Laser-TIG welding of galvanized steel – numerical and experimental assessment of the effect of arc in various setups

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Abstract. The technology of laser-TIG welding utilizes the arc as a secondary heat source during laser welding. In TIG-leading configuration, the low-current arc precedes the beam to preheat the material. The numerical simulations representing various setups combining laser and arc were performed to study the changes of thermal cycles on the interface of thin metal sheets of overlap joint. The relations between the position of the arc towards the beam, additional heat input, and temperature gradients are discussed. The technology of laser-TIG welding of zinc-coated deep-drawing steel was experimentally applied in the same joint configuration. A good agreement between the calculated and experimental welds was achieved. The arc current less than 40 A did not cause the vaporization, neither oxidation of zinc coating on the interface surface of metal sheets. Nevertheless, the quality of laser-TIG welds was better compared to laser welds. The 40A arc current increased the heat input by about 50% and led to an almost 60% decrease in cooling rate compared to autonomous laser welding. Prolonged heating and cooling time are the key factors of improving the weld quality.

1. Introduction

Galvanized steel is widely used in the automotive industry for body-in-white production. However, laser welding of galvanized steel is still challenging. Welding defects like spatter, blowholes, or inner porosity occurs. Kim et al. [1] demonstrated that the problems of defect formation during laser welding concerns especially overlap joints. In the case of bead-on-plate welding, good-quality welds were produced. The problems originate from a low boiling point of zinc. The vaporized zinc escape from the free material surface to the surroundings before the melting point of steel is reached. During the overlap welding, the zinc vaporizes also from the interface surfaces. The vapor has very limited space and time to exhaust during laser welding in a gap-free configuration. Therefore, some vapor is trapped by the melt pool when the beam penetrates through the interface of metal sheets. As the melt pool heats up, the zinc vapor expands. The zinc bubbles explode through the melt pool and/or escape through the keyhole usually destabilizing it (Norman et al. [2], Pan and Richardson [3]). The liquid metal is ejected from the weld pool and produces spatter, blowholes, and other weld defects (Kim et al. [1], Yang et al. [4], Ma et al. [5]). Yang et al. [6] recommend shielding with the addition of active gas (O₂ and CO₂) to enlarge and stabilize the keyhole so as the zinc vapor could escape through the keyhole. However, this approach modifies weld metal chemical composition determining its mechanical properties. Similar cons appear when welding with interlayer metal foil or powder (Zhou et al. [7]).

Mechanical or chemical methods of removing the galvanized layer expense the production. Effective methods of a larger gap between the sheets (Bley et al. [8], Ozkat et al. [9]) require sheets pre-processing...
and they are often problematic to be implemented in industry. Iqbal et al. [10] proposed a laser-cut kerf for zinc vapor ventilation before the welding itself. However, the kerf surface oxides increase oxygen content in further weld metal (Frostevarg et al [11]). Many other alternative approaches are summed up in Yang et al. [4] or more recently in Wang et al. [12].

Methods of preheating seem more effective. Production time is not increased. Based on the preheating peak temperature, the zinc melts (420 °C) or even evaporates (907 °C) and escape before laser beam impact. The melted zinc oxidizes rapidly. The zinc oxide (ZnO) melting point (1975 °C) is higher than the melting point of steel (about 1500 °C). Thus, it does not negatively affect the melt pool, as proved by Yang et al. [4]. What is more, the coupling efficiency of laser power is higher on oxidized surfaces thanks to the decreased reflectivity (Steen [13]). Thus, a deeper penetration can be achieved.

Only a local preheating is required not to decrease the protective purpose of zinc coating. Tandem laser beams (generated separately or split from the same source) or a laser with a shaped beam (Xie and Denney [14], Gäbler [15]) can be applied. These technologies are very sophisticated and effective. However, special welding facilities and welding heads are required. Laser welding supplemented with arc preheating provides a much cheaper solution. The welding electrode can be fixed to the current laser welding head easily and the power source can be carried by the positioning robot (Šebestová et al. [16]).

Laser-TIG technology combines laser beam with tungsten inert gas (TIG) welding. Although the laser-TIG technology is already known for a few decades, it is still somewhat challenging since the effect of arc is strongly dependent on individual setup and processing parameters. It allows modifying the weld shape, its microstructure, and mechanical properties. The setup is variable. The arc helps to bridge the gap in butt welding. The increase in the total power of welding technology is also beneficial. Therefore, it is a suitable technology for many industries.

