MANUFACTURING OF COMPLEX PARTS WITH CONTINUOUS FUNCTIONALLY GRADED MATERIALS (FGM)

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Abstract

One of major evolutions of the additive manufacturing is the ability to produce parts with functionally graded materials (FGM). However, manufacturing of these parts is limited to discrete or nearly continuous FGM on samples. To achieve this, it is necessary to have a global control of processes and to develop methodologies to help designers and manufacturers. A methodology to produce morphologically complex parts is proposed in this paper. It consists in classifying all typologies of bi-materials gradients with mathematical description. Each typology of gradient is associating with manufacturing strategies in order to choose slicing and path strategies. Afterwards, mathematical data are used to have a global control of a process. This paper presents the principle of this methodology and the mathematical models which are chosen to describe part and manufacturing.

Introduction

FGM - first proposed in 80's [1] - can be characterized by the variation in composition and structure gradually over volume. Structure of FGM enables to choose the distribution of properties to achieve required functions. It is possible to produce material gradients to change physical, chemical, biochemical or mechanical properties. Aeronautical and biomedical industries are particularly concerned by FGM developments, which began in the middle of 90's for metallic structures [2] and in the beginning of 2000's for metal-ceramic structures [3].

Additive manufacturing processes give the possibility to produce important size parts with complex morphology [4]. However, some scientific limits exist to manufacture FGM parts with these processes. From a material point of view, the studies focus on observation of structures of small sizes, mainly their micro-structure and their composition [5, 6]. Predetermination of these features is limited by thermal and metallurgical models [7, 8]. Concerning the product aspect, the state-of-the-art is still very limited, manufactured parts are morphologically simple and non-functional. The studies focus on observation of some characteristics of the product, such as hardness or biocompatibility [9, 10]. Process control is partially addressed by studies of the influence of specific parameters [11], but a comprehensive approach is needed to obtain functionally multi-materials parts. From a methodological point of view: design, representation and process plan aspects have been partially studied but the majority of studies don't take into account specificities of processes or are limited to discrete multi-materials manufacturing [12, 13]. Digital chain becomes adapted to additive manufacturing but not totally to FGM [14].

To obtain functionally parts it is necessary to develop methodologies with a global approach which take into accounts all process specificities.

Methodology for manufacturing FGM part

The main objective of this methodology is to find the best way to obtain a FGM part. It is decomposed in three steps: classification of gradient, determination of manufacturing strategies and global control of additive manufacturing (Fig. 1).

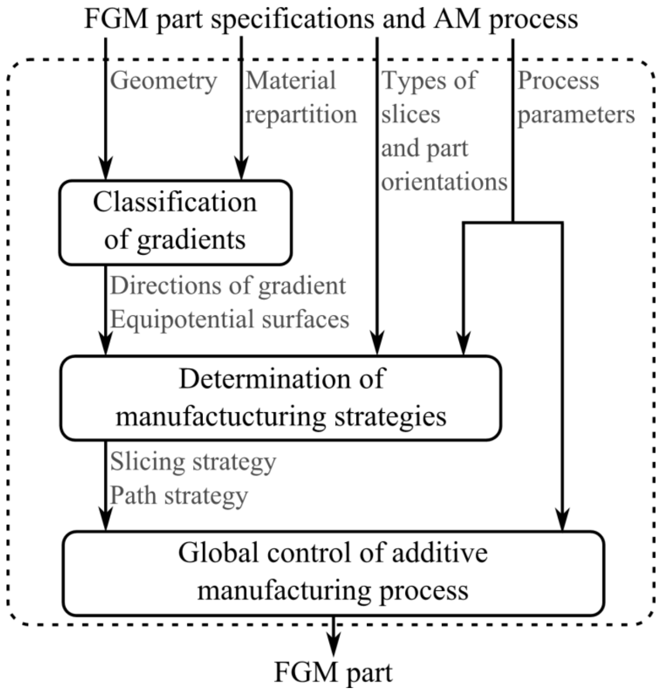


Figure 1. Principle of the methodology

The principle of the classification of gradient is to describe and classify multi-material part design given that the material repartition and the geometry of the FGM part are defined. All typologies of bi-material gradients are described with mathematical data. This mathematical description gives information about gradient direction and type of equipotential surfaces. Afterwards, manufacturing strategies are associated with each kind of gradient.

The optimal manufacturing strategies – slicing and path strategies [15] – are selected by using the mathematical data on the classification of gradients, types of slices considered and process parameters. Proposals are principally made in terms of material repartition but the geometry of part limits the possible types of slices and part orientations. That is why, the optimal strategies are chosen in terms of typology of gradient, geometry of the part and requirements of process. These strategies are proposed for discrete and continuous FGM manufacturing.

Global control of additive manufacturing is made from manufacturing strategy and process parameters. This control is performed with mathematical data obtained in the two first steps of the methodology.

Two parts of the methodology (*Classification of gradients* and *Types of slices*) are presented in this paper. An application of the methodology is made on a first example.

Classification of gradients

Definitions and assumptions

For this methodology, parts must be made up of two materials m_A and m_B. They consist of only one area with exclusively material m_A and only one area with exclusively material m_B.

