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Challenges of additive manufacturing technologies from an optimisation perspective

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Abstract – Three-dimensional printing offers varied possibilities of design that can be bridged to optimisation tools. In this review paper, a critical opinion on optimal design is delivered to show limits, benefits and ways of improvement in additive manufacturing. This review emphasises on design constrains related to additive manufacturing and differences that may appear between virtual and real design. These differences are explored based on 3D imaging techniques that are intended to show defect related processing. Guidelines of safe use of the term "optimal design" are derived based on 3D structural information.

Key words: Additive Manufacturing, Topological optimisation, Process-induced defects, X-ray micro-tomography.

1 Introduction

Additive Manufacturing (AM) is a collection of versatile techniques of rapid prototyping that allow material design from 3D digital models [1–3]. The term AM comes also under different other nicknames such as direct digital manufacturing or solid freeform fabrication [4, 5]. AM is rated as one of the most promising technology for design [6], presented as a new industrial revolution [7], and a vector for creativity [8], impact [9] and interrogations [10]. The laying down of the material in different states including liquid, powder and fused material defines roughly categories of AM [2, 7, 11–13]. More accurate classifications do exist such as the ASTM F42 reported in reference [14]. Wide varieties of materials can be processed using additive manufacturing including metals [15–18], alloys [19–22], ceramics [23–26], polymers [27–30], composites [31–34], airy structures [35, 36] and multi-phase materials [37–39].

The main characteristic of AM is the reduced number of manufacturing steps that stands between the virtual design and the ready-to-use part [40]. In addition, one major advantage of AM reported in the literature is the ability to process complex shapes that are not easy to design using traditional ways such as extrusion and moulding [3, 41, 42]. AM potential, as a leading design technique, is enormous and the related applications are huge [7, 43–47]. Different printing techniques are used in the biomedical sector [41, 48] more particularly for tissue engineering [5, 35, 49–51]. Preform design of composites is evidently an inspiring topic for AM [31] because of the wide possibilities in structuring yarns and reinforcing composite structures [34]. Aerospace applications of AM are the most challenging because of the extreme performance that need to be achieved under fine scale monitoring and in-service validation [52, 53]. Recent contributions by NPU demonstrates the central role of topology optimisation in additive manufacturing for aerospace applications [54, 55]. Micro-fabrication technologies emerge also as an efficient way to produce functional micro-components for microelectronics systems [42]. The scaling down of AM is now possible thanks to cutting edge processes that allow material design at a very fine scale like with different types of lithography [55, 56].

The idea behind AM is the direct import of CAD (Computer-Aided-Design) object as machine instructions (Figure 1). The preferred way to achieve this import is the transformation of surface tessellation representing the geometry of the virtual part into a set of toolpaths. One starts from an

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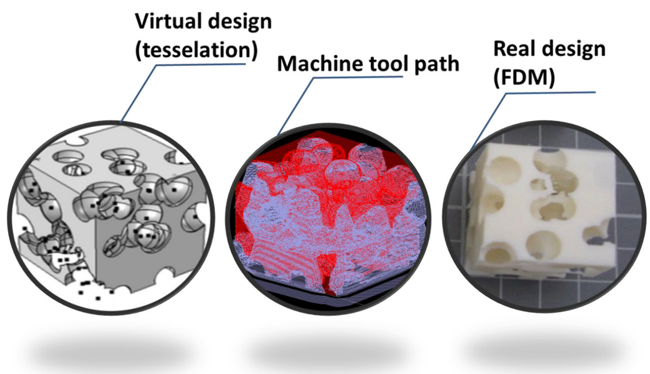

Figure 1. The process chain in typical AM.

STL or Standard Tessellation Language or STereoLithography file. All external boundaries and internal surfaces appear smooth and continuous using STL format. Generation of the toolpaths represents the first challenge and actually a limitation for AM [57]. The reason is that the building process in most 3D printing technologies relies on a successive layer-by-layer building process. So, starting from 3D space tessellation and ending with 2D building strategy is a first drawback. It is even worse when droplet based printing is considered because the fused matter is no more connected in any direction. Discontinuities may appear in all building directions (Figure 2) as a result of the layer-by-layer laying down process (Figure 3) [27]. The consequence of this appears to be the development of dimensional inaccuracy, inacceptable finishing state, structural and mechanical anisotropies, which are continuously addressed in many research contributions [12, 28, 58–64]. Anisotropy can be also inferred to the development of particular grain texture as revealed by laser melting deposition or arc welding alloying of metals [61, 65–68]. Reduction of anisotropy can be achieved by selecting the appropriate orientation of the virtual design [69–71]. Numerous papers mention strategies of common sense to build parts with acceptable performance, which are nearly equivalent or even superior to other design techniques. Scudino and others [67, 72] report that better ductility of metallic materials can be achieved using selective laser melting compared to casting as a result of the fine grain structure driven by AM. One particular feature highlighted in these contributions refers to avoid building the part along its largest surface. In other words, if the successive layers of the part exhibit a lack of cohesion, the large contact area between layers drives worse performance under tension. Some other strategies rely on reducing the lack of cohesion between layers or filaments by further processing of the real design. An example of radiation treatment is proposed in the work of Shaffer et al. [28].