In our research, we focus on galvanized thin sheet overlap laser-TIG welding with a low-current arc. Based on the numerical simulations of low-carbon deep-drawing steel welding, we evaluate the effect of position and heat input of arc on thermal cycles on the interface of metal sheets and discuss the possible behavior of zinc coating. Numerical simulations are supplemented with experiments performed with equivalent material. The aim is to distinguish whether the positive effect of arc addition results from the modification of the galvanic layer or from the overall increase in heat input.

2. Method and experimental setup

The technology of laser and laser-TIG welding in TIG-leading configuration were experimentally investigated during overlap welding of cold-rolled galvanized extra deep-drawing steel grade A14 (WSS-M1A365-A14-50G/50G). The average thickness of the zinc coating measured by PosiTector 6000 was 12 µm. The scheme of laser-TIG method and experimental setup are displayed in figure 1.

![Figure 1](image1.png)

**Figure 1.** (a) The scheme of TIG-leading laser-TIG overlap welding and (b) corresponding experimental setup.

The IPG YLS2000 fiber laser was used in our experiments. The laser beam was delivered by a 200µm optical fiber to the Precitec YW30 processing head. It was focused 1 mm under the metal sheet surface.
and reached 0.4 mm spot diameter at the surface. The ABB IRB 2400 robot was used for beam positioning. The Fronius MagicWave 1700 Job TIG power source was employed.

The TIG torch was fixed with a special holder to the laser welding head. It was tilted off 45 degrees towards the beam axis. The cathode with a 2.4 mm diameter was used. The tip of the cathode was placed 2 mm above the upper metal sheet surface and preceded the beam by 2 mm. The sheets with a thickness of 0.9 mm were fixed in the clamping jig in the gap-free configuration.

Argon 6.4 shielding gas, laser power 800 W, and welding speed 20 mm-s\(^{-1}\) were kept constant in the experiments. The applied arc current was 20 A, 30 A, and 40 A. Laser-TIG welds were compared to the laser weld prepared with the same laser power and welding speed (delivered heat per unit length 50 J-mm\(^{-1}\)). Note that the absorbed energy (heat input) is lower than that delivered. It is dependent on the absorption efficiency which is generally lower for arc compared to the laser welding technology.

Further, the autonomous TIG was used in the experimental setup of laser-TIG welding described above. The arc current 40 A and 80 A were applied at welding speed 20 mm-s\(^{-1}\) to evaluate the effect of arc heat on zinc coating oxidation.

3. Numerical simulation of laser-TIG welding

Commercial software ESI SYSWELD was used for transient finite element analysis of laser and laser-TIG welding corresponding to the setup displayed in figure 1a. This software does not provide a complete physical simulation of the welding process. However, it respects the thermal dependency of the physical and mechanical properties of a welded alloy. Concerning moving heat source, it calculates a temperature field in every time step of the simulation. It integrates the metallurgical phase transformations during the heating and cooling and predicts also weld deformations and mechanical properties. Such simulation allows us to estimate the effect of preheating source which is often problematic to be evaluated experimentally, especially in lap joint configuration.

The pre-defined 3D conical model of heat source (figure 2) characterized by power density function of gaussian type (equation (1)) is well adapted to describe thermal load to the material during laser welding. The volumetric power density \(Q\) in a node with coordinates \((x, y, z)\) can be expressed as follows:

\[
Q(x, y, z) = Q_0 \exp\left(\frac{-r^2}{r_0^2(z)}\right)
\]  

(1)

where \(Q_0\) is the maximum value of volumetric power density and

\[
r^2 = x^2 + y^2, \quad r_0 = r_e - \frac{r_e - r_i}{z_e - z_i}(z_e - z).
\]  

(2), (3)

