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Procedia CIRP 74 (2018) 733–737

www.elsevier.com/locate/procedia

10th CIRP Conference on Photonic Technologies [LANE 2018]

Study of the porosity generated by the use of cutting fluid in hybrid processes combining machining and Laser Metal Deposition (LMD)

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Abstract

The use of hybrid manufacturing processes that combine additive and machining operations is on increase and an example of it is the fact that the most advanced machine tool manufacturers have developed hybrid machines solutions. Nevertheless, cutting fluid required for machining operations can present several problems for the Laser Metal Deposition (LMD) process. In order to solve this issue, the present work evaluates the influence of the coolants in the LMD process from the point of view of pore generation and clad quality. For this purpose, several tests are performed on a part impregnated with cutting fluid, both directly and after the elimination of the fluid by means of different alternatives.

Keywords: additive manufacturing; laser metal deposition; hybrid machines; cutting fluid; coolant; lubricant; porosity; clad quality

1. Introduction

Global manufacturing demands processes that provide higher flexibility and efficiency, while maintaining part quality [1]. The production of high complexity parts may involve several process-stages and multiple setups until the final product is attained. However, combining different processes within a single machine presents interesting opportunities, such as improving material utilization and reducing processing times [2]. Modern industry is heading to the combination of additive and subtractive manufacturing, allowing the manufacturing of ready to use products within one single machine and, therefore, harnessing the potential of each process [3]. Leading machine tool manufacturers, such as DMG Mori or Mazak, have adopted Laser Metal Deposition (LMD) technology and CNC milling as additive and subtractive manufacturing methods, respectively [4, 5].

Laser Metal Deposition enables the fabrication of fully dense near-net-shape parts with high quality metallurgical bond to the substrate. The laser generates a melt pool by melting a thin layer on the surface of the substrate while filler material, in the form of wire or powder, is simultaneously fed into the melt pool. Line by line, new layers are generated and, consequently, the desired part geometry is attained [6]. The application of LMD focuses on the manufacturing or repair of high added value functional parts. Therefore, it has a wide spectrum of industrial applications, ranging from space and aircraft sectors to automotive or biomedical among others [7].

The integration of LMD and machining processes within a single machine strengthens both processes advantages. However, this combination gives rise to some problems, such as the presence of cutting fluid on the part after the machining stage, what may degrade the quality of the deposited material. In spite of the emergence of machining processes that use no cutting fluid, such as cryogenic or dry machining, their use is still quite limited when processing low machinability materials [8]. Therefore, cutting fluids are in many cases unavoidable and widely used when machining.

The present research work is based on a previous study [9] and aims to analyze the influence of cutting fluid in the LMD process by depositing Inconel 718 on a part previously impregnated with cutting fluid. Then, the influence of the different oil concentrations and cleaning methods employed is evaluated in terms of porosity and clad quality.

10.1016/j.procir.2018.08.021

2. Materials and Experimental Procedure

The investigations described in this work are executed on a 5-axis milling center rebuilt as a laser-processing machine. In addition, a Yb:YAG fiber laser source, Rofin FL010, with a maximum power output of 1 kW and wavelength of 1070 nm is employed. The laser beam is delivered through an optical fiber to the processing cell, generating a circular laser spot of 2 mm on the surface of the workpiece. The powder is fed by means of a Sulzer Metco Twin 10-C powder feeder and a coaxial LMD nozzle, the EHUCoax-2015 [10], while argon is used as both carrier and shielding gas.

Inconel 718 superalloy, widely known and employed in the aeronautical sector, has been chosen for the realization of the experiments. MetcoClad 718 gas-atomized nickel-base superalloy powder, with a particle size range between 44 and 90 µm and similar in composition to Inconel 718, has been used as filler material for the LMD process. The chemical composition of the materials is shown in Table 1 and Table 2.

Table 1. Chemical composition (wt. %) of Inconel 718 [11].

Cr	Mo	Nb	Fe	Ti	Si	Mn	C	B	Ni
19.0	3.0	5.0	18.0	1.0	0.2	0.08	0.05	0.005	Bal.

Table 2. Chemical composition (wt. %) of MetcoClad 718 [12].

Cr	Mo	Nb	Fe	Ti	Si	Mn	C	B	Ni
19.0	3.05	5.1	19.0	0.9	0.18	0.18	0.04	0.003	Bal.

