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Free-form fabrication of steel parts by multi-layer laser cladding

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Abstract

Laser Cladding (LC) is actually one of the most attractive techniques in the group of Material Accretion Manufacturing (MAM) processes. As a surface coating technique, laser cladding has been developed for improving wear, corrosion and fatigue properties of mechanical components. Multilayer laser cladding (MLC) can be used also for high performance part repair and as a rapid manufacturing process. Thus, the application of laser cladding technology is nowadays widely extended in several industrial sectors due to its advantages for high added value parts direct manufacturing and repairing.

Multilayer laser cladding (MLC) combines powder metallurgy, solidification metallurgy, laser, CAD/CAM, CNC, rapid prototyping and sensors technologies. This process allows to produce metal components ready to use, in a single step, without the need for molds or tools and using a wide variety of metals, including those very difficult to work with conventional techniques.

The aim of this work was to manufacture MLC steel parts using a CO_2 laser with a maximum power of 3kW. The effect of the main process parameters (laser power, travel speed, powder flow rate, degree of overlapping) on the properties of built parts was investigated. A Taguchi experimental plane was used to reduce the number of experiments and a mathematical model was applied in order to obtain an optimized degree of overlapping between adjacent layers and between tracks. Performance of the MLC samples were analyzed in terms of density, macro structure, adhesion to the substrate and microhardness. The powder material chosen for experiments had a composition close to a maraging steel (grade 300). Experimental results showed that high density parts could be produced with a limited number of tests.

Keywords: multi-layer laser cladding, process parameters, optimization, free-form fabrication

1. Introduction

The Multi-layer Laser Cladding (MLC) pertains to the group of technologies called Material Accretion Manufacturing (MAM), and, in particular, is based on the principles of rapid prototyping (RP) and laser

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cladding. The MAM technologies start by the 3D design to get the object in a single step through an additive processing, that is overlapping each other layers with a small thickness. In other words, there is a conversion of the three-dimensional piece into N two-dimensional overlapping pieces: the layers. Another feature of MAM processes is the selective creation of several kinds of materials, from plastics to metals (Choi et al., 2005, Peng et al, 2005, Santos et al., 2006, Zhang et al., 2003, Lu et al., 2001, Qian et al., 1998).

The development of MLC has been pursued simultaneously by a lot of researchers for several years and finally gave birth, in 1995-96, to three very similar processes. These processes are now known worldwide as Direct Light Fabrication (DLF), Laser Engineered Net Shaping (LENS) and Direct Metal Deposition (DMD), developed respectively at the Los Alamos National Laboratory (Los Alamos, New Mexico, USA), at Sandia National Laboratory (Albuquerque, New Mexico, USA) and at the University of Michigan (Ann Arbor, Michigan, USA) (Lewis et al., 2000, Atwood et al., 1998, Erzincanh et al., 2002).

MLC using powder additive materials has been successfully introduced into industry for the use in wear and corrosion applications and as repairs of e.g. turbine components, moulds, and dies and is increasingly being employed for varied 3-D applications as well (Hong et al., 2011).

The MLC combines powder metallurgy, solidification metallurgy, laser, CAD/CAM, CNC, rapid prototyping and sensors technologies. This process allows to produce metal components ready to use, in a single step, without the need for dies, molds or tools and using a wide variety of metals, including those very difficult to work with conventional techniques. By moving the laser beam on a substrate, structures can be built-up layer by layer with nearly no limitations to geometry constraints with the advantage of producing small heat affected zones (HAZ).

The process of LC is well developed, but MLC requires still further research because it depends on numerous parameters, which can affect the stability and the quality of the result.

The aim of this work was to manufacture MLC steel parts using a CO_2 laser with a maximum power of 3 kW. The effect of the main process parameters (laser power, scanning speed, powder flow rate, overlapping, step height) on the properties of built parts was investigated. A mathematical model based on previous studies made by Zhang et al., 2007, Colaço et al.,1996, Angelastro et al., 2011, Angelastro et al., 2013, together with an experimental analysis was implemented in order to evaluate the performance of the MLC process in terms of density, microstructure, microhardness. The powder material chosen for experiments had a composition close to a maraging steel (grade 300).