The function M represents the material composition of FGM in space. It is defined in a domain $D_M \subset R^3$, corresponding to the part:

$$M(x, y, z) : D_M \rightarrow [0 ; 1] \tag{1}$$

D_M can be decomposed in several sub-domains D_{Mi} (Fig. 2). In this case, methodology must be applied on all sub-domains.

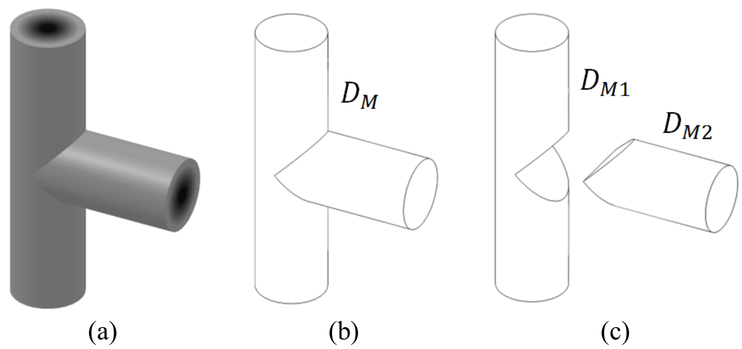


Figure 2. Example of a FGM part: (a) material repartition, (b) domain D_M and (c) sub-domains D_{Mi}

Material composition is defined by:

- $M(x, y, z) = 0$ if the part is made up of only material m_A,
- $M(x, y, z) = 1$ if the part is made up of only material m_B.

The gradient is the vector corresponding to the variation of the function M in D_M:

$$\overrightarrow{\nabla M}(x, y, z) = \left(\frac{\partial M}{\partial x}(x, y, z), \frac{\partial M}{\partial x}(x, y, z), \frac{\partial M}{\partial x}(x, y, z) \right) \tag{2}$$

Gradient dimension

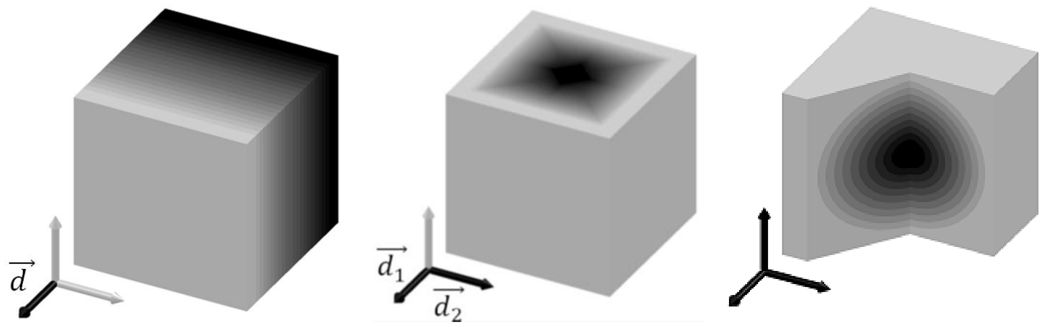
A gradient is a *one dimensional gradient* (Fig. 3(a)) if and only if there exists a constant vector, such that:

$$\forall (x, y, z) \in D_M, \overrightarrow{\nabla M}(x, y, z) = g(x, y, z). \vec{d} \tag{3}$$

A gradient is a *two dimensional gradient* (Fig. 3(b)) if and only if there exist two constant vectors, such that:

$$\forall (x, y, z) \in D_M, \overrightarrow{\nabla M}(x, y, z) = g_1(x, y, z). \overrightarrow{d_1} + g_2(x, y, z). \overrightarrow{d_2} \tag{4}$$

Others gradients are *three dimensional gradients* (Fig. 3(c)).



(a) (b) (c)

Figure 3. Gradient dimension: representation of (a) a *one dimensional gradient*, (b) a *two dimensional gradient* and (c) a *three dimensional gradient*

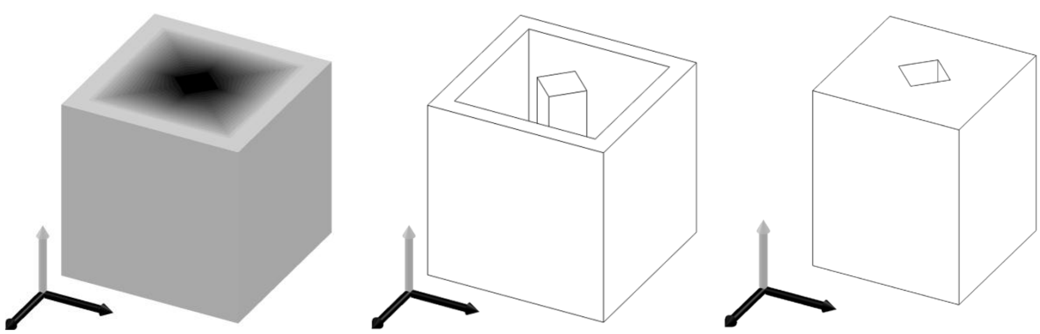
Equipotential surfaces

The spaces D_A and D_B (Fig. 4(b)) are defined by:

$$D_A : \{(x, y, z) \in D_M \mid M(x, y, z) = 0\} \tag{5}$$

$$D_B : \{(x, y, z) \in D_M \mid M(x, y, z) = 1\} \tag{6}$$

A *two dimensional gradien*t is an *open gradient* if and only if the space $\{D_M - D_A - D_B\}$ is simply connected. Otherwise it is a *closed gradient* (Fig. 4(c)).



