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Ikram KABBOURI[1*], Anass EL-QEMARY[1],
Mouhssine CHAHBOUNI[1], Said BOUTAHARI[1]

MODELLING GEOMETRIC DEVIATIONS IN ADDITIVE MANUFACTURING OF A CYLINDRICAL SURFACE

This work presents in a first part a state of the art on geometric deviation modelling in additive manufacturing. It then proposes a modelling geometric deviation methodology based on part discretisation, considering the systematic and random deviations. Systematic deviations are represented by three defect modes: meshing mode, radius change mode, and elliptical mode, while random deviations are generated automatically according to a normal distribution. A mathematical model is established to express geometric deviations at each point of the discretised surface. It is based on the nominal surface, with calculated deviations added. The goal of this model is to obtain the skin model surface, which represents the real surface. The methodology begins with the discretisation of the nominal surface, followed by the generation of systematic and random geometric deviations at each point of the nominal surface. After that, the skin model surface is calculated. An algorithm is developed to facilitate the calculation and tracing of the part's profile with defects. In the second part, a numerical study is carried out on a cylindrical part manufactured by the FDM process (fused deposition modelling) to validate certain assumptions related to this process. Finally, to consider an application in mass production, a simulation of geometric deviations for 100 parts was carried out, and their profiles were traced to facilitate the analysis of results.

1. INTRODUCTION

Additive manufacturing, also known as 3D printing, is rapidly growing across numerous industrial sectors due to its ability to produce complex parts more flexibly and cost-effectively than traditional manufacturing methods. However, these processes can lead to undesirable geometric defects, such as distortions, cracks, or surface irregularities, which may negatively impact the quality and performance of the manufactured parts.

Additive manufacturing also offers unique design opportunities, enabling the creation of complex and customized geometries that were previously difficult to achieve with traditional manufacturing techniques. This pave is the way for innovative applications. Despite its market potential, mastering additive manufacturing processes remains a major

[1] Laboratory of Technology and Industrial Services, High School of Technology, Sidi Mohamed Ben Abdellah University, Morocco
[*] E-mail: ikram.kabbouri@usmba.ac.ma
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challenge for ensuring the quality and reliability of manufactured parts. Geometric deviations can reduce the performance of these parts. Numerous studies have been conducted to identify the causes of these deviations and develop control and minimization strategies. This includes a better understanding of process parameters, the materials used, and their interactions, as well as numerical simulation tools and advanced quality control techniques.

The choice of the subject of modelling the geometric deviations of parts obtained by additive manufacturing aims to find a relationship between the sources of the deviations and the effects of these deviations on the quality of the final part. Based on this modelling, the final shape of the real part can be predicted, which allows the designer and the manufacturer to have an idea about the geometric deviations that can affect the quality of the part to be able to study the functionality of the part in an assembly.

The proposed work is closely linked to the additive manufacturing process, specifically the FDM (Fused deposition modelling) process. The modes used to model and predict geometric deviations are taken from the additive manufacturing process: conversion of the CAD file (Computer Aided Design) into an STL file (Standard Tessellation Language), thermal shrinkage of the plastic material, as well as the elliptical mode that present a mechanical clearances of the machine axes.

This work presents a mathematical modelling method for geometric deviations in additive manufacturing. This method is based on three defects modes: meshing mode, radius change mode, and elliptical mode, which represent systematic deviations. Additionally, a parameter representing random deviations has been introduced by generation of random values using a normal distribution.

To illustrate this method, a numerical study was conducted on a cylindrical part made of polylactic acid (PLA) using an FDM additive manufacturing machine. The overall objective of this study is to predict the geometric deviations of a cylindrical part obtained through additive manufacturing from the design phase, enabling an early analysis of the product's behaviour.

The structure of this work is as follows: first, a literature review is presented; next, we outline the method for describing geometric deviations based on defect modes, along with the mathematical description of each mode. Finally, a numerical study is proposed to apply the methodology, and the obtained results are interpreted.

