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YB-FIBER POWDER LASER CLADDING OF INCONEL 625

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Abstract. *There are several techniques to clad a surface and, therefore, change its properties. Among them laser cladding has as advantages low dilution and layer consistency. The use of powder as feedstock material in the laser cladding process turns possible the attainment of high quality coatings once there is higher deposition control, in comparison with the process feed by wire. Such laser cladding variant can be used in specific applications with high imbedded value, as gas turbine parts repair. The aim of this study is to produce a cladded surface by laser cladding based on a high-power Ytterbium Fiber laser source, using Inconel® 625 powder as feedstock material and A516 - Gr.70 as substrate material, while aiming for low dilution and high productivity. Scanning electron microscopy, energy-dispersive X-ray spectroscopy, optical microscopy and microhardness techniques were applied to investigate the interface between coating and base material. By varying speed rate (1000-4000 mm/min), distance to focus (15-35 mm) and power output (0.5-1 kW) it was possible to produce a surface with satisfactory layer consistency, low dilution and optimized productivity. Based on the results, laser cladding demonstrated itself as an efficient process and a possible technique for the application of high quality clads.*

Key-words: Inconel® 625, laser cladding, corrosion protection, metal powder.

1. INTRODUCTION

Laser technology has a wide range of application, as polishing, alloying, drilling, cutting, joining, soldering, hardening, marking, ablation, generating and cladding. Indeed, every year new applications are found for laser usage. Laser cladding, or Laser Metal Deposition (LMD), is a coating technique for surface modification and it consists in melting the clad material by using a laser beam while depositing it on surface of the substrate. When the laser beam is moved away from the melting pool, the liquefied coat material is rapidly cooled by the bulk volume of the substrate, resulting in a refined-cast structure (Propawe, 2012; Abioye, 2015, and Heigel, 2016).

The aim of cladding a surface is to improve part properties or performance, or to replace material that was degraded. There are three different forms to add the powder coat material on the surface: off-axis powder injection (Figure 1a), continuous coaxial powder injection (Figure 1b) and discontinuous coaxial powder injection (Figure 1c). The continuous coaxial powder injection has the advantage over the off-axis when the applications involve additive manufacturing, in other words, 3D printing. However, for some cladding systems, when a tilt angle higher than 20˚ is required, the geometry of the clad can be affected greatly (Propawe, 2012; Abioye, 2015, and Heigel, 2016).

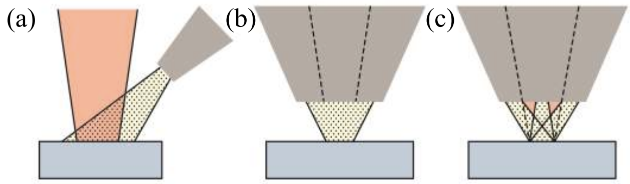

Figure 1. The most common types of powder injection approaches: (a) off-axis, (b) continuous coaxial and (c) discontinous coaxial. (Propawe, 2012)

In order to obtain good resistance against wear, erosion, oxidation or corrosion, the most popular alloys for cladding are those based on iron, nickel and cobalt compounds. Among these, Inconel® 625, a nickel-based-alloy, shows to be an usual choice for clads to prevent corrosion and to improve the material high temperature strength (Ion, 2005 and Al-Fadhli 2006). Inconel® 625 has a good advantage over other nickel-based alloys, because it has a good fusion weldability. Common uses for Inconel® clads are seawater exposed components, gas turbine ducting, hardware of furnaces and other applications from oil and gas industry (Lippold, 2008; Cielask, 1988; and Abioye, 2013).

Important parameters for the laser cladding process are laser power, beam diameter, processing speed, powder feeding rate, feeding gas rating and shielding gas ration. Their typical values according to Propawe, 2012 are showed in Tab. 1. In a materials science point of view, the coat and substrate material, powder morphology, powder grain size, degree of absorption and laser wavelength are also essential process variables to be considered (Propawe, 2012).

Table 1. Typical values of parameters for laser cladding (Propawe, 2012).

