1. Introduction

Thin galvanized zinc coated steel sheets are now widely used in the global automotive industry. Sheets of this type are used in the manufacture of automobile bodies in high volume production because of excellent corrosion resistance and relatively low costs [1-10].

The basic, conventional and used for many years method of joining of the car body parts is a resistance spot welding (RSW) [7-12]. In the case of car body parts with larger thicknesses, also the method of gas metal arc welding (GMAW or MIG/MAG) is used. The typical and conventional car body contains approx. 4500 resistance spot welds and also many meters of MIG and MAG weld beads [1,7,11-14]. Both joining methods mentioned above depend on laser welding conditions thus cooling rate and cooling times. The shortest cooling time $t_{8/5}$ was calculated for 0.29 s.

Keywords: car body steel, DC04, laser welding, disk laser, zinc

W artykule opisano wyniki badań procesu spawania laserowego bez materiału dodatkowego złączy doczołowych blach karoseryjnych odcynkowanych DC04 o grubości 0.8 mm. W procesie spawania zastosowano laser stały Yb:YAG TruDisk 3302 z wiązką laserową o średnicy ogniska 200 µm. Badano wpływ parametrów i warunków technologicznych spawania na kształt i głębokość ściegu spoiny, stabilność procesu spawania, mikrostrukturę i właściwości mechaniczne złączy. Stwierdzono, że wiązka laserowa zogniskowana na górnej powierzchni blach wykazuje tendencję do przenikania przez szczelinę złącza, szczególnie przy niskich energiach liniowych i dużych prędkościach spawania. W całym zakresie parametrów złącza były spawane z utworzeniem kanału parowego, a metal spoiny był wolny od porowatości. Wskazuje to, że konfiguracja złącza doczołowego stwarza dogodne warunki do ujścia par cynku, bez ryzyka porowatości spoin. Mikrostruktura, mikrotwardość i właściwości mechaniczne złączy zależą wyraźnie od warunków spawania, a więc szybkości stygnięcia i czasów stygnięcia. Najkrótszy wyznaczony czas stygnięcia $t_{8/5}$ był równy 0.29 s.

1. Introduction

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The basic, conventional and used for many years method of joining of the car body parts is a resistance spot welding (RSW) [7-12]. In the case of car body parts with larger thicknesses, also the method of gas metal arc welding (GMAW or MIG/MAG) is used. The typical and conventional car body contains approx. 4500 resistance spot welds and also many meters of MIG and MAG weld beads [1,7,11-14]. Both joining methods mentioned above are still used but the extent of their use systematically decreases [1,7]. The reason for this is the continuous introduction of new materials such as advanced automotive steels, galvanized high-strength dual-phase steel, trip steels, increase use of aluminium and composites, “sandwich” steel, and tailored blanks [2-4,7-37]. The conventional resistance and arc welding methods are not proper for welding of new materials and joints of dissimilar materials [38-42]. Therefore, the laser welding is increasingly used in the automotive industry [1,18-22]. The materials and connections techniques in automotive industry have to be considered under many requirements. One of the most important is vibration. That is how there are a lot of research on vibrations [43-48] and it should be analysed during the welding process as well in term of influence on the propagation paths. In addition to laser welding technology, the welding-brazing, hybrid welding, cold joining by forming and clinching, structural adhesive bonding are becoming increasingly important [1,8]. Laser welding offers many benefits such as high welding speed, low heat input, narrow weld and narrow heat affected zone (HAZ), high
precision, reliability, high efficiency, and high productivity, and improved corrosion resistance of welds, compared to the conventional welding methods [5,6]. However, during the laser welding of galvanized steel many defects may occur such as spatter, strong porosities of weld metal, and surface pits, poor fusion and cracks resulted in poor surface quality, and reduced strength, as well as the corrosion resistance [4,7]. The problems during laser welding of galvanized steels are related to the behaviour of zinc coating. The thickness of zinc coating in a case of car body steel sheets is usually approx. 10 µm or occasionally thicker than 20 µm for added protection [6]. In spite of such a small thickness of the coating, zinc tends to evaporate during the welding process because of low boiling point just 906 °C compared to the 1530 °C of steel. In most cases lap joint configuration is used in the automotive industry for laser welding of car body parts, e.g. door panels, roofs to side panels, etc. In lap configuration the pressurized vapours and zinc destabilize the keyhole and the bubbles are easily trapped in the weld metal. The problem of quality assurance is still valid, and the use of this technology in the industry is growing. For example, the Opel factory in Gliwice has implemented the laser welding technology at the end of 2014. Therefore, many researchers in the world are looking for solutions to increase the quality and productivity in this field. A variety of different methods and techniques were elaborated and proposed by researchers. Some of them are very original. For example W. Chen et al. proposed pre-drilling by a pulsed Nd:YAG laser to form vent holes along the weld line and then seam welding in the lap-joint configuration using a continuous wave CO2 laser [6]. J. Milberg and A. Trautmann produced defect-free overlap joints of galvanized steel using bifocal hybrid laser welding by combining an Nd:YAG laser with a high power diode laser [8,18-25]. S. Iqbal et al. elaborated the novel method of dual beam laser welding [9]. In this method the precursor beam cuts a slot, thus making an exit path for the zinc vapours, while the second beam performs the needed welding. Tzeng Yih-fong investigated the gap-free lap welding of zinc coated steel by pulsed CO2 laser [5]. He found that the proper selection of welding parameters at pulsed mode of laser beam generation allows producing visually sound welds. L. Mei et al. found that the composition of shielding gas during laser welding of galvanized steel has significant influence on the weld quality [10]. Especially the small addition of oxygen, approx. 2-4%, to argon gas mixture can effectively reduce the tendency of zinc to evaporation. J. Ma et al. proposed two-pass laser welding of galvanized steel [2]. The first pass is based on a defocused laser spot that scans across the top of the overlapped sheets and heats the zinc coating at the faying surface to be melted and vaporized, while the second pass is executed with a focused laser spot in order to perform the welding.

