The role of measurement and simulation in additive manufacturing within the frame of Industry 4.0

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***Abstract*— In recent years, manufacturing industry has been facing a new and powerful technology, able to produce complex and cost efficient parts, the additive manufacturing (AM). The rapid development and expansion of the use of this method was accompanied by a vast development of equipment and software in mainly two directions, namely the optimization of a designed part with respect to its weight and mechanical performance and the simulation of the fabrication of this part via AM. Nevertheless, several drawbacks on the fabrication of components of a variety of materials have been observed, especially with reference to the final product dimensions and the corresponding distortions caused by a number of factors that influence the final result. In the present work, the correlation between the measurements of specific characteristics of components fabricated via AM and the data provided by the simulation models are presented. Also, the role of these measurements on the development of a component consistent with the initial design is underlined. To this end, a test case is presented, in which a part of high geometrical complexity is realized using the Selective Laser Melting (SLM) method. The comparison between the measurements of the final product reveals the need of constant and consistent measurements for assuring the part's accurate fabrication.**

Keywords—additive manufacturing, simulation, experimental validation, measurement techniques, uncertainty

I. INTRODUCTION

Additive manufacturing (AM) is a relatively new manufacturing method whose main advantage is the creation of parts with high geometrical complexity and internal features that cannot be produced using conventional machine subtractive methods. It also contributes to the reduction of cost and time by reducing the machine and tooling set up assembly time [1]. It is reported that this method may be considered as among the most revolutionary industrial innovations [2] as it is already used for the realization of large part volumes of high complexity. By using certain AM methods, it is possible to realize components of high density by materials such as steels, aluminum or titanium alloys, metal-based and ceramic matrix composites [3]. Among the most popular methods for producing these parts are the Power Bed Fusion (PBF) and the Direct Energy Deposition (DED), having both their respective advantages and disadvantages. Within the principals of the first method, selective laser melting (SLM) and electron beam melting (EBM) are included. The present paper focuses on the use of the SLM technique, this latter being a suitable practical example on which testing the proposed methodology.

Due to its versatility, the AM plays a key-role in the Industry 4.0, saving time and costs, being decisive for process efficiency and reducing its complexity, allowing for rapid prototyping and highly decentralized production processes [4]. Though AM represents one of the central paradigms of Industry 4.0, it still requires further research and development. [5]

Among the most frequently addressed problems related to AM is the residual stresses caused mainly by the thermal cycle of the process itself [6]. Generally, AM in metal applications consists of rapid heating, several cooling rates and a relative re-melting of the secondary layer (after having been solidified) by the new upper material layer. This whole procedure generates thermal stresses which are then converted to residual stresses after the production of a certain part of the component, leading also to notable distortions as seen in [7-8], cracks and variations on the relative dimensions of the produced part. In the most cases, every part is subjected to post processing such as supports material removal or heat treatment which augments not only the residual stresses (and the distortions) but also the complexity of a potential manufacturing process simulation.

On the other hand, with the aim of foreseening the residual stresses of the AM on metals, there have been several attempts on developing the right numerical tools which are mainly based on multiphysics being either complicated and/or time consuming, or even simplified or case-specific [9-10]. Nevertheless, each simulation should be validated after the part manufacturing, especially after additional heat treatment by focusing on the measurement of several parameters such as the microstructural variations, the induced stresses and the deviations on the part dimensions [11].

Besides avoiding undesired scrap of material and controlling the manufacturing process itself, measurements on the AM process are indispensable for assessing whether or not the produced part:

- fits to the design requirements;
- allows its assembly with other parts;
- is energy efficient.

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Many measurement techniques exist, supporting both the product and the process quality. Most of them refer to the identification of the presence of residual stress in the component due to the disuniformities of the final internal structure of the component; its assessment is generally carried out by means of the X-Ray diffraction analysis, which is mainly based on computed tomography analysis of both the microstructure and the relative part dimensions [10-11].

Other measurement techiques are devoted to the measurement of the effects of residual stresses on a macroscopic scale, including, distortions, cracks and variations on the relative dimensions of the produced part. These are based on three-prong method (TPM) to measure residual stresses via a three-pronged cantilever component [12], Digital Image Correlation (DIC), Coordinate Measuring Machines (CMMs) and other Optical Measuring Machines (OMMs) which are very popular in the industry [13].

