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Hybrid manufacturing of complex components: Full methodology including laser metal deposition (LMD) module development, cladding geometry estimation and case study validation

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A R T I C L E I N F O

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A B S T R A C T

To optimize and satisfy current industrial requirements, during the last decade new alternatives to conventional manufacturing processes are implemented into conventional machines, leading to multitasking machines. Especially hybrid machines combining additive and subtractive technologies (AM/SM), have become a potential solution for manufacturing and repairing operations in terms of material waste reduction, time consumption and flexibility. Nevertheless, this technology has implications for the machine and the auxiliary elements as well as other challenges: digitalization, process parameterization or CAD/CAM solutions. Thereby, this work proposes a new methodology for hybrid manufacturing systems, a programmed interface to interact between additive and subtractive technologies within the same environment. The developed application-programming interface (API) offers a CAM module oriented to AM with appropriate laser metal deposition (LMD) parameters, with three different options of strategy programming: Planar LMD, 3-axis LMD and 5-axis LMD. Additionally, the value of this work stems from the implementation of an algorithm to estimate the cladding geometry, so, the full resulting geometry can be considered as the new blank for SM. A height measuring laser sensor was implemented in the LMD machine to obtain the real height of the generated clad, critical for the next machining step. Finally, to validate the methodology, a blisk made of Hastelloy®X was built-up on Inconel®718 with LMD and milled to the final size. Dimensional deviation was measured after each process.

1. Introduction

The machine tool sector has experienced a rapid growth to satisfy industrial requirements, and, therefore, new alternatives to conventional manufacturing processes are required. The concept of multitasking machines was born when machine tools, integrating both milling and turning processes, burst onto the market [1]. At the present time, multitasking developments are progressing to embrace new horizons, combining different manufacturing processes (conventional and non-conventional) with the aim of offering more flexible solutions and integrating innovative processes, i.e. super abrasive machining (SAM), deep boring, different grinding

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Nomenclature

m_i^i	Powder mass injected on i point [Kg]
m_p^i	Mass discrete element of material added on i point [Kg]
Δx	Base of the discrete element on x axis [mm]
Δy	Base of the discrete element on y axis [mm]
ϕ_i	Powder mass flow on i point [g/mm^2*min]
ϕ	Powder mass flow [g/ min]
t_{iny}	Powder injection time [s]
ΔS	Trajectory discretization distance step [mm]
ν_f	Process Feed rate [mm/min]
ρ_{mat}	Material density [Kg/m^3]
$\mathrm{H_i}$	Cladding height in i point [mm]

processes, electro discharge machining (EDM), etc. [2].

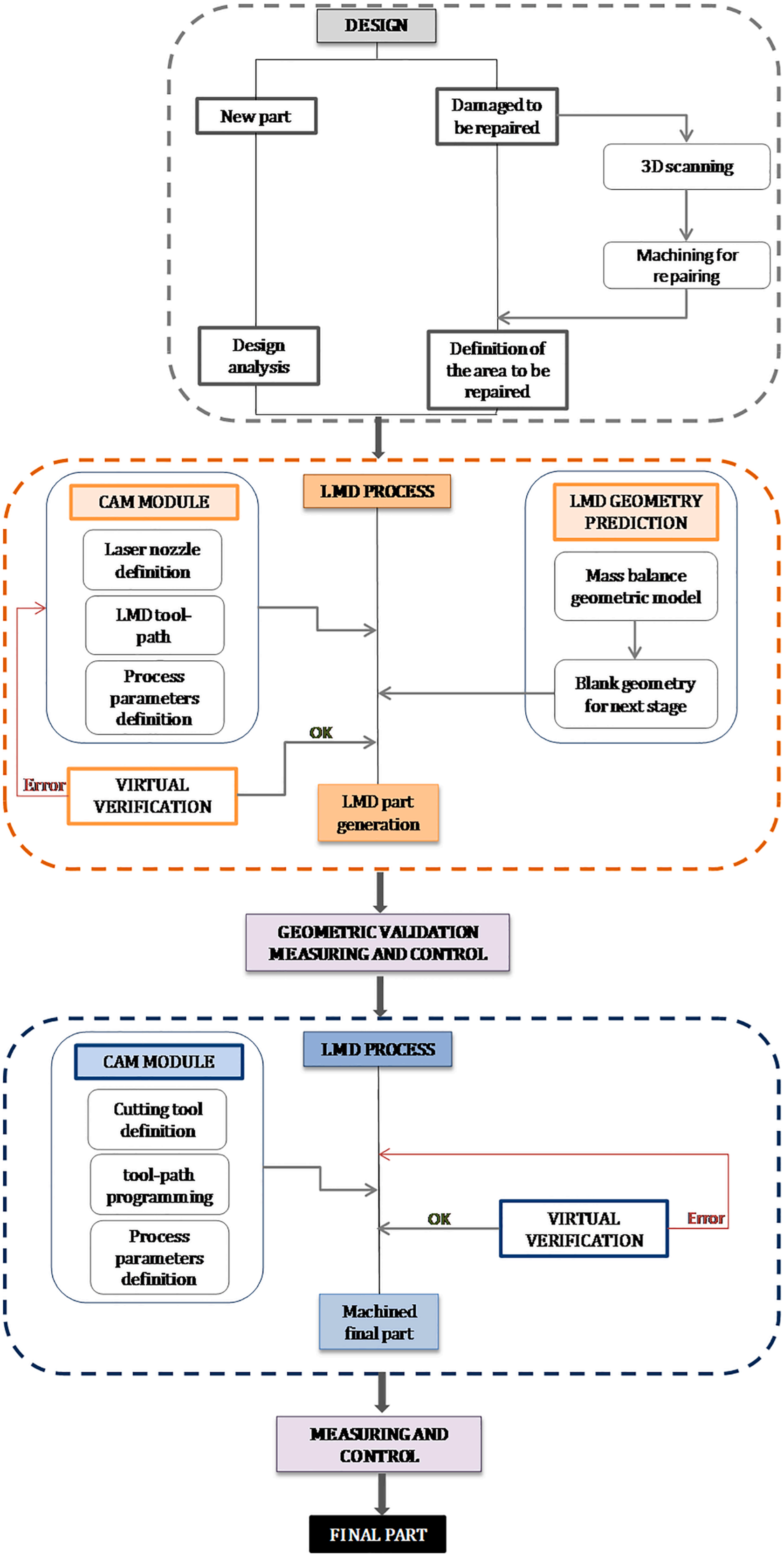
Industrial sectors now also have to face global competitiveness and the new trend of mass customization. Thus, there is a combination of processes that stands out, which is the case of hybrid manufacturing combining additive and subtractive manufacturing (AM/SM). AM is an emerging technology; however, SM is still required for final requirements of accuracy, dimension and surface roughness [3]. Furthermore, AM is considered a near-to-net-shape technology, managing cost-reduction in terms of material waste [4]. Additionally, aligned with the “circular economy” that promotes the recycling, remanufacturing, reusing and refurbishing, this technology provides opportunities to repair rather than discard damaged parts [5].

