Zinc-coated steels are increasingly used in the automotive industry due to their excellent corrosion resistance and long-term mechanical performance. However, it is still a great challenge to weld zinc-coated steels in a gap-free lap joint configuration. When zinc vaporizes at 906°C, which is much lower than the melting temperature of steel (1300°C), a high-pressure vapor will be generated at the faying interface of the steel sheets. If the zinc vapor is not appropriately vented out, a weld discontinuity such as porosity is usually produced in the weld and spatter is expelled from the weld.

In this paper, a new laser welding process is proposed to join zinc-coated steels in a gap-free lap joint configuration. The new process uses a suction device to create a negative pressure zone (relative to ambient) directly above the molten pool. The purpose of this negative pressure zone is two-fold. First, a drag force is generated due to the external suction device, which can counterbalance the shear force induced by the erupting zinc vapor. Secondly, the negative pressure zone facilitates the zinc vapor to escape along the suction direction. As a result, the molten pool becomes more stable and the keyhole will remain open to allow the escape of zinc vapor. With vacuum assist, welds free of spatter and porosity can be obtained. In addition, mechanical properties of the welds are evaluated by tensile shear test and microhardness measurements.
(GTAW) preheating technique to weld zinc-coated, high-strength, dual-phase steels in a gap-free lap joint configuration where GTAW preheating leads the laser beam and simultaneously moves with the laser beam. With the GTAW preheating, a portion of the zinc along the weld line at the interface of metal sheets is vaporized and part of the zinc is transformed into zinc oxide, which has a melting point (above 1900°C) greater than that of steel. Under these welding conditions, a completely defect-free weld in the zinc-coated steels was achieved. Furthermore, Yang et al. (Ref. 23) optimized the shielding conditions to stabilize the molten pool, thus achieving a constantly open stable keyhole. The stable keyhole provides a channel that allows the zinc vapor to escape from the interface of the metal sheets. Consequently, the molten pool is not disturbed by the zinc vapor and the formation of spatter and porosity in the welds is eliminated. Gu et al. (Ref. 25) utilized a remote laser welding technique with a high scanning speed called laser dimpling to create a dimple prior to welding, which provides a gap for the subsequent laser welding of the zinc-coated steels. Sound welds were obtained with this laser dimpling technology. In addition, Kim et al. (Ref. 24) developed a CO₂ laser microplasma arc hybrid welding to weld zinc-coated steels.

Although the aforementioned methods can address the issues arising from the welding of the zinc-coated steels in a lap joint configuration, there exist some limitations, such as high cost for implementation in the automotive industry. In order to reduce the cost and cycle time, the automotive industry looks for simple and flexible laser welding techniques, using a single laser beam to weld the zinc-coated steels in a gap-free lap joint configuration. Therefore, it becomes necessary to develop a new laser welding technique which can flexibly weld zinc-coated steels in a gap-free lap joint.

In this study, a 4-kW fiber laser was used to weld the zinc-coated steels. A suction device was developed to create a negative pressure zone directly above the molten pool. The presence of the negative pressure zone had two effects: The first was to help the generated zinc vapor to escape along the suction direction, and the second was to maintain the molten pool stability. In addition, tensile shear and microhardness tests were carried out to assess the weld mechanical properties.

**Experimental Setup**

The materials used in this study were zinc-coated dual-phase (DP590) steels. The zinc coating was hot dipped at a level of 60 g/m² per side. The tested coupons had the following dimensions: 120 × 85 × 1 mm. The two metal sheets were then tightly clamped together during the laser welding process so that there was no joint clearance. The overlap length between the two metal sheets was 25 mm, and the laser beam was located at the center of overlap. The lap-shear samples did not contain the start and stop of the welds. The laser welding process was performed with a 4-kW fiber laser. A multimode laser beam was brought into the laser welding head by an optical fiber and focused on the top surface of the workpiece. The laser spot diameter at focus was 0.3 mm. A high-speed camera with a frame rate of 4000 fps was used to record images of the laser-induced plasma in order to study its dynamic behavior. During the laser welding process, the laser beam was focused on the top surface of the two-sheet stack up. The experimental setup is shown in Fig. 1. The suction device used in this study was an AirStar vacuum cleaner with bag made by Philips (Model: HomeCare-FC8224), which has an input power of 1400 W and a maximum vacuum level of 29 kPa. A copper tube of 8 mm in diameter was connected to the cleaner to provide a negative pressure zone above the welding pool. It was positioned 3 mm in front of the laser beam and 6 mm from the top surface of the workpiece. In addition, the lap joint coupons were sectioned, ground, polished, and etched for hardness measurements and examination using an optical microscope. Vickers microhardness tests were conducted using a load of 100 g and a dwell time of 10 s.

