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Technical Paper

A comparative study of vision detection and numerical simulation for laser cladding of nickel-based alloy

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ABSTRACT

The vision detection system was built to detect the molten pool of laser cladding(LC), then the captured images by detection system were processed with image-processing technology, finally the shape and the characteristic parameters were obtained in real-time. Nevertheless, the simulation analysis is a useful mean to predict the temperature contour in practice, so the three dimensional numerical model with moving heat source was built by APDL technique to obtain the temperature distribution and then extract the shapes and sizes of molten pool from the temperature contour by a threshold value of material's melting point. After experiments, the microstructure was examined to analyze the height of cladding track and height of HAZ, and dilution as well. By comparing the result of vision detection and simulation results, the section of cladding track is crescent shape, and results by vision detection agree fairly well with that of simulation. Meanwhile, the relationship between dilutions, area, width, length of molten pool and input power, scanning speed and pre-placed powder thickness were studied respectively. The results shown that the dilutions, area, width, length of molten pool will decrease with the increased scanning speed, while the increased power input will cause the increase of molten pool area, size and dilution. Thicker powder result in larger area, width and length of molten pool while less dilution.

1. Introduction

Laser cladding(LC) is a modern technology which can generate the protective coating by high energy beam to meet industrial requirements such as reducing the wear of parts [1], worn part surface repair [2,3],die repair [4], rapid manufacturing [5,6] and etc. The laser coating has a metallurgical bonding with a variety of substrates, therefore, it can retain the excellent ductility, high strength of metal and, ever more, the Metal Matrix Composite (MMC) superior behavior and satisfy the customs requirements [6–8]. While LC is a complex process which involves more than 19 process parameters [6,9], it integrates physical, chemical process with phase transformation of solid-liquid-solid, and it is finished instantly and under very high temperature as well. Fused powder and the substrate forms a molten pool and the molten pool is very small in size. The molten pool is the "information center" in LC, the temperature distribution of that will reflect the internal heat transfer, convection and, ever more, mass transfer, and it further affects the solidification process and composition distribution [10].

Since LC is a fusion process, the molten pool size could be indicator of coating quality and temperature distribution. Until now, the cladding quality depends on the exploratory experiments and experience, that is, the process parameters are determined and optimized by those previous experiments. However, the size and even the properties of specimen in experiments are usually different from the workpiece, which means that the optimized parameters got from experiments can't be applied to actual production always. The process is always influenced by the unknown factors, as a result, the molten pool is in fluctuation. Hence, it is necessary to monitor the molten pool and obtain the key information as a control object so as to control the whole process. Generally, it is accepted that a homogeneous temperature field in laser cladding may obtain the better coating quality [11]. In practice, we control the process according to the size, shape, brightness and flow state of molten pool, because the molten pool include much information about the cladding parameters such as its width, height and so on. At present, the numerous research efforts had addressed on monitoring characteristics of molten pool such as the superficial area, radiant intensity and superficial temperature distribution

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[9]. Tan et al. [12] used a two-color infrared pyrometer with an optical detector to measure the temperature during laser solid forming(LSF) and built a system to estimate the clad geometrical characteristics. Salehi et al. [13] used a two-color pyrometer with range of 800–2500 and sampled area of 2 mm in diameter onto the molten pool surface to monitor and control molten pool temperature during LC, the experimental results shew that the quality of cladding was improved. The similar method also was adopted by Tang [14], the sampled area of 3 mm to measure the temperature. M.Pavlov et al. [15] realized multi-wavelengths pyrometer and infrared camera system to measure the brightness temperature distribution in zone of laser action, the pyrometer and infrared camera were fixed onto the laser head with 45 and 60 ° respectively. While M.Asselin et al. [16] developed trinocular charge coupled device (CCD) to measure the clad geometry, they used fuzzy adaptive threshold and other related method to extract the clad geometry, the results indicated that it works well for system. Based on this trinocular CCD system, Iravani et al. [17] developed an algorithm to extract the clad height in real time, which is based on image-based tracking and neural network. The performance was evaluated by laser cladding of 303L.The results showed that clad height was measured with 10 Hz and ±0.15 mm precision without dependency on the path. Song et al. [18] used three high-speed CCD cameras to observe layer height in laser cladding process. Meanwhile, a pyrometer is utilized to measure the molten pool temperature. The monitoring system offered a feedback to a controller so as to adjust the power input. Alireza Fathi et al. [19] developed a control system via a sliding mode controller (SMC) to control layer geometry of LC continuously. The controller is developed based on a parametric Hammerstein model using the scanning speed as the control input. The results showed that control system was robust to all model parameters' uncertainties and disturbances, the tracking accuracy was improved and the chattering effect was reduced as an integrator on the scanning speed was added.

