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Impact of inter-sheet gaps on laser overlap welding performance for galvanised steel

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ABSTRACT

For overlap joints with different galvanised sheet combinations, the inter-sheet gap size and range control under different conditions were experimentally studied, and the factors affecting the inter-sheet gap range were examined. The application of a δ control method to laser welding of car door parts was explored. The results indicate that the formation and strength of weld joints initially improve and then worsen as the inter-sheet gap increases. The inter-sheet gap for different types of sheet combinations has a specific range, the value of which is related to the sheet thickness, weld pool width, welding speed, and laser beam parameters. Further, the consistency of the size of δ along the entire welding bead can be maintained by using a subsection welding method. Application of the conditions identified here, in combination with optimal technological parameters, can facilitate the high-quality welding of auto-body parts.

1. Introduction

Laser welding of galvanised steel sheets in an overlap joint configuration is commonly used in the automotive industry. Technical problems arise when galvanised steel is laser welded in a zero-gap overlap joint configuration because the boiling point of Zn (906 °C) is well below the melting point of steel (1530 °C). Highly pressurised Zn vapour is easily generated on the faying surface of two metal sheets during welding. The Zn vapour vents out through the weld pool and results in the formation of blowholes, spatter, and lack of fusion, which dramatically reduce the weld strength, degrade the corrosion resistance, and affect the aesthetics of the weld seam, the overlap structure and gap size of which directly affect the welding quality.

To resolve these issues, several techniques have been proposed during the past decade. Wu et al. (2008) note that rebound deformations of auto-body parts tend to occur during stamping, and therefore, the overlap joint of two parts has a certain gap size even under the action of a clamping force. In addition, gaps tend to appear between the upper and lower sheets during overlap welding owing to the particular surface states of the auto-body parts, clamping force, fixture clamping method, and welding heat accumulation. These gaps significantly affect the formation and mechanical properties of auto-body weld joints. In galvanised steel welding, Zn vapour is prone to evaporation during welding because of its relatively low boiling point. Assuming that there is no gap in the overlap configuration, the vaporised Zn is pressurised until it meets a keyhole. Qin et al. (2012) reported that in deep penetration laser welding, a thin capillary, called a keyhole, is generated in the welded material at high laser beam intensities (>10^6 W/cm^2). Formation of the keyhole enhances absorption of the laser energy and facilitates the release of Zn vapour. Ribolla et al. (2005) and Chen et al. (2013a) found that the Zn vapour then damages the weld zone and creates blowholes in the seam, resulting in poor surface quality, reduced strength, and inferior corrosion resistance. Schmidt et al. (2008) reported that degassing of the Zn vapour through the molten material cannot be counterbalanced by rapid frequency modulation of the laser power and negatively affects the weld seam quality. To avoid weld defects caused by the highly pressured Zn vapour, several methods have also been introduced that create an escape for the Zn vapour generated during welding: Chen et al. (2009) used a pulsed Nd:YAG laser to create vent holes on the bottom steel sheet, and Gu and Shulkin (2011) used a laser to create humps at the faying surfaces. Iqbal et al. (2007, 2010) used a precursor beam to cut a slot along the joint line for welding of galvanised steel. Chen et al. (2014) adopted a suction device to provide a negative pressure zone on the surface of the keyhole to allow the highly pressurised Zn vapour to escape, and Gu (2011) reported the use of a laser dim-

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ple method to make a certain gap, which results in a good weld seam. Using a fillet joint welding configuration can also mitigate the problem of Zn expansion, but it requires edge tracking devices. Further, Zhang et al. (2012) used a 'sandwich' method to weld zinc-coated steel. However, all the approaches mentioned above require a pre-welding procedure that increases either the technical difficulties or the production cost. To avoid these potential drawbacks of the pre-procedures, alternative methods were proposed to mitigate the presence of Zn vapour during welding. Ma et al. (2012) used low-speed laser welding to create a larger molten pool, which would allow the Zn vapour an easier escape path from the weld pool. Xie and Denney (2001) split the laser beam into two beams for the welding of galvanised steel. Ma et al. (2013) proposed two-pass laser welding of overlapped galvanised steel; in the first pass, a defocused laser beam is applied to melt and vaporise the Zn coating at the faying surface, and in the second pass, a focused laser beam is applied to perform the welding. However, these processes could not satisfy the requirements in actual auto body production. Mei et al. (2009) found that with suitable gaps, the welding process is stable, and the weld surface quality is good. There are no welding defects, e.g. blowholes and spatters. Conversely, inappropriate gap control induces many weld defects during welding and can decrease the weld quality or even prevent melting–welding connection. If the gap is small, the escape of Zn vapour is unfavourable, resulting in an unstable welding process and poor weld appearance. If the gap is too large, the two parts cannot melt and therefore cannot be welded together. For auto-body galvanised steel sheets, because of the effects of vaporisation of the Zn coating, there are strict requirements for overlap weld joints regarding the shape and dimension of the auto-body stamping parts as well as the welding fixture. In particular, the gap between the overlap sheets should be rationally controlled both for quality assurance and to ensure that the Zn vapour can escape. Therefore, the inter-sheet gap δ between welding specimens is an important parameter that affects the welding quality and is also a key factor in auto-body welding.