This new concept of hybrid AM/SM led machine tool manufacturers to develop hybrid machines with the aim of providing solutions to both the global market requirements as well as industrial expectations. Flynn et al. [6] and M. Cortina et al. [7] studied the developments of AM/SM systems from an industrial and scientific point of view, analyzing future challenges and opportunities related to material, process, software and industrial requirements. Among different AM technologies, this work is focused on laser metal deposition (LMD) or laser cladding (LC). This technology consists of depositing a thin layer of metal onto a melting substrate. Either powder injection or wire feeding can perform this deposition can be performed by; among depositing methods, the powder injection is the most flexible and extensive one. In this process, the laser beam melts both, the substrate and the powder particles, depositing a cladding layer of metallic powder on the substrate [8]. When the cladding tracks are overlapped, a layer is presented and then, layer-by-layer strategies are used for producing complex geometries and freeform design. The process presents high flexibility and reduction of material waste, obtaining near-net-shape geometry [9,10]. Aerospace and medical industries are demanding this technique to repair highly value-added critical components that will reduce manufacturing costs [11]. Furthermore, manufacturers of automotive dies and molds are considering this technique to recover damaged components. Another application is for coatings that increase the life of components against corrosion and wear [12].

As expected from a growing process in the early stages, LMD presents many challenges to be faced related to the high number of factors involved in the process such as laser integration, material properties, powder flux, feed rate, and tool path definition [8]. Related to the process and additive strategy, Laura Arregui et al. [13] studied the geometrical limitation for inclined walls, observing good results for angles between 90° (vertical walls) and 60°. Regarding material challenges, some works cited focus on the microstructures and mechanical properties using LMD for Tungsten alloys [14], Ti/TiAL structural gradient material [15], and microhardness and thermodynamics in molten pools [16].

Related to this technology, a previous work of this author group [17] studied the feasibility of five continuous axes for LMD processes, proposing a criterion to determine optimal conditions and strategies. Regarding LMD process parameters, a feed rate calculation algorithm in order to maintain the laser feed rate constant according to the most restrictive axis and homogenize 5-axis LMD process on a blisk [18] was developed. Furthermore, the machinability and material properties of Inconel®718 focus on hybrid processes was analyzed in three stages: base material, LMD material before precipitation treatment and LMD material after precipitation treatment [19].

The Industry 4.0 brings two inherent concepts: digitalization and integration of products and services and new market models [20]. The second concept relates clearly to hybrid manufacturing and AM/SM systems owing to the offer of more flexibility, competitiveness, and a close to mass-customization solution to market needs, optimizing the use of material resources and promoting repair and remanufacture, transforming end-of-life products to good-as-new products [21,5]. Part reliability should be guaranteed even when working with divided teams in different locations, therefore, methodology for the creation of spare parts [22] is also a subject to be pursued. Nevertheless, the digitalization process is still in a critical stage of development; the number of variables involved in the process, the difficulties of communication between machine and designing software and, finally, the post-processing and standardization of the process have become a handicap studied on which recent research has focused [23]. The concept “digital twin” is the aim of developing a more autonomous and competitive process [24]. Performing a digital environmental consists of the virtualization the full process representing the reality before the hybrid processes, considering machine components and limitations as well as final expected results. For the same reason, one of the tools inside this digital environment is based on the CAM solutions for hybrid manufacturing. Hedrick et al. [25] divided AM oriented CAM software into two principal functions: Backplot and Machine simulation.



(caption on next page)

Fig. 1. Proposed methodology for hybrid manufacturing combining LMD with machining process.

On the one hand, the Machine simulation covers machine components, limitations and represents the real machine movement. On the other hand, the Backplot is focusing on tool-path programming and verification, considering the contact between the tool and the manufacturing part; thus, predicting intermediate and final results, geometries and errors derived from selected strategies for AM and SM.

With the new trend in "3D printers", the number of layer-by-layer software providers are increasingly growing. Nonetheless, the demand for 5-axis AM programming is an identified need for building up more complex surfaces. Many CAM software suppliers are developing solutions for AM/SM tool-path definitions and process verification. AIXpath GmbH developed a CAM module (ibeRep) specific for gas turbine blade repairing tasks, it is an optimal solution for laser micro-cladding, milling and measuring processes [26]. In the same line, The Fraunhofer Institute designed a process chain for LMD, supporting tool path programming layer by layer called LMDCAM2 [27]. AUTODESK developed a software solution (PowerMill Additive) offering the tool path definition layer by layer and previewing the generated material [28]. With the idea of providing a solution for hybrid manufacturing combining LMD and machining, Siemens developed a solution for hybrid manufacturing to be used initially with Lasertec 65 3D from DMG MORI. It contains the verification module for that machine and a LMD module to program tool-paths layer by layer for AM, and SM programming inside the same software [29].

However, there is not a 'full' solution combining the AM/SM technologies. There is a gap for laser cladding solutions including all the aspects such as real cladding geometry estimation, specific process parameters and strategies, process virtual verification, etc.

The originality of this work stems from the idea of proposing a methodology for hybrid manufacturing systems that any programmer could follow (if a specific additive module is not available and an 'open' CAM software is being used). A programmed CAM module including an interface to interact between additive and subtractive technologies inside the same environment is also developed. The developed application-programming interface (API) offers a CAM module oriented to additive manufacturing with appropriate laser metal deposition (LMD) parameters, with three different options of strategies programming: Planar LMD, 3-axis LMD and 5-axis LMD. Moreover, in order to obtain the LMD cladding geometry, a mass-balanced model for the estimation of the final geometry of the deposited material (considered as the new blank for the subtractive manufacturing) was implemented. Based on the process parameters, the algorithm calculates the cladding section and builds up the geometry considering programmed tool-paths. Finally, with the aim of verifying the proposed methodology and the cladding geometry estimation, a case study was manufactured along every stage of the hybrid manufacturing process. The clad height was sensorizated by a laser sensor, implemented and programmed through the CAM module, offering different height values during the manufacturing process at the beginning, intermediate and final generated geometry. This offers the opportunity of optimizing the LMD parameters need to obtain desired geometry for the next machining stage.