2. Experimental procedure

2.1. Experimental setup and materials

The experiments were carried out using a machine equipped with a 3 kW CO_2 laser, together with a powder supply system consisting of a pneumatic conveyor, a splitter, used to mix and divide the flow into three equal flows of carrier gas and powder mixtures, and, finally, a multijet nozzle having the function to direct the three powder flows coming from the splitter in the weld pool.

The investigated powder material is included in the category of maraging steels that comprise a special class of high-strength steels that differ from conventional steels because they are hardened by a metallurgical reaction that does not involve carbon. These steels are strengthened by the precipitation of intermetallic compounds at temperature of about 480°C. The term maraging is resulting from martensite age hardening ad denotes the age hardening of a low-carbon, iron–nickel lath martensite matrix. Maraging steels are also age–hardenable in the 400-650°C temperature range. The aging below 450°C produces ordered and coherent phases in a martensitic matrix (Casalino et al.,2015, ASM Handbook, 1990).

Marage 300 steel has excellent mechanical properties, high values of yield strength and tensile strength, high fatigue limit, high compressive strength, hardness and wear resistance. The chemical composition of the powder was studied by Energy Dispersive X-ray (EDX) analysis and it is reported in Table 1.

The powder was produced with particles of different size ranging since few micron to the maximum size of 40 µm.

The powder was deposited on a AISI 304 plate 8 mm thick producing 20 layers samples.

Table 1. Chemical composition of the employed powder determined by EDX analysis.

Powder Material	Ni	Mo	Co	Ti	C	Fe
18 Ni Marage 300	18.8	4.2	10.2	0.88	0.02	Balance

2.2. Experimental plane

In this study the variation of three parameters was considered: laser power, travel speed, powder flow.

A full factorial approach would require a total of 3^k experimental runs if there are k investigating factors, each one changed on three different levels. Application of the full factorial approach to the present investigation would require a total of 27 experimental runs.

To reduce the large number of trials required from a full factorial design, a Taguchi reduced experimental plan was used. The most appropriate orthogonal array that defined the experimental schedule was chosen on the basis of the degrees of freedom of the experiments.

An L9 orthogonal array was chosen. The three factors varied on three different levels, according to Table 2.

Table 2. Taguchi experimental plane.

Sample	Laser power [W]	Travel speed [mm/min]	Powder flow [g/min]	Energy density [J/mm^2]
1	1600	200	6	240
2	1600	300	8	160
3	1600	400	10	120
4	1750	200	8	263
5	1750	300	10	175
6	1750	400	6	131
7	1900	200	10	285
8	1900	300	6	190
9	1900	400	8	143

2.3. Mathematical model

Moreover a mathematical model based on previous studies of Zhang et al. and Angelastro et al. was implemented. In detail, the model allowed calculating optimal values of hatch spacing between adjacent vectors (*Sx*) and between layers (*Sz*) of the deposited material (Fig.1). These values should ensure an overlapping (*O%*) that maximizes the relative density of deposited tracks, a good adhesion between different layers and hardness comparable with that of the original material.

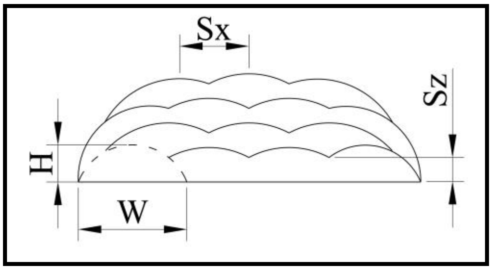

Fig. 1. Schematic drawing of the cross section of a deposited specimen

Single-track clads were deposited in order to find the width (*W*) and the height (*H*) for all combinations of process parameters. Values of *W* and *H* were measured and they are listed in Table 3. According to the considered model, taking into account the Fig. 2:

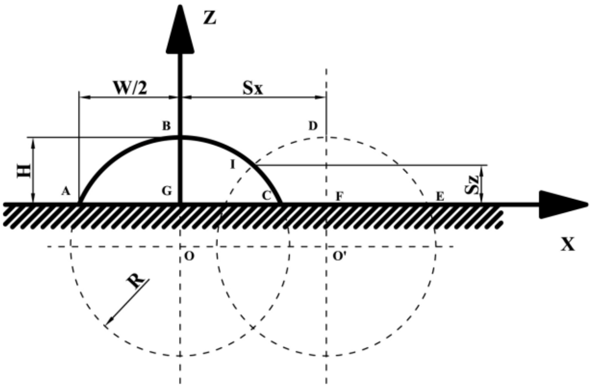

Fig. 2. Graphic representation of the mathematical model.

and imposing the following equation between areas:

$$A_{ABC} = A_{BDEC} = A_{BDFG} = H \cdot S_x \tag{1}$$

It is possible to calculate:

$$A_{ABC} = \left(\frac{\left(\frac{W}{2}\right)^2 + H^2}{2 \cdot H} \right)^2 \cdot \arcsin\left(\frac{2 \cdot \left(\frac{W}{2}\right) \cdot H}{\left(\frac{W}{2}\right)^2 + H^2} \right) - \left(\frac{W}{2}\right) \cdot \frac{\left(\frac{W}{2}\right)^2 - H^2}{2 \cdot H} \quad [mm^2] \tag{2}$$

$$S_x = \frac{A_{ABC}}{H} = \frac{1}{H} \left(\frac{\left(\frac{W}{2}\right)^2 + H^2}{2 \cdot H} \right)^2 \cdot \arcsin\left(\frac{2 \cdot \left(\frac{W}{2}\right) \cdot H}{\left(\frac{W}{2}\right)^2 + H^2} \right) - \left(\frac{W}{2}\right) \cdot \frac{\left(\frac{W}{2}\right)^2 - H^2}{2 \cdot H^2} \, [mm] \tag{3}$$

$$O_{\%} = \frac{W - S_x}{W} \cdot 100 \tag{4}$$

where *H* [mm] is the maximum height reached by the single track, *W* [mm] is the value of the maximum width at the base of the same, A_{ABC} is the area of the cross section, *O%* represents the degree of overlap of the generic track vector with an adjacent one, deposited within the same layer. Using this procedure it was possible to calculate the values of hatch spacing between adjacent vectors (*Sx*) to be used for each of the nine combinations of the considered parameters.

Table 3. Values of width and height of the single track clads for the nine combination of process parameters.

Sample	W [mm]	H [mm]
1	2,97	1,01
2	3,11	0,93
3	2,86	0,80
4	3,35	1,29
5	3,18	1,01
6	2,66	0,51
7	3,40	1,53
8	2,89	0,65
9	2,87	0,66

2.4. Multi-layer fabrication

Multilayer samples on an AISI 304 steel plate were fabricated (Figure 3) to define some deposited material properties, such as microstructure, micro-hardness and porosity. Optimal values of *Sz* [mm] were calculated by Eq. 5 and 6 (*R* is the circumference radius).