(a) (b) (c)

Figure 4. Representation of (a) a *closed gradient*, (b) the spaces D_A and D_B and (c) the space $\{D_M - D_A - D_B\}$

An equipotential surface is a surface on which the function M has a constant value. It is defined by:

$$S_{eq}(c) : \{(x, y, z) \in \{D_M - D_A - D_B\} \mid M(x, y, z) = c\} \tag{7}$$

A *two dimensional gradient* is an *offset gradient* (Fig. 5) if and only if:

$$\forall\, c \in [0\,;1], \exists\, k \mid \forall (x, y, z) \in S_{eq}(c), \left\|\overrightarrow{\nabla M}\right\| = k \tag{8}$$

A *three dimensional gradient* is an *offset gradient* if and only if there exist three real numbers a_1, a_2 and a_3, such that:

$$P_i(b) : \{a_1 x + a_2 y + a_3 z = b\} \tag{9}$$

$$\forall\, c \in [0\,;1], \forall\, b \in R, \exists\, k \mid \forall (x,y,z) \in \left(S_{eq}(c) \cap P_i(b)\right), \left\|\pi_b\left(\overrightarrow{\nabla M}\right)\right\| = k \tag{10}$$

Where $\pi_b\left(\overrightarrow{\nabla M}\right)$ is the orthogonal projection of $\overrightarrow{\nabla M}$ on $P_i(b)$.
Otherwise it is a complex gradient.

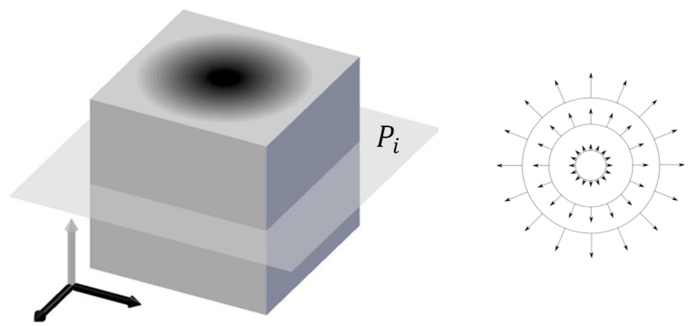


Figure 5. Representation of (a) an *offset gradient* and (b) equipotential lines in $P_i(b)$

Representation of classification

FGM parts which check assumptions (*Definitions and assumptions*) are classified in one of typologies of gradient (Fig. 6).

