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LASER OVERLAP WELDING OF Zn-COATED STEEL ON ALUMINIUM ALLOY FOR PATCHWORK BLANK APPLICATIONS IN THE AUTOMOTIVE INDUSTRY

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Abstract. The new generation of cars have to fulfil the strict regulations regarding fuel consumption and gas emission. Thus, lightweight structures are becoming an increasingly critical target in the car body design. At the same time, other indispensable design obligations, such as safety, ride quality and affordability, also have to be met. Tailor welded blank (TWB) and welded patchwork blank techniques have been extensively used in the automotive industry as an effective way of weight reduction and stiffness improvement. TWBs capacitate further weight and strength optimisation in design by integrating sheets of different materials with different thicknesses and/ or coatings into one part. Local reinforcement with welded patchwork blanks also contributes to the weight reduction and crashworthiness of the car body. The laser welding of tailored and patchwork blanks made of galvanised steel and aluminium is widely used in the automotive industry. The weld between Zn-coated steel and aluminium commonly suffers from defects such as spatter, cavity and crack. The vaporisation of Zn is commonly known as the main source of instability in the weld pool and cavity formation, especially in a lap joint configuration. Cracks are mainly due to the brittle intermetallic compounds growing at the weld interface of aluminium and steel. This study provides a review on the main metallurgical and mechanical concerns regarding laser overlap welding of Zn-coated steel on Al-alloy and the methods used by researchers to avoid the weld defects related to the vaporisation of Zn and the poor metallurgical compatibility between steel and aluminium.

1. INTRODUCTION

Automakers around the world have focused their efforts on developing cars with lightweight structures to reduce the energy consumption and environmental impact of vehicles. In 1964 the concept of tailor welded blank (TWB) was introduced to the automotive industry, as a new way of manufacturing body panels, in order to reduce the weight of structures and improve the body stiffness [1,2]. TWBs enable designers to include different sheets of different thicknesses and material characteristics into one part, prior to forming, to optimise their design for weight and strength [3].

TWBs became more attractive to the automotive industry when the laser welding process was introduced in the 1980s [2–4]. The significant advancements in laser sources and systems, over the past few decades, have evolved laser welding to an indispensable manufacturing process in the automotive industry [2,5,6]. Laser welding has been increasingly used for tailored blank applications because of its benefits such as high welding speed, high precision, low heat input and ease of automation [6–10]. CO_2 and Nd:YAG laser were traditionally the welding processes mainly used for TWB applications [3]. However, over the past few years, fibre laser has evolved as the automakers' prime

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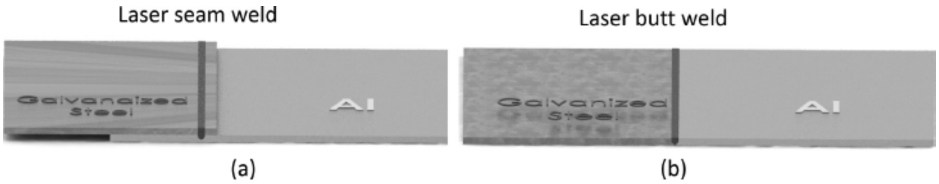

Fig. 1. Schematic of (a) laser welded patchwork blank and (b) laser welded tailored blank.

choice for welding applications because of its high power, excellent beam quality and high energy efficiency [2,11,12].

Galvanised steels have been extensively used in exposed car body panels to increase corrosion resistance [13,14]. The thickness of zinc-coating, in galvanised steels, is usually less than 10 μm on each side of the steel. Occasionally, steels with a coating thicker than 20 μm have been used for improved protection [15,16]. Currently, laser butt and lap welding of Zn-coated steels are broadly used in the automotive industry for tailored and patchwork blank applications [15–18].

The vaporisation of Zn due to its low boiling temperature (906 °C) is the main issue reported during the laser welding of galvanised steel. The vaporisation is particularly problematic in lap joint setups because of the restriction of Zn vapour venting [3,13,14]. The intense pressure of Zn vapour within the keyhole can cause an unstable and violent flow of the melting pool, resulting in the formation of spatter, cavities and craters [19–21].

TWBs of aluminium alloy and Zn-coated steel have been considered as a cost-effective solution to the car body mass reduction and to the increase of the structure strength [8]. Galvanised steels are also used for reinforcement purposes in patchwork blanks [2]. The laser welding of Zn-coated steel to Al has been studied by many researchers [13,14,17,22]. However, it is still very difficult to achieve a defect-free and high-strength weld. The difficulties arise from the differences in the thermo-physical properties of the two base metals and the formation of brittle intermetallic compounds (IMCs) because of poor miscibility and solubility of steel and aluminium.

