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Experimental Analysis of the Direct Laser Metal Deposition Process

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1. Introduction

In the current economic situation, with a liberalized and worldwide trade, the weight of time and costs reduction for developing new products increases. In particular, the tooling processes, which are already expensive and time consuming, recently became a critical trouble. The geometric complexity, the number of variants and the amount of requirements that characterize the products that are required by market increase this trouble. Reducing time to market and the international competitiveness are two of the biggest challenges for manufacturing companies of the twenty-first century. They not only have to produce component with high quality, low cost and better functionality than before, but also have to respond to customer requests in a more reactive way as possible. To do this they have to accelerate, of course, the tooling stage and to reduce processing times. Indeed, it is known that a delay of some weeks during the development and the commercialization of a new product may result in a loss of profits of 30%. These factors thrust the manufacturing companies to find solutions both in technology and in organization.

The Material Accretion Manufacturing (MAM), consisting of additive technologies, and the modern operational structures, such as those provided by the Concurrent Engineering, are effective tools that help to reduce time and costs. Probably, they are the best weapons that western industry can take to survive the fierce competition with those countries, mainly asiatic and eastern europe countries, where labor has a very low cost, but is nowadays able to achieve good quality products.

Among the various technologies MAM, thanks to which it is possible to apply the basic concepts of Rapid Prototyping to realize finished products, stands out, with its huge capacity, the Direct Laser Metal Deposition (DLMD) process of metal powders. But what are the key features of this process? What are the properties of the products it is able to accomplish? For what types of applications have already been used or are expected to do it? This chapter will give a comprehensive answer to these questions.

The DLMD pertain the group of technologies called Material Accretion Manufacturing (MAM), and, in particular, is based on the principles of rapid prototyping (RP) and laser cladding (Peng et al., 2005). The MAM technologies start by the 3D design to get the object in a single pass through an additive processing, that is overlapping each other layers with a small thickness. Other words, there is a conversion of the three-dimensional piece into N two-dimensional overlapping pieces, that constitute the layers.

The idea of making plastic, metal and ceramic functional pieces by overlapping layers of material led to the creation first of the rapid prototyping and then of the MAM technologies. In fact, the principles behind these technologies were already used in 1934, when a process which, by means of a blowtorch, allowed the fabrication of metal pieces by welding metal plates placed one above the other was invented. It followed the cladding technique made by means of the welding arc first and of the laser then, combined with the supply of material in powder or wire. However, the limitations in accuracy, in resolution and in mechanical properties of parts obtained by both processes still hampered the production of functional metal components. The development of the lasers and of the microprocessors used for an accurate position and speed control of the beam led, in the early '80s, to the birth of rapid prototyping, and in particular of stereolithography (Lewis & Schlienger, 2000).

The aim of the mechanical industry, however, has always been to use the basic principles of rapid prototyping to direct manufacture metal parts with mechanical properties as close as possible to those of parts obtained with conventional processes. This led to research and improvement of various technologies in that direction. With the development of computer aided design (CAD) and computer aided manufacturing (CAM) technologies, particularly with the advent of CAD/CAM and CNC systems, it was possible to combine the 3D CAD representation of the desired component and the deposition process that was able to achieve it (Zhong et al., 2001).

The accurate control of manufacturing processes so obtained allowed an increasing use of technologies like MAM for the production of metal parts with good mechanical properties. In conclusion, from prototyping, which creates objects with only an aesthetical, conceptual, technical or pre-series function, it has arrived to MAM technologies, which generates the finished and with good mechanical properties products (Angelaastro, 2010; Santon et al., 2006; Keicher & Smugeresky, 1997).

The creation of a component with a MAM technology, usually, takes place with the succession of the following phases:

1. *Creating the CAD model of the piece* - The piece has to be CAD designed using a three dimensional or surface modeling.
2. *Conversion of the CAD model into the STL format (Solid To Layer)* - The STL format implies tessellation (or mesh) of the inside and outside surfaces of the piece through triangular elements, each identified by the spatial coordinates of three vertices and three direction cosines of the external normal.
3. *Workpiece layout and orientation and support generation* - The direction of optimal growth of the product greatly influences dimensional accuracy, surface finishing, production time and costs. In some MAM technologies support generation is essential to support possible overhangs.
4. *Slicing* - The STL model is dissected by a series of planes perpendicular to the growth direction. Slicing can be uniform, resulting in layers of uniform thickness, or adaptive, in which case the thickness will be determined by the surface curvature, to minimize the steps appearance of the surface (staircase effect).
5. *Sections fabrication* - The physical construction of the piece is performed overlapping layers each other.
6. *Supports remove, cleaning and finishing* - Eventual supports are taken away from the piece; so the piece is cleaned, by removing the excess material attached to the inner and outer surfaces, and then finished.

2. Process

The development of Direct Laser Metal Deposition has been pursued simultaneously by a lot of researchers for several years and finally gave birth, in 1995-96, three very similar processes. These processes are now acknowledged worldwide, under the names of Directed Light Fabrication (DLF), Light 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 & Schlienger, 2000). The DLMD process combines powder metallurgy, solidification metallurgy, laser, CAD-CAM, CNC, rapid prototyping and sensors technologies (Zhong et al., 2004). 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 (Milewski et al., 1998; Choi & Chang, 2005).