The selected material to be generated was Hastelloy®X over Inconel®718, commonly used for critical turbomachinery rotary components. Thus, blisk geometry was chosen as a challenging complex geometry, requiring full 5-axis LMD operations. Finally, dimensional deviation was measured after AM and SM stage.

2. Methodology

Following the path of hybrid manufacturing tendency, this paper proposes a methodology for all stages covered in hybrid manufacturing (design, LMD, machining and control), focusing especially on the AM stage. Fig. 1 shows the methodology scheme divided into 3 main groups: design process, LMD process and subtractive processes. Measuring and control are considered after each operation in order to close the loop before moving to the next stage.

The first stage is based on the component design. In this phase, the geometry to be generated through hybrid manufacturing is defined. This AM/SM processes are commonly used in two different cases: new part conception or repair of damaged parts. The second case implies a previous process of 3D scanning of the damaged area, removing that section and defining the volume to be repaired by this procedure. In order to proceed with this stage, a deep knowledge of AM/SM possibilities to select adequate AM/SM processes (i.e. complex geometries, internal channels, final surface requirements…) is required.

Once the design is defined, the second stage is the AM process, in this case LMD. For this process, three key steps need to be followed: laser tool parameters definition, tool path programming and virtual verification. The geometrical prediction is considered critical at this stage to be used as the initial blank at the last SM stage. Before running the next AM stage, a measuring and control stage to evaluate the final AM results in terms of process quality is proposed. At this point, if obtained results are considered inadequate, a return should be made to design or redefine the strategy of AM process, reprogramming tool-path strategies and parameters. This stage is addressed in detail in the following section.

Finally, accomplishing AM measuring and control requirements the machining process can be carried out, defining cutting tools, tool-paths and process parameters. For the last stage, a final part control to accept or move backwards to the previous stage is needed.

3. LMD Process: CAM module development

The API (Application Programming Interface) concept is defined as a group of functions and procedures with a fixed objective presenting the peculiarity of being run by independent or external software. It is considered a strong tool due to the flexibility offered allowing different applications/software to keep a communicative understanding of each other. The use of APÍs is very extended within the manufacturing sector, for example to integrate cutting forces models into CAD/CAM environments. In line with this idea, the specific module for LMD programming presented in this chapter is a combination of two APIs integrated in the commercial CAD/CAM/CAE software NX™ from Siemens. This methodology may also be applied, with small modifications, within any open CAD/CAM system. Furthermore, NX™ offers a programming assistant tool denominated NX Open that facilitates the customization of APIs for this software, personalizing different procedures or complex tasks; even integrating third party applications through an open architecture using different programming languages such as C/C++, C#, Visual basic, Java or Python.

The first developed API 1 is related to LMD process programming, tool definition and mainly tool-path programming. This API could be applied for 3-axis and 5-axis simultaneous tool paths, as required for the generation of complex geometries. The second developed API 2 consists of a mass-balanced estimation to predict the LMD clad dimension and the entire generated surface according to the selected material and process parameters. Both are integrated in a newly defined module at the initial software window.

This LMD module considers critical process parameters, such as powder flux, laser power and focal distance. The main objective consists of unifying tool-path programming and SM included in the same environment, not only for 3-axis but also for 5-axis simultaneously. Fig. 2 represents the different steps covered inside the developed solution. On the one hand, it contains a user-friendly interface where the laser nozzle is defined as the process tool and process parameters are also implemented. Moreover, it is also possible to define tool-paths for planar LMD, 3-axis and 5-axis strategies.

However, of note is that when using AM processes, the obtained geometry is unknown for SM processes leading to unexpected data, increasing manufacturing time in terms of oversizing the safety factor to avoid collisions, overcuts, undercuts, etc. With the aim of performing a more effective process, the implemented cladding estimation offers an approximation of expected geometry, so the blank that needs to be machined to final size is known. For this purpose, an API was developed where the cladding geometry is generated according to a mass balanced geometric model.

This solution could offer important data for hybrid manufacturing processes (AM/SM), such as the effects of different LMD strategies on the final added geometry and new blanks generation for the next step (SM) as defined in the proposed methodology.

Finally, it is possible to run a virtual verification with machine components. The user-friendly interface is implemented at each software stage, in a similar manner as the machining module, including the API 2 for cladding geometry.

Following the path of hybrid manufacturing tendency, this paper proposes a methodology for all stages covered.

3.1. API 1. CAM module for LMD: interface, process parameters, tool definition, tool-path programming and operations

This LMD module considers process parameters, such as powder flux, laser power, focal distance, etc. The main objective is unifying tool-path programming and SM in the same environment, not only for 3-axis but also for 5-axis.

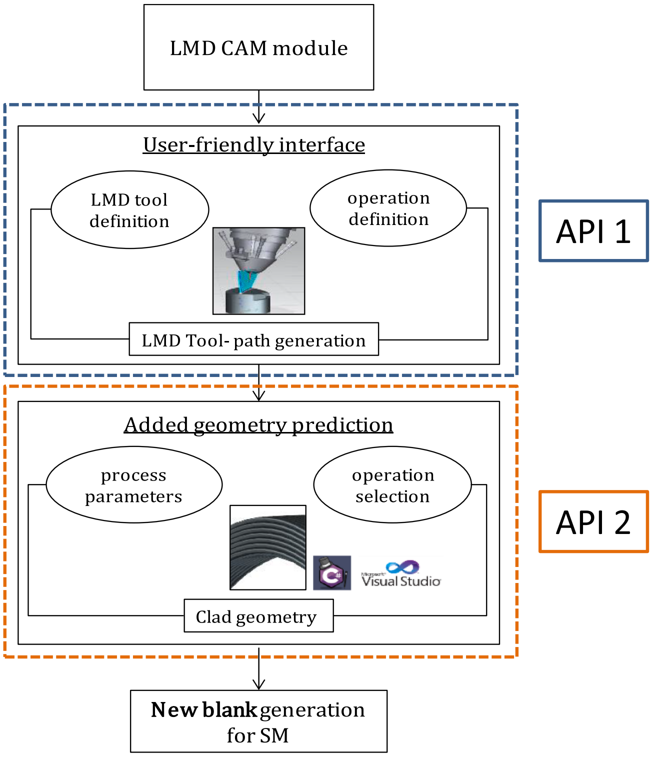


Fig. 2. Flowchart for developed APIs integration ~~for~~ as LMD CAM solution.

3.1.1. User-friendly interface

The first section for CAM module consists of different templates directly oriented to LMD process, such us tool definition and deposition operations. It is defined as an extra interface exclusively related to LMD, offering a quick access from AM to SM module.

