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Improvement of strategies and parameters for multi-axis laser cladding operations ☆

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ABSTRACT

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. At the moment, the process is mainly applied to 3 axis or 3+2 axis strategies, being numerous works focused on the obtainment of process parameters. Some industrial application imposes the use of 5 continuous axis kinematics to perform complex parts. This fact requires new processes design and new strategies for this type of operations. The presented work evaluates the steps to be followed before accomplishing 5 axis laser cladding operations. First, the design of a test part for the experimental tests is carried out, taking into account the machine kinematics. Afterwards, both, the process control parameters and the tool path strategies are analyzed. Finally, the optimization of process parameter and strategies is presented. Therefore, the work represents a useful tool for the industrial application of 5 axis laser cladding.

1. Introduction

Nowadays, industries oriented to high added value parts manufacturing are continuously searching for new innovative, economical and sustainable processes. Laser based technologies stands out due to the automation possibilities, processing speed and high quality processed areas. Within the laser material processing, laser cladding is one of the most emerging in the industry. It is based on the use of a high energy density spot in order to generate a melt pool on a substrate where a filler material is injected. High quality clads are generated and strongly joined to the substrate. Clads overlapping generates layers of added material that build up 3D complex geometries using the so called "layer by layer" method [1]. Therefore, laser cladding can be also used as an additive manufacturing technology, achieving all the advantages of these methods as complete freedom of design, adaptation of the geometry to very complex shapes and very close to the final design, machining volume reduction, etc. Laser deposition process dilution [2] and heat affected zone are minimum [3], which represents an overcoming advantage in relation to other traditional processes such as TIG or MIG welding whose main drawbacks are the large heat affected zones that could damage the part integrity. Laser technology also enables the process to be automated and integrated on traditional manufacturing machines. Besides, the filler and the substrate material can match up or in case of being different it can provide extra properties the substrate does not have, such as wear or corrosion resistance.

High added value parts coating is the most extended application of laser cladding. It can be used also for high added value part repair or even as a rapid manufacturing process [4]. It has been mainly used by mould industry for the generation of hard coatings on tool steels, fact which presents laser cladding as an alternative to traditional surface hardening processes such as nitriding or electrodeposition [5]. Laser deposition is also applied by mould manufacturers for mould worn parts recovering and lately it has been also used for small moulds or complex inserts direct manufacturing. Aside from mould industry, aerospace industry also involves high-added value parts where laser technology application is gaining more and more relevance. Each part of the aircraft, and particularly engine parts, represents commonly expensive elements. It is due to the complex geometry of these highly added value parts that their manufacturing cost increases. On the other hand, when it comes to replace such parts in case of breakage or damage the cost is even higher. Repairing those pieces and giving them a new use again is the solution for reducing costs in the aeronautic industry.

Regardless the application, they all require the optimal parameters to be obtained in order to achieve good mechanical properties. Some works have concluded that laser cladded parts with optimum process parameters result in similar fatigue life than casted and machined parts and mechanical behaviour is guaranteed [6]. Besides, possible

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Nomenclature

DR	deposition rate. Clad section multiplied by the feed rate [mm^3/min].
DR_{max}	maximum deposition rate value [mm3/min].
$\overline{DR}$	ratio between DR and DR_{max}.
H	mean clad height.
ΔH	height deviation. Standard deviation of the clad height values.
ΔH_{max}	maximum height deviation value.
$\overline{\Delta H}$	ratio between ΔH and ΔH_{max}.
W	mean clad width.
ΔW	width deviation. Standard deviation of the width values.
ΔW_{max}	maximum width deviation value.
$\overline{\Delta W}$	ratio between ΔW and ΔW_{max}.
θ	wetting angle. Angle measured through the clad and based material interface.
$\overline{\theta}$	ratio between θ and θ_{max}.
OF	optimization value depending on $\overline{DR}$, $\overline{\theta}$, $\overline{\Delta H}$ and $\overline{\Delta W}$.
Δz	laser head standoff values.

defects such as cracks appearance and porosities can be minimized. Moreover, these optimal parameters vary depending on the specific combination of substrate and added material. In this sense, these parameters are different depending on the materials used in the different application sectors, such as stainless steels [7], aluminium alloys [8], titanium alloys [9] or nickel based alloys [10]. All these becomes laser cladding tuning process a critical step during process design before its industrial application. So, it is necessary to have a properly designed tuning process in order to minimize the number of experimental tests to obtain optimal parameters of the process.

