3D-printing of thermoplastic structures by FDM using heterogeneous infill and multi-materials: An integrated design-advanced manufacturing approach for factories of the future

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Résumé :

Les usines du futur ambitionnent de mettre en oeuvre des approches de conception-production intégrées dans une démarche de « fabrication avancée ». Or, la combinaison de la fabrication additive (ou impression 3D) et de l'optimisation topologique du design offre de nouvelles opportunités pour créer des produits plus légers à impact environnemental réduit. Le procédé d'impression 3D par dépôt de fil fondu (FDM) est un procédé de fabrication additive très répandu et économique, et pour lequel le contrôle des paramètres de fabrication est très ouvert. L'objectif de ce travail est d'améliorer la conception des structures imprimées en 3D en utilisant l'optimisation topologique pour définir l'enveloppe extérieure des objets, puis d'utiliser soit un remplissage hétérogène de l'objet avec différents motifs cellulaires avec des gradients de densité ou d'utiliser plusieurs matériaux pour atteindre les propriétés d'usage ciblées. En se basant sur la simulation par éléments finis de la réponse mécanique de la géométrie optimisée, la distribution des contraintes mécaniques permet de localiser les zones critiques à renforcer par un meilleur remplissage (plus dense ou avec des motifs optimaux) ou par l'utilisation de matériaux renforcés. Dans le cas d'étude, deux matériaux thermoplastiques sont combinés : l'ABS vierge et de l'ABS conducteur électrique qui est chargé de noir de carbone. Dans l'approche d'optimisation proposée, le polymère conducteur peut être remplacé par un autre système polymère (polymère renforcé avec des charges, fibres courtes ou nanoparticules) pour accroître la rigidité. Lorsque la géométrie optimale interne et externe de la pièce est définie, un autre challenge est de définir les meilleurs paramètres de fabrication. Lors de l'impression 3D avec remplissage hétérogène ou avec utilisation de plusieurs matériaux des interfaces fragiles sont créées dont la résistance mécanique est fortement liée au choix du chemin de dépôt de fil fondu. Ce point est aussi évoqué dans cet article.

Abstract :

Factories of the Future (FoF) are expected to implement new integrated design-manufacturing approaches to go towards so-called 'advanced manufacturing'. Actually, combination of additive manufacturing (AM, or 3D-printing) and topological optimization offer new opportunities to produce lighter products with lower environmental footprint. Fused Deposition Modeling (FDM) is a widely used AM process which is affordable with a free control of process parameters. This paper aims at improving the design of 3D-printed structures using topological optimization to define the external geometry and then either heterogeneous internal filling or multimaterials to achieve targeted usage properties.

Based on structural mechanics simulation, parts of the structures where stresses field is high are printed with high density internal filling, or alternatively a new material with improved mechanical properties is added. In the present case study, two thermoplastic materials are combined: virgin ABS and conductive ABS (filled with carbon black). In the proposed optimization approach, the conductive polymer can be replaced with another polymer system (e.g. polymer reinforced with fillers, short fibers or nanoparticles) to increase the stiffness. While the optimal inner and outer designs are defined, another challenge is to identify the best manufacturing parameters. During 3D-printing of variable densities filled parts or multimaterials parts, weak interfaces are created, whose mechanical strength is strongly linked to the printing patterns. This particular issue is also addressed in the paper.

Keywords : Deposition Modeling, Topological optimization, Multimaterials, Inner Structures

1 Introduction

Combining topological optimization for the design and 3D-printing for the manufacturing, integrating the constraint of the process in the design, constitutes an integrated design-manufacturing approach which offers numerous advantages. Optimized hollow objects are lighter and reduce the raw materials consumption. Also, using multiple materials in the same 3D-printing process avoids the assembly steps which are time-consuming and expensive.