In addition to the role of anisotropy, differences between the virtual and real design can be striking knowing that AM resolution is finite due to available tooling [64]. If we consider the example of fused deposition modelling, which is a popular AM technique [12], the toolpath generation is referred as collection of filament paths of finite dimensions (Figure 3). This has three main consequences on the real design: internal structural features may not be well captured depending on their size; discontinuities may appear depending on local curvature; and the surface finishing state may be limited due to rough profiles [62]. These limitations are illustrated in Figure 2, which highlights simple and complex geometries and the corresponding toolpath generation using two software, one is Repetier from Hot-World GmbH & Co, Germany and the other is CatalystEx from Stratasys Inc. Eden Prairie MN, USA.

All limitations mentioned earlier assume implicitly the role of defects induced by AM. These need to be faced in order to deliver a design representing, with much accuracy, the result of an optimisation procedure. These defects are related to the porosities that develop as a consequence of the discontinuous process of printing and other issues related to process errors [73]. A large number of contributions is dedicated to the evaluation of the effect of porosities in printed parts. One particular consequence of the role of porosity is that a large amount of them reduces the mechanical performance. Such reduction is represented by a theoretical linear decrease of stiffness with the increase porosity level (if limited stress transfer between layers is neglected). Under tension, porosities act as stress concentrators and may induce lower mechanical strength by enhancing the development of damage in the form of micro-cracks. Under compression, different considerations can be pointed out. Even if the porosities are closed during compressive loading, lateral expansion due to Poisson's effect may cause failure driven by opening mode or shearing effects that are dramatically enhanced by the anisotropy [27, 58].

Porosity should not be considered systematically as a negative issue in AM since it can be a positive driving factor for permeability [74].

Another type of defects is the presence of support material trapped between internal surfaces. The material is needed to withstand the fragile printed structure during the printing process. While this material is studied to provide limited adhesion to the deposited materials, its residual amount contributes in increasing the weight of the structure and modifies the load bearing distributions. These two drawbacks alter the expected performance of the optimal design. In addition, none-optimised support deposition affects finishing state, material consumption, fabrication time, etc. [75]. Strategies exist to reduce the dependence of AM to the presence of a support material by operating smart or slimming support generation [75, 76]. For some strategies, the part orientation is continuously adapted during the processing [57]. Curved regions can be processed smoothly under continuous deposition mode and the presence of support material is no more needed. For other strategies, building complex shape without the support material relies on the intrinsic properties of the deposited material itself. These materials exhibit generally rapid cooling kinetics, which allow them to support their own weight and prevent the structure collapsing. This kind of strategies obviously limits the spectrum of materials that can be printed.

2 Optimisation in additive manufacturing

In this paper, our focus goes towards optimisation difficulties that are inferred to AM. With regards to the large number

