Lasers in Manufacturing Conference 2013

Optimization of laser cladding for Al coating production

A. Riveiro\textsuperscript{a,b}, A. Mejías\textsuperscript{c}, F. Lusquiños\textsuperscript{b}, J. del Val\textsuperscript{b}, R. Comesaña\textsuperscript{d}, J. Pardo\textsuperscript{c}, J. Pou\textsuperscript{b,*}

\textsuperscript{a} Centro Universitario de la Defensa, Escuela Naval Militar, Plaza de España, Marín, E-36920, Spain
\textsuperscript{b} Applied Physics Department, University of Vigo, EEI, Lagoas-Marcosende, Vigo, E- 36310, Spain.
\textsuperscript{c} Business Organization Department, University of Vigo, EEI, Lagoas-Marcosende, Vigo, E- 36310, Spain
\textsuperscript{d} Materials Engineering, Applied Mechanics and Construction Dpt., University of Vigo, EEI, Lagoas-Marcosende, Vigo, E- 36310, Spain.

Abstract

The production of aluminum based coatings on a stainless steel (AISI 304) substrate by side laser cladding, and using a high power diode laser was experimentally studied. Relevant processing parameters were found and correlations between them were determined. Furthermore, the influence of the processing parameters on the costs associated to the process was examined. These relationships can be used as a guideline for the selection of proper processing parameters for laser cladding of this kind of materials.

© 2013 The Authors. Published by Elsevier B.V. Selection and/or peer-review under responsibility of the German Scientific Laser Society (WLT e.V.)

Keywords: laser cladding; aluminum; optimization; costs

1. Introduction

Materials used in certain industries are often exposed to very aggressive environmental conditions, such as high temperatures (Padture et al., 2002), extreme wear conditions (Budinski, 1991) or high mechanical stresses (Christin, 2002), among others. In order to accomplish this task, materials with extreme bulk properties are required, but also, their surface properties should be able, to some extent, to withstand these demanding requirements. Therefore, a modification of the surface properties of materials is needed in order to accomplish both demands. Currently, laser cladding is one of the industrial preferred surface engineering...
techniques for its ability to apply a chemically different material as a layer onto a given substrate. Its relevance in the industrial practice is a consequence of its many advantages over conventional coating techniques (e.g. arc welding or plasma spraying). These ranges from the possibility to produce denser coatings with little or no porosity, minimal dilution, minimal distortion of the workpiece, reduced heat affected zone, better surface quality, simplicity to automate or reduction in processing times, as discussed by (Toyserkani et al., 2005).

Laser cladding allows to improve different properties in the surface of a workpiece (Yellup, 1995; Zhong and Liu, 2010): mechanical (hardness, fatigue resistance, wear resistance) (Lusquiños et al., 2008), corrosion resistance (Watkins et al., 1997), biocompatibility (Comesaña et al., 2011), etc. On the other hand, this technique is very flexible in materials. Different metals (Santo, 2008; Lusquiños et al., 2009), ceramics (Lusquiños et al., 2008) and polymers (Ayrault et al., 1996) can be successfully clad. However, despite the interest in the production of aluminum coatings, for example, for corrosion protection purposes (Song, 2005; Pardo et al., 2009; Liu et al., 2010), the application of the laser cladding technique has only been explored in the past to improve the wear and corrosion resistance of magnesium alloys.

In this paper, the process of aluminum laser cladding on AISI 304 stainless steel is explored and the production of sound coatings is demonstrated. Furthermore, a cost analysis has been developed in order to determine the economic viability of the process in the industry and to select the most appropriated cladding conditions.

2. Experimental Setup

2.1. Laser cladding

Commercial pure aluminum powder (99.5% aluminum) from Ecka granules, with a mean particle size of 100-350 μm, and irregular morphology was used as coating precursor material. Stainless steel (AISI 304) plates, with dimensions of 400×140×16 mm³, were used as substrate material.

In this work, the side powder blowing technique was applied to obtain the coatings by laser surface cladding. This technique involves blowing particles of the precursor material by a carrier gas over a substrate which is moved with regard to the powder flow and the laser beam. A stationary high-power laser beam heats up the precursor material and creates a molten pool on the substrate where the particles impinge. On the other hand, a shielding inert gas is injected into the interaction zone in order to avoid the oxidation of the molten material. Finally, a rapid quenching of the molten pool takes place as it goes away from the laser interaction region and a coating track is formed on the surface of the substrate.

All laser cladding experiments were performed with a high power diode laser (Rofin Sinar DL-015) emitting at a wavelength of λ=0.940 μm and with a maximum power of 1500 W. The rectangular laser beam, with a top-hat laser beam energy distribution in the focal plane, was focused onto the surface of the substrate using a fused silica lens (focal length: 80 mm). Thus, the spot of the laser beam onto the substrate was 1.7 mm × 3.8 mm.

In order to obtain a relative displacement of the substrate with regard to the laser beam and the powder flow, a computer numerically controlled XY table is used.

