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Geometrical variations management for additive manufactured product

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ABSTRACT

Additive manufacturing (AM) became an advanced research topic due to its ability to manufacture complex shapes. But the ability to achieve predictable and repeatable shapes is critical. Therefore, to optimize the design of an additive manufactured product, tolerancing is a key issue. This paper focuses on geometrical quality assessment of an AM product. It includes a process oriented geometrical model to predict the surface roughness and dimensional deviations, and a geometrical simulation tool to assess the impacts of these deviations on the geometrical behaviour of the joint. An application of the approach is illustrated through a case study.

1. Introduction

The development of new advanced additive manufacturing techniques has progressed greatly in the recent years. These new additive manufacturing (AM) techniques affect the manufacturing strategy of new products. They accelerate innovation, reduce the cost of supply chains, and reduce the waste [1].

To improve these new AM techniques and to increase the scope of their applications, research activities require to overcome some key technical challenges, mainly the following regards as critical: to achieve predictable and repeatable shapes. Process variability must be reduced, as must the sensitivity to process variations (the impact of these variations on the assembly behaviour).

To investigate the dimensional and geometrical accuracy (process variability) for new AM techniques, various designs of test artefact have been developed [2]. Standard test artefacts incorporate multiple features. The combination of these features provides a global assessment of the Geometrical Dimensioning and Tolerancing (GD&T) characteristics: "*a cube is used for perpendicularity, parallelism, linear accuracy and surface finish evaluation and a cylindrical hole is used to evaluate the roundness, cylindricity, radius accuracy and positioning accuracy. Some test artefacts incorporate some specific AM features: overhanging features, freeform geometries, features for part warpage and stairs*" [2]. Most test artefact applications are based on traditional GD&T characteristics, and they provide a global assessment proposed in the International Tolerance Grade of the AM techniques defined in ISO 286 [2]. In fact, the aim of these applications is the identification of influential process factors on the geometrical accuracy of additive manufactured parts; usually, this identification is based on Design of Experiments [3].

To investigate the dimensional and geometrical accuracy, another approach is the identification of predictive model of the additive manufactured parts geometrical defects [4].

As mentioned in the second paragraph, there exist two solutions to improve the geometrical quality of an additive manufactured product: the mitigation of the process variability and the mitigation of the sensitivity of the process variations. This paper focuses on the second solution and its tolerancing. To mitigate these variabilities, it is firstly required to model them and to identify what are the process and product design drivers involved. Being able to model them can help designers to assess, before the manufacturing of the part and/or product, what will probably be final shapes of the manufactured product to verify if functional surfaces remain in an acceptable range.

This paper is divided into two main sections: Section 1 presents the skin model representations of AM part, the mathematical models for the geometrical behaviour prediction of an AM assembly and an approach for AM tolerance analysis are illustrated in Section 2.

2. Surface roughness and dimensional deviations prediction of AM part

Tolerance analysis aims to simulate the "real-product" with the minimum uncertainty. This uncertainty is partly due to the geometrical deviation representations. A significant amount of research efforts has been carried out in the last decade to explore the mathematical models for geometric deviation representation: variational geometry approach, skin model shape, modal representation, etc.

The variational geometry approaches [5] are based on the parameterization of deviations from theoretic geometry. The real geometry of parts is considered by a variation of nominal dimension or it is apprehended by a variation (position and

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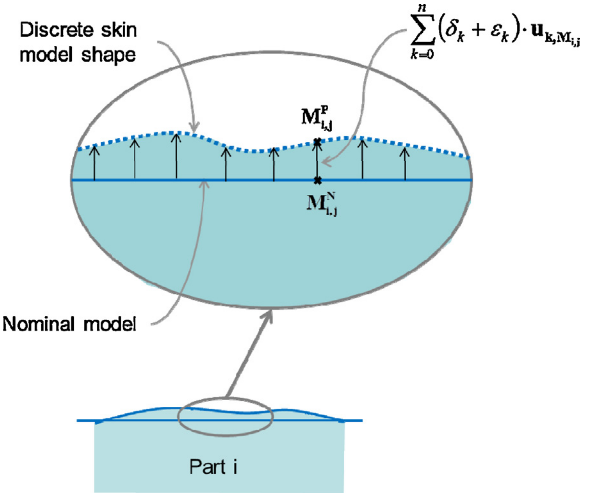

Fig. 1. Discrete skin model shape illustration and description.

orientation) of the nominal geometry. In this approach, the form defects are neglected. The representation of the skin model has been investigated only recently. Anwer et al. [6] proposed a comprehensive framework for skin model simulation. This representation includes position, orientation and form defects. The modal representation method of geometrical deviation decomposition has extensively been studied. Huang et al. [7] proposed discrete-cosine-transformation (DCT) based on decomposition method for form defects modelling. Samper et al. [8] developed the Discrete Modal Decomposition (DMD) considering modal shapes of a discretized feature. Usually, the technical interpretation of these modal representations is not easily achieved.

