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Customized design of artefacts for additive manufacturing

Saint-Clair T. Toguem[1], Charyar Mehdi-Souzani[1], Nabil Anwer[1], Hichem Nouira[2]

[1] *LURPA, ENS Paris-Saclay, Univ. Paris-Sud, Université Paris 13, Sorbonne Paris Cité, Université Paris-Saclay, 94235 Cachan, France*
[2] *Laboratoire National de Métrologie et d'Essais (LNE), 1 Rue Gaston Boissier, 75015 Paris, France*

stoguemt@ens-paris-saclay.fr

Abstract

Additive manufacturing (AM) artefacts are test parts used to optimize and assess accuracy and limitations of AM systems and processes. There are several artefacts developed for AM. However, few of them are provided with complete details on the general design method used for tolerance evaluation. Also, before starting a batch production with metallic AM systems, manufacturers need to make sure that AM system's GD&T (Geometric Dimensioning and Tolerancing) capabilities fit their requirements. This can be achieved with a customized artefact designed for the evaluation of specific GD&T characteristics. This paper follows a synthesis of the common practices in AM artefact design methods. The aim here is to introduce a detailed AM artefact design method for GD&T characteristics evaluation. Based on existing design concepts, the proposed approach sets up a design guideline starting from requirements definition, to the final test part. A case study is also detailed to evaluate the general GD&T accuracy capabilities and limitations of a metal PBF system. A test part is designed, built and the AM system's characterization is performed.

Keywords—Artefact, Additive Manufacturing, GD&T, Design guidelines.

1. Introduction

In the literature two main methods are proposed to improve AM systems and processes accuracy. The first is based on the measurement of identified characteristics directly on AM machines (online or offline metrology). This method is challenging and includes several difficulities such as the accessibility of the system's components, safety issues and technological limitation of measurement systems. The second method is based on the use of conventional measuring machines and techniques for measurement and characterization of test parts named artefacts. Currently, the second method is the most used for performance evaluation of AM systems and processes [1] [2]. One advantage of the second method is the possibility to efficiently compare several AM systems and processes.

Several artefacts have been developed in the literature but the design methods used are as different as their design purposes [3]. Also, there are few papers providing all the necessary details for AM artefact design and none of them provides a complete and detailed design guideline starting from the design purpose to the final printed part.

There are recent works conducted by the ISO technical committee on AM and the ASTM for standardization issues in AM artefacts. However, there is currently no standard artefacts introduced by standards organizations. Morover, even in case a standard artefact would be introduced, due to a large variety of AM systems and processes and other factors like available measurement systems, it can be difficult for a single artefact to be suitable for all AM systems and processes. Consequently, there exists several other artefacts designed based on specific requirements or constraints. This can explain why authors like *Rupal et al* [4] are claiming that a standard artefact is not practically advisable and it is appropriate to consider a standard AM artefact design method.

The present work proposes a detailed design method focused on GD&T characteristics. The aim here is to introduce design guidelines that could help both for the design of customized AM artefacts and for the establishment of standards for AM artefacts.

Section 2 details the proposed AM artefact design method from the design requirements definition to the design guidelines description. Section 3 shows an implimentation of the design method through a case study.

2. Artefacts design method

2.1. Requirements definition

The analysis of the literature shows that there are two global approaches for artefacts design requirements definition. The first is the oldest and most used. It has been proposed by *Jacobs* and *Richter* and focuses directly on the features of the test parts and their shapes when defining design criteria. Many test parts have been developed based on this approach [3] [5]. It suggests some requirement solutions as design criteria and is therefore restricting the scope of solutions for the designer and does not always lead to an optimal solution. For example, *Jacobs* and *Richter*'s approach suggests that artefacts should include enough features for repeatability evaluation. However, as highlighted by *Moylan* [1], repeatability cannot be efficiently evaluated by repeating multiple identical features on the artefact because the system performances also depend on the location on the building surface. This can explain why most of the proposed artefacts based on *Jacobs* and *Richter*'s design criteria are further criticized and ameliorated [3]. The second approach proposed by *Moylan et al* [1] cope with this problem by defining new design requirements. However, the defined requirements need to be completed [3].

Thus, the first step of our design approach consists in a mapping of *Jacobs* and *Richter* design criteria into design requirements. The purpose is to be precise, concise and avoid to suggest solutions while defining design requirements. These design requirements are then completed by *Moylan* design criteria and lead to a set of 18 design requirements which are to be used as inputs by the designer in the design process.

2.2. Design guidelines

The design method is an iterative approach starting from the design requirements previously defined. These requirements are classified according to the design purposes and the performances to be evaluated. The main requirements are then highlighted and their corresponding elementary requirements are grouped into modules of dependent requirements. Solutions are then chosen for each module including features selection, their sizes and orientations. The next steps are guided by the chosen solutions in order to obtain a final artefact fulfilling all the design requirements. Features are arranged and the CAD model is designed. The part is finally built, measured and the system is characterized (see Figure 1). If a problem occurs during the building process, the designer will either re-build the part or go back to the previous steps and change the design solution.