The irradiance of the laser beam onto the sample was varied from 18000 to 21000 W/cm², with precursor powder values in the range of 19 to 24 mg s⁻¹, and substrate processing speeds between 1.0 and 4.0 mm s⁻¹.
2.2. Coating characterization

All clad tracks were geometrical characterized using a stereoscopic microscope equipped with a XY stage positioner with 1 μm resolution (Nikon SMZ10-A). Selected samples were embedded in Acryfix acrylic resin in order to characterize the tracks in cross-sectional view. They were cut and subsequently polished with a series of abrasive SiC papers up to grade 1200, followed by diamond paste finishing up to 0.1 μm. Next, samples were carbon coated and examined using a Philips XL-30 SEM system.

The main geometrical features evaluated in this study were clad width (mm), height (mm), aspect ratio and geometrical dilution.

2.3. Economic analysis

Total costs associated to the process were estimated for laser cladding using a diode, CO$_2$, fiber, and a Nd:YAG laser source in order to compare results. The geometry of the clad track was assumed to be semicircular with a constant radius $r_c=1$ cm. Absorptivity of coating and substrate materials was considered constant and equal to that of the bulk material (see Table 1). Argon was considered to be the processing gas to carry and protect the powder jet of coating material with a volumetric flow rate, in both cases of $V=10$ l/min. Regarding the motion system, this was considered to be performed by a XY table with a power consumption of 4 kW. The processing speed was assumed to be constant and equal to $v=1.67$ mm/s. Maintenance costs were also taken into account. Finally, cost were calculated as the ratio of costs per unit length of clad track (€/cm), in order to compare costs.

| Laser Source      | Absorptivity (%) |
|-------------------|------------------|
| Diode laser λ=940 nm | 13%              |
| Nd:YAG laser λ=1064 nm | 4%               |
| Fiber laser λ=1075 nm | 4%               |
| CO$_2$ laser λ=10600 nm | 1.1%             |

3. Results

3.1. Coating results

As depicted in Fig. 1, homogenous and dense tracks were obtained under the studied range of parameters. A slight cracking was noted in the surface of the clad tracks as a consequence of the non-preheating of the substrate. Clad tracks, with a mean value of 4.5 mm in width, 0.66 mm in depth, and 1.25 mm in height were produced.

As shown in Fig. 2, the width is observed to depend mainly on the irradiance and processing speed. The width increment due to irradiance increase is dependent on the processing speed. At high processing speeds the effect of the irradiance is attenuated; as the processing speed increases less energy per unit length contributes to the molten pool formation. On the other hand, this effect is less important at low processing speeds and the width of the clad track is substantially increased with the irradiance; in this case, the width evolves from 4 to 6 mm for an increment of 3000 W/cm$^2$ at a processing speed of 1 mm/s.
The clad height shows a reduction when the processing speed is increased (see Fig 3). During laser cladding experiments, the laser beam is focused onto the surface of the substrate and the powder is injected from the side. In consequence, particles are not exposed to the laser radiation enough time to melt before impinging on the molten pool in order to form the clad track. On the other hand, as the processing speed increases less energy per unit length contributes to the molten pool formation.

The influence of the mass flow is opposed to that of the processing speed. As noted in Fig. 3, an increment of the mass flow tends to produce an increase of the clad height; however, this increment is only substantial at low processing speeds. As the processing speed is increased, the energy per unit length of clad track diminishes; then, this energy is not enough to melt larger quantities of powder when the mass flow is incremented.
The aspect–ratio (width/height) of the tracks is plotted against the processing speed and mass flow in Fig. 4. It can be clearly seen that the aspect-ratio of clad tracks is increased with the processing speed. An opposite behavior is promoted by the mass flow; however, influence of the mass flow is more restricted and a reduction of this parameter affects to a lesser extent than the processing speed.

Regarding to the dilution of the clad tracks, the measured geometrical dilution (this parameter was evaluated according to the following formula: geometrical dilution= h/(h + d), where h: clad height and d: clad depth, see (del Val et al., 2010)) was plotted as a function of the processing speed and the mass flow (see Fig. 5). Tested conditions lead to geometrical dilution values in an interval of 10-60%, approximately. As the processing speed is increased or the mass flow decreased, the geometrical dilution raises. The increment of this parameter is higher at low processing speeds and at high mass flow.
3.2. Economic analysis

The economics of the process of laser cladding of aluminum using a diode laser has also been analyzed. Total costs associated to the process has been estimated to be 0.79 € per coated centimeter. The comparison of the total costs associated to the process using a diode, fibre, Nd:YAG and CO₂ laser is summarized in Fig. 6. Total cost of the process using a Nd:YAG laser is a 56.2 % larger than if a diode laser is used, mainly due to the higher electrical costs associated to the operation of this laser source.

Reduced costs during the processing assisted by a diode laser can be attributable to the following reasons: (1) the higher efficiency of this laser source, (2) the larger absorption of the aluminum to the wavelength of the radiation emitted by the diode laser and (3) the lower price of this laser source. The combination of these facts makes this laser as the optimal source from an economical point of view; however, the poor beam quality (e.g. low beam coherence and high beam divergence) of diode lasers prevents the focusing to a very small beam spot and makes them not suitable to perform details. In order to overcome this drawback, fiber and CO₂ lasers are alternative solutions.

