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LASER CLADDING AS REPAIRING METHOD FOR PARTS MADE OF STAINLESS STEEL

Sabin MIHAI[1,*], Diana CHIOIBASU[2], Cristina MOHORA[3], Dana TILINA[4], Andrei C. POPESCU[5]

[1)] PhD Student, Eng., Doctoral School of Industrial Engineering and Robotics, University "Politehnica" of Bucharest, Romnaia
[2)] PhD, Eng., National Institute for Laser, Plasma and Radiation Physics (INFLPR), Magurele, Romania
[3)] Prof., PhD Eng., Robots and Manufacturing Systems Department, University "Politehnica" of Bucharest, Romania
[4)] Assoc. Prof., PhD, Robots and Manufacturing Systems Department, University "Politehnica" of Bucharest, Romania
[5)] PhD, Scientific Researcher, National Institute for Laser, Plasma and Radiation Physics (INFLPR), Magurele, Romania

Abstract: *This research study aims the rectification by coating of channels with depths of 0.5 mm, 1 mm and 2 mm, respectively. The experiments were carried out using the coating method by laser cladding with additive material in the form of 304 stainless steel powder particles. In a graphical engineering program were designed the technical drawings needed to create the channels by milling, which represent the macroscopic defects. In order to obtain homogeneous structures without internal defects, 600 W laser power, 0.6 m/min processing speed and 10 g/min powder flow assisted by a He gas mixture (4 slpm, carrier gas) – Ar were used (7 slpm, protective gas) process parameters were used. The width of a single line drawn using the optimal processing parameters was 1.9 mm and the optimal scanning strategy for the channel depth of 0.5 mm was 0.6 mm the distance of the hatch that forms the meander and in case of the other 2 different depths (1 mm and 2 mm) the horizontal distance was 1 mm and the vertical distance was 0.6 mm. Using these parameters, the rectification of macroscopic defects by laser cladding with additive material was achieved and the exceed material was kept at minimal values. The process proved to be thermally stable, the temperature varying between 1030–1100 °C. The lack of thermal fluctuations can be an indicator of the quality of the deposited structures. The cross-sectional microscopic analysis of the samples validated this theory, because all the structures proved to be free of internal defects.*

Key words: *laser melting deposition, stainless steel, laser cladding, macroscopic defects, rectification.*

1. INTRODUCTION

During the time of services of various industrial components, some of them can suffer heavy wear from the working conditions (sudden heating-cooling cycles or thermal stress) which can induce in certain local areas defects such as cracks or wear of the surfaces of a solid body by mechanical interaction with debris or with a fluid medium with solid particles in suspension. Furthermore, these components are usually expensive due to the complex geometries and strict standards of surface quality. Thus, it will increase the cost of overhaul dramatically to replace the worn components with new ones. So, developing a method that can repair the worn components becomes important.

Traditional repair methods, such as tungsten inert gas (TIG) welding, usually causes large heat-affected zone (HAZ) and visible deformation caused by high thermal stress, which is unsuitable for the repairs of different type of components. In this study, the laser melting deposition (LMD) technique was used as an innovative repair method for metal parts with increased added value and complex shape. By considering the advantages of laser processing the interest in this technique has raised exponentially [1]. In addition, a strategy at the level of the European Union aims to improve the development of sustainable products and the LMD technique for the rectification of worn surfaces aligns with this directive [2, 3]. This method involves the local melting by a high-power laser beam of an additive material in form of metallic powder on the surface of the component that requires operations to rectify macroscopic defects in the range of tens of mm^2 [4]. Laser cladding by definition is a material deposition technique in which the metallic materials in powdered form are supplied into an intense laser spot. A detailed description of the process and the experimental setup is presented in Chioibasu et al. [5].

Laser Melting Deposition (LMD) is an additive manufacturing process that is being applied for building 3D parts, also for the production of coatings on existing geometries or even the repair of damaged parts. Since the LMD process is based on a laser source, it is possible to add material over a substrate with minimal heat affected zone and geometrical distortions.

