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Typology of geometrical defects in Electron Beam Melting

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Abstract

Quality control in terms of material health, texture and workpiece geometry is not assured in additive manufacturing. Many literature studies address quality issues on a scale of less than one millimeter. On the other hand, few works concern geometrical defects at the level of the piece as a whole (form and dimension), on a scale therefore greater than several millimeters.
From the existing bibliography and the authors' experience, the objective of the article is to list the typologies of geometrical defects usually encountered and the configurations in which they appear.

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Keywords: Additive Manufacturing; geometrical defects; warping; Electron Beam Melting, loss of edge, loss of thickness …

1. Introduction

Additive Manufacturing (AM) is a technology based on "layer-adding" fabrications in order to directly produce functional parts from the CAD model [1]. AM has grown from a rapid prototyping technology, ten years ago, to offer capabilities for functional part production with different materials like metals [2], polymers [3] and ceramics [4]. Today, Metal AM is adapted for critical applications such as medical implants, aerospace and other fields with a clearly demonstrated ability to produce complex shapes [5]. In spite of the great capacity of AM process, difficulties remain to control the part quality in terms of mechanical properties and workpiece geometry (form and dimension). The defects lead to the weakening of the mechanical properties that are critical in some stringent industries such as the biomedical or aerospace industries [6, 7, 8]. Despite enormous improvements in the AM process, a variety of defects limits the process in terms of repeatability, accuracy, and resulting mechanical properties.

Compared to the laser technologies, for example selective laser melting (SLM), defect in Electron Beam Melting (EBM) is still poorly studied. The defects in the EBM process can be classified into three general groups depending on how they affect the printed part. These areas are depicted in the Fig. 1: (1) geometry and dimension (2) microstructure, and (3) mechanical properties.

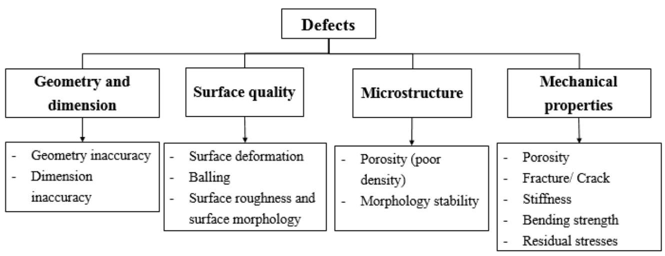

Fig. 1 Common defects in the EBM process

Many existing studies identify the defects related to the microstructure of the material like porosity (poor density) [9], balling [10], surface roughness and surface morphology [11, 14]; or related to mechanical properties of the part, for example, fracture / cracks [12, 14, 16], stiffness [13, 14, 15], bending strength [14, 15]. Few studies have emphasized the defects related to geometry and dimension inaccuracy. This article is mainly based on the existing bibliography and the authors' experience to list the typologies of geometrical defects on the EBM process with material Titanium (Ti6Al4V).

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2. Geometric and dimensional defects

It could be noticed that the quality of the part made by AM technologies has strong dependency with the actual feature geometrical designs [17]. Therefore, standard test parts with many representative features were proposed by various groups [18, 19, 20, 21]. Illustrations of the most common examples are available in Fig. 2.

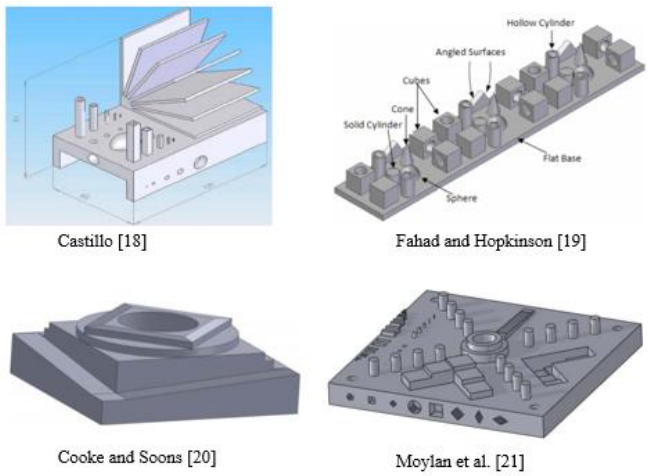

Fig. 2 Designs of standard test parts

In general, three main objectives are led with these different tests [19]:

- Evaluate the geometric quality of the features produced by machines.
- Compare the mechanical properties of features or geometries.
- Search for the optimum process parameters for features and geometries.