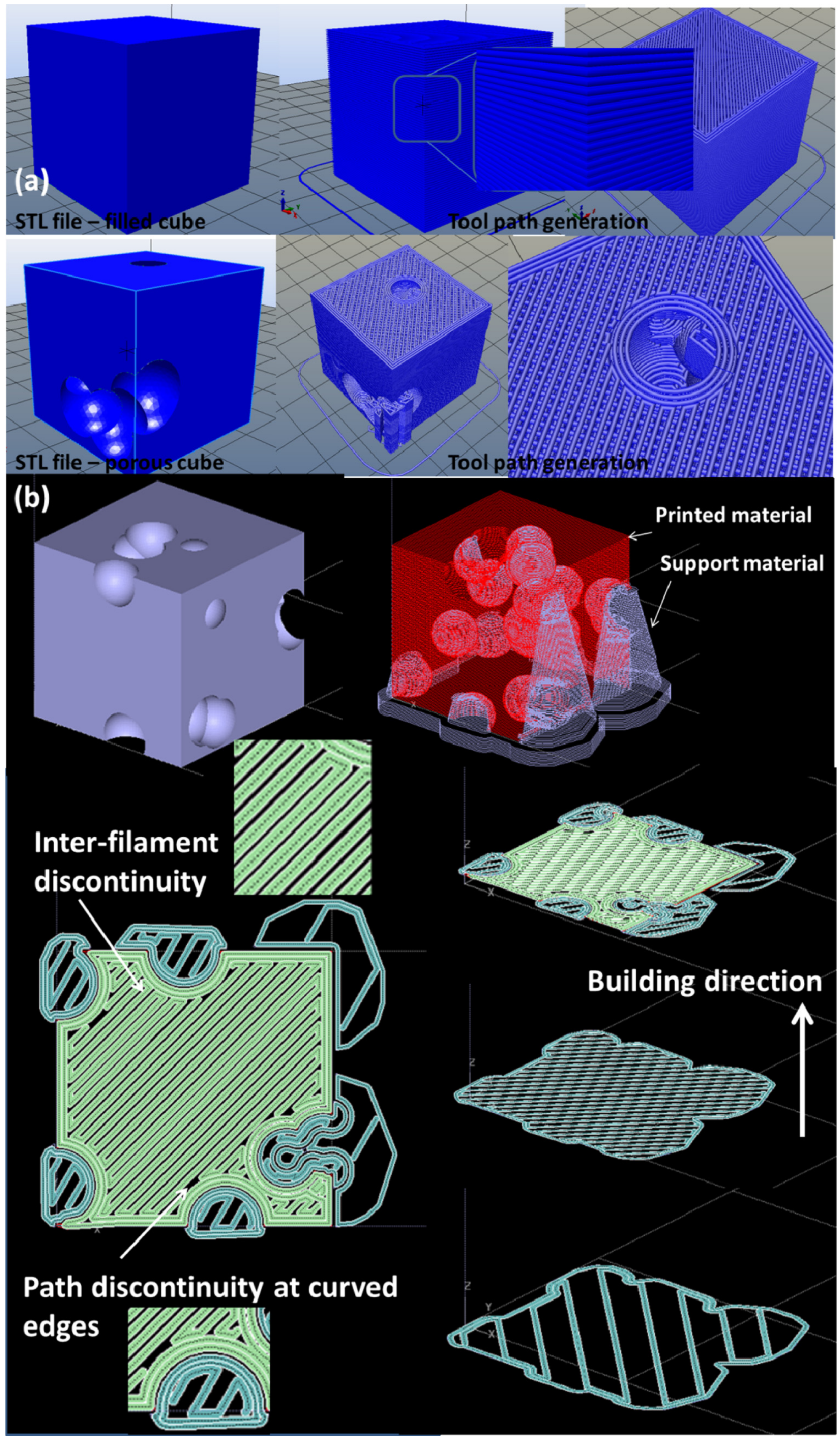

Figure 2. Typical examples of CAD objects transformed into collection of toolpaths using (a) Repetier and (b) CatalystEX software.

of disseminated works on the subject, common characteristics of optimisation in AM are highlighted in this section and described through selective literature work. In particular, several aspects of additive manufacturing can be optimized. Some of these aspects are related to design optimisation, more particularly topology optimisation. Some others like geometry accuracy, finishing state are tackled through process planning optimisation.

For most contributions, optimisation in AM is classically considered as a process parameter optimisation as it is the case for many design techniques [77, 78]. Raster angle, building direction, layer dimensions are some of the main parameters that find some interest in the literature. For instance, Garg et al. [79] present genetic programming approach as an intelligence tool to relate the AM process parameters to physical and structural outputs. While this is an important issue from the

Figure 3. Laying down process of fused ABS polymer in typical FDM equipment.

processing viewpoint, it is less attractive from a numerical analysis perspective, where strong and robust optimisation tools need to address more significant challenges. This does not diminish the purpose of the earlier approach. Accurate dimension, acceptable roughness and processing time are some of the important outcomes that justify the continuity of the research effort in this particular field. A typical example showing the importance of the process optimisation is provided in recent works [54, 55, 78]. The paper by Zhou et al. [78] introduces the concept of pixel blending to define the effect of neighbour pixels light intensity in solid freeform fabrication using photopolymerisation medium. The optimisation in such kind of studies is meaningful as the achievement of shape accuracy relies on the precise control of light intensity over a pixel-based image.

