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CAM development for additive manufacturing in turbo-machinery components

H. González*, I. Arrizubieta, A. Calleja, J. E. Ruiz, A. Lamikiz

Department of Mechanical Engineering. University of the Basque Country (UPV/EHU). Alameda Urquijo,s/n, Bilbao 48013, Spain

Abstract

Additive Manufacturing (AM) has become a constantly growing up technology due to the suitability and flexibility in terms of geometry and material diversity. It is applied in high value damaged part repairs from aeronautical, medical and molds and die sectors. This paper proposes an Application Programing interface(API) to be implemented in a commercial software (NX-Siemens) with the main objective of covering a full solution to AM simulation challenges. Experimental tests were carried out in a case of study in order to verify the suitability and reliability of the developed API. The selected material (Hastelloy X) is an additional challenge to be faced; some trials were performed to obtain optimal parameters for this material.

Keywords: Additive Manufacturing (AM); Hastelloy X; Application Programming interface (API)

1. Introduction

Along the last decade, Additive Manufacturing (AM) has suffered substantial improvements due to the flexibility related to complex geometries and material diversity. This technology implies a cost reduction comparing to traditional ones, considering near-to-shape fabrication and the material loss decrement [1]. This fabrication technology is adequate for freeform designed geometries with low rates of material waste [2].

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*H.González. Tel.: +34-946-013-932; fax: +0-000-000-0000 .
E-mail address: Haizea.gonzalez@ehu.eus

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Among different additive manufacturing techniques, Laser metal deposition or laser cladding has become popular due to the suitability for repairing high added value components in the aerospace and medical industries. Other application for this technology is the fabrication of molds and dies. There is a real need to control many factors involved in the process and the relationship between them, such as laser energy, process speed, powder feed rate, and material properties [3].

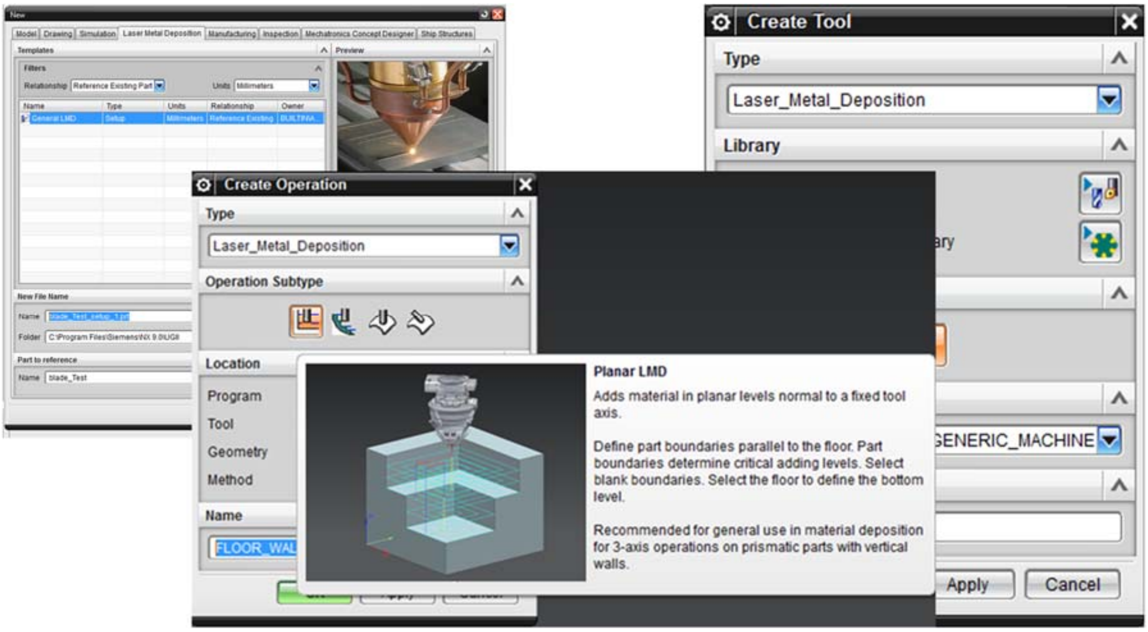
Additionally, Digitalization of LMD is an actual issue that needs to be faced. Communication between machine and designing software, post-processing and standardization are actual challenges present in recent researches [4].