**Results and Discussion**

Issues from laser welding of zinc-coated steels in a gap-free lap joint configuration are below.

Figure 2 shows the characteristics of typical laser welds in zinc-coated steels. As shown, a large amount of spatter and porosity are produced in the welds. It is well known that the highly pressurized zinc vapor is the root cause of these weld defects. When spatter is produced and expelled along the laser beam propagation direction, coupling of the laser beam energy to the workpiece is impeded resulting in only partial penetration (Fig. 2B) being achieved, even at high power levels. In addition, a turbulent molten pool is always observed due to the large difference in the velocity and pressure between the zinc vapor and the liquid melt. The instability of the molten pool manifests itself in the form of waves, which are generated on the molten pool with the associated swelling and troughs. Under these welding conditions, the laser beam is projected onto the uneven surface of the molten pool. This phenomenon is equivalent to changing the...
position of focus, the spot size, and the focus location of the laser beam, i.e., the laser beam intensity will be distributed unevenly at the spatial and temporal dimensions.

Figure 3A and B schematically demonstrate the different mechanisms of the absorption of the laser beam when the keyhole is unstable and stable, respectively. The absorption of the laser beam for the case of a stable keyhole is dramatically improved through multireflection within the keyhole. In contrast, the uneven surface of the turbulent molten pool causes a majority of the laser beam energy to be reflected. When the laser beam is projected onto the surface of the zinc-coated steel, the zinc is immediately vaporized as a result of the low boiling point of zinc. Furthermore, a large amount of time varying laser-induced plasma and plume is always produced during the laser welding process (Ref. 25).

Previous studies have found that the laser-induced plasma and plume fluctuates in a high frequency and changes its shape and size over time during the welding process (Refs. 11, 25). The uneven surface of the molten pool along with the fluctuating laser-induced plasma and plume deteriorates the coupling efficiency of the laser beam energy into the welded materials. Consequently, the keyhole size and depth changes during the laser welding process and is forced to collapse due to an insufficient power density of the incident laser beam into the workpiece. When the keyhole collapses or the keyhole depth can’t reach the faying interface, the zinc vapor pressure at the faying interface becomes lower than the threshold value after the zinc vapor is released during the turbulent period. Then as the pressure builds up over time to a point where the vapor is emitted from the molten pool, the cyclic nature of the molten pool turbulence is explained. This area of study requires further research.

Vacuum-Assisted Laser Welding of Zinc-Coated Steels

In the current body of work, a new method, vacuum-assisted laser welding, is proposed and developed for the welding of zinc-coated steels in a gap-free lap joint configuration where a vacuum system is integrated with the laser system. As shown in Fig. 1, a copper tube connected to the vacuum system is positioned directly in front of the laser focal point. During the laser welding process, the drag force produced by the vacuum system can be adjusted with a change in the pressure level within the vacuum system.

Figure 5 shows the initial experimental results, which exhibit neither spatter nor porosity in addition to full penetration. The main reason for achieving sound welds by the vacuum-assisted laser welding process is that a stable and open keyhole can be consistently created, which in turn, provides a stable channel for the zinc vapor to escape. For the conventional single laser beam welding of zinc-coated steels, a large shear force is always present and acts upon the molten pool resulting from the competing forces induced by the upward and lateral moving, unstable zinc vapor and the downward acting laser-induced plasma. Under this large fluctu-
ing shear force as the zinc vapor pressure builds, and subsequently releases, the molten pool becomes dramatically unstable and the keyhole tends to collapse. With the vacuum-assisted laser welding of zinc-coated steels, the leading vacuum system guides the laser-induced plasma and plume toward the welding direction, which provides an external force, i.e., a drag force, to counter-balance the shear force acting on the molten pool surface resulting from the zinc vapor.

