} \) is therefore of the order 6.2 kPa.
For the elongated keyhole, the keyhole rear wall is not significantly exposed to the laser beam due to the longer distance from the keyhole front wall, which explains the darker rear wall observed when welding zinc coated steels (see Figure 4.15). Based on geometrical considerations, radiation due to reflection from the keyhole front wall onto the rear wall may also be expected to be small, thus, there is little laser induced vaporization on the rear wall and the effect of \( p_v \) is minor. The shape of the rear wall is mainly controlled by the surface tension of liquid metal, the hydrodynamic pressure due to the flow of molten steel and the zinc vapour pressure exerted on the keyhole rear wall. Here the zinc vapour impinges upon the rear keyhole wall restricting its forward motion. The resultant pressure \( p_z \) plays an important role in maintaining an elongated keyhole. Fabbro et al.\(^7\) employed a simplified description of a free jet emitted from a nozzle to estimate the pressure \( p_z \) exerted on the keyhole rear wall. The flow on the axis of the jet is

\[
p_z = p_0 \left( \frac{X_0}{x} \right)^2, \quad x \geq X_0, \tag{4.6}
\]

where \( x \) is the distance along the axis of the jet from the exit of the nozzle (keyhole length here), \( p_0 \) is the reservoir pressure that feeds the jet and \( X_0 \) is a characteristic distance for the decrease of the velocity field of the emitted flow. An evaluation of \( X_0 \) for turbulent flow is given by the following empirical equation\(^7\)

\[
X_0 = \frac{3D \text{Re}_c}{16}, \tag{4.7}
\]

where \( D \) is a characteristic dimension of the nozzle exit, identified here as the total coating thickness at the interface, and \( \text{Re}_c \) is the critical Reynolds number characterising the laminar to turbulent transition for free jet flows. A typical value for \( \text{Re}_c \) of 40 is given in the literature.\(^4\),\(^5\)

It has been reported by Fabbro et al.\(^{23}\) and Kamimuki et al.\(^{24}\) that a side gas jet applied from a leading position can lead to a rearward melt flow. It is therefore reasonable to expect a similar effect when a vapour flow is applied from the middle of the keyhole front wall. Dasgupta et al.\(^{25}\) have modelled the velocity field of the melt during laser welding of galvanized steel by considering the effect of zinc as an additional pressure. They showed

Table 4.4: Orders of magnitude of the pressure terms.\(^{12}\)

<table>
<thead>
<tr>
<th>Pressure terms</th>
<th>Typical value (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_v )</td>
<td>( 10^7 )</td>
</tr>
<tr>
<td>( p_l )</td>
<td>( 50 )</td>
</tr>
<tr>
<td>( p_{dl} )</td>
<td>( 10^2 - 10^4 )</td>
</tr>
<tr>
<td>( p_s )</td>
<td>( 75 )</td>
</tr>
<tr>
<td>( p_z )</td>
<td>( 10^4 )</td>
</tr>
</tbody>
</table>
that the presence of zinc vapour increases the liquid metal velocity by 30\%, when welding sheets with a 7 \( \mu \)m coating thickness, with a laser power of 3 kW at a welding speed of 31 mm s\(^{-1}\). From the high speed images shown in Figure 4.12, it is observed that the melt pool at the sides of the keyhole become narrower when welding zinc coated steels, thus flow with higher velocity is required to maintain the mass balance. Hence the hydrodynamic pressure term \( p_{dl} \) needs to be taken into account. The magnitude of the hydrodynamic pressure, estimated based on the experimental observation of keyhole side walls, is given in table 4.5, which reveals that \( p_{dl} \) decreases with increasing coating thickness. Assuming the pressure balance according to Duley\(^{[12]}\) (equations 4.2 and 4.3) is correct, the pressure balance for an elongated keyhole is therefore

\[
p_t = p_t + p_{dl}
\]

where the surface tension term \( p_t \) is assumed to be constant and takes the same value calculated for the case of the cylindrical keyhole. This assumption is reasonable based on the observation that the radii of keyhole walls do not show significant differences when welding zinc coated or uncoated steels (see Figure 4.15). With known hydrodynamic pressure \( p_{dl} \), the zinc vapour pressure exerted on the keyhole rear wall \( p_z \) can be evaluated; \( p_z \) decreases with increasing welding speed and coating thickness as shown in table 4.5. If the surface tension term \( p_t \) is a constant and the hydrodynamic pressure term \( p_{dl} \) decreases with increasing welding speed (4.3) or coating thickness, a decreasing \( p_z \) is therefore required to balance (4.8). In addition, \( p_z \) varies inversely as the square of the distance \( x \) from the zinc vapour nozzle exit on the front wall of the keyhole according to (4.6).
Table 4.5: Measured keyhole and weld pool properties (measured keyhole length \( L \), \( w \) and \( b \) are defined in Figure 4.27) and flow velocity and derived pressures for different welding speeds.

<table>
<thead>
<tr>
<th>Welding Speed</th>
<th>Keyhole / Pool Property</th>
<th>Bare steel</th>
<th>7 µm coated</th>
<th>20 µm coated</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 mm/s</td>
<td>( L ) (mm)</td>
<td>0.56(±0.07)</td>
<td>0.72(±0.18)</td>
<td>0.93(±0.18)</td>
</tr>
<tr>
<td></td>
<td>( w ) (mm)</td>
<td>0.53</td>
<td>0.48</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>( b ) (mm)</td>
<td>0.23</td>
<td>0.15</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>( v_{\text{max}} ) (mm/s)</td>
<td>53(±4)</td>
<td>68(±7)</td>
<td>175(±18)</td>
</tr>
<tr>
<td></td>
<td>( p_{d,l} ) (Pa)</td>
<td>8</td>
<td>14</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>( p_{z} ) (Pa)</td>
<td>NA</td>
<td>6.14 × 10³</td>
<td>6.05 × 10³</td>
</tr>
<tr>
<td>35 mm/s</td>
<td>( L ) (mm)</td>
<td>0.57(±0.06)</td>
<td>0.82(±0.16)</td>
<td>1.17(±0.20)</td>
</tr>
<tr>
<td></td>
<td>( w ) (mm)</td>
<td>0.51</td>
<td>0.52</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>( b ) (mm)</td>
<td>0.21</td>
<td>0.07</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>( v_{\text{max}} ) (mm/s)</td>
<td>77(±5)</td>
<td>138(±19)</td>
<td>338(±32)</td>
</tr>
<tr>
<td></td>
<td>( p_{d,l} ) (Pa)</td>
<td>17</td>
<td>64</td>
<td>404</td>
</tr>
<tr>
<td></td>
<td>( p_{z} ) (Pa)</td>
<td>NA</td>
<td>6.09 × 10³</td>
<td>5.75 × 10³</td>
</tr>
<tr>
<td>45 mm/s</td>
<td>( L ) (mm)</td>
<td>0.58(±0.05)</td>
<td>0.91(±0.20)</td>
<td>1.34(±0.18)</td>
</tr>
<tr>
<td></td>
<td>( w ) (mm)</td>
<td>0.52</td>
<td>0.49</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>( b ) (mm)</td>
<td>0.19</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>( v_{\text{max}} ) (mm/s)</td>
<td>106(±9)</td>
<td>180(±25)</td>
<td>332(±35)</td>
</tr>
<tr>
<td></td>
<td>( p_{d,l} ) (Pa)</td>
<td>33</td>
<td>108</td>
<td>385</td>
</tr>
<tr>
<td></td>
<td>( p_{z} ) (Pa)</td>
<td>NA</td>
<td>6.05 × 10³</td>
<td>5.77 × 10³</td>
</tr>
<tr>
<td>55 mm/s</td>
<td>( L ) (mm)</td>
<td>0.59(±0.06)</td>
<td>0.96(±0.22)</td>
<td>1.42(±0.24)</td>
</tr>
<tr>
<td></td>
<td>( w ) (mm)</td>
<td>0.53</td>
<td>0.53</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>( b ) (mm)</td>
<td>0.16</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>( v_{\text{max}} ) (mm/s)</td>
<td>144(±8)</td>
<td>223(±15)</td>
<td>419(±39)</td>
</tr>
<tr>
<td></td>
<td>( p_{d,l} ) (Pa)</td>
<td>63</td>
<td>167</td>
<td>617</td>
</tr>
<tr>
<td></td>
<td>( p_{z} ) (Pa)</td>
<td>NA</td>
<td>5.99 × 10³</td>
<td>5.54 × 10³</td>
</tr>
</tbody>
</table>
Combining (4.3), (4.6), (4.7) and (4.8), and replacing \( v_{\text{min}} \) by the welding speed \( v \), results in the pressure balance

\[
\frac{1}{2} \rho_{\text{s},j} \left( v_{\text{max}}^2 - v^2 \right) + p_0 \left( \frac{3D R_{\text{z}}}{16 x} \right)^2 = p_f. 
\] (4.9)

The maximum velocity \( v_{\text{max}} \) is controlled by mass conservation. The metal melted at the keyhole front wall should be transported to the melt pool behind the keyhole. The mass of liquid steel melted per unit time is

\[
\dot{m} = (w + 2b) \cdot v \cdot 2t_{p} \cdot \rho_{\text{s},j}, 
\] (4.10)

where \( w \) is the keyhole width, \( b \) is the width of liquid metal at the keyhole side wall (Figure 4.27) and \( t_p \) is the sheet thickness. The values of \( w \) and \( b \), were measured from recorded images with a pixel resolution of \( \pm 0.015 \) mm, and are given in table 4.5. The mass flow rate given by (4.10) must be balanced by the melt that flows around the keyhole (along the keyhole side walls), which is of the order \( v_{\text{max}} \cdot 2b \cdot 2t_{p} \cdot \rho_{\text{s},i} \), thus

\[
v_{\text{max}} = \frac{w + 2b}{2b} \cdot v. \] (4.11)

The calculated \( v_{\text{max}} \) are given in table 4.5. In the case of bare steel, the results obtained are in agreement with the published calculated values\(^{[8,9,12]}\) (i.e., 2 to 3 times the welding speed). It is reasonable therefore to use this expression to estimate the flow speed when welding zinc coated steels. It is shown in table 4.5 that when welding sheets with the thicker coating, a higher melt flow velocity on the keyhole side wall is obtained, leading to a higher hydrodynamic pressure as discussed.

A number of estimations for the reservoir pressure \( p_0 \) can be found in the literature, ranging from the saturation pressure of zinc vapour at the steel melting temperature\(^{[7]}\)
Chapter 4. Welding of Hot-dip Galvanized (GI) Steel

(5 MPa) to the ferrostatic head pressure (~50 Pa). The reservoir pressure depends on the mass flow rate of zinc vapour given by

$$n_z = A_n \rho_{z,v} v_z = A_s \rho_{z-solid} v_z,$$

(4.12)

where $A_n$ is the nozzle (escape channel) area, $A_s$ the area of the zinc vaporization front and subscripts $z$, and $v$ refer to zinc and vapour state respectively. Equating the reservoir pressure to the (vapour) dynamic pressure yields

$$p_0 = \frac{1}{2} \rho_{z,v} v_z^2 = \frac{1}{2} \rho_{z,v} \left( \frac{A_s \rho_{z-solid}}{A_n} \right)^2 v_z^2.$$

(4.13)

Taking the first order assumption that the density of zinc vapour is proportional to the reservoir pressure; i.e., $\rho_{z,v} = p_0 \rho_{z,v}^{ref} / p_{atm}$, then

$$p_0 \approx k_v, \text{ where } k_v = \sqrt{\frac{p_{atm}}{2}} \left( \frac{A_s \rho_{z,v}^{ref}}{A_n \rho_{z,v}^{ref}} \right).$$

(4.14)

Here $v$ is the welding speed, $p_{atm}$ is the atmospheric pressure (1 bar). $A_n$ is the area of the gap at the keyhole front wall for zinc vapour escape and $A_s$ is the area of the vaporized zinc. $\rho$ is the density and subscripts $z$ and $v$ refer to zinc and vapour state respectively, and $\rho_{z,v}^{ref}$ is the zinc vapour density at standard pressure, which can be calculated using Clausius-Clapeyron equation.

**Table 4.6: Values of the variables involved in equation 4.14.**

<table>
<thead>
<tr>
<th>Welding speed (mm s⁻¹)</th>
<th>7 μm coated</th>
<th>20 μm coated</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>35</td>
<td>45</td>
</tr>
<tr>
<td>55</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>45</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>w (mm)</td>
<td>From table 4.5, it can be seen that w is insensitive to welding speed and coating thickness. Here an average of 0.51 mm is used.</td>
<td></td>
</tr>
<tr>
<td>r_v (mm)</td>
<td>1.16</td>
<td>1.01</td>
</tr>
<tr>
<td>A_s/A_n</td>
<td>4.5</td>
<td>4.0</td>
</tr>
<tr>
<td>ρ_{z,solid} (kg m⁻³)</td>
<td>7140</td>
<td></td>
</tr>
<tr>
<td>ρ_{z,v} (kg m⁻³)</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>$k_v (N \text{s m}^{-3}) \times 10^6$</td>
<td>5.4</td>
<td>4.7</td>
</tr>
<tr>
<td>3.9</td>
<td>4.6</td>
<td>4.3</td>
</tr>
<tr>
<td>$p_0 (\text{Pa}) \times 10^5$</td>
<td>1.4</td>
<td>1.7</td>
</tr>
<tr>
<td>2.0</td>
<td>2.2</td>
<td>1.2</td>
</tr>
<tr>
<td>1.9</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>
The values of the variables involved in the equation are estimated in table 4.6. $A_n$ and $A_s$ are given by

$$A_n = \pi \cdot \frac{w}{2} \cdot 2t_m$$

$$A_s = \pi \cdot r_s \cdot 2t_m$$

where $t_m$ is the coating thickness and $r_s$, the zinc boiling isotherm radius (defined in Figure 4.27). The latter is determined by temperature measurements performed at the interface between the welded sheets.

An accurate evaluation of $k_1$ requires accurate data of the thermal field surrounding the weld and measurements of both the keyhole and zinc vapour jet. The estimate shown in table 4.6 is approximate because the nozzle area $A_n$ is affected by the reservoir pressure. When the pressure is less than the surface tension pressure of the melt, this nozzle disappears. Hence the actual nozzle area $A_n$ in the case of 7 μm coating thickness may be smaller than the calculated value. This is also supported by the low appearance rate of the vapour escape channel when welding with a 7 μm coating thickness. According to equation 4.14, a decreasing $A_n$ results in a larger $k_1$ and $p_0$. In contrast, for the case of 20 μm coating thickness, $A_n$ can be larger than that calculated in table 4.6 because the vapour pressure makes a conically shaped nozzle as shown in Figure 4.10, leading to a reduction of $k_1$ and $p_0$. Welding speeds also influence $k_1$ by decreasing $A_s$ with increasing welding speed. All these factors can result in some deviations from the estimations given in the table.