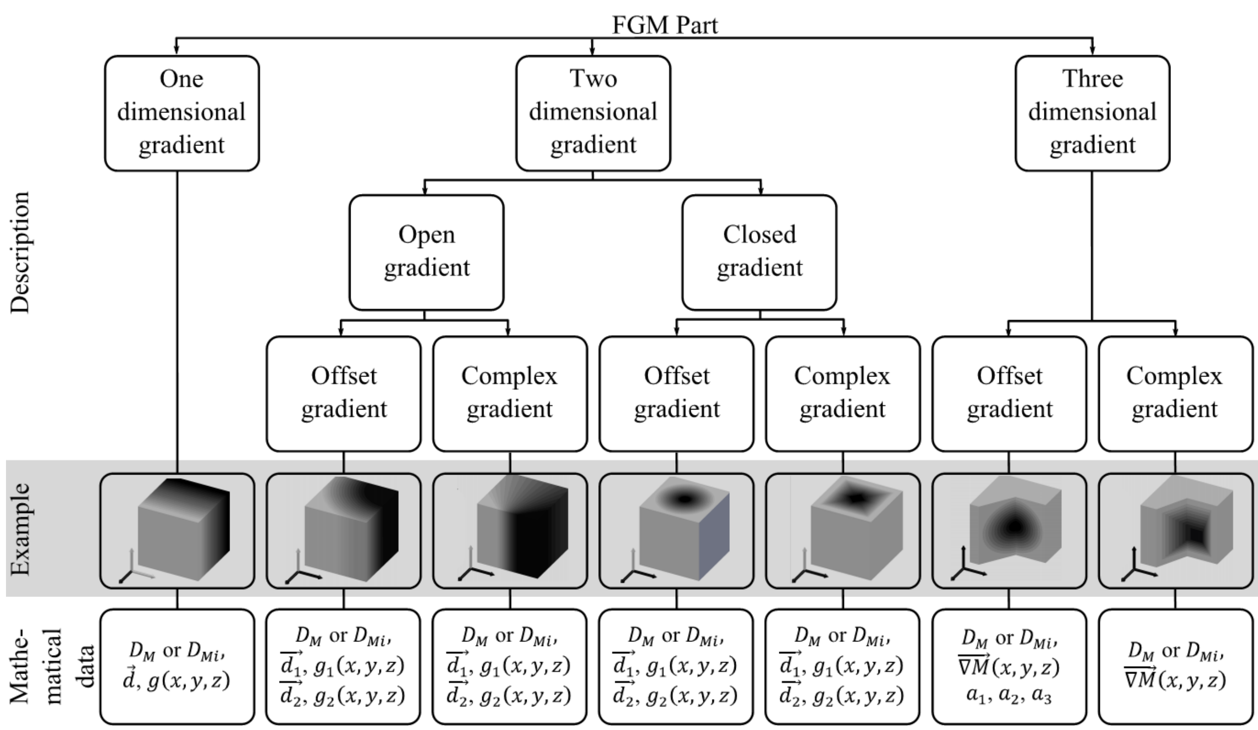


Figure 6. Representation of the classification

Types of slices and part orientations

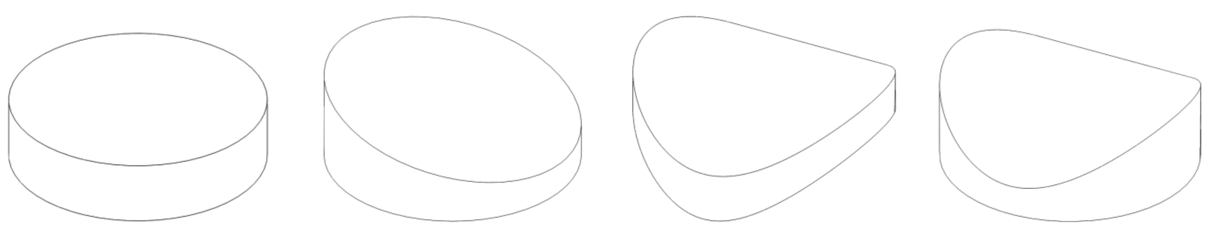
For this methodology, the types of slices and part orientations considered must be described with mathematical data. They are chosen according to the geometry of the part.

The domain of the part D_M can be decomposed in several sub-domains D_{Bi}. In this case, the method of manufacturing must be described on all sub-domains. A domain D_{S_i}, corresponding to the support, is assigned to domain D_M or each sub-domain D_{Bi}. This domain D_{S_i} doesn't have specification about material, it exists to support the manufacturing but will be removed by a post process.

Definitions

The slices are *planar* if the deposition is made on flat surfaces. If the deposition is made on other type of surfaces, the slices are *complex* (Fig. 7).

The slices are *uniform* if the height of deposition is constant throughout the layer. If the height is variable on the layer, the slices are *non-uniform* (Fig. 7) [Singh03, Ruan07]. Mathematical description of a manufacturing with *uniform* slices is detailed in this paper.

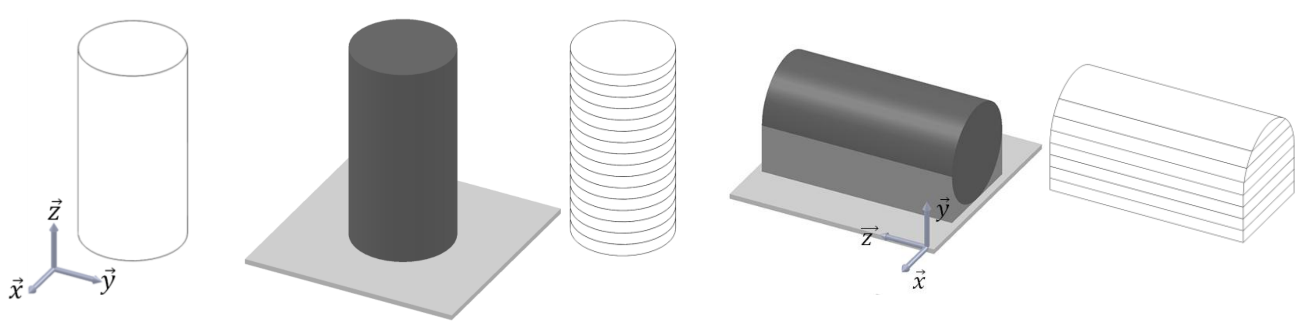


(a) (b) (c) (d)

Figure 7. Type of slices: (a) *planar* and *uniform* (b) *or non-uniform*, (c) *complex* and *uniform* or (d) *non-uniform*

Mathematical description

The method of manufacturing with *planar* and *uniform slices* (Fig. 7(a), Fig. 8) is defined by a vector $\overrightarrow{n_j}$. This vector is unit, perpendicular to the slices and its sense is such that it points in the direction the last slice.

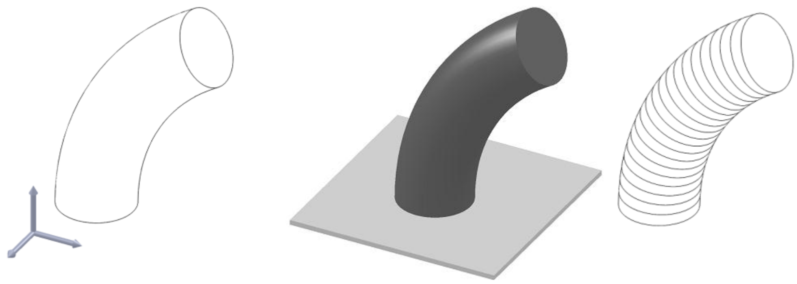


(a) (b) (c)

Figure 8. Example of a part: (a) domain D_M and two orientations of the part with *planar* and *uniform slices*: $(b)\left(\overrightarrow{n_1} = (0,0,1),\ D_{S_1} = \emptyset\right)$ and $(c)\left(\overrightarrow{n_2} = (0,1,0), D_{S_2}\right)$