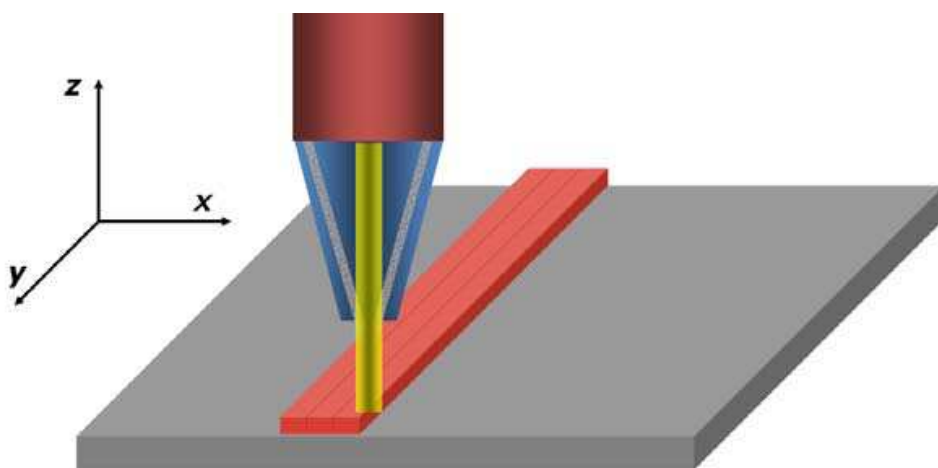


Fig. 1. Schematic representation of the process

The DLMD of metal powders is an additive process in which a metal powder is deposited on the base material, layer by layer, and melted with it. The connection between the metal powder and the below surface is similar to a weld with a high mechanical strength; subsequently the added metal can be subjected to any machining process. Fig. 1 shows a schematic drawing of the process.

The DLMD process starts from the three-dimensional CAD representation of the part and then fabricate it using the technique of layer by layer building (Dwivedi et al., 2007). Now two different processing solutions can be adopted, depending on the type of system used, which can be a 3-axis or a 5-axis CNC system. With the 3-axis systems the steps are identical to those described above for all MAM processes, and so it need for the conversion of CAD files in STL files. The model obtained is then equipped by supports, useful to sustain overhangs, and finally subjected to the stage of slicing. The slicing consists in a dissection of the model into a series of layers whose normal is parallel to the Z direction of construction. In systems with 5 or more axis, in addition to translations along X, Y, Z, the head of the machine can perform rotations around the same directions. For these systems, increasingly popular, the slicing operation is carried out directly on 3D-CAD model, with layers having its normal always parallel to construction direction, which may differ from the Z axis. In this case there is an advantage: it not needs the conversion of 3D-CAD model into the STL model

(Milewski et al., 1998). Furthermore, with 5-axis systems, components which require the deposition of layers with different orientation with respect to the previous ones can be fabricated by tilting the laser beam and nozzle that supplies powder or by tilting the piece under construction. Thus, the axis of the laser beam is always normal to the plane of deposition. This possibility provides another advantage: it is possible to produce protruding or overhanging parts without the need of supports or of a powder bed below them, like, for example, in SLS.

With the slicing, the geometry of each layer is determined and it is possible to define the path of the laser beam. Therefore, the movements of the machine head and of the worktable and the commands to control the laser and the powder feeder were defined. Because of the influence of high thermal stresses and of surface tension, the tool path for the DLMD is more complicated than that one of the traditional rapid prototyping processes. It is important to design an appropriate path, as it not only improves the quality of the final product, but also increases the efficiency of the manufacturing process. In the realization of the layers, DLMD technology incorporates laser cladding, a technique of metal surfaces coating performed by laser: so, someone calls it “three-dimensional laser cladding” (Zhang et al., 2003; Lu et al., 2001; Qian et al., 1997).

The laser beam, through its heat energy, creates a molten pool with dimensions, on the XY plane, varying from half to five times the diameter of the focal spot, according to the adopted power and scanning speed. A flow of metal powder is continuously injected in the molten pool, created on the substrate by the laser. Powder melts completely and then solidifies, making a very compact and welded to the substrate track. The beam scanning path causes the formation of a set of tracks, one next to the other, with a designated amount of overlap. Usually, each track is started and stopped on the outer edges of the piece until the entire first section, the first layer, is completed. The size of the molten pool is also influenced by the heat stored in the substrate or in the previously deposited material. If the heat loss occurs very quickly the width of the molten pool decreases, on the contrary, if the heat loss occurs very slowly the width of the molten pool increases: setting the laser power and the processing speed the width of molten pool can be determined. This is important because the size of the molten pool affects the properties of the final product (Lewis & Schlienger, 2000).

The first layer is built on a metal substrate that is the construction base of the piece. Usually, the substrate is made of the same material of the component has to be built. Sometimes a material best-able to dissipate the heat can be used as substrate material (Angelaastro et al., 2007a).

After deposition of the first layer, laser head, that includes focusing lens and powder delivery nozzle, moves in the construction direction (Z direction in the case of 3 axis systems) and starts deposition of the second layer. Therefore, process recurs, line-by-line and layer-by-layer, until the entire component is built up (Atwood et al. 1998; Angelaastro et al., 2007b). In some cases, the laser head is fixed and the worktable move.

3. Comparison with conventional manufacturing technologies

Typically, metal parts are produced by means of thermomechanical processes, including casting, rolling, forging, extrusion, machining and welding. Conventionally, to obtain the finished pieces multiple steps and heavy equipment, forms, dies and tools are required. However, the use of this equipment is justified and advantageous in mass and in large

batches production. But when the part is unusual in form, has complex internal cavities or has to be made in small batches costs and time to prepare the production rapidly grow and, therefore, conventional technologies are practically unenforceables (Zhang et al., 2003).

On the other hand, the DLMD process fabricates, in a single step, the required components already with the final material, with mechanical properties close to or, in some cases, higher than those obtained with conventional processes. It can make parts with extremely complex geometries, usually oversized of 0.025 mm, so after a quick cleaning, to obtain the tolerances and the surface finishes required, they are ready to use. For example, in the experimental tests of Lewis and Schlienger, the tensile properties of some deposited materials (AISI 316 stainless steel, Inconel 690 and Ti-6Al-4V) were measured and compared with those of the same conventional processed materials. These data show that it is possible to obtain equivalent and superior properties to those of wrought annealed materials. So, multiple thermomechanical treatments, required in conventional procedures, can be avoided (Lewis & Schlienger, 2000).

