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Matthieu RAUCH[1,2*]
Jean-Yves HASCOET[1,2]

OPENING NEW OPPORTUNITIES FOR AERONAUTIC, NAVAL AND TRAIN LARGE COMPONENTS REALIZATION WITH HYBRID AND TWIN MANUFACTURING

Additive Manufacturing (AM) consist in producing parts by depositing material in successive layers. These step-by-step processes proposes new innovative directions for high value components: complex geometries are accessible without strong efforts (such as hollow or lattice structures which dramatically reduce the component weight while keeping their at least similar mechanical properties), assemblies can be simplified, spare parts can be realized at demand… Hence, AM has benefitted from large research efforts over the last decade, almost all existing industrial sectors have benefitted from them. This paper introduces some opportunities and the associated challenges attached to Additive Manufacturing, to produce large metallic components for naval aeronautics and train industries. In particular, two innovative approaches are discussed in details: hybrid manufacturing and twin manufacturing. Hybrid manufacturing consists in integrating AM together with other processes for the realization of components, with the objective to benefit from the interests of each process while avoiding its drawbacks. Hence, AM can realize complex geometries or offer low buy-to-fly ratios while high speed machining generates very good surface properties (position, roughness). Processes can be carried out sequentially or simultaneously on the features to manufacture and finding the optimal manufacturing work plan can be challenging. The paper introduces some hybrid approaches developed in the laboratory. Twin manufacturing uses models and multiphysics simulation methods to create a digital clone of the process implementation within the manufacturing environment. Manufacturing preparation and optimization can be carried in the virtual workshop where various configurations and choices can be tested before being selected. To enhance its accuracy, the digital twin can also be fed by monitoring data captured during the process. Several digital twins developed in the laboratory are provided. The paper is illustrated with several proof-of-concept parts made with SLM, LMD, WAAM and hybrid approaches in the laboratory. Among them, a hollow propellers that has the same hydrodynamics efficiency for a reduced weight for the naval industry, an aircraft structural panel that demonstrates simplified assemblies increased performance/mass ratio, a train component that shows the ability to produce structural parts at demand.

1. INTRODUCTION

Additive Manufacturing (AM) consists in producing parts by depositing material in successive layers [1]. These step-by-step processes propose new innovative directions for high value components: complex geometries are accessible without strong efforts (such as

[1] Centrale Nantes / GeM – UMR CNRS, Nantes, France
[2] Joint Laboratory of Marine Technology (JLMT) Centrale Nantes – Naval Group, Nantes, France
[*] E-mail: matthieu.rauch@ec-nantes.fr
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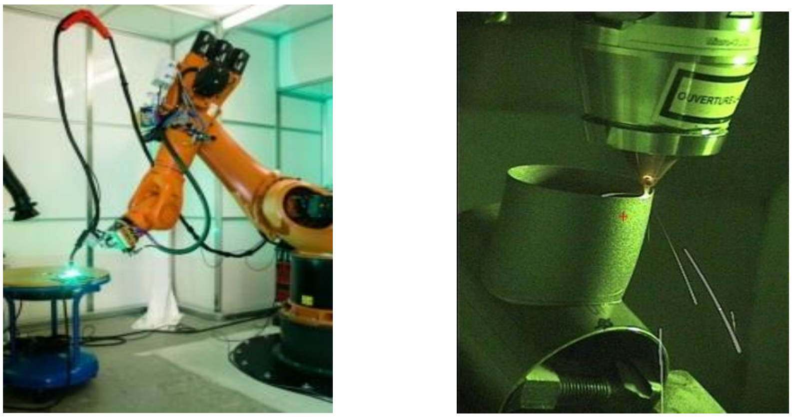
hollow or lattice structures which dramatically reduce the component weight while keeping their at least similar mechanical properties), assemblies can be simplified [2], spare parts can be realized at demand, Functional Graded Materials approaches are made possible [3].

Hence, AM has benefitted from large research efforts over the last decade, almost all existing industrial sectors have benefitted from them. However, AM does not intend to replace existing manufacturing processes, or to be employed alone to manufacture component in most of the cases. This is mostly due to cost and technological reasons. Cost reasons are linked to the "complexity for free" attributes usually associated to AM processes; because in contrast, simple geometries manufacturing can have a high cost with AM. The technological reasons are mostly linked to the properties of the surfaces generated by AM. If high functional requirements are demanded, a post processing process will be necessary.



a) b)

Fig. 1. Additive manufacturing processes: a) wire arc additive manufacturing – b) laser metal deposition

Among the AM processes ready for industrial applications, Wire Arc Additive Manufacturing (WAAM) is usually employed to realize large scale components (Fig. 1a.). The heat source is a high performance welding generator, most frequently a GMAW system but GTAW and PAW can be used as well for specific applications. The feedstock is a welding metallic wire. The motion system is often a 6dof robotic arm which flexibility is adapted to the process requirements such as offering variable tool orientation and a large workspace.

Laser Metal Deposition (LMD) is another Direct Energy Deposition (DED) additive manufacturing process (Fig. 1b.). The manufacturing of a part results in stacking successively layers of metal powder molten by laser. The powder is conveyed directly to a nozzle thanks to a carrier gas. It is adapted for production of parts with complex geometries, for short-run quantities or to improve a finished product with addition of new functionalities.

This paper introduces some opportunities and the associated challenges attached to Additive Manufacturing, to produce large metallic components for the transport industries (naval, aeronautics, trains, …). In particular, two innovative approaches are discussed in details: Hybrid Manufacturing, which objective is to set, prepare and carry out the best combination of manufacturing processes to realize a component, and Twin Manufacturing, which aims to solve most of the challenges in the virtual world before implementing the process on the manufacturing equipment.