Among additive manufacturing processes, Fused Deposition Modeling (FDM) is of particular interest for manufacturing of thermoplastic parts: this process is cheap, easy to use, the process parameters can be freely controlled, and it has limited design restrictions. Today the range of available materials is limited but it increases day after day with a large variety of micro- and nano-fillers added in the available polymer threads [1,2], or the development of high performance thermoplastic threads made of PEI (Polyetherimide) [3] or PEEK (Polyether ether ketone) [4] with new extruder capable of attaining processing temperatures up to 400 deg. C.

In the present work, after a first step of topological optimization, the capacity of FDM to control freely the infill of the printed objects and the use of multimaterials are investigated to improve the design of the manufactured part.

Topological optimization aims at developing an iterative simulation method that starts from a very simple external geometry to find after convergence a new geometry that reduces the weight of the structure while maintaining good physical performances. If the goal is to define an optimal geometry with good mechanical strength, the stiffness of the new structure, the total strain energy and stresses field concentrations are good indicators to evaluate the new design solution. Indeed, stresses concentrations indicate the locations where cracks can initiate.

As the resulting geometry can be very complex with hollow parts, where sometimes bio-inspired structures can appear, 3D-printing is particularly suitable for the manufacturing. To improve mechanical strength and fatigue life of the printed structure, it makes sense to focus attention during manufacturing in the areas where stress concentrations are high.

Two approaches are then proposed in order to reinforce the topological optimized structures: (i) increasing the filling density in the critical parts of the structure, and (ii) replacing the constituting polymeric material with another more resistant polymer system.

2 Topological optimization

A symmetric mechanical structure submitted to tensile loading is considered. The figure 1 shows the initial geometry and the corresponding boundary conditions. The combined topological optimization and structural mechanics simulations are performed using Comsol Multiphysics© Software.

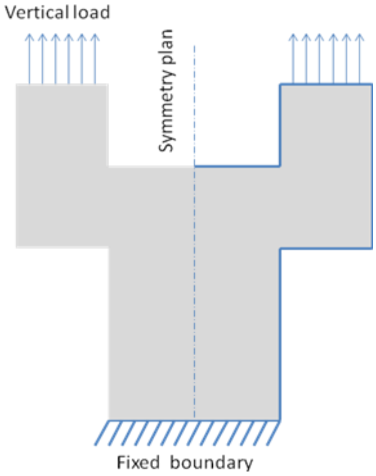


FIG 1 - Initial geometry and boundary conditions for the topological optimization

The goal of the optimization is to minimize the total weight with a distribution of materials that maximize the stiffness. The upper bound of the new surface area must be less than 50% of the initial surface area. The Solid Isotropic Material with Penalization method (SIMP) [5,6] is used to minimize the total strain energy W_s or maximize the stiffness for a fixed amount of material. The control variable is the artificial density ρ_{design}. Local Young's modulus is a function of the true Young modulus E_0 and is defined by the following equation:

$$E(x) = \rho_{design}\,(x)^p E_0 \tag{1}$$

The exponent p (p=5) is added in order to discourage the formation of intermediate density. The density parameter is constrained such that $10^{-9} \leq \rho^p \leq 1$. The small lower bound is used for numerical reasons. During the optimization process, the fraction of material used by the new structure is bounded by the following integral inequality constraint:

$$0 \leq \int_\Omega \rho_{design}\,(x) d\Omega \leq 0.5\mathrm{A} \tag{2}$$

where A is the initial surface area.