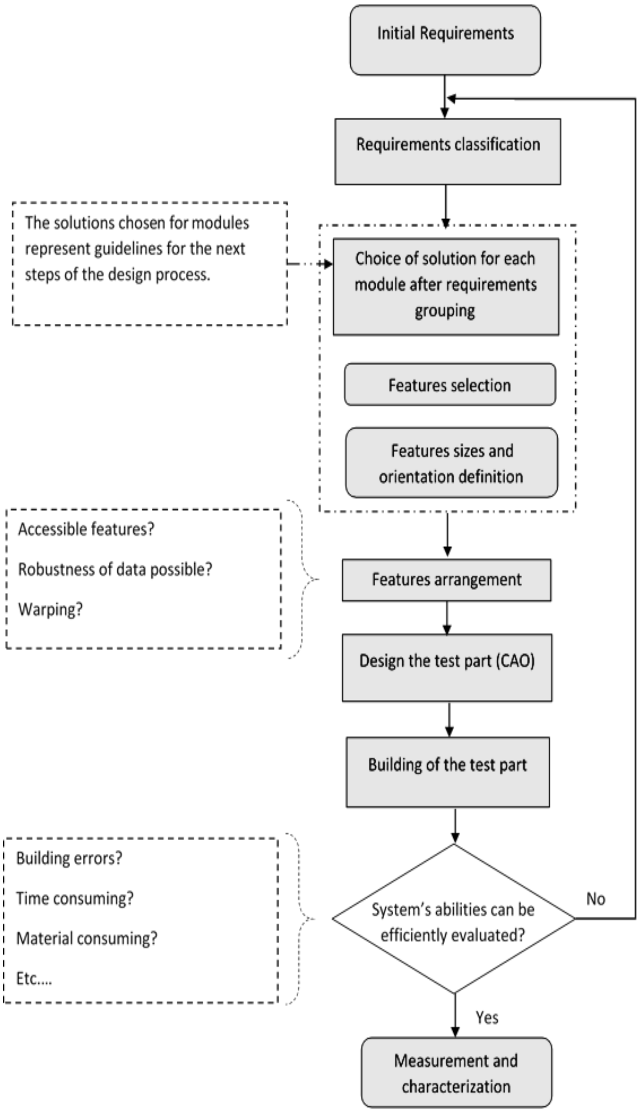

Figure 1. Design flowchart

In the requirement classification step, the designer first affects a flexibility level to each requirement to specify if the requirement is imperative or negotiable. This helps identifying requirements that are unnecessary to consider and thus avoiding them in the next steps. Requirements are then ranked by comparing them. This leads to a ranking and an identification of preponderant requirements. The result of this step depends on the design purpose, the system to be evaluated and the AM process.

In order to optimally choose solutions, requirements are grouped into modules based on the relationship between them. This leads to the definition of one solution for a set of requirements (e.g. a cube feature can help evaluate flatness, straightness, perpendicularity, surface texture and internal homogeneity of the built part). Grouping requirements into modules avoids unnecessary features and thus minimizes resources consumption (time and material). The choice of solutions includes features selection. Features sizes and orientation are then defined according to the design purpose and the measurement system constraints. This step depends on the available resources and the designer's experience and knowledge of the AM system and process to be evaluated.

For the arrangement of features, *Buyn* and *Lee* [6] proposed an approach to avoid redundancy while assuring system's performance evaluation along all the axis. Features arrangement must also consider features accessibility for measurements. Thus for an artefact designed for a specific use, measurement systems available need to be known. Their functioning and main characteristics (probe, the size of the measuring surface, etc.) also need to be considered. If the artefact is designed for a global use, features must be arranged to be as accessible as possible by any of the common measurement systems.

Once features are arranged, the CAD model of the artefact can be created. Before being transferred to the AM machine for the build, the CAD model needs to be converted into a specific file format (STL, AMF, etc.) and this step is thus subject to geometric and file conversion errors [7] [8]. It is highly recommended to check the converted file before sending it to the printing system to reduce geometric errors. The artefact can then be printed, measured and the system can be characterized.

3. Case study

The aim here is to evaluate the geometrical performance of an AM metal SLM (Selective Laser Melting) system. The study neither deals with fit for assembly considerations nor linking errors with their causes. In order to avoid measurement systems limitations, it is assumed that suitable measurement systems are available. However, the final artefact should deal with features accessibility optimization.

3.1. Artefact design

After classifying the input design requirements, some of them related to "fit for assembly consideration" and "linking errors with their causes", are not considered according to the initial assumptions of the problem.