Parameter	**Typical values for LMD**
Laser power	200-4000 W
Beam diameter	0.6-8 mm
Speed	200-2000 mm/min
Powder feeding rate	0.5-30 g/min
Feeding gas rate	2-15 l/min Ar or He
Shielding gas rate	2-15 l/min Ar or He

The parameters combination can lead to different resulting morphologies of the clad track, which can be adequate or not for the cladding application. The three usual morphologies derivable from the laser cladding process are:

a) Thin layer with high metallurgical bonding, low contact angle, low dilution and small heat affected zone (HAZ) (Figure 2a).

b) Thin layer with deep metallurgical bonding, low contact angle, high dilution and large heat affected zone (HAZ), due to excess of energy to melt the powder (Figure 2b).

c) Layer with low metallurgical bonding, high contact angle and small heat affected zone (HAZ). High contact angle generates lack of clad filling in the interface between the substrate and clad (Figure 2c) (Steen, 2010).

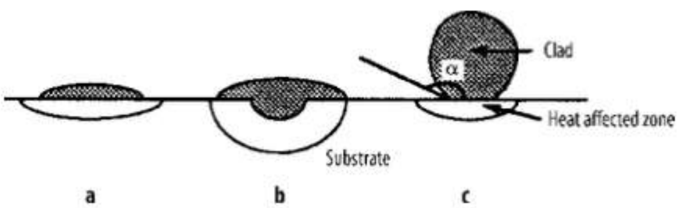

Figure 2. Main possible morphologies of the clad track (Steen, 2010).

An Yb-fiber laser is more appropriate for metal-applications that require precision, rather than a CO_2 laser. Also, laser cladding when compared with thermal spraying and arc weld, conventional techniques for coating, provides lower dilution, lower porosity, reduction in post-treatment machining operations, minimal distortion and equivalent – if not stronger - metallurgical bonding between clad and substrate (Abioye, 2015, Ion, 2005).

As feedstock material powder or wire can be used, however the choice of the feedstock will result in different depositions and process characteristics. Therefore, the advantages of using powder over wire are higher deposition control, suitable for a large range of materials, minimized heat input and distortion, layer thickness between 0.1 and 1.5 mm for a single layer, the flexibility of the process to change the variables and higher deposition quality attainment (Schneider, 1998).

2. EXPERIMENTAL PROCEDURE

2.1 Materials

Plates of ASTM A516 Gr. 70 were used as substrate material after sandblasting, to increase the surface laser absorptivity and to remove rust and other possible contaminations. Cladding material was Inconel® 625, supplied by Höganäs sieved to the particle size range of 53 to 106 µm. The chemical compositions of both material are given in Tab. 2.

Table 2. Chemical composition of Inconel® 625 and ASTM A516 - Gr.70.

	C %	Cr %	Si %	Ni %	Mo %	Fe %	Nb %	Mn%	S% (máx)	P% (máx)
Inconel 625	≤0.03	21.5	0.40	64	9	1.4	3.8	-	-	-
ASTM A516 - Gr. 70	0.27	-	0.13-0.45	-	-	Bal	-	0.85-1.2	0.02	0.02

Inconel powder was analyzed by Scanning Electron Microscopy (SEM) in different magnifications, with the intention of characterize the morphology and the particle size after sieving, which are key factors for having suitable flowability in the laser head and the powder feeder (Figure 3).

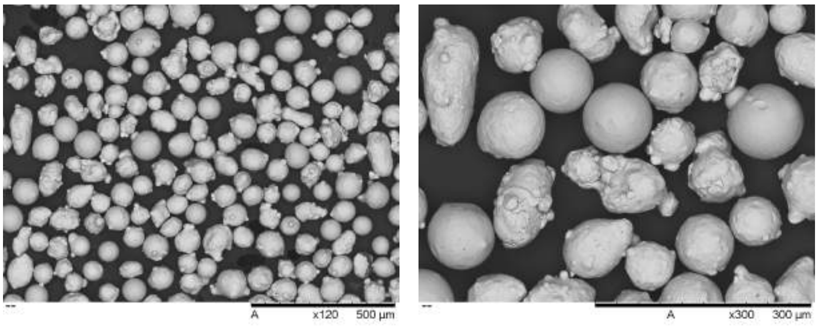

Figure 3. Morphology analysis by SEM of Inconel® 625 powder.