Figures 6 and 7 illustrate this mechanism. The removal of the laser-induced plasma and plume enhances the coupling
efficiency of the laser power into the weld. Furthermore, a negative pressure zone is created directly on the top of the molten pool when a vacuum system is used during the laser welding process. This suggests that the pressure level in front of the laser beam is always the lowest. The difference in the pressure level of the highly pressurized zinc vapor and that around the copper tube facilitates the zinc vapor to escape toward the lower pressure zone, i.e., the suction direction. Thus, the applied force on the surface of the molten pool from the zinc vapor and laser-induced plasma is reduced. Under these welding conditions, the molten pool remains stable and the coupling of laser power into the workpiece is consistent. As a consequence, the keyhole is stable and remains open during welding for the zinc vapor to escape.

Real-Time Monitoring of Laser-Induced Plasma and Plume

A high-speed camera was used to study the dynamic behavior of the laser-induced plasma. In this case, the illuminating green laser light was not used. Figure 8 presents successive top view images of the laser-induced plasma and plume taken by the high-speed camera. Figure 8A–F indicate the typical characteristics of the laser-induced plasma plume including weld spatter for conventional laser welding and Fig. 8G–M demonstrate the typical characteristics of laser-induced plasma plume with no weld spatter for vacuum-assisted laser welding. As shown in Fig. 8A–F, the laser-induced plasma and plume are highly dynamic and demonstrate rapid change in their shape and size over a short time. Because of the strong force the plasma and plume induce on the molten pool, the molten pool is severely disturbed and becomes very unstable when the laser-induced plasma and plume fluctuate in a large angle with respect to the top surface of the workpiece. Furthermore, changes in the shape and size of the laser-induced plasma and plume influences the coupling efficiency of the laser beam energy into the workpiece. As a consequence, the keyhole is unstable, and its depth and shape are changed. When the keyhole depth does not reach the faying interface of the two metal sheets or is collapsed, the highly-pressurized zinc vapor can’t find a channel to escape, and it expands inside the molten pool. Consequently, a large amount of liquid metal is expelled from the molten pool and spatter is observed, as shown in Fig. 8A. In contrast, the size and shape of the laser-induced plasma and plume are very stable when the vacuum system is applied. As can be seen in Fig. 8G–M, the laser-induced plasma and plume are guided by the vacuum system toward the direction of suction, and their shape and size exhibit little change over time.

The stability of the laser-induced plasma and plume facilitates coupling of the laser beam energy uniformly into the welded materials. Thus, the keyhole depth and shape do not vary dramatically, which helps the zinc vapor to escape from the interface. It is observed that when the vacuum system is applied, the weld penetration is nearly the same at different locations of the weld. Figure 9 presents a set of six sequenced images of the keyhole and molten pool recorded by a high-speed camera using an illumination light during the vacuum-assisted laser welding. These images clearly show that the shape and size of the keyhole vary within a small range, and the keyhole is maintained open during the entire sequence.

The improved stability achieved by vacuum-assisted laser welding can be explained from an energy point of view, by the fact that the suction device improves the molten pool/keyhole stability thereby reducing the effects of defocusing and absorption of laser-induced plasma and plume on the laser beam energy. Figure 10 schematically shows the improved laser beam transmission to the workpiece. According to the Beer-Lambert Law,

\[ I(Z) = I_0 e^{-\alpha Z} \]  

where \( I \) is the laser beam energy absorbed by the workpiece, \( I_0 \) is the incident laser beam energy, \( \alpha \) is the absorption coefficient of laser-induced plasma and plume, and \( Z \) is the height of the laser-induced plasma and plume. From Equation 1, it is found that changes in the height of the laser-induced plasma and plume are associated with changes in the shape and size of the laser-induced plasma and plume, which alters the amount of laser beam energy transferred to the workpiece. As shown in Fig. 10, the vacuum-assisted laser welding process has a lower height of laser-induced plasma and plume of \( Z_2 \) than that of \( Z_1 \) produced in the conventional laser welding process.