As part of our study, we focus on the first objective: the studies of geometric and dimensional variations. Based on the review of [18, 19, 20, 21], it could be noticed that the tolerances of parts were measured under six types of geometric characteristics, such as straightness, parallelism, perpendicularity, roundness, concentricity and the accuracy of the feature position by Yang et al. [17]. The result showed that the tolerances of parts manufactured by the EBM process range from 0.02 mm to 0.194 mm. There is a geometric and dimensional imprecision of the parts. The reason for this defect is an interesting study.

The geometrical and dimensional defects can be classified into two groups:

- The geometrical and dimensional inaccuracy: these defects are related to inaccuracy of dimensions and geometry.
- The geometrical deformation: these defects are related to the deformation of the geometry of the part.

3. Geometrical and dimensional inaccuracy

From the existing bibliography, defects related to dimensional accuracy depend on many effects. But in this paper, three sources of dimensional inaccuracy could be identified:

- The staircase: part orientation and layer thickness have an effect on the staircase error, see Fig. 3. Increasing layer thickness results in more pronounced staircase error.
- The error of the position of the energy source: the energy source is imperfectly positioned on the manufacturing platform, see Fig. 4. This figure refers to laser powder bed fusion but we considered that there was the same error with laser beam melting.
- The error of platform position, see Fig. 5: there are deviations between actual and ideal motions of manufacturing platform of the machine that introduce errors in the manufactured part's geometry and dimension.

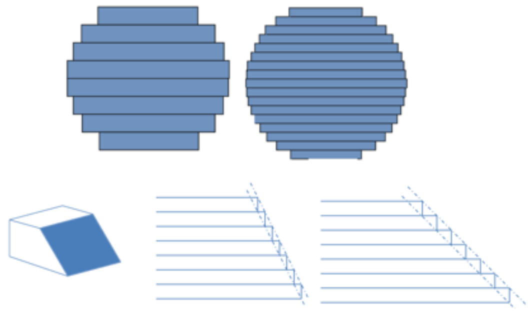

Fig. 3 Effect of layer thickness and part orientation on the staircase error [22]

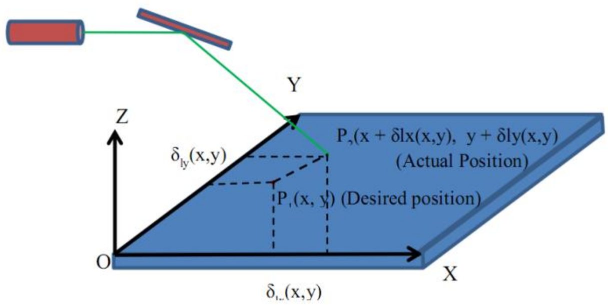

Fig. 4 Energy source positioning error [22]

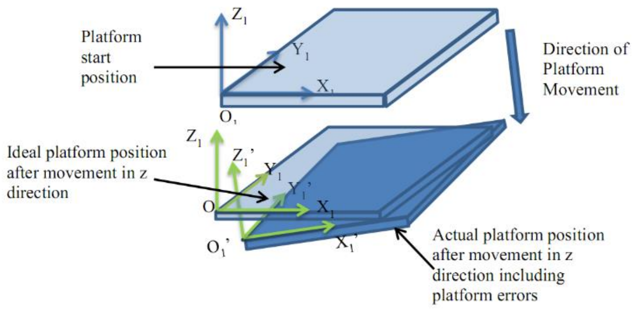

Fig. 5 Ideal and Actual Direction of platform motion [23]

In conclusion, on these defect types based on the bibliography sources, geometry and dimensional variations correspond to the measure of tolerances of the simple feature manufactured by additive manufacturing. The tolerance of part depends on effect of staircase and effect of the machine positional error (source energy and direction of the platform motion).