The paper is illustrated with several proof-of-concept parts made with LMD, WAAM and hybrid approaches in the laboratory. Among them, a hollow propeller that has the same hydrodynamics efficiency for a reduced weight for the naval industry, an aircraft structural panel that demonstrates simplified assemblies increased performance/mass ratio, a train component that shows the ability to produce structural parts at demand.

2. HYBRID MANUFACTURING

Hybrid manufacturing consists in integrating AM together with other processes for the realization of finished components, with the objective to benefit from the interests of each process while avoiding its drawbacks. Hence, AM can realize complex geometries or offer low buy-to-fly ratios while high speed machining generates very good surface properties (position, roughness). Processes are carried out sequentially or simultaneously on the features to manufacture and finding the optimal manufacturing work plan can be challenging.

The combination of various processes to manufacture a part by selecting the most appropriate one for each feature depends on techno-economical requirements [3]. The success of such approaches lies mainly upon the ability to solve several challenges: selecting the best process sequence with the best parameterization; decomposing the CAD model into appropriate manufacturing features, as illustrated in Fig. 2. This decomposition is not unique and is highly process dependent [4, 5].

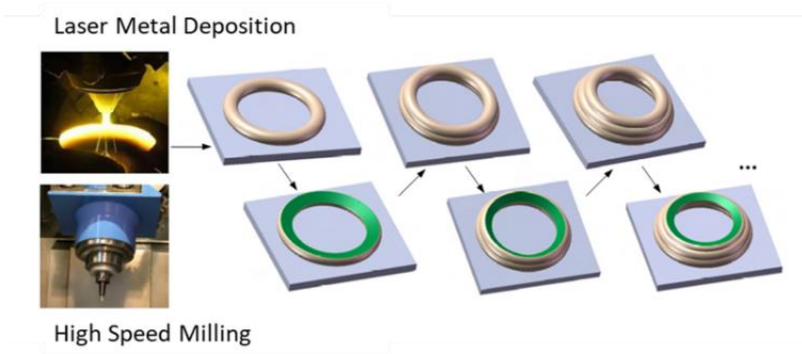


Fig. 2. Example of hybrid approach by sequentially combine additive and machining processes

This section introduces some hybrid approaches studied in the laboratory: the proposal of innovative numerical data chain for hybrid manufacturing approaches, the abilities to simplify high value assemblies and the proposal of component repair scenarios.

2.1. NUMERICAL DATA CHAIN FOR HYBRID MANUFACTURING: INTERESTS OF STEP-NC APPROACH

Implementing hybrid manufacturing raises challenges not only about the optimal processes combination to use. CAD/CAM/CNC data chains, and the associated numerical environment have also to evolve as well.

Actually, product manufacturing usually involves several processes. Most of them are integrated in a conventional numerical chain, also called CAx manufacturing chain. The Computer Aided Design (CAD) system creates a digital model of the part. Then, manufacturing experts translate this global geometry into a group of machining features well adapted to a defined machining process, relying on their own experience. Even if a CAD file is only containing a global geometry, the choice of a process to machine an area of the component leads to use machining features. A lot of factors can inflect the selection of the best machining process: feasibility of the part, respect of the tolerances, availability of the process in the factory, knowledge of a qualified subcontractor, price, cost, manufacturing time, etc. but also some more subjective criteria linked to the experience of the experts, which are difficult to capture.

The model information is then exported to Computer Aided Manufacturing (CAM) software. The CAM software enables the user to add manufacturing data linked to the selected process. For HSM, data such as machine tool, cutting strategies, tools, operation sequence are used to generate the tool paths that apply to the features. These object oriented information is stored in a proprietary CAM format. Today there is no standard to exchange manufacturing data between the CAM software of different companies. The CAM suites are often processing one single manufacturing process and compatibility between CAM software suites is hardly possible.

Hence, most CAD/CAM/CNC data chains are still mostly process specific, generating difficulties to control several processes together, as illustrated by Fig. 3.

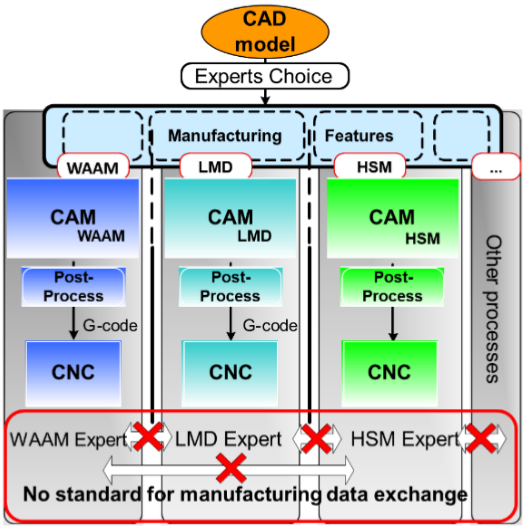
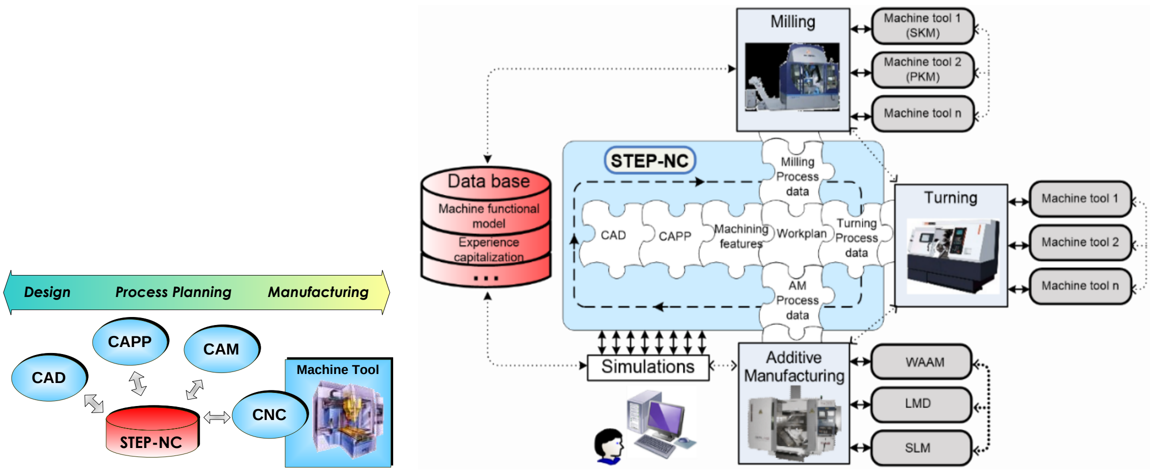