For simplicity, $k_1$ is treated as a constant of proportionality and chosen to match the measured values at a welding speed of 25 mm s$^{-1}$. The values of $k_1$ and $p_0$ are given in table 4.7. It can be seen that the values of $k_1$ shown in table 4.7 are generally of the same order of magnitude as the calculated values shown in table 4.6. It has been reported that the surface tension increases by 25% when the temperature is decreased from 3000 K to 2100 K for steel with 0.005% sulphur content.\cite{20,21} The choices of surface tension and resultant $k_1$ and $p_0$ influence the subsequent numerical estimates but do not affect the structure of the simple analytical model derived. The difference in $k_1$ for the different coating thickness can be supported by examining the order of magnitude of the surface tension of the melt trying to close the channel on the keyhole front wall. This is calculated using (4.5), with a local surface tension coefficient of 1.4 N m$^{-1}$ (at 3000 K)\cite{20} and radius of corresponding coating thickness, yielding a surface tension pressure of $7 \times 10^7$ Pa in the case of the 20 μm coating thickness and $2 \times 10^7$ Pa in the case of the 7 μm coating thickness. The higher surface tension in the case of thinner coating explains the higher reservoir pressure required to open the channel. Due to the less uniform coating as shown in Figure 4.2, the keyhole elongation is not sustainable because the delivery of zinc vapour is not consistent enough to maintain a zinc evacuation channel, resulting in significant keyhole fluctuation.
Table 4.7: Values of $k_1$ and $p_0$ obtained by matching with the measured values (at a welding speed of 25 mm s$^{-1}$)

<table>
<thead>
<tr>
<th>Welding speed (mm s$^{-1}$)</th>
<th>7 μm coated</th>
<th>20 μm coated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_1$ (N s m$^{-3}$) x 10$^6$</td>
<td>11.5</td>
<td>2.3</td>
</tr>
<tr>
<td>$p_0$ (Pa) x 10$^5$</td>
<td>2.9</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>5.1</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Figure 4.28: A comparison between the experimental and calculated values of keyhole lengths for welds made on GI zinc coated steels with 20 μm and 7 μm coating thicknesses. The error bars represent the standard deviation of 10,240 measurements of keyhole lengths made covering a welding time of 0.34s.

Despite these uncertainties, (4.14) may reasonably be employed together with (4.9) to determine the keyhole length $x$, viz:

$$x = \frac{3DR_{\text{vis}}}{16} \sqrt{\frac{p_0}{p_f - p_{\text{at}}}}, \text{ or}$$

$$x = \frac{3DR_{\text{vis}}}{16} \sqrt{\frac{k_1v}{p_f \left( \frac{1}{2 \rho_{\text{at}}} \left( v_{\text{max}}^2 - v^2 \right) \right)}},$$

(4.16)

(4.17)
The calculated keyhole lengths are compared with measured values in Figure 4.28. Predictions from this simple analytical model are in relatively good agreement with experimental measurements and the model provides an explanation for the major trends observed, including the elongation of the keyhole due to zinc vapour jetting and extension of keyhole length with increasing welding speed and coating thickness. With increasing coating thickness, the characteristic dimension of the nozzle exit $D$ increases and hydrodynamic pressure $p_{d,l}$ decreases. However, a smaller reservoir pressure $p_0$ is obtained with the thicker coating, which can be explained by the smaller surface tension pressure of the melt film on the keyhole front wall due to the larger gap. A combined effect of these factors leads to a longer keyhole. With increasing welding speeds, $p_0$ increases according to (4.14) and $p_{d,l}$ decreases according to (4.3), as more zinc vapour needs to escape through the keyhole per unit time through the same nozzle size and the melt velocity around the keyhole increases when welding at higher speeds.

It is important to stress that the analytical model described above has been developed to support conceptual descriptions of process behaviour derived from experimental observations and presented in sections 4.1 to 4.5. Care must be taken not to misinterpret the meaning or accuracy of the predictions, which at best give an indication of a general trend. The model describes aspects of a highly complicated and intricate physical system and is based on many questionable assumptions, beginning with equation 4.2. Although the equation is presented as a pressure balance, terms like the vapour recoil pressure $p_v$ and the hydrodynamic pressure $p_{d,l}$ are vector not scalar terms and hence not true pressures.\[27\] The formulation of equation 4.2 implicitly assumes averaged properties, whilst the application to elongated keyholes indicates a distribution in force per unit area around the keyhole. The surface tension term (equation 4.5) is dependent on position within the keyhole and is dependent on the radius of curvature in all directions, rather than a single value of the radius. In addition the surface tension coefficient is dependent on temperature and chemistry distributions and hence on position. The inviscid assumption upon which equation 4.3 is based is only valid for slow welding speeds and low velocity flows within the weld pool and is unlikely to be valid for the high speed sidewall flows encountered in this work. In addition the Bernouilli expression is unlikely to be adequate to describe the hydrodynamic term as it implicitly requires irrotational and adiabatic conditions, which are unlikely to describe the flow of fluid in the weld pool or across the pool – keyhole boundary.\[27\] The numerical influence of the hydrodynamic term is at least an order of magnitude smaller and often more than two orders of magnitude smaller than surface tension pressure $p_\gamma$ and has only a small influence on the position and shape of the curves shown in figure 4.28. Whether $p_{d,l}$ acts to open or close the keyhole (reverse sign in the denominator of 4.17), is still not certain; in fact even the question itself may not have any relevance given the limitations of the model formulation.

A more appropriate description of the melt-pool and keyhole would of necessity consider through thickness and in particular, radial and azimuthal variations in conditions. Such an approach could incorporate localised behaviour, viscous flow effects and vapour jet source and impingement influences, but would require a detailed three dimensional fluid dynamics model which is outside the scope of the present work.
4.7 Summary

The welding results revealed that laser welding of sheets with a 20 μm zinc coating thickness, which had more uniform surface profiles compared to those with a coating thickness of 7 μm, could produce welds of acceptable quality in an overlap condition without the introduction of a gap at the interface. The processing window showed that process stability was worse with increasing welding speed, whilst the effect of changing incident power was small. The coating thickness and welding speed modified the weld characteristics; increasing coating thickness or welding speed decreased weld area and made the weld cross-sectional profile more parallel.

The transient gap measurements showed upward deformations for the top sheets, whilst the deformations of the lower sheets were much less pronounced. A gap of a maximum of 15 μm therefore existed at the interface between two sheets during welding. However, the measured gaps were substantially constant for uncoated, 7 and 20 μm coated steels. This does not explain the different process stability when welding these materials.

High speed videos taken of the welding process revealed that the keyholes were elongated when welding the zinc coated steels. The keyhole length increased with increasing coating thickness and increasing welding speed and a more violent fluctuation of the keyhole rear wall was observed when welding sheets with a 7 μm coating thickness. The elongation behaviour could be correlated to the zinc vapour expanding into the keyhole through a channel on the keyhole front wall, which was evident in the images when welding coated steels. By injecting argon gas jets into a gap in between two sheets, elongated keyholes and welds with parallel shape were obtained. An increase in flow rate was shown to increase the keyhole length. These phenomena are similar to those observed when welding sheets with a 20 μm coating thickness.

Stable welds produced when welding the sheets with a 20 μm coating thickness have been linked to the development of an elongated keyhole with minimal positional fluctuations on the rear keyhole wall. The relatively high stability of the weld pool is ascribed to the consistent delivery of zinc vapour into the keyhole. High speed coaxial visualization has shown that a zinc vapour evacuation channel is present on the keyhole front wall almost continuously during welding of sheet steels with a 20 μm coating thickness, due to limited variations of coating thickness and a larger gap formed after vaporisation of the zinc coating. Keyhole rear wall fluctuations are therefore minimized. Conversely, for sheets with a 7 μm zinc coating thickness, the vapour is inconsistently emitted into the keyhole and the keyhole rear wall is subject to persistent and severe fluctuations.

For both coating thicknesses, relatively stable keyhole behaviour is observed at low welding speed, which is a result of a larger zinc vaporisation zone. More consistent zinc vapour supply into the keyhole can be expected when welding at the lower welding speed and this in turn contributes to process stability. In contrast, when varying laser power, the
Summary

change on the zinc fusion and vaporization characteristics is limited and therefore does not influence the stability significantly.

A simple analytical model has been developed to calculate the keyhole length, and predictions show reasonably good agreement with experimental results, indicating that the dynamic pressure of the zinc vapour is responsible for elongation of the keyhole. A longer keyhole was obtained when welding sheets with thicker coatings or when welding at higher speeds because in both cases more zinc vapour was produced and was evacuated through the keyhole, which results in a higher vapour pressure. By blowing an argon jet into a gap of 40 μm at the interface between two sheets, a dynamic pressure was applied on the rear keyhole wall. The resultant behaviour of the keyhole and melt pool and the evolution of the weld cross-sectional profiles are similar to those produced when welding zinc coated steels.
References


Chapter 5

Thermal efficiency

In this chapter, the influence of zinc vapour induced keyhole elongation on power distribution for a full penetration keyhole is presented. The fractions of laser power absorbed by the material and lost through the keyhole were measured calorimetrically, whilst the power directly transmitted through the keyhole was measured by means of a power meter. Based on the resultant experimental data, the power distribution during full penetration keyhole welding is described, and an uncertainty analysis of the experimental measurement is also reported. It has been shown in the last chapter that the keyhole can be elongated by the zinc vapour pressure when welding zinc coated steels in an overlap configuration, and a narrow weld pool is observed. This keyhole elongation behaviour is also the key to understand the observations in power distribution when welding zinc coated steels and in turn influences the evolution of weld dimensions and the weld cross-sectional profiles.

5.1 Experimental procedures

Linear welds of 105 mm length were made on hot dip galvanized (GI) sheets with sheet thickness of 0.8 mm and nominal coating thicknesses of 7 and 20 µm. The chemical composition of the base steel is given in table 3.1 (No.1 and No.2). For comparison purposes, welds were also made on steels without any coating. A nominal beam power of 3 kW was employed and welding speeds were varied in the range 25 to 45 mm s⁻¹. Other process parameters are the same as those given in table 4.2.

The arrangement and procedures for calorimetric measurements are detailed in section 3.6.1. Leaving the absorption backing bar under the workpiece (in the efflux channel) after welding enables measurement of the total energy absorbed by and transmitted through the workpiece, whilst removal after welding provides a measurement of the power absorbed by the workpiece only. The heat transfer (process) efficiency was estimated according to equation 3.1 in section 3.6.1. The fraction of incident power directly transmitted through the keyhole without any reflection was measured with a power meter positioned under the workpiece. The arrangement for this measurement is described in section 3.6.2. To determine the fraction of power contributing to the creation of a molten pool, the melting efficiency was calculated from equations 3.2 and 3.3 (section 3.6.3) based on the weld
cross-sectional area (shown in Figure 4.7), employing the physical properties given in table 3.4.

5.2 Power distribution during welding

The keyhole plays an important role in power absorption during laser welding, particularly when welding with a fully penetrating (open) keyhole, through which power transmission occurs\(^1\)\(^2\). During welding of zinc coated steels, it can be expected that an elongated keyhole will strongly modify the power absorption characteristics and in turn, influence the melt pool and weld geometries.

For a fully penetrating keyhole, the distribution of the input laser power can be expressed as,

\[
P = P_a + P_b + P_c + P_d + P_e + P_f + P_g + P_j,
\]

(5.1)

where:

- \(P\) is the incident laser power;
- \(P_a\) is the power required to melt the workpiece;
- \(P_b\) is the reflected loss from the top face of the weld zone;
- \(P_c\) is the power dissipated during vaporization;
- \(P_d\) is a combined convective and radiative thermal loss from the weld zone;
- \(P_e\) is the power dissipated from the weld zone by conduction;
- \(P_f\) is the power loss by direct transmission through the keyhole, which has no interaction with the welded material.
- \(P_g\) is the power loss due to leakage through the keyhole after multiple reflections;
- \(P_j\) is the power loss as a result of absorption by the plasma.

Figure 5.1 is a visual representation of equation 5.1, indicating all fractions that are related to the keyhole geometry. Any change in keyhole geometry can result in a redistribution of power.
5.3 Results

5.3.1 Heat transfer (process) efficiency and power transmission

The process efficiency $\eta_h$ is found to increase with increasing welding speed for both uncoated steels and the two zinc coated steels examined with nominal coating thicknesses of 7 and 20 µm. The greatest influence of welding speed on $\eta_h$ was observed for the uncoated steel (Figure 5.2). It is also notable that for a given welding speed, the uncoated steel has the highest heat transfer efficiency, whilst the sheet with 20 µm zinc coating thickness has the lowest.

The trend observed in the measurement of the directly transmitted power through the keyhole ($P_t$) is almost the reverse of that observed for the process efficiency. Transmission decreases with welding speed for all three materials, and at any given speed, transmission increases with increasing zinc coating thickness (Figure 5.3).

The sum of the directly transmitted power ($P_t$) and the absorbed power ($P_a$ and $P_e$) reveals that the combined efficiency decreases with increasing welding speed in the case of the coated steels (Figure 5.4). For the uncoated steel, in contrast, there may be a weak increase in this combined efficiency over the range of welding speeds examined (25 to 45 mm s$^{-1}$), although this lies within the limit of experimental uncertainty (see section 5.4).
Chapter 5. Thermal efficiency

The absorbed power ($P_a$ and $P_e$) together with the power transmitted through the keyhole and absorbed by a backing bar ($P_t$ and $P_d$) has been measured calorimetrically and the results are shown in Figure 5.5. It can be seen that for all materials, the combined efficiencies are substantially insensitive to the welding speed but increase with increasing coating thickness.

![Figure 5.2: The influence of welding speed on heat transfer (process) efficiency for steel sheets with various coating thicknesses.](image)

![Figure 5.3: The influence of welding speed on the fraction of power lost due to direct transmission ($P_f$) for steel sheets with various coating thicknesses.](image)
5.3.2 Melting efficiency

As mentioned in section 2.1.4, the melting efficiency is defined as the ratio of power fraction required to just melt the fusion zone (P_a) to the power absorbed by the workpiece (P_a + P_e), where the fraction P_a is determined from the weld cross-sectional area (Figure 4.7). The results of the melting efficiency calculation indicate a weak decrease of melting
efficiency with increasing welding speed in the case of the uncoated steels, whereas an increase of melting efficiency with welding speed is observed for both of the coated materials, and is more pronounced for the steel with the 20 μm zinc coating thickness. At welding speeds of 25 mm s\(^{-1}\) and 35 mm s\(^{-1}\), the highest efficiency appears when welding uncoated steel, whilst at a speed of 45 mm s\(^{-1}\) the highest melting efficiency is obtained when welding sheets with a 20 μm coating thickness (Figure 5.5). The spread in efficiencies shown in the figure arises from the repeatability of calorimetric measurement and variations of the weld cross-sectional areas.