From the authors' experiences, Piaget et al. [24] have identified a correlation between the geometry defect of specimens and their position in the manufacturing space. Therefore, 25 locations of the manufacturing space were tested in the experimentations. Two kinds of test specimens have been chosen for the test, see Fig. 6. The massive specimen is used to measure the height variation. The lattice structure is used to observe the variation of the geometry of the cell. The authors have obtained different kinds of defects and they concentrate their study on the distortion of the first layers, see Fig. 7.

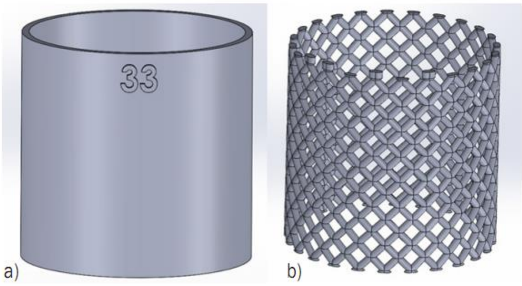

Fig. 6 Experimentation specimens; a) massive and b) lattice structure

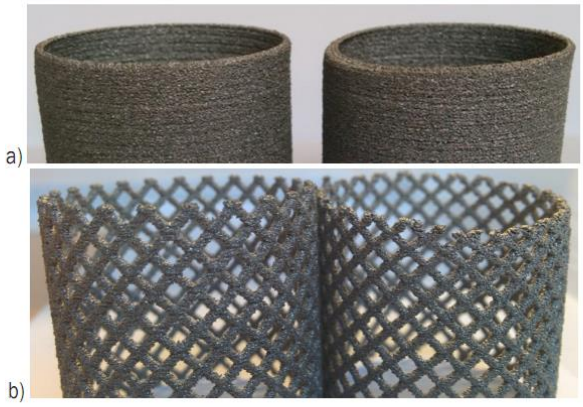

Fig. 7 a) Massive and b) Lattice specimen placed upside down

The distortions of the first layers of 25 massive specimens were measured by a three-dimensional optical control machine (Vertex from Micro-vu). This equipment is able to measure the height of each point in the first layer, see Fig. 8a. The difference between the nominal and the measured height is computed. The lattice structure defect is observed using a different measurement protocol, see Fig. 8b. A gauge tool was created to detect a ±10 % change in the shape of every cell of the part.

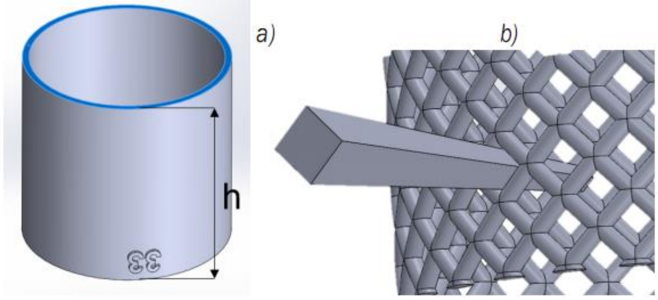

Fig. 8 Representation of the measurement processes: (a) massive and (b) lattice specimen

The different height variations of massive test specimens are presented in Fig. 9. An example of the height defect of one specimen is shown in Fig. 9a: the height defect is presented in function of the angular position of measured point. The defects cartography of 25 specimens is shown in Fig. 9b. It could be observed that the defect value is more important when the measured point on a specimen is close to the borders of the platform of the machine. The same conclusion was identified for the lattice structure.