Using DLMD of metal powders chemical segregation is eliminated. This problem occurs in parts obtained by casting and to cure it homogenizing heat treatments and plastic deformations for the grain refinement are indispensable. Chemical homogenization is achieved through randomization of composition by using powders as input material and by limiting chemical diffusion in the liquid state to the boundaries of the small molten pool that is used to deposit the entire component. (Lewis & Schlienger, 2000). Moreover, the high solidification rate, resulting from the narrow HAZ (Heat-Affected Zone), and the high temperature gradients, which are generated around the molten pool, allows a fine grain microstructure (Zhang et al., 2003).

Another positive aspect of this process consists in the production speed increasing. Indeed, a study by the National Center of Manufacturing Science, Michigan, showed that the direct laser deposition of metal powders can reduce by 40% the time to produce a mold.

The convenience of this technology is also determined by the reduction of the labor required and of the equipment cost, since there is only one machine that runs the entire process automatically. Later, a machine tool or EDM is used to finish the piece. This results in a decrease of the floor area needed for the factory and for the warehouse.

Even compared to the use of CNC machine tools, in many cases, DLMD is suitable because of at least further two advantages: no waste and higher material purity of the final component. In fact, the processes performed by the CNC machine tools do not result only in the finished part, but also in metal chips, fluids, lubricants for cutting and worn tools that need to dispose of. The DLMD process results only in the desired component. There are no wastes.

Since this process can be achieved in a controlled atmosphere, with high purity inert gas, powder that was not melted by the laser can be sucked and used again. This feature makes DLMD particularly attractive when it has to use very expensive or hazardous materials, which require containment during processing. Then, the material purity of the final piece is kept high by eliminating contamination resulting from contact with cutting tools, surfaces of the molds or forms, lubricants and chemicals for cleaning (Milewski et al., 1998).

4. Process equipment

The system which allows DLMD process of metal powders consists of a set of subsystems that are interconnected. These subsystems, during the process, provide a full control of laser power, speed, position of the spot, powder flow rate and size of molten pool.

All subsystems currently used consist basically of:

- control workstation;
- laser source;
- powder feeding system;
- multi-axis CNC system.

In some cases there are also a feedback control system and a controlled atmosphere chamber.

The control workstation is a PC that receives the part data in the CNC instructions format, derived from 3D-CAD model by means of a CAD/CAM software. Also it communicates with all the subsystems and allows, therefore, the intelligent control of the entire deposition process.

The laser source used must have a high power, typically between 500 W and 6000 W, to be able to melt both the metal substrate and the metal powder. By means of mirrors or optical fibers, the laser beam is conveyed to a lens that focalises it to an optimal spot size.

The powder feeding system make available the powder in the work area and also can mix the several types of powders when it needs to use them simultaneously. It consists of some containers and related devices for the mass flow rate control, a mixer and a nozzle to deposit the material into the molten pool. In systems with several containers it is possible to generate mixtures of powders, filling each one with a different powder and combining them. The mixing of powders can be obtained directly in the molten pool, feeding them simultaneously, or within the mixer. This solution makes the process able to produce different types of alloys or to vary the composition of the material, within the piece under construction, depending on the desired properties. The mechanisms for the mass flow rate control can be based on different operating principles.

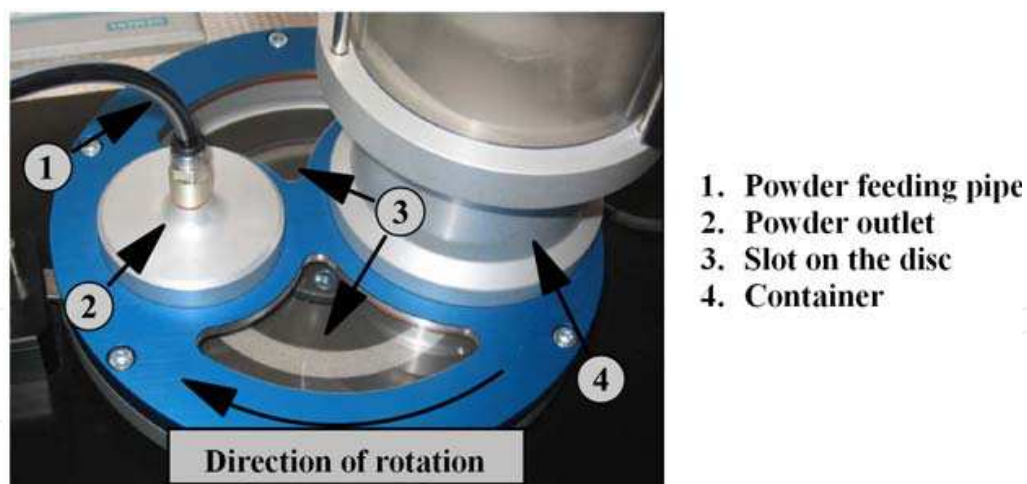


Fig. 2. Disc powder feeder

For example, a mechanism is constituted by a hopper, under each container, having a horizontal shaft with some caves on the lateral surface. The rotation speed of the shaft can be varied to control the mass flow rate. Another type of powder feeding system consists of a container from which the powder flows by gravity into a slot created on a rotating disc. The powder is transported to a suction unit, which through a carrier gas flow, sent it to a nozzle. The powder mass flow rate depends on the slot size and the rotating speed of the disc. The last type of powder feeding system consists of a pneumatic screw feeder; in this case the

mass flow rate of powder depend on the rotating speed and on the size of the screw. Then the powder has to be transferred to the work area: this can be done by means of a carrier gas (argon, helium, nitrogen) or simply by means of gravity.

