Mereo-DfAM: a methodological proposal of mereotopological design for additive manufacturing

Robin Kromer*[1], Chloé Douin[2], Elise Gruhier[2]

[1] University of Bordeaux, CNRS, I2M Bordeaux, F-33400 Talence, France
[2] Arts et Metiers Institute of Technology, I2M Bordeaux, F-33400 Talence, France
robin.kromer@u-bordeaux.fr

Abstract.
Opportunities are offered by multiple Additive Manufacturing (AM) processes nowadays. Design rules are evolving to lead to lighter and stiffer parts with really more complex shapes than those obtained by conventional processes. Worldwide, new methodologies/tools of assistance for the design are developed such as Design for Additive Manufacturing (DfAM). Additive manufacturing can allow the development of new metamaterials and health-matter evaluation based on energy flow evaluation. In this paper, the objective is to generate a new methodology with DfAM based on mesoscale knowledge. It is generated with open lab bench and simple object characterization. A methodology is presented to formalize and quantify information at multilayer dimension. A database is also generated following Design of Experiments (DoE) to obtain metamodels. They are developed for specific features representative of AM geometric class such as overhanging, holes or walls for instance. Mereotopological primitives with their AM definitions are used to define features in term of space and time variables. This theory enables the formalization of knowledge at the mesoscopic scale taken into consideration layer by layer build-up. It is then possible to use it to integrate data and information to the different feature juxtapositions using recognition algorithm. Information for each feature can then be included and explicitly used to help the designer during detailed design phase. A global 4-steps DfAM methodology maximizing the potential of AM is presented and validated through a part from the space industry use case. It includes the definition of skeleton/skin entities, pattern decomposition, information associated based on material evaluation and decision for AM part.

Keywords: Additive Manufacturing, DfAM, Mereotopology, Database

1 Introduction

The emergence of Additive Manufacturing (AM) processes is part of the primary key tools of the Industry 4.0. The recent product development employing these innovative tools has turned our knowledge upside down in terms of manufacturing but above all in terms of design. Design phase needs to consider the constraints imposed by manufacturing, and making sure to meet the requirements of the specifications using the manufacturing means (material, machine, process). Several Design for Additive Manufacturing (DfAM) methodologies are developed to take into consideration the possibilities and define some rules at macroscopic scales [1]. At the same time, data can be monitored and analyzed in the process or experiments with material characterization are developed in AM area with a large research field development [2]. The purpose of the project is to improve the design-manufacturing integration process as mentioned above as early as possible taken into consideration the AM information available.

"Skin / skeleton" entity are two geometric elements making possible to represent the elementary components of a product [3]. The entity "skin" is used to describe functional surfaces. There are two types: the "use skin" which groups together the surfaces on which the "energy flows" circulating through the connections of a product are applied, and the "professional skin" which brings together the manufactured surfaces of the product. All "skin" entities can be associated with type information: geometric, dimensioning or tolerancing. As for the "skeleton" entity, it represents the fiber neutral locating the material through which the "energy flows" will be conveyed. This is an important concept, necessary to be able to implement new development. To aid with this, various manufacturability analysis is available based on in-situ monitoring or 3D characterization that can be used to generate metamodel (use of neural network, fuzzy logic, agent-based systems, rule-based systems for instance) [4]. However, hardly any attempt has been made to automate the generation of a database analysis system for DfAM. A novel feature-based method for manufacturability analysis in AM is proposed by using mereotopology to generate feature and identify information in the database. It is then possible to integrate it into design features at mesoscale. The objective is to propose mereotopology description into DfAM methodology at the specific step. The idea is to pass law/data/experience on geometric features. This is the key step to create a realistic digital model of the part by specific AM technology. As the design progresses, these constraints will be associated based on skins and skeleton of the part. It could be used at different steps of the design phase. The product-process-material relationship is complex in AM but in-situ process information is available to help designer.

A literature review is presented to clarify the MereoDfAM position. It will present DfAM and mereotopology developments. Process discretization and design rules will be presented as a key step for the methodology. It will then be presented and discussed on a case study.