Brittle IMCs can reduce the weld strength by inducing cracking in the weld [23]. In the current study, the above-mentioned challenges are explained and their effects on the weld quality and strength are discussed. This study also provides an overview of the approaches proposed by different researchers to minimise the adverse effects of the pre-mentioned challenges and to improve the strength and quality of the weld between galvanised steel and Al alloy.

2. TAILOR WELDED BLANKS AND PATCHWORK BLANKS

Tailor welded blanks (TWBs) are made of two or more sheet metals, with different thicknesses, shapes, mechanical properties and/or coatings that are butt-welled together prior to forming [2,24,25]. TWBs are increasingly used with rather complex designs to minimise the weight and to optimise the engineering properties and cost of car body panels [3,6,26]. Another type of tailored blank is called patchwork blank which is commonly used for local reinforcement applications in the auto-body structures. A welded patchwork blank is made of one or more pieces of reinforcing sheet metal (patches) lap-welded onto the mainsheet. A comparison between laser welded patchwork and tailored blanks is schematically shown in Fig. 1.

Currently, laser welding is the most often used welding process for TWBs and welded patchwork blanks [24,25,27]. Some of the various applications of TWBs and patchwork blanks include the reinforcement of rails and pillars, inner door panels, cross-rail bumpers, floor panels and wheel housings [2,24,28]. The main applications of TWBs and patchwork blanks are illustrated in Fig. 2.

3. LASER LAP WELDING OF Zn-COATED STEEL ON AL ALLOY

To increase the corrosion resistance and durability of car body panels, Zn-coated steel sheets, galvanised or galvannealed, are increasingly used in the automotive industry [30]. The demand for environmentally friendly cars has made the manufacturers to reduce the overall weight of the vehicles. For this purpose, steel parts in the car body structures are progressively replaced with Al alloys [31]. However, making an all-aluminium car may not be a feasible solution due to the affordability concerns and because of the poor formability and insufficient fracture resistance of Al products [8,32,33]. The combination of Zn-coated steel and Al is a promising alternative to meet the design requirements in terms of safety, pollution and cost. Recently, the lap welding of Zn-coated steel on Al has been com-