The paper by Yang and Zhao [3] report one of the most recent review on AM-enabled design, which is the closest subject to topology optimisation. In their review, design guidelines are exposed and the focus on structure optimisation methodology is explored through different contributions. This kind of methodologies needs to take care about the specificities of the design in terms of material combination, shape complexity and the targeted in-service performance. In the same review [3], the authors bring to our attention the possibilities of process combination involving more conventional or AM-based techniques [80–82]. We consider that this research direction associating various processes is out of the scope of this paper from an angle view of topology optimisation. However, the other considerations discussed there are central to the topology optimisation such as those related to design simplicity, material choice efficiency, improved multi-functionality, integrated technical solutions [83], etc. The concepts of multiphase material [37] and functionally graded materials [84, 85] emerge as a direct consequence to point by point material control in AM [86]. Also, designers are no more bonded by the tooling which needs to be a factor in the design with traditional processing [87]. This opens new chances for simplifying the design but also for increasing the creativity [7]. This particular point helps significantly the designers who need generally to reshape the result of the topology procedure to fit processing constrains like the development of particular tooling. A simple example would be the conversion of a material deposition probability into a graded material [4] instead of thresholding to solid or air phase [88]. In addition, if the conditions of blending at the microscale or nanoscale are met, the achievement of multi-material design is not a threat for the design but mostly an advantage because of the possibility to further improve performance at a lower material consumption rate [4].

Considerations related to topology optimisation are numerous [37, 88]. Some of them depend on the level of access to the AM processing technology itself which is not systematically provided by the commercial solutions. Here are some of these considerations that are central to the development of robust AM solutions:

– Geometry of the CAD model: this is direct target of the topology optimisation, which needs to predict what would be the exact geometry that satisfies all model constrains. Successful examples of topology optimisation can be found in the literature for cellular materials [88, 89], multiphase materials [37], implants [90].
– Path generation: this is an important parameter that affects geometry accuracy, cohesion in the part, residual stresses, and the finishing state [20, 63, 91]. Path generation needs to handle as much the change in process speed and the transition time at the borders [92]. A specific

Figure 4. Two examples of airy randomly structured polymers designed using (a) fused disposition modelling (uPrint equipment in GEPEA lab., university of Nantes, France) and (b) photolithography (SPS350B equipment in ESAC lab, NPU, Xian, China).

branch of research is dedicated to the optimisation of tool generation path including studies related to the improvement of the scanning mode [93, 94], geometry slicing strategies [95, 96], optimal material deposition [97, 98], multi-directional AM [99], tool path anticipation procedures [100].

– Process selection: different technologies are developed to enhance the capabilities of AM like jet printing [26, 101], friction stir AM [102], welding based AM [94], ultrasonic AM [103], electrochemical AM [104], micro-plasma powder deposition [105], Solid freeform fabrication [106] and related variants such as selective laser sintering [107, 108], or directed light fabrication [20], selective infiltration manufacturing [109]). The outcomes of these technologies diverge. This reinforces specific aspects of AM like the material type, printing size, accuracy, speed, cost, etc. [110]. Figure 4 shows two examples of technologies applied for the design of airy structures, one based on FDM (uPrint® SE from Stratasys) and the other is a photolithography equipment (SPS350B from XJRP company). The earlier one is restricted to printing ABS polymer where the last one can process only photosensitive resins. The ability to control the process parameters is crucial to decide on the relevance of a particular AM process [111]. And perhaps, a badly performing design reflects only the lack of knowledge of the process. Thus, the mastering of the process parameters is a criterion for process selection.
– Process resolution: this is also an important aspect that guarantees the accuracy of the AM process [14, 112] and the development of appropriate scaling solutions for nano-, micro- and macro-features [38, 64, 113–116]. Some studies focus on slicing techniques to increase accuracy such as adaptive slicing proposed by Siraskar et al. [117] using volume decomposition by octants.
– Feed material properties: rheological and phase change properties of the feed materials are essential to the success of AM building capabilities especially for achieving standards in material selection [118]. This is a continuous research direction aiming at increasing the spectrum of printable materials and optimising the intrinsic material properties for a better performance during fabrication step [14, 19, 119–121].
– Support material: optimisation of the support material is now fully integrated in numerous commercial solutions, which require supporting of the part during processing. This optimisation relies on different options such as the

