Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 74 (2018) 201–205

www.elsevier.com/locate/procedia

10th CIRP Conference on Photonic Technologies [LANE 2018]

Characteristics of Fe-based powder coatings fabricated by laser metal deposition with annular and four stream nozzles

Pedro Ramiro[a,*], Mikel Ortiz [a], Amaia Alberdi[a], Aitzol Lamikiz[b]

[a]*Tecnalia Research and Innovation Paseo Mikeletegi 7, 20009 Donostia-San Sebastián, Spain*
[b]*Department of Mechanical engineering, Faculty of Engineering of Bilbao, University of Basque Country, Alameda de Urquijo s/n 48013 Bilbao, Spain*

* Corresponding author. *E-mail address:* pedro.ramiro@tecnalia.com

Abstract

The present work focuses on performing a comparative study in the field of Laser Metal Deposition (LMD) analyzing the obtained clads in terms of geometry and quality when vertically using a discrete coaxial nozzle or an annular one. A Fe-based alloy powder (Eutroloy 16606A.04) was used for the study, a heat treatable alloy, with high wear-resistant to abrasion and fatigue stress, typically employed for coating applications. The possibility of controlling the coating process with a non-coaxial thermographic camera has also been evaluated.

Keywords: Laser metal deposition; coatings; geometrical characteristics; Fe-Based alloy; continuous nozzle; discrete nozzle

1. Introduction

Some of the applications of the Laser Metal Deposition (LMD) are the coating and repairing of components subjected to high wear, replacing and bringing back to tolerance a coating that has suffered excessive erosion, thus increasing substantially the life-cycle of the component and reducing the need for the production of a new one. The resulting mixture changes the surface properties and the substrate becomes a composite material with improved properties. LMD process by powder injection has been demonstrated to be effective and flexible technology for this application [1] with a wide range of materials not available in wire form.

The objective of the present study is to manufacture high-resistant coatings by LMD with continuous and discrete nozzles and compare the obtained main geometrical parameters, hardness, quality, productivity and efficiency of depositions to determinate the best nozzle option in vertical applications. For that, this study presents an experimental study using three different coaxial nozzles: annular of 1.0mm powder focus diameter, annular of 0.5mm powder focus diameter and 4-stream one of 2mm powder focus diameter. Although the commonly used powder materials for this kind of applications are Ni-based or Co-based alloys [2,3], the selected material for this study was Eutroloy 16606A. 04, a martensitic Fe-based alloy that has previously shown good quality coatings in a hardened 42CrMoS4 steel substrate without the needed of preheating [4]. This substrate is typically used for the production of shafts, crankshafts and screws.

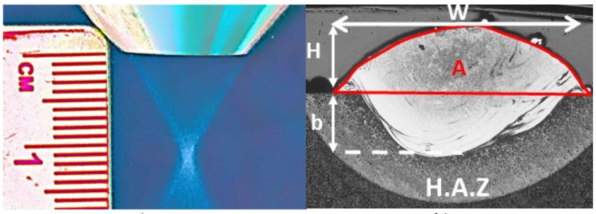
Furthermore, the coating process temperature was monitored with a thermographic camera, featuring a non-coaxial disposition, to obtain the relationship between the process parameters and the melt pool temperature.

2. Experimental procedure

2.1. Materials

The material used as a substrate material was a turned and hardened 42CrMoS4 steel alloy bar of 74 mm in diameter and 160 mm in length. Some of the properties of this material are a bad weldability, due to the high crack danger, and medium-good hardenability. In a previous work, it was demonstrated

2212-8271 © 2018 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license
(https://creativecommons.org/licenses/by-nc-nd/4.0/)
Peer-review under responsibility of the Bayerisches Laserzentrum GmbH.
10.1016/j.procir.2018.08.094



a) b)

Fig. 1. a) Powder mass flow of a continuous coaxial nozzle of 0.50mm b) single clad macrophotography: P=2.5KW, R50%, F=8.3mm/s, 4-way nozzle.

that is not necessary to preheat the substrate, as occurs in thermal spraying process, to obtain defects free coatings [4].