In order to ensure the reliability of the process, this paper shows a case of study and application of the programmed interface developed in order to virtualize LMD process. It is necessary to control critical factors involved in the process, i.e. machine kinematics, collisions detection, process conditions and clad formation geometry. The selected geometry consists on a single blade added with Hastelloy X, a common aeronautical material. Moreover, some material test were carried out in order to obtain the optimal parameters for that material to be added, due to the fact that there is a lack of information related to the characterization of it.

2. AM API development for CAD/CAM commercial software

2.1. Interface and AM palettes

In order to face AM virtual challenges, this research exposed an API development with a new module which embraces all the aspects involved in the process. The application is designed to be implemented in the commercial CAD/CAM/CAE software NX from Siemens. The LMD procedure is divided in 5 different stages: Tool definition for LMD, LMD strategies, post-processing, clad generation and machine verification. The Fig.1 shows the module initialization with tool and operation definition.



Relationship: Reference Existing Part
Units: Millimeters

Name	Type	Units	Relationship	Owner
General LMD	Setup	Millimeters	Reference Existing	BUILTINA...

Name: blade_Test_setup_1.prt
Folder: C:\Program Files\Siemens\NX 9.0\UGII
Name: blade_Test

Type: Laser_Metal_Deposition

Name: FLOOR_WAL

GENERIC_MACHINE

Planar LMD

Adds material in planar levels normal to a fixed tool axis.

Define part boundaries parallel to the floor. Part boundaries determine critical adding levels. Select blank boundaries. Select the floor to define the bottom level.

Recommended for general use in material deposition for 3-axis operations on prismatic parts with vertical walls.

Fig. 1.AM user-friendly interface and palettes for Siemens-NX CAD/CAM software.

- Tool definition for LMD

The tool definition module permits the user to define a full LMD tool with the nozzle (similar way the subtractive tools are defined in these CAM software) and also to establish laser beam parameters (i.e. focal distance).

- Operations definition: LMD strategies

The second step on the API is defining the possible strategies to be applied in AM. A.Calleja et al. [5] carried out several trials analyzing the different strategies applicable to LMD. With the aim of achieving optimal tool paths for 5-axis, a semispherical part was selected and they defined 9 different combinations of strategies. The three strategies selected were improved contour strategy, Spiral strategy and Zig-Zag strategy. They reached to the conclusion that the combination of different angles (horizontal, 45° and vertical Zig-Zag) achieved the optimal structure.

Based on the principle of perpendicularity between the laser beam and the surface to be generated, the API was designed to offer different additive strategies for 3-axis and 5-axis. Four different strategies are available:

- Planar LMD: 3-axis strategy, appropriate to layer by layer operations.
- Cavity LMD: 3-axis strategy. It adds material in planar levels normal to a fixed tool axis.
- Fixed Contour LMD: This strategy is oriented to (3+2)-axis.
- Variable contour LMD: This tool path is for 5-axis additive manufacturing. The tool orientation vector remains perpendicular to the generated surface.

- LMD post-processing

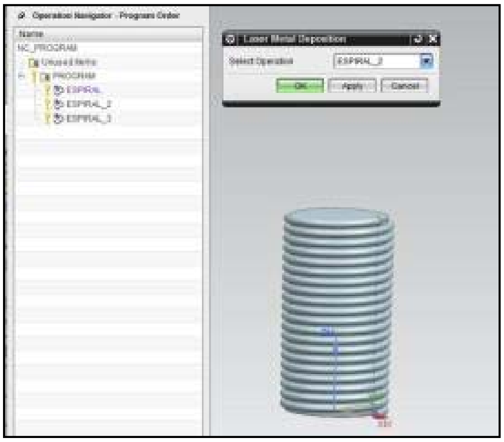
In a similar way as subtractive technology, once the strategies and additive parameters are defined, the following step is post-processing the CNC program to be introduced in the machine. The generated CNC program should contain specific LMD function as M04 (switch on the laser), M05 (switch off the laser) and G501 (keep constant the feed).

- Clad generation

As Robert W. Hedrick et al. [6] explained, the user interface in different CAM software, applicable to AM, offers two main tasks related to this technology, which are called Backplot and machine simulation. The first one is the tool path verification considering the tool geometry and the movement relative to the defined part. When it is applied to a subtractive technology, it is shown the removed material and the interference between the tool and the part. However, the machine simulation is a further step in the process, it analyses the defined process taking into account the components involved in the process. These two modules could be applied to AM technology as a verification of tool movements and machine behavior.

Notwithstanding, being able to predict the final part size in AM is a real needed on the process, this is the reason why this API was designed with an extra module directed to AM and, more precisely clad generation. Many factors are involved to determine the final clad size, such as Power, additive speed, additive material, powder flow and protection gas.