The method of manufacturing with *planar* and *non-uniform slices* (Fig. 7(b), Fig. 9) is defined by a set of unit vectors $\overrightarrow{n_{j,i}}$ stemming from parameterized curve $C_j(t)$:

$$\overrightarrow{n_{j,i}} : \begin{pmatrix} \alpha_{j,i} \\ \beta_{j,i} \\ \gamma_{j,i} \end{pmatrix} \text{ and } C_j(t) : \begin{cases} x_j(t) \\ y_j(t) \ \forall\, t \in [t_{min}\,, t_{max}] \\ z_j(t) \end{cases} \tag{11}$$



(a) (b)

Figure 9. Example of a part: (a) domain D_M, (b) and one orientation of the part with *planar* and *non-uniform slices*

The domain D_M is modified in k sub-domains $D_{B\,j,i}$. These domains are on planes $\Pi_{j,i}$. These planes are defined by:

$$\Pi_{\mathrm{j,i}} : \{\alpha_{j,i}x + \beta_{j,i}y + \gamma_{j,i}z = \delta_{j,i}\} \tag{12}$$

The real numbers $\alpha_{j,i}$, $\beta_{j,i}$, $\gamma_{j,i}$ and $\delta_{j,i}$ are obtained with k points $c_{j,i}$ of the parameterized curve $C_j(t)$. These points are spaced to the distance τ – length of the curve $C_j(t)$ on an interval $[t, t + \Delta t]$ – corresponding to the mean thickness of a layer:

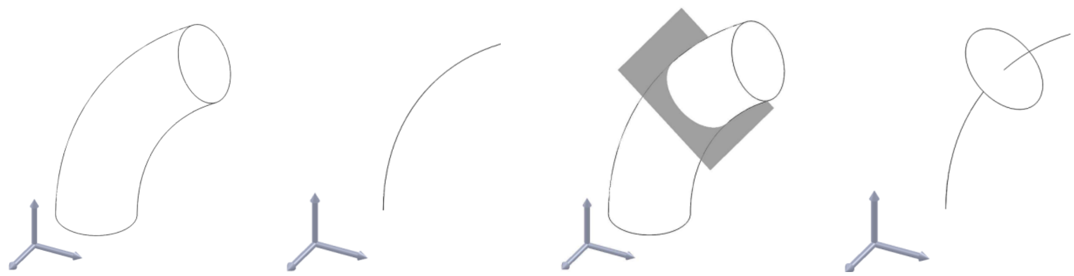
$$c_{j,i} : \begin{cases} x_j(i.\Delta t) \\ y_j(i.\Delta t) \text{ with } i \in [\![1\,, k]\!] \\ z_j(i.\Delta t) \end{cases} \tag{13}$$

$$\tau = \Delta t \times \int_{t_{min}}^{t_{max}} \sqrt{\frac{dx_j}{dt}(t)^2 + \frac{dy_j}{dt}(t)^2 + \frac{dz_j}{dt}(t)^2}\, dt \tag{14}$$

The planes $\Pi_{j,i}$ are perpendicular to the tangent of the curve $C_j(t)$ in $c_{j,i}$ and the point $c_{j,i}$ is in the plane $\Pi_{j,i}$:

$$\begin{cases} \alpha_{j,i} = \frac{dx_j}{dt}(i.\Delta t) \\ \beta_{j,i} = \frac{dy_j}{dt}(i.\Delta t) \text{ and } \delta_{j,i} = x_j(i.\Delta t) + y_j(i.\Delta t) + z_j(i.\Delta t) \\ \gamma_{j,i} = \frac{dz_j}{dt}(i.\Delta t) \end{cases} \tag{15}$$

The study of classification of gradient is made on sub-domains which are planes. In $D_{B\,j,i}$, it is possible to have a *homogenous material*, an *one dimensional gradient* or a *two dimensional gradient* (Fig. 10).

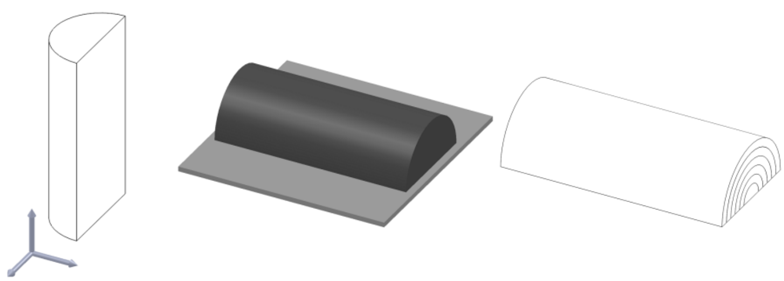


(a) (b) (c) (d)

Figure 10. Example of a part: (a) domain D_M, (b) parameterized curve $C_1(t)$, (c) plane $\Pi_{1,i}$ and (d) sub-domain $D_{B1,i}$

The method of manufacturing with *complex* and *uniform slices* is defined by the skin surface S_j (Fig. 7(c), Fig. 11).

The method of manufacturing with *complex* and *non-uniform slices* is defined by a set of surfaces $S_{j,i}$ (Fig. 7(d)). The domain D_M is modified in k sub-domains $D_{Bj,i}$. These domains are in surfaces $S_{j,i}$.