2. LITERATURE REVIEW

Modelling geometric deviations is a crucial challenge in additive manufacturing (AM), as it directly affects the dimensional accuracy, functional performance, and reliability of printed parts. The capacity to predict, model, and ultimately reduce these deviations is essential to achieving high-quality production and to improving the maturity of AM processes.

In AM, geometric deviations are typically described as displacements between the nominal surface and the actual surface of the printed part. These deviations can originate from several sources, including discretization errors during CAD-to-STL conversion, thermal effects such as material shrinkage or warping, and mechanical inaccuracies during layer deposition (Smith & Novak, 2024 [1]; Nguyen et al., 2023 [2]; El-Qemary et al., 2025 [3]). While some of these sources are common to other manufacturing processes, their manifestation in AM is often amplified by its layer-wise nature and complex thermomechanical interactions.

Several geometric modelling strategies have been proposed in the literature. Early methods introduced substitute surfaces to approximate real surfaces, though without explicitly accounting for shape defects (Homri et al., 2016 [4]). In contrast, skin model surface has been developed to represent geometric features while considering form deviations discretely, enabling improved tolerance analysis (Ballu & Mathieu, 1993 [5]; Schleich et al., 2016 [6]).

Form defect decomposition techniques have also gained prominence. Qiao et al. (2016) [7], introduced a curvilinear coordinate approach for representing non-ideal cylindrical shapes, which is particularly suited to symmetric geometries such as cylinders. Morière et al. (2010) [8] and Huang & Ceglarek (2002) [9] developed polynomial and DCT-based models, respectively, to decompose deviations into modal components. Similarly, Samper & Formosa (2007) [10], proposed modal decomposition using natural vibration modes of surfaces, allowing a compact representation of complex deviations.

Building on these methods, Chahbouni et al. (2014, 2020) [11, 12] applied modal decomposition method to assemblies, demonstrating the importance of form deviations in tolerance stack-up analysis. Chahbouni (2016) [13] extended this analysis to both worst-case and statistical tolerance approaches in mechanical assemblies.

In the context of additive manufacturing, recent studies have focused on identifying the specific deviation mechanisms that emerge from layer-based fabrication. Zhicheng Huang et al. (2018) [14] and Jean-Yves Dantan et al. (2018) [15] investigated predictive models to estimate the deviation patterns based on process parameters and geometry. Zhu et al. (2019) [16] proposed a statistical shape analysis framework that integrates measured deviations to build data-driven models. These studies highlight the necessity for tailored deviation models in AM, given the intrinsic variability and anisotropy of the process.

More recently, El-Qemary et al. (2025) [3] introduced a proactive approach for predicting and correcting deviations at the design stage, enabling design adjustments before printing. This work, aligned with the principles of design for additive manufacturing (DFAM), complements our current study, which proposes a mathematical model for describing circular geometric deviations.

In summary, although significant progress has been made in modelling geometric deviations for AM, current models are often limited to complex methods that are difficult to apply in industrial environments. Compared to these existing approaches, our method offers a simplified yet representative modelling of cylindrical form errors in FDM processes, making it particularly well-suited for early design validation and practical tolerance analysis in real-world applications.

Modelling geometric deviations remains a central challenge in additive manufacturing (AM), as it directly determines the dimensional accuracy, functional quality, and reliability of printed parts. Recent advancements in this field aim to understand and predict the discrepancies between the nominal and actual geometries, to anticipate their effects as early as the design stage. According to Wang et al. (2023) [17], these deviations are mainly caused by meshing errors (STL), thermal effects during layer-by-layer deposition, and mechanical inaccuracies in the system. To address these challenges, Chen et al. (2022) [18] proposed a hybrid modelling approach combining thermomechanical effects with deposition path strategies, while Zhao et al. (2024) [19] introduced a statistical prediction model based on machine learning. Other recent approaches, such as that of Martinez et al. (2021) [20], focus on the modal decomposition of form defects in complex cylindrical surfaces, using the natural vibration modes of the structure as a basis for analysis. Similarly, Gao et al. (2023) [21] developed an analytical method for error mapping based on boundary conditions specific to the FDM process. In parallel, Lee et al. (2020) [22] investigated the influence of build orientations on the morphology of geometric defects using adaptive geometric modelling techniques.

