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Coaxial monitoring of the fibre laser lap welding of Zn-coated steel sheets using an auxiliary illuminant

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ABSTRACT

In the laser welding process, weld defects are often caused by many factors, such as variations in the laser power, welding speed and gaps between two workpieces. In an auto-welding system, the on-line monitoring of the welding quality is very important in avoiding weld defects. In this paper, an on-line coaxial monitoring system with an auxiliary illuminant was built for the fibre laser welding of galvanised steel; images of the weld pool were taken during the welding process. Profiles of the weld pool and the keyhole were obtained by processing the images using the region-growing algorithm and the Canny algorithm. In this research, we used the on-line monitored weld pool width to monitor the weld surface width. The weld penetration status was divided into the three categories of incompletely penetrated, moderately penetrated and over-penetrated using the value of d (diameter at the bottom of the keyhole)/D (diameter at the top of the keyhole). Thus, the weld width and weld penetration status of fibre laser welding can be monitored on-line.

1. Introduction

Due to the rapid development of the automobile industry, laser welding technology plays a more important role in the manufacturing of component cover engine parts, transmission parts, alternators, solenoids, fuel injectors, fuel filters and air conditioning equipment. The attraction of using laser welding for these applications include the ability to weld precision components with a high speed, no contact, a restricted heat input and minimal distortion, especially for thin-walled assemblies and for the optimisation of the compactness of a component. A primary concern in the industry is the ability to detect weld defects rapidly, reliably and cost-effectively. Therefore, on-line inspection systems have been developed to improve the welding quality and to reduce overall costs by monitoring the acoustic, optical, visual, thermal and ultrasonic behaviour of the laser welding process [1–3]. Additionally, the geometric parameters of the keyhole and the melt pool contain useful information, which can be used to inspect the welding quality. Researchers are searching for highly desirable solutions to diagnosing the laser process quality, using these behaviours to understand, in particular, the relation between the behaviour and welding quality characteristics.

At present, the on-line monitoring of the CO_2 and YAG laser welding phenomena, such as the plasma characteristics and the dynamic behaviour of the melt pool, has proven effective in monitoring the welding quality. In 1995, V. V. SemakIn et al. [4] studied the dynamics of the melt pool and the keyhole during CO_2 laser welding using high-speed video photography and the laser reflectometer technique. Some scholars have studied the relation between the plasma that is produced during the laser welding process and the welding quality. J. Bruncko et al. [5] considered the laser welding of thin sheets (1.5 mm) of austenitic steel using a continuous-wave CO_2 laser. Their results showed that a typical laser-induced plasma spectrum emitted strong emission rays when the welding process was off-balance. T. Sibillano et al. [6] built a system based on spectroscopic techniques to monitor laser welding processes and implemented an on-line algorithm for both the calculation of the plasma electron temperature and an analysis of the correlations between selected spectral lines. In 2012, T. Sibillano et al. [7] used this system for the on-line monitoring of the joint penetration depth during stainless steel welding procedures that were performed with CW CO_2, CW fibre and pulsed Nd:YAG laser sources. Li, Zhiyong et al. [8] used a new hollow probe method to collect radiation from specific points within the arc plasma. The results showed that laser–MIG hybrid welding processes cause the plasma energy to focus at the centre of the welding arc and approach the welding pool. A.R. Konuk et al. [9] used an optical collimator to collect the optical emission with a fast spectrometer. Additionally, the authors studied the welding quality of overlap welds in AISI 304 stainless steel sheets that were created by both CW Nd:YAG and CO_2 lasers according to the electron temperature. Jun Wang et al. [10] studied the oscillation

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period of the plasma during fibre laser welding using high-speed video. The authors revealed that the plasma induced from high-power lasers oscillated above the weld pool surface periodically with 450–600 ms cycles.

During the welding process, there are other effective ways to monitor the welding quality on-line. Xu-dong et al. [11–13] thoroughly researched the coaxial monitoring of keyholes during a CO_2 laser welding process. The authors established a system for coaxially monitoring the penetration status during CO_2 laser welding and classified various penetration states during deep-penetration laser welding. The welding condition and weld bead formation of “weld pool penetration” and “moderate full penetration (keyhole penetration)” were described. The influences of the welding processing variables and of the penetration status on the coaxial optical signal were studied for the laser welding of planar plates. Their results showed that as the heat input increased, the variation in the slope of the signal intensity was maximal when the penetration status changed from “weld pool penetration” to “moderate full penetration”. M. Doubenskaia et al. [14] studied the surface temperature of Zn-coated steel sheets with various thicknesses during Nd:YAG laser lap welding and established a relation between the surface temperature and the welding quality for lap welding zinc-coated steels with different thicknesses under various gap conditions. Matsunawa et al. [15] studied the dynamic behaviour of the keyhole using vision-sensing technology and an Ar+ laser as an auxiliary illuminant. The Ar+ laser can effectively reduce the interference of the plasma to capture an imaging signal. However, the images of the weld pool and keyhole are oblique because they are not coaxially captured, so the keyhole cannot be completely observed. Cheol-Hee Kim et al. [16] built a system for the coaxial monitoring of Yb:YAG laser welding and, for different exposure times, captured images of the weld pool for lap welding steels and stainless steels at various welding speeds while using filters with different band-pass ranges.

