Thick Coating of 316L Stainless Steel on Carbon Steel Using a High Power Fiber Laser: An Experimental Investigation of the Process Characteristics and Materials Properties

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High quality and low distortion thick coatings can be deposited successfully on base materials using laser with blown metal powders. Thus far, only CO_2, Nd:YAG and diode lasers have been used commercially, so the potential advantages, in terms of cost and efficiency, of using a high power fiber laser have not been investigated. Due to the unique beam characteristics of a fiber laser, the work done with other lasers in this field can not be assumed to hold true for fiber lasers. The aim of this paper is to establish relationships between input parameters and the final material dimensions, and properties of the process by using a 1000 W fiber laser with a coaxial powder-feed nozzle. The application of a thick laser coating of 316 stainless steel onto a 1018 plain carbon steel substrate was investigated. The resulting composition, microstructure, dimensions and surface properties of the final coatings are correlated with the major input parameters. Characterization of laser coatings was carried out using optical microscopy, scanning electron microscopy and microhardness testing.

Keywords: *316L stainless steel coatings, laser powder deposition*

Introduction

Wear and corrosion are two dominant factors affecting the performance and lifetime of engineered components. The automotive, mining, power generation and aerospace industries are continually exploring new materials and processes that will not only result in new components with improved properties, but also in the refurbishment and repair of high value added components. Laser thick coating/cladding is one of the processes which is rising in importance as a high quality, flexible and relatively low heat input surfacing process.[1-3] The benefits in terms of increased process efficiency, reduction in production delay and total life cycle costs of a part have been recognized,[4,5] but the major obstacle to the introduction of laser based cladding so far has been the high equipment capital cost.

The high-powered fiber laser (HPFL) has the potential to change this. In just a few short years, fiber lasers have emerged to capture a significant share of the laser market, and have consumed a large share of the high-power diode lasers made every year.[6] Currently, high-power diode lasers, traditional Nd:YAG slab lasers and the new Yb:YAG fiber lasers are used as beam sources, in industry. The typical power range is between 1 and 6 kW. Lasers with higher power output are available, but for the most part are not cost effective for thick coating applications. Fiber lasers, a special type of solid state laser, represent a new generation of high power lasers for materials processing. A Yb-doped core of YAG glass fiber is the active medium in this laser. The beam quality is increased by about four times compared to conventional Nd:YAG slab lasers.[7] This greatly improves the ability to focus the laser beam which can be as small as 100 to 10 μm at long working distances. This results in the user having a wider window of process options:

- Long and short coating deposition optics and powder nozzles for better powder efficiency;
- Better accessibility of complex welding positions and
- Better 3-D operation capabilities.

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Compared to the traditional Nd:YAG slab laser, the fiber laser is more compact and smaller. The efficiency is much higher (power efficiency > 30%, compared to 5 to 15%), and the investment costs are less by a factor of 2 to 2.5.[8] So far, the relation between input parameters and final material dimensions and properties have not been established for thick laser coating deposition,[9] but if the potential of the fiber laser for thick layer deposition is to be realized, their investigation and qualification is necessary. This paper reports experimental work where a 1.0 kW fiber laser and a combined coaxial powder feeder and gas delivery nozzle were used to study the application of thick coating deposition while investigating some of the relationships mentioned previously.

Experimental

Laser material processing experiments were performed using a 1000 W fiber laser, of 1070 to 1080 nm output wavelengths (Fig. 1). Power, cooling and control is provided by a separate unit, which allows the actual laser output power to be monitored during the experiment. The CNC five-axis control provides precise (± μm) movement of the substrate relative to the laser beam. The *x* and *z* axes are controlled by a laser head mount, while the *y*, tilt and rotation axes move beneath the laser focus. The laser beam is focused on the surface of the substrate, using an objective lens of 200 mm focal length. The spot size at the deposition point was measured as 1.24 mm (diameter) using the standard "burn paper" technique.

