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Optical monitoring of high power direct diode laser cladding

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ABSTRACT

Laser cladding is one of the most advanced surface modification techniques which can be used to build and repair high-value components. High power direct diode laser (HPDDL) offers unique quality and cost advantages over other lasers (CO_2, Nd:YAG). Especially its rectangular laser beam with top-hat intensity distribution makes HPDDL an ideal tool for large area cladding. In order to utilize this technique successfully, the development of on-line monitoring and process control is necessary. In this study, an optical monitoring system consisting of a high-speed CCD camera, a pyrometer, and an infrared camera was used to analyze the mass- and heat-transfer in the cladding process. The particle transport in flight was viewed by a high-speed CCD camera; the interaction between powder flow and laser beam was observed by an infrared camera; and the thermal behavior of the molten pool was recorded by the pyrometer and the infrared camera. The effects of the processing parameters on the laser attenuation, particle heating and clad properties were investigated based on the obtained signals. The optical monitoring method improved the understanding about mutual interrelated phenomena in the cladding process.

1. Introduction

In recent years, the development of high power laser diode array has enabled the arrival of a new generation of high power direct diode lasers (HPDDL) up to 10 kW in power [1]. The HPDDL is characterized by high electricity efficiency, a long lifetime, and competitive capital and operational costs [2]. The short wavelength of HPDDL has found wide application in material processing by demonstrating good laser-beam coupling characteristics that increase beam absorption with respect to CO_2 and Nd:YAG lasers [3,4]. Due to the rectangular shape of the HPDDL beam with top-hat intensity distribution, HPDDL-based cladding is an ideal technique for large area coverage [5].

During laser cladding many physical phenomena take place simultaneously. A number of parameters affect the energy balance in the process, ultimately affecting the clad quality. Analytical [6], numerical [7] and experimental methods [8] were applied to improve the clad quality, process stability and reproducibility. Different aspects of cladding were studied, including equipment development [9], parameter selection [8], interaction of laser, gas and powder before reaching the substrate [10], interaction of laser, gas, powder and substrate at the molten pool [11], and final properties of the clad [12].

Several research works have been reported on developing the processing map and optimizing the processing parameters by using the experimental method [13–15]. Relationships were found between the relevant processing parameters (such as laser power, powder feeding rate, carrier gas, and scanning velocity) and the desirable clad results (such as clad geometry, surface roughness, microstructure and mechanical properties) and were used as guidance for selecting optimal processing parameters. The on-line monitoring method was used to gain a better understanding about mutual interrelated phenomena in the cladding process. This method not only helped to optimize the operative conditions but also was beneficial for building the closed-loop control system.

Li et al. [16] used the photodiode to detect the state of the molten pool. The obtained signal was able to recognize some cladding problems such as the clad-bonding condition, clad roughness, and clad thickness. Tewari [17] applied an optical spectrometer to monitor the cladding process of NbAlHf alloy on Nb substrate. He found that the emission intensity of plasma might be used to monitor the variation in the composition, thickness, and temperature of the clad. Hu et al. [18] applied thermocouples and a pyrometer to measure the molten pool temperature. They found that the temperature increased with laser power, while it decreased with powder feeding rate. Li and Steen [16] used a CCD camera to characterize the powder flow. Based on the measured powder concentration, the powder catchment efficiency could be predicted. Hu and Kovacevic [19] built a closed-loop control system based on infrared image for accurate control of the heat input and size of the molten pool. Smurov et al. [20] used an

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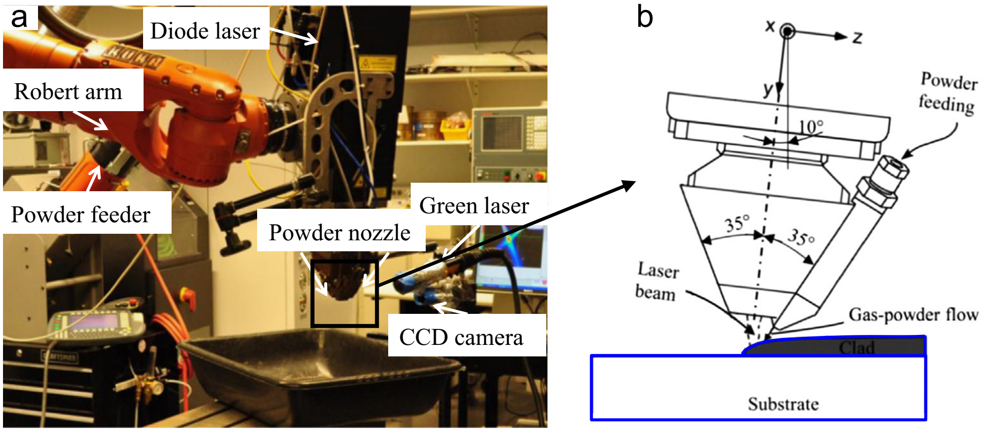

Fig. 1. (a) Experimental setup and (b) laser head installed with powder nozzles [21].

infrared camera to investigate the temperature distribution of the molten pool during deposition of the metal matrix composite with various contents of TiC. However, none of the research comprehensively studied wide-track laser cladding using the monitoring method.