A portion of the analyzed particles has nearly spherical shape without any satellite particles attached, while the rest has a rounded non-spherical shape with satellite particles attached. The overall particle size is confirmed to be under 106 µm. When analyzing the chemical composition from the two different-shaped particle groups through energy-dispersive X-ray spectroscopy (EDS), it was noted that each group has a different composition, what implies – when considering the powder production processes of atomization - that the Inconel® 625 powder supplied is in fact a mix of two powders that combined provide the final alloy. Now, considering that the particle size is adequate and the greater part of the particles are spherical or nearly spherical, the sieved Inconel® 625 supplied by Höganäs is proven ideal for this laser processing.

2.2 Laser processing

The depositions were made using an IPG Photonics PS-YLS-10000 Yb-fiber Laser source, which generates continuous power output mode with maximum reachable power of 10 kW and operating at 1064 nm wavelength. The laser head optics provide a beam diameter of 0.80 mm at the focus position. The powder feeder, from GTV, PF LC 2/1 model, is presented on Figure 4 together with the cladding head assembly, controlled in Z direction, and the processing XY table, linked with the process chamber.

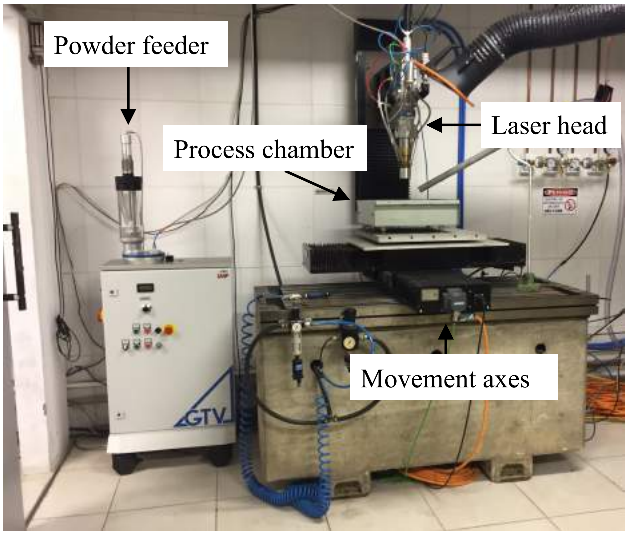

Figure 4. High power Laser processing system from Laboratório de Mecânica de Precisão (LMP).

In the initial tests, clad tracks of 20 mm long were made with varied speed rates (1000, 1500, 2000, 2500, 3500, 4000 mm/min), power outputs (0.5, 0.7, 1 and 1.2 kW), and distances to focus (15, 25 and 35 mm). All the tests were produced with powder flow of 15 g/min, argon was used as shielding gas (20 l/min) and carrier gas (5 l/min). Further on, based on quality aspects, three clad tracks were selected and used in overlapping tests, there with three different percentage values for the distance between the tracks (10%, 20% and 30%). Calculation of the overlapping was based on the Eq. (1) presented by Kairle (2012). Parameters are shown in Fig. 5.

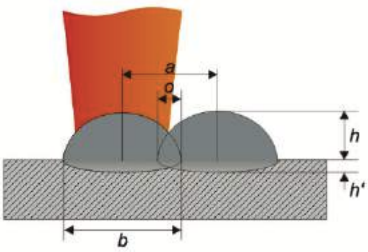

Figure 5. Parameters of laser cladding process (Kairle, 2012).

$$O = b - a/b \tag{1}$$

a = hatching distance, b = track width, o = overlap, O = overlap ratio.

2.3. Analysis

For clad and substrate characterization, scanning electron microscopy (Hitachi 3030), EDS, optical microscopy (Olympus BX60M) and microhardness techniques (Shimadzu HMV) were applied. As indicated at Fig. 6, the hardness outline was obtained by a Vickers microhardness testing machine. Hardness measurements I and II were made at the coated surface, III was made at the region of the substrate thermally affected zone and IV was at the original substrate. For a better data treatment, each measurement was repeated five times in the same overlapped sample, with intention to calculate average hardness values for each clad depth.