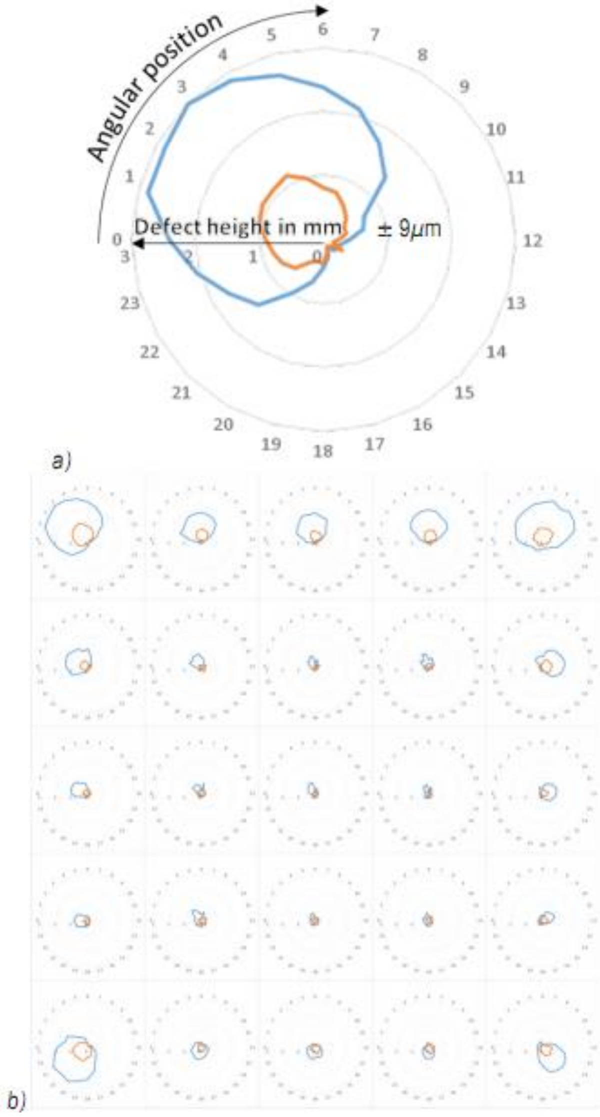

Fig. 9 a) Example and b) defect cartography of the massive specimen (blue: Ø30 mm, orange: Ø20 mm)

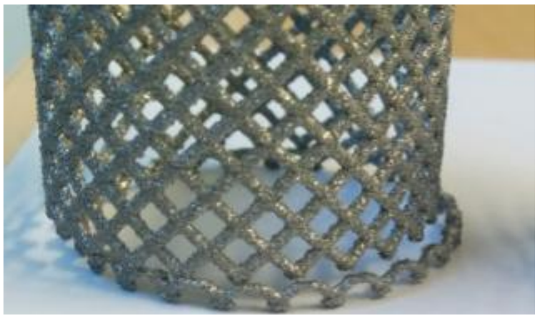

Fig. 10 Photography of the 2 mm mechanical shifting

Another interesting defect is the mechanical shifting of the first layers in the direction of the movement of the rake, see Fig. 10. This defect seems to be not repeatable from a sample to another one.

Piaget et al. have proposed three hypotheses to explain the source of the defects in their experiments:

- The first hypothesis is related to the electron beam: the shape of the beam changes from a circle to an ellipse when the electron beam moves from the center to the border of the manufacturing platform. The surface of transmission becomes larger and leads to a decrease of the energy broadcast. Therefore, it results a decrease of the temperature that leads to limit the quality of the powder melting. This hypothesis may explain the type and location of the defect.
- The second hypothesis is related to the loss of temperature. At the borders of the manufacturing platform, the cold powder and metal enclosure might absorb the energy of the sintered powder.
- The third hypothesis involves the rake to explain the mechanical shifting in Fig. 10. When the rake spreads the powder out, a portion of specimen is moved in the rake direction and might cause deformations.