Fig. 3. Current numerical data chains for hybrid manufacturing

Some CAD/CAM software developers have set up possibilities for multiprocess manufacturing by integrating AM operations in their workflow [6, 7]. It can be consequently possible to generate hybrid process plans. However, the data provided to the machine tools are often still separated in different part programs for each process. In addition, interprocess relations are difficult to handle. The modifications of some parameters on AM operation are difficult to be taken into account by the other following operations.

To overcome these limitations, STEP-NC high level approach could be of great interest. Based on the same principles than STEP, STEP-NC [8] is being developed for the middle of the 1990s and aims to replace the outdated G-code (ISO 6983) [9]. Instead of describing explicit tool path and parameters as G-code does, STEP-NC is based on high level object oriented descriptions of the manufacturing features, operations and workplans.



a) b)

Fig. 4. STEP-NC approach: a) vision of numerical data chain, – b) multiprocess environments

The purpose is to give information on “what to do” rather than “how to do” to the CNC controller of the manufacturing equipment. Hence, STEP-NC approach relies also on smart CNC controller that are capable to take some decision on the process as for example generating the explicit tool paths from the data and parameterization provided by STEP-NC part program [10] (Fig. 4). A major interest of STEP-NC is that is has being from its beginning made for several manufacturing processes, with data consistency over all the data models employed. Reference models for milling, turning, EDM, additive manufacturing are available so that a STEP-NC part program can integrate various nature of manufacturing operations in its workplans. An example is provided by fig, where in the STEP-NC file it is enough to modify the manufacturing process associated to the bosses, from milling to AM, to generate a consistent multiprocess manufacturing scenario.

As showed in Fig. 5, the interest of the approach is not only about numerical data but the manufacturing approach is different and provides new opportunities. From the same part program, several manufacturing scenarios can be run depending on the manufacturing equipment capabilities and the manufacturing processes available. In the usual single-process scenario, the bosses features are associated to HSM as the rest of the part. In the multiprocess scenario bosses features are expected to be done with additive manufacturing process LMD. When running the program, the NC controller of the multiprocess machine, does as if the bosses are absent and to generate the machining tool paths for a standard pocket. Then, when switching to AM process in the second step, only the bosses are considered and manufactured. This approach, despite introducing some complexity with the several process to handle, opens new opportunities with for example the ability to select a different material for the bosses, or to achieve repair operations on worn components.

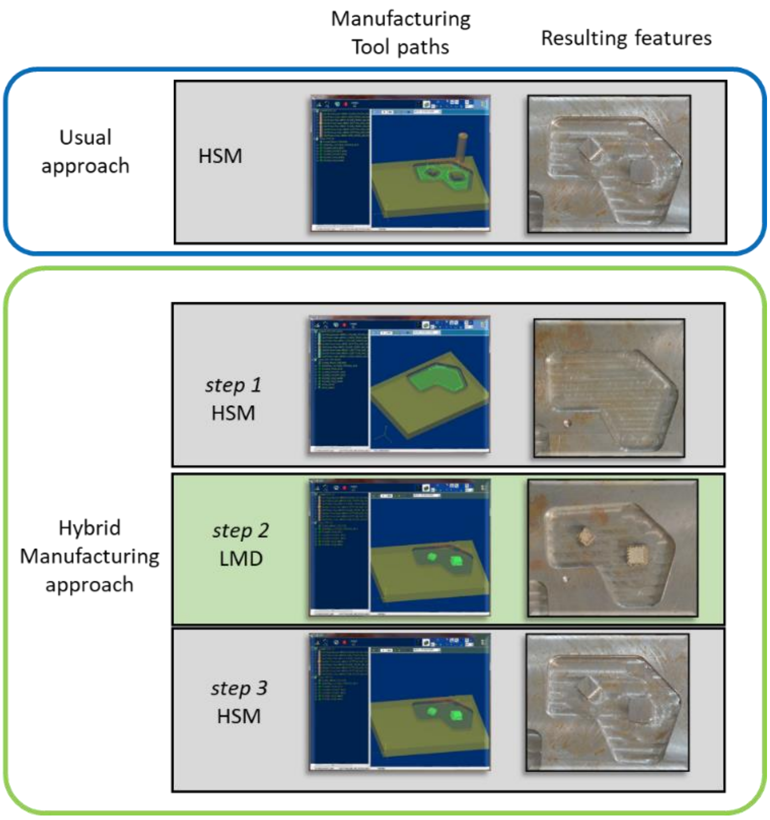


Fig. 5. Example of usual vs hybrid manufacturing approaches with STEP-NC

As a result STEP-NC approach provides an ideal framework for coherent and consistent numerical environment for hybrid manufacturing and proposes significant evolutions and interests.

2.2. REPAIRING HIGH VALUE COMPONENTS WITH HYBRID MANUFACTURING

Repairing components is usually highly complex compared to production, because of the variety of configurations and the necessity to adapt the process to this variety. In addition, several processes are usually involved, to clean the zone to repair, carry out the repair operation itself and clean the zone afterwards.

