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Formation quality optimization of laser hot wire cladding for repairing martensite precipitation hardening stainless steel

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ABSTRACT

Laser cladding is an advantaged repairing technology due to its low heat input and high flexibility. With preheating wire by resistance heat, laser hot wire cladding shows better process stability and higher deposition efficiency compared to laser cold wire/powder cladding. Multi-pass layer were cladded on the surface of martensite precipitation hardening stainless steel FV520B by fiber laser with ER410NiMo wire. Wire feed rate and preheat current were optimized to obtain stable wire transfer, which guaranteed good formation quality of single pass cladding. Response surface methodology (RSM) was used to optimize processing parameters and predict formation quality of multi-pass cladding. Laser power P, scanning speed V_s, wire feed rate V_f and overlap ratio η were selected as the input variables, while flatness ratio, dilution and incomplete fusion value as the responses. Optimal clad layer with flat surface, low dilution and no incomplete fusion was obtained by appropriately reducing V_f, and increasing P, V_s and η. No defect like pore or crack was found. The tensile strength and impact toughness of the clad layer is respectively 96% and 86% of those of the substrate. The clad layer showed nonuniform microstructure and was divided into quenched areas with coarse lath martensite and tempered areas with tempered martensite due to different thermal cycles in adjacent areas. The tempered areas showed similar hardness to the substrate.

1. Introduction

Martensite precipitation hardening stainless steel offers a comprehensive property of high strength, and strong toughness, as well as good corrosion resistance and weldability. It is particularly attractive for manufacturing load-bearing parts like turbines and shafts in power plant, oil and chemical industry. Despite that, some parts are found damaged because of severe working conditions, which brings to giant economic loss and much worse safety hazard [1]. It was reported that it costs $1.32 million for one day of outage in terms of lost revenue in a 350 MW combined cycle power plant [2]. It is economical and flexible to repair those parts instead of changing new ones. The repairing quality is a big question considering the overall properties of repaired parts should match up those of the substrate required in service. Laser cladding is regarded as an appropriate technology for repairing such parts due to low heat input, which brings to small distortion, low stress and minor damage to the substrate. It also shows high flexibility, allowing itself to perform repair on the site [3,4]. Powder is often used as the filler metal in laser cladding, since it is convenient to adjust chemical composition to match different substrate metal. However, powder delivering is usually followed by poor surface finish, low deposition efficiency and low material utilization [5]. Using wire is an alternative, but laser cladding with wire usually shows poor stability and low efficiency, since the limited laser energy must melt the substrate and the solid wire simultaneously.

Previous studies [6,7] have shown that laser hot wire welding can give superior results in processing quality and efficiency. In this process, substrate metal and filler wire are respectively heated by laser and resistance heat separately, which reduces the demand of high laser power and strict wire positioning. Moreover, high deposition efficiency and small heat damage to substrate can be obtained simultaneously. These features make it especially suitable for surface repairing. Shinozaki experimentally investigated the influences of welding parameters, such as laser spot diameter, wire current, laser-wire distance, wire feed rate on weld formation for the lap joint [8] and fillet joint [9]. It was critical to preheat wire to an appropriate temperature, which could guarantee stable wire transfer and good bead formation [10]. Nurminen compared the formation quality and efficiency of filler metal types between

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powder, cold wire and hot wire in laser cladding [11]. He found that laser cladding with hot wire showed the lowest dilution and the highest deposition ratio, and emphasized that the low heat damage to substrate by hot wire can bring in many merits in practical applications. But lack of fusion was easily found between clad layers with high wire filling volume.

Processing parameters have an essential impact on the clad formation quality, like geometry, dilution and defects. Formerly, process tests were used to find the optimized parameters through trial and error [12]. The results are based on sample quantity and artificial judgment. It cannot reflect the immanent regularity and is unable to find the best parameters combination accurately due to lack of systematic optimization. In recent years, the application of statistics with aid of computers to the optimization of processing parameters has received attention rapidly, like Taguchi method and response surface method (RSM) [13–18]. Yang et al. [14] experimentally studied the optimization of weld bead geometry during laser welding with wire using Taguchi method. Laser power, welding speed and wire feed rate were optimized to obtain the minimum weld bead width and the fusion zone area. Godfrey et al. [16] carried out an experimental investigation of the relation between three parameters and the clad height and clad width. A reliable mathematical model was developed, and then the optimal cladding parameters were predicted by RSM.