![Figure 5.6: Melting efficiency for steel sheets with various coating thicknesses, shown as a function of welding speed.](image)

### 5.3.3 Magnitude of power fractions

Contributions of the different terms to the power balance, equation 5.1, are given in table 5.1 and the magnitude of the major fractions is illustrated in Figure 5.7. They reveal that the uncoated steel has the highest reflection from the top face (\(P_b\)), whilst the sheets with a 20 μm coating thickness have the lowest. A weak increase in the power fraction required to melt the weld pool (\(P_a\)) with increasing welding speed is observed in all three materials and the uncoated steel has a slightly higher \(P_a\) than the coated steels, at any given welding speed. The conduction loss (\(P_e\)) increases significantly with welding speed when welding uncoated steels, whilst a substantially constant \(P_e\) is observed when welding sheets with a 20 μm coating thickness. Details of the magnitude assessment are discussed in section 5.4.
Table 5.1: Relative magnitude of the various power

<table>
<thead>
<tr>
<th>P[W]</th>
<th>Bare steel 25mm/s</th>
<th>35mm/s</th>
<th>45mm/s</th>
<th>7 μm coating 25mm/s</th>
<th>35mm/s</th>
<th>45mm/s</th>
<th>20 μm coating 25mm/s</th>
<th>35mm/s</th>
<th>45mm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pa</td>
<td>18.0%</td>
<td>21.6%</td>
<td>25.0%</td>
<td>14.8%</td>
<td>18.0%</td>
<td>20.1%</td>
<td>12.6%</td>
<td>16.4%</td>
<td>19.6%</td>
</tr>
<tr>
<td>Pb</td>
<td>13.0%</td>
<td>4.0%</td>
<td>Minor</td>
<td></td>
<td></td>
<td></td>
<td>Minor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pc</td>
<td>&lt;3.4%</td>
<td>&lt;4.0%</td>
<td>&lt;4.6%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pd</td>
<td>≤0.5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pe</td>
<td>27.7%</td>
<td>34.3%</td>
<td>40.6%</td>
<td>29.3%</td>
<td>33.5%</td>
<td>35.7%</td>
<td>25.7%</td>
<td>26.1%</td>
<td>23.1%</td>
</tr>
<tr>
<td>Pf</td>
<td>Total</td>
<td>37.4%</td>
<td>19.8%</td>
<td>45.8%</td>
<td>8.1%</td>
<td>10.3%</td>
<td>58.6%</td>
<td>9.6%</td>
<td>21.6%</td>
</tr>
<tr>
<td>Pa</td>
<td>Minor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pj</td>
<td>Minor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.4 Experimental uncertainty analysis

An evaluation of the maximum measurement and repetition limits is presented in Table 5.2. The measurement error describes the systematic error of the measuring methods and/or the accuracy of instruments, whilst the repetition error represents the variation from weld to weld for nominally identical processing parameters.

For the output power, the measurement error is dependent on the power meter accuracy\textsuperscript{[3]} and the repetition error is assessed based on the repeatability of the output power measurements and stability of the laser power\textsuperscript{[4]}.

---

\textit{Figure 5.7: A visual illustration of the relative magnitude of selected power terms.}
The absorbed power is measured calorimetrically, which has a low level of measurement error of ± 2% when carefully calibrated. When the calorimeter is in equilibrium, the output signal generated can be considered as the reference level, which is important for both calibration and measurement. It has been reported that changes in ambient air and coolant temperature may cause a drift in the reference level. Each measurement carried out in this study took more than 10 hours and some drift of the reference level was observed in most measurements because the ambient air temperature was subject to a change of up to 1.5 K; the accuracy of the measurements is therefore influenced by this drift. The nominal reference values were determined by taking the average equilibrium signal appearing at the end of the measurement for a period of 10 minutes. The measurement error is assessed based upon a comparison of integrated signals for the reference levels obtained from both the start and end of the measurement. The measurement error for the measurement of the transmitted power (in the power meter acceptance area) is dependent on the power meter accuracy. The repetition errors in both calorimetric measurements and transmitted power measurement represent the variation from weld to weld for the same processing parameters.

For weld area evaluation, calibration of the microscope and image processing software with a micrometer minimizes the measurement error. The repetition error is due to variation in the weld cross-sectional area over the three measurements made.

Since the energy loss due to spatter was accounted for by assessing the mass loss, uncertainty of mass measurement also affects the uncertainty of energy transfer efficiency. The mass was measured with a resolution of 0.1 mg, representing 0.04 Watt of power required for melting. The measurement error resulting from the mass measurement is therefore negligible. The repetition error is again due to variation from weld to weld.

The measurement and repetition error for the energy transfer efficiency are calculated in terms of the root sum square of uncertainties of output power measurement and calorimetric measurement of the absorbed power.

For the melting efficiency, the measurement error is primarily affected by the absorbed power measurement. Appropriate choice of the material parameters is also important for accurate estimation of melting efficiency. The error due to choice of material properties is estimated to be of the order ±5.0% as given by Geidt et al. The repetition error is primarily affected by the precision of the absorbed power measurement and the variation of the weld area.

The measurement error should be taken into account in the estimates of the order of magnitude for power terms. The relative importance of some power terms, for instance the power dissipated during vaporization $P_v$, is difficult to assess because they lie within the uncertainty level. However compared with the absolute measurement errors, which are systematic in nature, smaller repetition errors were generally obtained. Therefore the major trends observed in the measurements, including the different absorption and transmission measured for various welding speeds and coating thicknesses, are likely to be valid if variations exceed the repetition errors (presented in table 5.2).
Chapter 5. Thermal efficiency

Table 5.2: Summary of maximum measurement and relative errors.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Max measurement error</th>
<th>Max repetition error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power (W)</td>
<td>± 4.0%</td>
<td>± 2.2%</td>
</tr>
<tr>
<td>Absorbed power (W)</td>
<td>± 12.5%</td>
<td>± 6.7%</td>
</tr>
<tr>
<td>Transmitted Power (W)</td>
<td>± 4.0%</td>
<td>± 4.5%</td>
</tr>
<tr>
<td>Weld area (mm$^2$)</td>
<td>± 1.0%</td>
<td>± 4.1%</td>
</tr>
<tr>
<td>Mass measurement</td>
<td>Negligible</td>
<td>± 0.9%</td>
</tr>
<tr>
<td>Energy transfer efficiency</td>
<td>± 13.1%</td>
<td>± 7.1%</td>
</tr>
<tr>
<td>Melting efficiency</td>
<td>± 13.3%</td>
<td>± 7.9%</td>
</tr>
</tbody>
</table>

5.5 Discussion

5.5.1 Estimate of power distribution

The uncoated steel is adopted as an example to show how the power distribution is determined. For the zinc coated steels, the procedures to estimate the power fractions are the same. The effect of an elongated keyhole is stressed in the following discussion where it influences the power distribution.

For uncoated steel, at a welding speed of 25 mm s$^{-1}$, the efficiency was 46% (Figure 5.2), while 37% of the incident beam power was lost due to direct transmission through the keyhole (Figure 5.3). Increasing the welding speed to 35 mm s$^{-1}$, the process efficiency increased to 56% while the fraction of transmitted power decreased to 27%; further increasing the welding speed to 45 mm s$^{-1}$, resulted in 66% absorption and 20% transmission. It is interesting to note that the sum of these fractions remain virtually constant at around 84% (Figure 5.4 and 5.5), which is composed of fractions representing melting, conduction, direct and indirect transmission, $P_a$, $P_c$, $P_d$, $P_g$. The remaining 17% is the combined sum of all the other terms $P_b$, $P_r$, $P_d$ and $P_j$ related to reflection, vaporisation, convection and radiation, and plume absorption respectively (see equation 5.1). Here $P_d$ (convection and radiation) is included in the losses because the calorimeter is closed only after welding is completed.

For the short duration welding times employed (< 4.2 s), the power loss due to radiation and convection has been estimated to be no more than 1% of the power absorbed by the workpiece;[6] thus of the order 0.5% of the incident power. Some boiling and (possibly) ionization of the metallic vapour takes place in the keyhole. Spatter droplets on the top surface of the workpiece and on the removable bar were collected and weighed after each weld. There was at most a mass difference of 0.23 g between the mass of the workpiece weighed before welding and the combined mass of the workpiece and droplets weighed
after welding (uncoated steels welded at 25 mm s\(^{-1}\)). From equation 3.3, the power required to vaporize this amount of material \(P_c\) is found to be 3.4% of the incident power.

Top surface reflection mainly occurs from two areas; the area in front of the keyhole and the area of the molten weld to the side of and behind the keyhole. The former becomes important only when welding at very high speed. High speed images taken coaxially show that there is no laser beam ahead of the keyhole front wall for the speeds employed here (see Figure 4.15). A sequence of pictures taken by Fabbro \textit{et al.}\textsuperscript{[7]} to illustrate the relative positions of the keyhole to the laser spot when welding 1 mm thick steel sheet with a 3 kW Nd:YAG laser show that the laser beam ahead of the keyhole front wall is not significant until the welding speed exceeds 83 mm s\(^{-1}\). Hence it can be concluded that the reflection mainly occurs from the weld pool.

When welding steels with a 20 µm coating thickness, the sum of absorption and transmission, measured calorimetrically, yields a total of 96.5% (Figure 5.5). Since the keyhole is elongated (see Figure 4.12 and 4.15), the keyhole rear wall is not directly exposed to the incident beam; as a result, the effect of top side reflection is less important. Hence the residual 3.5% power fraction is primarily accounted for by vaporization, convective and radiative losses, and plasma absorption losses, \(P_c\), \(P_d\) and \(P_j\) respectively. Considering \(P_c\) should be higher in this case compared to the uncoated steel because of the vaporization of zinc, the fraction of \(P_j\) must be small. This is consistent with the experimental results reported by Fabbro \textit{et al.}\textsuperscript{[7]} where plume absorption was studied by measuring transmission rate through a plume produced during laser welding and no modification was seen when the plume was blown away by a gas jet parallel to the specimen surface. Assuming the same fractions of \(P_c\) and \(P_j\) when welding uncoated materials, reflection from the weld pool \(P_b\) in this case is of the order 13.0% of the incident beam power.

The power loss in the form of transmission can be further broken down into direct losses and indirect losses due to multiple reflections. The technique employed to measure the direct losses works well at welding speeds of 35 and 45 mm s\(^{-1}\) but not at the lower welding speed of 25 mm s\(^{-1}\). The reason is that when the measurement is performed at the lower welding speed, part of the reflected beam from the keyhole front wall is also captured by the power meter. This can be demonstrated by the simple geometric construction shown in Figure 5.8. Two extreme situations are considered, beam 1 and beam 2, which are reflected at the top and bottom edges of the keyhole front wall respectively. The distances from reflected beam 1 and 2 to the keyhole – power meter central line when they reach the power meter top surface are

\[
d_1 = (2r_x + h_p) \cdot \tan(2\alpha) - r_x, \quad \text{and}
\]

\[
d_2 = h_p \cdot \tan(2\alpha) - (r_x - l),
\]

where all the parameters involved have been defined in Figure 5.8. The assumptions for the calculation are that the front keyhole wall inclination is constant along the depth; the reflected beam is subject to planar reflection and all the reflections from the front wall will
Chapter 5. Thermal efficiency

exit the keyhole. The calculated results of all parameters are given in Table 5.3 which indicates that most of the reflected beam will be detected by the power meter \((d_1 \leq r_3)\) when welding at 25 mm s\(^{-1}\). This explains why the values shown in Figures 5.4 and 5.5 for this specific speed are similar. With increasing welding speeds, the beam reflects away from the acceptance area of the power meter and therefore does not contribute to the data presented in Figure 5.4, but is included in the calorimetric measurements shown in Figure 5.5. The difference between these two figures can then be interpreted as the fraction transmitted after multiple reflections. Similar levels have been observed in Figures 5.4 and 5.5 for the uncoated steel, which indicates little indirect transmission because for a cylindrical keyhole, most of the beam reflected from the keyhole front wall impinges on the rear wall and in turn is absorbed instead of exiting via the keyhole root. The effect of the multiple reflections and higher absorption is consistent with the larger melt pool for the uncoated steel (see Figure 4.12c and d), and also confirmed by the higher absorption when welding uncoated steels (Figure 5.2). In contrast, when welding sheets with a 20 μm coating thickness, a much weaker increase of process efficiency (Figure 5.2) and different fractional sums of absorbed power and transmitted power were observed as shown in Figures 5.4 and 5.5. These observations can be explained by the elongated keyhole, which not only allows nearly all the beam reflected from the front wall to exit the keyhole, but also permits some of the laser beam to go directly through the keyhole without any interaction with the melt pool.

Figure 5.8: Estimated position of the reflected beams, where \(t_p\) is the sheet thickness, \(h_p\) is distance from the lower sheet surface to the top surface of the power meter, \(r_k\) is the radius of the keyhole top aperture, \(r_3\) is the radius of the power meter acceptance area and \(d_1\) and \(d_2\) are the distances from reflected beam 1 and 2 to the keyhole – power meter centre line when they reach the power meter top surface.
Discussion

Table 5.3: Values of the parameters shown in Figure 5.8.

<table>
<thead>
<tr>
<th></th>
<th>25 mm s⁻¹</th>
<th>35 mm s⁻¹</th>
<th>45 mm s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ (°)</td>
<td>6.2</td>
<td>9.7</td>
<td>12.5</td>
</tr>
<tr>
<td>$r_k$ (mm)</td>
<td>~ 0.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$l$ (mm)</td>
<td>0.17</td>
<td>0.27</td>
<td>0.35</td>
</tr>
<tr>
<td>$\rho_l$ (mm)</td>
<td></td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>$h_p$ (mm)</td>
<td></td>
<td>36.5</td>
<td></td>
</tr>
<tr>
<td>$r_1$ (mm)</td>
<td></td>
<td>8.4</td>
<td></td>
</tr>
<tr>
<td>$d_2$ (mm)</td>
<td>7.9</td>
<td>12.8</td>
<td>17.1</td>
</tr>
<tr>
<td>$d_1$ (mm)</td>
<td>8.1</td>
<td>13.1</td>
<td>17.5</td>
</tr>
</tbody>
</table>

Based on the melting efficiency calculation, the absorbed power can be separated into $P_a$ used to form the weld pool and $P_e$ lost to the surrounding environment by conduction. For all three materials, a weak increase of $P_a$ with welding speed has been observed (Figure 5.7). However, when welding uncoated steels, the conduction loss is observed to increase substantially with welding speed, whilst when welding sheets with a 20 μm coating thickness $P_e$ appears to be insensitive to welding speeds. This can be explained by the evolution of the weld area as shown in Figure 4.7. When welding uncoated steels, although the process efficiency increases with increasing welding speed (Figure 5.2), the weld area shows a rapid decrease. Hence there is an increasing fraction of power being absorbed but not contributing to melting, which subsequently dissipates due to conduction. This is consistent with the weak decrease of the melting efficiency as shown in Figure 5.6. For the coated steel with a 20 μm coating thickness, weld area decreases only slightly with increasing welding speed (Figure 4.7), and correspondingly increasing melting efficiencies are observed in Figure 5.6. The weak decrease of the weld area and the weak increase of the process efficiency with increasing welding speed indicate that both absorption and the power used for melting are not strongly dependent on the welding speed and thus nearly identical conductive losses $P_e$ are obtained.