There are many studies done on the molten pool. Likewise, width and length of molten pool are important for cladding quality and efficiency. Consequently, it is quite important to seek a direct and significant method to monitor and control the size of molten pool. Fortunately, machine vision technology has been widely used in modern industries, thus, it is reasonable to use the machine vision technology to detect and analyze the captured image and thus to control the input parameters for improving the cladding efficiency. Hu and Kovacevic [20] installed infrared camera coaxially to acquire the image of molten pool and its surrounding thermal area, then got the area of molten pool. Doubenskaia et al. [21] applied an infrared camera to measure radiation emission field and transformed them into brightness temperature by black-body calibrated camera, and then indirectly acquired the molten pool images. Zhang and Gao [22] applied high speed camera system with an auxiliary laser light source to acquire the images of molten pool and analyze the molten pool information with fitting methods in laser welding process. An in-chamber infrared camera and a dual-wavelength pyrometer were used to recode the molten pool temperature history and inspect direct laser deposition (DLD) by Marshall et al. [23], therefore, temperature gradient, cooling rates were investigated to fabricate Ti-6Al-4C cylindrical samples.

Numerical simulation is always an effective tool in prediction the thermal behaviors in laser cladding process. For example, Alireza Fathi et al. [24] predicted temperature field, depth of molten pool and dilution by a mathematical model of laser powder deposition(LPD). They found that depth of molten pool and dilution is a function of clad height and clad width, while a non-linear relationship is between depth of melt pool and process speed. The results obtained from the numerical and experimental indicated that this model can predict the characteristics of the LPD process accurately. Santanu Paul et al. [25] developed a three-dimensional finite element(FEM) thermal model for powder injection laser cladding of CPM9V on H13 tool steel, they took the attenuation of laser beam into consideration, which is caused by injected powder, the results showed that the reasonable accuracy with the model. Nie et al. [26] employed FE model, which involved the trajectory of the powder stream, irradiation of the laser, mass addition and heat transfer to investigate the addition of material and thermal history in the cladding structure. The simulation results agreed well with experimental observations. Lee et al. [27] compared the numerical results and experimental of width, height and penetration depth of weld pool by a 3D transport model. Kolossov et al. [28] also developed a 3D physical model of AM process to test the validity of the model by an IR camera to measure the temperature on the top of the powder layer.

So far, the size of the pool was indirectly acquired by detecting the temperature distribution, and the FEM model were used to verify the results obtained by complex thermal sensors. From this point, this paper will focus on vision detection of molten pool as the Ni60 alloy coating is fabricated on the ANSI 1045.Therefore, the effective optical detection system is set up to directly detect the molten pool and extract the information about the its size such as area, width and length. In addition, the numerical model is developed, which is simulated according to the given load and boundary condition, to obtain the temperature distribution so as to validate the effectiveness of optical detection system.

2. Hardware and image acquisition system

2.1. Set-up of image acquisition system

Laser cladding system is made of a 3 kW continuous wave CO_2 laser, Siemens 802 CNC system, image acquisition system and image process system. The frame of camera used in image acquisition system is 60 frame per second, and it is mounted onto and move with the laser head, as shown in Fig. 1, the structure of lens of camera is listed in Fig. 2. Using quartz glass as a filter to protect lens from splash damage of particles come from molten pool, and the inputted light is abated by neutral attenuator and controlled by adjustable aperture, the 850 nm narrow band pass filter is used to filter the light emitted from the molten pool. Finally, the vivid image is captured by adjusting the camera parameters and optimizing the neutral attenuator and optical filter, the sampled capture image as shown in Fig. 3.

2.2. Procedure of image process system

The LabVIEW software package has a function of image processing, and the NI Version Development Modular services as a supplementary tool. Main image processing steps including noise filtering, thresholding, calibrating, and segmenting [12]. The images were firstly filtered by low-pass spatial filtering to remove single bright pixels which may be caused by hot particles. Next, the images were converted into a binary image to threshold by gray gradient algorithm, which means that the thresholding value is decided according to the melt pool boundary by method of gray threshold segmentation. The third step involved the appropriate gray-level morphological close operation, which can smooth the extractive boundary. Calibrating was used to obtain the real molten pool size because the camera was mounted at a given angle, it not only corrects the error come from the distance of setup but also adjusts the image distortion. The final process focused on the extraction of molten pool area.

The captured image and processed image were shown in Fig. 4, the region marked by red circular is recognized as the molten pool and its character size are calculated as well and therefore the results