(a) (b)

Figure 11. Example of a part: (a) domain D_M, (b) and one orientation of the part with *complex* and *uniform slices*

Representation of classification of types of slices

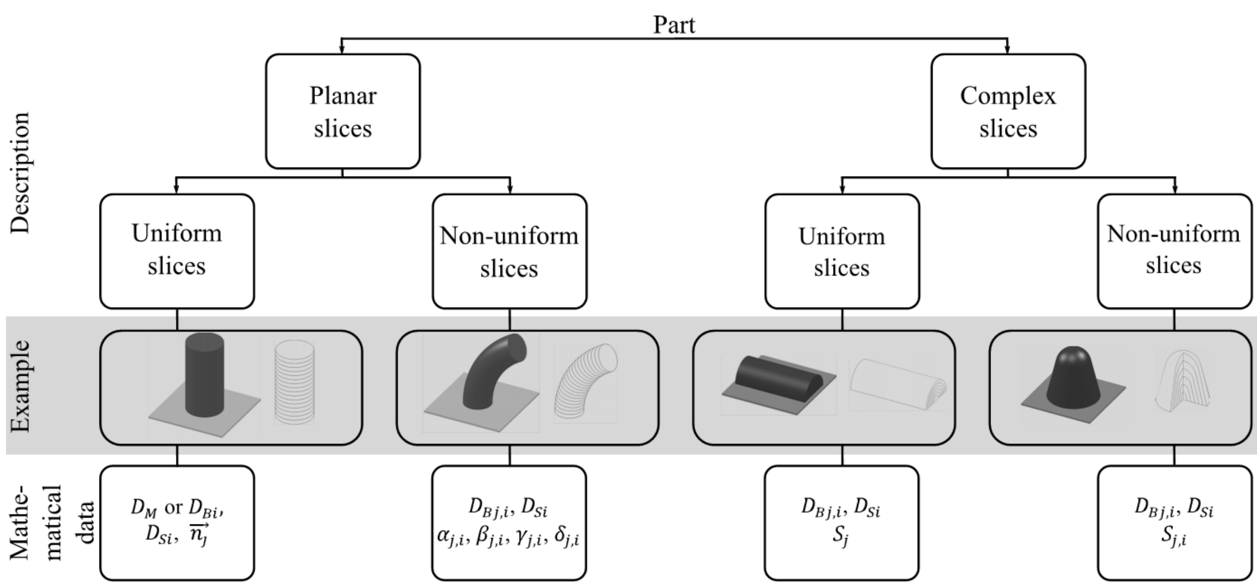


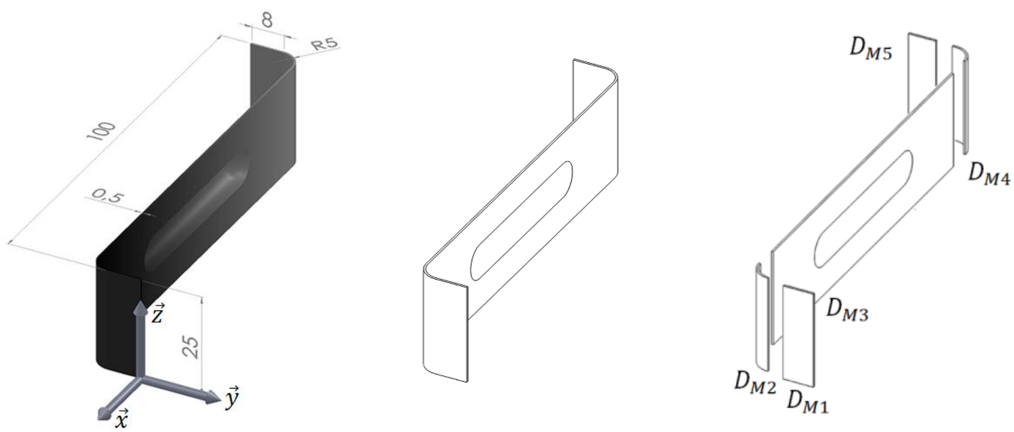
Figure 12. Representation of the classification

Example of application of the methodology

The step *Classification of gradients* – with input data *Material reparation* and *Geometry* – and input data *Types of slices and part orientations* of step *Determination of manufacturing* strategies are applied on an example part. Material repartition and geometry are given. It is necessary to select possible methods of build.

Material repartition and geometry

The domain D_M is decomposed in five sub-domains $D_{Mi},\ i \in [\![1\ ,5]\!]$ (Fig. 13).



(a) (b) (c)

Figure 13. Example of a part [16]: (a) material repartition with characteristic dimensions (*mm*), (b) domain D_M, (c) and sub-domains D_{Mi}

The material repartition is worded in each sub-domain. In domains D_{M1} and D_{M5} the material is homogeneous, so the function $M(x, y, z)$ is constant. In others, the function $M(x, y, z)$ is linear from 0 to 1 along the part.