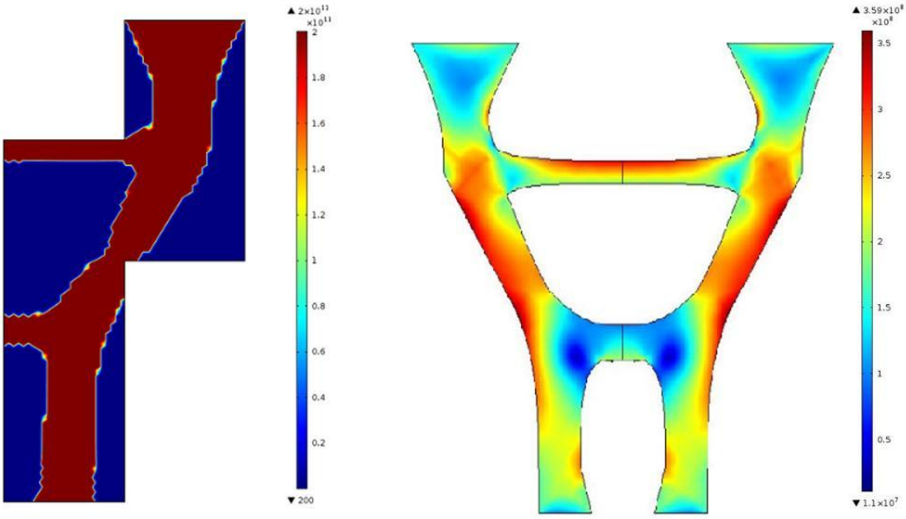
Minimizing the total strain energy while limiting the variation of density in the computational domain is realized minimizing the following objective function:

$$f = \frac{(1-q)}{Ws_0} \int_\Omega W_s(x) d\Omega + q\,\frac{h_0 h_{max}}{A} \int_\Omega \left|\nabla \rho_{\mathrm{design}}\,(\mathrm{x})\right|^2 d\Omega \tag{3}$$

where q is a parameter that controls the fraction (1-q) of objective term (first term) and the fraction q of the penalty term (second term). Ws_0 is the total strain energy stored by the non-optimized structure for a constant fraction ρ_{design} set to 0.5 in the whole domain.

h_0 and h_{max} are respectively the initial mesh size and the current mesh size. The first integral term of equation (3) corresponds to the minimization of the normalized total strain energy. The last integral term is added to penalize the total variation of the design variable.

The figure 2 shows the distribution of Young's modulus after optimization which defines the optimal geometry by color contrast (a) and the corresponding Von Mises stresses fields evaluated on a optimal cleaned structure (b). Cleaning procedure consists in making binary image of figure 2a, detecting edges and extracting points coordinates using ImageJ© software. After curves interpolations, a 2D-3D STL conversion by shape extrusion is performed using Comsol Multiphysics©.



(a) (b)

FIG 2 - Young's modulus (Pa) distribution defining the optimal shape (brown domain) (a) and stresses field (Pa) in the cleaned geometry (b).

The figure 2b shows the stresses distribution in the optimal structure extracted from the topological optimization simulation after cleaning. Stress level is particularly high in the middle height of the part. The next step is to manufacture the structure by fused deposition modeling considering firstly a heterogeneous filling and secondly the use of multimaterials. The goal is to apply a specific manufacturing process in the critical zones of the structure corresponding to high stress level.

In order to apply a specific manufacturing treatment in the mid-height of the part, the structure is divided into three domains as defined by figure 3. This choice is based on stresses concentration field (Fig2b) to include high stresses domains in a high performance material domain.

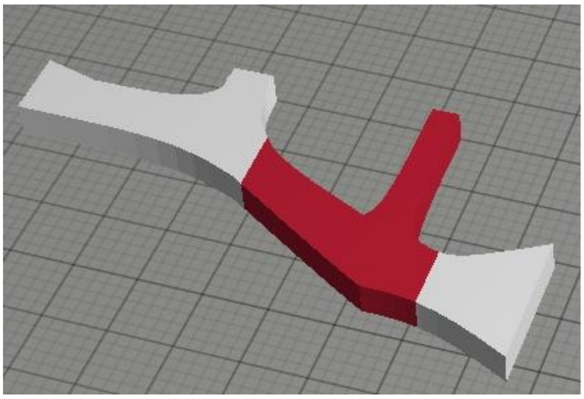


FIG 3 - Splitting of the optimal geometry to apply a specific manufacturing treatment in the middle zone