Optimization of process parameters is not the only aspect that has to be taken into account in laser cladding application but it is also necessary to consider the appropriate strategies or laser cladding paths. Laser deposition for direct manufacturing or complex parts recovering is generally the initial step of the complete process since there is a final machining step [11]. This way, the laser deposition process is usually carried out in a 3 or 3+2 axis kinematics, but the concurrence of more demanding complex geometry parts requires the process to be performed in a five continuous axis kinematic [12]. Therefore, five axis laser cladding technology represents a research challenge considering the characteristics involved in the process and the absence of specific process oriented CAM software [13]. For this reason, the development of optimal tool path strategies as well as a strict control on five axis laser cladding parameters is hard to achieve and the common industrial solutions are based on hand-made programming and trial-error optimization [14].

Laser cladding can be performed with different strategies, involving different laser paths, overlapping, etc. Basically, the more uniform the laser cladding strategy the more uniform the height of the deposited material [15]. Thus, the quality of the part is directly dependant on the deposition strategies. All these aspects regarding deposition strategies are nowadays only studied for 3 axis laser cladding process, opening a great research field in five continuous axis application.

Thereby, this article presents the steps to be followed for the design of industrial applications of multi-axis laser cladding process. The five continuous axis laser cladding technology is shown along the manufacturing of a specifically designed test part. The optimal parameters for the five axis laser deposition process have been obtained by a quantitative criterion, based on a weighted optimization factor (OF) taking into account common indicators such as the deposition rate, the wetting angle and the height and width deviations. This minimizes the previous experimental tests and optimizes the time expended during tuning process. Different tool path strategies have been designed making use of commercial CAM software, showing some aspects to take into account when using a software developed for machining operations in additive processes. Finally, once the optimal parameters and strategies were designed and obtained, the part surface has been coated making use of the process data obtained in the study.

2. Experimental procedure

The tests were carried out using a laser cladding system based on a fiber laser Rofin FL010 with a 1 kW maximum power. The powder material was injected with a discrete coaxial nozzle DCN/EHU-4 (Fig. 1a) developed and manufactured by the Department of Mechanical Engineering of the University of Basque Country (UPV/EHU). All the tests have been performed into a laser cell based on a conventional five axis machine tool with 3 linear axis and two rotary axis on a tilting table (Fig. 1b and c). The powder is injected into the nozzle by a SULZER Metco Twin-10C powder feeder. Argon was used both as protective and carrier gas using a 13 and 5.5 l/min flows, respectively. It was used an AISI 1045 structural steel as substrate material and an AISI 316L stainless steel as filler material. Table 1 shows the chemical composition of both materials. The AISI 316L powder is manufactured by gas atomization with a particle size range of $+45$–$150\ \mu m$.

The designed test part consists of a semi-spherical feature. It can be consider as specifically designed for five continuous axis laser cladding application, since the complete range of normal angles are tested. As seen in Fig. 2, a serial of clads were designed with 5° tilt angle respect to the sphere generatrix and 13° separated from each other. Each clad is composed of 5 layers with 0.2 mm standoff between them. Regarding toolpath strategies, the laser beam is maintained perpendicular to the surface as required by laser cladding technology to avoid reflexions and obtain maximum energy absorption. In this sense, the tool path deposition strategies were programmed with commercial CAM (Computer Aided Manufacturing) software Siemens NX7.5® and this perpendicularity requirement was programmed considering the laser beam as the tool axis for a milling operation. Therefore, all the options that allow the control of the tool axis on a commercial CAM system can be used for the positioning of the laser beam with respect to the part surface.

Initially, different conditions were established in order to determine which parameters correspond to the optimal ones. As it is shown in Table 2, the laser power, the feed rate and the powder flow were the parameters studied in this case.

Once the process window is established, the tests carried out and the clads measured, it is necessary to define the criterion to be followed in order to determine which ones are the optimal parameters that will result in obtaining a quality and continuous clad.

Considering there are several aspects that play an important role on the clad quality and continuity, a weighted criterion taking into account several aspects was defined. Therefore, optimal deposition rates (DR), defined as the amount of deposited material, is needed to guarantee the productivity. Moreover, optimal wetting angle values (θ) were only considered because values out of the optimal range will result in defective overlapping. On the contrary, large height (ΔH) or width deviations (ΔW) will have a negative influence on the clad continuity. For this purpose, the