A.K. Dasgupta and J. Mazumder investigated the laser welding of zinc coated steel with addition of copper as an alloying material. In this case before the steel is melted, a zinc-copper compound is formed, which has a higher melting point (1083°C) than the boiling point of zinc, so the formation of zinc vapour is avoided [11]. Similar effect may be achieved when a thin aluminium alloy foil is set along the weld line at the interface of metal sheets in order to alloy the zinc [12, 22].

The most original technique for laser welding of galvanized steel sheets was proposed by S. Yang and Z. Chen et al. [12,13]. They elaborated a suction device with a nozzle to provide highly pressurized zinc vapour to escape.

However, in industrial practice the most commonly used solution is introducing a joint gap between the sheets so as to provide escape route for zinc vapours [1,7,13-18]. However, providing a homogeneous gap requires complex clamping systems and usually a spacer as an additional material, or projections made in one of the sheets to be welded. Therefore, it is difficult to provide high repeatability and quality of welding in high volume production [1,7,19-25].

Another problem during laser welding of zinc coated steel sheets is severe Zn plasma formation over the keyhole. Problems related to the Zn plasma are described by W. Chen, et al. [6]. They found that the Zn plasma plume disrupts the absorption and scatters the laser beam. The high number of publications concerning the laser welding of zinc coated steel indicates that the process is thoroughly tested and well described. Most of these publications relate to the welding of overlap joints by means of gaseous CO2 and solid state (rod) Nd:YAG lasers [16-29]. However, there are few publications on butt welding of car body zinc coated steel sheets. In addition, thanks to the continuous and dynamic development in physics and optics of lasers, new types of laser devices are available now. The most modern lasers introduced for welding are the fibre and disk lasers [14-18,20]. They are characterized by a number of advantages compared to the conventional CO2 and rod Nd:YAG lasers [26,29].

Therefore, the studies of butt joints welding of car body double sided zinc coated steel sheets with a thickness of 0.8 mm, by means of the modern disk laser, were undertaken by authors of the manuscript.

The effect of laser welding parameters on the process stability, microstructure of fusion zone and heat affected zone, microhardness distribution, mechanical properties such as tensile strength and bending angle of test joints have been evaluated.