In a similar manner as in CAD/CAM common environments, it is possible to jump from one module to the other effectively. In this case, it is possible to move from the modeling module to machining or laser metal deposition module templates. This option covers all steps needed for hybrid manufacturing: modeling the initial design, moving to LMD and generating the added geometry and finally moving to subtractive module and removing the extra material to obtain the desired final dimensions.

3.1.2. Process parameters and tool (nozzle) definition

In order to adapt the API 1 to the process, it is necessary to identify the main process parameters to be considered and defined in the API user windows. There are some fundamental parameters related to the process, to the cladding geometry generation and the laser nozzle. Considered parameters relative to the process to be implemented into this API are laser power [W], nozzle feed rate [mm/min] and powder flux [g/min].

On the other hand, regarding tool (nozzle) definition (Fig. 3), considered parameters are focal distance [mm], spot size [mm] and laser beam cone angle [degrees]. Additionally, with the aim of offering a more realistic process, it is possible to integrate the CAD model of the LMD nozzle with all components. This input contributes to process virtual verification including collision detection.

3.1.3. Tool-paths programming

The LMD process is increasingly widespread in industrial sectors, but the growing complexity of the components geometries to be dealt with, leads to the necessity of 5-axis machine kinematics. This implies that one of the main challenges for this technology resides on the optimal tool-path definition and CNC code programming. The selected operation would affect not only the geometrical results, but also the mechanical properties and process quality. Besides, 3-axis operations should be distinguished from the 5-axis operations requirements, due to the differences in the tool-paths programming.

Therefore, it is important to determine the correct CAM programming algorithms aligned with LMD process. Afterwards, these algorithms are considered in the LMD operations definition, adjusting the inputs options at the operations menus to the minimum expression in order to facilitate programming to the user and enclosing the LMD specific and non-changeable requirements internally. Nonetheless, as opposed to conventional machining processes, the AM processes start the generation of the desired geometry from the bottom to the top; so, the first and most important constraint is related to the geometry generating growing direction. This direction was one of the non-changeable requirements programmed internally in the user-friendly environment, giving the user the possibility to defined the tool-path strategies (i.e. zig, zig-zag, helical) but avoiding the possibility to change that growing direction.

Fig. 4 shows different parameters and concepts included in the tool-paths internal programming implemented in the machine postprocessor, such as laser on/laser off option, tool-paths stepover, spot center location and laser beam orientation.

3.1.4. LMD operations definition

Following the criteria established for LMD tool-paths generation, the next step inside this API is the CAM operations programming, defining different operations, strategies and designing the user environment.

In the search for optimal LMD strategies and based on the most commonly strategies studied in the literature, the developed module offers 3 different operations to be applied according to the selected geometry to be added and the process requirements (Fig. 5).

- Planar LMD: operation designed for planar geometries. Widely used for layer-by-layer manufacturing. The user defines the planar area to be fulfilled and the distance between cladding layers, as well as the pattern to be followed by the laser.
- 3-axis LMD: operation designed for geometries working under 3-axis movements. Recommended for simple geometries, coatings or one-cladding geometries. The user defines the tool orientation, the surface to be coated and the distance between cladding layers.

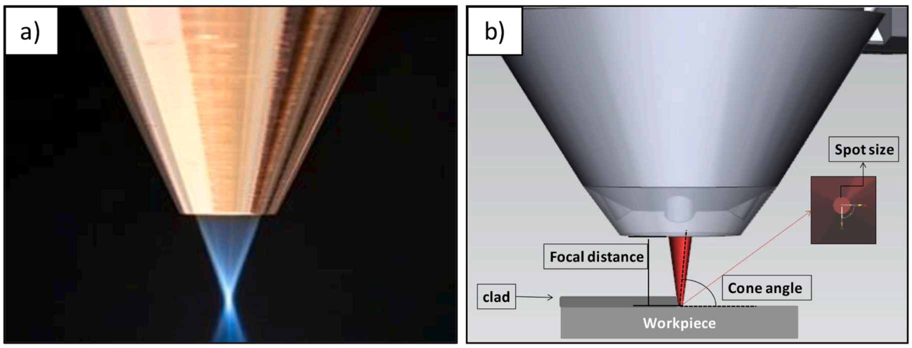


Fig. 3. a) Coaxial nozzle [30]. b) Laser beam modelling for the LMD CAM module.

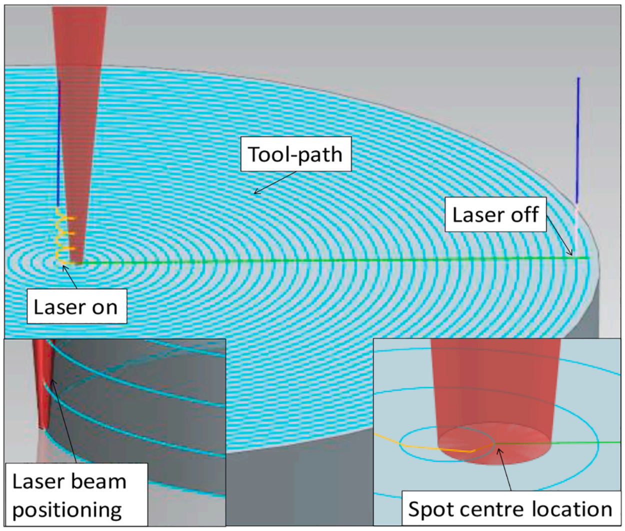


Fig. 4. Parameters considered for LMD tool-paths generation.

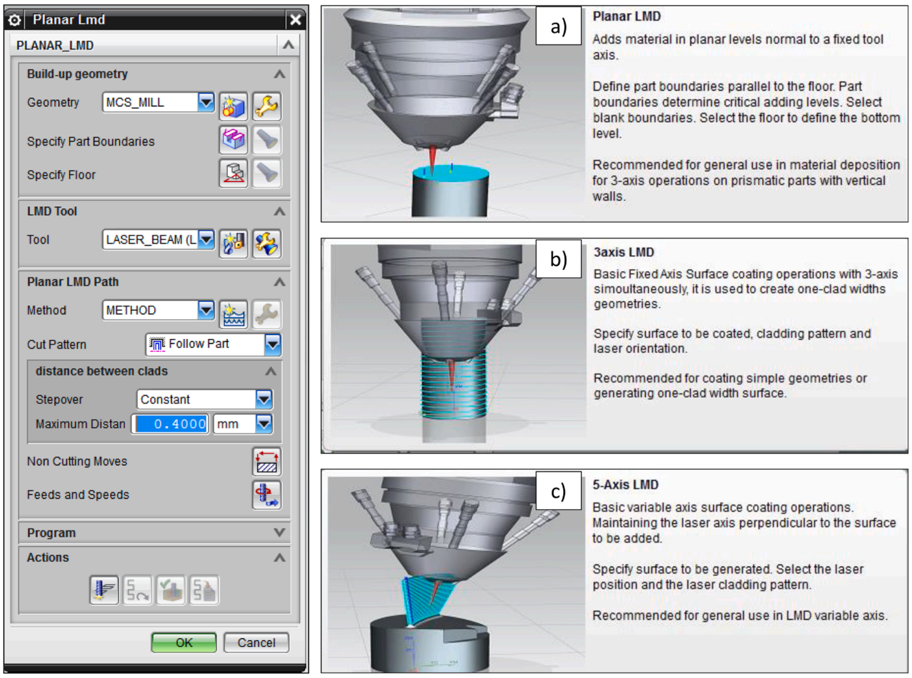


Fig. 5. LMD defined strategies inside the interface.