Compared to conventional welding repair processes (welding with a metal electrode in a protective gas environment – MIG or with a non-fusible tungsten electrode in an inert gas environment – WIG), the LMD technique has several important advantages: i) low heat input that leads to reduced deformation and low thermal damage of the base material and ii) possibility of obtaining a controlled and stable amount of energy that is

* Corresponding author: Splaiul Independenței 313, district 6, 060042, Bucharest, Romania,
Tel.: 0040736280639,
E-mail addresses: *mihai.sabin1996@gmail.com* (S. Mihai).

produced by the laser source, offering a high level of repeatability of the cladding process [6–8]. The use of the additional material in form of the powder allows flexibility in the process, both regarding the chemical composition and the accessibility of the areas of interest that require rectification [9]. The LMD technique is used in numerous industrial applications [10–12] to improve the physical properties of surfaces or to repair existing defects by filling them with material [13].

In this paper, the LMD technique was used to repair macroscopic defects obtained by milling channels with different depths to demonstrate the feasibility of the process. The microstructures of the repair coating are studied. The results may lead to an increasing interest in the investigation of increasing service life and decreasing cost in the industrial components field, and also provide a guideline for their further application.

2. MATERIAL AND METHODS

For this study, 3 stainless steel 304 plates with dimensions 100 x 100 x 10 mm (Fig. 1,*a*) were used. Each plate was processed by milling to obtain channels with depths of 0.5 (Fig. 1,*b*), 1 (Fig. 1,*c*) and respectively 2 mm (Fig. 1,*d*). It was decided to mill the channels (Fig. 2) because regardless of the type of defect that we want to rectify (crack or wear), it is necessary to make a shape with known dimensions of the surface that will be processed by laser deposition with the addition of material. This step is indispensable in the stage of establishing the scanning strategy to rectify by filling the macroscopic defects.

The materials used in this study were gas atomized Stainless Steel 304 in shape of spherical powders (Fig. 3) with a nominal particle size distribution between 45–106 µm (Carpenter Additive, Philadelphia, United States). It can be observed from Fig. 3 that the SS304 powder consists mainly of spherical particles with an average diameter of 80 µm, with smooth surfaces.

The SS304 is selected due to its relatively good aptitude for the LMD process and wide applications in the industry. Table 1 present the chemical composition of the SS304.

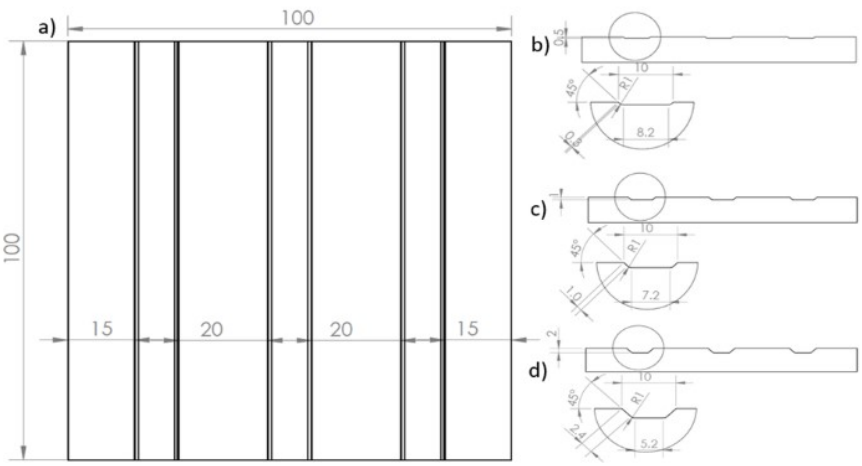

Fig. 1. Technical drawings for: *a* – channel positioning on stainless steel plate 304; *b* – channel with a depth of 0.5 mm; *c* – 1 mm; *d* – 2 mm.