From the analysis of several scientific publications dealing with geometric deviations and tolerancing in mechanical manufacturing, it appears that the majority of the works are adapted to subtractive manufacturing processes. On the other hand, research into parts produced by additive manufacturing remains limited. Most existing studies on geometric deviations focus primarily on the influence of machine parameters on part geometry, without integrating the entire numerical process, which often results in purely statistical models.

The objective of this work is to propose a scientific approach to model and predict the geometric deviations of parts obtained by additive manufacturing. This method is based on specific process to additive manufacturing, using representations of deviations directly linked to the FDM (Fused Deposition Modelling) process. The approach is consolidated by an experimental study carried out on a test part to better identify certain parameters influencing the mathematical model. This approach is then applied to a numerical study on a simple cylindrical part. Two major advantages emerge from the proposed approach: on the one hand, the methodology is structured in the form of an algorithm, which facilitates the automation of calculations and the visualization of results; on the other hand, it is integrated into a series production simulation, thus allowing a global evaluation of the behaviour of the model and the impact of random deviations on the final geometry of the part.

3. MODELLING GEOMETRIC DEVIATION IN ADDITIVE MANUFACTURING

3.1. GEOMETRIC DEVIATION DESCRIPTION METHOD

A nominal surface is represented by a set of discretized points. Geometric deviations can be defined as a displacement of these points caused by set defects modes. Consider the example of a cylindrical surface: initially, the nominal surface is represented by a set of discretized points, while the actual surface is calculated by the displacement of these points caused by a set of geometric defect modes specific to the additive manufacturing process. Considering the following Fig. 1.

The following formula expresses the displacement of a real point

$$\mathrm{OM}_i^R = \mathrm{OM}_i^N + \sum_{k=1}^{n} (\lambda_{k,M_i}).\, u_{k,M_i} + \varepsilon_{M_i} \quad (1)$$

where:

OM_i^N : The coordinates of point M_i in the nominal surface.
OM_i^R : The coordinates of point Mi in the real surface.
λ_{k,M_i} : Amplitude of the systematic geometric deviation at point M_i due to mode k.
ε_{M_i}: amplitude of the random geometric deviation at point M_i.
k : number of geometric defect modes.
u_{k,M_i}: geometrical deviation orientation by the k^{th} geometrical defect mode applied on the point of nominal.

Geometric deviations between the nominal surface and the actual surface are defined by the sum of the deviations caused (Fig. 1) by all defect modes at each point on the surface. Based on these deviations, it can predict a surface with defects, referred to as the skin model surface.

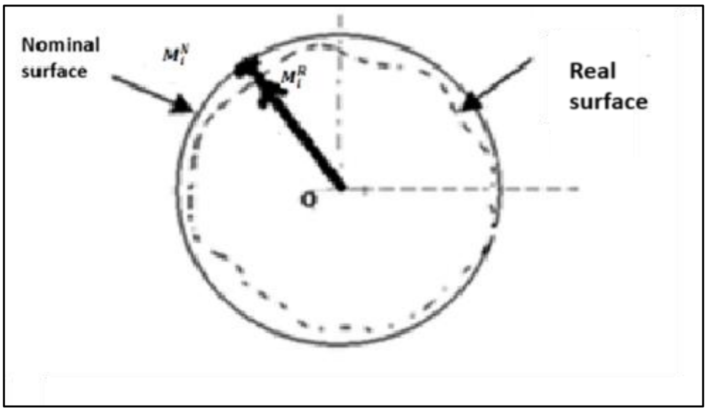

Fig. 1. Description of Geometric Deviations of the actual Surface

3.2. GEOMETRIC DEFECTS MODES

3.2.1. MESHING MODE

The transition from a CAD file in modelling software to an STL file intended for 3D printing often leads to meshing defects that simplify complex shapes into simpler forms. For example, a circle with a radius R is often represented as a polygon with several edges (Fig. 2). Consequently, the most important parameter is the number of polygon edges, which indicates the accuracy of the conversion from CAD file to STL file. In this case, maximum deviation $\lambda_{1\max}$ can be expressed by the equation below.

$$\lambda_{1max} = R - (\sqrt{\left(R^2 - (\mathrm{Rsin}\left(\frac{\pi}{ne}\right)\right)^2} \tag{2}$$

where: “ne” as the number of polygon edges in the mesh and R as the radius of the part, it can be deduced that a greater number of points reduces the angle and increases the number of polygon edges, therefore minimizing the error.