Process monitoring can be achieved by means of the following techniques, using contact and non contact sensors:

1) Thermal techniques: thermocouples and thermography for the monitoring of deposition temperature [14].

2) Optical techniques: pyrometers and infrared (IR) cameras.

3) Acoustic techniques: laser ultrasonic (LU) and spatially resolved acoustic spectroscopes (SRAS)

4) Magnetic techniques: i.e. based on magnetic characteristics of the material (eddy current sensors).

Also, a virtual instrument was created to perform automatic control of electron beam-PBF technology, achieve parameter modification to attempt temperature stabilization and to detect porosity, even though these are not used for further post-processing and merging of data. It has to be pointed out that many manufacturers now offer additional modules which can be added onto the basic AM machine, although further analysis based on these data is not carried out [15].

It appears evident that many quantities are of interest at micro- and macro-scale, during the manufacturing process, requiring that many measurment techniques should be used and merged, in order to get useful information. The phenomena the AM is based on, are typically non-stationary ones and require complex models for simulation, in order to take into account all the possible aspects of interest for process control and optimisation. Due to this consideration, as for simulation, the main issue is related to the identification of the most meaningful quantities and aspects, in order to simplify the approach, guaranteeing the models are trustable and efficient from the processing load point of view. Furthermore, tight interaction is required with experimental activity in order to allow mutual validation.

As for experimental activities, the topics of interest refer to the following:

- sensor fusion and integration of different data bases, depending on specific measuring chains,
- data fusion between measurement data and simulation ones [16],
- optimisation of experimenatal activity (e.g. DOE, in-situ calibration, virtual instruments, data validation) [17],
- synthesis of information for definition of meaningful features for application of advanced algorithms of Machine/Deep Learning [18-19]

In the present work, a case of an aerospace part optimization and realization, a potential iterative simulation for the development and production of a metal component of high geometrical complexity which may be produced using the AM process, is presented. The iteration steps will be carried on according to intermediate validation phases, by means of geometrical evaluation on parts, according to [20] and taking into account the experimental temperature measurments realised by means of thermocouples and thermography.

Requirements of the measurement techniques are discussed in order to obtain measurements realiable for the validation of the simulation model and for the understanding of the physical phenomea involved in the process. The methods able to measure the effect of residual stress on a macro-scopic scale will be considered, in particular CMMs and other optical measurement techniques, based on laser displacement sensor. The need of post-processing will be also discussed with reference to the integration of measurements and model data.

II. MATERIALS AND METHODS

A. The test case

The test case refers to a part, which is the support of the antenna of a satellite, in close collaboration with Thales Alenia Space as seen in Fig.1.

This part started from an initial conventional design and was re-formed several times using topological optimization tools aiming to reduce the total weight of the component and maximize, in parallel, its rigidity. This process includes several steps like stress-analysis (external loads) and topological optimization (re-design) of it with respect to these specific loads. Both the original and the optimized components may be seen in Fig.2. and Fig.3, respectively.

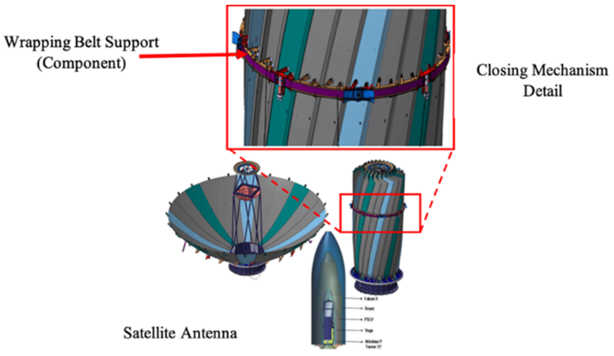

Fig. 1. The satellite antenna mechanism and the belt support studied.