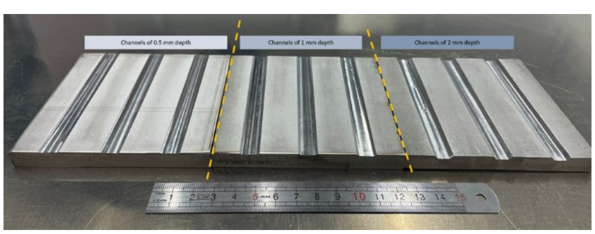

Fig. 2. Channels with different depths obtained by a subtractive process.

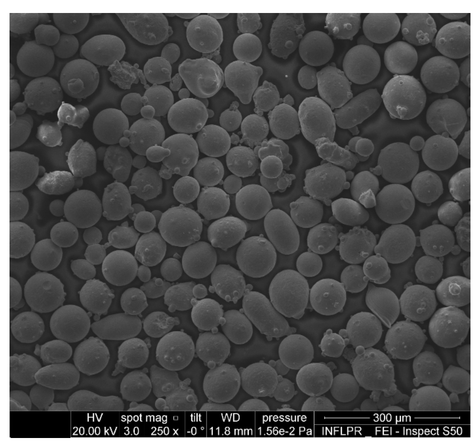

Fig. 3. SEM micrographs of the SS304 powder used in the experiments.

Table 1

SS304 chemical composition

Component	C	Cr	Fe	Mn	Ni	P	S	Si
Wt [%]	≤ 0.08	18–20	Ball.	≤ 2	8–10.5	≤ 0.045	≤ 0.03	≤ 1

The powder material was introduced into a particle distributor with hoppers (GTV, Verschleißschutz GmbH, Germania), which delivers the powder through hoses (Ø6 mm) to a nozzle with 3 beams. The quantity of powder delivered is calibrated and sent throught hoses to the common point with the focalized laser beam. The powder is transported by a carrier gas, He, optimized at a flow rate of 4 slpm. Together with He and the powder mixture, a protective gas, Ar, is delivered through the same hoses at a flow rate of 7 slpm in order to ensure a uniform distribution of the powder flow and a proper gas shroud around the working area that protects the deposited sample against corrosion.

The laser deposition experiments were performed using an integrated processing system, TruLaser Robot 5020 (Trumpf, Ditzingen, Germany) which is composed of a Yb:YAG laser source operating in continuous mode, TruDisk 3001, with a maximum power delivered on the workpiece surface of 3 kW, optical fiber that carries the laser beam from the source to the processing optics, a powder particles distributor, a robotic arm with 6 degrees of freedom and a LMD processing optics that is equipped with a delivery nozzle of metal powders through 3 channels. The diameter of the laser spot focused on the surface to be processed was 800 µm. For this study, a 304 stainless steel powder with spherical particles was subjected to a moisture removal process in an oven for 1 hour at 60 °C. The melting temperature of stainless steel 304 is in the range of 1400–1450 °C. After milling, the 304 stainless steel plates were cleaned with alcohol to remove residual oils and impurities that could affect the adhesion of deposits or induce porosity in their structure.

The optimal process parameters used in order to obtain a defect free deposited line from powder material were 600 W laser power, 0.6 m/min processing speed and a powder flow of 10 g/min assisted by a He (4 slpm, carrier gas) – Ar (7 slpm, protective gas) gas mixture. The next important step, after establishing the process parameters, is represented by the identification of the scanning strategy, which consists in determining the optimal degree of overlap of the horizontal and vertical lines, in order to obtain dense and defect-free structures. The width of a single line drawn using the optimal processing parameters was 1.9 mm and to cover a surface of several mm^2 a meander trajectory was selected. Table 2 presents the preliminary parameters studied in order to identify the optimal scanning strategy.