- 5-axis LMD: operation designed for geometries working under 5 continuous axis movements. Following the principle of laser beam perpendicularity to surface as the optimal solution for generating complex geometries, the tool orientation is predefined to be normal to the surface.

3.2. API 2. Estimation of cladding geometry

In this section, the developed API 2 for the estimation of the cladding geometry is presented. The aim of this API is to create the final geometry from LMD process related to the programmed tool-path.

3.2.1. Cladding geometry: user-defined diameter or mass balance calculation

With the aim of generating cladding dimensions and consequently the final geometry representing the added part, two different alternatives were considered. The first one consists of, supposing a circular section cladding shape, introducing the cladding diameter as a constant value determined by the user; the second one is based on a mass balance algorithm, where added material becomes the final cladding, considering that the material is homogeneous and isotropic. For the first option, the cladding diameter value to be generated is defined by the user. The second option calculates cladding height based on mass balance. In this case, the cladding size is calculated according to the process parameters definition.

As a basis for programming this geometrical estimation, Tabernero et al. [31] proposed a geometric modeling of added layers on which data was supported from other developed models such as powder flux model, attenuation model and thermal model. Establishing this geometric modeling as a reference, and including data by the user from experimental tests, such as powder flux and material density, this API calculates cladding diameter through stated equations.

Fig. 6 shows the discrete element generated in the control point where the material will be added. Therefore, the Eq.1 determines the cladding volume for defined parallelepiped:

$$Clad_{volume} = \Delta x^{*}\Delta y^{*}H \tag{1}$$

As previously stated, the geometric model consists of a balance between the powder mass injected material in the point i and the parallelepiped added mass in the same point i.

$$m_i^i = m_p^i \tag{2}$$

Added mass on i point depends on the powder flux in i point (ϕ_i) during the time spent for that addition in that point (t_{iny}).

$$m_i^i = \phi_i{}^{*}\Delta x^{*}\Delta y^{*}t_{iny} \tag{3}$$

Injection time in turn depends on tool-path discretization length (Δ_s) divided by nozzle feed rate (v_f).

$$t_{iny} = \frac{\Delta S}{v_f} \tag{4}$$

Besides, parallelepiped mass depends on material density (ρ_{mat}) and generated volume.

$$m_p^i = \rho_{mat}{}^{*}\Delta x^{*}\Delta y^{*}H_i \tag{5}$$

In this way, it is possible to calculate cladding height for each point using Eq. (2) and replacing values with Eqs. (3)–(5):

$$m_i^i = m_p^i \rightarrow \phi i^{*}\Delta x^{*}\Delta y^{*}\Delta s/v_f = \rho_{mat}{}^{*}\Delta x^{*}\Delta y^{*}H_i \rightarrow H_i = \frac{\phi i^{*}\Delta s}{\rho_{mat}{}^{*}v_f} \tag{6}$$

Finally, as identified in Fig. 6, it is assumed that cladding diameter has the same value than cladding height for API calculation (Eq. (7)).

$$Clad_{Diameter} = H_i \tag{7}$$

Eq. (6) presents the dependency of cladding diameter on four different parameters. As initial assumption and according to the process, value of tool-path discretization length (Δ_s) is defined during operation parameters, in a similar manner as in machining operations. Thus, at this point the API, the programmer needs to introduce the following information: powder flux (ϕ_i), material density (ρ_{mat}), and the feed rate (v_f) values; calculating internally the final cladding section before generating added geometry.

3.3. API integration

Programmed API is fully integrated in the CAM module. After tool-path programming inside the LMD interface, the next step is obtaining the resultant geometry. The user interface is simplified to generate the final geometry.

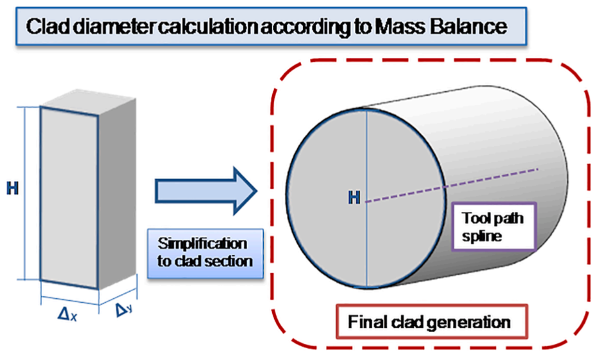


Fig. 6. Calculation of LMD cladding diameter according to mass balance.

The programming of the API required different steps to be performed internally once the command of LMD cladding generation is activated. The programmed tool-paths were imported to visual studio 2010® to be integrated into the API. At the same time, all programmed steps for this API are performed according to NXOpen functions. The implementation of LMD CAM programming and cladding estimation would add valuable information for predictive manufacturing and process digitalization.

The following points describe the steps followed to achieve the final manufactured component:

1 In the first step, the user introduces process information in the API, such as the programmed tool path, and, the choice of method to be used for cladding generation. If more than one operation is programmed, this step offers the possibility of selecting just one of them.
2 In the second step, the API takes the ISO code file from the programmed tool-path, saves it and adapts the file to usable format (x, y, z) to work with.
3 In the third step, the file with coordinate points from the ISO code generates a new spline that represents the selected tool-path, through all CAM programmed points. These points will be the CNC code after post-processing the program for LMD.
4 The fourth step is the cladding generation. At this point there are two options. The first one takes the diameter value introduced by the user and creates a circle at the initial point of the tool-path. The second option takes the inserted values for the process and calculates the cladding diameter according to mass balance required to create the circle.
5 In the last step, the cladding section is swept through the imported tool-path from point 2. A solid is generated with the different cladding layers within the defined geometry. This solid then becomes the blank for the machining stage.