For the realization of the experiments, Inconel 718 substrate is covered with an oil-water emulsion with the help of a dropper so that a constant liquid layer thickness was guaranteed. The emulsion is prepared by mixing water and Houghton HOCUT B-750 cutting fluid, which is used as coolant and lubricant in machining processes with oil concentrations of 5-10% [13]. Hence, oil concentrations of 5, 10 and 100% are selected for the execution of the present research work. For each concentration, the same LMD tests are performed, the difference resides on the cleaning methods employed. A list of the laser parameters used is shown in Table 3.

Table 3. List of LMD process parameters.

LMD process parameters	Value
Continuous wave laser power (W)	571
Scan velocity ($mm \cdot min^{-1}$)	525
Overlap between tracks (%)	26
Powder feed ($g \cdot min^{-1}$)	8.78
Protective gas flow rate ($L \cdot min^{-1}$)	14

A preliminary test without any cutting fluid is performed in order to determine clean results and use them as a reference. Then, for each concentration, 1) direct deposition (without cleaning), 2) deposition after air blasting and 3) after laser cleaning are performed. Air blasting is done with 7 bar air pressure, while laser cleaning is carried out at 200 W and 100 mm defocusing distance.

Three cross sections of each sample are extracted, polished and etched. Afterwards, images of each section are acquired and Matlab R2017b software is used for analyzing the images and determining the resulting porosity within the deposited material. In addition, clad quality is also analyzed in qualitative terms.

3. Results and Discussion

The results collected after the analysis of the different samples are presented in the form of percentage of porosity, which represents the amount of pores within the deposited material. Afterwards, these results are compared to the reference test performed on clean substrate, where a 0.002% porosity is measured, as shown in Fig. 1b. The quality of the clads is also analyzed by comparing metallographies of the deposited material etched with Marble solution.

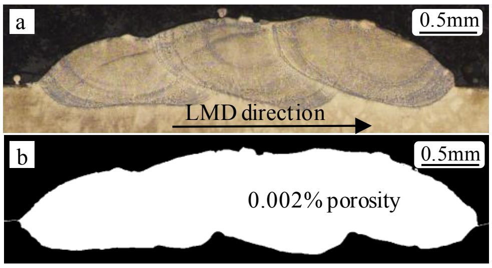

Fig. 1. Reference test (a) metallography; (b) average porosity results.

In Fig. 1a above, both the dilution of the deposited material and the penetration of the laser beam in the substrate are qualitatively appreciated.

3.1. 5% concentration results

An average porosity of 0.019% is obtained for direct LMD (no cleaning), while results attained after air blasting, 0.002%, and laser cleaning, 0.003%, show a considerable decrease on the average porosity value compared to no cleaning. Results are shown in Fig. 2.

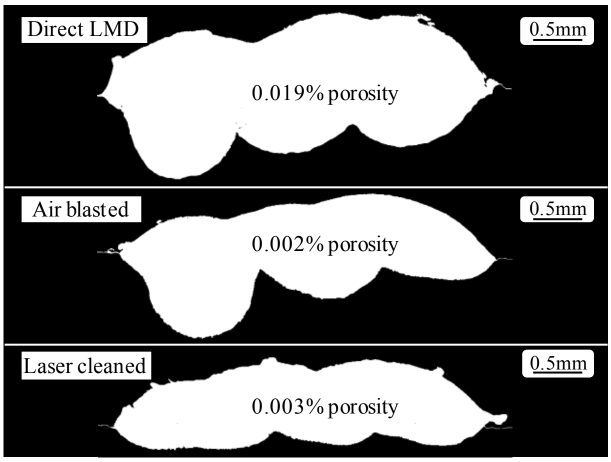

Fig. 2. 5% concentration tests porosity results.

Besides, the direct LMD test (no cleaning) shows a bigger penetration of the deposited material within the substrate, which is reduced in cleaned tests (air blasted and laser cleaned). An example of the appearance of the cross sections of the tests is shown in Fig. 3.

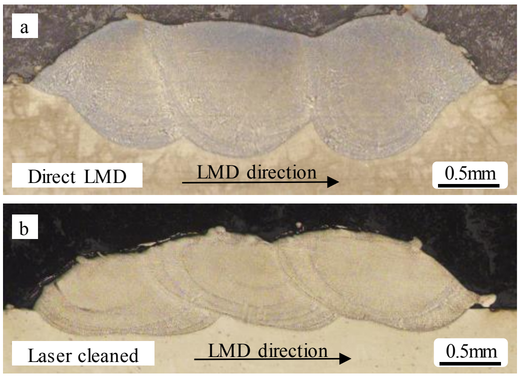

Fig. 3. 5% concentration tests (a) direct LMD; (b) laser cleaned.