For the rectification process by filling the channels, scanning strategies in form of meander with different

Table 2

The parameters of the scanning strategy in order to obtain a structure without defects

No.	Hatch distance [mm]	Layer distance [mm]	No. of layers	Theoretical height [mm]	Experi-mental height [mm]
1	1.3	-	1	-	0.6
2	1	-	1	-	0.6
3	1	0.3	10	3	6
4	1	0.4	10	4	5.8
5	1	0.5	10	5	6.5
6	1	0.6	10	6	6.8

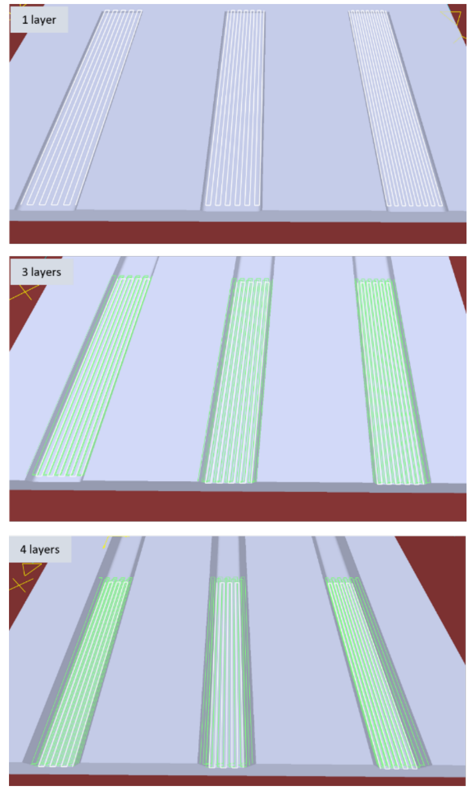

Fig. 4. Scanning strategy used for repairing process by covering channels with different depths obtained by a subtractive processing method.

Table 3

Scanning strategy parameters for the repairing process by LMD technique

No.	Depth [mm]	Hatch distance [mm]	Layer spacing [mm]	Number of layers
1	0.5	1	-	1
2	0.5	0.8	-	1
3	0.5	0.6	-	1
4	1	1	0.5	3
5	1	1	0.6	3
6	1	0.8	0.6	3
7	2	1	0.5	4
8	2	1	0.6	4
9	2	0.8	0.6	4

characteristics were generated in a computer-aided manufacturing program, TruTops Cell (Fig. 4), and the geometric parameters are presented in Table 3. For each depth of a channel, three different dimensional characteristics of the scanning strategy were used in order to obtain a dense deposition, without porosities, but at the same time respect the dimensional constraints that are written in the technical drawings.

After the experiments, to characterize the quality of the deposited material the parts were examined through a destructive analysis method. A metallographic line was used in order to perform the analyses. The first step was to cut some sections from repaired parts by a disc cutting machine – Brilliant 200 (ATM, Germany) with a disc rotation speed of 2850 rpm. The sectioned elements were embedded in a synthetic resin using a hot-pressing machine with a cylinder diameter of Ø30 mm Opal 410

(ATM, Germany). A pressure of 50 bar and a temperature of 200 °C were applied. The resin used, through hot pressing, develops the following characteristics: it allows obtaining an insoluble, thermostable, electrically insulating, hard and shock resistant solid material. Finally, to highlight the structural defects, the surfaces of the embedded parts were polished to mirror quality using a Saphir 520 type machine (ATM, Germany) equipped with automated rotation support. Optical microscopy studies were performed using a BX51M optical microscope (Olympus, Japan). The investigations were carried out both at low magnifications (objective with 5x magnification), to provide an overview of the structure, but also at higher magnifications (objective 100x), to highlight some interesting structural details.

The obtained structures were metallographically prepared and chemically attacked for 4 minutes with the V2A reagent in order to highlight the microstructure and the metallic phases. A DM4000 B LED optical microscope (Leica, Wetzlar, Germany) was used for analyzing the geometrical characteristics of deposited material. Temperature fluctuations during processing were recorded using a thermal camera, thermo IMAGER TIM M-05 (Micro-Epsilon, Ortenburg, Germany), with a temperature measurement range between (900–2450) °C, which was connected to a dedicated program for monitoring these values, TIM connect (Micro-Epsilon, Ortenburg, Germany), that was used for post-processing the obtained data.