The substrate material used was 1018 steel (0.18% C) of 50 × 50 × 6.25 mm plates. Surfaces of the samples were ground to give a uniform finish and cleaned just before the laser treatment by blasting with glass beads. Samples with this surface finish showed an enhanced absorption of laser radiation as compared to polished or milled surfaces, which reflected more of the energy and required more power. The composition of the laser coating powder was similar to the composition of stock 316L stainless steel (Table 1) and its particle diameter was less than 45 μm. The powder was dosed by a Sulzer Metco powder feeder, transported by a flux of argon gas with the flow being delivered to the laser generated melt pool through a Precitec coaxial nozzle. The carrier gas flow was approximately 5 L/min; a 20 L/min flow of argon gas through the surrounding annulus shrouded the process from oxidation. Various combinations of laser travel speed (2 to 10 mm/sec) and powder mass flow rate (0.033 to 0.167 g/sec) were performed at laser power levels of 400 to 800 W.

After the laser depositions were completed, the laser thick coatings were prepared for metallographic examination. The surfaces and cross-sections of the specimens were examined using a Hitachi scanning electron microscope (SEM) and an EDAX elemental analysis system. Metallographic samples were mounted in a cold setting resin, ground and polished. Vickers microhardness measurements were performed across the cross-section of a polished substrate/coating interface, at incremental distances.

Figure 1—The set-up used for laser thick coating deposition.

Results and discussion

A scanning electron micrograph of the cross-sectional view of a thick laser coating of 316 stainless steel on a 1018 steel substrate including the film/substrate interface is shown in Fig. 2. Figure 2b is an enlarged view of the interface region of Fig. 2a. It is obvious that the coating is characterized by high integrity as depicted in the micrograph, especially along the coating/substrate interface where neither pores nor inclusions are observed, denoting good coating adhesion. Micro-indentations on the coating cross-section as well as on the substrate were performed as presented in Fig. 2. The effects of the processing parameters on the hardness of the coatings across the cross-sections are presented in Fig. 3. Higher hardness of the stainless steel coating compared to 1018 steel is evident. The hardness values of the stainless steel coatings were in the range of 300 to 400 H_V, while the 1018 substrate had a hardness of 150 H_V. In this investigation, for the same powder feed rate and traverse speed, higher laser power generated greater hardnesses. However, the speed effects are not clear, and require further investigation. The coatings are distinct and have low dilution from the substrate as depicted in Fig. 3. In all three coatings, the interface regions are less than 300 μm in depth. This suggests that the coatings have distinct properties from the substrate with a minimal interface dilution, as would be expected for a high quality coating.

