The formation and control of porosity during laser DP780 dual-phase galvanized steels

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Abstract. DP780 dual-phase galvanized steels with 0.8mm thickness were lap welded by 4kw continuous fiber lasers to investigate the formation of porosity. By observing the welding parameters and recording the welding process with high speed cameras, the formation mechanism of internal porosity and external porosity was proposed. Based on the formation mechanism of porosity, we established the escape channel model of zinc vapor leaving the molten pool during the welding process, by controlling the dynamic balance of the pores of each channel to reduce the welding internal pores and external porosity defects, improve the welding quality.

1. Introduction
Car body lightweight is one of the most important development tendency for vehicle manufacturing, advanced high strength steels (AHSS) is one of the most widely used material in the automotive industry for lightweight and higher qualities. These steel grades include dual phase (DP) steels, transformation-induced plasticity (TRIP) steels, high hole expansion (HHE) steels, complex-phase (CP) steels, martensitic steels (MS), and twining induced plasticity (TWIP) steels [1, 2]. Additionally, these steels are galvanized in order to improve the surface corrosion resistance for automotive parts. However, it is still a great challenge to laser weld galvanized steels in a zero-gap lap joint configuration, since the zinc coatings at the faying interface will vaporize; due to the lower boiling point (907 ºC) of zinc as compared to the melting temperature of steel (above 1500 ºC), causing the highly pressurized zinc vapor to expel the liquid metal out of the weld pool, resulting in spatter on adjacent surfaces in addition to blowholes and pores which dramatically decrease the mechanical properties of the weld [3, 4].

In order to study the influence and kinetics of the molten pool on the hole escape at the keyhole, a large number of scholars have introduced the on-line monitoring means during the welding process. For example, Norman used high speed cameras to observe the zinc vapor on the laser welding process [5]. Panwisa was C established a physics-based model for keyhole welding to simulate keyhole and porosity formation during laser welding of Ti-6Al-4V titanium alloy [6]. Kong applied spectroscopy to study the correlations between the optical emission of the plasma and zinc vapor induced welding defects in the laser welding of galvanized steel for a lap joint configuration [7]. However, there is relatively little research on the laser trapping channel of galvanized sheet laser welding, and the new
steam escape has important influence on the quality of the welded joint. Therefore, it is necessary to study the formation mechanism of porosity of laser welding of galvanized sheet.

In this paper, DP780 galvanized dual phase steels were laser lap welded by 4 kW continuous fiber lasers. The effect of pores on the molten pool was studied. The mechanism of formation of internal porosity and external porosity was explained and analyzed. Based on the analysis of the formation mechanism of porosity, we established the escape channel model of zinc vapor leaving the molten pool during the welding. We used the high speed camera to verify the correctness of the model. We were controlling the dynamic balance of the zinc vapor of each channel to reduce the welding internal porosity and external porosity defects, improving the welding quality.

2. Test materials, equipment and research methods

2.1. Experimental materials
In this experiment, laser welding of galvanized high-strength steel (DP780) with the size of 100×30×0.8mm was conducted. The chemical composition and mechanical properties of DP 780 steel are shown in table 1 and table 2, respectively.

| Table1. Mechanical properties of DP780 galvanized high-strength steel. |
|-----------------|-----------------|-----------------|
| Yield strength  | Tensile strength | Elongation      |
| Re / (MPa)      | Rm / (MPa)      | ψ/ (%)          |
| 500~650         | ≥780            | ≥10             |

| Table2. Chemical composition of DP780 galvanized high-strength steel (wt%). |
|-----------------|-----------------|-----------------|
| C               | Si              | Mn              | P               | S               | Al               |
| 0.094           | 0.140           | 1.990           | 0.0056          | 0.0023          | 0.036            |

2.2. Experimental equipment
The equipment used in this experiment includes KUKA robot laser welding system, high speed camera system, material stretching machine, microscope, laser microscope, high-speed camera and x-ray instrument (figure 1). Fiber laser welding fixed on KUKA robot was applied to weld the high-strength galvanized steel, the welding process was observed by the CR600X2 high-speed camera. The KUKA robot for welding system was composed of 4KW fiber laser, water cooling system, optical path system, robot system, gas protection system and welding head system. The fiber laser with 0.68mm spot diameter was produced by IPG company.