3. RESULTS

A parametric study of the various process parameters was carried out to characterize the variation of deposition dimensional characteristics. The first parameter studied was the horizontal distance between the lines that form the meander trajectory used as a scanning strategy for repairing process by filling the channels by LMD technique. Deposition was made with a distance of 1.3 mm and 1 mm, respectively, which represents an overlap of 32% (Fig. 5,*a*), respectively 47% (Fig. 5,*b*). After analyzing the appearance of the deposited material under the optical microscope, the coating with an overlap of 47% was chosen to ensure the highest degree of uniformity of the deposited layer. The second parameter studied was the vertical distance between the layers. Experiments were carried out at 0.3 mm, 0.4 mm, 0.5 mm and 0.6 mm distance between the meanders and 10 layers were deposited for each parameter. As can be seen in Table 2, the heights of the deposits did not vary significantly, therefore it was decided to use the distance of 0.5 mm, respectively 0.6 mm.

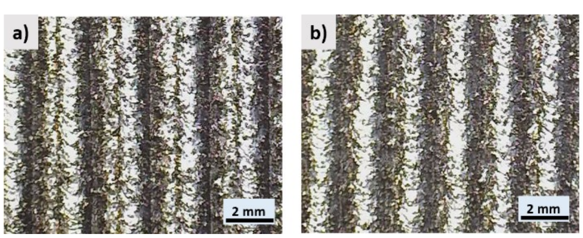

Fig. 5. Optical micrographs of the deposited material with an overlap of: *a* – 32%; *b* – 47%.

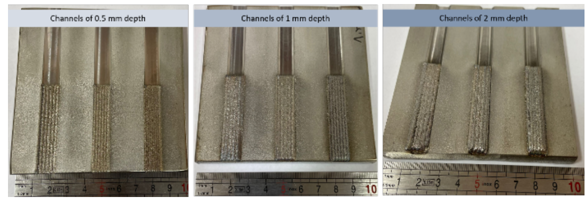

Fig. 6. Rectification by coating using the LMD technique of channels with different depths.

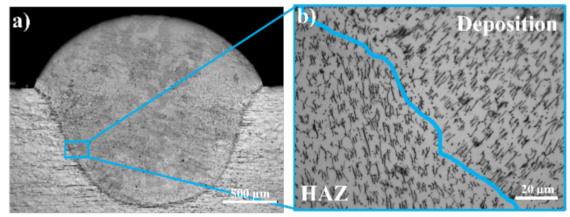

Fig. 7. Optical micrographs of the microstructure of deposited SS304 (a) and a zoom in the interface zone (b) showing δ-ferrite dendrites in the austenite matrix.

The next step was to carry out the rectification process by depositing material from the channels using the characteristics of the scanning strategies presented in Table 3. The results obtained can be seen in Fig. 6.

Transversal cross sections through deposited layers were performed for each experimental conditions and the resulting surfaces were prepared for analyses. Figure 7,*a* present the optical microscopy image of a transversal cross-sectioned mirror-polished deposited layer of SS 304 on stainless steel substrate. Different cuts were performed in arbitrary locations of the sample in order to check for the presence of possible defects. Tests were performed for determination of the optimal distance between the lines of deposited material, to obtain a defect-free continuous deposition. A 47% overlap ratio between the meander lines when depositing the material was found to be the optimal value for achieving a homogenous, cracks and pores-free surface. This was consistent for all depositions on four studied samples. A typical cross section is presented in Fig. 7,*b* is showing a defect-free bounding interface between the deposited material and substrate.

The grain size is one of the reasons that affect the tensile properties. The average grain size of the deposited material by laser melting deposition was much smaller in comparison with material manufactured by conventionally methods. Thus, the smaller the grain size, the more the grain boundaries are in the same area. The rapid cooling rate during LMD process was usual between 10^2 K/s to 10^4 K/s [14], which was higher than that during the conventionally manufactured process. The differences in cooling rate are the main reason that conduct to the different grain sizes.