The powder feeding system ends with a nozzle that has to inject the powder into the molten pool (Lin, 1999b). So that the capture efficiency of powder by the molten pool can be high, the nozzle has to be placed very close to the pool itself (Lin, 1999a). This implies that the nozzle is subjected to high thermal loads and, therefore, is usually made of brass. So it also is able to reflect the laser radiation which is back-reflected from the molten pool (Lin, 1999c). The nozzle can have different configurations. There are two basic ones: with a coaxial supply and a lateral supply of powder (Weerasinghe & Steen, 1983; Zekovic et al., 2007). In the first one, there is the advantages of the independence from the moving direction of the head, of the controlled heating of the powder before it goes into the molten pool and of the high capture efficiency of powder by the molten pool. In this case, the powder moves coaxially to the laser beam. The nozzle, cone-shaped, includes two internal annular interstices. The carrier gas, or primary gas, is used to transport powder outer the first interstice. A secondary gas, usually argon or helium, is injected into the inner interstice to perform various functions: to avoid fraying of powder flow, ensuring the confinement along the nozzle axis, and to protect the molten pool from oxidation. Not all the components, however, may be accessible by a coaxial powder nozzle. On the other hand, the lateral supply of powder allows the treatment of all types of geometries, designing dedicated nozzles. Basically, the nozzles are lateral pipe with tailored length, shape and diameter (Schneider, 1998).



Fig. 3. Coaxial nozzle

The multi-axis CNC system monitors the position, the speed and the motion path of the laser spot. The motion path is determined by slicing the STL model or directly from 3D-CAD model, if the system has 3 or more axis (usually 5) respectively.

In some cases it is also envisaged the use of a feedback control system. Indeed, actually, the deposited powder mass results to be irregular because of the oscillation of the laser power and of the difficulty of controlling the powder mass flow rate (Fearon & Watkins, 2004; Mazumder et al., 2000). This factors result in a defective deposition, characterized by uneven surfaces and lack of adhesion between the layers. To control the height of the deposition, that is corresponding to the layer thickness, a feed back control system can be used. This subsystem makes the control of some variables, such as the energy density and powder flow rate (Choi & Chang, 2005; Krantz & Nasla, 2000). It generally consists of a detection height unit (Height Sensing Unit), a processing unit of the feedback signal (Signal Processing Unit)

and an optical sensors apparatus consisting of CCD cameras. The detection height unit elaborates the images from the optical sensors apparatus, which generally consists of at least two cameras in order to neutralize the effect of the laser head movement (Mazumder et al., 1999). Through the processing unit it is possible to remedy an anomalous deposition. During the trial, a deposition lower than desired may be covered by repeating the path on the same layer before moving to the next. Instead, a deposition greater than desired can be resolved reducing the laser power and the powder flow rate as quickly as possible or (Bi et al., 2006). When the use of shielding gas ejected from the head is insufficient to have a good deposition, the process can be performed in a sealed chamber in which it is created a controlled atmosphere consisting of inert gases, such as argon, helium or nitrogen. Without this condition, the fabricated component may have excessive porosity and oxidation, with insufficient adhesion between layers and, consequently, with poor mechanical properties (Erzincan & Ermurat, 2005). When a controlled atmosphere chamber is used, DLMD becomes a free waste process. Indeed, the powders not fused by the laser during the process can be retrieved through a suction system, filtered and reused. This characteristic makes it particularly attractive when it has to process very expensive or hazardous materials, that require containment during processing.

5. Process materials

Lots of materials can be used with this process, including those very hard to work with conventional technologies. Some of tested materials are (Alemohammad et al., 2007; Simchi, 2006; Wu et al., 2002; Yellup, 1995):

- stainless steels (316, 304L, 309, 420);
- maraging steels (M300, M2);
- tool steels (H13, P20, P21, S7, D2);
- nickel-based alloys (Inconel 600, 625, 690, 718);
- titanium alloys (Ti-6Al-4V);
- aluminium;
- copper and its alloys;
- stellite;
- tungsten carbide.

Although the material can be supplied both in powder and in wire form, powder is generally used for several reasons: the process is more flexible because, at any time, the changes in the layer thickness and in the composition of material are possible; many more elements and alloys are available in powder; there is no direct contact with the molten pool; the laser beam can pass through the powder flow, instead of being intercepted by the wire.

The flexibility that acquires the process through the use of powders of different metals is extraordinary (Liu & DuPont, 2003). In fact, the properties of the product can be controlled almost point by point by combining different powders in various amounts during the process. The powders of different metals can be premixed and then conveyed by a single powder feeder to the work area. But in this case, due to different densities, sizes and shapes of particles, vibrations in the feeding system can cause segregation of the powders, which, in turn, may change uncontrollably composition and properties of deposited material. This problem is completely eliminated conveying the different powders toward the work area using separate powder feeder and injecting them simultaneously, with desired proportion, directly into the molten pool (Schwendner et al., 2001). Thus, the desired functional

composition gradients can be obtained by increasing or decreasing the feeding speed of the various metals. Also, any type of composition, with the types of powders available, can be easily used, eliminating all the necessary steps for the production of the powders of the desired alloy (Lewis & Schlienger, 2000).

6. Process parameters

The quality of the parts that can be achieved with DLMD is strongly influenced by numerous process parameters. The problem of determining what are the parameters that influence the final properties and in what measure is complicated by the significant interactions between them (Choi & Chang, 2005).