As a result, the hypothesis kept is a combination of the previous ones: the different contact area shape of the electron beam on the powder bed from the center to the border provides less energy to the powder. In addition, energy leaks near the border make the sintering of the powder weaker. Then, the rake passage might easily move the poorly sintered powder and the molten material. According to these investigations, the two main reasons of these defects are the loss of temperature and the contact of the rake with the specimen during the production.

4. Geometry deformation

One of the most relevant advantages of the AM is the design freedom in geometry. However, the overhang part of a product, see Fig. 11, is one of the challengers to manufacture. Some geometric deformations occurs on the overhang zone during the build, as warping (or "curling" depending on the authors), loss of thickness and loss of edge.

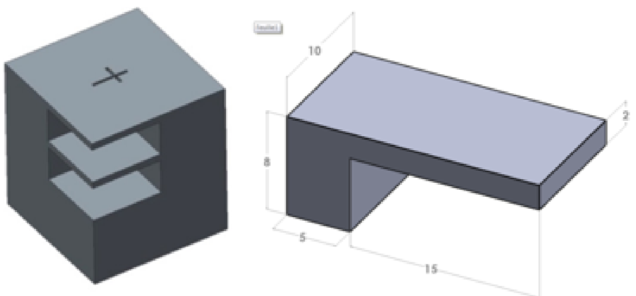

Fig. 11 Overhang structure

4.1. Warping or curling

Warping defects or curling defects corresponds to the curvature of the upper horizontal surface of an overhanging part, see Fig. 12 [25]. This effect has been observed in the existing bibliography and authors' experience.

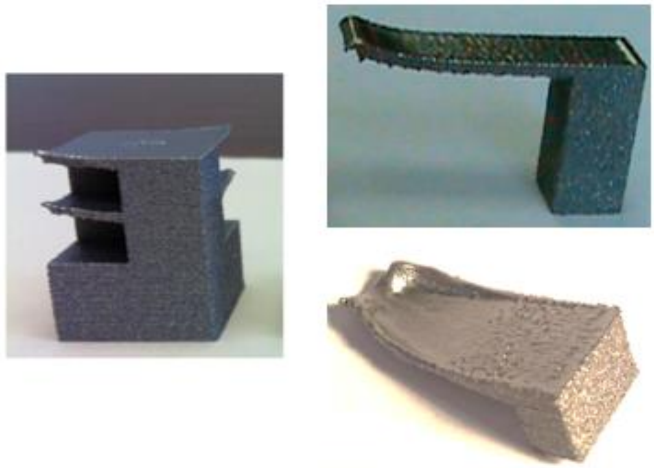

Fig. 12 Warping defect in the existing bibliography and authors' experience

Warping defect is due to the thermal stress formed by the rapid solidification during the EBM process. The deformation occurs when the thermal stress exceeds the strength of material.

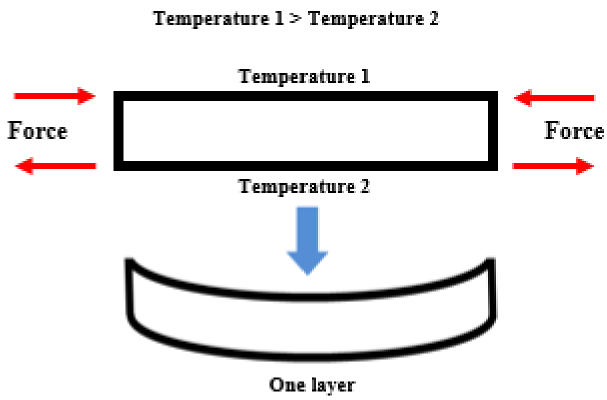

Fig. 13 Temperature gradient induced deformation [26]

The thermal stress can be explained from temperature gradients [26; 27]. Fig. 13 shows the temperature gradient inducing deformation of feature due to rapid heating of the upper surface caused by the fast moving of the electron beam and the relatively slow heat conduction. Since the temperature of the upper surface is higher, a temperature gradient is observed. Then the expansion of the heated top layer is restricted by the underlying material (having a lower temperature), and counter compressive strain phenomena are induced. During the cooling of the zone, the compressed upper layers start to shrink and leads to the warping of the overhang surfaces. Thus, the temperature gradient is the main physical phenomenon in the apparition of the warping defect.

