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Real-time monitoring of laser hot-wire cladding of Inconel 625

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ABSTRACT

Laser hot-wire cladding (LHWC), characterized by resistance heating of the wire, largely increases the productivity and saves the laser energy. However, the main issue of applying this method is the occurrence of arcing which causes spatters and affects the stability of the process. In this study, an optical spectrometer was used for real-time monitoring of the LHWC process. The corresponding plasma intensity was analyzed under various operating conditions. The electron temperature of the plasma was calculated for elements of nickel and chromium that mainly comprised the plasma plume. There was a correlation between the electron temperature and the stability of the process. The characteristics of the resulted clad were also investigated by measuring the dilution, hardness and microstructure.

1. Introduction

Laser cladding is the fusion of a metal of superior properties to a substrate surface, with a minimum melting of the substrate. During the laser cladding process, the metal can be transferred by preplaced or blown powder or a cold/hot wire feeding method. Laser cladding by powder injection has achieved a high level of commercialization due to its flexibility and accuracy. However, this method has some disadvantages, such as low material utilization efficiency and pollution of the working environment by powder [1]. The cold wire feeding method as an alternative way for feeding the material in laser cladding is characterized by a high material utilization efficiency and a high deposition rate. This method is mainly applied in the manufacturing of large structures. However, a poor absorption of laser energy by the wire, discontinuous wire feeding, and high dilution are the main limitations for wider applications of this feeding technique in laser cladding [2].

The laser hot-wire cladding (LHWC) method that has been introduced can effectively increase the productivity and save the laser energy. Nurminen et al. [3] compared the three laser cladding techniques with powder, cold- and hot-wire. They found that the deposition rate in laser hot-wire cladding was four times higher than in the other techniques. In LHWC, the wire is preheated by electrical resistance before entering the molten pool. Laser energy as a precision heating source is mainly used to melt the substrate surface to form a metallurgical bond. Hinse-Stern et al. [4] found that up to 50% of the needed process energy can be supplied by preheating the wire. Hence, preheating of the filler wire can effectively decrease the laser power consumption and increase the deposition rate. Especially in the deposition of large structure, LHWC has been gaining considerable attention. The contact between the wire tip and the molten pool ensures the formation of the hot-wire current loop. The wire was heated up to near the melting point, which has large adaption to the experiment conditions such as substrate roughness, feeding rate and feeding angle. The most common defects that can appear during LHWC process are high dilution, porosity, lack of metallurgical bonding, non-uniform clad geometry and rough surface. Especially, the arc and spatter generation are found to be the main issues. If the wire tip is melted, as a result, a gap will be formed between the wire tip and the substrate. Current from the power supply system will continue to flow and generate an arc. The arc is much hotter than the wire preheated by resistance, resulting in spatters, excessive melting of the substrate material into the clad, and instability of the deposition process. Peters of the Lincoln Electric Co. [5] has made the efforts to suppress the arcing in LHWC by developing a feedback system to control the voltage.

The development of a monitoring system in LHWC that detects the defects in time is necessary. It will help to prevent the continuous occurrence of defects and optimize the processing parameters. Currently, a number of on-line monitoring techniques have been developed, such as infrared thermography [6], CCD-based machine vision [7,8], acoustic inspection [9], and spectroscopy [10,11]. Among these monitoring techniques, spectroscopy is a cost-effective method to detect the behavior of the plasma plume over the molten pool in real time. Plasma is formed by a high level of ionization and excitation of the metal vapor. Its instability reflects the perturbations in the molten pool and the possible defects in the process. Therefore, signals coming from plasma such as emission intensity, chemical composition, and electron temperature could be utilized to control the process in real time. Brueggemann and Benziger [12] pointed out that by

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using the spectrometer, a good weld quality could be achieved by suppressing the fluctuation of the plasma plume. Ancona et al. [13] presented a correlation between the standard deviation of the electron temperature and the quality of the weld joint. The best result was obtained at the lowest value of the electron temperature standard deviation. Kong et al. [14] and Ma et al. [15] applied a spectrometer to analyze the stability in the welding process of galvanized high strength steel and found that the spectrum intensity was strongly affected by the zinc vapor induced spatters. Liu et al. [16] analyzed the weld-bead features in laser hot-wire welding by correlating the electron temperature. They found that the electron temperature was proportional to the heat input in the process and was related to the formation of weld defects.