2 Literature review

2.1 Design for Additive Manufacturing

The benefits and drawbacks of AM are different from traditional processes. Technologies production in layers opens up possibilities of producing very different shapes from those designed and produced by traditional manufacturing processes (such as machining, forging or still casting). However, this apparent freedom of design is subject to new manufacturing constraints such as those imposed by processing and post-processing. Several attempts at classifying research in the area of DfAM exist: system design, part design and process design [5]. Designers must consider these elements and adopt methods adapted to the exact process used. The notion of DfX refers to the fact of orienting the design of a product according to a constraint or a stage of the product life cycle [6]. It is important to state that even if the design for a specific process is the last step. Design categories also involve process-specific details. Process aspects should be included in the design process. This classification has a direct connection to the DfAM. Design activities are connected (standardization necessary).

Several generic design methods for AM:

(1) Hällgren et al. [7] discuss experience and design rules associated topological optimization (TO). Ponche et al. [8] define three-step methodology and identify a build orientation and use an optimization tool with manufacturing settings. Salonitis and Zarban [9] propose five-step methodology which covers steps with a multi-criteria decision-making process with objectives.

(2) Vayre et al. [10] use a step of design optimization based on a parametric CAD model after creating an initial design. Orquéra et al. [11] mentioned opportunities and constraints of AM, and Designing for manufacturing (DfM).

(3) Boyard and Rivette [12] offer another twist where DfM is combined with Design for Assembly (DfA) to better use AM's possibility. Within the DfM part, database is used with design rules and manufacturing constraints that is automatically evaluated.

From this literature review, the methodologies still have one drawback. They fail to consider the mechanical properties and geometric dimensions and tolerancing deviation considered database from previous experiments. For instance, Laser Powder Bed Fusion (LPBF) of Ti-6Al-4V enables the manufacturing of complex parts for lightweight applications. The emerging microstructure in the LPBF process and thus the mechanical properties are defined by the thermal cycles, which are locally variable for complex geometries. Predictions of local mechanical properties by simulation or with data-base could improve new part development [13] Knowledge based development to optimize manufacturing orientation is developed to increase manufacturability and part geometric specifications [14]. The dimensional or geometric deviations that have occurred in the parts manufactured by AM was also been addressed in the methodologies [15] and defects/microstructure monitoring is still in progress [16]. They have a macroscopic or microscopic point of view. Neither the sources of these deviations have been identified in terms of mesoscopic scale and pattern assembly. As AM is a layer by layer manufacturing, few method or study were developed to optimize manufacturability in the design phase [17]. Recognizing a shape for more than what it represents, embedding the manufacturing knowledge as well as processing techniques, will leverage shape recognition in industrial setup and would generate a real cost saving tool for industries [4]. The idea is to anticipate imbedding the shape with its meaning, being its: design parameters, manufacturing know-how and techniques, testing and quality, end of cycle treatment amongst others. The resulting methodology looks at the typical mechanical feature identification research and attempts to profit from recent progress in mechanical research fields.

2.2 Mereotopology

AM consists in a progressive addition of material over time, and is therefore suitable for spatial, temporal and spatiotemporal (ST) descriptions, which can be formulated by using mereotopology. This type of description is particularly relevant at the mesoscale, which implies transformations between successive layers, and thus a spatial evolution over time. Mereology refers to the study of parthood relations between parts and wholes [18], and topology to the connectedness relations between entities in space [19]. The theories linking these two notions are called mereotopology. In other words, mereotopology is the study of contact and connectedness relations between parts, wholes and boundaries. In the context of design, the following study is based on Smith's axiomatic mereotopology. This type of approach allows the description of relations between geometric entities, restricted only to areas of interest through the use of ontological laws [20].

The entities between which interactions take place are called *regions*. The relations between them can be described using *primitives* whose nature can be spatial, temporal or spatio-temporal. A set of spatial primitives that is commonly used in literature is the one formulated by Smith [20]. These primitives describe the interactions between two spatial regions, namely x and y. For instance, x**D**y means that x is discrete from y and thus don't have any contact with this region. Regarding spatial interactions, Allen's primitives [21] are often used. In this case, x and y are time regions (TR), which means that they can be assimilated to a time interval or a precise moment in time. For example, the primitive “x finishes y”, written “x**f**y”, means that y starts before x but that they both finish simultaneously. Mereotopology can be applied to a wide range of fields, from geography to artificial intelligence [22]. In the context of design, the JANUS theory [23] enables the description of an assembly by decomposing the evolution of its parts from a spatial, temporal, and ST perspective.

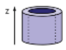
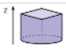
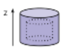
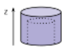
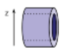
A set of ST primitives is developed in order to define the changes taking place during an assembly, such as the "addition" or "deletion" of a part. Regarding AM, a similar mereotopological approach could be an efficient means to formalize data by discretizing the manufacturing process in time, space and space-time.