There are multiple parameters during laser hot wire cladding, some related to laser energy and resistant heat, while others related to wire filling. Unlike single pass cladding, the criteria of formation quality for multi-pass cladding are also multiple and needed to be balanced. Besides, processing parameters have combined influence on the multiple criteria of formation quality in multi-pass cladding. Thus, the optimization of processing parameters are quite complex for laser hot wire cladding. It is theoretically unclear so far how to control the process and obtain good formation quality especially for multi-pass cladding. In this study, wire feed rate and preheat current were optimized to preheat wire to the optimal by temperature measurement. With the appropriate temperature, the filler wire can maintain stable transfer with much low laser energy, which helps reduce the heat damage to the substrate. RSM was used to develop the empirical relationship between parameters and formation quality. With the optimized parameters, a large area of clad layers with good formation quality is obtained. Finally, the microstructure and mechanical properties of clad layers were tested and discussed.

2. Experimental method and materials

The experimental setup is shown in Fig. 1. An IPG fiber laser with the maximum power of 2000 W and the wavelength of 1.07 μm was used. The focal length was 200 mm. The filler wire

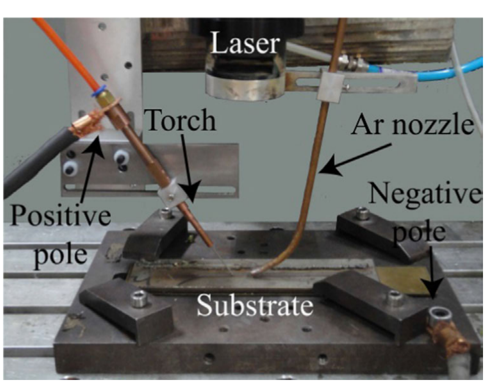

Fig. 1. Experimental setup of laser hot wire cladding.

was supplied via a lateral feed torch and was preheated by resistance heat provided by a Panasonic YC-400TX power source. When the wire touches the substrate metal, a circuit forms and heats the electric part of wire. Argon gas was used to shield the molten pool from oxidation. A Raytek MR1SCSF infrared ratio thermometer was used to measure the temperature of the wire tip outside the molten pool.

The substrate metal was martensite precipitation hardening stainless steel FV520B with dimensions of $100 \times 60 \times 8$ mm. It had been heat treated with solution and aging in service status. The working surface was cleaned with absolute ethyl alcohol. The filler wire was martensite stainless steel ER410NiMo (Mod.) with 1.2 mm diameter. The chemical composition of the substrate metal and the filler wire is shown in Table 1. Multiple passes were carried out to form the clad layer. The cross section of the layer was polished and etched by Fry's etchant. Microstructure was observed by optical microscope, and Vickers microhardness was measured using a load of 100 g with a dwell time of 10 s. Samples were cut from both the substrate and clad layers to test mechanical properties by tensile test and Charpy U-notch impact test in room temperature.

Preliminary experiments were carried out to identify key processing parameters at first. The key parameters includes laser power (P), scanning speed (V_s), wire feed rate (V_f), overlap ratio (η), and current (I). For each key parameter, the working range was obtained; while other parameters were fixed at relatively optimal value in accordance with preliminary experiments. The fixed parameters contains the followings: 3 mm for laser spot diameter, 1 mm for initial distance between laser spot center and the wire tip, 70° for wire feed angle, and 35 mm for the initial wire length. Central composite rotatable design (CCD) was used to investigate the influence of the key parameters on formation quality. By establishing a reliable empirical relationship between variables and responses, RSM method provided the optimized window of parameters for the specific formation quality.

3. Experiment design of RSM

3.1. Optimal preheat temperature of hot wire

The wire temperature is mainly determined by V_f and I when other feeding parameters are kept constant [10]. Fig. 2 shows single-pass bead formation under different currents with V_f as 2 m/min. It is found that the bead formation is good and stable as long as the wire melts continuously in the molten pool. If the wire is preheated to enough high temperature, it only needs a little heat from the molten pool to melt. When $I = 90$ A, good and smooth bead is obtained as Fig. 2a shows. The temperature of wire tip, a point 30 mm away from the contact point, is measured as 1325 °C by the infrared thermometer, which approaches to the solidus temperature of wire 1381 °C. The total length of heated wire is 35 mm, which equals to the initial length of wire between the contact point and the surface of molten pool. The infrared measurement fails if the measurement point is much closer to the molten pool. With increasing I to 95 A, the wire fuses outside the molten pool, which means the wire is preheated higher than the fusion point. Once this phenomenon occurs, the wire transfer becomes unstable, resulting in an uneven and discontinuous bead as Fig. 2b shows.

Normally, FV520B is regard as sensitive to cold crack and needed to be preheated in welding and surfacing. By laser hot wire cladding, crack defect doesn't appear without additional preheating. No porosity is found in the clad as well. Fig. 2c shows the cross section of a single pass obtained by laser hot wire cladding. Thus, a single-pass clad with good formation quality, meaning smooth surface and no defect, can be obtained when the