Requirements are then ranked among each other. It comes that according to the initial design purpose, the preponderant requirements are related respectively to form, orientation and dimensional accuracy evaluation, measurement systems limitations and digital chain errors minimization.

Elementary requirements grouping leads to an optimal choice of solutions. For form, orientation and dimensional tolerance requirements, linear and planar features (flatness, straightness, linear/planar orientation and spatial repeatability, etc.) are grouped into different modules according to the machine's axis assessed. Also, for circularity, different modules are defined depending on the evaluated axis. Other modules are defined for coaxiality, for minimum feasible size and complex shape both extruded and holed. For each module one feature is chosen and repeated if necessary for spatial repeatability evaluation. Alternatively, features chosen as solution are used to assess other performances (related to location, dimensions, surface texture, internal structure of the material, etc.).

As shown in Figure 2, the test part consists in a set of features arranged on a base plate. A base plate is chosen for features arrangement to limit post-processing errors. The base plate facilitates handling and avoid features from warping during post-processes (extra-material removal, separation from the supports and building plate). Table 1 gives a brief description of the characteristics investigated by each feature of the proposed test artefact. Figure 3 provides an overview of the artefact's dimensions.

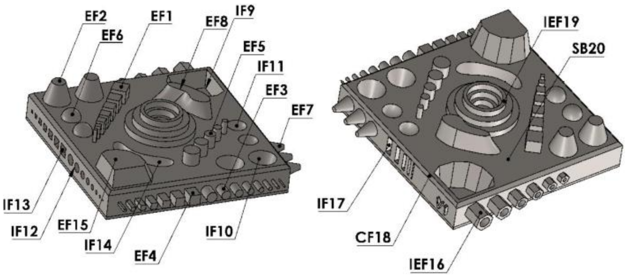

Figure 2. 3D model of the designed artefact

Table 1. The features description and characteristics evaluated

FEATURES	DESCRIPTION	PERFORMANCE EVALUATED
EF1	Set of 07 extruded cubes with decreasing sizes and same height oriented along Z-axis	Flatness, Location, Angularity, Straightness and Orientation at different scales, spatial repeatability of forms (cube)
EF2 & IF10	02 truncated extruded/holed cones aligned along X-axis	Circularity at different heights and scales, Flatness, taper, location, spatial repeatability of sizes and forms (cone)
EF3 & IF12	08 extruded cylinders with decreasing diameters and same height aligned along X-axis/Y-axis	Circularity, cylindricity, minimum feasible size (extruded/holed), location, spatial repeatability of forms (cylinder) along the X-axis/Y-axis
EF4 & IF13	Set of 07 extruded/holed cubes with decreasing sizes same height aligned along X-axis/Y-axis	Flatness, Location, Angularity, Straightness and Orientation at different scales and along the X-axis/Y-axis, spatial repeatability of forms (cube), minimum feasible size (extruded/holed)
EF5	05 extruded cylinders with decreasing diameters and same height oriented along Z-axis	Circularity, cylindricity, location, spatial repeatability of forms (cylinder)
EF6 & IF11	02 extruded/holed hemispheres	Sphericity , spatial repeatability of forms and dimensions (sphere)
EF7	03 truncated extruded cones aligned along Y-axis	Circularity at different heights and scales, Flatness, taper, location, spatial repeatability of sizes and forms (cone) along the Y-axis
EF8 & IF14	Complex feature extruded/holed from NURBS	Performance to build complex forms both extruded and holed
IF9 & EF15	Holed/extruded form made of oriented plans	Flatness, Angularity, Straightness both extruded and holed
IEF16	Set of 06 holed extruded hexagons aligned along X-axis	Flatness, Angularity, Straightness, minimum feasible size, coaxiality
IF17	Set of 05 slots with decreasing sizes	Minimum feasible size along the Y-axis
CF18	Chamfer	Flatness, angularity
IEF19	A set of 03 coaxial extruded holed cylinders	Coaxiality, Cylindricity, Flatness, location, perpendicularity
SB20	Base plate	Flatness, perpendicularity

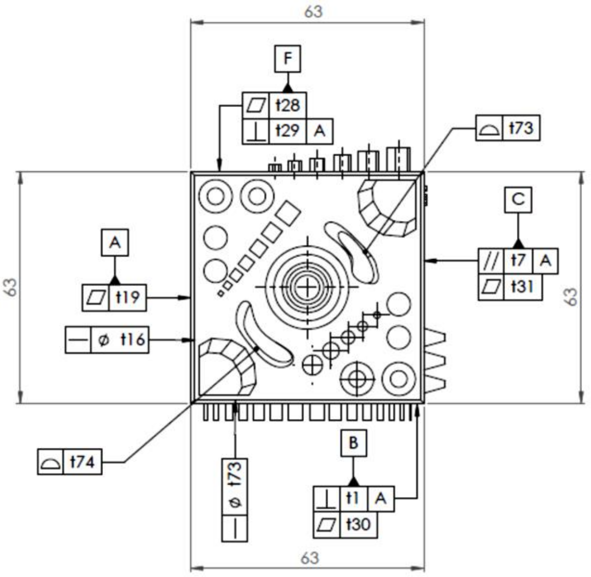

Figure 3. A partial engineering drawing of the proposed test artefact: overview of the dimensions (dimensions are in mm)