On the path of verifying the full process through the developed API, a simple geometry, the cylinder shown in fig.2 was selected. The strategy set, among the different strategies offered by the application, was a continuous spiral along the part surface. The material and LMD parameters are required in order to establish the final clad dimension. In this case, the material defined generated a clad height of 0.4 mm per layer.



Select Operation ESPIRAL_2

Fig. 2.API clad generation around a cylinder through spiral additive strategy.

- Virtual verification

Additionally to AM conditions, when this technology is applied to complex geometries, all components implied in the process need to be considered, such as nozzle, fixtures, machine axis and machine kinematics (machine axes over-travel). At this point the machine verification acquires the main role. This phase is important to evaluate the suitability of the strategy related to the machine kinematics. Furthermore, the machine virtualization offers the opportunity to predict and prevent the collisions that could appear during the real process between different machine components, i.e. nozzle and part, nozzle and clamping fixture, nozzle and machine axes, part and machine components, etc.

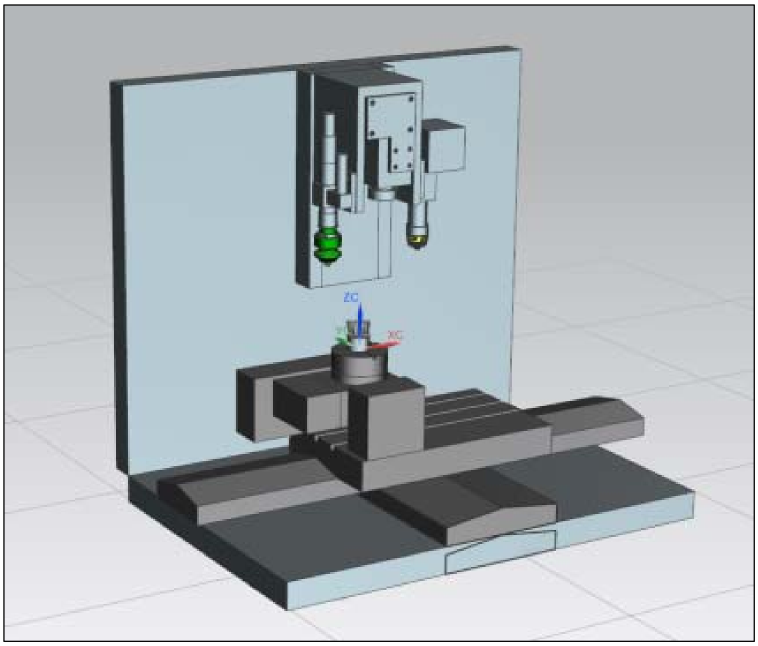


Fig. 3.Machine virtualization module.

3. Case of study

3.1. Material properties and characterization

The Hastelloy X is a solid solution-strengthened nickel-based superalloy that offers an excellent combination of outstanding oxidation resistance and good mechanical properties at high temperatures [7]. In Table 1, it is detailed the chemical composition of this material:

Table 1. Chemical composition of the Hastelloy X [8].

Chemical composition (weight %)												
Ni	Cr	Fe	Mo	Co	W	C	Mn	Si	B	Nb	Al	Ti
47 (bal.)	22	18	9	1.5	0.6	0.1	≤1	≤1	≤0.008	≤0.5	≤0.5	≤0.15

Thanks to the high percentage of chromium, the Hastelloy X has good resistance to oxidizing, reduced and neutral atmospheres and makes the material adequate for jet engine operations up to 1204ºC. Moreover, it is able to retain the protective oxide layer at high temperatures and consequently, retains the oxidation resistance [9]. Therefore, it is widely used in aircrafts and gas turbine engines for combustion-zone components, furnace and chemical processing industries [10]. In the following diagram the UTS and elongation values for a solution treated and rapidly cooled Hastelloy X are shown [9].

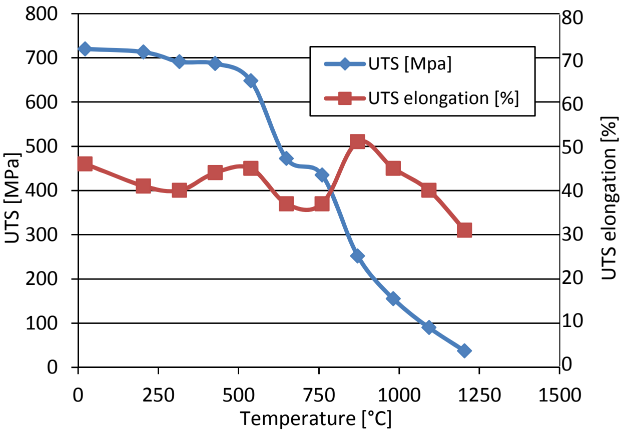


Fig. 4.UTS and elongation values for a solution treated and rapidly cooled Hastelloy X [9].