In order to identify the optimal scanning strategy for obtaining a structure without microstructural defects, for the channel depth of 0.5 mm, deposits were made using the meander trajectories with a distance of 1 mm (Fig. 8,*a*), 0.8 mm (Fig. 8,*b*) and respectively 0.6 mm (Fig. 8,*c*), which represents a degree of overlap of 47%, 57% and 68% respectively. For this purpose, the samples were analyzed in cross-section and it can be easily observed that the coating with the largest overlap is the most suitable strategy for rectifying the channel with a depth of 0.5 mm because a dense deposit and a height of approximately 300 µm more than the channels, which allows a post-processing stage for surface rectification.

For the rectification by covering the channel with a depth of 1 mm, 3 scanning strategies with 3 overlapping layers were used: i) horizontal distance of 1 mm and vertical distance of 0.5 mm (Figs. 8,d and *g*), ii) distance on a horizontal distance of 1 mm and vertical distance of 0.6 mm (Figs. 8,*e* and *h*) and iii) horizontal distance of 0.8 mm and vertical distance of 0.6 mm (Figs. 8,*f* and *i*). The same scanning strategies were used in the case of the channel with a depth of 2 mm, but with 4 overlapping layers. All scanning strategies proved to be suitable, in the sense that in all situations dense depositions without defects were obtained, but the first and second strategies can be considered optimal since the height of the excess material (processing allowance) is smaller (~ 500 µm), which implies lower post-processing costs and reduced processing times.

All experiments were thermally monitored and for all coating rectification processes, the temperature of the melt pool varied between 1030 °C and 1100 °C. A representative graph of the evolution of the temperature fluctuation during the process for a layer of deposited material on an area of 500 mm^2 is presented in Fig. 9. It can be seen that the temperature of the process is quite stable, and the coating duration for a layer is ~1 min.

The fluctuations of the temperature during the processing can lead to the apparition of cracks or pores. This phenomenon can be explained by the mechanism of elastic deformation caused by the temperature variation developed during the laser deposition process. The power of the laser beam generates different temperature gradients in the vertical direction and along the scanning direction. Thus, by rapid solidification, characteristic of the LMD process, the variation of the material volume is constrained by the coefficient of thermal expansion of the substrate, which generates the occurrence of internal stress. This is directly proportional to the characteristic Young's modulus of the used material. Cracks tend to propagate in the direction of grain boundaries due to the necessity of a low amount of energy. Another problem that can occur due to the excessive heat generated by the laser beam is the appearance of porosity. One of the causes of the formation of this type of defect can be considered the possibility of local vaporization of elements from the composition and the generation of gases that remain trapped in the deposited volume due to the reduced cooling time.

4. DISCUSSION

SS304 is a common austenitic stainless steel and was selected for this study due to widely range of applications in vary fields, such as petroleum, nuclear and chemical industries due to its excellent corrosion resistance, mechanical properties and high cost-effect. For any industrial application the adequate mechanical properties are of high importance.