The collected results show that in this case direct LMD leads to an average porosity slightly higher than the reference value. However, both cleaning methods reduce the average porosity until acceptable values comparable to the reference (0.002%). Moreover, the excessive dilution present in the direct LMD test is corrected after cleaning, returning to the appearance of the reference test in the case of laser cleaning.

3.2. 10% concentration results

In this case, average porosities of 1.876%, 0.074% and 0.016% are measured for direct LMD, air blasted and laser cleaned tests, respectively (see Fig. 4). Therefore, the average porosity seems to be significantly reduced by the effect of the cleaning techniques.

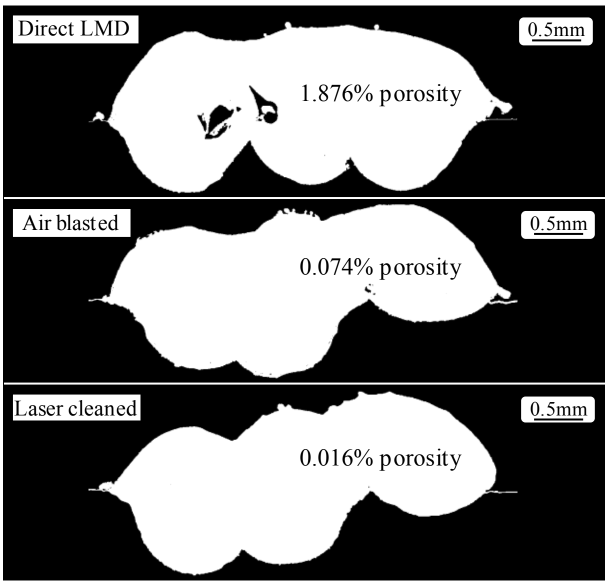

Fig. 4. 10% concentration tests porosity results.

Direct LMD results appears to present bigger penetration and dilution than the reference test. Moreover, the cleaning processes do not seem to reduce them to reference values (see Fig. 5).

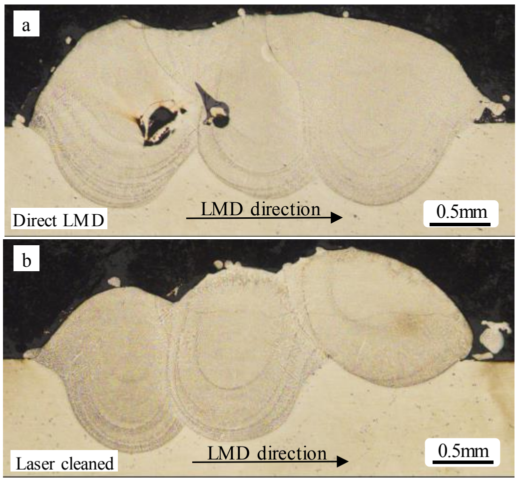

Fig. 5. 10% concentration tests (a) direct LMD; (b) laser cleaned.

Although both cleaning methods reduce the average porosity, only laser cleaning makes it low enough to be considered admissible. Nevertheless, the dilution attained after cleaning is qualitatively bigger than in the reference test.

3.3. 100% concentration results

This concentration simulates the situation in which pure oil is used instead of an emulsion. In a similar way to the previous results, air blasting and laser cleaning methods prove to decrease average porosity values from 3.261% (direct LMD) to 0.752% and 1.157%, respectively (see Fig. 6).

Despite it is demonstrated that the porosity can be lowered by applying cleaning methods, none of the values attained are comparable to the reference test and they are therefore unacceptable.

Regarding dilution, for 100% concentration tests the penetration of the deposited material within the substrate starts to be so low that it may affect the metallurgical bonding, see Fig. 7.