Hardening started with a heating process in an oven at 850ºC for 2.5h, quenched in oil, tempered at 250ºC for 2.5h and cooled down slowly at room temperature. The hardness was measured before and after the hardening process, obtaining a hardness of 33 and 52 HRC respectively.

The powder used to produce the coatings was Eutroloy 16606A .04 (Fe-based) and was characterized in terms of morphology determined by SEM, size distribution determined by laser diffraction, fluidity according to ISO 4490 standard and chemical analysis. Low sphericity, small powder grain size and low fluidity have consequences of producing irregular powder mass flow rate. In this case, the powder presented a regular mass flow (Table 1).

Table 1. Properties of Eutroloy 16606A.04 powder and chemical compositions of both powder and substrate materials (wt %)

Shape	*Size (µm) d50*	*Fluidity (s/50g)*	*Density (g/cm³)*	*Tap Density (g/cm³)*
spherical	113	11.9	7.9	4.6

	C	*Si*	*Mn*	*Cr*	*Mo*	*W*	*V*
Powder	0.86	0.31	0.31	4.60	4.90	6.50	1.70
Substrate	0.40	0.31	0.76	1.04	0.16	-	-

2.2. Hybrid (LMD+machining) machine

All tests were performed in an IBARMIA ZVH45/1600 Add+process hybrid machine. This multiprocess machine combines the LMD technology with 5 axis milling and turning capacity. This machine is equipped with a Precitec YC52LMD coaxial head with the possibility of assembling annular or 4- stream powder feed modules. The system also uses a Sulzer Metco TWIN-10-C Powder Feeder and an Yb-Fiber Rofin FL030 Laser generator of 3kW with a continuous wavelength of 1.07 µm. The laser head features a focusing screw that offers the possibility of moving up to 10mm the collimating optics in the direction of focusing optics changing the laser beam diameter in the powder focus.

2.3. Experimental testing

The experimental testing consisted on first, performing single clad tests at different conditions of laser power (P), feed rate (F), laser head focusing screw and powder mass flow rate (ṁp) for selecting four optimum process combinations for each nozzle. Then, the selected combinations of parameters were validated by performing overlapped tests.

The tests were performed with the laser beam focused at different distances above the substrate surface depending on the distance of the minimum diameter of the powder focus that each nozzle featured (Figure 1-a). This distance was determinate for each nozzle by means of an image analyser software (Clemex Captiva®).

The substrate material was cleaned and degreased before the additive process with acetone and centered with a roundness of ±0,01mm deviation. The bar was rotated in the horizontal turning spindle. Since the powder feeding is regulated by a rotating wheel, the parameter that defines the powder mass flow rate is the percentage of the maximum rotation of the wheel. The relation between the powder feeder rotating wheel speed percentage (R) and the powder mass flow rate (g/s) was defined by collecting and weighting the powder delivered in three minutes at different values of R and can be expressed by the linear equation 1.

2.3.1. Single clads

In order to select optimum process parameters in terms of quality (no pores and cracks), efficiency and MDR for each nozzle, first, single clads were carried out at all parameters combinations stated in Table 2. The conclusions obtained in the study performed with the discrete 4-stream nozzle that had been previously carried out [4] were used to define an improved process parameter window for the study of the annular nozzles. In the mentioned study, higher laser power than 2000W was necessary to obtain an acceptable clad integrity.

All clads were observed in the microscope to analyse the microstructural integrity of the deposition using optical and scanning electron microscopy. The samples were chemically etched by Vilella etching. In addition to the microstructural integrity, each single clad was measured geometrically in terms of height (H), width (W), penetration (b) and area (A) by employing image analyzer software (Clemex Captiva®), as shown in Figure 1-b. The dilution (d), the Material Deposition Rate (MDR) and the powder efficiency (η) were calculated using the following equations:

$$\dot{m}p = 0.0066 \cdot R(\%) \quad (1) \qquad \eta = \frac{MDR}{\dot{m}p} \quad (2)$$

$$MDR = A \cdot \rho \cdot F \quad (3) \qquad d\,(\%) = \left(\frac{b}{b+H}\right) \cdot 100 \quad (4)$$

Table 2. Main process parameters. Single clads tests conditions.