3 Process discretization and design rules

3.1 Mereotopological discretization of the process

A spatial and temporal discretization of the AM process can be performed using Smith’s and Allen’s primitives. Objects observed at the macro scale can be divided into a group of simple geometrical elements, enabling mesoscale study. These elements can be of three different natures: they are either made of material intended to be kept on the object (matter), of material intended to be removed (support), or of void. By isolating a printing layer, we observe that the sections of these elements can be arranged in different ways, which can be described by Smith's primitives. Furthermore, considering the printing of a single layer isolated from an object as a temporal unit, called Temporal Region (TR), we can determine temporal intervals corresponding to the printing of each of the geometric elements. The relations of simultaneity or non-simultaneity of these temporal regions can be described using Allen's primitives. A third dimension can then be considered. To characterize the evolution of spatial interactions over time, spatiotemporal primitives have been formulated [24]. This type of primitives enables the description of spatial regions in two dimensions, on an isolated layer. However, geometric features must be defined in order to describe interactions between spatial regions over several layers. A set of features has been developed (table 1), based on benchmark artifact developed by Vorkapic et al. [25] to test parameters and printing quality of a machine, and using the spatiotemporal primitives described above. Complex models can thus be split into a static assembly of features. Each of them is composed of a series of printing layers, corresponding to a spatial region, and is associated with a time region which is the layer interval for its manufacture.

Table 1. Set of geometric features.

Scheme	Name	Complement	Scheme	Name	Complement
	Extrusion	Orthogonal		Vertical hole	
(cont.)	(cont.)	Swept	(cont.)	(cont.)	
	Variable section volume			Overhang surface	With support
	Hollow volume	With support	(cont.)	(cont.)	Without support
(cont.)	(cont.)	Without support		Bridge	With support
	Shell	Right side up	(cont.)	(cont.)	Without support
(cont.)	(cont.)	Upside down		Rib	
	Horizontal hole	With support		Slot	
(cont.)	(cont.)	Without support			

3.2 Rules based on a mereotopological description

Spatial, temporal and spatiotemporal patterns are correlated with manufacturing defects based on printed models by following the protocol developed by [24]. A set of rules is created by associating a configuration with a defect, as shown in fig. 1. The column “Feature” provides the name of the relevant elements, their corresponding features among the set developed on table 1, and their type, which can be “M”, “S” or “Ø”. The next three columns describe the condition for the rule, i.e. the combination of spatiotemporal, spatial and temporal primitives involved. The “consequence” part of the table describes the effects that the condition may imply. The last two columns are using the defect classification developed by Malekipour et al. [26] in order to organize the rules by type of outcome.

Condition						Consequence			
Feature			Mereotopological primitives			Possible consequences	Possible defects	Category	Type
			ST	Spatial	Temporal				
x y	Extrusion swept Variable section volume	M M	xMey		xoy	Unsupported surfaces	Surface collapsing	Surface quality	Surface roughness/morphology
x y1 y2	Extrusion orthogonal Extrusion orthogonal Extrusion orthogonal	M M M	y1Sey2	xTy1	xsy1 xmy2	Sudden area variation	Offset layer	Microstructure	Porosity

Fig. 1. Example of rules formulated with a mereotopological description

The configuration for the first rule enunciated on fig. 1 is the presence of two spatial regions x and y, respectively a swept extrusion and variable section volume, of type “matter”. If x and y merge together over an interval of layers (x**Me**y), and the manufacture of x overlaps y’s, meaning that the interval of layers corresponding to the fabrication of x starts before the beginning of y’s building and ends during it (x**o**y), then the condition for the first rule is fulfilled. The consequence of this configuration can be that the surface y is not supported. This could lead to a collapse or even a non-printing of the surface. The second rule implies the presence of three extrusions of type “matter” that are printed orthogonally to the printing plate. The condition of application of this rule is that y1 separates from y2 (y1**Se**y2), that x is tangent to y1 over a given time interval (x**T**y), that the construction of both x and y1 start simultaneously, but that x finishes printing before y1 (x**s**y1), and that the manufacture of y1 starts when x’s finishes (x**m**y2). In other words, the end of x's printing interval coincides with the separation of y1 into two parts, y1 and y2. The simultaneity of these two events causes a sudden area variation: x is no longer there and y is now formed of two smaller sections. A possible consequence would be that the layer corresponding to this event is slightly offset, leading to more porosity or a microstructure disturbance.