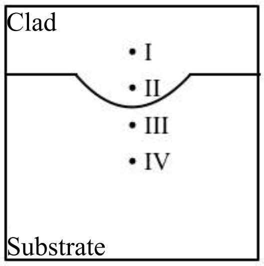

Figure 6. Scheme the positions of microhardness measurement points.

3. RESULTS AND DISCUSSION

Some of the results produced by the Inconel® laser cladding tests are presented on Fig. 7, with distance to focus fixed in 25 mm.

For the tests with speed rate of 4000 mm/min there was no deposition adhesion for the samples with lower power output (0.5, 1 kW) and higher distance to focus (25, 35), indicating that the power density was not enough to consolidate the clads. In addition, for some samples, the dilution and the heat affected zone (HAZ) clearly increases with higher levels of power output, as seen in the increase from 1.0 kW to 1.2 kW at 2000 mm/min (1% to 26%) and at 2500 mm/min (5% to 16%).

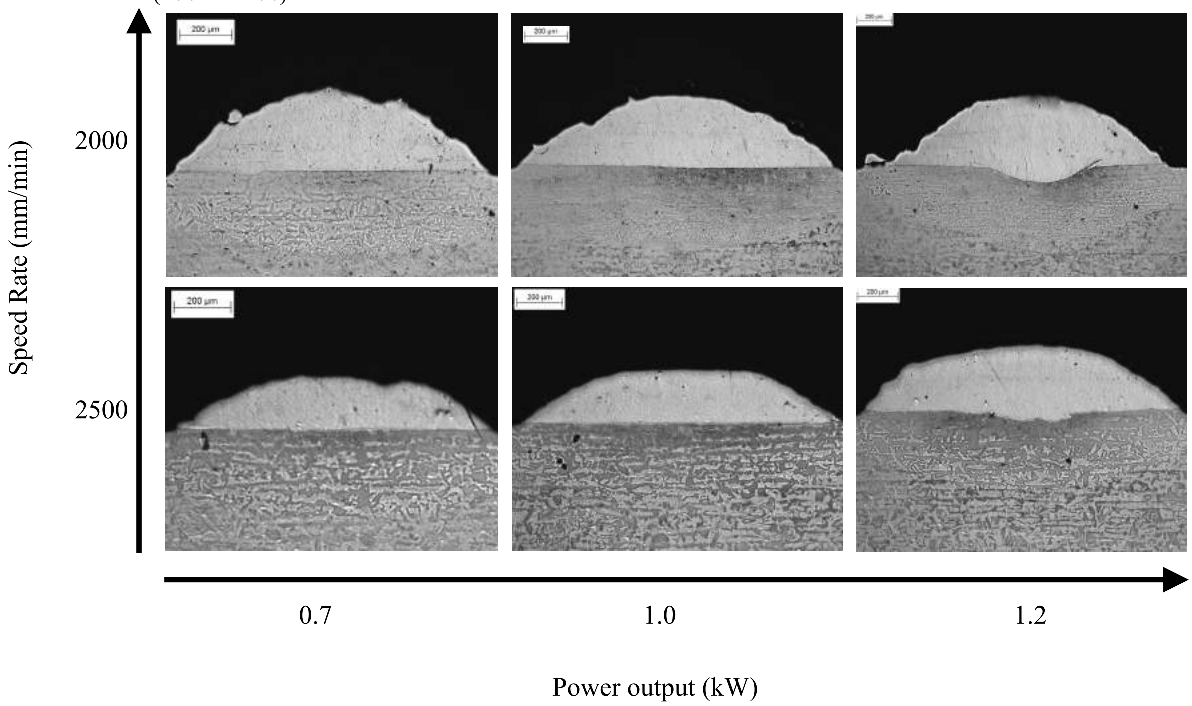

Figure 7. Micrographs from single clad lines.

Further, with the reduction of the distance from the sample's top surface to the laser focus there was an increase of dilution and of material deposition (Figure 8). The distance to focus of 15 mm generated dilution ratios up to 50%, much higher than the target of 8 to 10% (Figure 8a). The increase in the distance to focus, from 25 mm to 35 mm, caused a slight decrease of layer thickness, because the energy distribution on the material is higher when the distance to focus is lower.