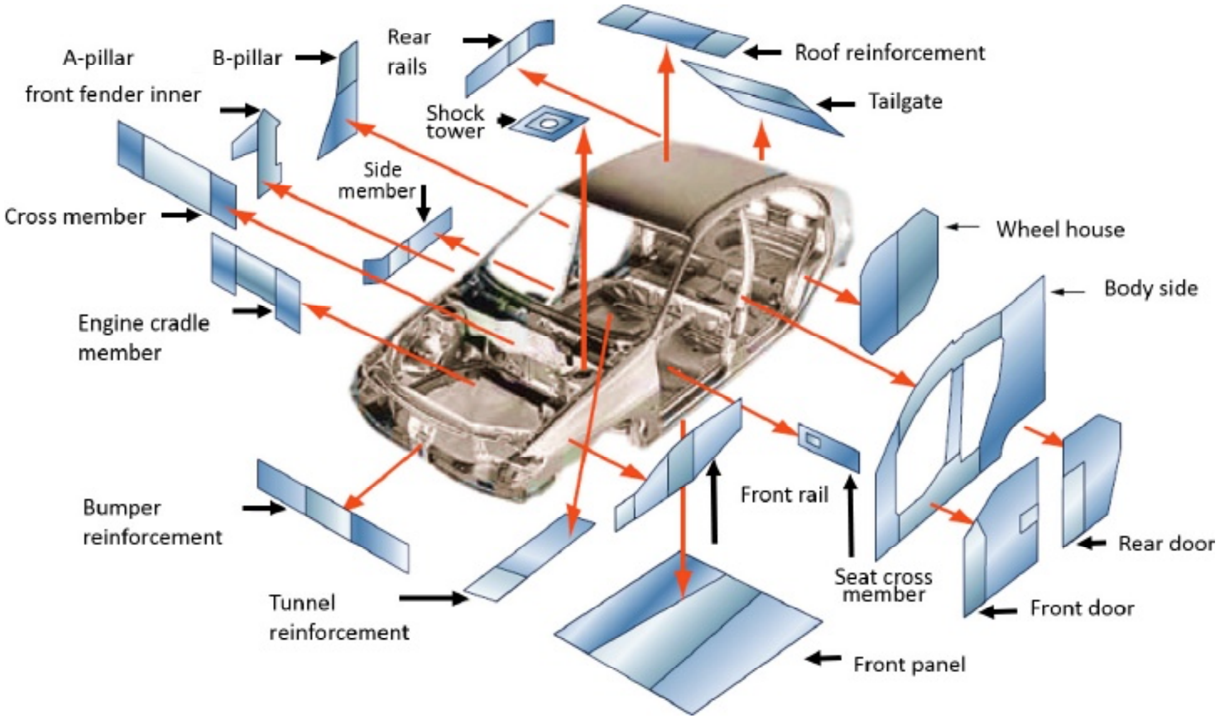

Fig. 2. The main applications of tailor welded blanks and patchwork blanks in a car-body, reprinted with permission from ArcelorMittal Tailored Blanks, Merelbeke, Belgium, www.arcelormittal.com.

monly used for the manufacture of car doors [10,15]. Laser welding is the most preferred process in the automotive industry because of its high speed, low heat input and ease of interface with robots [15,30].

Laser has been studied by many researchers for overlap welding of Zn-coated steels with Al alloys [13,14,17,22] or un-coated steel on Al alloys [7,32,34–39]. Despite successful achievements in the laser welding of Zn-coated steel on Al in lap joint setup, producing a defect-free weld can be still very challenging, especially under high welding speeds [8]. The formation of defects, such as porosity, spatter and the brittle intermetallic compound (IMC) layer at the weld interface are the main issues concerning the laser welding of Zn-coated steel on Al alloy [32,40,41].

During the laser welding of Zn-coated steel on Al, Zn vapour causes instability in the melting pool, resulting in spatter, porosity and crater defects [19–21]. The vaporisation of Zn is almost inevitable because the boiling point of Zn (906 °C) is considerably lower than that of Al (2520 °C) and Fe (1538 °C) [8].

Different approaches have been suggested in the literature to reduce the porosity occurring in the laser lap welding of Zn-coated steels. Milberg et al. [13] proposed the use of a bi-focal hybrid laser which combines an Nd:YAG laser with a high power diode laser to increase the robustness of laser welding. Pre-drilling vent holes along the welding line was suggested by Chen et al. [15] and Gualini et al. [42]. Chen et al. [15] claimed that the vent hole method allowed a proper outflow of Zn vapour. Moreover, a considerably strong weld was produced by the riveting mechanism. The rivet-shaped weld produced in this experiment can be seen in Fig. 3.

Li et al. studied the use of a commercial purity Al foil between the frying surfaces of Zn-coated steel.

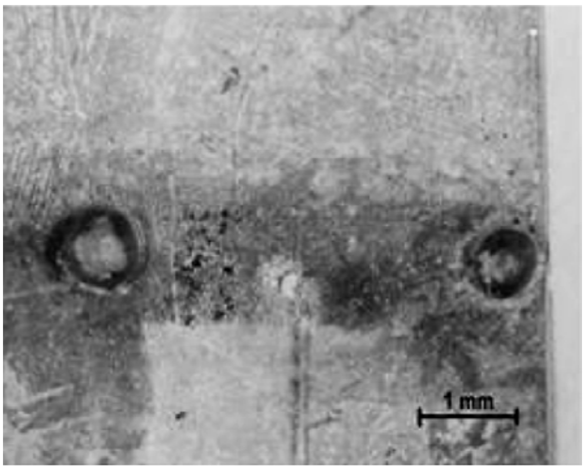

Fig. 3. Laser lap-welded sheets using vent hole produced rivet-shaped welds (welding parameter: 1.5 kW CO_2 laser, 7.62 m/min), reprinted with permission from W. Chen, P. Ackerson and P. Molian // Mater. Des. 30 (2009) 245, (c) 2009 Elsevier.