3 Fused deposition modeling with heterogeneous infill

The FDM additive manufacturing process makes it possible to control the internal structure of the 3D-printed object. Indeed, the slicer software proposes settings to control the fraction of material and the infill pattern geometry. Infill optimization is another way to reduce weight while maintaining good mechanical performances. For example, it is well known that honeycomb shapes provide a high resistance in compression with a high fraction of voids and are thus used for load-bearing structures.
Rectilinear patterns are used for the different parts of the structure with a fraction of 20% of material for the external parts (grey zones in figure 3) and a fraction of 60% of material for the mid-height part (red zone in figure 3). The corresponding fractions are selected to create a more resistant domain in the high stresses concentration domain (middle part) while maintaining a light structure.
The elementary cell has a squared shape which is mechanically performant for tensile loading conditions. The figure 4 shows the 3D-printed structure with the corresponding infill. Virgin ABS material colored in red is used in this case.

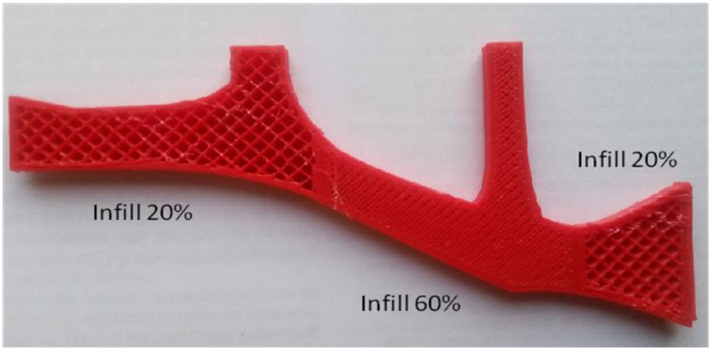


FIG 4 - Inner rectilinear filling of the optimized structure with variable densities

The infill angles are 45 and -45° related to the height direction. The increasing of infill density is an efficient way to improve stiffness.

4 Fused deposition modeling with multimaterials

Some FDM 3D-printers are equipped with multiple extruders, making it possible to produce multimaterials manufactured objects. Multimaterials can be the association of different thermoplastics or of a given thermoplastic and its filled/reinforced counterpart. Multimaterials can be used to improve flexibility or to increase the stiffness in specific parts. Conductive polymers can be used to convey electricity in the core or the surface of the object or to attenuate electromagnetic interference emissions [7].
In the present case study, the critical part for the structure (mid-height part) is made of carbon black-filled ABS while keeping virgin ABS elsewhere. Addition of fillers results in a conductive polymer by percolation. The conductive polymer can be easily replaced by stiff particles-filled polymers to improve the stiffness.

FIG 5 - Optimized structure printed with two different materials

Finding the optimal conditions for good adhesion between the different polymers used is a challenge. First of all compatibility between polymers is of course required. Considering the printing process, the polymer thread temperature at each side of the interface must be close to the melting temperature. Printing of threads at each side of the interface must be consecutive to insure these temperature conditions.

To find the best conditions for 3d printing of multimaterials with good resistance at the interfaces, we have printed three bi-materials samples with various process conditions and have submitted them to tensile tests. The samples are shown in figure 6. The first sample has been printed in vertical position (vertical stacking of parts) where the interface layers are printed consecutively. We expect that in this configuration the interface resistance will be optimal. The second sample has been printed in horizontal position with two parts placed side by side without gap between them. Unfortunately the quality of the interface is very brittle and is easily fractured by hand traction. For the third sample, to improve the adhesion between layers at the interface, we propose a horizontal printing configuration but with alternative interpenetration of each material layer on a short distance at the interface.