To the best of the authors' knowledge, there is no reported systematic analysis of the impact of inter-sheet gaps on welding performance during auto-body laser welding. In many of the works that focus on laser overlap welding of galvanised steel sheets, the inter-sheet gap method has been employed to eliminate the impact of the rapidly expanding Zn vapour. However, these works have all used a specific inter-sheet gap (δ), without any discussion of the criteria for selecting this value or any systematic analysis of the impact of gaps on weld quality. A preliminary analysis of the gap size as a key factor was conducted previously by the authors' team, but a comprehensive and systematic analysis of the factors that affect gap control has not been performed. To this end, this paper aims to study the impact of inter-sheet gaps on auto-body welding performance, to analyse key factors that affect the gap setting, and to derive the range of values of the inter-sheet gap under different conditions. The purpose of this study is to provide theoretical guidance and to serve as a practical reference for addressing technical issues in laser welding of auto bodies.

2. Experimental materials and methods

The experimental materials include 0.8-mm-thick and 1.2-mm-thick DC56D galvanised steel sheets along with 2.0-mm-thick DP780 high-strength galvanised steel sheets, which have been used in car door parts. The chemical components and mechanical properties of these sheets are given in Table 1. First, the sheets are cut into specimens 60 mm × 30 mm in size using a CO_2 laser.

The major technological parameters of deep-penetration laser overlap welding include the laser power (P), welding speed (v), defocusing amount (Δf), shielding gas flow (q), and inter-sheet gap (δ). To obtain an optimal set of these parameters, a five-factor and five-level [$L_{25}(5^5)$] orthogonal test is designed. On the basis of these parameters, the inter-sheet gaps are varied to analyse the impact of gap size on welding performance. The sizes of the optimal and maximum inter-sheet gaps are studied to identify various sheet thicknesses and weld pool widths that yield joints that meet the weld joint appearance requirements and have the correct mechanical properties. To simulate different inter-sheet gap scenarios, in-house fixtures and a standard feeler gauge are used to control the gap size in the experiments. In addition, gap-varying laser overlap welding experiments are conducted using different combinations and the same sheet. Fig. 1 shows the rationale and setup of the inter-sheet gap experiments. To ensure that the gap between two overlapping sheets is consistent and homogeneous after clamping by the fixture, two pieces of feeler gauge of the same size as the gap are placed between the two sheets that are under the clamping force. The sheet combinations used in the experiments and the corresponding technological parameters are given in Table 2.

The experimental equipment includes a YLR-4000-ST2 fibre laser, a DC025 slab CO_2 laser, a robot, and a laser processing machine (Figs. 2 and 3). The maximum power output of the fibre laser is 4.0 kW (continuous output) with a peak wavelength of

Table 1
Chemical components and mechanical properties of galvanised steel sheets.

No.	Material mark	Material thickness (mm)	Yield strength (MPa)	Tensile strength (MPa)	Chemical components (mass fraction, %)					
					C ≤	Si ≤	Mn ≤	P ≤	S ≤	Others ≤
1	DC56D+Z 45/45-FD-O	0.8 1.2	120–180	270–350	0.01	0.01	0.30	0.025	0.020	0.215
3	DP780+ZF 30/30	2.0	400–590	≥780	0.20	0.80	2.5	0.035	0.030	–

Table 2
Laser welding technological parameters.

No.	Combination	Weld pool width (mm)	Laser welding parameters				
			P (kW)	v (m/min)	Δf (mm)	q (L/min)	δ (mm)
1	1.2-mm DC56D 1.2-mm DC56D	1.0	2.0	1.7	−0.4	15	0.2
		1.5	1.6	1.1	0	10	0.3
		2.0	2.0	0.8	+0.4	15	0.3
2	0.8-mm DC56D 0.8-mm DC56D	1.0	2.0	1.7	+0.4	15	0.15
		1.5	1.6	1.1	+0.4	15	0.25
5	2.0-mm DP780 2.0-mm DP780	–	4.0	2.5	−1.0	15	0.2