The gaussian parameters \(r_e\) and \(r_i\) are upper and lower cone radius, respectively. The difference \(z_e - z_i\) represents the depth of the melt pool. These parameters should be optimized to achieve the required shape of the weld metal.
Goldak’s double ellipsoidal heat source model (figure 3) is used for TIG welding simulation. This model is built of two ellipsoids placed perpendicular to each other. The model is described by two equations, separately for the front and rear part of the ellipsoid:

\[ Q_f(x, y, z) = \frac{\nu \sqrt{3} f_i Q}{abc_{i} \pi \sqrt{\pi}} \exp \left[ -3 \left( \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c_i^2} \right) \right] \]  

\[ Q_r(x, y, z) = \frac{\nu \sqrt{3} f_i Q}{abc_{i} \pi \sqrt{\pi}} \exp \left[ -3 \left( \frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c_i^2} \right) \right] \]

where \( Q_f \) and \( Q_r \) are the volumetric power density in the front and rear part of the model, respectively, \( Q \) is the total introduced power, and \( a, b, c_i \) and \( c_r \) are the width, depth, and length of the front and rear part of the estimated melt pool, respectively. The parameters \( f_i \) and \( f_r \) characterize the portion of total heat transferred to the front and rear part of the ellipsoid. For more details, see [17] or [18].

3.1. Geometrical model, material, and simulated welding conditions

The geometrical model of the simulated overlap joint is shown in figure 4. The total width of the model is 95 mm. The weld length is 15 mm. The two 0.9mm thick sheets are separated by the 0.05mm gap in the model. It represents a possible air gap that is always present because of sheet surface roughness or and/or dust presence.

Based on the materials available in the database of SYSWELD, the low-carbon deep-drawing steel DC04 was chosen for the simulations. The prescribed chemical composition is concluded in table 1. This steel is equivalent to the alloy used in the experiment. The galvanic layer itself is not included in the model because of its very small thickness (typically up to few tens of microns). Therefore, its effect on the temperature field can be neglected. However, the behavior of possible galvanic layer can be discussed relative to the calculated sheet surface temperatures.

|    | C [%] | Mn [%] | Si [%] | S [%] | P [%] | Al [%] |
|----|-------|--------|--------|-------|-------|--------|
|    | ≤ 0.08 | ≤ 0.4  | ≤ 0.1  | ≤ 0.025 | ≤ 0.025 | ≥ 0.02 |

The effect of beam-electrode distance (BED) and the effect of arc heat input were simulated at constant laser heat input per unit length 33 J-mm\(^{-1}\) and welding speed 20 mm-s\(^{-1}\). Temperature field distribution and thermal cycles of laser-TIG welds are discussed relative to laser weld.

3.2. The effect of TIG position on temperature field distribution during laser-TIG welding
The three different positions (3 mm, 5 mm, and 7 mm) of the electrode towards the beam were simulated at constant arc heat input 17 J mm\(^{-1}\) (arc current 40 A). The thermal analysis for autonomous TIG (17 J mm\(^{-1}\)) was also calculated to compare corresponding thermal cycles. Figure 5 shows the temperature field distributions for different setups at the same time moment.

![Temperature field distribution](image)

**Figure 5.** Temperature field distribution during (a) laser welding and laser-TIG welding with the electrode preceding the beam by (b) 3 mm, (c) 5 mm, and (d) 7 mm; clipping plane given by the beam axis and the trajectory of welding.

The thermal cycles in an axial node on the bottom sheet interface surface (marked with the black arrow in figure 5a) are displayed in figure 6 for laser, TIG, and laser-TIG welds. The autonomous TIG heats up the sheet interface up to 471 °C. The time above the melting point of zinc is 125 ms. The autonomous laser heats the interface from the melting to boiling point of zinc in 18 ms. The arc preheating with 3mm and 5mm BED allows prolonging this time to 74 ms and 171 ms, respectively. The 7mm BED would be sufficient for the zinc re-solidification before the laser passes. Increasing BED decreases both weld fusion and heat-affected zone since the welding processes become more separated.

Based on the thermal cycles, the cooling times \(\Delta t_{8/5}\) (and corresponding cooling rates) in the range 800 °C to 500 °C were calculated. It reached 0.276 s (1086 °C s\(^{-1}\)) for laser weld. The heat of the arc prolonged the \(\Delta t_{8/5}\) to 0.672 s, 0.676 s, and 0.671 s for the BED of 3 mm, 5 mm, and 7 mm, respectively.
**Figure 6.** Thermal cycles of laser, TIG, and laser-TIG welding for different electrode-beam distances at the same arc heat input.

3.3. *The effect of arc heat input on temperature field distribution during laser-TIG welding*

The arc current 40 A, 60 A, and 80 A corresponding to the arc heat input 17 J·mm⁻¹, 26 J·mm⁻¹, and 34 J·mm⁻¹, respectively, were considered for the simulation of laser-TIG welding at constant BED (3 mm). Increasing heat input leads to the transformation of rather a combined laser-arc process into a hybrid process during which only one melt pool is formed (figure 7). The decrease of BED would have a similar effect.