5.5.2 Weld dimension and cross-sectional profile

As described in section 4.2.3, the weld dimension and cross-sectional profiles can be strongly modified when welding zinc coated steels. The smaller cross-sectional area during welding of coated steel is consistent with the smaller melt pool observed in Figure 4.12d. This can be explained by two effects. In the first, both direct absorption of the laser beam and absorption due to multiple reflections are reduced as a result of the keyhole elongation, as discussed in section 5.5.1. In the second, Fabbro et al. and Kamimuki et al. have suggested that when a side gas flow is applied, the liquid is propelled rearwards; and thus the lateral convection flow, which broadens the top and lower parts of the melt pool, is
Chapter 5. Thermal efficiency

reduced. It is reasonable to consider that the jet emitted from the gap at the front keyhole wall can result in the same effect. This is supported by the evolution of weld profiles where the widths of the weld top and root decrease when welding zinc coated steels or when applying an argon jet with adequate flow rate.

5.6 Summary

Several interesting features were noted in the power distribution when welding zinc coated steels, including lower process efficiency, more direct transmitted power ($P_t$), higher fractional sum of absorbed power and total transmitted power ($P_a$, $P_e$, $P_t$ and $P_g$), and the characteristic increase of melting efficiency with welding speed compared to measurements made when welding uncoated steel. All these observations can be correlated with the development of an elongated keyhole, which allows a substantial fraction of the laser beam to pass through the weld zone without any interaction with the melt pool, and subsequently reduces the absorption of laser power by the melt pool and reflection from the top face of the melt pool. This together with the reduced lateral convection flow resulting from the zinc vapour pressure explain the decrease of cross-sectional areas and parallel sided weld cross-sectional profiles when welding zinc coated sheets.
References


Chapter 6

Evacuation of Zinc Vapour Through the Melt Pool

In chapter 4, evacuation of zinc vapour through the keyhole and the interaction between the keyhole and the zinc vapour have been discussed in terms of the keyhole elongation and fluctuation of the keyhole rear wall. Besides this, zinc vapour venting through the weld pool is also observed and is responsible for the formation of instabilities in the pool, often resulting in weld defects. The relationship between the zinc vaporization position relative to the keyhole and process stability was investigated. The evolutions of instabilities generated in the weld pool were studied by means of high speed video imaging. Entrapped zinc vapour in the weld pool was found to escape either through the weld top or root faces. This tendency of the vapour to expand preferentially toward one or other of the weld pool free surfaces is also addressed. Questions concerning when and how the zinc vapour escapes through the weld pool, the response of the pool and subsequent influences on the process stability are considered in this chapter.

6.1 Experimental procedures

Welding was performed at a beam power of 3 kW and with various welding speeds in the range of 25 to 65 mm s⁻¹. Other conditions are the same as those employed for the keyhole – zinc vapour interaction studies given in table 4.2. Linear welds of 100 mm length were made on hot dip galvanized (GI) zinc coated sheet steels with sheet thickness of 0.8 mm and zinc coating thickness of nominally 7 and 20 µm (No.1 and 2 in table 3.1). The influence of the zinc vapour generated ahead of or at the side of a keyhole on the weld stability was studied by removing the coating from specific positions.

After welding, the specimens were checked visually and weld quality was quantified by length fraction as defined in section 3.3.1. Weld transverse and longitudinal sections were made to study the weld profiles and to show the tendency of defects to appear preferentially on weld top or root faces respectively.

Instabilities generated at the keyhole rear wall and in the weld pool were observed by placing the high speed camera coaxially with the laser beam (position 1 in Figure 3.5), at
Chapter 6. Evacuation of Zinc Vapour Through the Melt Pool

the side of the sheets (position 2) or aiming the camera towards the lower side of the welded sheets at an angle of 35º to the normal of the sheet surface (position 3). The images taken from the coaxial top view were also used for particle tracking velocimetry (PTV) to estimate the flow velocity at the weld pool top surface.

6.2 Experimental results

6.2.1 Welding sheets with a 7 μm combined coating thickness

By welding an uncoated sheet to a sheet with a 7 μm zinc coating thickness in an overlap joint, a combined coating thickness of 7 μm was obtained. The weld quality (quantified by the length fraction) as a function of welding speed is shown in Figure 6.1. Unlike the results shown in Figure 4.4 (where both sheets were coated), weld quality deteriorated with increasing welding speed. The weld quality is unacceptable at low welding speed but improves with increasing speed up to 45 mm s⁻¹. Further increasing the welding speed from 45 mm s⁻¹ to 65 mm s⁻¹ results in a rapid decrease of the weld stability. It is also notable that at low speed, the weld defects primarily appear at the root face but switch to the top face with increasing welding speed. This trend is clearly shown in longitudinal cross-sections of welds made at different welding speeds (Figure 6.2). When welding at 25 mm s⁻¹, porosity shows a tendency to expand towards the weld root face, and blowholes were formed when the porosity breaks the weld surface. A very characteristic blowhole on the root face is observed at the weld end, as shown in Figure 6.3, whilst the top remains intact. At a welding speed of 45 mm s⁻¹, the cross-section shown in Figure 6.2b illustrates that the weld quality is significantly improved, with fewer and smaller pores formed. The pores are located in the middle of the weld with no visible tendency observed for expansion toward either the root or top faces. Welding at 65 mm s⁻¹ shows decreasing weld stability with severe porosity and blowholes, and these holes were formed primarily on the weld top face (Figure 6.2c).

The welding speed also influences the weld profiles, as shown in Figure 6.4. A wider weld is obtained when welding at 25 m m s⁻¹ with a wide weld root and a blowhole appears on the weld root face. In the case of the 45 mm s⁻¹ welds, although the weld root is still wider than the top, this effect is much less pronounced. when increasing welding speed to 65 mm s⁻¹, the weld top is larger than the root and a pore is contained in the weld, which most likely initiated at the interface but expanded towards the top face.

The severe porosity and blowholes formed when welding at the low welding speed were studied by adjusting interface positions. Sheets of 0.8 mm with a 7 μm coating thickness and an uncoated sheet of 1.5 mm thick were welded at 25 mm s⁻¹ in two overlapped configurations. In the first, the thicker sheet was placed on the top. A large number of pores and root face blowholes are observed when welding in this configuration (Figure 6.5a). Conversely, with the thinner sheet on the top the amount of porosity is significantly reduced.
Experimental results

(Figure 6.5b). The gas pores still show a tendency to expand toward the root face, even though the interface is located closer to the top surface.

![Graph showing the fraction of acceptable weld as a function of the welding speed. Photos of top and root faces are shown for the welds made at welding speeds of 25, 45 and 65 mm s⁻¹.]

Figure 6.1: Fraction of acceptable weld as a function of the welding speed. Photos of top and root faces are shown for the welds made at welding speeds of 25, 45 and 65 mm s⁻¹.

![Longitudinal cross-sections of welds made at welding speeds of (a) 25, (b) 45 and (c) 65 mm s⁻¹.]

Figure 6.2: Longitudinal cross-sections of welds made at welding speeds of (a) 25, (b) 45 and (c) 65 mm s⁻¹.
Chapter 6. Evacuation of Zinc Vapour Through the Melt Pool

Figure 6.3: (a) The weld end crater on the root face, made at a welding speed of 25 mm $s^{-1}$ and (b) a transverse cross-section of the weld end crater.

Figure 6.4: Transverse cross-sections of welds made at welding speeds of (a) 25, (b) 45 and (c) 65 mm $s^{-1}$.

Figure 6.5: Cross-sections of welds made with (a) the 1.5 mm thick uncoated sheet on the top and (b) the 0.8 mm sheet with 7 μm coating thickness on the top.
6.2.2 Visualization of instabilities occurring in a melt pool

It has been shown that when welding zinc coated steels, the melt pool became smaller than that of uncoated steels under nominally identical welding conditions (see Figure 4.7). The top face of a melt pool produced when welding the combination of uncoated sheets and coated sheets with a coating thickness of 7 μm was imaged coaxially and compared with those produced with pairs of uncoated sheets and pairs of sheets with 7 or 20 μm coating thicknesses (Figure 6.6). It can be seen that at a given welding speed the sizes of the melt pools decrease substantially when welding coated sheets and the smallest was produced when welding with a 20 μm coating, whilst the largest was produced with uncoated steels. When welding the combination of an uncoated sheet and a coated sheet with a coating thickness of 7 μm, the size of the melt pool is visually similar to that produced with two uncoated steels. In addition, the size of the melt pool decreases with increasing welding speed with the exception of the 20 μm coating, where the melt has similar dimensions at welding speeds of both 25 and 45 mms⁻¹.

The widths of the welds at the sheet interface (weld waist) were measured for welds made on various coating thicknesses and with various welding speeds (Figure 6.7). Each data point shown in the figure is a mean value calculated from three weld cross-sections per set of parameters. The trend observed is similar to that shown in Figure 6.6. At any given welding speed, the smallest weld waist is observed with the 20 μm coating thickness, whilst the largest was formed when welding the uncoated sheets. The width generally decreases with welding speed but is less pronounced in the case of the 20 μm coating thickness. For the cases of uncoated sheets and the combination of an uncoated sheet and a sheet with a 7 μm coating thickness, it can be seen that the decrease of weld width with increasing welding speed becomes less significant at higher speeds.
Chapter 6. Evacuation of Zinc Vapour Through the Melt Pool

Figure 6.6: High speed video images showing the top face of melt pool when welding uncoated sheets and sheets with various coating thickness at the interface.

Figure 6.7: The width of the weld waist, when welding uncoated sheets and sheets with various coating thickness at the interface.
Experimental results

The formation of the blowholes shown on the weld root faces was observed and an example is shown in Figure 6.8. It can be seen that tearing (separation) of the weld pool root face occurred at a position far behind the keyhole aperture (labelled by arrows in Figure 6.8c-f).

Instability in a melt pool can also be more severe. Figure 6.9 shows an example of a melt pool eruption at a welding speed of 45 mm s\(^{-1}\) when welding sheets with a 7 μm coating thickness. Two different types of melt ejection can be distinguished. The first is an eruption of the melt pool occurring far behind the keyhole, simultaneously observed at both top and root faces (labelled by the arrows in Figure 6.9c-f). It is also notable that this eruption process is associated with a closure of the keyhole and a change of the vapour plume from an angle of about 35° to 90° to the plate surface. The second type of ejection is a melt splash generated at the keyhole rear wall, which is labelled by the arrows with broken lines in Figure 6.9c-f. These different types of instabilities are consistent with the results reported by Kageler et al.\(^1\)

The evolution of different types of melt ejection was also observed from the top face. The results indicate that eruptions occurring far behind the keyhole often lead to a through hole in the weld pool (Figure 6.10), whilst an enlarged keyhole is formed as a result of a droplet ejection generated at the keyhole rear wall (Figure 6.11). It should be noted that the latter mode of instability occurs more often than the former. The through hole formed behind the keyhole stays in the melt pool, whereas the enlarged keyhole resulting from the droplet ejection at the keyhole rear wall can be healed by the liquid generated at the keyhole front wall and no hole is left after solidification.

Figure 6.8: Successive high speed video images showing tearing on the weld root surface at a welding speed of 25 mm s\(^{-1}\). The interval between images is 0.1ms. The broken lines indicate the boundaries of the weld pool and the arrows in c-f mark the position where tearing occurs.
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Figure 6.9: Successive high speed video images showing a lateral view of two modes of eruptions in the melt pool and keyhole rear wall. The interval between images is 0.1ms.

Figure 6.10: Successive high speed video images showing a through hole in the weld pool when welding sheets with a 7 μm coating thickness at 45 mm s⁻¹. The interval between images is 1 ms. The broken lines indicate the boundaries of the weld pool and the through hole is marked with arrows.
Experimental results

Figure 6.11: Successive high speed video images showing a droplet ejection occurring at the keyhole rear wall and a subsequently enlarged keyhole, when welding sheets with a 7 μm coating thickness at 45 mm s\(^{-1}\). The interval between images is 1 ms. The broken lines indicate the boundaries of the weld pool and the droplet is marked with arrows.

6.2.3  Welding with various coating configurations

In previous chapters, it has been shown that the zinc vapour generated ahead of the keyhole can penetrate the keyhole front wall and escape through the keyhole aperture. Hence zinc vapour generated from other positions, for example at the side of the melt pool, is suspected to be the reason of the instability occurring in the melt pool. The influence of the zinc coating from different positions was examined by etching the coating from specific positions as shown in Figure 6.12. When the coating at the interface is 7 μm thick but only 1 mm wide, a weld made over the coating line shows good stability with only few blowholes (Figure 6.12a). In contrast, it is shown in Figure 6.12b that sheets welded with a 1 mm wide gap at the interface show decreased weld stability. In Figure 6.12c, a 1 mm wide gap was made in a 20 μm thick coating, where an even more unstable weld was produced.

Figure 6.12: Sheets with zinc coating etched at selected positions and the corresponding welds, (a) zinc coating of 7 μm thick and 1 mm wide, (b) a gap of 1 mm wide made in the coating with thickness of 7 μm thickness and (c) a gap of 1 mm wide made in the coating with thickness of 20 μm. Welds are made at 45 mm s\(^{-1}\).
Similar tests were also conducted to determine the size of a zinc removal area necessary to generate a stable weld. Trapezoidal shaped zinc removal areas were made on sheets with a 7 μm coating thickness as shown in Figure 6.13. Visual examination of weld surfaces show that when the width of the zinc removal area is larger than 2 mm, no defect appears on the weld faces. A longitudinal cross-section (Figure 6.13c) shows the porosity and blowholes contained in the weld, indicating that when the width of a zinc removal area is greater than 2.2 mm, very little zinc will be vaporized, leading to virtually pore free welds.

Figure 6.13: (a) Sheets with zinc coating etched at a selected position, (b) the corresponding weld faces, and (c) a longitudinal cross-section. The weld was made at a speed of 45 mm s⁻¹.