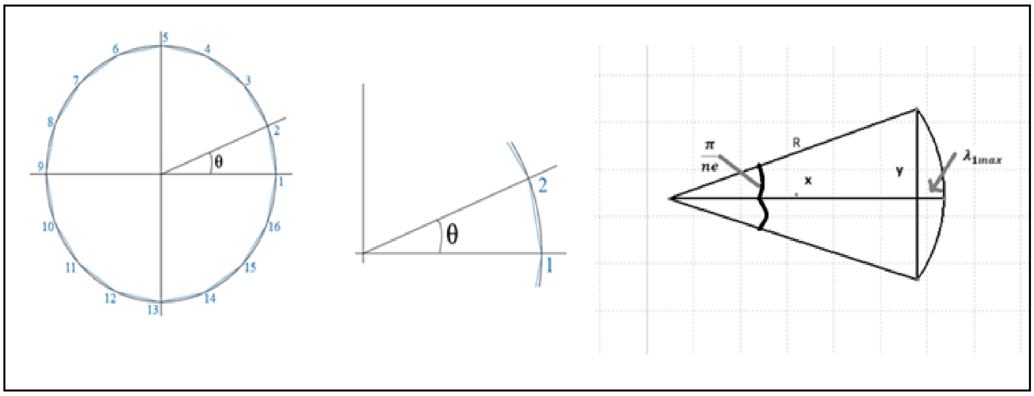

Fig. 2. Deviations due to meshing mode

3.2.2. RADIUS CHANGE MODE

The fused deposition modelling (FDM) process is based on heating and melting plastic material to produce the desired shape of the part. During cooling, the part undergoes a radius change phenomenon. PLA shrinkage in FDM is primarily caused by thermal contraction after extrusion and the accumulation of internal stresses. This deviation $\lambda_{2,\mathrm{Mi}}$ can be expressed by the radius change mode, which can be characterised by the following parameter:

$$\lambda_{2,M_i} = R - R' \tag{3}$$

where:

R is the nominal radius of the part

R' is the radius of the part obtained after the radius change (Fig. 3).

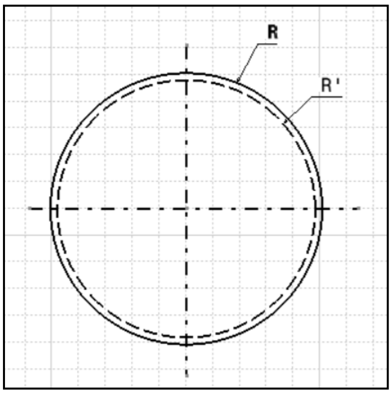

Fig. 3. Radius change Deviations

3.2.3. ELLIPTICAL MODE

Geometric deviations due to the mechanical limitations of the machine are represented by the elliptical mode. In practice, an ideal circular section tends to deform into an elliptical shape under the effect of thermomechanical constraints, positioning inaccuracies (especially in the *X* and *Y* axes of the machine). These deformations are often anisotropic, that is to say more remarkable along one axis (for example *X* or *Y*), which is precisely modelled by an ellipse. On the other hand, the elliptical form reflects the systematic errors specific to the machine's kinematics as mechanical clearances in the axes, calibration differences between stepper motors. Other modes represent the geometric deviations due to the machine, the example of the rounded rectangle mode, which studies the rounding of corners, but this mode can be relevant if the shape studied is a square.

Elliptical deviations (Fig. 4), presented as eccentricity, express the shape deviation between the final form and a perfect circle with zero eccentricity. The following figure represents this mode defect.