2. Material and experimental procedure

The material was used was 0.8 mm thick electro-galvanized steel sheet DC04 with approx. 10 µm pure zinc coating on both sides. The chemical composition of steel substrate and mechanical properties are given in Table 1 and 2, and in Fig. 1. Samples in dimension of 200.0 x 110.0 mm were cut from a flat sheet 0.8 mm thick by a mechanical guillotine. A disk laser Yb:YAG TRUMPF TruDisk 3302 with maximum output power 3300 W and beam parameter product (BPP) 8.0 mm mrad was applied for this study. The detailed technical data of the applied laser are given in previous manuscripts [14-18]. The circular laser beam having a wavelength of 1.03 µm was delivered into the focusing optics via fiberglass. The focusing optics was configured in such a way to achieve the spot beam diameter equal to 200 µm. The laser welding head was mounted on the vertical drive, while the plates to be welded were mounted on the “x,y” table of experimental CNC controlled stand, Fig. 2. During the welding tests the laser head was stationary, while the plates were moved linearly. Based on the experience of previous laser welding studies, the laser beam was focused on the top surface of butt joints to provide the highest welding speed.
In order to determine the parameters for autogenous laser welding of the 0.8 mm thick steel sheets, first the bead-on-plate welding trials were carried out. At the stage of bead-on-plate welding the influence of laser output power and welding speed, thus the heat input of welding (defined as the ratio of laser power and welding speed) on the penetration depth, shape of the weld and process stability was determined. The parameters and technological conditions of test joints welding are given in Table 4. After welding, first the visual inspection was performed, and next the weld appearance and topography were examined using an optical microscope (OM). In the next step samples were cut perpendicularly to the joint axis at the mid-length of the joint for further metallographic examinations. Samples were mounted in resin (thermosetting), grinded and polished, then etched by Adler reagent for macroscopic observations, and by Nital solution (3.0%) to reveal the microstructure of the welded joints. Mechanical tests and microhardness measurements were also performed. Vicker’s microhardness at a load 200 g was measured on cross-section in the middle of sample thickness.

**TABLE 1**

Chemical composition of the zinc coated steel sheet substrate, Fig. 1

<table>
<thead>
<tr>
<th>Grade</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>other</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC04</td>
<td>max 0.08</td>
<td>max 0.4</td>
<td>-</td>
<td>max 0.03</td>
<td>max 0.03</td>
<td>-</td>
</tr>
<tr>
<td>According to EN10130-2006</td>
<td>0.02</td>
<td>0.14</td>
<td>0.008</td>
<td>0.006</td>
<td>0.014</td>
<td>Al. 0.033 Ti 0.087</td>
</tr>
<tr>
<td>According to the certificate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 2**

Mechanical properties of the zinc coated steel sheet substrate (for cold re-rolled condition), Fig. 1

<table>
<thead>
<tr>
<th>Grade</th>
<th>Tensile strength Rm, MPa</th>
<th>Yield point Rp0.2, MPa</th>
<th>Fracture elongation A5, %</th>
<th>Vertical anisotropy rmin</th>
<th>Work hardening exponent n10-20</th>
<th>Bending angle α, º</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC04</td>
<td>270–350</td>
<td>140–210</td>
<td>0.62</td>
<td>38</td>
<td>1.6</td>
<td>0.18</td>
</tr>
</tbody>
</table>

**TABLE 3**

Parameters of bead-on-plate welding of 0.8 mm thick zinc coated steel sheet DC04 by disk laser TruDisk 3302