4 MereoDfAM

4.1 General overview

The new design potentials as well as the limitations in relation to the product development process need to be considered and DfAM can answer [27]. Additionally, Tang and Zhao [28] provide a general guidance (necessary for non-experts of AM). They define an opportunistic DfAM methods and tools aim at a systematically exploitation of the new freedom in design. They also explain a restrictive DfAM that supports design rules and ensures manufacturability. In any case, design phase starts with design requirements. Manufacturer also defines a set of manufacturing constraints based on the characteristics of usable AM process and system and its currently known limitations. Similarly, the metrologist defines a set of measurement constraints based on the considered instrument characteristics and limitations. Design requirements, taken with manufacturing and measurement constraints are the inputs. Actors are defined: a designer (need), a manufacturer (skills) and a metrologist (knowledge). For instance, a requirement is a part surface roughness specification with is link to different overhang. It is possible to evaluate with several planes with different slope angles. Manufacturer’s suitability for overhanging feature knowledge is known and is considered based on topology. Additionally, the feature slope angle impacts the measurement procedure as well as the measurement time, due for example to the increased focus range needed when measuring tilted features. References zone is required for tolerancing evaluation. Otherwise, stitching procedure should be added with stitching uncertainties and processing time. Quantified information is hence required from manufacturing and metrology. Our approach builds upon the work of both Kumke et al. [29] and Laverne et al. [27] (Fig. 2) consisting of four main phases: requirements; conceptual design; embodiment design; and detail design, along with feedback of material and AM process information. These stages are consistent with several generic design process models and need to consider manufacturing and measurement knowledge. Pradel et al. [30] presented a mapping DfAM and seek to collate/organize this knowledge using a single and coherent conceptual framework. In this paper, data from manufacturing and metrology will be used to obtain values for the designer.

Features (observed in benchmark parts) can be considered as a characterization ambiguity, mixing up design and usage aspects. As previously explained, manufacturers designed generic artefacts and they obtain process capabilities for specific features. They first choose the geometrical definition and tolerancing parameters and secondly pick up the required typical feature. However, Rupal et al. [31] suggest that such method is not advisable. It provides an overview. Indeed, benchmark artefacts should be specifically designed according to geometrical requirements with other feature associations. Authors conduct an opposite approach. First think about features size, position with others and orientation. Quantification can then be obtained with based on Design of Experiment development. Then, geometric definition and tolerancing analysis is conducted based on pattern recognition. Indeed, accuracy of printed features are deeply linked to the thermo-physical mechanism, to the process and to the toolpath generation of the specific studied AM machine.

The authors propose hence an addon on previous DfAM method to conduct design and characterization of AM processes and machines. The method may use several artefact designs. AM processes on a knowledge base stemming from experiments. This step aims at finding optimized parameters (such as orientation, layer thickness...), link to geometrical parameters which influence geometrical quality and which allow tolerance data to be understood. Secondly, shape descriptor is performed with 3D object analysis based on deep learning algorithms with an identification as a member of some feature category. A data-based approach, by taking tolerance, geometric and material specifications, assembly constraints or process applications, can then be attributed to features. This method is therefore independent of the process used, and leads to a robust feature-based characterization of an AM process and machine. Douin et al [25] development is used to generate rules and data based associated to original DOE (Sobol definition).

The proposition allows providing the proposed methodology which relies on several models: FBS model, Usage model, Manufacturing model, and Interface Processing Engine. In this methodology, material data sheets and different types of AM technologies as AM database are important information. In-situ monitoring and material characterization are necessary in AM processes for industrialization. The authors proposed to generate geometric and its analysis to obtain a data based. Design of

Experiments (DoE) and machine learning algorithm are used to investigate the different patterns and their evolution. An integration in the design phase is proposed below. Meta-model based on in-situ monitoring and analysis associated to metrology data must be considered in all steps of this approach. It is suggested to work in Conceptual using FBS model. It is achieved by analysis of the product specifications which are predefined due to the customer requirements. It helps to provide an initial model by analysis of the product function, behavior, and its structure. Therefore, it helps to recognize the usage model. Usage and manufacturing models are identified simultaneously which consists of skin and skeleton. The usage model demonstrates the product features which is created through an optimized model due to mass and structure optimization regarding product function. It helps to identify features by classification algorithm. In parallel, the manufacturing model determines the process parameters and rules based on AM database. Therefore, this usage and manufacturing models help to determine usage and manufacturing attributes and criteria which are needed in providing an interface processing engine. An interface processing engine is proposed which plays an important role in completing and defining the product model by considering design and manufacturing attributes, criteria, and constraints concurrently. The main difference that distinguishes from other researches is the interface and loop processing. This engine used layer-by-layer description for features as an interface between design and manufacturing. This interface processing engine should be a decision-making tool for the user that help to find the best manufacturable design regarding the manufacturing and metrology criteria.

