Optics Communications 402 (2017) 147–158

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Influence of laser beam incidence angle on laser lap welding quality of galvanized steels

Lifang Mei [a,b,*], Dongbing Yan [a,c], Genyu Chen [d], Zhenhui Wang [a], Shuixuan Chen [a]

[a] College of Mechanical and Automotive Engineering, Xiamen University of Technology, Xiamen 361024, China
[b] Fujian Key Laboratory of Advanced Design and Manufacture for Bus & Coach, Fujian 361024, China
[c] Fujian Collaborative Innovation Center for R&D of Coach and Special Vehicle, Fujian 361024, China
[d] College of Mechanical and Vehicle Engineering, Hunan University, Changsha 410082, China

ARTICLE INFO

Keywords:
Laser lap welding
Galvanized steel
Incidence angle
Influencing factor
Performance

ABSTRACT

Based on the characteristics of laser welded structural parts of auto bodies, the influence of variation in laser beam incidence angle on the lap welding performance of galvanized auto-body sheets was studied. Lap welding tests were carried out on the galvanized sheets for auto-body application at different laser beam incidence angles by using the optimal welding parameters obtained through orthogonal experiment. The effects of incidence angle variation on seam appearance, cross-sectional shape, joint mechanical properties and microstructure of weldments were analyzed. In addition, the main factors influencing the value of incidence angle were investigated. According to the results, the weld seams had a good appearance as well as a fine, and uniform microstructure when the laser beam incidence angle was smaller than the critical incidence angle, and thus they could withstand great tensile and shear loads. Moreover, all tensile–shear specimens were fractured in the base material zone. When the laser beam incidence angle was larger than the critical incidence angle, defects like shrinkage and collapse tended to emerge, thereby resulting in the deteriorated weldability of specimens. Meanwhile, factors like the type and thickness of sheet, weld width as well as inter-sheet gap all had a certain effect on the value of laser beam incidence angle. When the sheet thickness was small and the weld width was narrow, the laser beam incidence angle could be increased appropriately. At the same time, small changes in the inter-sheet gap could greatly impact the value of incidence angle. When the inter-sheet gap was small, the laser beam incidence angle should not be too large.

Introduction

Advances in automotive technology have constantly put forward new requirements for the auto-body material, connection structure and connection performance, which increased the difficulty in the welding of auto-body parts [1,2]. Due to the inability of conventional welding processes to meet the changing requirements on auto bodies, they are gradually replaced by new techniques [3]. Furthermore, laser welding technology is increasingly valued owing to its advantages such as high energy density, fast welding, small heat-affected zone and abilities to improve auto-body strength, stiffness, assembly precision as well as safety performance. It has been widely applied to auto-body welding and fabrication and has become a major welding process for the new generation auto-body manufacturing [4,5]. Therefore, the weld seam quality of laser lap welding, as the most widely used form of laser welding in the auto-body application, can directly affect the performance of auto bodies [6]. In real auto-body welding process, the welding head often interferes with fixtures or structural parts due to the impacts of the welding heads' structural shapes, auto-body parts and fixtures. Thus, the welding cannot be achieved if the welding head is not deflected, as shown in Fig. 1. If the welding head deviates at a certain angle from the vertical direction, the interference problem can be well solved. However, the vertical incidence of laser beam onto the workpiece surface during welding cannot be ensured, thereby producing a laser beam incidence angle. When the laser beam strikes at a certain angle of inclination, the spot area and laser reflectivity acting on the workpiece surface will be changed and the power density will be reduced, which may affect the welding quality. Therefore, incidence angle is an important factor that influences the laser welded structural parts of auto bodies. Hence, it is of great practical value to analyze

* Corresponding author at: College of Mechanical and Automotive Engineering, Xiamen University of Technology, Xiamen 361024, China. Fax: +86 592 6291386.
E-mail address: meilifang0804@163.com (L. Mei).

http://dx.doi.org/10.1016/j.optcom.2017.05.032
Received 18 March 2017; Received in revised form 5 May 2017; Accepted 14 May 2017
0030-4018/

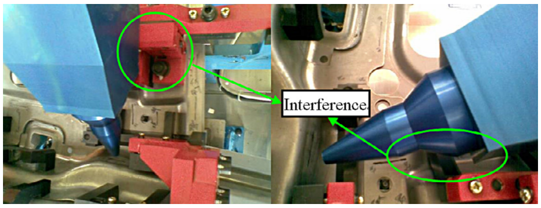

Fig. 1. Interference of welding heads with fixtures and parts.

the influencing law of laser beam incidence angle variation on the galvanized sheet welding quality and to explore the value range of incidence angle under different factors.