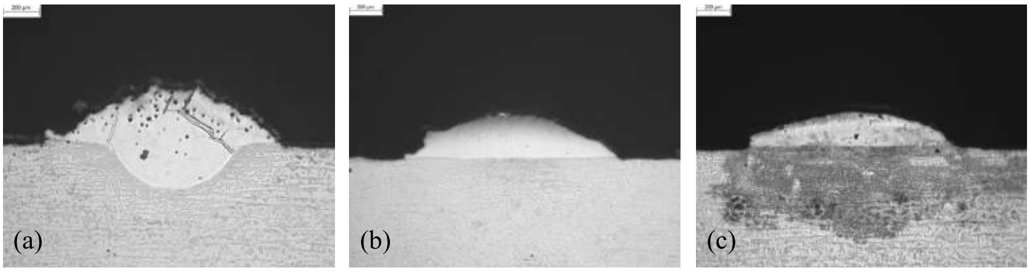

Figure 8. Parameters (a) 1.0 kW, 15 mm, 2500 mm/min; (b)1.0 kW, 25 mm, 2500 mm/min; and (c) 1.0 kW, 35 mm, 2500 mm/min

Taking also in consideration the process productivity (area that the material was deposited during a certain period of time), dilution ratio and integrity of the layer (low porosity and other defects), the samples selected for the further overlapping tests, with overlap ratio calculated by Eq. (1), were those with the following parameters: 0.5 kW, 15 mm, 1000 mm/min; 1 kW, 35 mm, 1000 mm/min; and 1.2 kW, 25 mm, 3000 mm/min (Figure 8). Each one of these three sets of clad parameters was used to produce overlapping samples with 10%, 20% and 30% of overlapping ratio.

From the nine samples produced, the three with better results with respect to dilution, productivity, absence of defects and coating thickness are depicted on Fig. 9, with 30% of overlapping (a, c) and 20% (b).

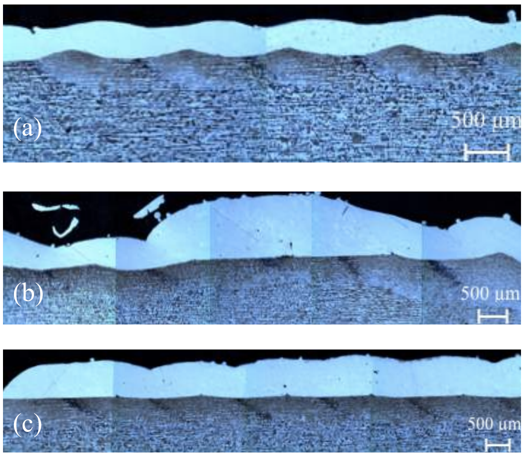

Figure 9. Parameters (a) 0.5 kW, 15 mm, 1000 mm/min, 30%; (b)1 kW, 35 mm, 1000 mm/min, 20%; and (c) 1.2 kW, 25 mm, 3000 mm/min, 30%.

As discussed before, the 0.5 kW resulted in a thinner layer (Figure 9a), however with this combination of speed rate, power output and distance to focus, higher dilution has been produced in contrast to the other two with higher powder output, but with different combinations of speed rate and distance to focus. The second sample (Figure 9b) presented higher porosity than the other ones. In the same sample, between the third and fourth clad it is possible to notice a lack of filling, probably due to an unfortunate blockage in the cladding nozzle caused by powder feedstock contamination. The last sample (Figure 9c) presented low dilution and strong metallurgical bonding between the substrate and coating. Further on, it exhibited the higher material deposition, however it presented a small porosity percentage.

With these samples, microhardness tests were made over the overlapped test, tracing the previously drawn outline between coat and substrate. Therefore, a similar behavior can be noticed between the three samples. The two first measurements (I, II) have qualitatively the same number for the three conditions. However, laser cladding with the following parameters 0.5 kW, 15 mm, 1000 mm/min (Figure 10 - black line) e 1 kW, 35 mm, 1000 mm/min (Figure 10 - gray line) presented a significant increase of microhardness in III. Processing with 1.2 kW, 25 mm, 3000 mm/min maintained the hardness practically constant until the original AISI 516 gr.70 alloy is reached (Figure 10 - blue line). All of them had a low and similar substrate hardness.