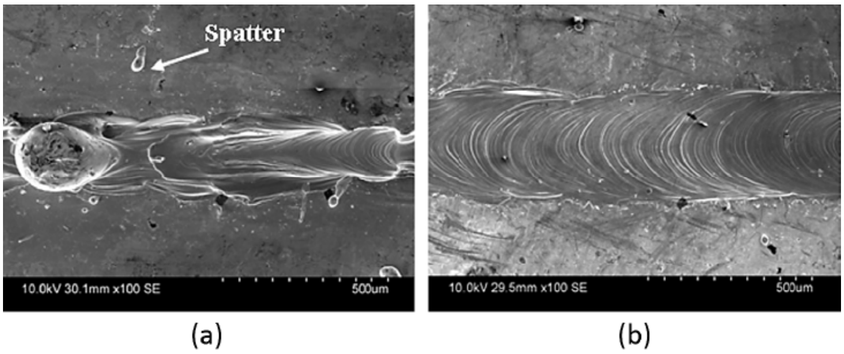

Fig. 4. Comparison between weld appearances produced from (a) a single pass and (b) double pass fibre laser welding with N_2 shielding gas, (first pass welding parameters: 650 W, 100 mm/s, f.p.p. of 0 mm, second pass welding parameters: 200 W, 75 mm/s, f.p.p. of +2 mm), reprinted with permission from H.C. Chen, A. J. Pinkerton, L. Li, Z. Liu and A.T. Mistry // Mater. Des. 32 (2011) 495, (c) 2011 Elsevier.

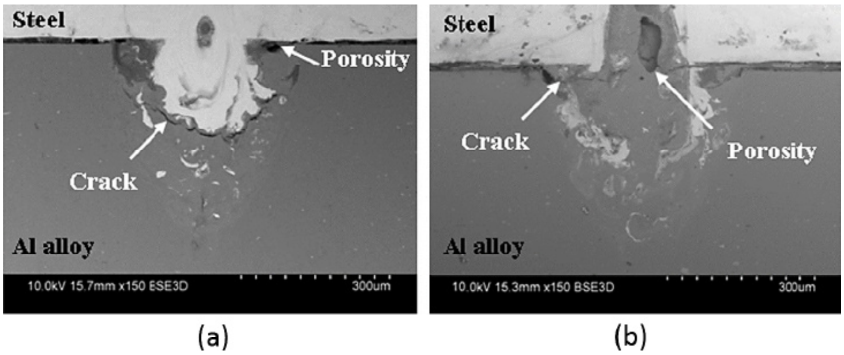

Fig. 5. Backscattered electron image of the cross-section of the weld made using laser double pass welding with (a) Ar gas and (b) N_2 gas, (first pass welding parameters: 650 W, 100 mm/s, f.p.p. of 0 mm, second pass welding parameters: 200 W, 75 mm/s, f.p.p. of +2 mm), reprinted with permission from H.C. Chen, A. J. Pinkerton, L. Li, Z. Liu and A.T. Mistry // Mater. Des. 32 (2011) 495, (c) 2011 Elsevier.

They used Al foil as a process stabiliser in high-speed keyhole welding. The test was based on the hypothesis that the reaction between Al and Zn prevents the evaporation of Zn by forming Al-Zn which has a higher boiling point than Zn and remains in the crevice. It was claimed that the addition of Al foil resulted in a considerable improvement in the stability of welding and a significant reduction in porosity [14].

Amo et al. [20] and Graham et al. [43] proposed keeping a gap between the surfaces to be welded to let the evaporated Zn escape from the gap. Amo et al. [20] reported a successful weld without any cracks or porosities, using a gap opening of no more than 0.1 mm. However, this method may not be proper for production environments [30].

Chen et al. [10] tried the use of double pass laser welding with a defocused beam. Welding was performed in the first pass with a focused laser beam, and then a defocused beam was applied for the second pass. Double pass welding was performed using either Ar or N_2 as a shielding gas. The weld pool was reported unstable and spatter was observed with both the Ar and N_2 gases. According to this experiment, applying a second pass weld with a defocused laser beam improved the weld appearance, shown in Fig. 4.

A higher risk of porosity has been found to exist when a higher density gas is used, because the gas is more likely of being trapped in the keyhole and the weld after solidification [44]. However, Chen et al. [10] reported porosity and crack in the weld produced with double pass laser welding using either N_2 or Ar gas, without any obvious relation between the type of gas used and the porosity found in the weld samples, seen from Fig. 5.