Scholars have carried out some researches on the influence of laser beam deflection angle on the laser processing quality. For instance, Korean scholars have studied remote laser welding with DISK laser, with the result suggesting that continuous penetrating welds can be obtained when the angle of laser beam incidence is less than or equal to 20°; and when the angle is larger than 25°, the welds will be discontinuous [7]. Chen et al. discuss the influence of incidence angle on the laser butt welding performance of high-strength steels. They believe that the quality of butt welded specimens is good when the laser incidence angle is less than 40°; and when the angle is larger than 40°, single-sided welds will be formed on the back seams [8]. Meanwhile, they also investigate the effect of incidence angle on the laser cutting quality, which indicates that the increase of beam incidence angle will lead to the increase of reflection and the decrease of laser energy actually input into the workpiece material. Changes in the laser beam incidence angle will give rise to the variation in slit width. When the incidence angle changes within a range of 20°, its influence on cut surface roughness is very small; while when the incidence angle exceeds 20°, the cut surface will be severely burnt, which will significantly increase the roughness and bring about very poor cutting quality [9]. In addition, according to the report of Liao et al. on the effects of laser beam energy and incident angle on the pulse Nd:YAG laser spot welding of stainless steel thin sheet, as the laser energy rises, the penetration depth, bead length and bead width of the welded spot will increase as well. However, as the laser incident angle rises, the penetration depth and the bead width will increase, while the bead length will decrease. The results illustrate that the shape and size of the welded spot depend not only on the laser energy, but also on the incident angle of laser beam [10]. Liu et al. explore the influence of laser beam incidence angle variation on material absorptivity during laser bending process [11]. Their results show that when the workpiece with absorbing layer is scanned for multiple times with laser, the laser absorptivity will be improved because of the enlarged incidence angle at the deformed part. Meanwhile, the laser power will be reduced by the enlarged spot area, due to which the laser energy factors acting on the workpiece surface will be changed. This is the primary cause of bending angle variation. Furthermore, Li et al. analyze the temperature field of high reflection film induced by long-pulse and short-pulse lasers under different irradiation angles [12]. Azhikannickal et al. use the (of) thermal imaging to characterize laser light reflection from thermoplastics as a function of thickness, laser incidence angle and surface roughness. As a result, they find that the reflection not only decreases slightly with the increasing thickness, but also decreases with the increasing incidence angle within the range of the studied angles [13]. With the application of fiber laser, Suvradip et al. report the effect of laser incidence angle on the cut quality of 4 mm-thick stainless steel sheet [14]. Dong et al. analyze the effects of different laser beam incidence angles on the surface hardening effect, with a conclusion drawn that the larger the incidence angle is, the shallower the hardened layer under the same laser hardening process parameters will be. Nonetheless, the width of the quench hardened layer increases gradually [15]. Khan et al. adopt an on-vertical configuration (A: 15°–30°–45°) of the laser beam with respect to the material surface to generate combined pre-and-post-heating areas, which for the weld material experiences less severe heating and cooling rates. As a result, they find that increase in beam incident angle results in shallower weld penetration and shorter minimum crack-path, and the beam incident angle is to be around its limiting value of 15° [16]. The incidence angle is also used for precision laser treatments to improve outcomes. Lutey et al. propose a new method for pulsed laser profiling of grinding wheels based on a pre-specified incidence angle and radial laser progression or predicted single-pass incision depth, with a conclusion drawn that the laser incidence angle is found to have a profound effect on the resulting incision, both in terms of material removal rate and final profile accuracy [17]. Above studies mainly focus on the impacts of beam incidence angle on the quality of laser cutting, forming as well as hardening processes, and analyses on the quality of laser welding also concentrate primarily on butt welding and remote welding. However, the effects of laser beam incidence angle on the lap welding quality of galvanized steel sheets are seldom studied or systematically reported both. In the early research of major factors influencing the laser lap welding of galvanized steels, the effects of different inter-sheet gaps on the laser welded seam performance were preliminarily analyzed by our team [18]. On this basis, the influences of different laser beam incidence angles on the seam appearance quality, cross-sectional shape, joint strength as well as hardness and microstructure of weldments were systematically studied in this research, so as to explore the influencing law of laser beam incidence angle on the welding performance of galvanized steels. Meanwhile, the value range of incidence angle was investigated under different thicknesses of the same sheet, different sheets with the same thickness, different initial weld widths and inter-sheet gap conditions. In this way, the major factors influencing the size of incidence angle can be analyzed.

1. Equipment and methodology

DC025 CO_2 slab laser (ROFIN, Germany) and five-axis laser processing system (Prima, Italy) were used in the tests. The maximum power output of the CO_2 laser was 2.5 kW (continuous or pulse output), with a peak wavelength of 10.6 m and an output mode of TEM00. What is more, the beam divergence half-angle was α<0.15 mrad, the focusing lens was selenium arsenide lens with a focal length of $f = 127$ mm, and the focal spot diameter was 0.4 mm.

The test materials included DC56D galvanized steel sheets with thicknesses of 0.8 mm and 1.2 mm used for certain door parts as well as DP780 high-strength galvanized steel with a thickness of 1.2 mm. Their chemical compositions and mechanical properties were listed in Table 1. Firstly, the sheets were cut into specimens of 60 mm×30 mm with laser.

To ensure the consistent gap between two sheets in the welding of auto-body parts and improve the welding quality, seams were generally arranged on the plane, as given in Fig. 2. For the sake of conducting the comparative analysis on the mechanical properties and microstructure of specimens at different incidence angles easily while saving the cost of specimens, plate specimens were employed in this paper to simulate the lap joint welding mode of auto-body parts. The major technological parameters of deep-penetration laser overlap welding included the laser power (P), welding speed (v), defocusing amount (Δf), shielding gas flow (q) as well as inter-sheet gap (δ). To obtain an optimal set of these parameters (See Table 2), a five-factor and five-level [$L_{25}(5^5)$] orthogonal test was designed. Then based on these parameters, the laser beam incidence angles were varied to analyze the influence of angle size on welding performance. The size of the critical laser beam incidence angle was also studied to identify various sheet thicknesses and weld pool widths that met the weld joint appearance requirements and had the correct mechanical properties. According to the welding characteristics of auto-body structural parts, lap welding was adopted in the tests, and specimens were clamped with welding fixtures. Since