<table>
<thead>
<tr>
<th>Bead No.</th>
<th>Laser power, W</th>
<th>Welding speed, mm/min (mm/s)</th>
<th>Heat input, J/mm</th>
<th>Width of the HAZ, mm</th>
<th>Width of the weld face, mm</th>
<th>Width of the weld root, mm</th>
<th>Shape of FZ</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>750</td>
<td>5000 (83.3)</td>
<td>9.00</td>
<td>0.13</td>
<td>0.47</td>
<td>0.23</td>
<td>Y</td>
<td>NO,FP,FF,NS</td>
</tr>
<tr>
<td>B2</td>
<td>750</td>
<td>4000 (66.6)</td>
<td>11.2</td>
<td>0.20</td>
<td>0.57</td>
<td>0.37</td>
<td>Y/V</td>
<td>NO,FP,FF,NS</td>
</tr>
<tr>
<td>B3</td>
<td>750</td>
<td>3000 (50)</td>
<td>15.0</td>
<td>0.37</td>
<td>0.73</td>
<td>0.53</td>
<td>V</td>
<td>NO,FP,FF,NS</td>
</tr>
<tr>
<td>B4</td>
<td>750</td>
<td>2000 (33.3)</td>
<td>22.5</td>
<td>0.41</td>
<td>0.83</td>
<td>0.66</td>
<td>V</td>
<td>NO,FP,FF,NS</td>
</tr>
<tr>
<td>B5</td>
<td>750</td>
<td>1000 (16.6)</td>
<td>45.2</td>
<td>0.51</td>
<td>1.13</td>
<td>1.08</td>
<td>II</td>
<td>NO,FP,FF,NS</td>
</tr>
<tr>
<td>B6</td>
<td>750</td>
<td>500 (8.33)</td>
<td>90.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>BT</td>
</tr>
<tr>
<td>B7</td>
<td>750</td>
<td>750 (12.5)</td>
<td>60.0</td>
<td>0.76</td>
<td>1.41</td>
<td>1.29</td>
<td>II</td>
<td>FP,FF,NS</td>
</tr>
<tr>
<td>B8</td>
<td>2000</td>
<td>6000 (100)</td>
<td>20.0</td>
<td>0.16</td>
<td>0.5</td>
<td>0.5</td>
<td>X</td>
<td>NO,FP,FF,NS</td>
</tr>
<tr>
<td>B9</td>
<td>1500</td>
<td>6000 (100)</td>
<td>15.0</td>
<td>0.18</td>
<td>0.51</td>
<td>0.52</td>
<td>X</td>
<td>NO,FP,FF,NS</td>
</tr>
<tr>
<td>B10</td>
<td>1000</td>
<td>6000 (100)</td>
<td>10.0</td>
<td>0.16</td>
<td>0.5</td>
<td>0.4</td>
<td>X/I</td>
<td>NO,FP,FF,NS</td>
</tr>
<tr>
<td>B11</td>
<td>750</td>
<td>6000 (100)</td>
<td>7.50</td>
<td>0.1</td>
<td>0.46</td>
<td>0.25</td>
<td>X</td>
<td>NO,FP,FF,NS</td>
</tr>
<tr>
<td>B12</td>
<td>750</td>
<td>6000 (100)</td>
<td>5.00</td>
<td>0.07</td>
<td>0.43</td>
<td>-</td>
<td>V</td>
<td>LP</td>
</tr>
</tbody>
</table>

Remarks, other parameters of bead-on-plate welding: wavelength of laser radiation 1.03 µm, focal length of focusing lens: 200.0 mm, focal length of collimator lens: 200.0 mm, fiber core diameter: 200.0 µm, nominal beam spot diameter: 200.0 µm, shielding nozzle diameter: 8.0 mm, shielding gas: Ar (99.999%), gas feed rate 15 l/min, Quality assessment of the welds: FP – full penetration, BT - burn through, LP – lack of penetration, NO – no oxidation, FF – flat weld face, NS – no spatter
Samples for tensile tests were cut perpendicularly to the joint axis and shaped by milling with intensive water cooling to avoid the effect of heat on the performance of test samples. Static tensile tests were carried out at room temperature.

Finally, the technological bend tests of the laser welded joints were performed on samples having a width of 20.0 mm. Samples for the bend test were cut in the same way as the samples for tensile tests, perpendicularly to the joint axis.

### 3. Characteristic of bead-on-plate welds

In the initial stage of the study the influence of laser welding speed and laser output power on the fusion zone (FZ) shape and penetration depth was investigated. Under this approach, the aim was to determine the minimum heat input of laser butt joint welding at the maximum welding speed. Therefore, the laser beam was focused on the top surface of the 0.8 mm thick sheets to provide maximum power density, and thus maximum penetration depth at a given laser output power. Results of the bead-on-plate laser welding tests showed that the heat input required for full penetration of the butt joint of 0.8 mm thick zinc coated steel sheets DC04 is relatively low and equals approx. 7.5 J/mm, at the laser power just 750 W, and so high welding speed 6.0 m/min (100 mm/s), as shown in Fig. 4a and Table 3.