Ma et al. [8] proposed two-pass laser welding for producing a lap joint between Zn-coated high-strength steel and Al alloy. For the first pass, they used a defocused laser beam to preheat the components and to partially melt and vaporise the zinc coating of the galvanised steel sheet. Then, welding was performed with a focused beam in the second pass. They reported that a defect-free lap joint with partial penetration was produced with the use of two-pass laser welding. They also stated that the

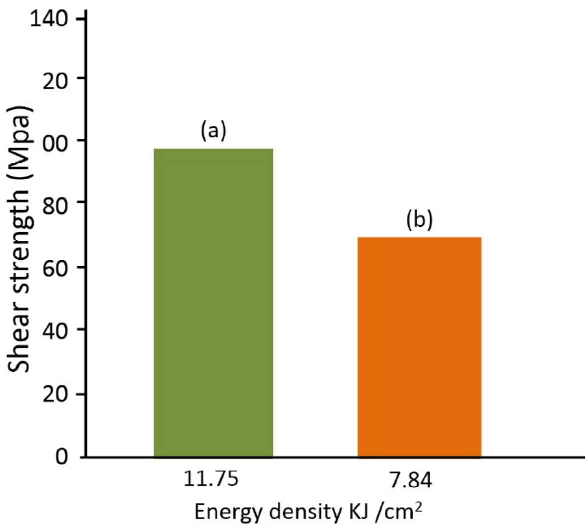

Fig. 6. Shear strength of the laser welded lap joint between low-carbon galvanised steel and AA2024 aluminium alloy using fibre laser (spot diameter: 13 mm, power density: 4.52 kW/cm^2, (a) travel speed: 0.3 m/min, (b) travel speed: 0.45 m/min), reprinted with permission from S. Meco // Int. J Adv. Manuf. Technol. 67 (2013) 647, (c) 2012 Springer.

process was very stable and almost no spatter, crack or blowholes were present in the welds.

As was mentioned before, another concern in welding Al and steel is the growth of brittle Fe–Al intermetallic compounds (IMCs) within the welds as a result of poor solid solubility of the Fe element in Al [7,31,34]. IMCs consist of ductile Fe-rich and brittle Al-rich phases. FeAl and Fe_3Al belong to Fe-rich phases, whereas Al-rich phases include $FeAl_2$, Fe_2Al_5, $FeAl_3$, and Fe_4Al_{13} [35,45–47]. Brittle Al-rich IMCs have a deteriorative effect on the mechanical performance of the weld and can induce cracks within the fusion zone [31]. The type and morphology of IMCs are highly dependent on the type of steel and aluminium alloy; even small variations in the melting temperature, the fluidity of the molten pool, solute diffusivity and thermal conductivity can affect the kinetics of intermetallic phase formation [32].

Ozaki et al. [45] proposed laser roll welding to reduce the effect of IMCs. This method combines a CO_2 laser and a roller compressing the frying surfaces of the Al alloy and Zn-coated steel to be welded. The idea behind this technique was to minimise the formation of brittle IMCs by shortening the heat cycle and increase the heat transfer rate between the contacting surfaces under pressure. They produced a weld with a maximum shear strength of 162 N/mm when the welding speed was 8.3 mm/s and the roller pressure was set to 150 MPa. They also reported that the shear strength declines when the thickness of the IMC layer exceeds 10 μm. It has also been reported that when the thickness of the IMC layer is less than 10 μm the specimen under a shear test fails in the base, not in the weld [45,48,49].

Meco et al. [31] studied the use of fibre laser for the conduction welding of Al to Zn-coated steel in overlap configuration. They stated that using conduction mode laser welding enabled them to control the heat input and thereby control IMC formation. They also reported that shear strength in the Zn-coated steel and Al joint was higher when a higher energy density was used, seen in Fig. 6. This could be contrary to the assumption that a higher heat input can increase the formation of IMCs and cause degradation in the mechanical strength of the weld [10]. They concluded that mechanical strength is not solely dependent on the thickness of the IMC layer. Instead, a combination of the intermetallic layer thickness and its composition, the orientation of IMCs, as well as bonding and diffusion between the elements can affect the mechanical strength [31].

Chen et al. [10] reported a considerable reduction in IMCs as a result of using N_2 shielding gas in the fibre laser welding of Zn-coated steel on Al alloy. They also noticed lower variations in hardness in the fusion zone when N_2 gas was used which can also indicate less IMC formation. They stated that a higher shear strength was obtained with N_2 gas than with Ar, observable in Fig. 7. This can be attributed to the higher thermal conductivity of N_2 compared to Ar that can increase the cooling rate of the melt pool during laser welding. The increased cooling rate can reduce the extent of heat flow and diffusion activity in the melt pool. Thus, the base materials will be mixed in a limited degree and the growth of IMCs will be obstructed, leading to even more hardness distribution and improved shear strength [50]. The reactivity of N_2 plasma with Al can also be beneficial in limiting the extent of Al-rich intermetallic phases, particularly in laser keyhole welding. The reaction between the vaporised Al and ionised N_2 leads to the formation of aluminium nitride AlN [10,44 51] in the weld in replace of Fe–Al intermetallics [10].