In this study, an on-line coaxial monitoring system with an auxiliary illuminant was developed for the fibre laser welding of galvanised steel, and images of the weld pool and the keyhole were clearly captured during the deep-penetration laser welding process. These captured images were processed using the region growing algorithm and the Canny algorithm. Thus, greyscale images and profiles of the keyhole and the weld pool with smooth edges were obtained. The weld width was then obtained from the grey level distribution in the greyscale image perpendicular to the welding speed. The relation between the grey level distribution of the keyhole in the greyscale image and the depth of the weld pool was analysed for different penetration statuses, and the on-line monitoring of the welding quality during deep-penetration laser welding was realised.

2. Experimental setup

2.1. Fibre laser welding system

The experiments were conducted using a continuous-wave fibre laser with a maximum power of 4 kW, as listed in Table 1. The laser beam is transmitted through an optical fibre 300 μm in diameter to a welding head. The focused diameter of the laser beam is 0.4 mm after passing through a collimating lens (focal length of 150 mm) and a focusing lens (focal length of 200 mm) in the welding head. The robotic laser welding system consists of a servo-controlled, six-axis mechanical arm with the laser welding head mounted to the faceplate of the robotic arm. The chemical composition of the tested material is shown in Table 2. The thickness of the test specimen is 1.2 mm. The welding joints are made in a lap joint configuration using the following welding process. In this paper, we focus on the coaxial monitoring of the weld width and of the weld penetration status during the fibre laser welding of a lap joint. Thus, we used the same lap gap to avoid any impact on the welding quality, and the size of the gap is 0.2 mm.

Table 1
Fibre laser in the welding system.

Type	IPG, YLS-4000-S2T-CL
Laser power	≤4.0 kW
Focused beam diameter	0.4 mm
Center wavelength	1070 ± 10 nm
Diameter of delivery fiber	300 μm

Table 2
Chemical composition of B340/590DPD+Z (mass fraction %).

grade sf steel	C	Si	Mn	P	S
B340/590DP	0.180	0.800	2.200	0.035	0.030

Note: The zinc coating thickness of 200 g/m^2 (double), coating thickness of 20 um

2.2. Analysis of interfering signals

An online CCD assisted vision system was used to measure the penetration status and the melt-collapse to identify direct and indirect faults. Additionally, camera-supported images can be collected to detect the tiniest faults in the weld seam. The measurement principle for the on-line system is characterised by significant illumination differences among the keyhole area, the fusion zone and the base material during the welding process. Therefore, interfering signals should be analysed and considered to avoid noise effects as much as possible during the monitoring process.

In the process of laser welding galvanised steel, the zinc evaporates rapidly under the irradiation of the laser, forming a zinc vapour cloud. As the process proceeds, the zinc vapour continues to absorb the laser energy and is ionised into a zinc plasma. Simultaneously, part of the shielding gas and the iron vapour are also ionised. Although the light emission from the laser-induced plasma for fibre laser keyhole welding is weaker than that for CO_2 laser keyhole welding, an image of the fusion welding process is still shielded by the plasma and the vapour. The wavelength range of the plasma that is generated during the welding process was detected using the experimental device that is shown in Fig. 1.

As shown in Fig. 1, the laser welding system includes a fibre laser, an optical system, a gas delivery system and a robotic laser welding system that consists of a servo-controlled, six-axis mechanical arm with a laser welding head. The single-channel spectral acquisition system includes an imaging lens, optical detection components, a two-dimensional (2D) displacement platform, spectrometers, an area array charge-coupled device (CCD), the WinSpec/32 software produced by Princeton Instruments in U.S and a computer. The imaging lens was fixed onto the welding head. The galvanised steel generated a large amount of plasma due to the high-energy-density laser beam. The spectral signal of the plasma that radiated outside of the keyhole was amplified by an imaging lens, was then received by a fibre optic probe and was coupled to the spectrometer after transmission through the optical fibre. The collected spectral data were transmitted to the computer using a data cable (USB interface) and were observed and analysed