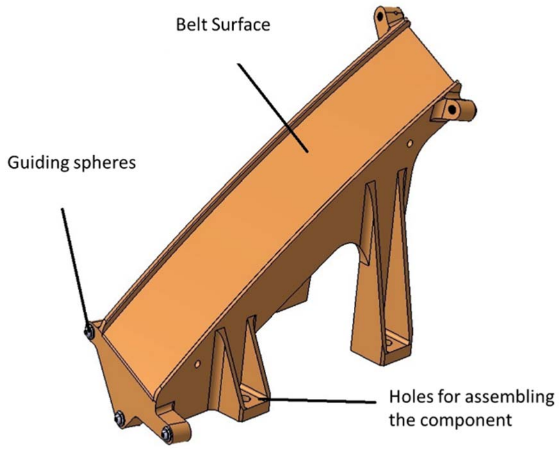

Fig. 2. The original component for the antenna support.

Fig. 3. The optimized component for the antenna support.

The material of this part is the Inconel 625 nickel-iron alloy which is frequently used in additive manufacturing process (PBF). The estimated weight of the initially designed part was 300 g while the final optimized design has an estimated weight of 270 g. The stress analysis and the topological optimization of the part are conducted using the Inspire SolidThinking software. Thus, using a certain procedure of iterative stress analyses and optimizations, the mechanical performance of the component is simulated and optimized. After this process, the component has been realized by Renishaw by the PBF method.

B. The simulation approach and the validation actions

According to the scheme of Fig. 4, the measured quantities available are the following ones:

- the position of points of interest on the surface of the manufactured specimen (i.e. with reference to Fig. 4, *Dim1* and *Dim2*, provided by the the measurement actions M1 and M2, respectively),
- the temperatures (T) during the thermal treatment (T.T.) aimed to reduce the residual stress.

In this frame, there are two main directions towards the proper and accurate fabrication of a component.

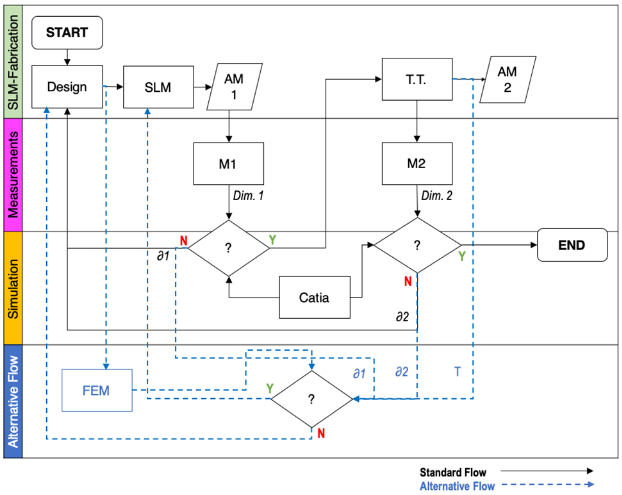

Fig. 4. The Flow Diagram: standard and alternative flows

The first one is described by the black continue line of Fig.4. After having designed and optimized the component, the fabrication follows, using a proper AM method (SLM, in this case). Then, measurements of the component dimensions are compared with the nominal dimensions of the component using the Catia V5R21 software (the component is indicated as AM 1 and the software as Catia). Consecutively, if the dimensions fit the demanded tolerances, the thermal treatment of the component is conducted and new measurements of the dimensions are made. If in each step, before and after the thermal treatment, a deviation between the actual and the nominal dimensions is detected, then the procedure returns to the design phase in order to re-design the part, taking into account the actual distortions. With reference to Fig. 4, these deviations are called *∂1*, or *∂2*, depending on the stage at which the measurements are made, i.e. M1 or M2; it has to be pointed out that the component having received thermal treatment represents a different measurement object, which is called AM 2.

The second approach is described by the blue dotted line of Fig. 4. It is based on the finite element method (FEM) using traditional (e.g. ANSYS, Abaqus) or case specific software packages (e.g. Amphyon) that simulate the manufacturing process. To this end, after the topological optimization, the designed part's fabrication is simulated and the corresponding distortions are predicted. Then, after the actual fabrication and the thermal treatment, measurements are used to validate the accuracy of the numerical simulation's predictions and to ensure the component's adequacy for further processing or use. If the comparison returns satisfactory results, (i.e. Y, standing for YES, in Fig. 4, as one of the output of the decision shape of the flowchart), the validation is confirmed and the output of the FEM simulation could be used as an input for the set-up of the manufacturing process itself (SLM). Otherwise, if the validation fails (i.e. N, standing for NO, in Fig. 4), the comparison is exploited to give benefits in term of improvement of the optimized nominal geometry, which has been indicated as the output of the Design step of the flowchart.