As a result, most of repairs processes are done manually and rely on user know-how. To fill the gap, a semi-automatic method has been proposed by the research group and is based on hybrid manufacturing approaches [11]: it applies to external or internal defects that have been machined into a surface cavity, to clean the zone to repair. This cavity is to be refilled in such a way as to recover the local geometry of the part, without the need of a nominal CAD model and with minimal user intervention.

As given in Fig. 6, the method can be segmented into several hybrid manufacturing steps: part inspection and defect identification, machining of the defect into a cavity, cavity identification, Additive Manufacturing tool paths generation and cavity refill, finishing operations by machining.

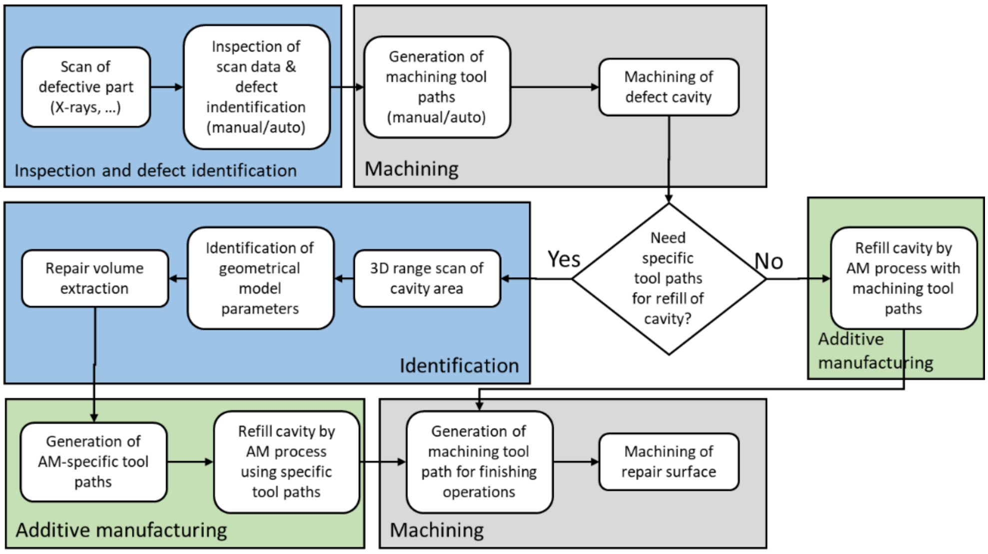


Fig. 6. Semi-automatic hybrid repair method

At first, the defective metallic part is scanned by imaging equipment, such as radiography or CT scans. The scan data is then inspected for defect identification, either manually by an operator or automatically by machine vision algorithms such as in the work of Mery [12]. A machining operation is usually necessary to prepare the repair, by removing the defective material. In very few cases, the machining tool paths can be recycled into scan paths for refilling the cavity [13] and the repair can be done immediately. But, in most practical cases, the cavity edges and volume have to be identified and this is the purpose of this step of the method, called InterSAC [11]. At the end of this step, the repair volume is fully identified and localized on the part or the AM machine workspace. The repair AM tool paths can be generated to fill the cavity and then finishing operations by machining clean the surface and remove excess of materials.

This approach lies on the adequacy of the hybrid manufacturing sequence employed. A singularity is that the initial CAD model of the part to repair is not compulsory for its effectiveness as InterSAC approach enables to reconstruct the CAD geometry of the machined cavity. It is also important to mention this method is well suited for multiprocess machines that combine machining with additive manufacturing within the same setup configuration of the part to repair into their workspace.

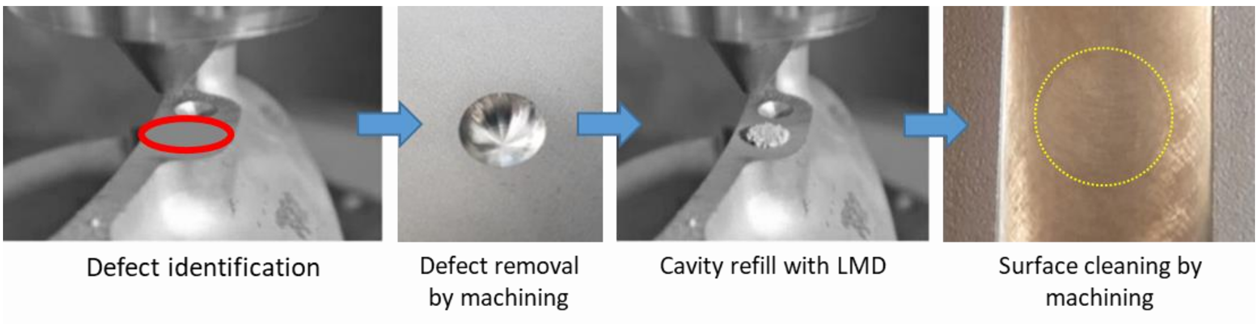


Fig. 7. Examples of aeronautical components repair with the proposed method

To illustrate the performance of the hybrid manufacturing repair approach, an aeronautical complex casted component is shown as use case. The approach has been carried out on the hybrid machine (LMD/Machining) of the laboratory and the steps are shown in Fig. 7.

2.3. HYBRID MANUFACTURING TO SIMPLIFY ASSEMBLIES: EXAMPLE OF AN AIRCRAFT STRUCTURAL PANEL

Combining additive manufacturing with usual manufacturing processes such as machining opens also new opportunities. A complete change of the design is possible to meet the functional requirements while simplifying the assemblies and gain weight.
Hence, another remarkable use case showing the interest of hybrid manufacturing is the realization of a self-stiffened double curvature structural panel. The hybrid manufacturing approach employed here is based on Design for Additive Manufacturing and proposed an innovative aircraft fuselage concept.