P (W)	*R (%)*	*F (mm/s)*	*Coaxial Nozzle (focusing screw)*
1500-2500	*50-75%*	*12.5-20.8*	*Discrete 4-stream (10)*
1500-2100	*10-20-30%*	*8.3-15*	*Annular 0.5mm (2)(4)*
2100-2700	*30-40%*	*8.3-15*	*Annular 1.0mm (6)(8)*

2.3.2. Overlapped clads

The analysis of single clads served to select the optimum processing conditions for each nozzle. In the 4-stream nozzle case, the optimum parameters consisted on a powder feed rate correspondent to a R50% and 2.5 kW of laser power. In the case of coaxial nozzles, the test conditions with focusing screw values of 4 and 8 were selected as optimum parameters. These conditions were used to fabricate overlapped clads by rotating the steel bar meanwhile the laser track moved along the traversal axis. To obtain a uniform thickness, all the coatings were created with 40% and 50% overlapping of the single clad width. In the overlapped clads, in addition to the characteristics measured and calculated in the single clads (H, W, b, MDR, η and d), the productivity rate (Pr) was also calculated as the surface area coated per minute, which can be calculated using the equation 5. The cylinder was weighted before and after the cladding process for obtaining the deposited powder.

$$Pr = W \cdot (1 - overlap\%) \cdot F \quad (5)$$

2.4. Thermographic measurements

The temperature of the melt pool in the overlapped case was registered using an Optris Thermographic camera with a wavelength of 0.5 µm. Infra-red cameras provide detailed information with a higher spatial and temporal resolution than the pyrometers. The camera was joined to the headstock with an articulated arm. A protective lens was used to protect the camera from damages due to laser reflections.

The camera was positioned in a fixed position focused to the melt pool, being the measured area the same in all coatings. The evolution of the maximum, minimum and mean temperature values was compared and a relation between the trend of the temperature and the main process parameters was found in agreement to Bi G et al [5]. The emissivity was set in order to delimiting the measurements to the range of measurement (1000-2000ºC) of the thermographic camera. Thus the obtained temperature values are considered relative.

3. Results and discussion

3.1. Single clads analysis

All single clads were cracks free but the efficiency was noticeably lower at fewer power and focusing screw values. The clad quality, geometric characteristics and efficiency were higher at higher laser power and lower speed rates. Furthermore, the efficiency has an inflexion point that depends on the powder mass flow (Table 3) and the type of nozzle. The higher efficiency was reached with an annular nozzle of 0.5 powder focus diameter (79%). The annular nozzle of 1mm reached an efficiency of 69% and the 4-stream nozzle of 45%.

In the discrete 4-stream nozzle case, the best clads were obtained with 2500W laser power and 50% powder feed rate. In the 0.5mm coaxial nozzle case, the best clads were obtained with a focusing screw value of 4 and 2100W laser power whereas in the case of 1mm coaxial nozzle, the focusing screw value was 8 and laser power value 2700W.

Table 3. Efficiency values for the 0.5mm annular nozzle, (focusing screw 4).