### 6.3 Discussion

#### 6.3.1 Defects on weld faces

The observation that majority of the weld bead defects appeared on the weld root face when welding at 25 mm s⁻¹ can be related to the weld profile; the width of the weld root is much wider than that of the top (Figure 6.4). For a molten pool, the maximum pressure that can be supported by surface tension pressure $\rho_s$ is given by $\rho_s^{[5]}$.
Discussion

\[ p_r = \frac{\gamma}{r_w} \]  

(6.1)

where \( \gamma \) is the surface tension coefficient and \( r_w \) is the radius of the melt pool. Given that the surface tension of steel typical for the range of mean pool surface temperature experienced is of the order 1.6 N m\(^{-1}\)[35][3], and taking a radius of 2.1 mm, which is the average radius of the reinforcement at the top face estimated from 3 weld cross-sections when welding at 25 mm s\(^{-1}\), the pressure that can be suppressed in the weld is of the order 760 Pa.

Based on the weld cross-section shown in Figure 6.4, schematics of the weld profiles when welding the combination of a sheet with a 7 \( \mu \)m coating thickness and an uncoated sheet have been constructed as shown in Figure 6.14. When welding at 25 mm s\(^{-1}\), assuming a situation that the melt pool reinforcement caused by the internal pressure is the same for the top \( (h_{top}) \) and root faces \( (h_{root}) \); i.e., \( h_{top} = h_{root} \), a radius of curvature of 6 mm is obtained on the root face and the maximum pressure required to overcome surface tension is of the order 270 Pa. The buoyancy force is estimated by \( \rho_{sl} \cdot g \cdot 2t_p \) to be the order of 110 Pa, where \( \rho_{sl} \) is the density of liquid steel, \( g \) the gravitational constant and \( t_p \) the sheet thickness. The pressure necessary to overcome the surface tension pressure on the root face is much smaller than that necessary to overcome the surface tension pressure on the top face, and the zinc vapour tends to take the path of least resistance. This explains why when the weld root face is substantially wider than the top face, zinc vapour always expands towards the root face regardless of the position of the interface. In addition, since the root of the weld is wider than the top, it is reasonable to expect it to solidify later; hence any remaining vapour trapped inside the melt is constrained to expand towards the root. This conceptual description is supported by the characteristic blowholes observed at the weld ends, as shown in Figure 6.3, where the weld root surface was strongly displaced compared to the top face.

At the welding speed of 45 mm s\(^{-1}\), the difference between weld top and root widths is significantly less (Figure 6.4b), and the tendency to form root face defects becomes less dominant. The improved weld quality with increasing welding speed, as shown in Figure 6.1 and 6.2, is mainly a result of reduced zinc vapour evacuation through the melt pool, (which will be discussed in the next section). However it is notable that both weld top and root are smaller with increasing welding speed, caused by the reduced heat input per unit length. If the reinforcement is the same as that at 25 mm s\(^{-1}\), a pressure of 840 Pa is required to overcome surface tension, which is higher than when welding at 25 mm s\(^{-1}\). This may also partly contribute to a weld with less surface defects. However, it can be imagined that once excessive amounts of zinc vapour accumulate in the melt pool and the pressure builds up to the critical limit, a more violent instability is likely to be triggered. When further increasing the welding speed, a weld with a wider top was obtained and the defects therefore switched to the top face.
6.3.2 Instability in a melt pool

Two modes of melt pool instability were observed when welding sheets with 7 μm coating thickness at a welding speed of 45 mm s\(^{-1}\) (Figure 6.9). Although the melt ejection generated at the keyhole rear wall was found to occur more often during a welding process, high speed camera images reveal that the eruption occurring far behind the keyhole is more destructive to the weld quality because the resultant through hole cannot be healed and remains in the melt pool during solidification (shown in Figure 6.10 and 6.11). The melt generated from the keyhole front wall flows around the keyhole and this flow can heal the extended keyhole generated as a result of droplet ejection occurring at the keyhole rear wall (Figure 6.15a). Conversely, for a through hole appearing behind the keyhole due to the melt eruption, the melt flow is less likely to heal it because the melt flowing around the keyhole will collide with the weld pool before reaching the defect (Figure 6.15b) and the dynamic pressure of the flow in the weld pool and the surface tension pressure on the wall of the through hole are not able to overcome the zinc vapour pressure in the through hole.

The liquid flow velocity at the weld pool top surface was estimated from high speed images using particle tracking velocimetry (PTV). The movement of oxide particles
floating on top of the melt pool surface were traced, as illustrated in Figure 6.16. The average velocity of the weld pool surface was obtained by tracing 6~7 oxide particles per set of parameters and all these particles are selected in the area where the through hole often initiates (Figure 6.10b). The average velocities of the weld pool surface are shown in Figure 6.17 and the error bars represent the range of the observed particle velocities. It can be seen that the velocity of the weld pool surface is higher when welding zinc coated steels. Similar result were reported by Dasgupta et al.\cite{6} showing that the liquid velocity at the surface was increased by 30% when welding zinc coated steels and the dynamic pressure of zinc vapour was suggested to account for the velocity increase. At lower welding speeds, the highest mean velocity is observed for sheets with a 7 \( \mu \)m coating thickness, whilst at higher speeds the highest mean velocity appears when welding sheets with a 20 \( \mu \)m coating thickness. However, the differences are small compared with the variations between individual measurements. The results shown here provide an order of magnitude indicator for the flow velocity. Analysis of more particles and a construction of the flow velocity field based on particle image velocimetry (PIV) are required to give a more accurate estimate of the flow velocity.

![Figure 6.16: Tracking of an oxide particle when welding uncoated steel at 45 mm s\(^{-1}\). The particle is marked by circle and the dots indicate the position of the particle in the first frame. The dotted lines indicate the boundaries of the melt pool.](image)

Discussion
Chapter 6. Evacuation of Zinc Vapour Through the Melt Pool

Figure 6.17: Flow velocity at the weld pool top surface, estimated using particle tracking velocimetry.

Ki et al. observed the liquid flow on the melt pool surface by tracing the disturbance (hump) generated due to keyhole oscillation. They reported that the velocity at the melt pool surface reaches 1.5 m s\(^{-1}\) when welding with an incident power of 3.2 kW at a welding speed of 34 mm s\(^{-1}\). In their measurement, there was some uncertainty due to the wave characteristic of the hump. The hump velocity is approximately the sum of the liquid flow velocity and the phase velocity.

\[
v_{\text{hump}} \approx v_{\text{flow}} + v_{\text{ph}},
\]

(6.2)

where \(v_{\text{hump}}\) is the hump velocity, \(v_{\text{flow}}\) is the flow velocity and \(v_{\text{ph}}\) is the phase velocity of the hump, which is defined as

\[
v_{\text{ph}} = \frac{\omega}{k_2} = f \cdot \lambda,
\]

(6.3)

where \(\omega\), \(k_2\), \(f\) and \(\lambda\) are angular frequency, wave number, frequency and wave length respectively. The wave length was measured from high speed images as shown in Figure 6.18 to be approximately 0.4 mm, which is of the same order as the value reported by Ki et al.\(^{[7]}\) (0.3 mm), whilst the frequency of hump generation was reported to lie between 600 Hz to 3500 Hz depending on processing and material parameters.\(^{[8]}\)\(^{[10]}\) The phase velocity \(v_{\text{ph}}\) therefore lies between 0.2 and 1.4 m s\(^{-1}\) and the resultant flow velocity according to (6.2) is of the same order to the values presented in Figure 6.17.
The velocity obtained by this method is found to be at the same order or even higher than the flow velocity around the keyhole (table 4.5), which is expected to be the highest liquid flow velocity in a weld pool\cite{11,12}. This is because that the velocity of the melt top surface is driven by surface phenomena, such as the surface tension force and the vapour drag force. It is believed that there is a large velocity gradient at the liquid-vapour interface (melt pool surface), and therefore, the surface velocity is much higher than that inside the pool\cite{7,13}. Nevertheless, the maximum dynamic pressure of the melt calculated based on the velocities given in Figure 6.17 is of the order 410 Pa according to equation 4.3 and the surface tension pressure of a through hole is of the order 6.2 kPa according to equation 4.5. The sum of the above two pressures is much smaller than the pressure of the zinc vapour in the through hole, which is of the order 1.6 MPa to 5.6 MPa at temperature from 1300 K to 1800 K according to Clausius-Clapeyron equation\cite{14,15}. The melt pool flow therefore fails to heal the holes.

To avoid the instability occurring in the melt pool, it is necessary to limit the amount of zinc that evacuates through the pool. Results shown in Figure 6.12 suggest that the zinc vapour generated in front of the keyhole had less negative effects on stability (Figure 6.12a), whereas that generated at the side of or behind the keyhole accounted for the instabilities in the melt pool (Figure 6.12b, c). When welding a combination of an uncoated sheet and a sheet with 7 μm coating thickness, a circular shaped keyhole occurs and the melt pool expanded significantly behind the keyhole as shown in Figure 6.6. It can therefore be expected that additional zinc vaporisation occurs behind the keyhole.

A schematic view of the keyhole, melt pool and zinc boiling isotherm at the joint interface is shown in Figure 6.19. It is reasonable to assume that all zinc vapour generated ahead of or at the side of the keyhole can escape through the keyhole, whilst the zinc vapour generated behind the keyhole may escape through the weld pool. The volume of the zinc vapour generated per unit time $\dot{V}_{gen}$ and the volumetric flow escaping through the keyhole $\dot{V}_{key}$ can be expressed as

$$
\dot{V}_{gen} = 2 \cdot t \cdot h \cdot \frac{\rho_{vapor}}{\rho_{z}},
$$

$$
\dot{V}_{key} = 2 \cdot t \cdot h \cdot \frac{\rho_{vapor}}{\rho_{z}},
$$

(6.2)
Chapter 6. Evacuation of Zinc Vapour Through the Melt Pool

\[ \dot{V}_{\text{key}} = 2 \cdot t_{zn} \cdot b_2 \cdot v \cdot \frac{\rho_{z\text{-solid}}}{\rho_{z,v}}, \]  

(6.3)

where \( t_{zn} \) is the coating thickness, \( v \) is the welding speed, \( \rho_{z\text{-solid}}, \rho_{z,v} \) are the density of solid zinc (7.1 \( \times \) \( 10^3 \) kg m\(^{-3}\)) and zinc vapour (21.9 kg m\(^{-3}\)), \( b_1 \) and \( b_2 \) are distances of vaporisation isotherm as defined in Figure 6.19. The maximum volumetric flow rate of the zinc vapour venting through the weld pool \( \dot{V}_{\text{melt}} \) can be estimated from

\[ \dot{V}_{\text{melt}} = \dot{V}_{\text{gen}} - \dot{V}_{\text{key}} = 2 \cdot t_{zn} \cdot v \cdot \frac{\rho_{z\text{-solid}}}{\rho_{z,v}}(b_1 - b_2), \]

(6.4)

Figure 6.19: Schematics showing the zinc coating vaporized behind the keyhole when welding the combination of an uncoated sheet with a coated sheet with a 7 \( \mu \)m coating thickness at (a) 25 mm s\(^{-1}\) and (b) 45 mm s\(^{-1}\). \( b_1 \) and \( b_2 \) represent the greatest width between the boiling isotherm, and the width of the zinc boiling boundary just behind the keyhole respectively.

When welding at a welding speed of 25 mm s\(^{-1}\) (Figure 6.19a), the position where the maximum temperature is approximately equal to the zinc boiling point is around 1.4 mm from the weld centre line, which is determined from the temperature measurements at the sheet interface; thus \( b_1 \) is 2.8 mm. The ratio between \( b_1 \) and \( b_2 \) is estimated from high speed video images by comparing the width of the weld pool just behind the keyhole and the maximum width of the weld pool; \( b_2 \) is 90\% of \( b_1 \). The maximum volumetric flow rate of the zinc vapour venting through the melt pool is therefore of the order 16 mm\(^3\) s\(^{-1}\). With increasing welding speed, \( b_1 \) decreases from 2.8 mm to 2 mm at 45 mm s\(^{-1}\). This is
consistent with the observation shown in Figure 6.6, showing the narrower weld pools when welding at the higher speed. Since the effect of the weld pool enlargement is reduced, the difference between $b_1$ and $b_2$ reduces; $b_2$ approaches 95% of $b_1$ (Figure 6.19b). The maximum volumetric flow rate of zinc vapour escaping through the pool therefore decreases to around 10 mm$^3$ s$^{-1}$, resulting in reduced instability. Further increasing the welding speed, the decrease of $b_1$ is not significant as suggested in Figure 6.7, the zinc vapour escaping through the melt pool therefore increases since more zinc vapour is generated per unit time. This explains the decreased weld stability when welding with higher welding speeds (Figure 6.1).

Results shown in Figure 6.5 provide some support for the above explanation. The weld width at the joint interface obtained in the configuration of the thick sheet on the top (Figure 6.5a), is 20% wider than that obtained with the inverse configuration (Figure 6.5b). Even though the tests were made at the same welding speed, the narrower weld waist due to the characteristics of the weld profile lead to a narrower zinc boiling isotherm and therefore smaller difference between $b_1$ and $b_2$ at the interface, which contributes to the weld pool stability.

The effect of the zinc vapour evacuation through the melt pool discussed in this chapter can be integrated with the mechanism of keyhole elongation developed in Chapter 4 and the resultant power absorption discussed in Chapter 5. A schematic demonstrating the position of the zinc boiling isotherm when welding sheets with a 20 μm coating thickness is shown in Figure 6.20. It has been shown in Figure 6.6 and 6.7 that a strongly elongated keyhole was formed when welding coated sheets with a 20 μm coating thickness, associated with a narrow melt pool, which is a result of reduced laser power absorption and lateral convection flow (section 5.4.2). Without the influence of a melt pool enlargement behind the keyhole, $b_1$ has been found to be similar to $b_2$ at any given welding speed, leading to a minimal vapour evacuation through the weld pool. Additionally, it is also reasonable to expect that with an elongated keyhole, there is more time available for zinc vapour to escape through the keyhole and consequently less vapour escapes through the weld pool.
6.4 Summary

In this chapter the mechanism of the zinc vapour evacuation through the melt pool and subsequent defects generated has been examined. It is observed that zinc vapour can escape
either through the keyhole or through the weld pool, the latter resulting in severe instability in the melt pool including weld face tearing and melt pool eruption.

Root face tearing mostly occurred at lower welding speeds when welding with a thin coating thickness at the joint interface; e.g., 7 μm, made up from a combination of an uncoated sheet and a sheet with a 7 μm coating thickness. The defects generated can be ascribed to the wider weld root, which leads to a reduced surface tension retaining force. When welding with higher speeds, for example 65 mm s⁻¹, the weld top is wider than the root; correspondingly, the majority of the defects appeared on the top surface.

Two modes of instabilities were observed, droplet ejection occurring at the rear keyhole wall and melt pool tearing/eruption occurring in the melt pool. Droplet ejection occurring at the rear keyhole wall results from keyhole closure or due to variation of the zinc vapour pressure in the keyhole. This in turn leads to temporary enlargement of the keyhole but it can be healed by liquid metal transported around the keyhole. In contrast, melt pool tearing or eruption occurring in the melt pool (far behind the keyhole) is due to zinc vapour escape through the melt pool and often results in permanent defects (through holes) in the weld because the liquid flow in the melt pool cannot close the hole. This indicates that the instability occurring in the melt pool has a greater influence on the final weld quality.