![Figure 1. High speed camera recording during laser welding.](figure1)

3. Observation and analysis of porosity of laser welding of DP780 galvanized steel
The formation of porosity in the weld seam of the galvanized steel sheet was mainly affected by the solubility of the gas in the molten metal, gas partial pressure, temperature, viscosity of the molten pool
and the settling time of the molten pool. The boiling point of zinc is 906 °C, much lower than that of steel. Some zinc vapor escapes outside while the other part keeping the gaseous state enters into the molten pool [7].

It was often accompanied with splash and internal porosity during laser welding of galvanized steel. In order to explore its relationship with the zinc escape and the welding process, a high-speed camera is used to observe the phenomenon. The relevant picture was concluded as follows. A typical pores escape and the formation were recorded by high-speed camera. As shown in figure 2, the process of pores escape was diverse, and it had impact on the welding forming the appearance and internal structure.

![Figure 2. Zinc vapor escape form.](image)

The shape of the zinc vapor escaped the pool in a variety of forms, some of it pooled at the keyhole was like a boiled water, from the keyhole in a pointed mouth, or in a large group of clouds [8]. Laser radiation of zinc vapor completely escaped. Some zinc vapor escaped from the gap between the two plates. When the gap was small, the zinc vapor couldn’t gently escape from the reserved gap, the remaining zinc vapor accumulated at the keyhole were to splashing out and breaking the keyhole to escape. As shown in the following figure 3, (a) (b) (c) shown the external porosity and internal porosity of the welded joint.

![Figure 3. The escape of vapor and formation of pores.](image)
4. Mechanism of porosity formation and dynamic equilibrium of zinc steam escape channel

4.1. Mechanism of porosity formation

When observed the forming the internal porosity, we proposed a new porosity formation mechanism. As shown in the figure 4 and figure 5, zinc vapor led to two parts, the internal porosity and the external porosity. The moving of zinc vapor caused the formation of internal porosity. During the welding process, zinc vapor escaped when the zinc-coating temperature beyond the zinc melting point, before the melting of two-phase steels. Due to the low solubility in the solid, the zinc vapor would move in the direction of the metal liquid behind the melting pool and remained in the welded joint to form the internal porosity after curing.

As shown in figure 6, when the buoyancy of the zinc vapor at the keyhole was greater than the sum of viscosity of the liquid metal and the gravity of the zinc vapor itself, the zinc vapor escaped with the molten metal solution, causing splashing. when the buoyancy of the zinc vapor at the keyhole does not reach the sum of viscosity of the liquid metal and the gravity of the zinc vapor itself, the zinc vapor stayed in the melting pool. The corresponding escape form and process have the following effects on the shape of the welded joint. When the zinc vapor escapes from the molten pool with the molten metal melt, the welded joint would have an external pore defect, and when the zinc vapor fails to escape in time, it would form the internal porosity inside the pool, affecting the strength of welded joints.
4.2. Dynamic equilibrium of zinc steam escape channel

When the reserved gap was small, it couldn’t rule out the zinc vapor through it, causing a large amount of zinc vapor accumulated at the keyhole without being eliminated in time. This led to the result that the buoyancy of the zinc vapor at the keyhole was greater than the sum of viscosity of the liquid metal and the gravity of the zinc vapor itself, splashing at the same time.

From the welding process of High-speed camera, it could be found that zinc vapor escaped from three-channel, as shown below (figure 7).

![Figure 7. Zinc vapor escape three-channel equilibrium diagram](image)

As shown in the figure 7, the zinc vapor accumulated in the keyhole, and the orifice escape direction 1 escaped upward, which was caused by a large number of zinc vapor flow. When the buoyancy of the zinc vapor was greater than the sum of viscosity of the liquid metal and the gravity of the zinc vapor itself, the zinc vapor escaped outside. In this point, when the zinc vapor was more, the zinc vapor to the molten metal out of the pool will form external pores, which has a great impact on the strength and aesthetics of the welded joints.

As to escape direction 1, when the zinc vapor was more, it escaped from the keyhole with a pointed mouth, bringing out the molten metal. At this time, many melt was out of the keyhole, which caused obvious hole on the surface of galvanized sheet, causing welding of external porosity. When the pores moved from the channel 3, there was no escape before the melt was solidified, the zinc vapor remain in the welding joint was formed the internal porosity.