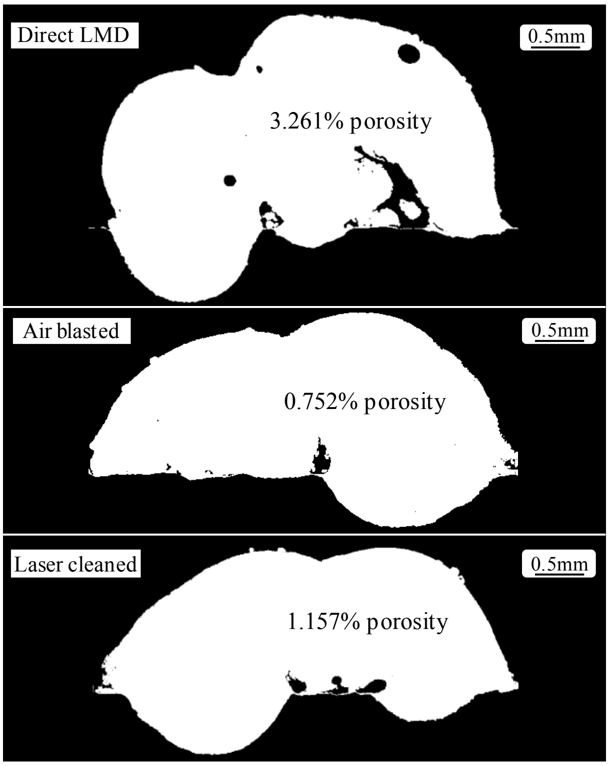

Fig. 6. 100% concentration tests porosity results.

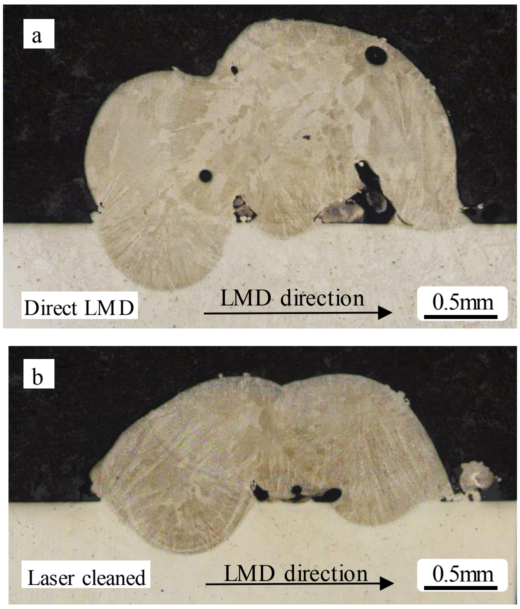

Fig. 7. 100% concentration tests (a) direct LMD; (b) laser cleaned.

The following graph shown in Fig. 8 represents the average porosity results obtained for each test realized (direct LMD, air and laser cleaned). Besides, the dispersion of the results is indicated. The presence of a 100% oil concentration not only increases the porosity value in the clad, but also decreases the repeatability, what is detrimental to the LMD process.

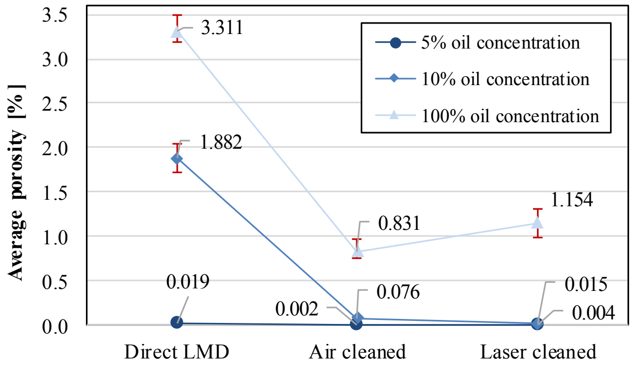

Fig. 8. Average porosity attained for each test.

4. Conclusion

The present research work has permitted to establish a relationship in terms of porosity and clad quality between LMD and the presence of cutting fluid remnants on the substrate.

After the realization of this work, it is concluded that the lower the oil concentration, the lower the average porosity results, the 5% oil concentration being the most favorable situation when using lubricant. In addition, the performance of an intermediate cleaning step between the machining and the laser process leads to the attainment of both lower porosity and dilution values. Furthermore, admissible porosity results similar to the reference value with no lubricant (0.002%) have been attained for laser cleaning combined with 5% oil concentration usually employed in machining. However, the cleaning methods studied are not able to reduce porosity as required when the substrate is impregnated with pure oil (100% concentration). Nevertheless and with regard to dilution and clad quality, admissible results are only attained with 5% concentration (and laser cleaning), being both dilution and porosity values qualitatively comparable to those of the reference test.

To sum up, it is therefore demonstrated that admissible clads in terms of porosity and dilution can be obtained in hybrid processes of machining and LMD by introducing an intermediate cleaning stage.

Acknowledgements

Special thanks are addressed to H2020-FoF13-2016 PARADDISE project (contract No. 723440). This work has been also carried out in the framework of the POCTEFA 90/15 Transfron3D project.

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