Previous experience in laser welding of thin steel sheets indicates that the mechanism of butt joint welding is slightly different, compared to the bead-on-plate welding, and also the stability of butt joint welding may be significantly lower. Therefore, the welding speed of 6.0 m/min was set as the maximum welding speed, despite a significant laser power reserve (up to 3.3 kW) and possibility of further increasing the welding speed.

### Table 4

<table>
<thead>
<tr>
<th>Test butt joint</th>
<th>Output laser power, W</th>
<th>Welding speed, mm/min (mm/s)</th>
<th>Heat input, J/mm</th>
<th>Width of the weld face, mm</th>
<th>Width of the weld root, mm</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>1000</td>
<td>4000 (66.6)</td>
<td>15</td>
<td>0.8</td>
<td>0.78</td>
<td>NP, FC, RC</td>
</tr>
<tr>
<td>J2</td>
<td>1000</td>
<td>3000 (50)</td>
<td>20</td>
<td>0.73</td>
<td>0.85</td>
<td>FC, RC, JD, UF</td>
</tr>
<tr>
<td>J3</td>
<td>1000</td>
<td>2000 (33.3)</td>
<td>30</td>
<td>0.92</td>
<td>0.96</td>
<td>NPJD</td>
</tr>
</tbody>
</table>

Remarks, other parameters of butt joints laser welding are given in Table 3. Quality assessment of the welds: NP – no porosity, FC – weld face concavity, RC – weld root concavity, JD – joint distortion, UF – uneven weld face.
the heat input to 90 J/mm resulted in severe burn through, as shown in Fig. 3 (bead B6, Table 3). The visual inspection of bead-on-plate welds revealed that the single beads produced on the 0.8 mm thick zinc coated steel sheet DC04, at the heat input up to approx. 20 J/mm (B1-B4, B8-B11, Table 3), are very narrow, and simultaneously the damage of zinc coating is negligible.

In the case of bead-on-plate welds produced at the heat input up to 20 J/mm the weld width doesn’t exceed 0.5-0.7 mm, Fig. 3-6, Table 3. Surfaces of the weld faces as well as weld roots are flat and even, without any spatter traces of zinc neither steel vapours or slag, Fig. 3. It is worth mentioning that during the bead-on-plate laser welding tests a blue/white plasma plume was observed over the laser beam interaction area. The plasma plume is characteristic for laser welding at the keyhole mode (deep penetration). The minimum level of laser output power applied during bead-on-plate welding tests was set at 500 W. Taking into account that the diameter of the laser beam spot is equal to 200 µm, the power density at the lowest output power of 500 W is 3.9 $\times$ 10^7 W/cm^2. So even at the minimum laser power the power density was over the threshold required for a keyhole welding of structural mild or low alloyed steel sheets [14]. Figures from 4 to 6 show the macrostructure of the bead-on-plate welds. The shape and the depth/width ratio of the individual beads confirm that most of the bead-on-plate welds were produced at the keyhole welding mode, Fig. 4-6.

Close observation of the macrographs of bead-on-plate welds showed that the three characteristic regions, such as fusion zone (FZ), heat affected zone (HAZ), and the base metal (BM), are easy to identify, as can be seen in Fig. 4 to 6. The fusion lines (FL) are very clear and additionally the width of the individual regions of welds are easy to estimate and measure, as given in Table 3. As can be seen, the shape and the depth/width ratio of the individual beads depend on the laser welding parameters, thus thermal conditions of heating, melting and subsequent solidification. Laser bead-on-plate welding of the 0.8 mm thick DC04 steel sheet at high speed 5.0 m/min, and simultaneously low power 750 W (heat input just 9 J/mm), resulted in “Y” weld configuration, Table 3. The depth/width ratio in this case is 1.7, so typical for a keyhole laser welding. Reduction of welding speed, at unchanged laser power, resulted in changing the shape of the weld. For example the bead-on-plate weld produced at 2.0 m/min (B4, 22.5 J/mm, Table 3) has a “V” shape of the fusion zone and the depth/width ratio in this case is just 0.96, but still typical for a keyhole laser welding mode. Whereas, the bead-on-plate weld produced at 1.0 m/min (B5, 45.2 J/mm, Table 3) has a columnar “I” shape at the depth/width ratio 0.7, which is close to the limit for the keyhole.