A careful control of process parameters becomes crucial to obtain products having a satisfactory dimensional accuracy and good mechanical properties. The main process parameters are:

- powder feed rate;
- laser power;
- scanning speed;
- beam diameter;
- layer thickness;
- overlap percentage;
- energy density.

The powder feed rate is the amount of powder per time unit which exits from the nozzle. It affects especially the layer thickness: high flow rates result in very thick layers. In turn, the thickness of the deposited layer determines not only the dimensional and geometrical accuracies of the product, but its mechanical properties also. In fact, with the same laser power, it becomes more difficult to obtain good adhesion between the layers when layer thickness increases.

With the same material to be deposited, the laser power depends on the type of laser used. Currently, the laser sources most widely used for DLMD process are CO₂ and Nd:YAG sources. The power of lasers which are usually used for the process stands in the range from 1 to 18 kW. The main difference between the CO₂ and Nd:YAG lasers is the wavelength. The Nd:YAG laser has a wavelength of 1.06 μm while that of the CO₂ laser is 10.6 μm . The absorption of the laser energy for most metals increases when the wavelength decreases. Various studies showed a greater depth of molten pool through the use of a Nd:YAG laser due to increased energy absorption. However, most commercial machines are equipped with a CO₂ laser because of its high efficiency, lower cost and easier maintenance than Nd:YAG laser.

The scanning speed is the speed with which the laser beam executes the tool path about the section that has to be built. If the scanning speed increases, the time required to complete sections and, thus, to realize the component decreases. However, in this case there are some disadvantages that affect the quality of the final component. For example, because of the high speeds, the layers may not achieve the desired thickness or a difference in height between the edges and the central part of the part may originate: in fact, to reverse the scanning direction the laser head slows down until to stop in correspondence of the layer edge and then accelerates to the set speed: if the speed increases the time needed to slow

down and accelerate increases accordingly, leading, with a constant powder feed rate, to the deposition of a greater amount of material at the edge than the center of each line.

The beam diameter is a key parameter for the laser processing. It determines the spot diameter, which is equal to the beam diameter at the focus, and, consequently, the size of the track. In turn, the size of the track affects the surface roughness and the minimum size of achievable features. Finally, the beam diameter affects directly the energy density, which is after defined.

The thickness of the layer, as seen for all MAM processes, is defined by the slicing of the CAD model. One of the greatest difficulties in the DLMD is just to maintain the desired layer thickness. Therefore, it is preferable to use a feedback control system.

The overlap percentage is defined as the ratio between the area of overlap between two adjacent tracks and the total area of the track itself, measured on the work plane (Schneider, 1998):

$$\%O = \frac{A_{overlapped}}{A_{tot}} \quad (1)$$

The overlap percentage affects the porosity and, consequently, the density and mechanical properties of the deposited material.

Several studies have shown that the quality and mechanical properties of the DLMD components are strongly influenced by the size of the molten pool and by the residual stresses, which can be directly controlled from the laser energy input (Peng et al., 2005). The laser energy input can be described by the specific energy or energy density E [J/mm²], defined by the following equation:

$$E = \frac{P}{hv} \quad (2)$$

where P is the laser power [W], h is the hatch spacing [mm], defined as the distance between the vectors drawn from the center of the laser spot in two parallel and consecutive tracks, v is the scanning speed [mm/s]. In the case of overlapping zero, h becomes equal to the spot diameter.

7. Main experimental results

In this paragraph, the main results on experimental tests conducted by the authors on the Nickel alloy (Colmonoy 227-F) will be illustrated. This material, usually used to manufacturing moulds, is characterized by an elevated hardness (22-27 Rockwell C), a density of 8.53 g/cm³ and a melting point of 915 °C; it is able to tolerate extreme job conditions because of its elevated resistance to abrasion, to corrosion, to stresses and to high temperatures. Colmonoy 227-F is furnished in powder form with granules of spherical shape which have a maximum size of 106 µm.

The aim of experiments was to obtain deposited layers, welded to the substrate and between them, in order to realize good quality 3D parts by means of the DMLD process. A six axis machine, equipped with a welding head and with a CO₂ laser with a maximum power of 3kW, was used for experiments.

7.1 Gravity distribution system

First, a gravity distribution powder apparatus was designed and built. In this system the powder was deposited by gravity over an AISI 304 steel substrate with a thickness of 10 mm. The main components of this system are illustrated in Fig. 4 and consisted in:

- a powder container;
- a device for ON/OFF regulation of the powder feed rate controlled electrically by means of signals coming from the laser machine;
- a nozzle for the coaxial deposition of the powder on the melt pool created from the laser, working by gravity or by a carrier fluid.