To tackle the warping defects on the overhang structure, support structures could be introduced. The supports are useful to dissipate the heat, to stiffen the surface and thus to limit its deformation and to anchor the surface to the starting plate or in the consolidated powder [28]. The authors have produced specimens with supports, see Fig. 14. In these conditions, the warping defect do not occur but other defects can be noticed, like the loss of thickness and / or the loss of edge, see Fig. 15.

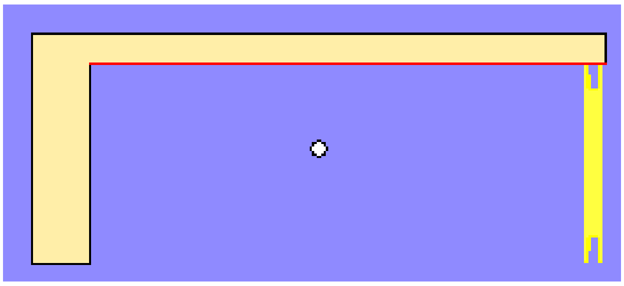

Fig. 14 Overhang structure with support

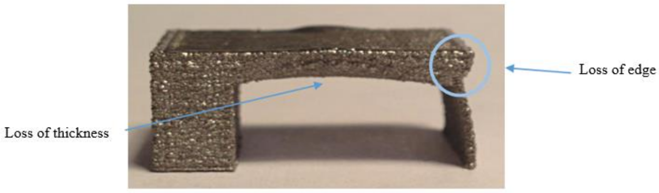

Fig. 15 Another defect: loss of thickness and loss of edge

4.2. Loss of edge

The loss of edge defect is a loss of side geometry at the end of the overhang portion, see Fig. 16. This geometric defect may be explained by the decrease of the layer length due to the cooling phenomenon from previous melted layer to the new one.

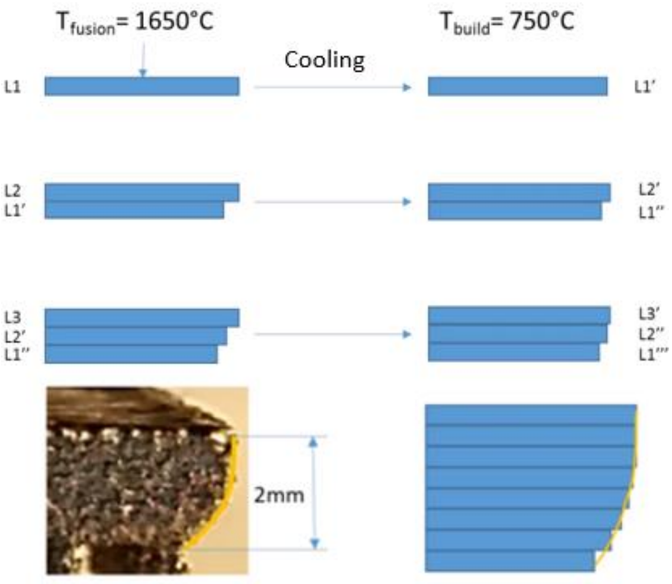

Fig. 16 Loss of edge defect and explanation

Once the first layer of a surface has cooled, it shrinks due to the temperature gradient (from 1650ºC to 750ºC). The powder of the next layer is distributed and melted. An offset is produced between successive layers. The offset between two layers would be caused by the shrinkage between 1650 and 750ºC, as the upper layer is warmer, it is a little longer and it clings to the previous layer with a shift. The second layer also undergoes a narrowing that causes the first layer to shrink since the force exerted is greater than the elastic limit of the material. The first layer is plastically deformed. This phenomenon is repeated for each layer but the deformation becomes smaller due to the opposite deformation of the previous layers and the increase of the part stiffness. The gap between the two layers becomes smaller each time.