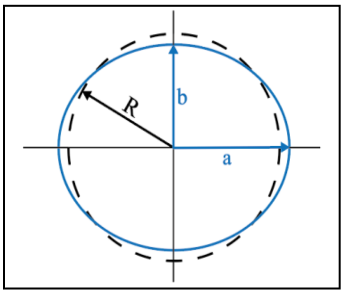

Fig. 4. Elliptical Deviations

This defect mode can be represented by the following parameter: λ_{3,M_i}

$$\lambda_{3,M_i} = R - R_E \tag{4}$$

$$R_E = \frac{R.R\prime}{\sqrt{R^2 sin^2(\theta)+R\prime^2 \cos^2(\theta)}} \tag{5}$$

$$\lambda_{3,M_i} = R - \frac{R.R'}{\sqrt{R^2 sin^2(\theta)+R\prime^2 \cos^2(\theta)}} \tag{6}$$

where:

R: Nominal radius of the part.

R’: Minor radius of the ellipse.

R_E: Radius of the ellipse as a function of the angle $\boldsymbol{\theta}$.

3.2.4. RANDOM DEVIATION MODE

The random deviations ε_i of parts produced by additive manufacturing (FDM) are modelled using a centred normal distribution with a mean of 0 and a standard deviation σ. The following formula expresses the random geometric deviations:

$$\varepsilon_i = \sigma \cdot N(0,1) \tag{7}$$

where: N(0,1) is a centred normal distribution.

3.3. METHODOLOGY FOR MODELLING GEOMETRIC DEVIATIONS

To facilitate the study, it is assumed that the modelling of geometric deviations of a part obtained by additive manufacturing is based on three defect modes: meshing mode, radius change mode, and elliptical mode. These three defect modes generate geometric deviations in the plane. Based on these assumptions, our study of a cylindrical part becomes a study in the plane of a circular section. The result obtained will be projected onto the cylindrical part.

- Modelling Steps.
- Discretisation of the nominal contour (Fig. 5) into a set of points: each point is represented by its polar coordinates (radius R and angle $\boldsymbol{\theta}$).

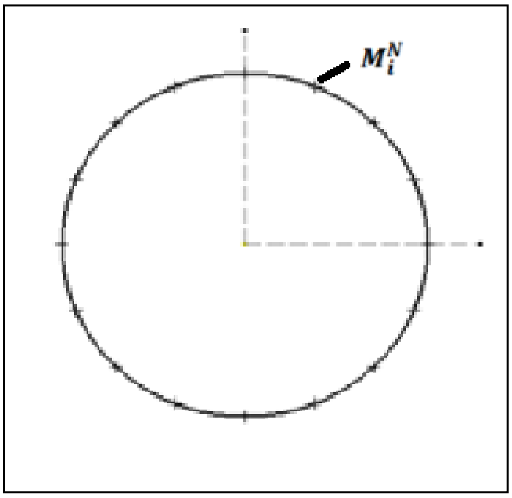

Fig. 5. Discretization of a nominal circle

- For each nominal point M_i^N of the circle, the radius of the part with deviations is calculated, as sum of the nominal radius and the deviations caused by the different applied modes, according to the formula:

$$R_i^d = R_i^N + \sum_{k=0}^{n}(\lambda_{k,M_i}) + \varepsilon_{M_i} \tag{8}$$

where:

R_i^d : Radius of part with deviations

R_i^N: Radius of the nominal part

λ_{k,M_i} : Amplitude of the systematic defect due to mode k, in our study we have three modes: λ_{1,M_i} , λ_{2,M_i} , λ_{3,M_i}

ε_{M_i} : Amplitude of random deviations.

- Reconstruct the circle with deviations from the calculated radius by positioning it according to the angle. The resulting circle, extended along the height, represents the skin model of the studied cylindrical part.

4. NUMERICAL STUDY: STUDY OF A CYLINDRICAL PART

4.1. STUDY DATA

The study is conducted on a cylindrical part with a diameter of 40 mm and a length of 30 mm, made of polylactic acid (PLA) using a 3D printing machine. The circular section of the part is discretized into 32 points and represented by a polygon with 16 edges. For the calculation of geometric deviations in the plane, the meshing mode, radius change mode, and elliptical mode. The random geometric deviation, which is generated according to a normal distribution.