The demonstrator has a double curvature geometry on which primary (“T” shape, in beige) and secondary (thin wall, in blue) stiffeners are manufactured. The main radius is 2000 mm and the secondary 9500 mm. This proof of concept is issued of the French DGA/DGAC collaboration project DEFACTO which involved several industrial and academic partners: Stelia aerospace, Constelium, Centrale Nantes and CT Ingenierie. The objective was to use the new opportunities of WAAM, combined with finishing by machining to propose innovative structures for the aircraft of the future.

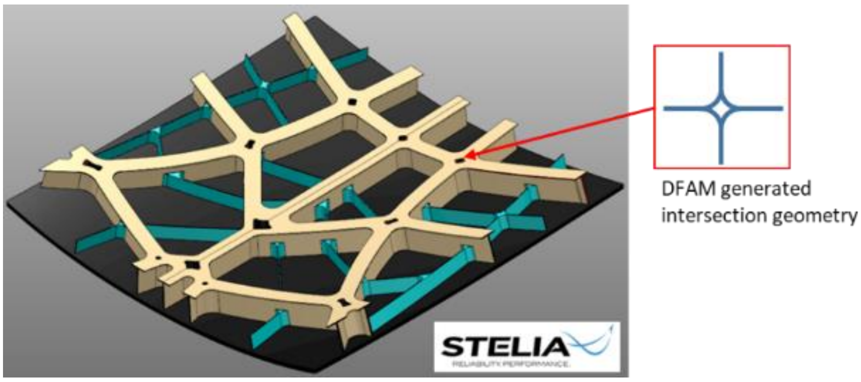
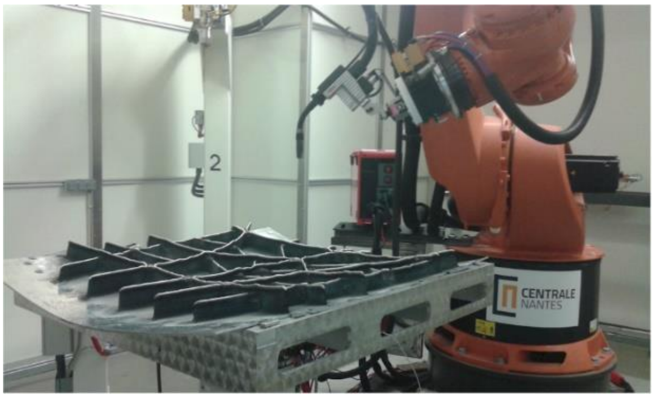


Fig. 8. Structural panel demonstrator after DFAM

Compared to usual aircraft structures which are made of profiles assemblies, the concept was to use the external skin as substrate and realize the stiffeners by WAAM. Hence, the process requirement and the design opportunities offered by AM have been identified and transferred to the design stage, to generate a geometry well adapted to the manufacturing process, while meeting the functional requirements of any aircraft structure.

In particular, an innovative “roundabout” design strategy has been employed for the primary stiffeners (Fig. 8). As the surface finishing process was multiaxis machining, the pattern at the center of the intersection was adapted to enable a milling tool to machine the external surface of it.

After the DFAM stage, the component has been manufactured in the laboratory using variable torch axis tool paths to deposit the thin walls (the stiffeners) on a curved substrate, as presented in Fig. 9a. As displayed on the same figure, a specific tooling has been develop to limit the substrate deformations during and after the process. Then, the realization of horizontal tail of the primary stiffeners has been realized using the cornice welding strategy. The tail has been considered as two distinctive walls that could be manufacturing independently. A major interest of AM could be employed here with the ability to make wall height and tail geometry vary locally depending on the local loads applied to the structure.



a)

b)

Fig. 9. Self stiffened panel: a) – during the additive manufacturing phase, b) – after machining and painting

The resulting part is shown in Fig. 9b., the left half has been kept as is after WAAM while the right half has been machined finished and painted as any aircraft structure. The results are very promising for the use of WAAM to realize such structures. Compared to usual structural components, this demonstrator geometry saves material while better following the load paths on the service and demonstrate the ability to simplify assemblies thanks to hybrid manufacturing.

3. TWIN MANUFACTURING

Twin manufacturing uses models and multiphysics simulation methods to create a digital clone of the process implementation within the manufacturing environment. Manufacturing preparation and optimization can be carried out in the virtual workshop where various configurations and choices can be tested before being selected. To enhance its accuracy, the digital twin can also be fed by monitoring data captured during the process.

In this section some digital twins approaches developed for manufacturing purposes in the laboratory are introduced. At first the direct link with virtual workshop concepts is recalled. Then, the use of digital twins to realize high value large components is introduced and illustrated by two use cases; finally the interest of coupling simulation approaches with monitored process data into the digital twin are discussed through an example coming from machining.

3.1. FROM VIRTUAL WORKSHOP TO DIGITAL TWIN

The concept of digital twin is strongly linked with the introduction of Industry 4.0 [14]. However, the idea to set a virtual environment to optimize at low cost a manufacturing scenario is not new. It was already proposed at the end of the 1990 under the "virtual workshop" concept. At this time, the idea was to base on multiphysics simulation to model and predict the behavior of the triangle: component, manufacturing equipment and process implementation. The aim was to define at low cost – compared to experimental campaigns the best process implementation to meet the technical and economical requirement of a dedicated application.

Figure 10 illustrates the Virtual Workshop developed for high speed machining in the laboratory. It was based on several simulation tools developed in house to evaluate the machining process implementation, select the most appropriate tool path strategies combination, the most capable machine tool for a dedicated applications.