Table 1

Nominal chemical composition of DIAM 1003 stainless steel

C	Mn	Cr	Ni	Mo	Si	P	Fe
0.03	1.30	16.89	10.71	2.26	0.48	0.02	Balance

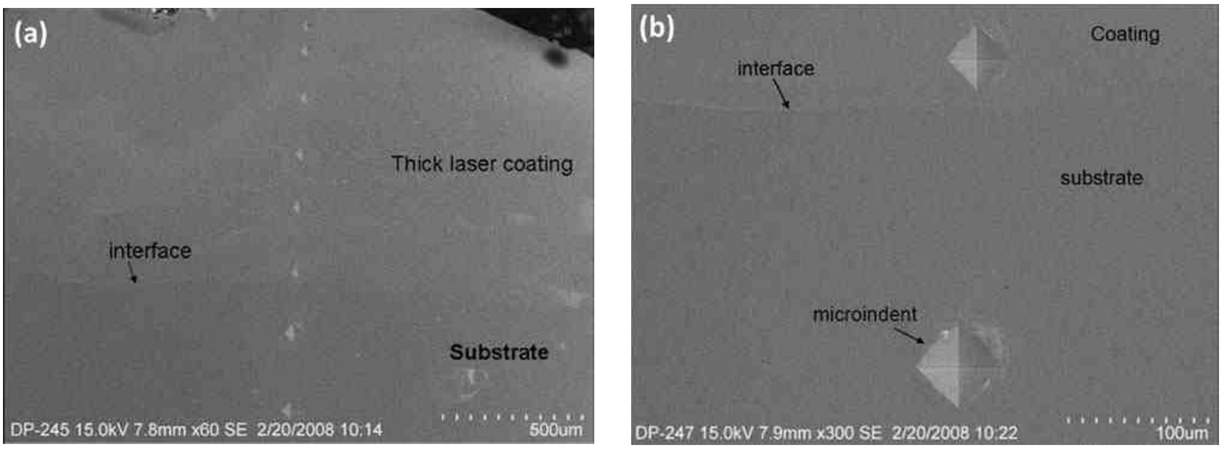

Figure 2—SEM micrographs of (a) the cross-section of a thick laser coating on 1018 steel, showing micro-indentation marks and (b) an enlarged view of the interfacial region, deposited by fiber laser at 800 W with a powder mass flow rate of 0.068 g/sec and a traverse speed of 5 mm/sec.

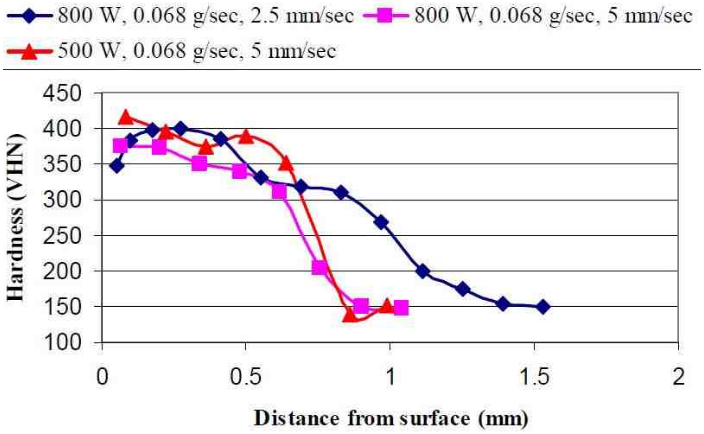

Figure 3—Vickers hardness values along the surface to substrate cross-sections of coatings, deposited by 800 W with a powder mass flow rate of 0.068 g/sec and a traverse speed of 5 mm/sec.

The microstructure and EDAX analysis of the cross-section of a stainless steel coating are shown in Figs. 4a and b, respectively. The sample mainly had an austenitic structure. EDAX analysis of the coatings indicated no major oxidation, only the presence of the dominant 316 composition, *i.e.*, Fe, Cr, Ni. A similar finding has been reported by Pinkerton, *et al*. on deposition of stainless steels with a diode laser.[10] Figures 2 and 4 show coatings that are devoid of pores and cracking, with what appears to be a high quality homogeneous coating.

Changes in the layer thicknesses and widths are compared with main process parameters are shown in Fig. 5. Layer thicknesses and widths increased with increased powder mass flow rates, but a significant increase in thicknesses and widths was observed with a powder feed rate of 0.167 g/sec (Fig. 5a). Both layer thicknesses and widths decreased with increased traverse speed (Fig. 5b). Higher laser power generated greater layer thicknesses and widths, which were independent of traverse speed.