It is shown that the zinc vapour entrapped in the melt pool, which is mainly generated behind of the keyhole, is responsible for the decrease of process stability. The generation of this vapour is coupled with the melt pool shape. When a circular keyhole shape is obtained with melt pool enlargement behind the keyhole, for example when welding a combination of an uncoated sheet and a sheet with 7 μm coating thickness at 25 mm s⁻¹, a significant quantity of vapour can be generated behind the keyhole, causing a defective weld. In contrast, when a (stably) elongated keyhole associated with a smaller melt pool is obtained, for example when welding sheets with a 20 μm coating thickness, vapour evacuation through the melt pool can be minimized, producing welds with fewer defects.
References


Chapter 7

Welding of Sheets with Various Coating Types

The link between process stability and the dynamic balance between the zinc vapour, the keyhole and the weld pool has been discussed in previous chapters. Stable welds are associated with a constant supply of zinc vapour into the keyhole, limited fluctuation on the keyhole rear wall and limited zinc vapour venting through the weld pool. Whether this mechanism, proposed to explain the observed behaviour when welding GI coated steels, is also valid when welding steels with other metallic coatings, is the question considered in this chapter. A study of the weldability of steels with different coating types, namely electrogalvanized (EZ), galvanealed (GA) and Mg-Zn coated steels with various coating thicknesses was performed and the results are presented. Comparison is made with a range of GI coating thicknesses. The influences of coating properties (thickness, melting temperature) and welding speed on the weld stability are highlighted.

7.1 Experimental procedures

Linear welds of 100 mm length were made on all coated sheets examined. Various combined coating thicknesses at the interface of two sheets were examined by reducing the coating thickness of GI steels for an initial 20 μm coating thickness. The sheets were immersed in dilute hydrochloric acid for different periods of time. Welds on these sheets were made at welding speeds of 25 and 45 mm s⁻¹. The same welding speeds were also employed for welds made on GA sheets. The GA sheets used here were made from GI sheets (materials No. 1 and 2 given in Table 3.1) by annealing for 15 or 30 minutes at 410 °C to form a Zn-Fe alloy coating. Commercially produced EZ sheets with coating thickness of 4 and 7 μm (table 3.2) were welded at welding speeds in the range 25 to 75 mm s⁻¹. To examine the influence of thicker EZ coatings, uncoated base steels (with the coating completely removed in hydrochloric acid) were electrogalvanized to coating thickness of 10 and 20 μm. These recoated sheets were also welded at welding speeds of 25 and 45 mm s⁻¹. Finally, the Mg-Zn coated sheets with coating thickness of 5 and 10 μm were welded at welding speeds in the range 25 to 65 mm s⁻¹. Other processing parameters are the same as those given in table 4.2.
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The quality of the welds was checked visually and assessed by a fraction of acceptable weld length as defined in section 3.3.1. For the welds made on GA sheets, the weld ending positions were photographed to determine the zinc fusion zone. A high speed camera was placed coaxially with the laser beam (position 1 in Figure 3.5) during welding to observe the keyhole and melt pool dynamics.

7.2 Experimental results

7.2.1 Welding with etched GI sheets

Prior to welding of the etched sheets, samples were sectioned to examine the remaining coating thickness. The results show that although a longer etching time results in a decrease of average coating thickness, the coatings were not removed uniformly (Figure 7.1). For a longer etching time (12.5 minutes) the zinc coating has been completely removed at some places, whereas at other positions, the remaining coating still has a thickness of more than 15 μm.

![Coating thickness variations after etching in dilute hydrochloric acid.](image)

For welds made at a speed of 25 mm s⁻¹, the weld quality begins to deteriorate when the average zinc coating thickness is reduced below 13-14 μm, the worst weld quality obtained is at a coating thickness of 6-7 μm. The majority of defects appeared on the weld root face, and the root width is wider than the top width of the weld (Figure 7.2a). Further etching the sheet so that the zinc layer was completely removed, resulted in improved weld quality, and
defect free welds were obtained. In contrast, when welding at 45 mm s\(^{-1}\), the variation of coating thickness only shows a weak influence on the weld quality. The process remains relatively stable at all coating thickness although a few blowholes were observed on the weld surface when the remaining coating thickness was of the order 6-7 μm (Figure 7.2b).

When welding GI coated sheets with a 6-7 μm coating after etching, at 25 mm s\(^{-1}\), a circular shaped keyhole is observed, with occasional enlargements as shown in Figure 7.3. Correspondingly, an enlarged melt pool appears behind the keyhole. In contrast, when welding at 45 mm s\(^{-1}\), an elongated keyhole with a narrower melt pool is observed (Figure 7.4). In addition, the keyhole evolution over 0.2 s reveals that the keyhole length mostly oscillates in a range between 0.5 mm and 0.9 mm, with occasional fluctuations with large amplitude (Figure 7.5). This is a relatively stable manner compared with the keyhole oscillation obtained when welding commercially produced sheets with a 7 μm coating thickness as shown in Figure 4.18.

![Figure 7.2: Effect of the coating thickness on the quality of welds, at two welding speeds of 25mm s\(^{-1}\) (a) and 45mm s\(^{-1}\) (b). The coating thicknesses marked with the etching time are average values measured by making cross-sections through the material and measuring at 50 positions.](image-url)
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Figure 7.3: Successive high speed images showing the keyhole dynamics when welding GI coated sheets with a 6-7 μm coating after etching. The welding speed was 25 mm s⁻¹. The interval between images is 0.2 ms. The broken lines indicate the boundaries of the weld pools and a droplet ejection associated with the keyhole enlargement is marked with arrows.

Figure 7.4: High speed image showing the top face of a keyhole and melt pool produced when welding GI coated sheets with a 6-7 μm coating after etching. The welding speed was at 45 mm s⁻¹ and the contour of melt pool is indicated by the broken line.
Experimental results

7.2.2 Welding EZ coated sheets

Commercially produced electrogalvanized zinc coated (EZ) sheets with 4 and 7 μm coating thicknesses (substrate thickness 0.7 and 0.8 mm respectively) were welded and the weld quality obtained is shown in Figure 7.6. In the case of welding with a 4 μm coating thickness, the weld quality is worse when welding at a low speed of 25 mm s⁻¹, with many blowholes appearing on the weld root face. With increasing welding speed (to 55 mm s⁻¹), the quality is improved. However, when further increasing the welding speed, a deterioration of weld quality is observed and majority of the defects switch to the weld top face. Conversely, when welding with a 7 μm coating, welds with better quality were obtained with lower welding speeds and increasing welding speed decreases the length fraction exhibiting acceptable quality, with through holes observed in the welds.
When welding the recoated sheets with coating thickness of 10 and 20 µm, severe defects appear on sheets with both coating thicknesses although the welds made on the sheets with the thicker coating have slightly better quality in terms of a reduced number of surface blowholes (Figure 7.7). In the region surrounding the weld bead, pores and cavities are observed in the coating layer adjacent to the weld and the coating layer is expanded to 40 µm from a nominal 20 µm (Figure 7.8a). Further from the weld location exfoliation of the coating layer was observed, as shown in Figure 7.8b. The exfoliation and cavities in the coating are only found when welding re-coated sheets but not in the commercially produced EZ sheets with 4 µm or 7 µm coating thicknesses.

The keyhole was found to be elongated with a magnitude comparable to that obtained when welding GI steels. However, liquid metal ejection (splash) was generated from the side walls towards the centre, which interferes with the evolution of an elongated keyhole often resulting in severe process instability (Figure 7.9).
Experimental results

Figure 7.7: Surface appearances of welds made on EZ sheets with 10 and 20 μm coating thicknesses.

Figure 7.8: (a) Pores in the coating adjacent to the weld and (b) expansion of the coating layer when welding recoated sheets with a 20 μm coating thicknesses.

Figure 7.9: successive images showing the splashes generated from both sides of a keyhole when welding EZ sheets with a 20 μm coating thickness at a welding speed of 45 mm s⁻¹. The interval between images is 0.2 ms.

7.2.3 Welding of sheet with a Zn-Fe alloy coating layer (GA)

It has been shown that the GI coating contains mainly pure zinc according to the GDOES measurements shown in section 3.1. With various heating time periods at 410 °C,
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the GI coatings were transformed into the GA coatings with different iron contents. Examples of the alloy coating composition profiles made with this method are shown in Figure 7.10, indicating dissolution of the Al barrier at the Zn–Fe interface (see Figure 3.1) and the growth of an alloyed layer with increasing heating time. The results of welding performed on these galvannealed sheets are shown in Figure 7.11. More stable welds were produced on sheets with a 20 μm coating thickness and for both coating thicknesses, an increase of weld surface defects appears with an increasing iron composition in the coating layer.

Figure 7.10: Zn, Fe and Al profile across the coating layers with 20μm thicknesses, after heating at 410 °C for (a) 15 min and (b) 30 min.
7.2.4 Welding of Mg-Zn coated sheet

Mg-Zn coated sheets (substrate thickness 0.8 mm) with coating thicknesses of 10 μm and 5 μm, which contain 1–2 wt.% (4–8 vol.% Mg, were tested at speeds from 25 to 65 mm s$^{-1}$. The quality of the welds as a function of the welding speed is shown in Figure 7.12. A decrease of weld quality is observed with increasing welding speed when welding sheets with a 10 μm coating thickness, whilst an increase in quality is observed with the welding speed increasing from 25 mm s$^{-1}$ to 45 mm s$^{-1}$ when welding sheets with a 5 μm coating thickness. It is also notable that in this range of welding speeds, the majority of the defects appear on the root faces. However, the weld quality deteriorates when further increasing the welding speed and majority of the defects switch to the weld top face.

In high speed video images, circular keyhole shapes were produced when welding sheets with a 5 μm Mg-Zn coating thickness, whereas those produced with the 10 μm Mg-Zn coating were observed to be elongated, the elongation being more pronounced at the higher welding speed, as illustrated in Figure 7.13. The elongated keyhole is observed to be subject to violent oscillation as shown in Figure 7.14. The amplitude of the oscillation is...
comparable to that observed when welding sheets with a 7 µm coating thickness (Figure 4.18).

Figure 7.12: Fraction of acceptable weld for weld beads made on sheets with 5 and 10 µm Mg-Zn coating thicknesses.

Figure 7.13: High speed video images showing the top face of melt pool when welding Mg-Zn coated sheets. The contours of melt pools are indicated by broken lines.
7.3 Discussion

7.3.1 Welding of etched GI sheets

When comparing the stability exhibited when welding commercially produced GI sheets with a 7 µm coating thickness (Figure 4.4) and etched GI sheets with a 6-7 µm average coating thickness after etching (Figure 7.2, after etching 12.5 min), significant differences are found. The welds made on etched sheets have more instabilities at a welding speed of 25 mm s\(^{-1}\), but show better quality at 45 mm s\(^{-1}\). The blowholes that primarily appear on the weld root face when welding at 25 mm s\(^{-1}\) (see Figure 7.2a) are due to zinc vapour evacuation through the melt pool and a wider weld root as discussed in section 6.3.1. This is supported by photos shown in Figure 7.2a revealing a wider weld root, and the significant weld pool enlargement behind the keyhole (Figure 7.3). When welding at 45 mm s\(^{-1}\), an elongated keyhole with limited positional fluctuation on the rear wall (Figure 7.4 and 7.5) and a narrower melt pool was observed (Figure 7.4). Keyholes and melt pool with these characteristics have been shown to be beneficial to avoid the generation of instabilities (see section 4.6.3 and 6.3.2). In addition, a larger gap at the interface between the two etched sheets is formed compared to that occurring with the commercially produced GI sheets with a 7 µm coating thickness as a result of the non-uniform nature of the etched coating (Figure 7.1). With a larger interface gap, the liquid on the keyhole front wall can be penetrated at lower pressure due to the reduced surface tension forces, as discussed in section 4.6.3. Despite the non-uniform coating thickness after the etching (Figure 7.1), the length of non-coated regions observed in cross-sections is in the range 10 ~ 50 µm, which is smaller than the distance from the zinc fusion boundary to the keyhole front wall (> 200 µm as shown in Figure 4.24). A relatively consistent supply of zinc vapour into the keyhole can therefore be
expected. It has been argued in chapter 4 that less uniform coating leads to the inconstant delivery of zinc vapour into the keyhole. However, the non-uniform coating discussed there is with a larger scale reaching 0.5 mm as shown in Figure 4.3.

### 7.3.2 Welding of EZ sheets

The results of welding EZ sheets with 4 and 7 μm coating thicknesses (Figure 7.3) showed good agreement with the welding of GI coated sheets with equivalent coating thickness. These results are expected because the coating composition measurement indicates that both the EZ and the GI coating with a thickness of 7 μm contain mainly pure zinc (Figure 3.1). However, when welding sheets with re-coated 10 and 20 μm coating thicknesses, severe instability was observed, as shown in Figure 7.7 and 7.8. These results differ from those obtained when welding GI sheets with a 20 μm coating thickness. It is shown in Figure 7.8 that pores were formed in the coating layer adjacent to the melt pool, which led to an increase of the local coating thickness. The reasons for the pore generation are not fully understood, but are likely to be associated with residual nitrogen, as a result of solvent or moisture entrapment during the coating process. This pore formation is also evident in the coating at an interface of the two sheets; however, there was no observable increase of local coating thickness since the sheets were tightly clamped (Figure 7.15). It is therefore reasonable to expect that the resultant vapour must evacuate through the keyhole or melt pool, which explains the ejected metal splash generated from both side walls of the keyhole as illustrated in Figure 7.9. The process instability can be accounted for by these splashes, which generate sudden instabilities during the development of an elongated keyhole.

![Figure 7.15: Cross-section showing bubbles and cavities in the coating at the interface of two sheets when welding re-coated EZ sheets with a coating thickness of 20 μm at a welding speed of 25 mm s⁻¹.](image)

### 7.3.3 Welding of sheet with an alloyed coating layer

Compared with the welds made on GI sheets shown in Figure 4.5, the results presented in section 7.1.3 indicate that the weld quality deteriorates with increasing iron composition in the coating. This observation is in agreement with the results reported by Lu et al. and Akhter. One possible explanation suggested by Lu et al. is that a narrower zinc fusion zone is formed in front of the keyhole when welding GA sheets due to its higher melting temperature, resulting in the zinc vaporization being sensitive to the coating characteristics; e.g., uneven coating thickness. Temperature measurements were performed on the top
surface of the specimen as described in section 3.7 to determine the position of the coating melting isotherm at the side of a weld. The results shown in Figure 7.16a reveal that the positions where the maximum temperature reaches the equilibrium melting temperature of a GA coating (893 K) and the melting temperature of zinc (693 K) are approximately 1.8 and 2.4 mm from the weld centre line respectively, which are consistent with the distances determined from photomicrographs by tracing the zinc fusion boundary (Figure 7.16b and c). Hence it is reasonable to use this boundary to determine the fusion zone in front of the keyhole as shown in Figure 7.17. Compared to those obtained when welding GI sheets (Figure 4.24), the fusion zones shown here are smaller, and as expected, increasing iron composition in the coating layer decreases the distance between the coating melting isotherm and the keyhole front wall.