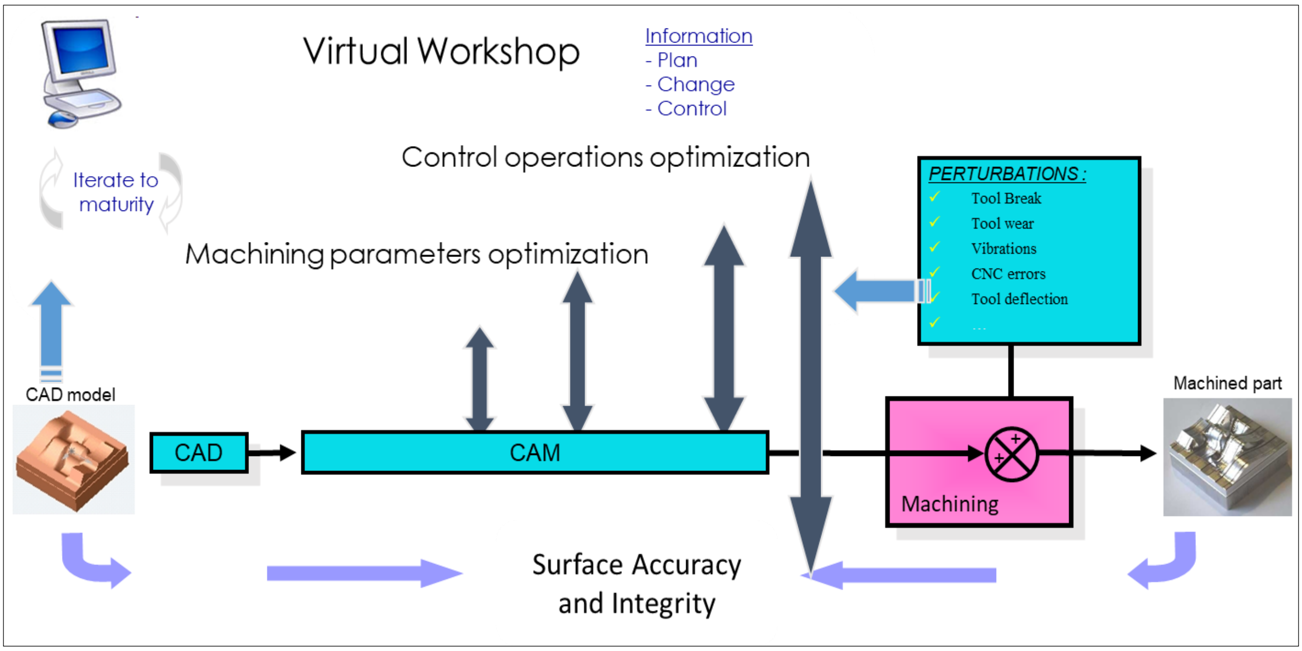


Fig. 10. Example of virtual workshop [15]

The need to virtually optimize the manufacturing process for complex scenarios has also been identified for the STEP-NC approach introduced in a previous section of the paper, in particular for multiprocess manufacturing approaches and the multiplicity of available scenarios. The STEP-NC Platform for Advanced and Intelligent Manufacturing proposed within this framework [10] was also based on coupling monitored process data with off-line simulation results at the NC controller level, as recalled in Fig. 11.

Digital Twin approaches are definitely resulting from these kind of initiatives and go further in the communication between virtual and real environments thanks to the process of IT technologies.

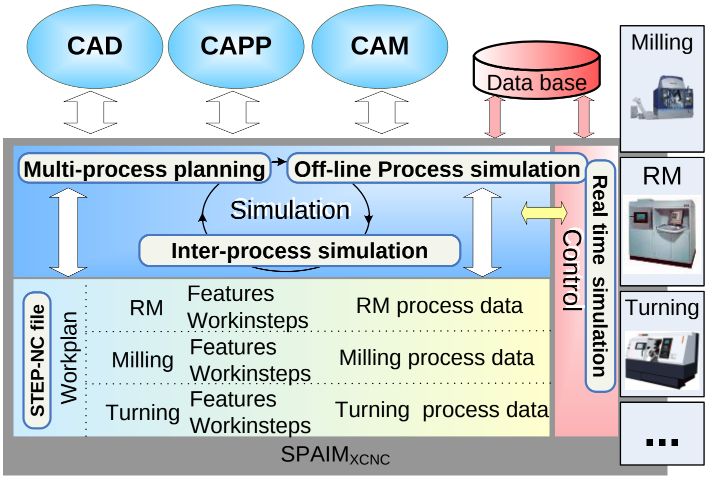


Fig. 11. Coupling offline simulation and STEP-NC controller for multiprocess manufacturing

3.2. TOOL PATHS GENERATION AND CONTROL WITH THE DIGITAL TWIN: EXAMPLE OF A HOLLOW PROPELLER BLADE AND A TRAIN PIVOT

H2020 European project RAMSSES [16] objectives were to develop, validate and integrate maritime parts and processes for the new generation of ships. An objective was to realize a proof of concept of significant efficiency improvements for propellers made with Additive Manufacturing. As a result, the idea was to start the design process from its beginning with the functional requirements given from fluid mechanics. Then, step-by-step, the digital twin of the propellers was created with all the needed data. Structural mechanics behavior was calculated to define the external geometry and the minimal thickness. It gave the opportunity to leave a cavity inside and consequently propose a hollow blade design [17]. Hollow blades are a very powerful concept as the reduce noise and vibrations of propellers, and are thus beneficial to the marine wildlife. Also, it improves their hydrodynamic efficiency by reducing cavitation phenomenon, resulting with interesting economic impacts. a 1.5 m high hollow blade was manufactured.