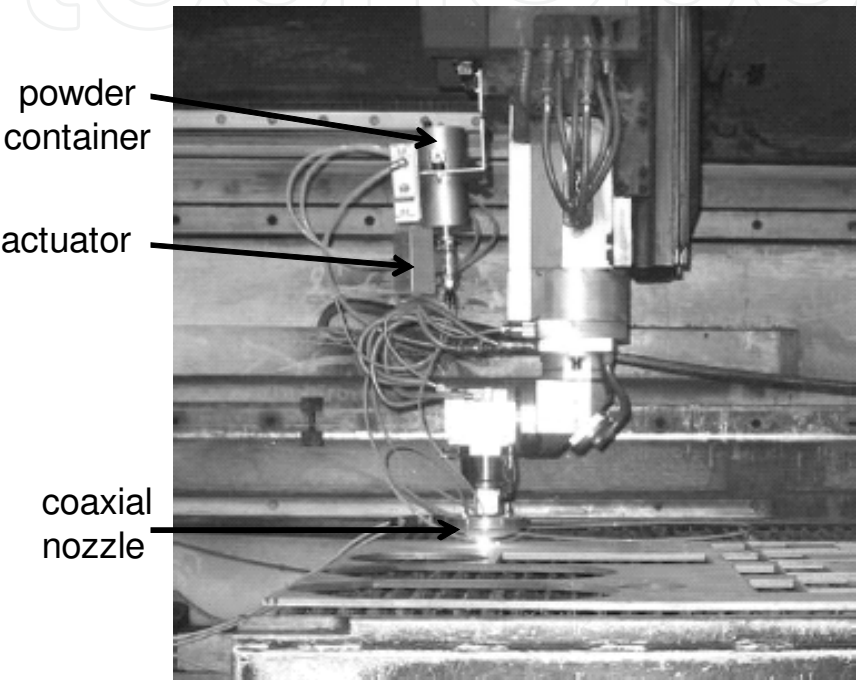


Fig. 4. Gravity powder feeding system

One layer specimens were produced with this system changing the two factors laser power and scanning speed.

Table 1 shows the experimental plane that was used in this step.

Test Number	Laser Power [kW]	Scanning Speed [m/min]	Energy Density [J/mm ²]
A1	0.5	1.2	83.3
B1	0.5	3.0	33.3
C1	0.5	4.8	20.8
D1	1	1.2	166.7
E1	1	3.0	66.7
F1	1	4.8	41.7
G1	1.5	1.2	250
H1	1.5	3.0	100
I1	1.5	4.8	62.5

Table 1. Experimental plane

The Energy Density was calculated by means of equation 2 setting overlapping to zero and the value of hatch distance equal to the spot diameter (0.3 mm in this case). The built samples were analyzed in terms of adhesion to the substrate, porosity and cracks.

Fig. 5 shows transversal sections of the nine samples. The analysis of results showed that good result could be obtained setting laser power to 1.5 kW and the scanning speed to 3.0 m/min. Moreover, if the powder feed rate could be regulated, better structure would be achieved with specific energies lower than 100 J/mm², using both lower values of the laser power and of the scanning speed.

Sections orthogonal to laser scanning direction (Fig. 5) showed that almost all samples had a wide cavity between deposited metal and substrate. In these specimens only few initial tracks were stuck to the substrate, whereas all the others stayed above it. Only samples H1 and I1 showed a full adhesion between the deposited metal and the substrate.

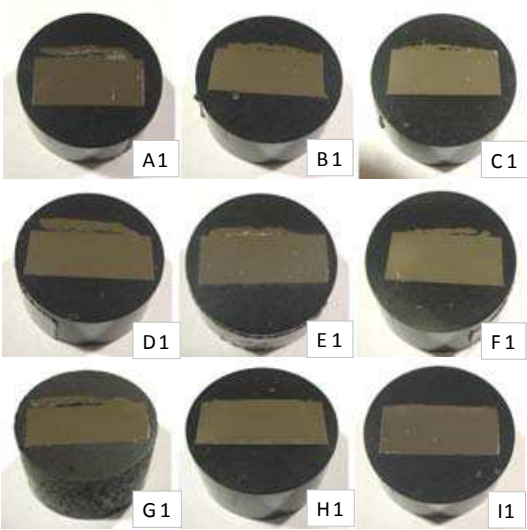


Fig. 5. Transversal cross sections of specimens

The sample I1 realized with a specific energy of 62.5 J/mm², even if it was almost free of porosity, was afflicted with a very large number of vertical cracks (Fig. 6), probably due to the very high thermal gradient and the excessive cooling rate caused by the application of a very high laser power (1500 W) at a high scanning speed (4.8 m/min). Therefore, it was possible that cracks were generated from residual stresses melted and re-solidified metals of the deposited layer and of the substrate, having different expansion coefficients, couldn't be able to contrast stresses with an adequate strain.

At last, considering such factors as adhesion on the substrate, porosity and presence of cracks it can be concluded that, the best specimen was H1. This sample (Fig. 6) was obtained

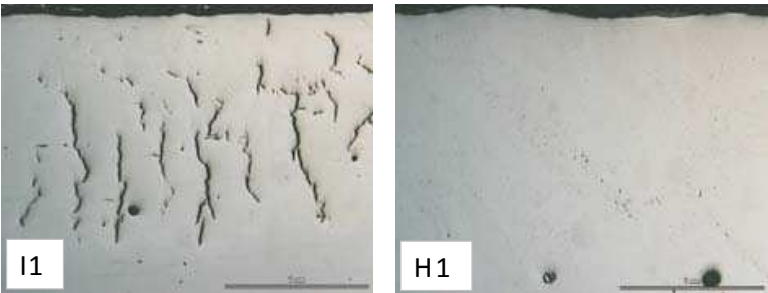


Fig. 6. 50X magnification of transversal sections for specimens H1 and I1

with a laser power of 1 kW and a scanning speed of 3.0 m/min, resulting in a specific energy of 100 J/mm². Nevertheless, it showed some spherical cavities, although limited in number, probably due to the gas among the powder grains before the process or generated itself from decomposition of metal during the process.

7.2 Pneumatic distribution system

Later on it, a pneumatic system for the distribution of the powder was designed and built; it was able to make a discreet control of the powder feed rate. This system was installed again on the 6 axes laser machine, which was used before together with the gravity system (Fig. 7). This distribution system allowed a control of the powder feed rate in a range between 20.1 g/min and 29.2 g/min, acting on pressure and flow rate of carrier gas (Argon), which was taken directly from the laser machine.