3.4. *Virtual verification and collision detection*

Digitalization is considered one of the Industry 4.0 pillars. With the aim of covering this step inside proposed methodology, the virtual environment was completed with the digital integration of the used machine. Fig. 7 shows the real machine and different components/parameters considered to define the digital environment.

The machine is a 5-axis retrofitted machine (3 linear axes and 2 rotary axes on a tilting table), equipped with a fiber laser Rofin FL010 with a maximum power of 1 kW. Additionally, the machine was equipped with a height-measuring sensor and a coaxial nozzle; the exact definition of the geometry related to these components, as well as machine tool base and tilting table are crucial to preview collisions. According to machine specifications, kinematics and axes limits are defined in the machine kinematic tree; this function analyses the feasibility of AM selected strategies to be performed with the available machine.

4. CASE STUDY: Blisk hybrid manufacturing and API validation

With the aim of verifying the proposed methodology and the developed API, a blisk is selected as a complex geometry to be manufactured by the proposed hybrid process.

18 blisk blades were generated requiring 5-axis continuous movements representing a real application for material waste reduction and feasibility evaluation of this hybrid manufacturing system with complex surfaces and difficult-to-cut materials. This is a challenging type of geometry and an adequate demonstrator for process virtualization in terms of tool-path definition, collision detections

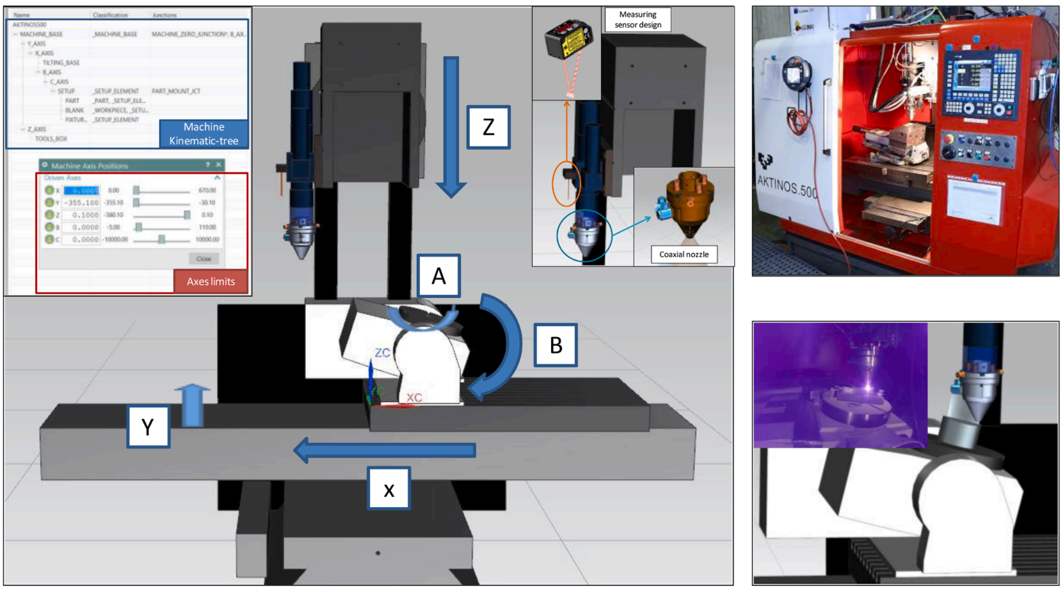


Fig. 7. Digitalization of retrofitted Kondia B-500 and single-blade real process verification.

and machine limitation. Fig. 8 shows the proposed methodology applied to a blisk design. Firstly, LMD process with CAM programming, virtual verification and part generation followed by a machining process from CAM programming, virtual verification and final part quality analysis.

Hereafter, the process is divided into three different steps. The first step consists of material definition; LMD process parameters definition and API cladding generation verification. The second step addresses complex geometries LMD programming, real part generation and obtained results for this intermediate process. The final step of this methodology is the machining process and dimensional deviation obtained results.

4.1. Material and cladding dimensions

One of the first steps consists of material and process parameters definition. In line with actual repairing applications, Hastelloy®X was selected to be built-up over an Inconel®718 material base.

Hastelloy®X consists of a nickel-based superalloy that presents an excellent balance between resistance to oxidation and maintaining mechanical properties working under extreme temperatures, up to 1204 °C [32,33]. This superalloy is widely used in aircrafts and turbine engines for combustion-zone components [34]. Notably this material has excellent weldability properties will well suit the LMD process [35]. Table 1 shows Hastelloy®X chemical composition, mechanical and physical properties.

With the aim of obtaining optimal LMD parameters for adding Hastelloy®X over Inconel®718, González et al. [36] performed 12 tests with different combinations of AM conditions (laser power, feed rate, powder mass flow) determining the test number 10 as the one which obtained optimal results. Among those tests, Table 2 displays 3 of them based on the optimal ratio between the height and the width of the cladding, considering this parameter as a key for cladding dimension and process feasibility. Additionally, an extra column related to the diameter estimation is added, with the aim of validating and comparing programmed geometry estimation with real cladding dimensions.

4.2. LMD process

Blades geometries were built-up using the LMD machining center defined at the virtual verification stage. Table 3 shows the process parameters selection according to the optimal LMD conditions for Hastelloy®X on an Inconel®718material base.

Adequate tool-path selection is crucial to generate an optimal solution for a complex geometry generation. This optimal solution should follow the perpendicular principle and with a non-stop additive process. This principle consists of keeping constant the perpendicularity between the nozzle and the surface to be generated during the entire process. For complex geometries, this is just possible using 5-axis continuously movements.