Then, in Embodiment design, a development with a multi-objective optimization problem based on parameters to suggest orientation and material at the first step based on skin and skeleton [32].

Once the best orientation and material are defined, the algorithm can be applied throughout the embodiment design. In detailed design, it is proposed to developed a specific benchmark part that contains features necessary to propose AM limitation and define AM rules is the material and processes are not known. DOE can be used in this case to generate metamodels. Statistic defects and geometric deviation are quantified based on in-situ monitoring and metrology. The mereotopology with classification development is used to discretize the object (10 to 100 zones with build-up orientation) and line up information/quantification criteria can be addressed. Defects are not eliminating but quantified valuers for a specific feature, material, process (fixed strategy and parameters). It possible to give such information to the designer as soon as possible to avoid pattern incompatibilities. They are already translated in AM rules with fillet of homogeneous volume build-up. It contributes to improve and formalize new AM rules based on processing experiments. Scale-invariant heat-kernel signature for pattern classification is used. Data can then be associated with tags. A case study is used to illustrate this method.

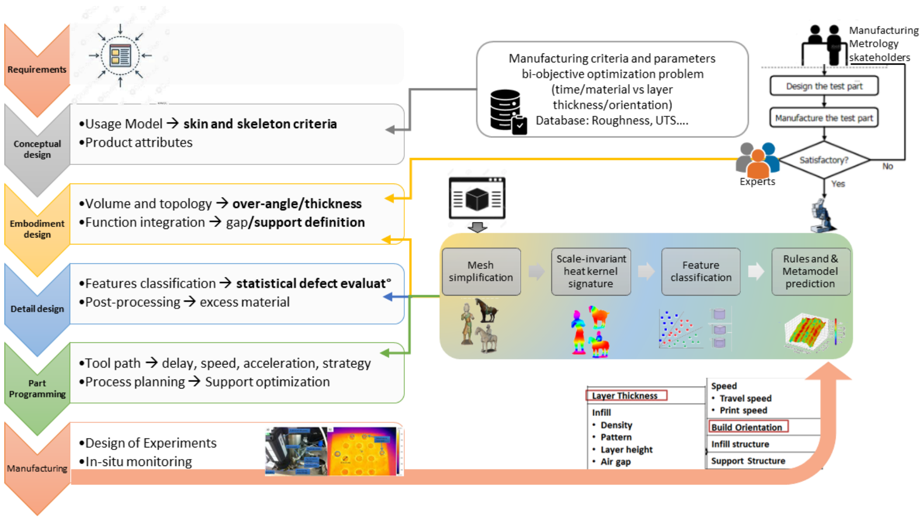


Fig. 2. MereoDfAM - Use of multi-objective algorithm, features recognition and metamodel based on data from in-situ monitoring and metrology for quantify criteria.

5 Case study

5.1 Mereotopological description

The studied part is a support component used in the aerospace field. It has three bases, connected to a hoop inclined at 35° to the reference surface of the bases, by six branches. This tripod must therefore respect planarity constraints for the surfaces under the bases and on the outer surface of the hoop, in order to enable its installation on the other parts of the assembly. This part should also be as light as possible due to its affiliation to an aerospace system, hence its configuration with thin and rectilinear branches. This tripod is studied according to the direction defined by the system of axis on fig. 3, to confirm the relevance of the rules formulated previously. Orientation was computed considering Grandvallet et al. [1] work. It is first divided into geometric features, and manufactured using Fused Deposition Modeling (FDM) with the same orientation as the mereotopological study. The Z axis represents the printing direction, the circular part is lying flat on the printing table, and the three bases are the last elements to be printed.