In both two approaches, the required measurements may be considered indispensable for assessing the quality of the final component by doing a comparison between the nominal dimensions of the component and those of the final product, before and after the thermal treatment.

C. *Assessment of the component's dimensions*

Each software uses the position of points of interest in a different way: surface grid for the optimized nominal geometry, interpolation surface for Catia V5R21, added volumes according to a surface grid for FEM. Therefore, in order to fuse these data a suitable homogenization is required.

In the present work, the component's dimensions are measured using a contact method. To this end, the characterization of the dimensions, and thus the distortions, was conducted by implementing two series of measurements namely one after the SLM process and one after the thermal treatment. Consequently, the comparison of the two series of measurements may identify the corresponding deviation from the nominal design and dimensions.

Considering the above, the measurements were taken from the upper surface of the previously described component of the satellite due the fact that it should host the closing belt of the satellite antenna. The tolerances described by the designer are 0.05 mm as seen in Fig. 5.

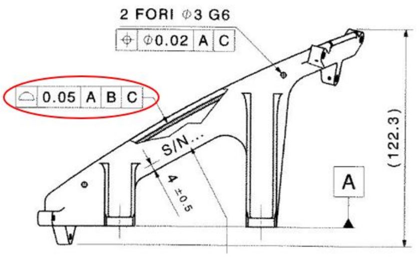

Fig. 5. The tolerances imposed to the component during the design phase.

Consequently, the measurements' campaign starts with the identification of the component within the overall measuring volume as seen in Fig.6, thus to set the local-global coordinate system. To this end, the holes of the supporting screws utilized as their nominal coordinates were already known. The centers of these holes were identified easily and are consequently considered as the centers of the potential local Cartesian coordinate systems BF1, BF2 and BF3 respectively as seen in Fig 7a.

Fig. 6. CMM machine for measuring the component's surface

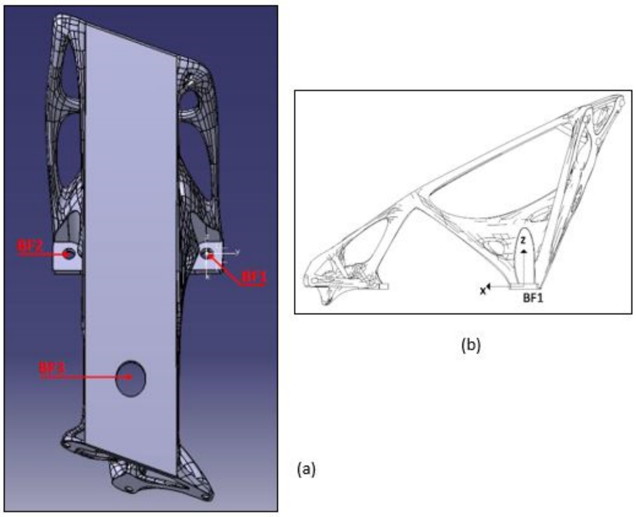

Fig. 7. (a). The hole centers BF1, BF2 and BF3. (b) Global coordinate system

After having identified the coordinates of the points BF1, BF2 and BF3 respectively, the global coordinate system starting from the point BF1 was considered. The whole operation is supported by the measuring machine software throughout an algorithm which permits the alignment of the reference system (nominal) as described by the design of the component and the actual one, minimizing this way the corresponding position error. As a result, every point that is acquired by the machine afterwards has coordinates that refer to the nominal coordinate system set and aligned, using the previously procedure, with the actual one.

For characterizing the surface on which fits the closing belt of the antenna, a number of 66 points are acquired creating the point pattern described by Fig.8.