**Figure 7.** Temperature field distribution during laser-TIG welding with arc heat input (a) 17 J·mm⁻¹, (b) 26 J·mm⁻¹, and (c) 34 J·mm⁻¹ at constant BED; clipping plane given by the beam axis and the trajectory of welding.

The width of a weld can be evaluated from the isotherms of peak temperatures on the weld cross-section (figure 8a–c). Increasing heat input increases both the fusion and the heat-affected zone (HAZ) width. The temperature range above the boiling point of steel (about 2862 °C) represents the keyhole formation in the simulation. The calculated keyhole opening is wider at higher arc heat inputs.

Figure 8d displays the effect of arc heat input on the thermal cycle of the node marked with the black arrow in figure 8a (the same node as marked in figure 5a). The cooling times Δt₈/₅ (and corresponding cooling rates reached about 0.68 s (442 °C·s⁻¹), 0.90 s (334 °C·s⁻¹), and 1.16 s (260 °C·s⁻¹) for arc heat input 17 J·mm⁻¹, 26 J·mm⁻¹, and 34 J·mm⁻¹, respectively. The deeper penetration can also be expected since the peak temperature is higher at higher arc heat inputs. As well as the higher preheating temperatures can be reached at the same depth.
Figure 8. The peak temperatures in the perpendicular cross-section in the middle of the weld length for arc heat input (a) 17 J·mm⁻¹, (b) 26 J·mm⁻¹, and (c) 34 J·mm⁻¹, and (d) thermal cycles of the same node for three different arc heat inputs at constant BED.

4. Experimental verification

Unacceptably large depressions and blowholes (up to a third of sheet thickness) of both face and root surface were observed in laser weld. Increasing arc current led to the smoothing of both surfaces of laser-TIG welds (figure 9). The face depression was present also in the case of laser-TIG welds. Nevertheless, it did not exceed 0.1 mm. Increasing heat input led to the widening of both the fusion zone and HAZ. The higher widening was detected in the upper metal sheet.

Figure 9. The macrostructure of A14 overlap (a) laser weld and laser-TIG welds made with (b) 20 A, (c) 30 A, and (d) 40 A; cross-sections perpendicular to the direction of welding.
Laser-TIG welds were free of ZnO on the interface surfaces. However, the ZnO was present in the HAZ of both laser and laser-TIG welds on both the face and root side. Laser-TIG welds exhibited a narrower zone of oxides in the root region compared to laser weld.

Then, the autonomous TIG was applied in the same experimental setup with a disabled laser beam. The arc current 40 A was sufficient to melt the interface surface of the upper sheet, whereas the galvanized layer on the interface surface of the bottom sheet was only tempered. In the case of arc current 80 A, the steel sheets were fused by the melted zinc. Nevertheless, no eye-visible ZnO was present on the sheet interface after breaking the metal sheets apart (figure 10).

Figure 10. Surfaces affected by the autonomous arc (80 A). (a) The face and (b) the interface surface of the upper metal sheet, and (c) the root and (d) the interface surface of the bottom metal sheet. The yellow arrow represents the direction of welding.

5. Discussion
Laser welding is characterized by rapid heating and cooling. In our numerical simulation of laser overlap welding, the heating time (heating rate) and cooling time (cooling rate) in the temperature region 500–800 °C reached 0.014 s (22095 °C·s⁻¹) and 0.276 s (1088 °C·s⁻¹), respectively. The time interval between the melting and boiling point of zinc is only 18 ms on the interface of sheets. During the experiment, such rapid vaporization could destabilize the melt pool and promote the formation of welding defects. Laser-TIG welding in TIG-leading configuration was simulated to discuss the effect of local arc preheating on thermal cycles on the interface of metal sheets in lap joint.