The Hastelloy X has an excellent weldability and no preheating is required [8], what makes this material suitable for the LMD process. However, no data regarding the LMD process of this material has been found.

Blue et al. studied the welding of the Hastelloy X to Inconel 718 [11]. They used an infrared joining process instead of plasma spray or other laser based additive techniques. The ground of this decision was based on to the extensive setup and controlled environment requirements of the other processes. However, all these drawbacks are overcome by means of the LMD process.

Moreover, the Laser Material Deposition offers certain advantages, such as the directional solidification. Combining the appropriate deposition strategy and correct process parameters, the solidification direction can be controlled, what enhances the mechanical properties of Ni-based superalloys [12].

Therefore, in the present work the viability of a Hastelloy X filler material addition over an Inconel 718 substrate is studied. Moreover, the optimum process parameters and resulting microstructure and mechanical properties have been analyzed.

In the following table are detailed the initial test conditions and the resulting dimensions of the deposited clad. In each test, a single clad has been deposited. The ratio between the height [H] and width [W] of the clad is used as the key parameter to determine the optimum process conditions. This parameter is directly related with the wetting angle of the clad (variable studied previously by [13]). In Table XX "H" is the clad height, "W" the clad width and "D" the clad depth and after the analysis of the obtained results, it is concluded that the test 10 generates the best clad.

Table 2. Process conditions of the initial tests and the dimensions of the deposited clad.

Test	Laser Power [W]	Feed rate [mm/min]	Powder mass flow [m/min]	Clad dimensions			
				H [mm]	W [mm]	D [mm]	H/W
1	500	500	4	0,24	1,38	0,66	0,18
2	600	500	4	0,24	1,57	0,69	0,15
3	700	500	4	0,21	1,73	0,67	0,12
4	400	400	4	0,21	1,29	0,65	0,16
5	500	400	4	0,24	1,53	0,93	0,16
6	600	400	4	0,31	1,66	0,76	0,19
7	500	500	6	0,35	1,62	0,98	0,22
8	600	500	6	0,35	1,68	0,98	0,21
9	700	500	6	0,32	1,72	0,96	0,19
10	400	300	3	0,33	1,41	0,75	0,23
11	500	300	3	0,25	1,71	0,95	0,14
12	600	300	3	0,26	1,85	1,07	0,14

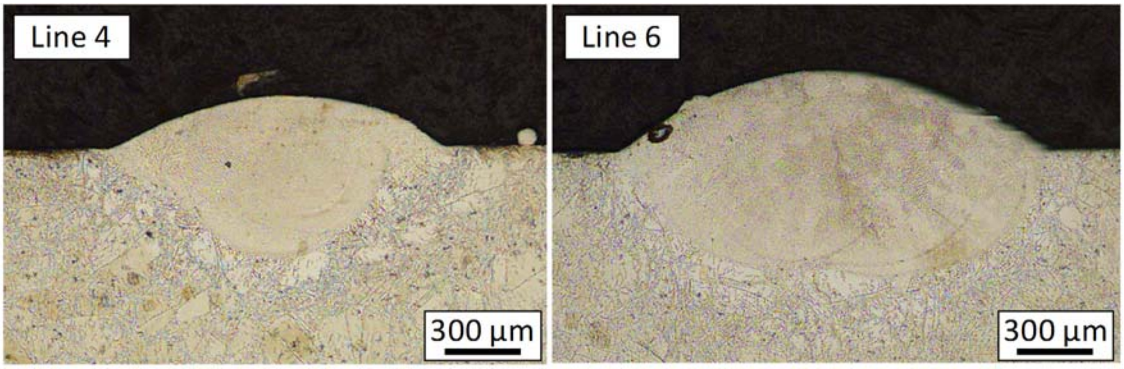


Fig. 5. Cross sections of the deposited clad 4 and 6. The cross sections have been polished and etched using Kalling II.