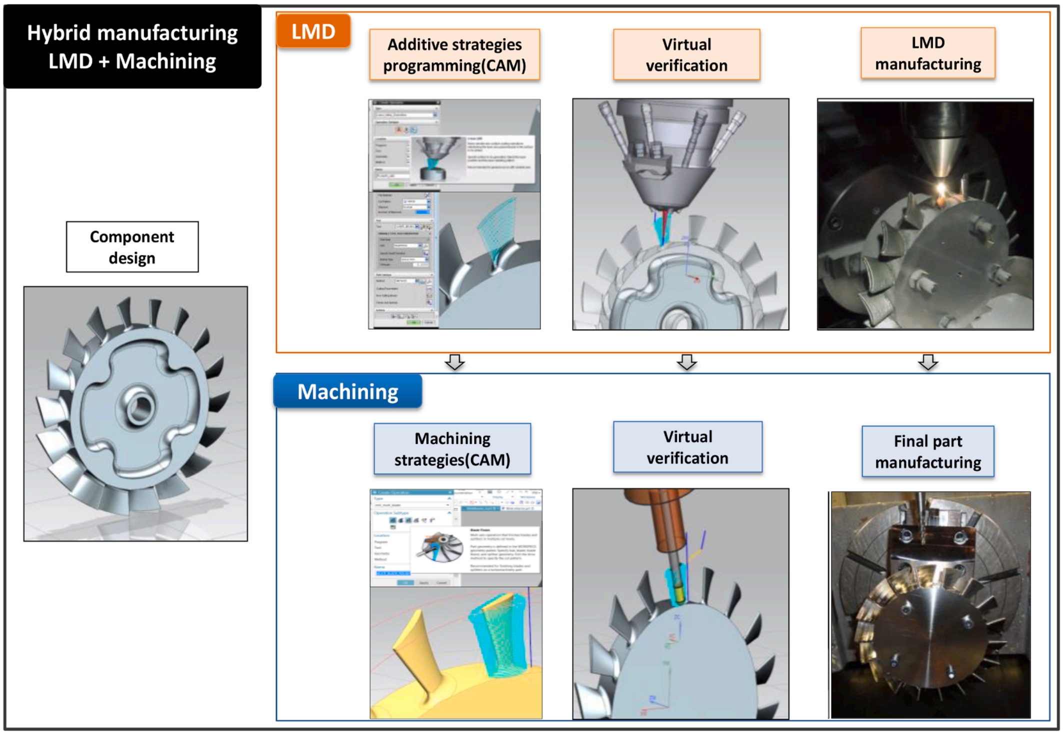


Fig. 8. Defined methodology applied to a turbomachinery component (Blisk).

Table 1
Hastelloy®X composition, mechanical and physical properties [33,35].

Chemical composition (%) of Hastelloy®X												
Ni	Cr	Fe	Mo	Co	Tg	C	Mn	Si	B	Nb	Al	Ti
47	**22**	**18**	**9**	**1.5**	**0.6**	**0.1**	**1 max.**	**1 max.**	**0.008 max.**	**0.5 max.**	**0.5 max.**	**0.15 max.**
Mechanical and physical properties												
Young's Modulus	Tensile Strength	Density	Specific Heat	Melting Temp.	Thermal Conduct							
205 GPa	0.765 GPa	8220 kg/m^3	4861 J/(kg·K)	1580 K	9.1 W/(m·K)							

Table 2
Validation of API cladding diameter calculation.

Test	Laser Power [W]	Feed rate [mm/min]	Powder mass flow [g/min]	Cladding dimension H [mm]	API Cladding diameter [mm]	Error [%]
6	600	400	4	0,31	**0,30**	3,2%
7	500	500	6	0,35	**0,36**	2,85%
10	400	300	3	0,33	**0,30**	9,09%

Table 3
LMD process parameters.

Protector gas flow rate	13 l/min (5 bar)
Carrier gas flow rate	5.5 l/min (1 bar)
Laser Power	400 W
Feed rate	300 mm/min
Powder flow	3 g/min

In this case and according to the perpendicular principle, among the different strategies inside the performed interface (Fig. 5), 5-axis LMD strategy was selected. Each blade was generated with helical and continuous movements. Virtual verification is necessary for this tool-path strategy, as every machine component is moving at the same time with a real risk of collision.

With the aim of measuring dimensional deviation of the resulting component before the LMD process, an optical scanner (ATOS GOM®) based on blue light was used. The measurement generated a cloud of points to be compared with the original design. As it is shown in Fig. 9, LMD process generated the desired geometry with an extra material in width within 0.5–1.5 mm. These values need to be considered as excess material for the next step inside the hybrid manufacturing in order to be removed. It should be noted that the final tolerances required for this turbomachinery rotary components are below 50 µm [36].

The cladding height parameter considered by this API for geometrical calculation, could suffer a variation of 30% using 5-axis movements, depending on the laser position relative to the flat surface [37].

4.3. LMD clad height sensorization

The machine was implemented with a height measuring sensor (range from 50 mm to 210 mm) aligned with the machine spindle. Hence, this device uses the same tool-path programmed for LMD but relocated in X direction to be aligned with the micro laser remote sensor. This offers the possibility of measuring intermediate and final part height avoiding unclamping errors and optimising the process timing without removing the piece for an inspection approach. Fig. 10 shows the obtained results at the height of 20 mm.

Obtained results shown two main issues presented in the 5-axis LMD blade manufacturing. On the one hand, the orange circle shows the narrowest area presented in the designed geometry and undesired extra material. This issue is derived from the difficulties on the geometry that requires a completely change of direction in one point, so the machine spends more time adding material at that point that the optimal one. On the other hand, blue circle represents an area where the material did not grow as much as programmed. This issue is a consequence from 5-axis movements; it depends on the inclination angle at those points. Therefore, the clad height is reduced when the process is under 5-axis movements. The main reason for this issue is explained by the differences found in the Gaussian distribution compared with a flat substrate.

4.4. Machining process

In order to meet required dimensional tolerances, the blades surface is milled. NX- Siemens CAM software was used to design tool-path strategies and verify the process. According to the complexity of the geometry, and, in concordance with the strategy used to build up the blisk, a variable contouring milling strategy was selected. Thus, this tool-path requires 5-axis simultaneous movements, and, virtual verification is required to avoid collisions and machine limitations. The selected tool is a ball nose milling tool with 2 flutes and a cutting length of 15 mm. Table 4 contains milling process parameters.

Fig. 11 shows the blisk during machining process and final measurement of dimensional deviation. The evaluation of this dimensional deviation was focused on the blade surface finishing, not performing finishing process over the hub and the blend. As it is shown in the obtained results, it is shown a defect of material on the tip derived from the 5-axis LMD process described previously. In order to avoid this issue, extra material should be added in the previous additive process.

5. Conclusions

In this work, a methodology for hybrid manufacturing (AM/SM) is presented, concretely LMD & milling. Included in this proposed methodology it was developed different applications to ensure a good CAM programming, this main advances are highlighted hereafter:

- CAM module oriented to LMD process, including laser tool definition, process parameters, optimal tool-paths programming and virtual verification.
- An API was programmed to generate the expected LMD geometry based on a mass balance geometric model.
- The developed solution is implemented in CAD/CAM/CAE software with the main objective of including all hybrid stages inside the same environment and facilitate the hybrid process intuitively manufacturing.
- This work unifies in the same software a complete solution for hybrid manufacturing (LMD/machining). The proposed LMD CAM module was based on scientific and experimental results.