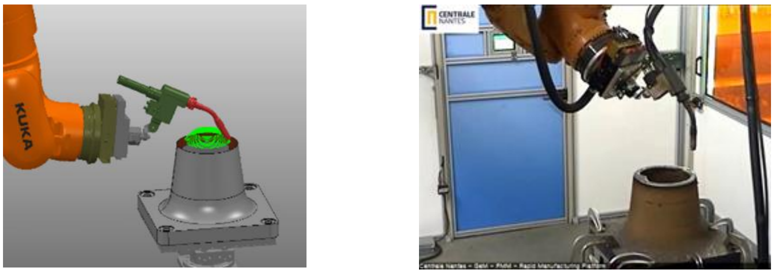
WAAM process was chosen and due to the complexity of the blade geometry a six dof robot equipped with a 2-axes positioner was selected as manufacturing equipment. This 8 axis machine is quite difficult to program manually. The additional geometric redundancy consequently increased the number of kinematic joint configurations for a given oriented position. However, this freedom gain requires constraining the robot to prevent unexpected configurations or collisions. Furthermore, the kinematic architecture of the robot can introduce singular positions that is harmful to the robot movements. Tool path simulations on a numerical environment is essential to predict and control the robot behavior at this stage. The digital twin created here includes not only the kinematics and geometries but also the NC controller behavior when executing the part programs.

This twin manufacturing use case illustrates the interest of digital twins to prepare and control the explicit tool paths on high dof AM equipment, which are often employed for DED AM applications. The main challenge is to control the accuracy of the digital model so that it behaves the same than the real manufacturing equipment (Fig. 12).

a) b)

Fig. 12. a) – Control of the melting pool orientation by using the digital twin of the manufacturing cell, b) – View of the hollow blade during manufacturing

A similar approach was employed for another additive manufacturing use case: the realization of a train structural pivot. This axisymmetric part of 500 mm height and of 400 mm diameter was manufactured with the hybrid manufacturing robotic cell of the laboratory. The WAAM process was chosen for realization due to its cost-effectiveness of large parts manufacturing. For this use case, the initial geometry was not open for design modifications as the objective was to test the ability to realize spare parts on demand.



a) b)

Fig. 13. Interest of the digital twin to generate complex tool paths: a) – tool path generation in the virtual environment with the digital twin, b) – tool path execution in the real environment

As shown on Fig. 13, the digital twin of the manufacturing robotic cell was employed to set the tool paths and robot configurations. The objective was to lever most of the difficulties in terms of robotic configurations, welding bead position, and material deposition evolution. One key aspect was to be able to employ specific WAAM tool paths strategies, developed internally, and leading to high material properties.

After WAAM deposition and machining of reference surfaces, the pivot went under a severe fatigue test and came out successfully. As a result, the interest of digital twin to prepare and optimize virtually additive manufacturing processes has been highlighted.

3.3. COUPLED SIMULATION / MONITORING APPROACHES WITHIN THE DIGITAL TWIN

A further step can be taken by coupling the digital twin model with data acquired during the running of the process. Such approach has been already developed in the laboratory for machining use cases and can be extend to AM application.

The main goal is to set a closed loop control of the manufacturing equipment, based on a twin manufacturing approach. In other words, the digital words contains a behavior model, obtained by simulation and some data acquired during the process help to select the model fitting that correspond to the actual situation in the real world. A key challenge is to propose communication ways between the digital and the real world so that the digital identification can be accurate enough to provide data for closed loop control.

This approach will be illustrated in this section on the following use case: a curved sheet metal is set up on the fixture of the tilting table, on which a constant depth slot is to be machined. Actual curvature and sheet metal position into the clamping system are unknown. The initial toolpath is a flat line, the test aims to modify this tool path online to adapt to the real curvature and realize the slot at constant depth. (Fig. 14).

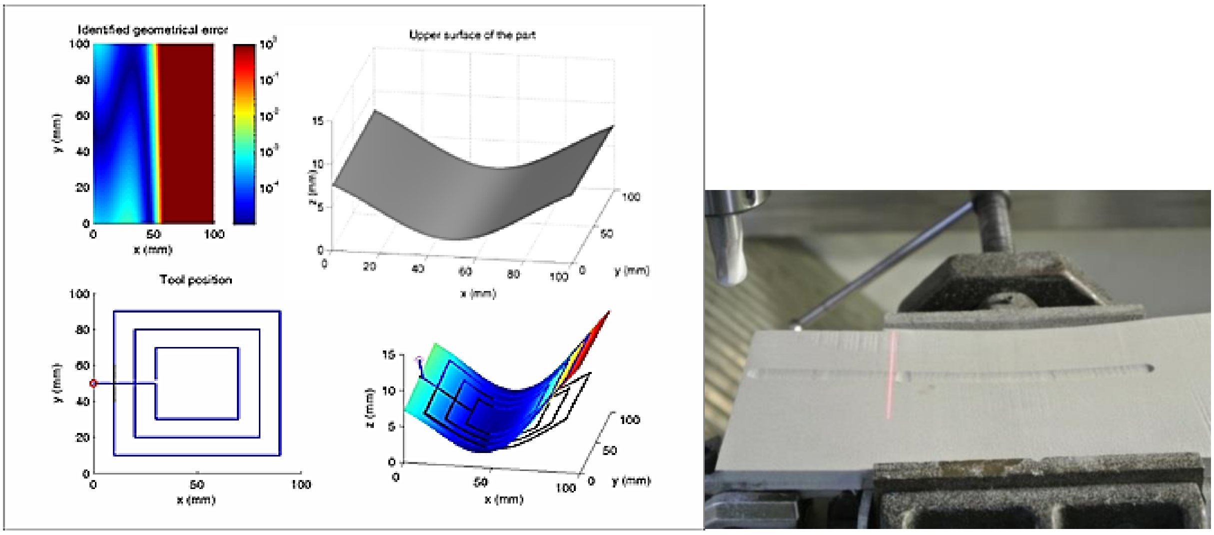


Fig. 14. Digital twin of the surface / real surface being identified

Prior to machining, the digital twin of the setup and manufacturing process are configured. This operation has only to be done once. The real surface approximation algorithm is based on the Proper Orthogonal Decomposition (POD) method. The POD is an efficient technique to extract relevant information from a large set of data. From a mathematical point of view, the dimension considered here being finite and the decomposition being truncated, the POD is equivalent to the Principal Component Analysis (PCA) [18]. To approximate the real surface, from a large set of surfaces called “snapshots”, a reduced basis of modes or “principal surfaces” is extracted and used as a basis of approximation for the actual geometry measured online.