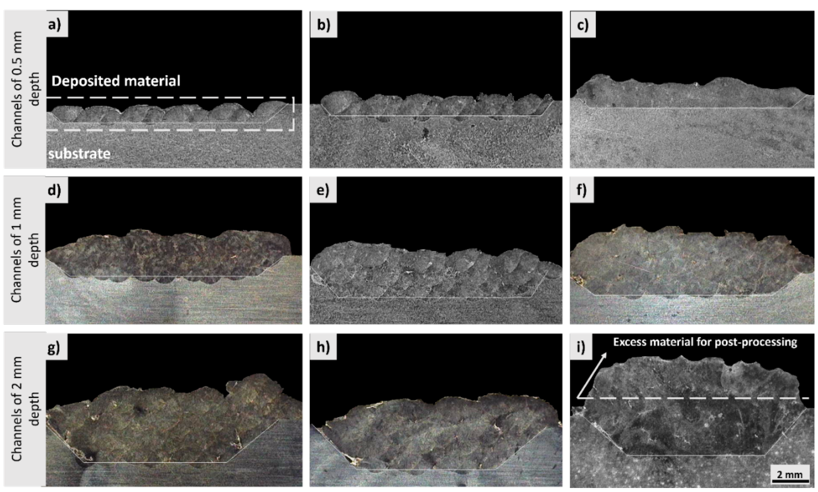

Fig. 8. Cross-section images of the channels rectified by coating using the LMD technique with depths of: *a–c* – 0.5 mm; *d–f* – 1 mm; *g–i* – 2 mm.

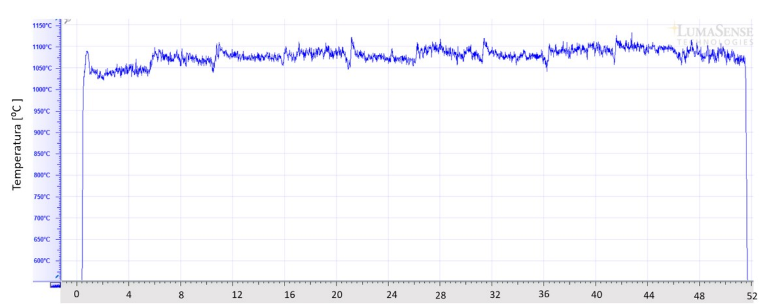

Fig. 9. Temperature fluctuations during the LMD process.

Laser cladding can be the most commonly achieved LMD. Laser deposition is a versatile technique, allowing for manufacturing of multilayer structures or parts with gradient composition that can improve the quality of the parts maintaining the fabrication costs at minimum.

As shown in the results section, the scanning strategy represent a determinant role on the quality of the LMD deposited sample. For each geometry of a damage part, the scanning strategy is important to be in accordance with the dimensions and the shape of the defect.

In all cases, using a mix of experimental conditions that we optimized in time and changing the scanning strategy, allowed for strong bonded interface between deposition and substrate without defects.

The importance of choosing an adequate scanning strategy is essential, because can influence the quality of the repair. Thus, a scanning strategy that is not suitable for the geometry of the damage part, allow pores to be trapped in the volume of material and create stress concentration centers that in time might generate fractures in case of highly solicited parts. Therefore, the elimination of pores or their drastically reduction is e prerequisite in numerous quality control procedures.

The best conditions to obtain defect-free bulk samples are not certainly the best conditions for adding the optimal amount of material in order to repair the damage part. It is highly possible that with the best conditions for defect-free samples to obtain a discrepancy in dimensions (especially height) between the theoretical conditions and the actual deposition. Our solution was to keep constant the optimal process parameters for a single line and the hatch superposition, to obtain defect-free samples. The next step was to vary the offset between deposited layers in order to achieve the match with the theoretical aspects.

5. CONCLUSIONS

The optimal parameters for the LMD process of SS304 on stainless steel substrates are: (a) laser power = 600 W, (b) laser scanning speed = 0.6 m/min, (c) argon gas flow rate = 7 slpm, (d) He gas flow = 4 slpm, (e) powder flow rate = 10 g/min and (f) robot tilt angle = 0°.

Technical drawings were made for the execution of channels with varying depths in an engineering graphics program, necessary for the mechanical and laser processing of the metal surfaces.

Channels with different depths were milled in order to carry out the rectification process by coating using the LMD technique.

The trajectories of the scanning strategies necessary for the coating rectification process were generated in a computer-aided manufacturing program,

The laser processing parameters were identified and the scanning strategies necessary to obtain dense structures without internal defects were optimized.

The temperature during each process varied in the range of 1030–1100 °C showing a stable evolution.

Channels with different depths were repaired successfully by LMD technique using metallic material in form of spherical powder particles.

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