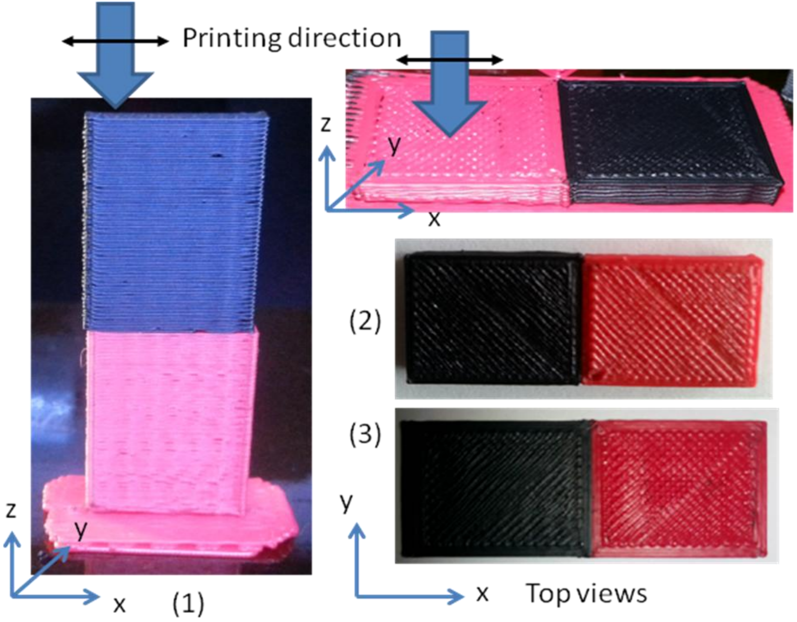


FIG 6 – Bimaterials samples : (1) vertical printing, (2) horizontal printing with side by side parts, (3) horizontal printing with side by side and interpenetrated layers at the interface.

As the sample 2 interface is very brittle, tensile tests are only conducted for bi-materials samples 1 and 3, loaded in z and x directions respectively. Tensile tests are also conducted for each ABS material for comparisons. Results are summarized in table 1.

	bi-materials			One material	
Sample configuration	1	2	3	Black ABS	Red ABS
Sample position during printing	vertical	horizontal	horizontal	horizontal	horizontal
Ultimate tensile strength (Mpa)	3.2	brittle	6.24	10.55	23

Table 1 : Mechanical performance according to the printing configurations

Table 1 shows that multimaterials interface weaken the mechanical performance of 3d printed objects. However, an optimal stacking strategy with interpenetration of layers at the interface can clearly improve the ultimate tensile strength. In our case, ultimate tensile strength is twice for sample 3 compared to sample 1.

As the printing of each material is sequential, extruders which are not used have some waiting time. During this period of inactivity the end of the polymer thread is heated but not extruded (i.e. its residence time in the extruder barrel is long).

Purge walls, which correspond to external structures placed close to the object, are used to clean the extruder before the change of material and to reach a steady-state deposition configuration before printing the object. These purge walls reduce mixing of materials but they increase the printing time and influence the thermal cooling history. Vertical printing of sample 1 with purge walls increase by a factor three the printing time comparing to sample 3 with purge walls.

5 Conclusion

Topological optimization was combined with heterogeneous infill or with the use of multi-materials during 3D-printing by Fused Deposition Modeling. Infill density distribution can be optimized to improve the stiffness in the stress concentration zones of the manufactured thermoplastic part. A stiffer polymeric material can also be added in these specific areas to improve the mechanical performance of the structure. Using particle-filled polymer threads in the critical zone of the structure while using virgin non-reinforced threads in the other zones, is a suitable solution to insure compatibility between thermoplastics. Finally, proper definition and control of the manufacturing parameters and more particularly the printing pattern are also crucial to ensure good adhesion between materials. We have also shown that 3d printing of horizontally placed parts with interpenetration of bi-material at the interface can really improve the mechanical strength and reduce significantly the printing time compared to printing of vertically placed parts. This offers good prospects for multimaterials 3d printing improvement.

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