There were no signs of porosity or any instability of the bead-on-plate laser welding process. It must therefore be concluded that the laser welding of zinc coated steel sheets in butt configuration provides excellent conditions to escape for zinc vapours. The process of laser bead-on-plate welding was very stable in the range of investigated parameters, so no evidence was found to disrupting the laser beam by the plasma plume.

4. Structure and properties of butt joints

After the detailed analysis of the effect of laser bead-on-plate welding on the penetration depth and shape of fusion zone, next the trials of butt joints welding were undertaken. The first attempts to weld of butt joints of the 0.8 mm thick zinc coated DC04 steel sheets have revealed significant differences and difficulties in the process.

The first trials of laser welding at the laser power of 750 W and welding speed of 5.0 m/min were unsuccessful because of insufficient heating and just slight melting of the sheets edges. The reason for this was small laser beam diameter of 200 µm, which just “flew” through the joint gap.

Despite the precision cutting of the samples for welding and accurate fit prior to welding by the stiff clamping device,
in some areas the gap width was up to 0.1 mm, so exactly 50% of the laser beam spot diameter. Thus, due to the high precision of the laser beam spot, as a welding heat source, the required accuracy for joints preparation must be adequate to the beam diameter. It was not possible to ensure greater accuracy of sheet edges preparation and less width of the gap than 0.1 mm. Thus, in order to allow welding, it was necessary to correct the range of processing parameters.

Fig. 7. A view of the weld face (top surface) of the test joints of 0.8 mm thick electro-galvanized steel sheet

Fig. 8. A view of the weld root (bottom) of the test joints of 0.8 mm thick electro-galvanized steel sheet DC04, autogenously welded by a disk laser (Table 4); a) J1, b) J2, c) J3

Full and proper penetration of the entire length of the butt joint requires higher heat input of welding, at least 15 J/mm, at the laser output power 1.0 kW and welding speed 4.0 m/min, as shown in Table 4. For comparison the minimum heat input required for full and proper penetration of the sheet during bead-on-plate welding was just approx. 7.5 J/mm, so twice lower, Table 3. The increased heat input during butt joints welding resulted in increasing of the volume of melt pool. The molten metal flows into the gap between the sheets and fulfils it. Therefore the conditions for absorption of laser energy and proper fusion of both sheets are favourable.

Full and proper penetration of the entire length of the butt joint J1 produced at the minimum heat input of 15 J/mm, laser power 1.0 kW, and welding speed 4.0 m/min is flat and even, as can be seen in Fig. 7a. Similarly the root of this joint is flat and shiny, Fig. 8a. In turn, the faces of joints J2 and J3 produced at higher heat input are uneven, Fig. 7a,b. The surface of weld face J2 is concave and there are some undercuts, as can be seen in Fig. 7b.

Additionally, subsequent studies showed that, despite a rigid mounting of the steel sheets, it is difficult to provide laser welding of the butt joints without distortion, Fig. 9. As can be seen in Fig. 9 the extent of butt joints deformation is directly proportional to the thermal conditions of laser welding, thus heat input of welding. The butt joint J1 produced at the lowest heat input of 15 J/mm has not been deformed, Fig. 9a, Table 4.

While the joint J2 laser welded at the heat input higher by approx. 30%, compared to the joint J1, has been slightly deformed, Fig. 9b, Table 4. Most intense deformation can be observed in a case of the joint J3 welded at the highest heat input of 30 J/mm, so twice higher compared to the joint J1, Fig. 9c, Table 4.
Fig. 10. Microstructure of the weld metal of 0.8 mm thick butt joints of electro-galvanized steel sheet DC04, autogenously welded by a disk laser (Table 4); a) J1, b) J2, c) J3, \( \alpha_{pf} \) – polygonal ferrite, \( \alpha_{wf} \) – Widmanstatten ferrite, \( \alpha_{af} \) – allotriomorphic ferrite, \( \alpha_{ac} \) – acicular ferrite.