With the aim of verifying the methodology and the cladding estimation, a blisk was manufactured by hybrid manufacturing, using the developed CAM module, and programming the LMD in 5-axis helically and continuously movements. Dimensional deviation was measured and, finally, it was machined to the final size. The material used in this case was Hastelloy®X over Inconel®718.

The main conclusions and major findings derived from this work are listed below:

- Hybrid manufacturing systems are presented as a solution for repairing highly value-added critical components. Nevertheless, the interaction between different technologies for hybrid manufacturing leads to the necessity of a consistent knowledge of implied processes.
- In the presented work, LMD challenges were analyzed and a solution for CAM programing, considering critical parameters studied in the literature is proposed. 5-axis continuous tool-paths are still a challenge where nozzle inclination and manufactured geometry are influenced by the programed tool-path. It was shown that the height could be reduced up to 30% depending on the inclination of the nozzle at each point.
- The prediction of the geometry implies cost reduction in terms of optimizing SM strategies and process parameters. To offer a more controlled hybrid process, the geometric model was implemented inside the CAM module, with an error less than the 10%.
- The necessity of getting these new technologies to the final user implies the development of a user-friendly interface. Since, the spread of knowledge and promotion of hybrid manufacturing may be easily performed.

Therefore, this novel CAM module implies better control of hybrid manufacturing and a user-friendly interface based on the integration and digitalization principles of Industry 4.0. This solution works for a suitable, controllable and predictable process to manufacture and repair highly value-added critical components made of thermoresistant superalloys, through hybrid manufacturing

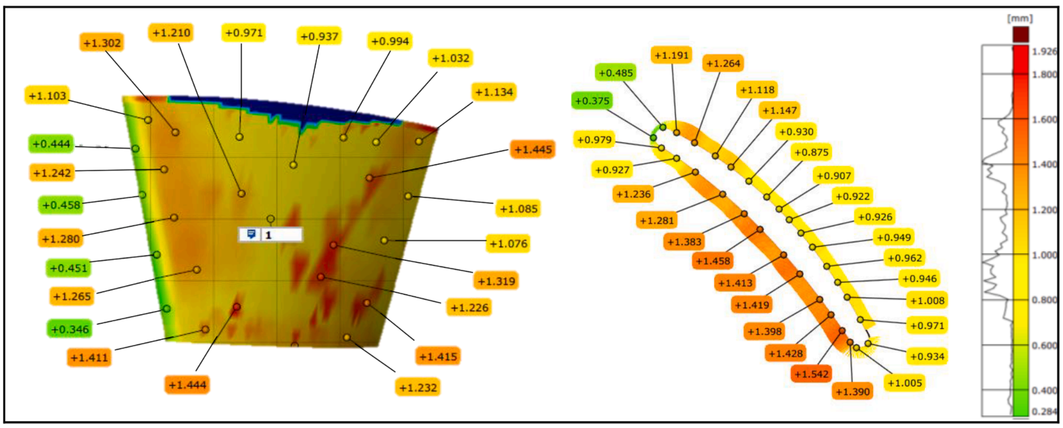


Fig. 9. LMD process dimensional deviation measurement.

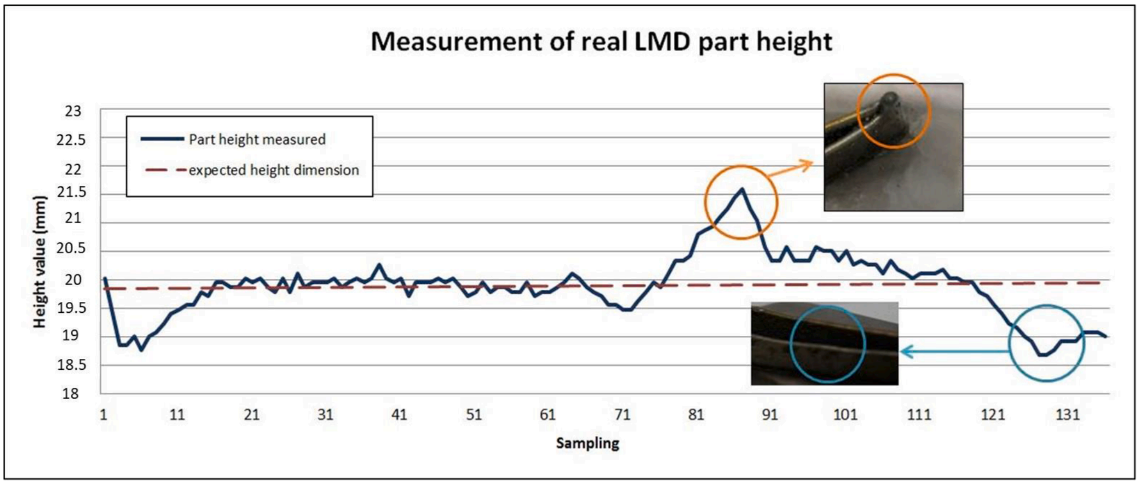


Fig. 10. LMD blade intermediate height measurements and different issues observed in 5-axis LMD process.

Table 4
Blisk machining conditions.

a_p (axial depth)	0.45 mm
a_e (radial depth)	0.2 mm
S (spindle speed)	2000 rpm
f_z(Feed)	200 mm/min
Machining strategy	Variable contour

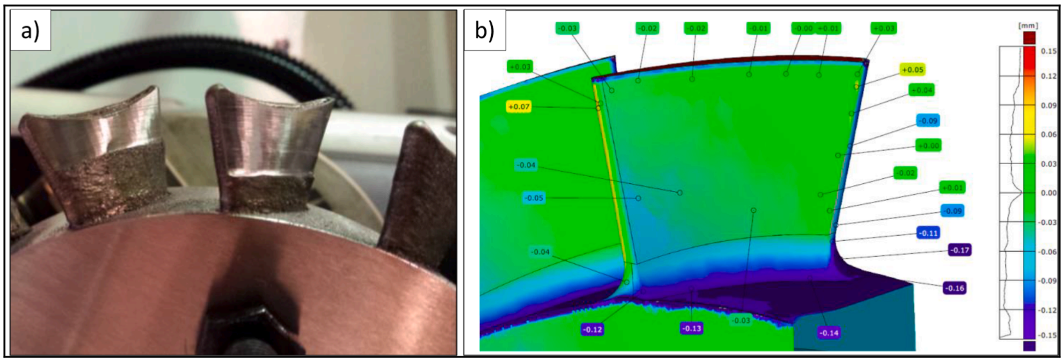


Fig. 11. a) Machining process after LMD (b) and final dimensional deviation measurement.

systems.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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