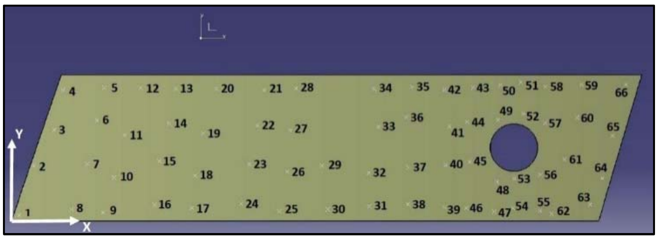

Fig. 8. The pattern of the acquired points

After having acquired the coordinates of the previously described points, the software CATIA V5 is used in a manner to identify the deviation between theses points and the nominal surface as described by the original design of the component. In parallel, the analysis of the CATIA V5 (the calculated deviation between the points and the surface) is validated using Microsoft Excel. The best-fit module of the CATIA V5 is used, which permits the proper alignment of the points' cloud to the nominal surface of the component using the global coordinates starting from the BF1 point. After this procedure, the calculation of the distances between the points and the surface is conducted and, consequently, the analysis of these results may be divided in 5 individual zones of the fabricated component as seen in Fig.9.

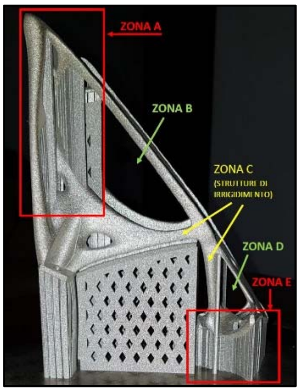

Fig. 9. Distribution of the supports with respect to the upper surface.

An assessment of the surface quality and deformations before (after the SLM process) and after the thermal treatment is presented in Fig.10 and Fig.11 respectively. As seen there, the measured deviations, in both cases, obviously create a certain pattern which is highly connected with the design of the individual supports. For instance, zone B is free of supports and derives a different pattern than zone A. The same pattern is observed even after the thermal treatment.

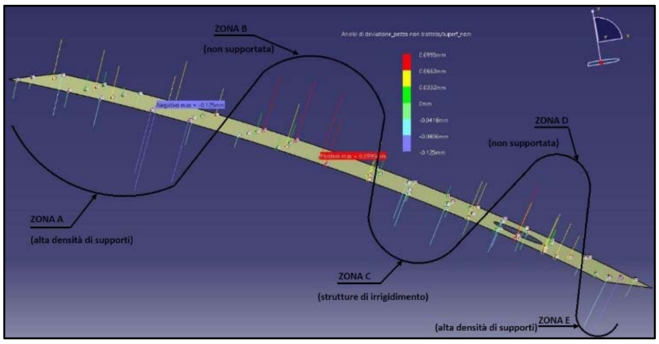

Fig. 10. Deformation pattern after the manufacturing process

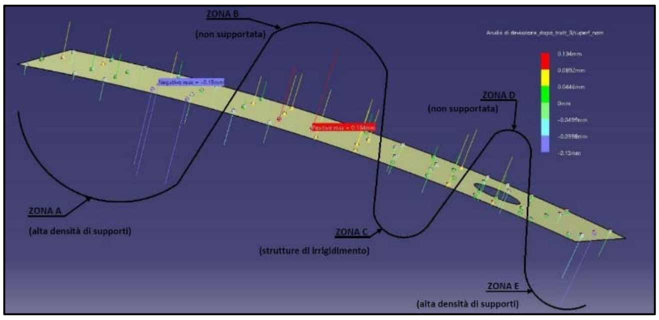

Fig. 11. Deformation pattern after the thermal treatment

On the other hand, within the limits of the regions A and E observed are the most serious deviations from the ideal/nominal geometry, a fact which also supports the effect of the design of the supports of the component and its influence on the relative deformations probably during the cooling down phase. Either way, the deviation may be positive or negative, a fact which corresponds mostly to the original component design.

Aiming to understand more profoundly the relative deformations, the surface is also sub-divided into 4 parallel sections namely, a, b, c and d, which correspond to the 4 longitudinal axes of the plane of the created grid of the points of the surface. The distance between the nominal surface and the line before and after the thermal treatment are presented in Fig.12 and Fig.13 respectively.

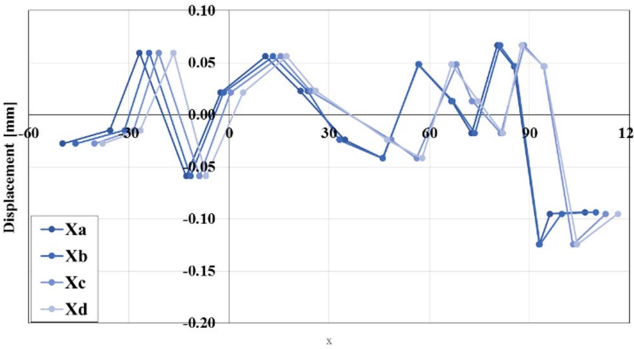

Fig. 12. Y deformation with respect to the 4 X axis a,b,c and d after the additive manufacturing process.