First, the effect of BED was evaluated at constant both laser and arc heat input (33 J·mm⁻¹ and 17 J·mm⁻¹). Increasing BED decreased both weld fusion and heat-affected zone since the welding processes become more separated. The heating time between the melting and boiling point of zinc was calculated. It reached 74 ms and 171 ms for BED 3 mm and 5 mm, respectively. In the air environment, the melted zinc could oxidize producing the ZnO with a high melting point. Slower heating prolongs the time available for zinc oxidation or escape. The autonomous arc (17 J·mm⁻¹) heated up the sheet interface up to 471 °C. The time above the melting point of zinc was 125 ms. According to the welding speed of 20 mm·s⁻¹, the 7mm BED would lead to the re-solidification and/or oxidation of the melted zinc on the interface of metal sheets before the laser passes.

Second, the effect of arc heat input at constant BED (3 mm) is discussed. Increasing heat input increased both weld fusion zone and HAZ. The Δt8/5 reached about 0.68 s, 0.90 s, and 1.16 s for arc heat input 17 J·mm⁻¹, 26 J·mm⁻¹, and 34 J·mm⁻¹, respectively. Corresponding cooling rates were reduced to 442 °C·s⁻¹, 334 °C·s⁻¹, and 260 °C·s⁻¹, respectively. The slower heating and cooling would promote a more fluent escape of the possible zinc vapor from the melt pool.

The isotherm representing the boiling point of steel could represent the keyhole width. However, the process of keyhole formation is more complex and this simulation does not cover complete physical phenomenon (material losses caused by evaporation, the pressure inside the keyhole, melt flow, the effect of shielding gas, etc.).

The values presented above were derived from the linear interpolation of calculated time-temperature data. According to the time step of simulation (23 ms) these values can be subject to relatively large error, especially in the heating period. Nevertheless, the found trends are unambiguous.
Finally, the experiment of overlap laser-TIG welding was performed. The BED was set to 2 mm. The arc was unstable at higher BEDs at low arc currents. Assuming 65% absorption efficiency, the experimental arc current 20 A, 30 A, and 40 A correspond to the arc heat input 9 J·mm⁻¹, 13 J·mm⁻¹, and 17 J·mm⁻¹, respectively. The last mentioned was considered in the simulation. Laser-TIG welds reached a higher quality level compared to laser weld. On the other hand, the increasing arc current led to the widening of both the fusion zone and HAZ. The higher widening was observed in the upper sheet which corresponds to the results of simulations.

The simulation of autonomous TIG welding predicted that arc heat input 17 J·mm⁻¹ should be sufficient to exceed the melting point of zinc on the interface surface of the bottom metal sheet. To validate this presumption, the corresponding experiment was performed. Nevertheless, 40 A did not lead to the melting of the zinc layer in this region. The calculated overheating is probably not sufficient for the phase transformation of zinc. Note that the latent heat of zinc melting is not included in the simulation.

The same experiment was performed at arc current 80 A which was already sufficient to join the metal sheets by the melted zinc. The metal sheets were broken apart to evaluate the formation of zinc oxide on their interface. No eye-visible ZnO (white powder) was present. We assume that the amount of oxygen between the sheets is not sufficient for the melted zinc oxidation, which is in contrast to the observations of Yang et al. [4]. The oxides were present only on open surfaces in the HAZ. The presence of ZnO on the face surface of the upper sheet indicates insufficient argon shielding.

6. Conclusions
Laser, TIG, and laser-TIG overlap welding of low-carbon deep-drawing steel were numerically investigated. We focused on the modification of thermal cycles on the interface of metal sheets by the variation of arc position and heat input and discussed the behavior of the possible zinc coating.

The autonomous low-current TIG does not vaporize the zinc on the interface of metal sheets. It only heats this region slightly above the melting point of zinc. The time for zinc oxidation is very limited. The TIG preceding the beam by 5 mm increases the heating time between the melting and boiling point of zinc almost ten times compared to autonomous laser welding.

Increasing arc heat input at the fixed beam-electrode distance modifies rather a combined process into a hybrid process with one melt pool. We showed that about a 50% increase in heat input leads to an almost 60% decrease in cooling rate compared to autonomous laser welding.

The effect of TIG heat input on galvanized steel A14 laser-TIG lap joints was experimentally verified. The surface defects were reduced compared to laser weld. A good agreement was found between the experimental and simulated weld cross-sections. Although the maximal applied pre-heating itself was sufficient for the zinc melting on the interface surfaces of metal sheets, no ZnO was found here.

The positive effect of TIG addition in our experiments is rather in increased heat input than in the modification of the zinc interface layer by the arc before the laser pass. Reduced both heating and cooling rates result in a less violent, smoother welding process.

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