R (%)	P(W)	F(mm/s)	Efficiency (%)
10	2100	8.3-15	73.20-65.01%
20	**2100**	**8.3-15**	**79.10-73.98%**
30	2100	8.3-15	71.82-65.91%

3.1.1. Relationship between clad characteristics and process parameters

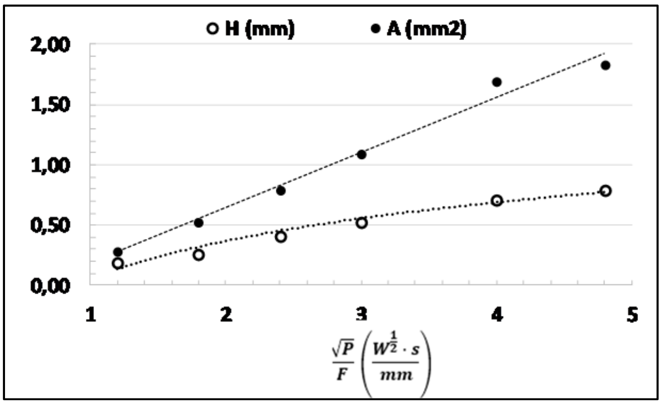


Fig. 2. Area (linear) and height (logarithmic) trend, 4-stream nozzle, R50%, P=2500W, Focusing screw 10. Y-axis: area and height values.

The single clads done with annular nozzles showed the same relationships between the clad characteristics and the main process parameters (P and F) found using the 4-stream nozzle. The dependence with such parameters and the type of trend for each characteristic was explained in a previous work [4]. 6 clads were done to validate this trend with the 4-stream nozzle at the bests conditions (2500W, R50%, focusing screw at 10) and a feed rate range of 10.4 to 41.7mm/s. The dependence with such parameters for each characteristic is summarized in Table 4. Some examples of these relationships are shown in Figure 2.

Table 4. Dependence of the single clads parameters.

Clad Characteristic	Dependence parameter	Type of trend
Width, efficiency and deposition rate	$\frac{\sqrt{P^3}}{F}$	Logarithmic and polynomial
Height and area	$\frac{\sqrt{P}}{F}$	Logarithmic and linear

Note. Adapted from “Characteristics of Fe-, Ni- and Co-based powder coatings fabricated by laser metal deposition without preheating the base material”, by *Ramiro et al*, 2018, Procedia CIRP, 68, p. 381-386.

3.2. Overlapped clads analysis

All the coatings showed homogenous characteristics after the third overlapped clad. The coatings done with the same parameters of the best single clads and showing a dilution range between 20-40% presented the best quality. In most cases, the dilution of the coatings with cracks or lower hardness was higher than 40% and big pores or lack of fusion appeared with dilution fewer to 20%. The coatings in the range of 20-40% of dilution showed defects free structure or with fewer than 10 pores of 75-35µm, and high hardness. The best coatings done with the annular nozzle of 1.00mm were overlapped at 40%. In the other nozzles, at 50%. With the annular nozzle of 0.50mm, it was necessary to decrease the feed rate to 5mm/s at R20% to obtain a good quality clad. The results regarding the best coating parameters and their associated characteristics for each type of nozzle are summarized in Table 5.

Table 5. Best coatings parameters and characteristics.

INPUTS					
Coaxial nozzle	R (%)	P (W)	F (mm/s)	Overlap (%)	Focusing screw
Annular D0.5mm	20	2100	5	50	4
Annular D1mm	40	2700	8.3	40	8
Discrete 4-stream	50	2500	12.5	50	10

OUTPUTS					
H (mm)	d (%)	MDR (g/s)	η (%)	Pr (mm^2/s)	HRC
1.90	27.5%	0.10	76.8%	6.65	61
1.47	28.6%	0.21	80.0%	17.4	63
1.15	22.7%	0.16	45.0%	18.2	62

3.3. Monitored temperature analysis

The mean and minimum temperature values showed low differences varying the coating parameters. On the contrary, the maximum temperature showed logic variations as a function of the employed process parameters.

The temperature evolution in all cases featured a peak value at the beginning of the coating with a gradual decreasing until the third clad, where the signal became more regular. The noise measured was caused by the disturbances produced by the powder flow. A quantitative analysis of the measurements points out that the temperature of the melt pool increases both increasing the overlap value and the laser power or on the contrary, reducing the powder flow or feed rate value.