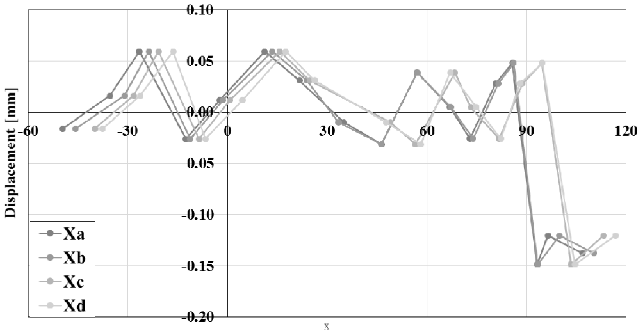

Fig. 13. Y deformation with respect to the 4 X axis a,b,c and d after the thermal treatment.

By comparing the two graphs of the Fig.12 and Fig.13, an amelioration of the deformations is observed at the initial part of the component, which corresponds to Zone A. Moreover, general ameliorations of the deformations within the limits of Zone D are observed and a serious increment of the deformation of Zone E.

III. DISCUSSION

During the post-processing stage, the experimental measured points are aligned to the nominal reference surface provided by the model made in CATIA V5; therefore, these measurements provide indications about the deviation from the nominal geometry. On the other hand, in order to provide fruitful indications from the simulation stage, displacement of the geometry in the 3D space is necessary; however, this is not a trivial task. In fact, the results obtained by the simulation suggested that the most significant deviations occur in the A and E zones of fig. 9, i.e. those referred to the supports. In this preliminary analysis, deviations in the order of 0.02 mm are obtained by a suitable alignment of the reference system of the component under analysis to the reference system of the CMM, by means of a roto-translations of both. Deviations in the order of 0.4 mm are obtained by the simulation stage, which, derives from the selection of many parameters in the software.

A direct comparison between simulation approach and experimental data is not possible due to many factors:

- Uncertainty of experimental data, due to multiple alignment procedure;

- Reduced differences among misalignments with reference to the nominal surface, if the pre- and after thermal treatment is considered;
- Resolution of the simulation software, if the uncertainty about the used parameters are considered;
- Different zones of the specimen mostly taken into account by the CMM (i.e. the upper surface of the part of the satellite antenna) and by the simulation software (i.e. the supports).
- The effect of clamp and alignment of the component is during the measurement stage.
- The way the conventional software is conducting the best fitting process: the results are dependent on that.

For the above-mentioned reasons, an integrated approach sharing the positions of interest is needed.

IV. CONCLUSION

The main goal of this work is to identify the role of the proper and accurate measurements in the field of additive manufacturing and to identify the problems that arise from it. A second goal achieved was to analyze the dimensional deviations caused by the different data processing approaches and to compare them to the specification requirements set during the Design phase.

Obviously, due to the complexity of the processes, the structure (in terms of design) and the materials, the need of proper measurements of the surface quality and the deformations is highly related to the component development and realization. As all the simulations of a manufacturing process or a structural analysis are based on severe assumptions and simplifications, the correlation of the output of these simulations with the measurements appears to be inevitable for validating the constructed virtual models.

Nevertheless, many problems even in the post-manufacturing phase are observed. These problems and uncertainties are connected with either the acquisition processing or the data analysis. For instance, during the acquisition of the coordinates, the proper clamp and alignment of the component is of extreme importance. Also, the way the conventional software is conducting the best fitting process is sometimes questionable and the results are highly dependent on that.

To conclude, the quantitative results were translated to each phase of the process the dimensional information in the form, which is the most suitable and accurate from the physical point of view. This means adapting both experimental and theoretical dimensional information to the need of each software tool (SLM, Catia and FEM) taking into account that the experimental measured surface positions may not correspond to those created by software tools for modelling, simulation and fabrication.

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