Sub-domain	Material function $M(x, y, z)$
D_{M1}	0
D_{M2}	$\sin\left(\tan^{-1}\left\lvert\frac{y+8}{x+5}\right\rvert\right)\times\left(\frac{5\pi}{2}\times\frac{1}{5\pi+90}\right)$
D_{M3}	$\frac{-(x+5)}{90+5\pi}+\left(\frac{5\pi}{2}\times\frac{1}{5\pi+90}\right)$
D_{M4}	$\sin\left(\tan^{-1}\left\lvert\frac{y+13}{x+100}\right\rvert\right)\times\left(\frac{5\pi}{2}\times\frac{1}{5\pi+90}\right)+1-\left(\frac{5\pi}{2}\times\frac{1}{5\pi+90}\right)$
D_{M5}	1

Table 1. Material function in each sub-domain

Classification of gradients

The study of classification of gradient is made on sub-domains D_{M2}, D_{M3} and D_{M4}. On the domain D_{M2} the gradient is defined by:

$$\forall(x,y,z) \in D_{M2}, \overrightarrow{\nabla M}(x,y,z) = g_{2,1}(x,y,z).\overrightarrow{d_{2,1}} + g_{2,2}(x,y,z).\overrightarrow{d_{2,2}} \tag{16}$$

with $\overrightarrow{d_{2,1}} = (1,0,0)$ and $\overrightarrow{d_{2,2}} = (0,1,0)$, so the gradient is a *two dimensional gradient*. The spaces $\{D_{M2} - D_{A2} - D_{B2}\}$ is simply connected, so the gradient is an *open gradient*. The equipotential surfaces are not offset, so the gradient is a *complex gradient*. The same analysis is made on the domain D_{M4}, the gradient on this domain is the same type as the gradient on the domain D_{M2}.

On the domain D_{M3}, the gradient is defined by:

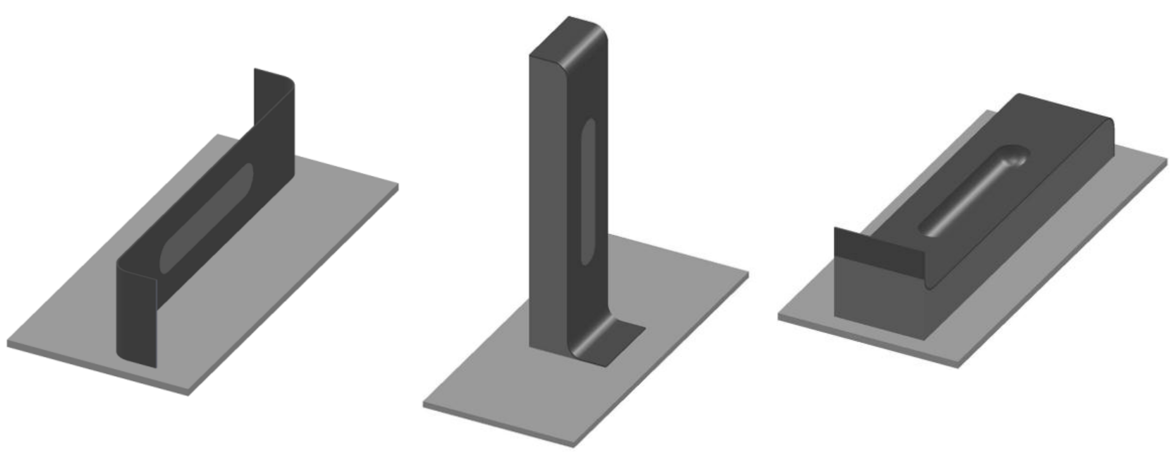
$$\forall(x,y,z) \in D_{M3}, \overrightarrow{\nabla M}(x,y,z) = g_3(x,y,z).\overrightarrow{d_3} \tag{17}$$

With $\overrightarrow{d_3} = (1,0,0)$, so the gradient is a *one dimensional gradient*.

The part is described and each sub-domain is classified. Mathematical data given by the step *Classification of gradient* are the sub-domains D_{Mi}, $i \in [\![1\ ,5]\!]$, type of gradient in each sub-domain, the directions of gradients $\overrightarrow{d_{2,1}}$, $\overrightarrow{d_{2,2}}$, $\overrightarrow{d_3}$, $\overrightarrow{d_{4,1}}$, $\overrightarrow{d_{4,2}}$ and the gradient functions $g_{2,1}(x,y,z)$, $g_{2,2}(x,y,z)$, $g_3(x,y,z)$, $g_{4,1}(x,y,z)$ and $g_{4,2}(x,y,z)$.

Types of slices and part orientations

Possible types of slices and part orientations must be described with mathematical data. Initially, it is important to have a significant number of choices to avoid forgetting an optimal strategy. Several examples of build are showed in this section. It is possible, for example, to manufacture this part with *planar* and *uniform slices* (Fig. 14).