There are typically two ways of obtaining initial snapshots of the surface: using data coming from previously measured parts or building up the initial set by numerical generation. According to the latest approach, geometrical features such as the type of curvature (single or double), the range of possible radii of curvature or the amount of twist, are used for generating surfaces, thanks to a suited mathematical formulation. The twin model of the real part is consequently modeled as a linear combination of known geometrical features, as depicted in Fig. 15.

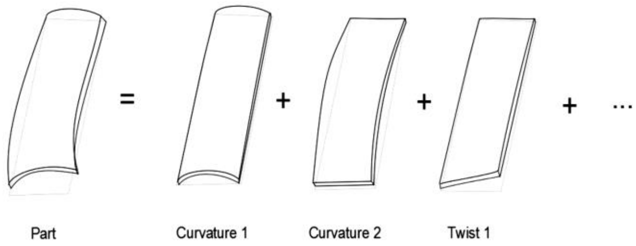


Fig. 15. Digital twin modeling as a combination of known features [19]

During the machining process, a laser scanner is fixed on the machine tool spindle and scans the upcoming regions of the sheet metal to provide height information while the toolpath is being travelled. This information is directly fed to the digital twin so that surface identification algorithm can be computed and the toolpath compensation algorithm feeds the new tool path control points back to the CNC machine. During the approach phase, when the cutting tool is not already upon the surface to machine, the data acquired by the laser scanner help to feed the POD basis and start the toolpath compensation.

Some results are depicted in Fig. 16, which compares the ideal compensated tool path with the expected toolpath to machine a slot at constant depth on the test sheet metal. The difference of altitude with respect to the ideal path designed from the exact measured geometry does not exceed 0.15 mm, which is very good in regards with the functional expectations.

This experimental study demonstrates the feasibility of an online measurement-based strategy for the update of the toolpath. Other tests have been carried out in a conclusive way. It highlights the interest of coupling simulation approaches with monitored data into the digital twin of the component with the selected manufacturing process.

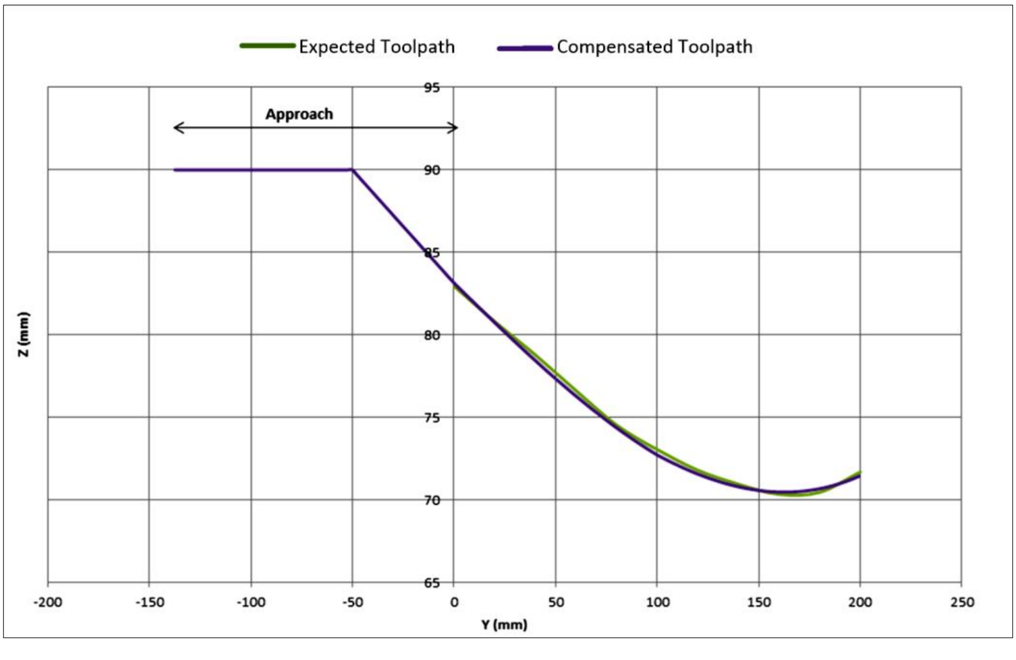


Fig. 16. Comparison of expected and compensated toolpaths for a curved sheet metal [3]

4. CONCLUSION

Additive Manufacturing processes offer new opportunities for large scale components manufacturing and this paper discussed two approaches to implement them. In addition to specific know-how and expertise, it is essential to fit AM in the global manufacturing process chain, and the development of hybrid approaches is of great use. The challenges lies not only at process implementation level but it is also essential to base on high level CAD/CAM/CNC environment to handle the associated complexity.

The second innovative approach on which the paper focused was twin manufacturing. With the rise of Industry 4.0 concepts, it is now possible to extend the virtual workshop approach to powerful digital twins and benefit from them to improve, optimize and prepare the manufacturing processes at low cost, thanks to real time monitored process data, which can be coupled to multiphysics simulation results. Eventually, both hybrid and twin manufacturing are consistent and can be used together to set innovative multiprocess manufacturing approaches.

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