Ma et al. [8] claimed that controlled preheating and welding parameters during double-pass laser welding of Zn-coated steel and Al, can limit the thickness of Al-rich IMCs to around 5 μm. They found that too much heat input during preheating can entirely remove the Zn-coating which makes the weld prone to the formation a Fe–Al layer. They declared that a lower heat input during the welding process

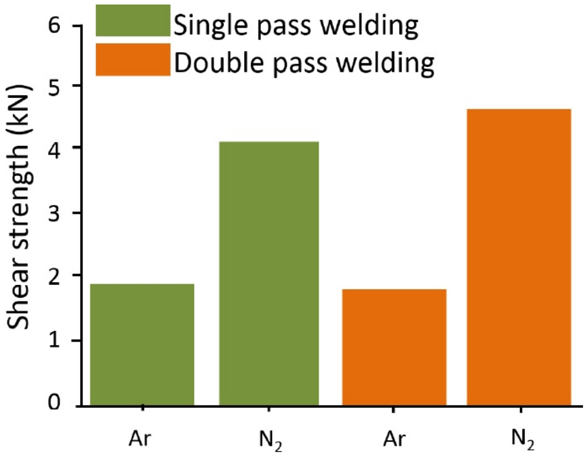

Fig. 7. Comparison between the effect of Ar and N_2 shielding gases on the shear strength of the laser welded lap joint of Zn-coated steel (DX54) and Al alloy (5754), using either single pass or double pass fibre laser (first pass welding parameters: 650 W, 100 mm/s, f.p.p. of 0 mm, second pass welding parameters: 200 W, 75 mm/s, f.p.p. of +2 mm), reprinted with permission from H.C. Chen, A. J. Pinkerton, L. Li, Z. Liu and A.T. Mistry // Mater. Des. 32 (2011) 495, (c) 2011 Elsevier.

resulted in a higher shear strength. They also claimed that the presence of Zn in the IMCs could improve the strength of the welded lap joint between Zn-coated steel and Al.

Corrosion resistance is a principal requirement of the welded joint between Zn-coated steel and Al. The corrosion resistance of the weld can be mainly affected by microsegregation, the growth of intermetallic phases, loss of Zn due to vaporisation and defects [52,53]. The degradation of corrosion performance can occur within the fusion and heat-affected zones due to intergranular corrosion and segregation or the growth of a secondary phase [10,53,54]. It is known that inert gases with a higher density can provide better protection over the melt pool against oxidation and loss of alloying elements [15]. It has been reported that weld samples made with Ar shielding gas showed better corrosion resistance than with N_2 gas [10]. This can be due to the higher density of Ar that protected the base metals more efficiently against oxidation [10]. Generally, the prevention of the weld defects and smoothness of the weld surface can be considered as an effective way to improve the corrosion resistance of the weld [10,53,55].

4. CONCLUSIONS

In this study the application of tailor welded blanks (TWBs) and patchwork blanks in the weight reduction and reinforcement of car-body panels was explained. The main issues associated with the laser lap welding of zinc-coated steel on aluminium, which is commonly used in patchwork blank applications for the manufacture of car bodies were discussed and different approaches presented in the literature to avoid these issues were reviewed. The main conclusions are:

Pre-drilling vent holes along the welding line can let the Zn vapour to escape and eliminate the risk of porosity in the weld. Keeping a gap between the surfaces to be welded can be another solution for venting Zn vapour. A more practical solution would be using a defocused laser beam to partially remove the Zn layer and to preheat the top surface, followed by second-pass welding with a focused laser beam.

Higher heat input can expedite the growth of brittle intermetallic compounds (IMCs). Generally, a higher mechanical strength of welds has been achieved when the thickness of the brittle IMC layer has been less than 10 µm. Besides the thickness of the IMC layer, other factors such as the composition and orientation of IMCs, as well as bonding and diffusion between the elements may be determining the weld strength. Double pass welding with optimised parameters for preheating and welding can be a workable solution to the formation of a brittle IMC layer.

The use of N_2 as a shielding gas can have beneficial effects as to the formation of brittle IMCs, thereby improving the weld strength. This may be due to the higher thermal conductivity of N_2 compared to Ar as well as the likeliness of reaction between N_2 plasma and Al vapour to form aluminium nitride instead of Al-rich IMCs.

The type of shielding gas can have influence on the corrosion resistance of the weld. Inert gases with higher density can protect the molten pool against oxidation which may benefit the corrosion resistance performance of the weld.

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