- The meshing mode is represented by the parameter λ_1, which is calculated based on the part discretization data, using the value of λ_{1max} calculated as a function of the nominal radius and the number of polygon edges, which in our case is equal to 16 segments.
- The radius change mode is represented by the parameter λ_2, which is based on the material of the part. In our case, using PLA material, this parameter is estimated to be 0.5% of the dimension value.
- The elliptical mode is represented by the parameter λ_3, which is calculated based on the angle, the nominal radius of the part, and the minor radius of the ellipse. In our case, there is a maximum difference of 0.2 mm between the two radiuses, based on the measurement results of the test part.
- The random deviation is represented by the parameter ε_i, which is randomly generated according to a normal distribution with a mean of 0 and a standard deviation of 0.06. The standard deviation is calculated using the 6σ method based on the maximum value of the random error, considered to be 50% of the previously calculated systematic error.

4.2. MANUFACTURING OF TEST PART

To verify certain parameters and validate the assumptions of radius shrinkage and the elliptical effect, a part with a diameter of 40 mm and a length of 30 mm was fabricated.
The material of the part is PLA.
Machine used: ULTIMAKER
Manufacturing parameters:

- Layer thickness: 0.15 mm.
- Printing speed: 80 mm/s.
- Movement speed: 100 mm/s.
- Fill density: 4%.

The CAD file was created using CAD software, then the file was converted to an STL file and sent to the machine for manufacturing. The following Fig. 6 illustrates the part and the machine used.

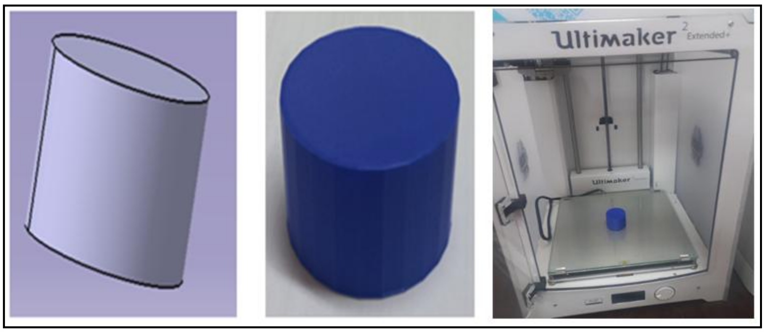

Fig. 6. Test part manufactured and FDM machine Ultimaker used

- Measure of part test
  Using a digital calliper (Fig. 7), 10 measurements of diameter were taken in rotation relative to the cylinder in different sections.

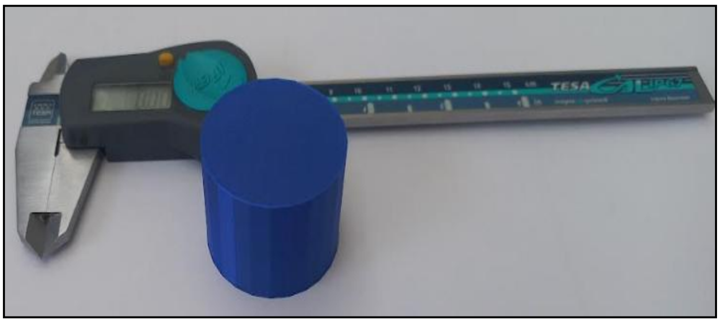

Fig. 7. A digital calliper used

The following Table 1 shows the measurements taken.

Table 1: Measurement of part test

Measures	Diameter (mm)
1	39.36
2	39.6
3	39.5
4	39.2
5	39.24
6	39.6
7	39.4
8	39.46
9	39.24
10	39.44
Average	39.404
Max	39.6
Min	39.2
Max-Min	0.4

Measurements taken on the part showed a difference of 0.4 mm between the maximum and minimum diameters. The maximum diameter is 39.6 mm, indicating the effect of diameter change.