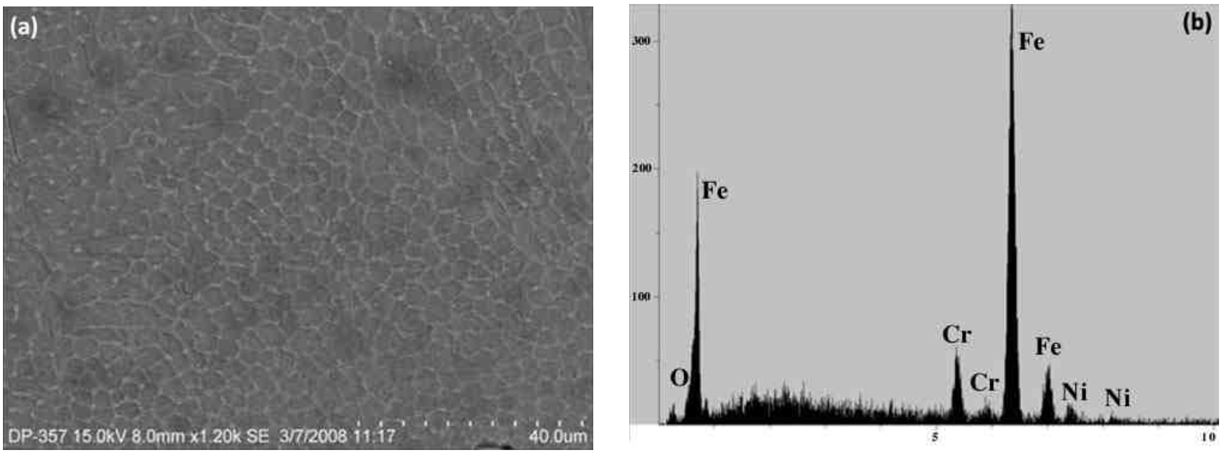

Figure 4— (a) SEM micrograph (etched with 1:1:1::HCl:HNO_3:H_2O) and (b) EDS spectra on 316 stainless steel coatings processed by 500 W fiber laser with a powder mass flow rate of 0.068 g/sec and a traverse speed of 5 mm/sec.

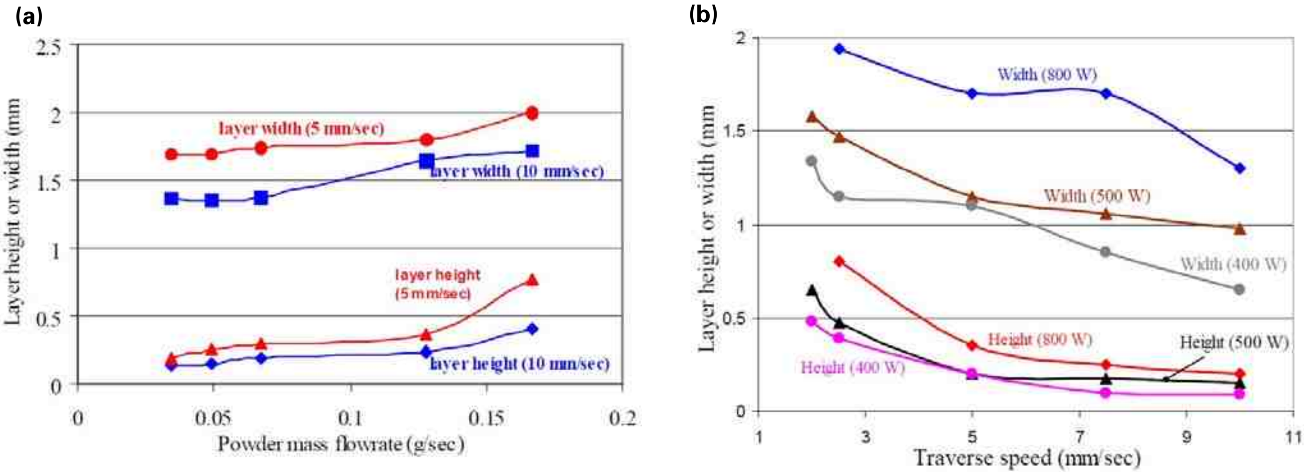

Figure 5—Mean layer dimensions of thick laser deposited coatings applied by fiber laser with a range of operating parameters (power 800 W, powder mass flow rates, traverse speeds).

The laser energy input of the process can be described by the specific energy E (J/mm^2), which is calculated using the simplified equation:

$$E = \frac{P}{DS} \quad (1)$$

Where P is the laser power (W), D is the diameter of the laser spot and S is the velocity. The thicknesses of the layers increased approximately linearly with increasing specific energy independent of the laser power (Fig. 6). Layer widths increased with increasing specific energy, but larger laser power creates a wider layer for the conditions studied. Similar findings have been reported by Brandt, *et al*.[11]

As the powder mass flow rate was increased, the increase in layer thickness produced higher surface ridges and thus greater macroscopic roughness, as observed in previous findings for laser coatings produced with other types of lasers.[10,12] Closer SEM examination also showed a change in surface morphology (Figs. 7a and b), with discontinuous surface sections characterized by a rougher surface at a higher feed rate (0.167 g/sec). A series of larger discontinuities, identifiable as partially assimilated particles (Fig. 7b), also became increasingly common at higher powder flow rates. No significant surface oxidation was observed, which is independent of power levels and powder flow rates.