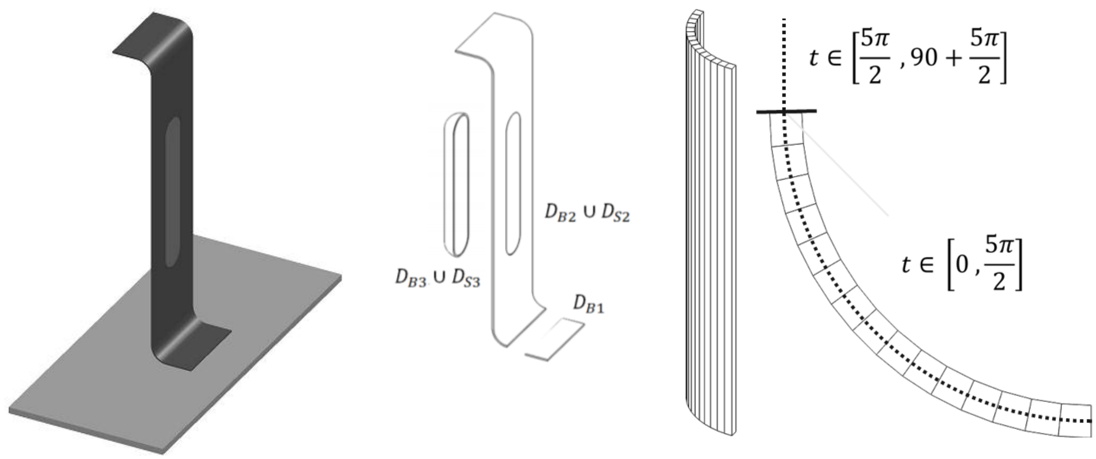


(a) (b) (c)

Figure 14. Few examples of methods of build with *planar* and *uniform slices*: (a)$\left(\overrightarrow{n_1} = (0,0,1),\ D_{S_2}\right)$ (b)$\left(\overrightarrow{n_1} = (-1,0,0),\ D_{S_2}\right)$ and (b)$\left(\overrightarrow{n_3} = (0,1,0), D_{S_3}\right)$

It is possible to have a decomposition of the domain D_M in several sub-domains D_{Bi}. An example of this kind of manufacturing is presented (Fig. 15). In this example, two types of slices are present in three sub-domains. In the domain D_{B1}, the method employed is a manufacturing with *planar* and *uniform slices*. There is not support, so $D_{S1} = \emptyset$. The method of manufacturing is represented by the vector $\overrightarrow{n_4} = (-1{,}0{,}0)$. The same method is used in the domain D_{B3}, with $D_{S3} \neq \emptyset$ and $\overrightarrow{n_5} = (0, -1{,}0)$. A manufacturing with *planar* and *non-uniform* slices is employed in the domain D_{B2}. For this domain, the type of slices is represented by a parameterized curve $C_1(t)$:

$$C_1(t): \begin{cases} \begin{cases} x_1(t) = 5\left(\cos\left(\frac{t}{5}\right) - 1\right) \\ y_1(t) = -5\sin\left(\frac{t}{5}\right) - 8 \end{cases} \forall\, t \in \left[0\,, \frac{5\pi}{2}\right] \\ \begin{cases} x_1(t) = -\left(t - \frac{5\pi}{2}\right) - 5 \\ y_1(t) = -13 \end{cases} \forall\, t \in \left[\frac{5\pi}{2}\,, 90 + \frac{5\pi}{2}\right] \\ \begin{cases} x_1(t) = -5\sin\left(\frac{t - (90 + 5\pi/2)}{5}\right) - 95 \\ y_1(t) = 5\left(\cos\left(\frac{t - (90 + 5\pi/2)}{5}\right) - 1\right) - 13 \end{cases} \forall\, t \in \left[90 + \frac{5\pi}{2}\,, 90 + 5\pi\right] \\ \begin{cases} x_1(t) = -100 \\ y_1(t) = -\big(t - (90 + 5\pi)\big) - 18 \end{cases} \forall\, t \in [90 + 5\pi\,, 98 + 5\pi] \\ z_1(t) = 12{,}5 \;\; \forall\, t \in [0\,, 98 + 5\pi] \end{cases} \tag{18}$$



(a) (b) (c)

Figure 15. (a)(b) Example of methods of build with decomposition in several D_{Bi} and (c) slicing of the domain D_{B2} with $t \in \left[0, \frac{5\pi}{2}\right]$

Conclusion of example

With data about material gradient and slices, the optimal manufacturing strategies can be determined. Optimal choices depend on objectives and requirements. To do that, it is necessary to define criteria, such as support volume or discretization of the gradient by the process. In terms of criteria chosen, the strategy is optimized according to cost, quality or time of manufacture.

Conclusion

In this paper, the principle of a methodology to find best way to produce FGM parts is exposed. A classification of gradients is proposed from material repartition. Mathematical data about gradients are obtained with this classification. The input data types of slices and part orientations are explicated and the principle of strategies choice and main issues are introduced. The classification of gradients and the description of possible choices of types of slices are applied on a first example.

Further researches will be conducted in two ways. Firstly, to develop the methodology: strategies must be proposed for each type of gradient with novel paths, criteria must be established to choose best strategies in terms of material, geometry and process.

Secondly, to have a global control of a process for multi-materials manufacturing. Test parts and functionally complex parts will be produced to show the interest of the methodology. Laser direct metal deposition experiments were conducted with a process based on the three dimensions layer by layer deposition of laser melted powders. This system consists of a five-axis nozzle coaxial powder feed system, a fiber laser and three powder feeders. The control is performed on the kinematic of the machine axis, laser parameters and powder feeders parameters with mathematical data obtained in the two first steps of the methodology.

This work was carried out within the context of the working group Manufacturing 21 which gathers 16 French research laboratories. The topics approached are: the modeling of the manufacturing process, the virtual machining and the emerging of new manufacturing methods.

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