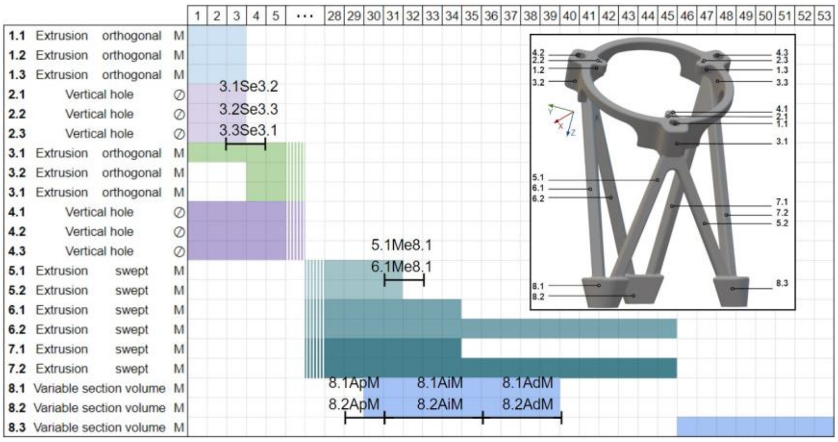


Fig. 3. Spatiotemporal discretization of the tripod

The model can be discretized into several features identified by two numbers. Features with similar behavior are assigned the same first number, and are then listed following the trigonometric order around the Z axis. Starting from the first layer, the 3 small extrusions inside the hoop (3) correspond to number 1 and are perforated by three vertical holes (2). The hoop separates itself into three parts each perforated by another vertical hole (4). Two branches (5.1 and 5.2) are extruded from the feature 3.1, two from the feature 3.2 (6.1 and 6.2) and two from the feature 3.3 (7.1 and 7.2). Finally, the three bases (8) are printed on top of the branches. The behavior of these features in time, space and space-time is studied by applying the mereotopological analysis protocol proposed by Douin et al. [25]. An extract from the spatiotemporal table is presented fig. 3, showing the primitives relevant for this study. The model is divided into 53 layers, each represented by a column in the table fig. 3, and the time needed to print one of these layers is used as time unit. For example, the interval labelled "3.1**Se**3.2", "3.2**Se**3.3", "3.3**Se**3.1" represents the separation of the hoop into three parts during the interval going from the third to the fourth layer.

5.2 Rules application

The printed part presents two defects that can be linked to the rules developed in section 3.2. The first defect is shown on fig. 4 a. The printing of 1.1, 1.2, 1.3, 3.1, 3.2 and 3.3 start at the same time, but the features 1 finish first. At the same time, 3.1 separates into three parts, meaning the apparition of 3.2 and 3.3, and the features 1 are spatially tangent to feature 3.1. From a temporal point of view, the intervals corresponding to 1.1, 1.2 and 1.3, and the intervals corresponding to 3.2 and 3.3 are thus linked by the primitive "meets". The coincidence of the end of the extrusion with the separation of the loop causes an abrupt variation of surface and is the condition of the first rule. The consequence of this rule is the appearance of an offset layer, which corresponds to the defect present on the tripod.

a.  b. 

Fig. 4. Defects on the manufactured tripod

The second defect is presented on fig. 4 b. This defect is located within the area from column 29 to 33 of the table fig. 3. The spatiotemporal interactions of base 8.1 are its merging with branches 5.1 and 6.1 (5.1**Me**8.1 and 6.1**Me**8.1). However, fig. 3 shows that the appearance of 8.1 occurs before the merging with the branches. The intervals of 5.1 and 6.1 temporally "overlap" the interval of 8.1. This corresponds to the condition for the second rule, and illustrate the collapsing of a surface in this configuration. Indeed, if the base is printed before merging with the branches, its first few layers are not relying on any surface, and cannot be well printed. Metamodels based on temperature measurements can show that a temperature gap is observed due to the condition of deposition in the air. DoE were developed considering different geometric variables and defect analysis gives a statistic error criterion in those kinds of area. This topic will be presented later.

6 Conclusion

This paper presents a new approach based on DfAM applied at the mesoscopic scale through the use of mereotopology. A literature review on DfAM highlights the lack of research conducted on structural and geometric deviations at the mesoscopic scale. The study of mereotopology puts forward spatial and temporal primitives that allow the definition and description of geometrical features as well as a way to formalize knowledge at the mesoscopic scale. It is then possible to integrate knowledge such as defect formation. The proposed method is based on the work conducted on feature discretization and the formalization of design rules. Its purpose is to transmit information on the geometrical characteristics of the model as the design evolves, according to the skins and skeletons of the part. It would apply to the conceptual, embodiment and detailed design phases, allowing the user to adapt his design while taking into account how it would impact the manufactured part. Lastly, the application on an industrial case study illustrates the method by providing a concrete example of application of the work carried out.

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