4.3. ALGORITHM FOR GENERATING THE SURFACE WITH DEFECTS

Start
Initialize:
R = 20
λ_2 = 0.1
R' = 19.8
λ.max =0 .38
For i from 1 to 32
ε_i = A random value according to the normal distribution (m = 0, σ = 0.06)
$\boldsymbol{\theta}_i$= (i-1)*π/16

$$\lambda_{3,i} = R - \frac{R.R'}{\sqrt{R^2 sin^2(\theta_i) + R'^2 cos^2(\theta_i)}}$$

if i is pair: $\lambda_{1.i}$=0
else: : $\lambda_{1.i}$ = 0.38
End-if
$R_i = R- \lambda_{1.i}-\lambda_2-\lambda_{3,i}+ \varepsilon_i$
M= [$\boldsymbol{\theta}_i$, R_i]
End For
Drawing the Polygon Representing the Surface with Defects Based on the Coordinates ($\boldsymbol{\theta}_i$, R_i)
End

- Graphical Representation of the Part with Deviations.

The following diagram (Fig. 8) represents the part obtained by considering the different types of geometric deviations: systematic and random. The blue polygon represents the part without deviations, while the red polygon represents the part with the geometric deviations generated by the previous algorithm.

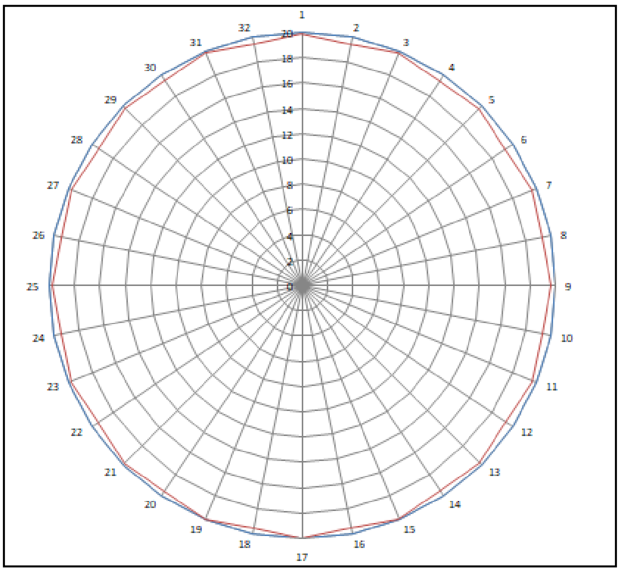

Fig. 8. Profile of part with deviation

4.4. SIMULATION OF MULTIPLE PARTS

In order to illustrate the impact of geometric deviations during additive manufacturing, we performed a simulation of multiple parts. This involves generating the geometric deviations on 100 parts of the same type, with a diameter of 40 mm, based on systematic deviations represented by the meshing mode, the radius change mode, and the elliptical mode, as well as the random deviation which varies for each point on each part.

To approximate the simulation to real production, we generated the random deviation using the normal distribution function with a mean of 0 and a standard deviation of 0.06 mm.

- Algorithm for generating multiple parts with deviations.

Start
Initialize:
$R = 20$
$\lambda_2 = 0.1$
$R' = 19.8$
$\lambda_{1max} = 0.38$

For j from 1 to 100
For i from 1 to 32
ε_i = A random value according to the normal distribution ($m = 0$, $\sigma = 0.06$)

$\boldsymbol{\theta}_i = (i-1) * \pi/16$

$$\lambda_{3,i} = R - \frac{R.R'}{\sqrt{R^2 sin^2(\theta_i) + R'^2 cos^2(\theta_i)}}$$

if i is pair: $\lambda_{1.i}=0$
else: $\lambda_{1.i} = 0.38$
End-if
$R_i = R - \lambda_{1.i} - \lambda_2 - \lambda_{3,i} + \varepsilon_i$
$M = [\boldsymbol{\theta}_i, R_i]$
End For
Draw the Polygon Representing the Surface with Defects Based on the Coordinates ($\boldsymbol{\theta}_i$, R_i)
End For
Draw the Polygons Representing the Surfaces with Defects Based on the Coordinates ($\boldsymbol{\theta}_i$, R_i) on the Same Graph
End of Algorithm

- Graphical Representation of the Part with Defect.