Once the optimum process conditions for the deposition of single clad have been determined, the overlap distance between two adjacent clads needs to be fixed. For this purpose, different tests with 30-40-50 % of overlap have been carried out. The overlap distance has a direct influence on the stability of the process and the resulting roughness of the deposited layer. After the evaluation of the obtained results, a 40% overlap is determined to provide the best results.

In the following figure, longitudinal and transversal cross sections of 5 lines and 10 layers are shown. As it can be seen, almost no pores have been found, what ensures almost 100% density material. Over the same figure, the microhardness value evolution is plotted at different distances from the top of the deposited material. For the hardness measurement, a Knop indenter and a 100 g load have been used during a 12 s dwell time.

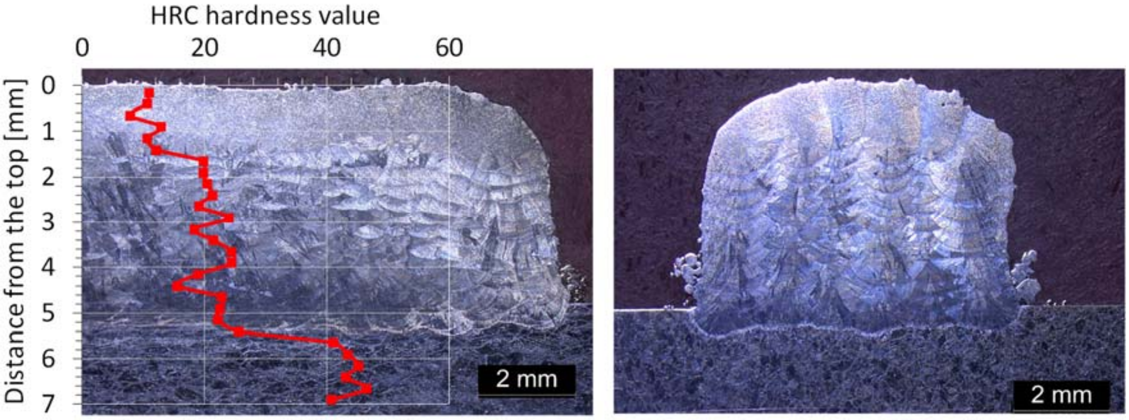


Fig. 6.Microhardness value evolution from the top of the deposited material

3.2. Real application: single blade

For the purpose of verifying the designed application and considering the additional difficulty that means a complex geometry that requires 5-axis to be generated; the designed test consists on a single blade feature.

The trials were manufactured using a fiber laser Rofin FL010 with a maximum power of 1kW. This laser is mounted in a retrofitted five axis conventional machine adapted to LMD technology. The machine consists of 3 linear axes and 2 rotary axes on a tilting table; it also has a sensor with a range between 50 and 210 mm to measure the clad final height., the selected powder was Hastelloy X and according to the material characterization, the optimal parameters are cited hereafter: Laser power 400 W, Feed rate 300 mm/min and powder mass flow 3 g/min. It was noticed that clad height minimizes when the process is under 5-axis movements, around 30% under the expected size in 3-axis. This is due to the fact that the Gaussian distribution differs from a flat substrate to other geometries.

Regarding the toolpath strategies, following the criteria of maintaining the laser beam perpendicular to the added surface, among the different options given by the API it was decided a continuous spiral path on the designed surface. The selected strategy requires movement of the 5 axis simultaneously to assure the perpendicularity.

Once defined the part geometry, the material and the strategy, the next step is running the virtual simulation. This step is crucial to verify the capability of the machine kinematics and machine components to follow the defined strategy, or on the contrary, redefine the toolpath fixing it to the machine requirements. Considering all components involved in the process, possible collisions and tool movements were check. Finally, the clad was generated through the API and the final geometry was predicted. After the virtual full process verification, the CNC code was post-processed in order to introduce it in the machine, carry out the real process and obtain the part (shown in Fig.7).

Fig. 7.API clad generation (a) and final geometry generated by LMD process (b).

4. Conclusions

As mentioned during the literature, the LMD is currently a growing up technology with many factors involved in the process. Due to the application to complex geometries and challenging materials, the virtualization of the process is an actual researching field covered along this work.

This paper exposes a full solution for LMD process unifying CAD, CAM, Additive Manufacturing and virtual verification. Nevertheless, this purpose offers extra advantages such as LMD optimal tool paths programming and a friendly interface directly related to industrial demand.

As a result of the API application to a real geometry, the final height accomplishes the clad estimation from the virtualization with a small deviation of 1 mm.

Acknowledgements

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