On the other hand, a high increase in the range of the noise was detected when the protective lens of the laser head suffered damage (Fig. 3). This fact combined with the sensibility of the temperature changes related to variations in values of laser power, feed rate and powder flow rate suggest the possible application of the non-coaxial camera set-up like an alarm system to detect an incorrect operation of the coating process comparing the noise with a control signal.

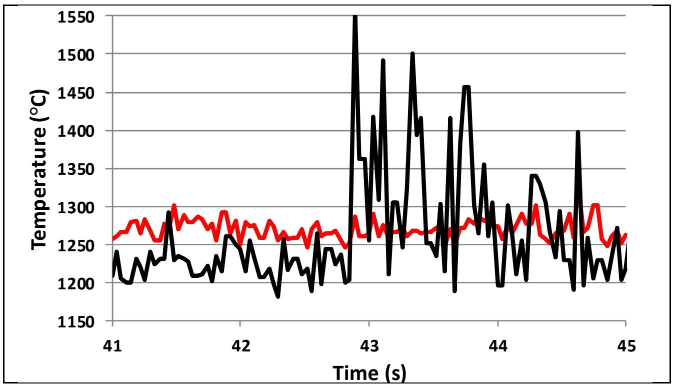


Fig. 3. Maximum temperature measurement with a 0.50 mm coaxial nozzle, 2100W, 15 mm/s, R30%, overlap 40%. Red line: control signal, Black line: Increase of the noise due to the damage of the protective lens.

4. Conclusions and future work

This study demonstrated that coating by laser metal deposition a hardened 42CrMoS4 steel substrate with Eutroloy 16606A.04 without preheating process and defects is possible using both annular and 4-stream nozzles. However, the best results for vertical applications were obtained with the annular nozzle of 1.00 mm with zero defects, a hardness of 63 HRC, a productivity of 17.4 mm^2/s, a MDR of 0.21 g/s and an efficiency of 80%.

Regarding the single clad analysis, the obtained trends in a previous work between clad characteristics and both laser power and the feed rate were observed in the clads done with annular nozzles and was validated with the 4-stream nozzle. The possibility of obtaining an equation for each single clad characteristic as a function of these parameters has to be studied.

The thermographic measurements of the melt pool obtained by means of a non-coaxial disposition have shown logic variations depend on the employed process parameters. This fact suggests the possible application of the presented camera set-up like an alarm system to detect an incorrect operation of the coating process. A deeper study of this possibility has to be done.

Acknowledgements

The authors acknowledge the European Commission for support of Project "PARADDISE: a Productive, Affordable and Reliable solution for large scale manufacturing of metallic components by combining laser-based ADDItive and Subtractive processes with high Efficiency" (Grant Agreement 723440), which is an initiative of the Photonics and Factories of the Future Public Private Partnership.

References

[1] Houdková, Šárka, Zdenek Pala, Eva Smazalová, Marek Vostřák, and Zdeněk Česánek. Microstructure and sliding wear properties of HVOF sprayed, laser remelted and laser clad stellite 6 coatings. Surface and Coatings Technology

[2] Hemmati, I., V. Ocelík, and J. Th M. De Hosson. 2013. Toughening mechanism for Ni–Cr–B–Si–C laser deposited coatings. Materials Science and Engineering: A 582 (10/10): 305-15.

[3] Ocelík, V., J. Bosgra, and J. Th M. de Hosson. 2009. In-situ strain observation in high power laser cladding. Surface and Coatings Technology 203 (20–21) (7/15): 3189-96.
[4] Ramiro, P., Alberdi, A., Ortiz, M., Lamikiz, A., Ukar, E. Characteristics of Fe-, Ni- and Co-based powder coatings fabricated by laser metal deposition without preheating the base material. Procedia CIRP 68: 381-386.
[5] Bi G, Gasser A, Wissenbach K, Drenker A, Poprawe R. Identification and qualification of temperature signal for monitoring and control in laser cladding. Optics and Lasers in Engineering 2006 December 2006;44(12):1348-59