The following diagram (Fig. 9) represents the profiles of the parts obtained by considering the geometric deviations. According to this pattern we observe:

- The profile of the parts follows the same profile.
- The small random variations in the radius are due to the random deviations generated by the automatic function.

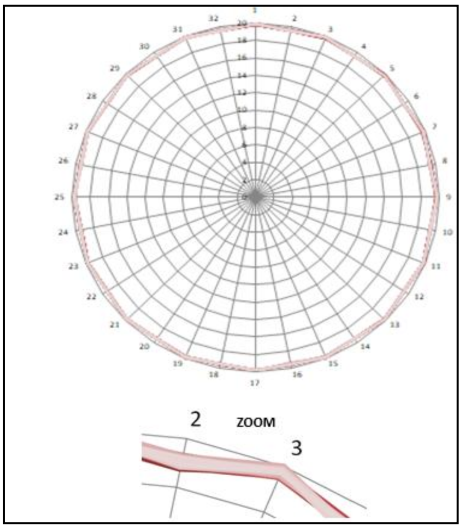

Fig. 9. Simulation of deviations for 100 Parts

The following figure (Fig. 10) illustrates the variation in the average radius for all parts, which range between 19.58 mm and 19.64 mm, with a standard deviation of 0.01 mm

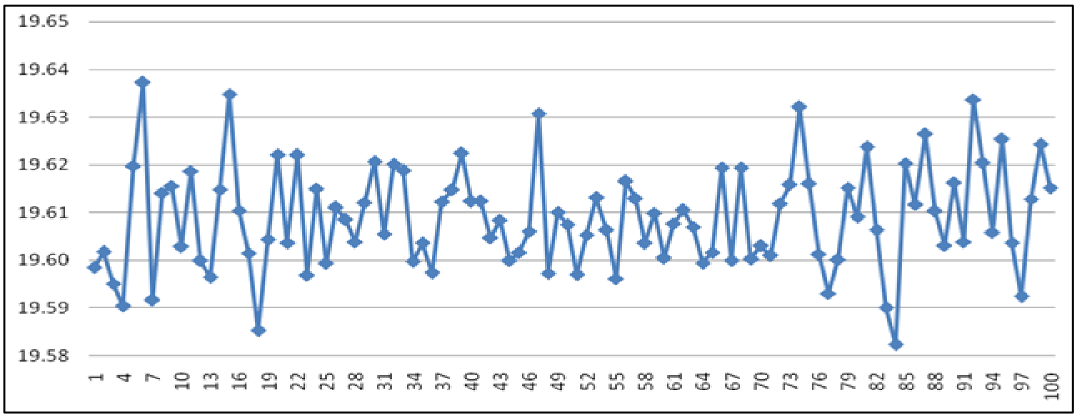

Fig. 10. Average radius of 100 parts

According to the calculations made, it observed that the diameter of the obtained part is always smaller than the diameter of the nominal part, due to the meshing, and the radius change of the part.

5. CONCLUSION

In this work, first, a state of the art on the modelling of geometric deviations in the context of additive manufacturing is presented. Then, the methodology for modelling the geometric deviations of parts is introduced, based on the discretization of the part, considering both systematic and random deviations. The systematic deviations are represented by three sources of deviation: the meshing mode, the radius change mode, and the elliptical mode. On the other hand, the random deviations are automatically generated based on the normal distribution law. A scientific approach to model and predict the geometric deviations is developed. This method is based on a process specific to additive manufacturing, using representations of deviations directly linked to the FDM (Fused Deposition Modelling) process. The second section of this work presents a numerical study of a cylindrical part obtained through the FDM process. The first step is the manufacturing of the test part to validate some hypotheses related to the FDM process, followed by the generation of geometric deviations based on both systematic and random deviations to plot the profile of the part with the generated deviations. An algorithm is developed to facilitate the calculation. To project this methodology onto mass production, a simulation of geometric deviations for 100 parts has been carried out and profiles of surfaces are plotted to facilitate the interpretation of the results.

Based on the results obtained during this study, it observed that a diameter of the real part is lower to the nominal part diameter. As a prospect of this work is the exploitation of this methodology in the tolerances analysis of the assembly obtained by additive manufacturing.

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