$$R = \frac{1}{2 \cdot H}\left(\frac{W^2}{4} + H^2\right)[mm] \tag{5}$$

$$S_z = \sqrt{R^2 - \left(\frac{S_x}{2}\right)^2} - R + H \quad [mm] \tag{6}$$

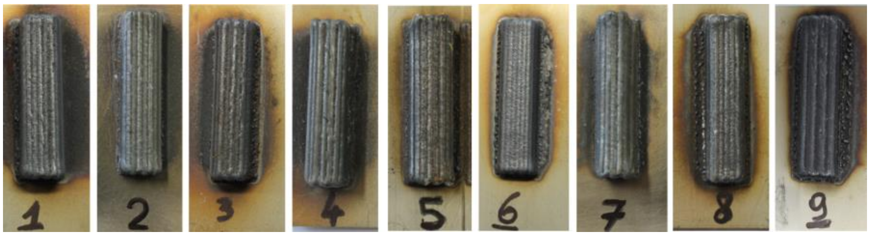

Fig. 3. MLC built samples

3. Results and discussion

Density tests were performed using the ‘Archimedes-method’ by weighting the samples in air and subsequently in demineralized water. The effect of Energy Density (*Ed*) on Relative Density (*Rd*) was plotted and analyzed (Figure 4). Values of *Ed* ranges between 120 to 285 J/mm^2. The true density of the material is 8.01 g/cm^3; this clearly indicates that *Rd* of built parts changes between 97.6% and 99.3%. It is evident that density of parts is almost constant with the increase of energy density, reaching an average values of 98.2%. This result confirms that the used mathematical model, together with the use of a reduced experimental plan, allow to arrive faster and with limited number of tests to high values of energy density.

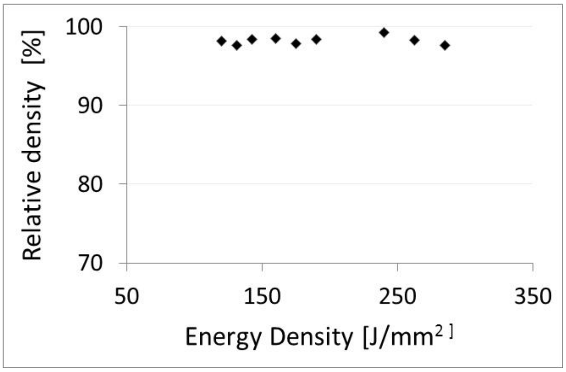

Fig.4. Relative Density as function of the Energy Density

Multilayer samples were cut, polished and etched for macro-and microstructure examinations along the transverse cross-section. An optical microscope was used to analyze the microstructure of samples. Figure 5 shows the macrostructure of the transverse cross-section for samples 1, 2 and 8, having the highest values of density. The macrostructure of the cross-section reveals a pattern of layer-by-layer deposition. Moreover the deposited material appears with a limited number of pores.

Specifically, the analysis of porosity was performed using an image processing software. An equivalent pore diameter ranging between 0.01 and 0.08 mm was found.

The average microhardness of samples 1 and 2, having the highest values of relative density, was measured, at various locations along the transversal section, using a Vickers indenter Remet HX 1000, with a 200 gf load for 15 s. Figure 6 shows the microhardness profile along the cross section of the multilayer samples on the base metal. It was seen that the average microhardness of the deposited material (approximately 350 HV) was higher than the microhardness of the stainless steel substrate (approximately 206 HV), as expected by the different properties of the substrate and the deposited material.