Reserved gap can greatly ease the zinc vapor in the keyhole at the gas pressure, so it was helpful for the entire process of zinc vapor escape dynamic equilibrium that we can control zinc vapor to escape as much as possible from it [9]. When the channel 2 was blocked, the keyhole was prone to welding splash. When the direction of 2 sets a larger gap, Reserved gap enhance the channel 2 of the exhaust capacity, but in this time it was prone to welding incompatibility. Tests have shown that the channel 2 can be controlled by adjusting the reserved gap of the weld to change the formation of the pores. When the Reserved gap was 0 or 0.1mm, the channel 2 was smaller at this time. The zinc vapor was accumulated through the keyhole. It was the limited exhaust capacity of the channel 2. It was occurring serious splash that zinc vapor escape channel failed to dynamic balance. When the galvanized sheet was laser welded at a reserved gap of 0.2-0.25mm, the zinc vapor formed at the keyhole and quickly discharged through the channel 2. At this time, the welding joint was beautiful. zinc vapor was achieve dynamic balance equilibrium. when the reserved gap was greater than 0.3mm, the welding molding was poor, there was not penetration of joint in the situation. At this time welding metal did not quickly fill the welding channel, ausing welding joints subsidence.
When the dynamic equilibrium control of zinc vapor escape channel was better, the process of zinc steam escape was more stable and the porosity was less [10]. As shown in the figures 8, 9, it was the typical diagram of the welded joint what used the zinc vapor escape control.

![Figure 8](image1)

Figure 8. Microstructures of welded joints under dynamic equilibrium and non-dynamic equilibrium conditions. (a) Microstructures at non-dynamic equilibrium conditions. (b) Microstructures at welded joints under dynamic equilibrium.

![Figure 9](image2)

Figure 9. Welded joints under dynamic equilibrium and non-dynamic equilibrium conditions X-ray. (a) Welded joint under dynamic equilibrium conditions x-ray equilibrium. (b) Welded joint under dynamic equilibrium conditions x-ray equilibrium.

During the test, the welding process parameters of control zinc vapor in the three-channel escape to achieve dynamic balance was conducive to the effective escape of zinc vapor. Experiments showed that when the size of the reserved gap value effectively controlled the escape of zinc vapor with the reserved gap of 0-0.1mm, the welding channel 2 was seriously blocked resulting a large number of zinc vapor gathered in the keyhole, the increasing of pressure, zinc vapor splashed out of molten metal. When the reserved gap was 0.2mm-0.25mm, the three-channel escape process to achieve dynamic balance, the zinc vapor was better to escape, so the welding joint shape was better and no splash occurred. When the reserved gap was greater than 0.3mm, it appeared welding incompatibility, because the molten pool of metal was not enough to set aside the gap.

5. Conclusions
Through the above experimental study and analysis, we draw the following conclusions:

(1) This paper presented the formation mechanism of internal porosity and external porosity. The formation mechanism of the internal pores was that the zinc vapor always moves toward the metal liquid with greater solubility. The formation mechanism of the external porosity was that the zinc vapor dynamic equilibrium of the molten pool was broken, then the buoyancy of the zinc vapor at the keyhole reach the sum of viscosity of the liquid metal and the gravity of the zinc vapor itself, showing outward splash or escape.

(2) summarized the three channels of welding zinc vapor escape, through reserve gap to adjust the controlled affect the zinc vapor channel to achieve dynamic balance, adjusted to the zinc vapor can
effectively escape the molten pool, so that the welding joints of the external porosity and internal porosity reduced, thus enhance the welding quality, improve the welding appearance.

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References
[1] Pouranvari M and Marashi 2013 Science and Technology of Welding and Joining 18 361–403
[2] Ma J 2013 Experimental and numerical studies on the issues in laser welding of galvanized high-strength dual-phase steels in a zero-gap lap joint configuration (Dallas: Southern Methodist University) p 3
[3] Volpp J 2017 Production Engineering 11 9–18
[4] Atabaki M M, Ma J, Liu W and Kovacevic R 2015 Materials & Design 67 509–21
[5] Norman P, Eriksson I and Kaplan A 2009 Proc. on FORCE Technology (Copenhagen) pp 24–6
[6] Panwisawas C, Perumal B, Ward R M, Turner N, Turner R P, Brooks J W and Basoalto H C 2016 Acta Materialia 126 251–63
[7] Kong F, Ma J, Carlson B and Kovacevic R 2012 Optics & Laser Technology 44 2186–96
[8] Huang L, Chen X Z and Zheng H Z 2016 Journal of Shanghai Jiaotong University 50 121–4
[9] Chen Z, Yang S, Wang C, Hu X, Shao H and Wang J 2014 Journal of Materials Processing Technology 214 1456–65
[10] Stützer J, Zinke M and Jüttner S 2017 Welding in the World 61 351–9