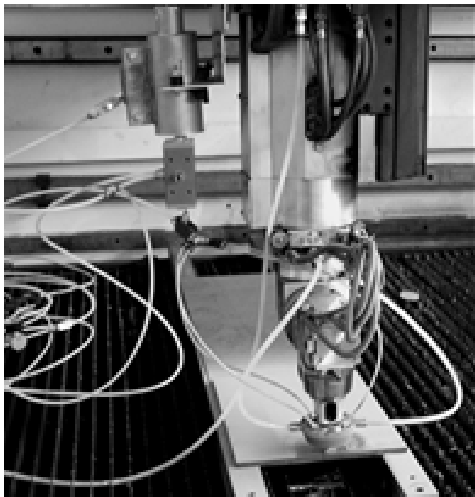


Fig. 7. Pneumatic distribution system

A reduced orthogonal experimental plan was chosen to plan experiments. Three factors were considered: powder flow rate (q), laser power (P) and scanning speed (v). They were changed on three levels, as shown in Table 2, resulting in 9 combinations of the parameters.

Test Code	Powder Flow Rate [g/min]	Laser Power [W]	Scanning Speed [m/min]	Energy Density [J/mm ²]
A2	20.1	500	1.2	83.3
B2	20.1	750	3.0	50.0
C2	20.1	1000	4.8	41.7
D2	23.8	500	3.0	33.3
E2	23.8	750	4.8	31.3
F2	23.8	1000	1.2	166.7
G2	29.2	500	4.8	20.8
H2	29.2	750	1.2	125.0
I2	29.2	1000	3.0	66.7

Table 2. Experimental Plane used for the pneumatic distribution system

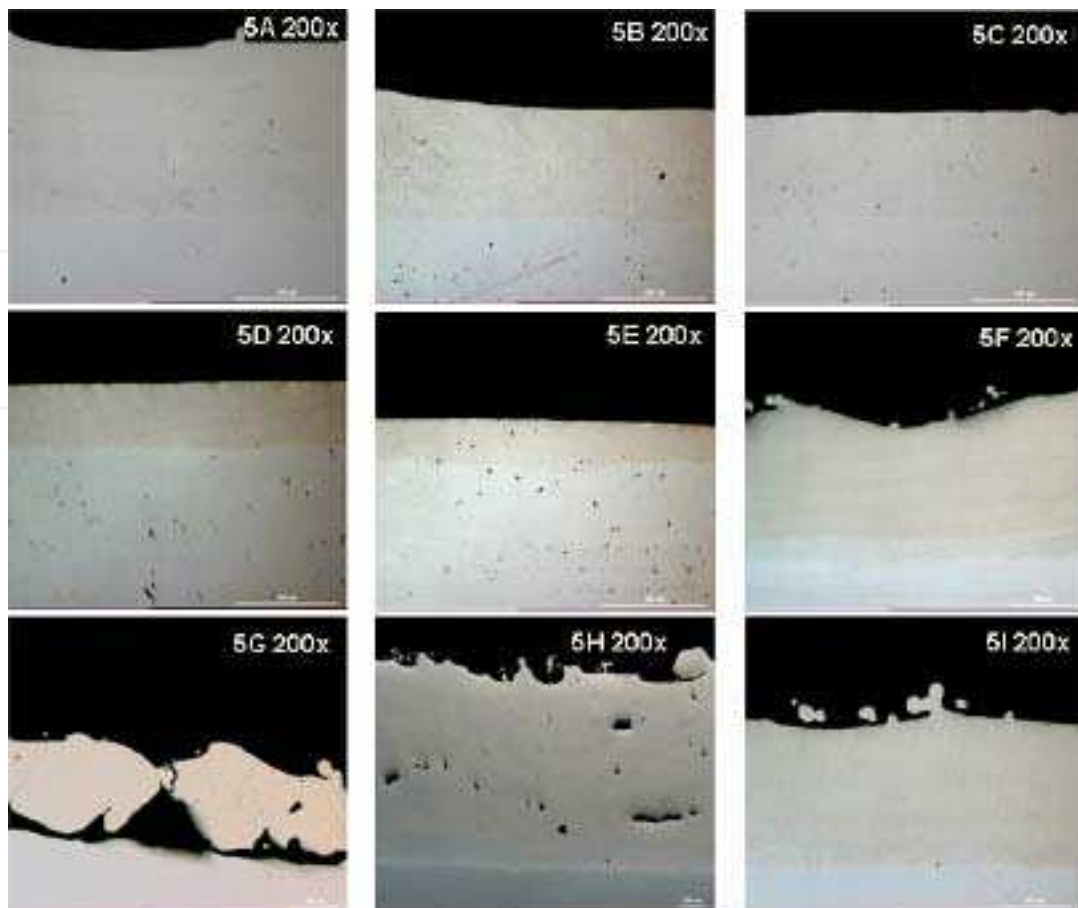


Fig. 8. 200X magnification of cross sections of five layers samples.

Values of the Energy Density E are also reported in Table 2.

One layer samples were obtained with the pneumatic powder feeding system. The quality of the parts, in terms of porosity and adhesion to the substrate, was evaluated. First of all, the 9 one layer samples were observed at the optical microscope in order to evaluate the adhesion between the layer and the substrate. The analysis of samples sections revealed that the material deposited has a good adhesion, excluding samples G2, H2 and I2, all three achieved with greatest powder flow rate (29.2 g/min).

Following a qualitative evaluation, it was possible to say that in the samples made with low and medium powder flow rate levels the porosity of deposited material was very low, so as to be comparable with that of the substrate. Porosity of samples G2, H2 and I2, made with greatest powder flow rate, amounting to 29.2 g/min, seemed to be worse than the others. Subsequently, the same experimental plan were used to realize 5 layers samples.

The 5 layers samples were analysed with the optical microscope, assessing, in this case too, adhesion between the first layer and substrate and between a layer and the contiguous one. Fig. 8 shows transversal sections for five layer samples. Also in this case, it was found that low (20.1 g/min) and medium (23.8 g/min) powder flow rate generate better results than high powder flow rate. In fact, specimens 5A, 5B, 5C, 5D, 5E, 5F, shows a good adhesion between a layer and the contiguous one; 5G, 5H and 5I were characterized by the worse adhesion between a layer and the contiguous one.