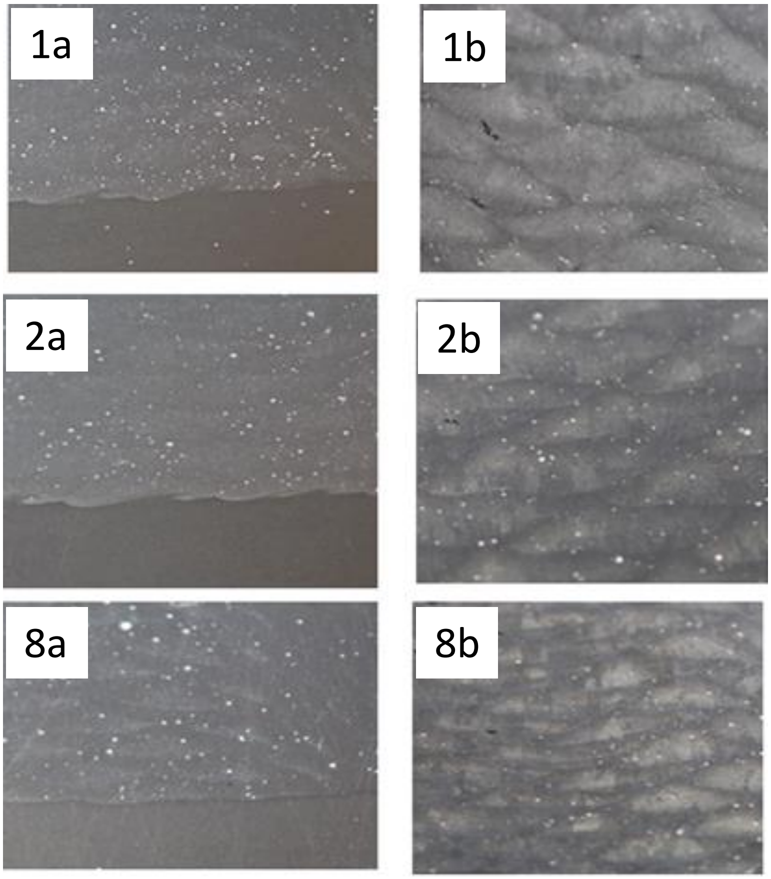

Fig.5. (1a), (2a), (8a) Interface between the deposited material and the AISI 304 substrate; (1b), (2b), (8b) macrostructure of the deposited material.

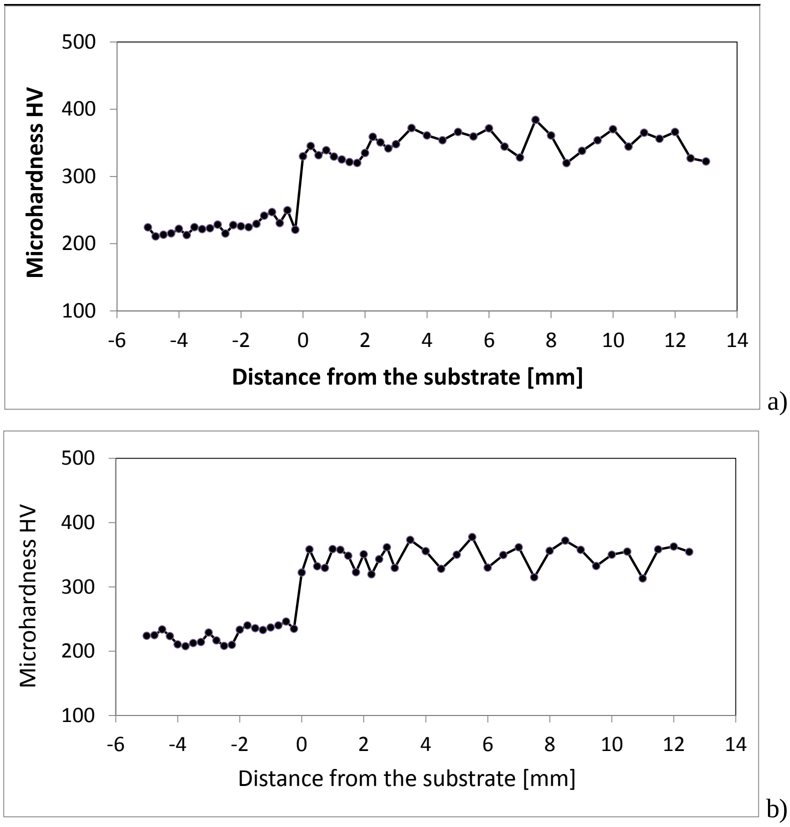

Fig.6. (a) Microhardness profiles for samples 1 and (b) 2.

4. Conclusions

In this work MLC steel parts were manufactured using a CO_2 laser with a maximum power of 3 kW. The effect of laser power, travel speed, powder flow rate, degree of overlapping, on the properties of built parts was investigated. A Taguchi experimental plane together with a mathematical model was used to obtain an optimized degree of overlapping between adjacent layers and between tracks. Performance of the MLC samples were analyzed in terms of density, macrostructure, adhesion to the substrate and microhardness. The powder material chosen for experiments had a composition close to a maraging steel (grade 300). Experimental results showed that high density parts could be produced with a limited number of tests, reaching a relative density having an average value of 98.2% and a maximum value of 99.3%. Samples after metallographic analysis appeared with a limited number of pores with an equivalent pore diameter ranging between 0.01 and 0.08 mm.

Finally, an approximately value of 350 HV for microhardness was found in the deposited material. This result is in line with properties of the maraging steel (grade 300) reported in ASM Handbook.

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