Fig. 11. Microhardness distribution (profile) across the butt joints of 0.8 mm thick electro-galvanized steel sheet DC04, welded by a disk laser (Table 4).

Width of the HAZ is in a range of 0.2-0.4 mm for the test butt joints. The microstructure in the HAZ is very fine grained. This is a result of metal recrystallization at very rapid cooling rates. The cooling times \( t_{8/5} \) in HAZ were calculated in such a way described in details in the Ref 14. The calculations showed that the cooling time \( t_{8/5} \) in a case of the joint J1 welded at the minimum heat input is extremely short approx. 0.3 s, as given in Table 5. On the other hand the cooling time \( t_{8/5} \) calculated for the joint J3 welded at the highest heat input doesn’t exceed 1.2 s, Table 5. Microstructure of the DC04 steel consists of ferrite with clear segregation shearing lines, which are the result of a plastic deformation during steel coil rolling, Fig. 1,4-6,9,10. Figure 10 shows the microstructure in the fusion zone of the individual butt joints, Table 4. As can be seen, the microstructure of weld metal is also correlated to the conditions of laser welding, thus heat input. Microscopic observations confirmed that the weld metal is free of any imperfections such as porosity, inclusions, or cracks, as widely reported in a case of overlap laser welding of zinc coated car body steel. The weld metal consists of different types and size of ferrite, as shown in Fig. 10. At low heat input of laser welding the cooling rate of weld metal is rapid. Under such conditions the share of acicular ferrite is higher, as can be seen in Fig. 10a. The weld metal of the joint J1, produced at the minimum heat input of 15 J/mm, consists mainly of polygonal ferrite but also significant share of acicular ferrite may be observed, Fig. 10a. The microstructure of the joint J2, produced at higher heat input, is slightly different, Fig. 10b. In this case, beside the polygonal and acicular ferrite, additionally the allotriomorphic ferrite was identified, Fig. 10b. The microstructure is associated with a lower cooling rate, Table 5. Quite different is the microstructure of the weld metal in a case of the joint J3, produced at the highest heat input of

<table>
<thead>
<tr>
<th>Test butt joint</th>
<th>Output laser power, W</th>
<th>Welding speed, mm/min (mm/s)</th>
<th>Heat input, J/mm</th>
<th>HAZ width, mm</th>
<th>Cooling time ( t_{8/5} ), s</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>1000</td>
<td>4000 (66.6)</td>
<td>15</td>
<td>0.37-0.39</td>
<td>0.29</td>
</tr>
<tr>
<td>J2</td>
<td>1000</td>
<td>3000 (50.0)</td>
<td>20</td>
<td>0.4-0.42</td>
<td>0.52</td>
</tr>
<tr>
<td>J3</td>
<td>1000</td>
<td>2000 (33.3)</td>
<td>30</td>
<td>0.45-0.5</td>
<td>1.16</td>
</tr>
</tbody>
</table>
30 J/mm, Fig. 10c. In this case the share of acicular ferrite is significantly lower, Fig. 10c. In addition the size of polygonal ferrite grains is higher, and also the share of Widmanstatten ferrite increased significantly, Fig. 10c.

After measuring the microhardness distribution (profile) across the butt joints found that it is also clearly dependent on the welding conditions, thus microstructure of the weld metal and heat affected zone, Fig. 11. As can be seen in the microhardness graph, the Vickers microhardness measured in the region of base metal is approx. 90-100 HV0.2, Fig.11. In every case the maximum values of microhardness were measured in the region of weld metal (fusion zone FZ). Then, the microhardness decreases gradually from the fusion line (FL) to base metal (BM), in the region of HAZ, Fig. 11.

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of zinc coated steel sheets in butt configuration provides excellent conditions to escape for zinc vapours. Microstructure, microhardness and mechanical performance of the butt joints depend on laser welding conditions, thus cooling rate and cooling times $t_{\text{co}}$. All the test butt joints exhibit excellent tensile strength of the base metal level.

REFERENCES


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