4.3. Loss of thickness

The defect of loss of thickness, see Fig. 15, is related to the decrease of the melted material in the middle of the overhang part. This geometric defect is due to thermal phenomena between the melted layers and supports.

The defect of loss of thickness occurred on another experiment that investigated the influence of the process parameters, such as current value, offset and speed function, on the geometry of the part. In Fig. 17, three specimens were manufactured with different current value. A weak current (C) gives a better geometry because it seems to avoid the problems of overheating but decreases the melting of the powder.

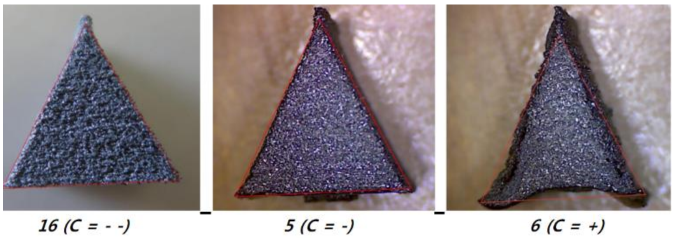

Fig. 17 Another example with loss of thickness

In this paper, the overheating was identified as a cause of the defect of loss of thickness.

5. Conclusion and future work

This paper focuses on the geometric defects of the part during it's built by EBM process with material Titanium (Ti6Al4V). Based on both bibliographic review and author's knowledge, a fish-bone diagram of EBM defect presents a clear summary of the main defects occurring in the EBM process, the physical phenomena and the stated hypotheses, see Fig. 18.

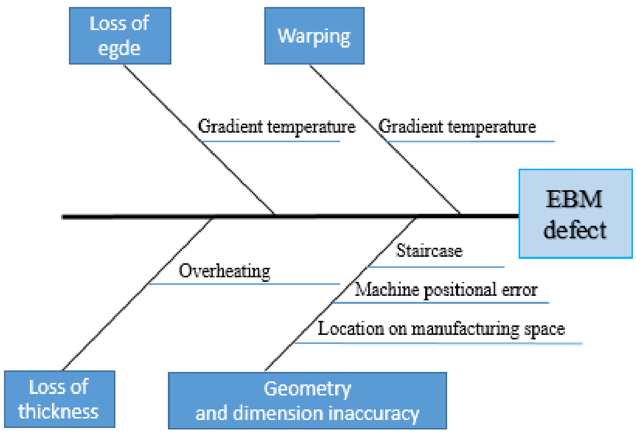

Fig. 18 Fish-bone diagram of EBM defects

Several investigations will be performed in the next few months to valid and to improve the knowledge of the complex phenomena during the EBM process. It will be mainly based on experimental approaches (development of experimental devices), development of numerical simulations of process and parametric study of process parameters on real production of parts.

For the next time, the study will be focused on the loss of edge defect. A plan of experiments will be made to evaluate the effect of gradient temperature on the dimension of the overhang, such as the length (L) and the thickness (H), see Fig. 19. This study may help us to understand the loss of edge defect phenomena and discover design guidelines for the overhang structure.

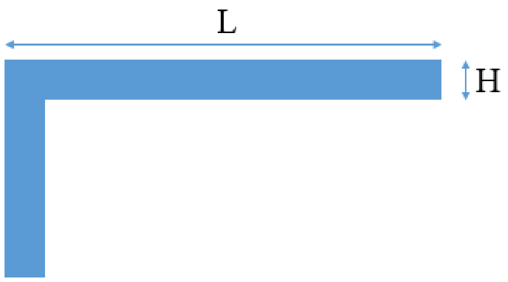

Fig. 19 Overhang's dimension

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