A schematic showing the influence of coating characteristics on the zinc vapour pressure in front of a keyhole is shown in Figure 7.18. It has been shown that the coating thickness is not uniform over the surface (Figure 4.1 and 4.2). Assuming an extreme situation where there is no zinc coating on either sheet over a certain length (Figure 7.18a), in the case of GA sheets, a substantial increase of the volume of the zinc vapour occurs when the melting front crosses the non-coated area (Figure 7.18b) because the pressure of the zinc vapour is reduced as it expands into the free gap between the sheets. In contrast, for GI sheets, which have a larger fusion zone, the increase of the vapour volume is less significant and the reduction of the vapour pressure is limited (Figure 7.18c). This relatively consistent zinc vapour pressure contributes to a constant supply of zinc vapour into the keyhole and therefore stabilizes the process, as discussed in section 4.6.3.

Figure 7.16: (a) Temperature measurements for a weld made on uncoated sheets, for varying distances from the weld centre line; (b) the distance between the zinc fusion boundary and the weld centre line measured for a weld made on GI sheets with a 20 µm coating thickness, and (c) the distance between the zinc fusion boundary and the weld centre line measured for a weld made on GA sheets (GI sheets after heating at 410 °C for 30 min). All welds were made at 45 mm s⁻¹.
Figure 7.17: Zinc fusion zones in front of the weld end crater for welds made on GA sheets. The GA sheets were made by heating GI sheets with 20 μm coating thickness in a furnace at 410 °C for (a) 15 min and (b) 30 min.
Discussion

Figure 7.18: (a) Two zinc coated sheets in an overlap configuration with a non-coated area at the interface, (b) and (c) schematic illustrations of the zinc vapour expansion in the interface when the fusion front crosses the non-coated area during welding of GA and GI sheets respectively.

It should be noted that the influence of Zn-Fe alloy on the process stability is less dominant than the effect of the coating thickness. Increasing iron composition in a coating of 20 μm thickness decreases weld stability. However, at any alloying levels examined, stability of the 20 μm coating thickness GA welds is always better than that of welds made on the GI sheets with a 7 μm coating thickness.
Chapter 7. Welding of Sheets with Various Coating Types

The above discussion concerning the effect of the melting temperature of a coating on the weld stability can be extended to explain the results observed when welding the Mg-Zn coated sheets. For a 5 μm Mg-Zn coating thickness, the stability trend exhibited is similar to that obtained when welding a combination of an uncoated sheet and a GI sheet with 7 μm coating thickness (Figure 6.1); although in the range of higher welding speeds (> 45 mm s⁻¹), the quality of the welds showed a faster deterioration. When welding Mg-Zn coated sheets with an 10 μm coating thickness at 25 and 35 mm s⁻¹, the weld quality was comparable to that of GI sheets with a 7 μm coating thickness; however, again at higher speeds welds showed more severe instabilities. Since both the melting (923 K) and boiling (1380 K) temperatures of Mg are higher than those of Zn, it can be expected that smaller coating fusion and vaporisation zones appear in front of the keyhole when welding the Mg-Zn coated sheets. In common with the GA coated sheets the behaviour of laser welds made on the Mg-Zn coated steel is governed primarily by the influence of Mg on the melting and vaporisation temperature of the coating.

7.4 Summary

The weldability of steels with EZ, GA, Mg-Zn and etched GI coatings were discussed in term of surface defects and compared to that of GI steels with equivalent coating thicknesses. The process mechanisms suggested in previous chapters including the keyhole elongation and zinc vapour evacuation through the melt pool are also applicable for these coating and can be used to explain the phenomena observed when welding coated steels.

GI sheets with different average coating thickness were obtained by immersing sheets with a 20 μm coating thickness in a hydrochloric acid solution, however, this method led to non-uniform coating profiles. A circular keyhole shape was produced when welding at 25 mm s⁻¹ with melt pool enlargement behind the keyhole, leading to welds with severe defects on the root faces. In contrast, when welding at 45 mm s⁻¹, relatively stable welds were obtained, as a result of an elongated keyhole and narrower melt pool, which reduces the likelihood of zinc evacuation through the melt pool.

The quality of the welds produced on EZ sheets with 4 and 7 μm coating thicknesses was comparable to that with GI coated sheets with equivalent coating thickness. However, when welding sheets with re-coated EZ coating, severe surface defects appeared. This was ascribed to vapour generated in the coating adjacent to the weld zone, possibly due to contamination during the coating process. The vapour generated at the interface of the sheets has to escape through the keyhole or melt pool, inevitably causing instability.

Welds made on GA sheets have been found to have greater instabilities compared to those made on GI sheets. This is ascribed to the higher melting temperature of the Zn-Fe alloy, which leads to a smaller zinc fusion zone in front of the keyhole. Similarly, this effect can also explain the weld stability deterioration when welding Mg-Zn coated steels at higher welding speeds.
References


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Chapter 8

Conclusions and Recommendations

Conclusions

An investigation into the mechanism of a stable laser weld of zinc coated steel without a pre-set gap has been presented in this thesis. The welds with acceptable quality are linked to the development of an elongated keyhole, limited fluctuation on the keyhole rear wall and minimal vapour evacuation through the melt pool. This mechanism was proposed as a result of observations during an experimental study on laser welding of hot dip galvanized steels, and then used to explain the behaviour observed when welding other coated materials including EZ, GA and Mg-Zn coated steel. Key conclusions from this investigation are presented below.

- Laser welding of commercially produced GI sheets with a 20 μm zinc coating thickness, in an overlap condition and without the introduction of a gap to vent the zinc vapour, can produce welds of acceptable quality. Conversely, no weld with acceptable quality could be made on GI sheets with a commercially produced 7 μm zinc coating thickness.

- The stable behaviour of GI sheets with a 20 μm zinc coating thickness is linked to the development of an elongated keyhole with minimal positional fluctuations on the rear keyhole wall. High speed coaxial visualization has shown that a zinc vapour evacuation channel was present on the keyhole front wall almost continuously, indicating a consistent delivery of zinc vapour into the keyhole, and corresponding keyhole rear wall fluctuations were relatively small. Conversely, for sheets with a 7 μm zinc coating thickness, the vapour was found to be inconsistently emitted into the keyhole and the keyhole rear wall was subject to persistent and severe fluctuations.

- For both 7 and 20 μm coating thicknesses, welds made at lower welding speeds are more stable than those made at higher speeds, which is a result of more consistent zinc vapour supply into the keyhole when larger zinc vaporisation and fusion zones are formed.
Conclusions and Recommendations

- An analytical model was developed to calculate the keyhole length, showing good agreement with the experimentally observed behaviour. This model indicates that the dynamic pressure of the zinc vapour, which expands into the keyhole through the channel on the keyhole front wall, is responsible for elongation of the keyhole. A longer keyhole is obtained when welding sheets with thicker coatings or when welding at higher speeds, because more zinc vapour is produced per unit time and escapes through the keyhole, leading to a higher vapour dynamic pressure.

- By blowing an argon jet into a gap of 40 μm at the interface between two sheets, a vapour pressure was applied on the front keyhole wall. The resultant behaviour of the keyhole and melt pool and the evolution of weld profiles are similar to those produced when welding zinc coated steels. The average keyhole length determined by means of high speed imaging shows an increase with increasing flow rate of the argon jet (increasing dynamic pressure). This gives additional proof that the zinc vapour expanding into the keyhole is responsible for the elongated keyhole, narrower weld pool and weld profile with modified shape.

- For laser welding with a full penetration keyhole, the heat transfer (process) efficiency increases with increasing welding speed, this effect is most significant when welding uncoated steel and least significant in the case of zinc coated steel sheet with a 20 μm coating thickness. Conversely, the fraction of incident laser power that transmits through the keyhole without any interaction with the welded material shows a decrease with welding speed, and an increase with increasing coating thickness. Keyhole elongation during the welding of zinc coated steels, together with the inclination angle of the keyhole front wall and impingement of the reflected beam on the rear wall are contributory factors.

- A narrower melt pool is often associated with the elongated keyhole. This is explained by two effects.

  - A larger keyhole allows more laser beam transmission through it without interaction with the melt pool. In addition, radiation due to reflection from the keyhole front wall onto the rear wall is limited, thus there is less laser energy absorbed by the melt pool.

  - The zinc vapour emitted from the channel on the keyhole front wall propels the liquid rearwards; and thus the lateral convective flow, which broadens a melt pool, particular at the top and root faces, is reduced.

- A weakly decreasing melting efficiency with increasing welding speed appears when welding uncoated steels, whereas increasing efficiencies have been observed when welding zinc coated steels. This is consistent with evolution of weld cross-sectional areas. When welding uncoated steels, the weld areas are larger than those made when welding zinc coated steels for all welding speeds examined, but decrease significantly
Conclusions and Recommendations

with increasing welding speed although the heat transfer (process) efficiency increases, indicating an increasing fraction of power dissipating through conduction.

- Zinc vapour can escape either through the keyhole or through the weld pool. The vapour that evacuates through the melt pool often leads to surface tearing of the melt pool (mostly occurring at lower welding speeds) or melt pool eruption (mostly occurring at higher welding speeds), which are more detrimental to the final quality of a weld compared to instabilities occurring at the keyhole rear wall.

- Weld instabilities appear preferentially on the weld free surface with a lower surface tension retaining force. The majority of weld defects appear at the root of the weld when welding at lower speeds, and with increasing welding speed, these switch to the top surface of the weld. At low welding speeds, the weld root is wider than the weld top, which leads to a weaker surface tension force at the root face. In addition, the root of the weld also solidified later than the top, leaving more time for zinc vapour to expand towards the root. At higher welding speeds, the size of weld root decreases and becomes smaller compared to the top width of the weld. Therefore, zinc vapour takes the path through the weld top surface to escape, leading to instabilities at weld top.

- The zinc vapour generated in front of the keyhole has less negative effects on stability compared to that generated at the side of or behind the keyhole. When a melt pool enlargement behind the keyhole is observed, a considerable amount of zinc vapour can be generated behind the keyhole, some of which escapes through the melt pool resulting in instabilities. The narrow weld pool obtained when welding sheets with a 20 µm coating thickness minimize the vapour evacuation through the melt pool, leading to stable welds.

- In general, EZ, GA and Mg-Zn coated sheets showed similar trends to those observed for GI sheets with equivalent coating thickness, except for the re-coated EZ sheet with 20 µm coating. The severe surface defects appeared in this case during welding are ascribed to the vaporization of residual elements in the coating layer from the electrogalvanizing process. The vapour generated at the interface has to escape through the keyhole or melt pool, causing instabilities. The welds made on GA and Mg-Zn coated sheets show greater instabilities compared to those made on GI sheets, due to the higher melting temperature of the Zn-Fe or Mg-Zn alloys, which lead to a smaller zinc fusion zone in front of the keyhole.

Recommendations

Although a systematic experimental study into the laser welding of zinc coated steel without a pre-set gap was carried out in this work, following opportunities are opened for further research to improve the weld stability and build more in depth understanding into the physics behind the welding process.
Conclusions and Recommendations

- A side gas jet applied on the keyhole rear wall can be used to stabilize the welding process during joining of zinc coated steel in an overlap configuration without a pre-set gap. The dynamic pressure of this side gas jet is beneficial to maintain the dynamic balance between the vapour pressure and the keyhole and melt pool.

- Control algorithms can be developed based on the images taken in this work to improve the weld quality. The grey scale value of pixels at critical areas (the keyhole rear wall) can be used as input signals for an adaptive beam scanning to reduce the oscillation at the keyhole rear wall.

- The effects of the reservoir pressure, the size of the gap at the interface between two sheets on the opening of the channel on the keyhole front wall should be studied to determine the critical conditions for a stable supply of zinc vapour into the keyhole.

- A dynamic model describing the interaction between the zinc vapour and the keyhole and melt pool should be developed to build a comprehensive understanding on the mechanism of zinc vapour evacuation and its impact on the process stability. This model should include the behaviour of the zinc vapour in the keyhole and the resultant velocity field in the melt pool and temperature field in the liquid and solid domains. The model can also be extended to the zinc vapour behaviour at the interface between two sheets, which allows a quantitative analysis of the amount of zinc vapour evacuating through the melt pool.
Summary

The major problem during laser welding of zinc coated sheet steel in an overlap configuration is the zinc vapour produced at the interface between two sheets. The vapour tends to evacuate through the keyhole and melt pool, particularly when no gap is present between the overlapped sheets. This causes process instabilities and results in the formation of pores and severe undercut.

Several techniques have been suggested to reduce the influence of zinc vapour on the process stability. One of the first methods introduced and still in use today is to set a gap between two sheets to provide a channel to vent the zinc vapour. Another method is to use an enlarged keyhole, produced by dual laser spots or a tilted laser beam, as the channel for the escape of zinc vapour. Other methods include laser-arc hybrid welding, pulsed welding or inserting copper or aluminium foils into the interface to reduce the generation of zinc vapour. The common disadvantage of these methods is the additional steps introduced and/or the pre-treatment or measurement required, which limit their applications in an industrial environment. Laser welding of zinc coated steels without any special arrangement was also studied extensively. Although stable welds were reported, the mechanisms responsible for the observed results were not fully understood.

The aim of this work is to build an understanding of the material behaviour, particularly the zinc behaviour when welding zinc coated steels in overlap configuration without a preset gap. The interaction between zinc vapour and welded materials was investigated mainly by experimental approaches. Questions concerning when and how stable welds can be obtained are answered by introducing a mechanism describing the dynamic balance between the zinc vapour, the keyhole and the weld pool.