From Fig. 6, it should be noted the higher performance of a fibre laser for this process, mainly due to the higher wall-plug efficiency (around 30%) as compared to the Nd:YAG laser.

On the other hand, a comparison of the costs associated to each identified contribution, namely, costs of processing gases, filler material, accessories (such as processing head or beam delivery systems), the laser and cooling system and the electrical costs, has been performed. It can be noticed that the cost associated to the filler material is the most relevant (see Fig. 7). Up to a 57% of the total cost can be related to the consumption of the filler material. Therefore, a main goal in diode laser cladding of aluminum should be the improvement of the powder catching efficiency in order to reduce costs associated to the process.

The contribution of the consumption of the processing gas has also a considerable impact on the total cost of the process. Its average influence on the total cost is up to a 27%.

The electrical costs are not very influential during the diode laser cladding process. This cost was estimated to be a 2% of the total cost, being this value even smaller than the cost due to the laser unit and its chiller (8%) or accessories (lenses, windows, etc.) 7%.
4. Conclusions

In this study the feasibility of diode laser cladding for the production of aluminum coatings was demonstrated. Clad tracks, approximately, 4.5 mm in width, 0.66 mm in depth, and 1.25 mm in height were produced. Behavior of geometric characteristics of the clad tracks as a function of the processing parameters has also been determined.

On the other hand, total costs of the process have been studied and the contribution of each part of the process determined. An average cost for the process around 0.79 €/cm was estimated. The analysis of the influence of each parameter on the total cost of the process reveals the filler material as the most influential parameter. This parameter is more decisive on the total cost than the laser unit and cooling system. This rejects the conventional idea of the high capital cost related to the laser source, because its influence in the total cost of the process is limited compared to the contribution of filler material to the total cost of the process or the gas consumption.
Relationships found in this work for processing can be used as a guideline for the selection of proper processing parameters for laser cladding of this kind of materials in order to optimize results, both, from the point of view of the coating quality or process economy.

Acknowledgements

This work was partially supported by the Spanish Government (CICYT/FEDER MAT2009-14412) and by Xunta de Galicia (CN2012/292).

References

Ayrault, S., Canonge, C., Vannes, A.B., 1996. Laser cladding on thermoplastic polymers, Lasers in Engineering 5, p. 11.
Budinski, K.G., 1991. Tribological properties of titanium alloys, Wear 151, p. 203.
Christin, F., 2002. Design, fabrication, and application of thermostructural composites (TSC) like C/C, C/SiC, and SiC/SiC composites, Advanced Engineering Materials 4, p. 903.
Comesaña, R., Lusquiños, F., del Val, J., López-Alvarez, M., Quintero, F., Riveiro, A., Boutinguiza, M., de Carlos, A., Jones, J.R., Hill, R.G., Pou, J., 2011. Three-dimensional bioactive glass implants fabricated by rapid prototyping based on CO₂ laser cladding, Acta Biomaterialia 7, p. 3476.
del Val, J., Comesaña, R., Lusquiños, F., Boutinguiza, M., Riveiro, A., Quintero, F., Pou, J., 2010. Laser cladding of Co-based superalloy coatings: Comparative study between Nd:YAG laser and fibre laser, Surface and Coatings Technology 204, p. 1957.
Liu, L.M., Wang, Z., Song, G., 2010. Study on corrosion resistance properties of hydrothermal sealed arc sprayed aluminium coating, Surface Engineering 26, p. 399.
Lusquiños, F., Comesaña, R., Riveiro, A., Quintero, F., Pou, J., 2009. Fibre laser micro-cladding of Co-based alloys on stainless steel, Surface and Coatings Technology 203, p. 1933.
Lusquiños, F., Pou, J., Quintero, F., Pérez-Amor, M., 2008. Laser cladding of SiC/Si composite coating on Si-SiC ceramic substrates, Surface and Coatings Technology 202, p. 1588.
Padture, N.P., Gell, M., Jordan, E.H., 2002. Thermal barrier coatings for gas-turbine engine applications, Science 296, p. 280.
Pardo, A., Casajús, P., Mohedano, M., Coy, A.E., Viejo, F., Torres, B., Matykina, E., 2009. Corrosion protection of Mg/Al alloys by thermal sprayed aluminium coatings, Applied Surface Science 255, p. 6968.
Santo, L., 2008. Laser cladding of metals: A review, International Journal of Surface Science and Engineering 2, p. 327.
Song, G., 2005. Recent progress in corrosion and protection of magnesium alloys, Advanced Engineering Materials 7, p. 563.
Toyserkani, E., Khajepour, A., Corbin, S., 2005. Laser cladding. CRC Press, Boca Raton.
Watkins, K.G., McMahon, M.A., Steen, W.M., 1997. Microstructure and corrosion properties of laser surface processed aluminium alloys: a review, Materials Science and Engineering: A. 231, p. 55.
Yellup, J.M., 1995. Laser cladding using the powder blowing technique, Surface and Coatings Technology 71, p. 121.
Zhong, M., Liu, W., 2010. Laser surface cladding: The state of the art and challenges, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 224, p.1041.