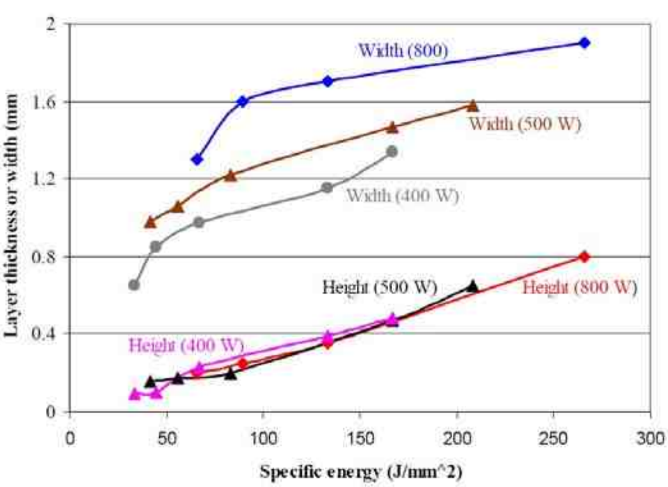

Figure 6—Dependence of layer thickness and width on specific energy.

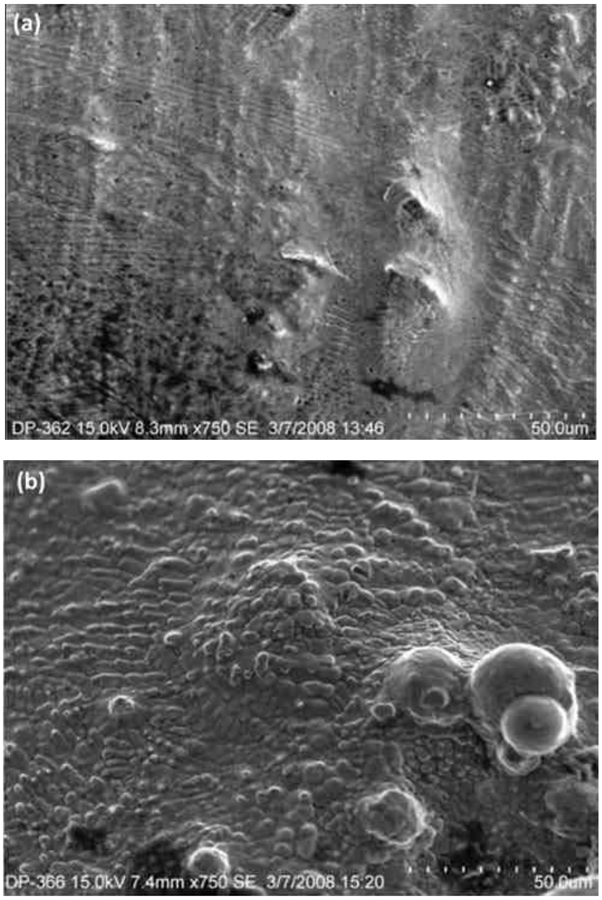

Figure 7—SEM images of the surface of thick layers deposited using a fiber laser: (a) 800 W, 0.068 g/sec powder mass flow rate, 5 mm/sec traverse speed; (b) 800 W, 0.167 g/sec powder mass flow rate, 5 mm/sec traverse speed.

Conclusions

A high quality thick coating of 316 stainless steel on SAE 1018 steel, devoid of porosity and cracking can be produced by a high power fiber laser using the powder spray technique. Hardness tests suggest that there is negligible dilution of the coating at the coating/substrate interface, indicating that its desirable properties remain unchanged. The coating microstructure is a uniform austenitic structure, which suggests that the coating properties will be uniform throughout. Mean layer thicknesses and widths increase with increased powder mass flow rate. Both thicknesses and widths decreased with increased laser traverse speeds. The thicknesses of the layers increased approximately linearly with the increase in specific energy, independent of laser power, while layer width changes depended on laser power changes. Rougher and more irregular surfaces were formed at higher powder mass flow rates.

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