3.2. Building, measurement and qualification

The building strategy was a contouring coupled by a hatching to fill layers. The laser power was 190 W and 201W respectively for the contouring and the hatching. It is important to notice that the build plate was not preheated, this causes non-uniform heat distribution in the part during the building and thus increases defects on the test part. The temperature of the build chamber was set between 20 °C and 60 °C with a pressure between -10 mbar and 10 mbar. The material is NC718 (Inconel alloy 718), a Nickel alloy and the layer thickness was set to 40 µm. The building time was around height hours. Figure 4 shows the built artefact on the build plate.

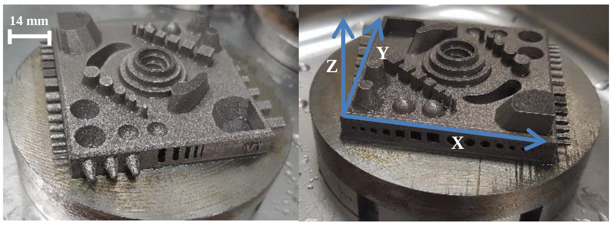

Figure 4. Built test artefact on the build plate; Z-axis is the build direction.

Measurements have been performed using a CMM with a Kreon laser-plan scanner. The collected data are cleaned to remove measurements noise and filtered to have a uniform density. Then a global inspection of the part is performed to match the measured part with its CAD model. Figure 5 shows that the average deviation from the CAD model is under 1.6 mm and that hollow features are less accurate than extruded features.

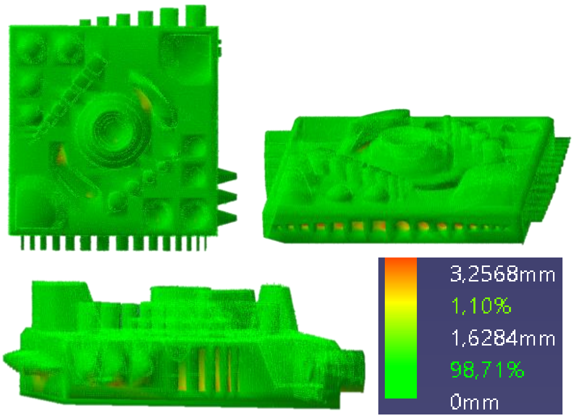

Figure 5. Global inspection of the measured test part

Global inspection reveals important defects on overhanging features due to the lack of support structures (Figure 5 and Figure 6). This can be caused by thermal deformation occurring during the building.

To compute form and orientation deviations, a CMM with a contact stylus have been used. Deviations were evaluated according to ISO GPS standards. Processing of measurement data shows achievable accuracy (e.g. flatness of 0.01 mm for vertical planes).

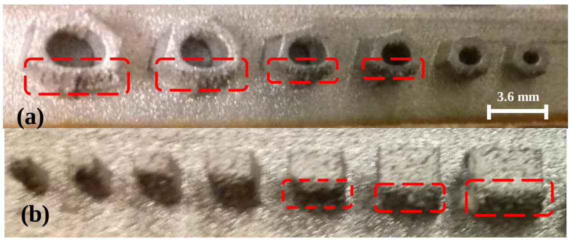

Figure 6. Building errors on hanging features : (a)= features IEF16, (b)= features EF4

4. Conclusion

Artefacts can be used to accurately evaluate AM systems and achievable tolerances to efficiently characterize and optimize them [6] [9] [10]. Several test parts have been developed in the literature. Among them, some test parts have been designed for standardization issues. However, few of them are provided with complete details on the design method.

In this paper, a detailed AM artefact design method has been presented starting from requirements definition to the final artefact. The design method uses tools from design theory and methodology such as module grouping to optimize the number of features and their orientation. Requirements classification is used to highlight the preponderant requirements on which the designer should focus on. *Buyn* and *Lee*'s [6] features arrangement methods have been used to optimally arrange features on the test part. A case study is developed with the aim to evaluate the overall geometric accuracy of a metal SLM system. A 73.8x68.85x16.65 mm artefact is designed and printed.

Further work should focus on enhancing the proposed design requirements and solutions, developing and assessing the method for specific performance evaluation for industrial cases. Concerning the case study, the proposed artefact should be built and measured several times to evaluate the system's repeatability and to validate the results. Another interesting issue is the integration of thermomechanical deformations of the part to verify some critical designed features.

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