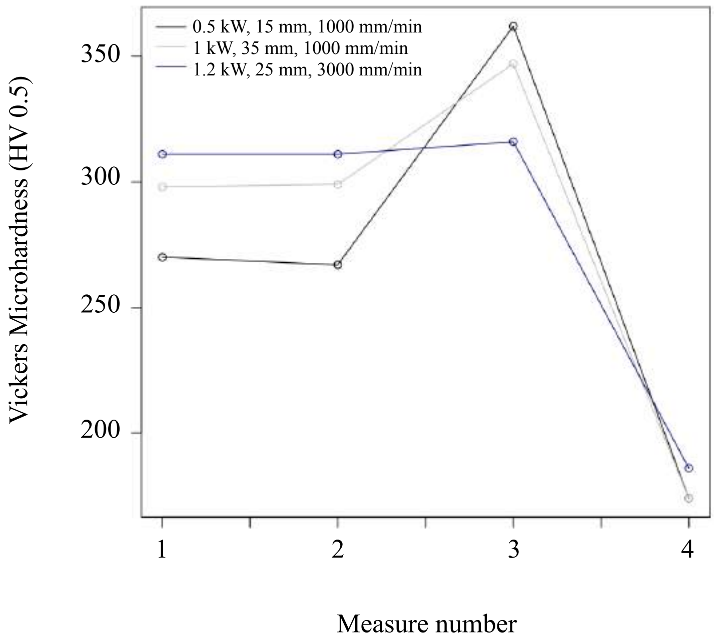

Figure 10. Microhardness (HV 0.5 for 10 seconds).

In the area with the increased microhardness, a martensitic microstructure was found (Figure 11). Thus, it can be concluded that with the increase of the temperature generated from the laser process and the successive rapid cooling, the material was quenched. Therefore, martensite was formed and, consequently, the microhardness in the area increased.

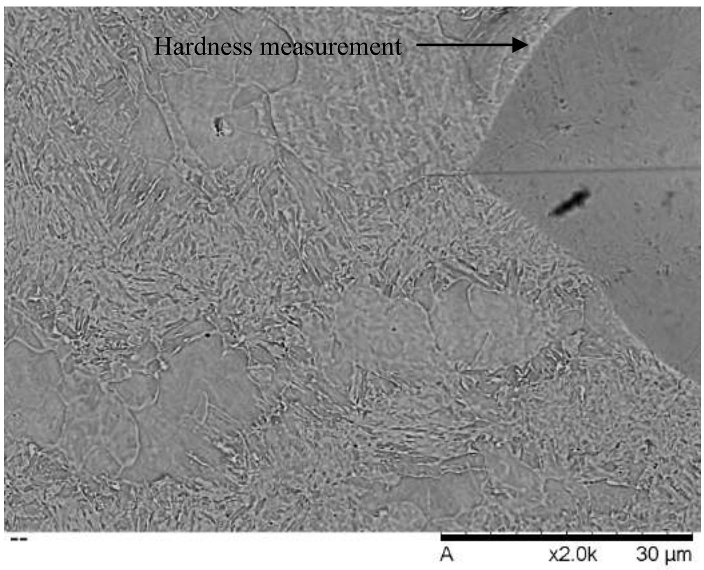

Figure 11 - Martensite microstructure in the sample 1 kW, 35 mm, 1000 mm/min.

4. CONCLUSIONS

The addition of Inconel® 625 powder by laser cladding on the surface of ASTM A516 – Gr. 70 substrate was successfully made, proving that the technology can be implemented at an industrial environment and adapted to suit specific application needs. Results proved that low dilution (below 5%) and strong metallurgical bonding between clad and substrate is attainable, as shown in literature. Significant martensite formation can be controlled by proper process parametrization.

In this study it was possible to infer that with constant powder feeding, higher power output and lower speed rate can lead to higher dilution, however, also in higher material deposition. Furthermore, a small distance from the substrate surface to the focus leads to higher dilution and higher layer thickness. Besides, the Inconel 625® clad promotes higher microhardness and corrosion resistance, if no cracks or damage of the coating layer were produced, thus, improving the surface properties of the ASTM A516 - Gr. 70 steel.

5. ACKNOWLEDGMENTS

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