Welds made on hot-dip galvanized (GI) sheets reveal that acceptable quality can be made on sheets with a 20 µm coating thickness. These stable welds are associated with the development of an elongated keyhole with minimal positional fluctuations on the rear keyhole wall. High speed coaxial visualization has shown that a zinc vapour evacuation channel is present at the keyhole front wall almost continuously during welding of steels with a 20 µm coating thickness, indicating a consistent supply of zinc vapour into the keyhole. This is due to the smooth coating surface profile and a larger gap between the two sheets formed after vaporization of the zinc coating. With this consistent flow of zinc vapour, fluctuations at the keyhole rear wall are limited. Although the keyhole elongation is also observed when welding sheets with a 7 µm zinc coating thickness, the vapour is inconsistently emitted into the keyhole and the rear wall is subject to persistent and severe fluctuations, resulting in more weld instabilities.
An analytical model was developed based on the pressure balance analysis on the keyhole rear wall. The surface tension pressure, trying to close the keyhole, is balanced primarily by the zinc vapour pressure. Though simplifications were made when estimating the surface tension and hydrodynamic terms, the predictions of the keyhole lengths show good agreement with the major trend observed in experimental results, indicating that the zinc vapour pressure is responsible for the elongation of the keyhole. The reservoir pressure of zinc vapour that feeds into the keyhole was chosen to match the calculated keyhole length to the measured keyhole length at a welding speed of 25 mm s⁻¹. This derived vapour pressure has been found to be of the same order of magnitude as the value estimate based on the surface tension of the melt on the keyhole front wall trying to close the channel.

An argon jet was injected into a gap of 40 μm at the interface between two sheets to apply a dynamic pressure on the front keyhole wall. Similar keyhole and melt pool behaviour were obtained to those produced when welding zinc coated steels with a 20 µm coating thickness. This provides further evidence that the keyhole elongation is accounted for by the zinc vapour expanding into the keyhole through the channel at the keyhole front wall.

For both 7 and 20 µm coating thicknesses, relatively stable keyhole behaviour is observed at low welding speed, which is a result of larger zinc vaporisation and fusion zones. More consistent zinc vapour supply into the keyhole can be expected when larger vaporisation and fusion zones are obtained. However, when welding the combination of an uncoated sheet with a sheet with a 7 µm coating thickness at lower welding speeds, severe defects were observed on the weld root face. This can be ascribed to an enlargement of the melt pool behind the keyhole, causing mass vapour evacuation through melt pool. It has been experimentally shown that the zinc vapour generated behind the keyhole significantly degrades the stability of the process. Tearing of weld root face was observed through high speed imaging, due to the wider dimension of the weld root, which leads to a weaker surface tension force. At higher welding speeds, the quality of the weld is improved because of a significant decrease of the weld width. However, when further increasing the speed above 65 mm s⁻¹, the decrease of the weld width becomes less pronounced and the weld became unstable again due to the increasing volume of zinc vapour generated per unit time. Under these conditions the defects switch to the top face because the weld top became wider than the root.

The stable behaviour when welding sheets with a 20 µm coating thickness is also linked to a narrower melt pool compared to that produced when welding sheets with a 7 µm coating thickness. The narrower melt pool without a significant enlargement of the melt pool after the keyhole minimizes the zinc vaporization behind the keyhole and therefore improves the weld stability. This narrow melt pool is also associated with the development of an elongated keyhole. The power distribution measurements show that due to the elongated keyhole, there is more laser beam power transmitted through the keyhole without any interaction with the welded material. The power absorption on the keyhole rear wall due to reflected beam from the keyhole front wall is also reduced. Therefore the absorption of laser power, represented by the process efficiency showed a decrease with increasing
coating thickness. In addition, the zinc vapour emitted from the keyhole front wall propels the liquid rearwards; and thus reduces the lateral convection flow which broadens the melt pool. This is supported by the evolution of weld profiles where the weld width, particularly the widths of the weld top and root decrease when welding zinc coated steels.

Welding tests were performed on etched hot dip galvanized (GI), electrogalvanized (EZ), galvanealed (GA) and Mg-Zn coated sheets. Non-uniform coating profiles were obtained by etching the GI sheets in a hydrochloric acid solution. Welding etched materials led to severe instabilities at lower welding speeds but a relatively stable weld when welding at higher welding speeds. This has been ascribed to the large gap at the interface between the two sheets, which allows more consistent supply of zinc vapour into the keyhole. For EZ sheets with 4 and 7 μm coating thicknesses, similar trends of weld quality as functions of welding speed were observed to those encountered when welding GI sheets with equivalent coating thickness. However, when welding sheets with recoated zinc coatings of 10 and 20 μm thick, severe weld instabilities were observed. The cavities in the coating adjacent to the weld and even exfoliation of the coating layer indicated that some contaminations were contained in the coating layer during the recoating process and were vaporized during welding. The vapour generated at the interface between the two sheets has to escape through the keyhole or melt pool, causing instabilities. GA sheets were made by annealing the GI sheets in a furnace at 410 °C. Welds with better quality were still obtained with sheets with a 20 μm coating thickness, but all GA sheets show slightly more weld instabilities compared with GI sheets. This can be explained by the high melting temperature of Zn-Fe alloy, which leads to a smaller zinc fusion zone in front of the keyhole. Under these circumstances, the zinc vapour supply into the keyhole becomes more sensitive to the sporadic changes in the coating thickness. This effect can also explain the weld stability deterioration when welding Mg-Zn coated steels at higher welding speeds.
Samenvatting

Het belangrijkste probleem tijdens het laserlassen van verzinkt staal in een overlapconfiguratie is de ontwikkeling van zinkdamp aan het grensvlak van beide platen. De zinkdamp heeft de neiging om te ontsnappen via de keyhole en het smeltbad, vooral als er geen spleet aanwezig is tussen de overlappende platen. Dit veroorzaakt procesinstabiliteiten en resulteert in de vorming van poriën en ernstige randinkarteling.

Verscheidene technieken zijn voorgesteld om de invloed van zinkdamp op de processtabiliteit te reduceren. Eén van de eerste geïntroduceerde methoden, die vandaag de dag nog steeds wordt toegepast, maakt gebruik van een openingsspleet tussen beide platen, als afvoerkanaal van de zinkdamp. Een andere methode is het gebruik van een vergrote keyhole als een kanaal voor het ontsnappen van zinkdamp, gecreëerd door een dubbele laserspot of een gekantelde laserbundel. Andere methoden zijn laser-boog hybridelassen, gepulseerd lassen of het tussenvoegen van koper- of aluminiumfolie tussen beide platen om de ontwikkeling van zinkdamp te verlagen. Het gemeenschappelijke nadeel van deze methoden, die het toepassen in een industriële omgeving beperken, zijn de aanvullende processtappen en/of de benodigde voorbehandeling of metingen. Laserlassen van verzinkt staal zonder speciale voorzieningen is ook uitgebreid bestudeerd. Hoewel stabiele lassen zijn gerapporteerd, worden de mechanismen, die verantwoordelijk zijn voor de verkregen resultaten, niet volledig begrepen.

Het doel van dit onderzoek is het verbreden van het begrip ten aanzien van het materiaalgedrag, in het bijzonder het gedrag van het zink, tijdens het lassen van verzinkt staal in de overlapconfiguratie zonder spleet. Een experimentele benadering is gekozen om de interactie van de zinkdamp en het te lassen materiaal te bestuderen. Vragen met betrekking tot wanneer en hoe stabiele lassen kunnen worden vervaardigd zijn beantwoord door de introductie van een mechanisme, dat de dynamische balans tussen zinkdamp, keyhole en lasbad beschrijft.

Er is aangetoond dat lassen met een acceptabele kwaliteit kunnen worden vervaardigd, op dompelverzinkt (GI) staalplaat met een zinklaagdikte van 20 µm. Deze stabiele lassen kunnen geassocieerd worden met de vorming van een uitgerukte keyhole, met minimale fluctuaties in de positie van de achterwand van de keyhole. Hoge snelheid coaxiale visualisatie bij het lassen van staal met een zinklaagdikte van 20 µm heeft aangetoond dat er bijna voortdurend een kanaal voor de afvoer van zinkdamp aanwezig is aan de voorzijde van de keyhole, tijdens het lassen. Dit geeft aan dat er een consistente toevoer van zinkdamp is naar de keyhole. Dit is het gevolg van het gladde coatingoppervlak en een grotere spleet tussen de twee platen ten gevolge van het verdampen van de zinkcoating. Met deze consistente toevoer van zinkdamp zijn de fluctuaties aan de achterzijde van de keyhole beperkt. Hoewel ook een verlenging van de keyhole is waargenomen bij het lassen van staal
Samenvatting

met een zinklaagdikte van 7 μm, wordt de damp niet consistent uitgestoten naar de keyhole en is de achterzijde van de keyhole onderhevig aan hardnekkige en hevige fluctuaties, resulterend in een toename van de lasinstabiliteiten.

Een analytisch model is ontwikkeld gebaseerd op een analyse van de drukbalans over de achterzijde van de keyhole. De oppervlaktespanning, die het lasbad tracht te sluiten, is in evenwicht met de zinkdampdruk. Hoewel vereenvoudigingen zijn aangebracht bij de schatting van de oppervlaktespanning en de hydrodynamische termen, laat de voorspelling van de keyhole-lengte een goede overeenkomst zien met de belangrijkste, experimenteel waargenomen trend, namelijk dat de zinkdampspanning verantwoordelijk is voor de verlenging van de keyhole. De druk in het reservoir, waaruit de zinkdamp wordt gevoed naar de keyhole, is zodanig gekozen dat de lengte van de keyhole overeenkomt met de gemeten lengte bij het lassen met een snelheid van 25 mm s⁻¹. De afgeleide dampdruk is van dezelfde orde van grootte als de waarde geschat op basis van de oppervlaktespanning aan de voorzijde van de smelt van de keyhole, die de keyhole tracht te sluiten.

Een argon jet is geïnjecteerd in een opening van 40 μm op het grensvlak van de twee platen om een dynamische druk op de voorzijde van de keyholewand te verkrijgen. Het keyhole- en smeltbadgedrag was gelijk aan het gedrag tijdens het lassen van verzinkt staal met een zinklaagdikte van 20 μm. Dit levert aanvullend bewijs op, dat de verlenging van de keyhole wordt veroorzaakt door de zinkdamp die zich uitbreidt in de keyhole door een kanaal aan de voorzijde van de keyhole.

Zowel voor een zinklaagdikte van 7 als 20 μm is een relatief stabiel keyholegedrag gevonden voor lage lassnelheden. Dit is het resultaat van een grotere hoeveelheid zink dat verdamp t en een groter smeltbad. Onder deze omstandigheden kan een meer consistente toevoer van zink verwacht worden. Als echter een onverzinkte plaat met een lagere laslengte gelast wordt aan een verzinkte plaat met een laagdikte van 7 μm, worden ernstige defecten aangetroffen in de onderzijde van de las. Dit kan toegeschreven worden aan een vergroting van het smeltbad achter de keyhole, dat gepaard gaat met een massale evacuatie van zinkdamp via het smeltbad. Het is experimenteel aangetoond dat zinkdamp die aan de achterzijde van het smeltbad gegenereerd wordt, de stabiliteit van het proces aanzienlijk verslechtert. Het scheuren aan het oppervlak van de wortel van de las is geobserveerd door middel van high speed video. Scheurenvorming is het gevolg van een breder onderzijde van het lasbad, en dit leidt tot een geringe oppervlaktespanningskracht. Bij hogere laslengthen verbetert de kwaliteit ten gevolge van een significante vermindering van de lasbreedte. Als de snelheid echter groter wordt dan 65 mm s⁻¹ is de afname in lasbreedte minder uitgesproken en neemt de stabiliteit weer af doordat het volume aan geproduceerde zinkdamp per eenheid van tijd toeneemt. Onder deze omstandigheden verschuiven de defecten zich naar de bovenzijde van de las, omdat de bovenzijde van de las breder is dan de onderzijde.

Het stabiele gedrag bij het lassen van 20 μm zinklaagdikte is ook gekoppeld aan het smallere lasbad, in vergelijking tot de breedte die optreedt bij het lassen van plaat met een laagdikte van 7 μm. Het smallere lasbad, zonder een significante vergroting van het
smeltbad achter de keyhole, minimaliseert de verdamping van zink en verbetert daarmee de stabiliteit van de las. Dit smalle smeltbad is ook geassocieerd met de ontwikkeling van een verlengde keyhole. Metingen van de vermogensverdeling tonen aan dat, door het langer worden van het smeltbad, een grotere fractie van het laserbundelvermogen door de keyhole verdwijnt zonder enige mate van interactie met het te lassen materiaal. De absorptie van het vermogen aan de achterzijde van de keyhole van de aan de voorzijde van de keyhole gereflecteerde bundel neemt ook af. Daarom neemt de absorptie van laservermogen, gerepresenteerd door het procesrendement, af bij toenemende zinklaagdikte. Tevens stuwt de zinkdamp, die uitgestoten wordt aan de voorzijde van de keyhole, de vloeistof naar achteren en verlaagd daarmee de laterale/zijsling convectiestroming die het smeltbad verbreed. Dit wordt ondersteund door de ontwikkeling van het profiel van de las, waar de lasbreedte, met name de breedte aan de bovenzijde en teen van de las, afneemt als verzinkt staal wordt gelast.

Lasexperimenten zijn uitgevoerd op geëtst dompel verzinkt (GI) elektrolytisch verzinkt (EZ), galvanealed gegalvaniseerd (GA) en Mg-Zn gecoate plaat. Niet-uniforme coating profielen zijn verkregen door het etsen van GI plaat met een zoutzuuroplossing. Het lassen van geëtst materiaal leidde tot ernstige instabiliteiten bij lage lassnelheden, maar tot relatief stabiele lassen bij hogere lassnelheden. Dit wordt toegeschreven aan de grote spleet aan het grensvlak van de twee platen, waardoor een meer consistent toevoer van zinkdamp gewaarborgd is. Voor EZ en GI platen met zinklaagdiktes van 4 en 7 μm worden gelijke trends ten aanzien van de laskwaliteit als functie van de lassnelheid gevonden. Als echter lassen worden gemaakt op herverzinkte plaat met een zinklaagdikte van 10 en 20 μm worden ernstige instabiliteiten geconstateerd. De caviteiten in de coating naast de las of zelfs het loskomen van de coatinglaag wijzen erop dat tijdens het herverzinken verontreinigingen in de laag worden opgenomen die tijdens het lassen verdampen. De damp die aan het grensvlak van de twee platen wordt gevormd, moet door de keyhole of het lasbad ontsnappen, wat de instabiliteiten veroorzaakt. GA platen zijn vervaardigd door GI platen een warmtebehandeling te laten onder gaan in een oven op 410 °C. Lassen van een betere kwaliteit werden nog steeds verkregen in staal met een zinklaagdikte van 20 μm, maar alle GA gaf altijd wat meer instabiliteiten vergeleken met GI platen. Dit kan worden verklaard door de hogere smelttemperatuur van Zn-Fe legeringen, die leidt tot een kleinere zone waarin zink gesmolten is aan de voorzijde van de keyhole. Onder deze omstandigheden is de toevoer van zinkdamp naar de keyhole gevoeliger voor sporadische veranderingen in laagdikte. Dit effect kan ook de verslechtering van de lasstabiliteit verklaren bij het met hogere snelheid lassen van Mg-Zn gecoat staal.
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List of Publications


Laser welding is an amazing process; even when welding fumes and spatter appear terrible, good quality welds can still be achieved.
Curriculum Vitae

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