Previous studies have found that the absorption coefficient of laser-induced plasma and plume is relative to the temperature and electron density. The higher the temperature and electron density, the higher the absorption coefficient and recombination index of the laser-induced plasma and plume (Refs. 27, 28). When using the suction device, the plume is quickly diluted and removed, i.e., the electron density is reduced and the value of laser-induced plasma and plume absorption is reduced. As a consequence, the vacuum-assisted laser welding process has a lower value of \( Z \) than that in conventional laser welding.

Based on Equation 1 and considering the constant incident laser beam energy, the laser beam energy absorbed by the
laser-induced plasma and plume during vacuum-assisted laser welding process is lower than that produced in conventional laser welding process. In addition, the laser beam could be defocused by the laser-induced plasma and plume during the laser welding process. As shown in Fig. 10A, the incident laser beam spot is enlarged due to the refractive effect of the
laser-induced plasma during the conventional laser welding process. However, the defocusing effect of the laser-induced plasma and plume is reduced during the vacuum-assisted laser welding process, as shown in Fig. 10B. Based on the above analysis, the coupling efficiency of the laser beam energy is improved by vacuum assisted laser welding in comparison to conventional laser welding.

**Tensile Tests**

Tensile shear testing was carried out to determine the peak load, which is used as a measure of strength for base and weld metals. Three tensile test specimens were machined from the same weld for both the vacuum-assisted and without applied vacuum conditions, both of which were welded under the same conditions. The average value was used to compare the vacuum-assisted laser weld strength to that of the single laser weld strength. The load-bearing area of the weld was assumed to be the weld length at the faying interface as measured on polished cross sections. For the base metal, its tensile strength is 0.78 kN/mm, as calculated from the peak load divided by sample width. All of the vacuum-assisted laser welds fractured in the heat-affected zone (HAZ) adjacent to the base metal. Figure 11B shows the characteristics of a typical fracture in a sample produced by vacuum-assisted laser welding. The average maximum tensile strength of the vacuum-assisted laser weld was 0.77 kN/mm. Similar to the previous studies (Refs. 22, 23), the weld strength achieved by the vacuum-assisted laser welding process approaches that of the base metal. However, the laser welds obtained by regular laser welding fractured in the weld zone under tensile loading resulting in an average strength of 0.51 kN/mm. The formation of weld defects such as the porosity degraded the weld strength. Figure 11C shows that when deep porosity was present in the weld, cracking first initiated along its edge and then propagated into the base material.

**Microhardness Tests**

Microhardness tests were also conducted across the weld using a 100-g load and 10 s holding time. Figure 12 shows 1) the relative position of the hardness measurements, and 2) the microhardness distribution profile for a typical vacuum-assisted weld. As is typical for steel, the highest hardness value is within the weld zone due to a quenching effect following the laser welding process. The hardness value in the weld zone was relatively uniform. Furthermore, the hardness values decreased from the weld zone, through the HAZ and to the base metal. The lowest hardness value was located in the region close to the base metal. No internal porosity was found in the welds, which is similar to the results obtained by the previous studies (Refs. 22, 23).

**Conclusions**

Experiments for zinc-coated steels were conducted by vacuum-assisted laser welding. The conclusions of this study can be summarized as follows:

High-quality, gap-free lap joints in zinc-coated steels can be obtained by using a vacuum-assisted laser welding process. This is achieved because a stable and open keyhole can always be produced when the suction is turned on. Therefore, the highly pressurized zinc vapor can be vented out through the open keyhole.

Aside from the zinc vapor itself, the laser-induced plasma and plume are key factors that influence the stability of the laser welding process. When using a single laser beam, the shape and size of the laser-induced plasma and plume fluctuate at a high frequency. This imposes a large force on the molten pool and results in a turbulent molten pool. A large amount of liquid metal is squeezed out of the molten pool and spatter is observed when laser-induced plasma and plume vibrate at a large angle.

The laser-induced plasma and plume are guided by the vacuum system and move
along the suction direction, which also helps to stabilize the molten pool. Vacuum-assisted laser welding can also have a higher coupling efficiency of the laser beam than that of the conventional laser welding.

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