In this study, a comprehensive monitoring of the mass- and heat-transfer phenomena during the HPDDL cladding process was performed by optical diagnostics. A CCD camera was used to detect the particle-in-flight behavior. A pyrometer and an infrared camera were used to visualize the interaction of laser beam and powder flow and to measure the molten pool temperature. The influences of the main processing parameters such as laser power (P), powder feeding rate ($\dot{m}$), carrier-gas flow rate (CG), and scanning speed (V) on the powder feeding behavior and the thermal behavior of molten pool were investigated.

2. Experimental setup

The experimental setup shown in Fig. 1 is comprised of an 8-kW Coherent HPDDL, a 6-axis KUKA robot, an AT-1200 high-pressure rotary powder feeding system, and two powder feeding nozzles installed symmetrically with the laser head at an angle of 35° with respect to the vertical axis of the laser head. The exit of the powder feeding nozzle had a rectangular shape with the dimensions of 10 mm × 1 mm. In order to protect the lens from the reflection of light and ricochet particles, the entire laser head tilted 10° with respect to the vertical axis. The HPDDL operated at the wavelength of 980 ± 10 nm. The optical lens focused the laser beam into a 12 mm × 3 mm rectangular spot. The divergence angles of laser beam for the x slow axis and the z fast axis were $\alpha = 23^\circ$ and $\beta = 19^\circ$, respectively. At the focal position, the laser intensity distribution measured by a beam-viewer is shown in Fig. 2. The image illustrates that along the slow axis, the beam intensity shows a trapezoid distribution. Along the fast axis, the beam intensity shows a Gaussian distribution. The laser scanning direction was perpendicular to the slow axis so that the clad width was determined by the 12 mm (trapezoid) dimension of the laser beam.

Argon gas was used as a carrier and shielding gas. A Fe-based alloy powder was used during the experiments. The particle size D_p ranges from 45 μm to 150 μm in diameter. A36 mild steel was used as the substrate. The chemical composition of the powder and some of its physical properties are listed in Tables 1 and 2, respectively.

The powder flow ejected from the nozzle illuminated by a 532-nm wavelength green laser is shown in Fig. 3. The image of the flow pattern was captured by a CCD camera at the exposure time of 0.02 s. In order to reduce the effects of the particle random movements, an average image was obtained from 25 continuous images. The particle velocity V_p at the nozzle exit could be obtained by a CCD camera at the exposure time of 0.0002 s.

The pyrometer was used for temperature measuring in the center of the laser spot during laser cladding, as shown in Fig. 4(a). The measurement temperature of the device was in the range of 470–3000 °C. The acquisition time was 0.5 s in a spot with a diameter of 0.25 mm. The measurement distance to the target was set to be 198 mm. The angle of observation was 45° with respect to the horizontal plane.

The surface temperature distribution of the molten pool was recorded by the infrared camera under the following conditions: the exposure time was 50 μs, the observation zone was 150 mm × 200 mm, the angle of observation was 60° with respect to the horizontal surface and the measurement distance was 500 mm. Transverse and longitudinal profiles of temperature were obtained by data averaging of 10 consequent thermal images, as shown in Fig. 4(b). The pyrometer and the FLIR Thermovision A40 infrared camera were calibrated by blackbody model #463. Nine experiments designed to investigate the effect of processing parameters on the thermal field of the molten pool during the cladding process are listed in Table 3.

The hardness of the clad was measured by a micro-hardness tester with a load of 0.2 kg and a dwelling time of 15 s. The final clad hardness was calculated by taking an average of different measurement values. The weight of the sample was measured before and after cladding to get the net clad weight. The ratio between the net clad weight and the fed powder weight was defined as the powder catchment efficiency.

3. Results and discussion

3.1. Particle in-flight monitoring

The characteristics of the powder flow were one of the critical factors largely affecting the coupling with the laser beam, molten pool generation, powder catchment efficiency, clad geometry, and final properties of the deposition. The key characteristics of the powder flow included the particle velocity, powder concentration distribution, intersection position of the powder streams, and intersection position of the powder streams and laser beam.

3.1.1. Particle transport

Based on the Mie theory law (i.e., the luminance intensity is proportional to the number of particles irradiated per unit area)