In this work, a wire of Inconel 625 was deposited on a A36 mild steel plate with the LHWC technique. During the cladding process, an optical emission spectrometer was used to detect the emission signal of the plasma plume over the molten pool. At various experimental conditions, the intensities of emission lines were analyzed. Electron temperatures of the selected elements of nickel and chromium were calculated according to Boltzmann plot. Properties of the deposited clads such as surface appearance, clad dilution, hardness, and microstructure were examined. A correlation between the results of spectroscopic analysis and the clad quality was found. It is expected that the spectroscopy method has the potential to detect the instability in the process and can be used for the optimization of the processing parameters.

2. Experimental setup and procedure

The experimental setup in laser hot-wire cladding consisted of a 4 kW fiber laser at a wavelength of 1070 nm, a hot-wire system (electrical power supply, wire feeder, wire torch), and a 5-axis CNC machine center, as shown in Fig. 1(a). The wire was fed through a conductive torch where it picked up an electrical charge. When the wire touched the substrate, the electrical circuit was completed and current flowed through the wire. Due to the electrical

Table 3
Design of experiments.

Exp. no.	P_l (kW)	V_s (mm/s)	d_l (mm)	V_f (mm/s)	U (V)
1	2	5	6	90	6
2	2	5	6	90	8
3	2	5	6	90	10
4	2	5	6	90	12
5	2	5	6	90	14
6	2.5	5	6	90	8
7	3.0	5	6	90	8

Table 4
Spectroscopic constants of nickel and chromium transitions selected for the calculation of the electron temperature [20].

Selected emission line	Wavelength, λ_m (nm)	Energy of the upper level, E_m (eV)	Statistical weight, g_m	Transition probability, A_m (s^{-1})
Ni I	368.271	3.635	7	4.5e5
Ni I	429.722	6.726	7	1.7e7
Cr I	335.04	3.695	7	1.2e5
Cr I	429.35	5.8	10	2.5e6

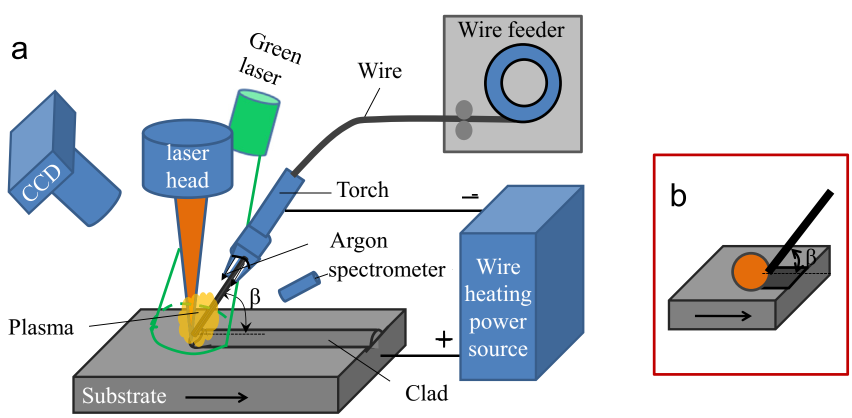

Fig. 1. (a) Schematic diagram of experimental setup for laser hot-wire deposition, (b) wire feeding direction and location.

Table 1
Chemical compositions (%) of Inconel 625 and A36 mild steel [16,17].

Element	C	Mn	Si	Cr	Ni	Mo	P	S	Fe
Inconel 625	0.03	2	1	16–18	Bal.	2–3	–	–	–
A36	≤ 0.25	≤ 0.01	≤ 0.4	–	–	–	≤ 0.04	≤ 0.05	Bal.

Table 2
Electrical resistance of Inconel 625.

Temperature (°C)	21	38	93	204	316	427	538	649	760	871	982	1093
Resistance (μΩ cm)	129	130	132	134	135	136	138	138	137	136	135	134