Based on these concepts, a skin model representation is proposed to predict the geometrical quality of additive manufactured parts. This representation is simplified to obtain a finite description like a discrete shape. To define the discrete shape model, the nominal shape is sampled into a set of points, and the discrete skin model shape is apprehended by the displacement of each point, leading to a large number of parameters (Fig. 1). To reduce the number of parameters, a geometrical deviation decomposition based on the definition of process oriented geometrical defect modes is proposed:

$$\begin{aligned}&\textit{Substitute surface}\ \text{model} = \textit{No minal surface}\ \text{model}\\&\quad+\textit{Position defect}\ \text{mode}+\textit{Orientation defect}\ \text{mode}\\&\quad+\textit{Form defect}\ \text{mode}\ \textit{due to the mesh}\\&\quad+\textit{Form defect}\ \text{mode}\ \textit{due to layers strategy}\\&\quad+\textit{Form defect}\ \text{mode}\ \textit{due to the geometrical defects}\\&\quad\textit{of the machine}\\&\quad+\ldots\end{aligned}\tag{1}$$

The amplitude of each deviation includes a systematic component δ_k and an aleatory component ε_k. Therefore, the skin model representation (Fig. 1) of each surface in the local coordinate system is given by:

$$\mathbf{O_iM^P_{i,j}} = \mathbf{O_iM^N_{i,j}} + \sum_{k=0}^{n}(\delta_k+\epsilon_k)\cdot\mathbf{u}_{\mathbf{k},\mathbf{M}_{\mathbf{i},\mathbf{j}}}\tag{2}$$

with $\mathbf{Q_i}$: datum of the feature i, $\mathbf{O_iM^P_{i,j}}$: coordinates of the predicted point j of the feature i, $\mathbf{O_iM^N_{i,j}}$: coordinates of the nominal point j of the feature i, $\mathbf{u}_{\mathbf{k},\mathbf{M}_{\mathbf{i},\mathbf{j}}}$: kth modal deviation expressed at the point $\mathrm{M}_{\mathrm{i,j}}$, δ_k: systematic component of the amplitude of the kth mode, ϵ_k: aleatory component of the amplitude of the kth mode.

Based on the additive manufacturing processes knowledge, this modal representation is established. The amplitude assessment is the result of a set of experiments and fitting operations between the measured points and the modal representation. The built defect modes can be thus predicted for an AM geometrical feature with satisfactory accuracy.

To better illustrate the developed model, a simplified test artefact is proposed as a case study and Fused Deposition Modeling (FDM) is studied. This test artefact incorporates three cylinders with radiuses from 10 mm, 20 mm, to 30 mm respectively in order to identify the relationship between defect mode caused deviations and the part design parameters. All test artefacts were printed on the Replicator 2× FDM printer using 1.75 mm diameter PLA filament and they were measured using an coordinate measuring machine (CMM) with an accuracy of less than 4 µm (around 5000 measured points for each cylinder).

Geometrical defect modes (Fig. 2) for AM manufactured cylinders are modelled and generated by considering additive manufacturing process characteristics. When transform the CAD model to STL file, the mesh generation operation would turn the section of cylinder into polygon which is defined as the Mesh Mode in this study. While manufacturing parts, FDM extrudes heated material deposited on a substrate though a movable nozzle and cooled down until it solidifies before new layer is deposited. The "Layer upon layer" method as well as the deposited material shape would cause the Layer Mode. The shrinkage after cooling down would result in the Radius Mode, etc. Machine movement control defect would form the Ellipse Mode and Rounded Rectangle Mode. Geometrical deviation of the machine is also considered in this study, defect mode caused by the gap in the machine moving axis is defined as the Gap Mode. This modal representation could include others technical modes.

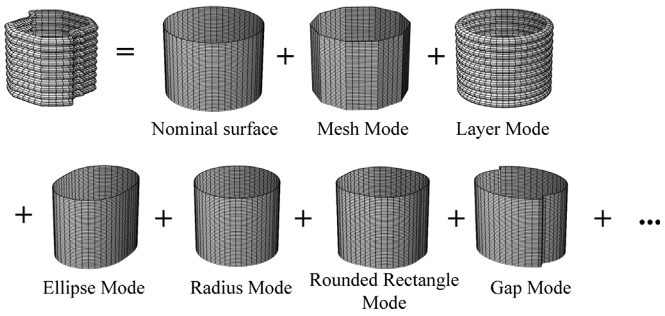

Fig. 2. Cylindrical prediction surface generation with process oriented geometrical defect modes.

The final cylindrical prediction surface shape is resulted by the combination of the defect modes added onto the nominal surface as Fig. 2 shows.

The identification of the systematic and aleatory components of the modal representation is performed on the measured points of test parts by the iterative least square method. To highlight the impact of the AM form defects, Table 1 contains a comparison between the results of a fitting operation of cylinders (without form defect modelling) and the results of the identification of the

Table 1
Prediction result and defect modes caused deviations (mm).

	Radius 10	Radius 20	Radius 30
Measurement accuracy	0.004		
Distance between measured points and cylinders			
Max distance	0.183	0.244	0.306
Average distance	0.107	0.156	0.232
Standard deviation	0.053	0.042	0.049
Distance between measured points and prediction points after applying the geometrical defect modes			
Max distance	0.072	0.088	0.075
Average distance	0.018	0.015	0.019
Standard deviation	0.013	0.011	0.014
Deviation caused by each geometrical defect mode			
Mesh Mode	0.007	0.013	0.003
Layer Mode	0.019	0.006	0.005
Radius Mode	0.208	0.273	0.358
Ellipse Mode	0.116	0.081	0.073
Rounded Rectangle Mode	0.025	0.035	0.044
Gap Mode	0.051	0.049	0.042

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