Roughness tests were also performed on built samples. Results for roughness showed that it increases with powder flow rate and laser power but it decreases with scanning speed.

It means that good surface samples can be obtained setting the powder flow rate and laser power to the minimum value and the scanning speed to the maximum value; on the other hand, considering factors as adhesion and presence of pores and cracks, the best results can be obtained in correspondence of minimum values for the three analysed process parameters. Thus, 3D components can be realised by means of the DLMD process using low values for powder flow rate, laser power and scanning speed (20.1 g/min, 500 W, 1.2 m/min, in this case).

8. DLMD applications

The above mentioned capacities of DLMD process allow to build, modify and repair any metal piece reaching results unimaginable at a previous time. The application field of the process is very broad and its expansion rate does not mention decrease. Some of today's applications cover the following areas:

- fabrication of metal products and functional prototypes without tools;
- cooling of molds and inserts used in casting;
- tools reconfiguration;
- repair and restoring of tools;
- cladding;
- smart components (sensors embedded in the component);
- functionally graded materials (materials with a gradual variation of composition);
- fabrication and repair of components for aviation and aerospace industries;
- fabrication and repair of military equipment;
- rapid production of molds and dies from metal sheets;
- creation of custom implants and surgical instruments.

Thanks to the know-how acquired over several years of experimentation on the DLMD process, performed in collaboration with the ELFIM company, it was possible to achieve the claddings and restorings of worn parts, some of them having very complex geometries.

Nowadays, it is widely known that the application of coatings by means of conventional processes, such as CVD (Chemical Vapour Deposition), PVD (Physical Vapour Deposition), PTA (Plasma Transferred-Arc) and other thermal spray methods, can significantly improve wear and corrosion resistance of a surface. However, these processes can generate only coatings very thin (1-10 μm) and somewhat porous, even causing heat affected zones of considerable size. On the other hand, DLMD is able to create a strong metallurgical bond between very different materials and allows to obtain coatings from 10 to 100 times thicker than those conventionally produced. Currently, this process is used to deposit a wide variety of stellites and nickel based alloys on the tool surfaces subject to very hard working conditions, increasing their life of about 5 times compared to traditional ones.

This is the case of the impeller of a centrifugal pump used for the extraction of natural bitumen (Fig. 9). Due to the passage of this highly viscous and containing sulphur liquid, the impeller suffers wear and corrosion that damage and put it out of use very quickly. Therefore, a manufacturer of these pumps has required the cladding with tungsten carbide, about 10 mm thick, upon specific surfaces of the impeller. Because of the enormous diversity of the expansion coefficients of the two materials, it was not possible to deposit tungsten carbide directly on steel of the impeller. So, it was used a nickel alloy as buffer material. Therefore, first it was deposited the pure nickel alloy and then the gradually variable

composition layers were fabricated. Exactly, in their composition while the percentage of the nickel alloy reduces that of the tungsten carbide increases, to obtain a semi-finished whole surface of tungsten carbide.

Another application of the DLMD process was performed on a cochlea for the vegetable oil industry. This stainless steel screw, used to knead the olive paste, is subject to high wear, especially on the surfaces far from the rotation axis, where, of course, the tangential velocity is highest. Therefore, as shown in the Figure 10, a cladding of nickel alloy, which is more wear-resistant than stainless steel, was made.

The replacement of a broken or worn tool, generally, is not a convenient choice because of high costs and delays to support in production. However, the conventional repair processes, almost always, result in tools with properties below of the quality standards and in long waiting time due to pre- and post-heating and final finishing. Indeed, for example, to prevent cracking and excessive deformation, the steel tools, before welding, are heated to about 550 °C, after that all the parts which can not withstand heat up to this point are removed, held at this temperature for several hours and then post-heated after the repair. Moreover, the part repaired by welding is not as strong as the original tool and tends to be again damaged during the use. Thus, many companies do not allow the use of welding on tools because of the risk of damaging their base material.



Fig. 9. Coated pump impeller



Fig. 10. Coated cochlea



Fig. 11. a) Restored mold component; b) Restored component of the crushing machine

The DLMD makes it easy to repair or restore damaged or worn out tools so that they become like new. In fact, this process allows to deposit, without creating porosity, the metal having the same composition and properties of the base material, creating a high resistance bond with it. The almost total absence of heat affected zone allows to preserve the properties of the tool, eliminates the pre-and post-heating, avoids the risk of causing deformation and minimizes the time required for final finishing.

This application has been used to rebuild the worn out parts of a mold for the production of glass bottles and a tool of a crushing machine, which is able to crushing stones. In Fig. 11a and Fig 11b the components after deposition and before the finishing are shown.

9. Conclusions

This chapter has been organized to pursue the following objectives: a) to describe the DLMD process and its performances, in terms of capacities and applications; b) to seek, through experimental analysis, the functional relationship between certain attributes of quality of built parts and the parameters used to control the process.

First, a description of the DLMD systems in terms of equipments and process parameters was furnished. Later on it, some experimental tests were presented in order to obtain 3D good quality parts.

Finally, some industrial applications were illustrated. It was demonstrated how it is possible to achieve the claddings and the restoring of worn parts, some of them having very complex geometries.

10. Acknowledgments

The authors wish to acknowledge Elfim srl Company for the support given to the experimentation.

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Edited by Meng Joo Er

ISBN 978-953-307-212-8

Hard cover, 444 pages

Publisher Sciyo

Published online 02, November, 2010

Published in print edition November, 2010

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