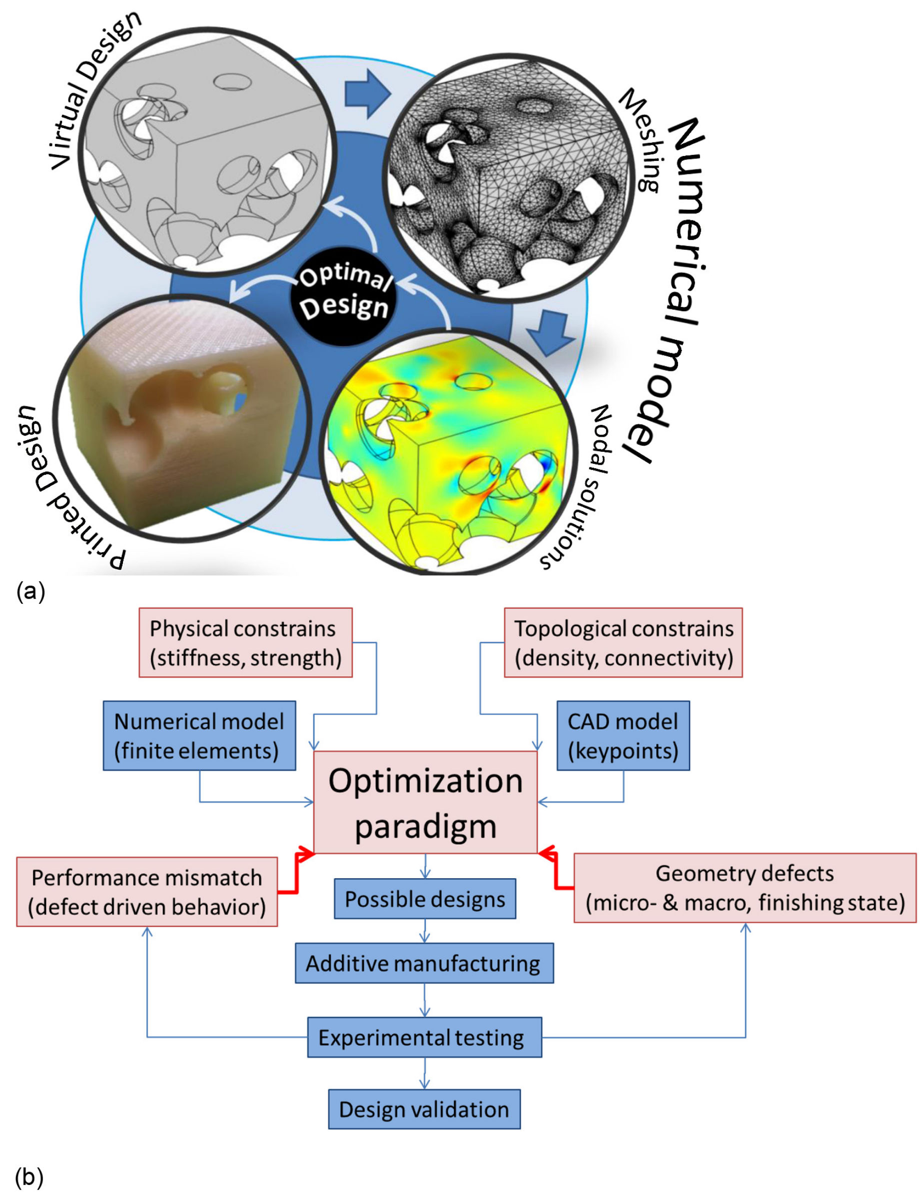

Figure 5. (a) Classical view of topological optimisation, (b) Modified scheme with defect sensitive topology optimisation of AM.

smart deposition for which only reduced amount of support material is needed [76]. Some research works still contribute in this particular area to improve the spatial distribution of airy support material [75, 122].

The logic behind topology optimisation is illustrated in Figure 5. The geometry of the CAD model can be something to discover through the optimisation procedure or assisted by imaging tools such as micro-CT scanning [123]. Since the optimisation combines physical and geometrical constrains, numerical solutions need to be available to predict what would be the result of the part performance [14, 112]. This is generally addressed using finite element computation [53]. The numerical model needs to converge in all design situations within a short time because the process is meant to be repeated several times. Depending on the nature of the physical constrain, the numerical model can be more or less sophisticated. For instance, residual stress analysis requires most of the time solving a multi-physics problems [124, 125]. If numerical models are able to handle technological, physical, and geometrical constrains, design guidelines can be adopted by coupling the optimisation tool to decision making paradigms. Some studies show that AM process simulation is possible [125, 126] but the ultimate goal would be to bridge such realistic tools with the optimisation paradigm. Recent works prove unfortunately that we are far from such ideal situation [127].

Topology optimisation needs to cope with the specificities of AM. As this process generates a complex network of 3D defects, numerical models need to integrate the result of defect in the analysis as an implicit performance perturbation or explicit defect influence. This is the main difference between the two schemes presented in Figure 5. The classical scheme (Figure 5a) does not handle the defects induced by processing,

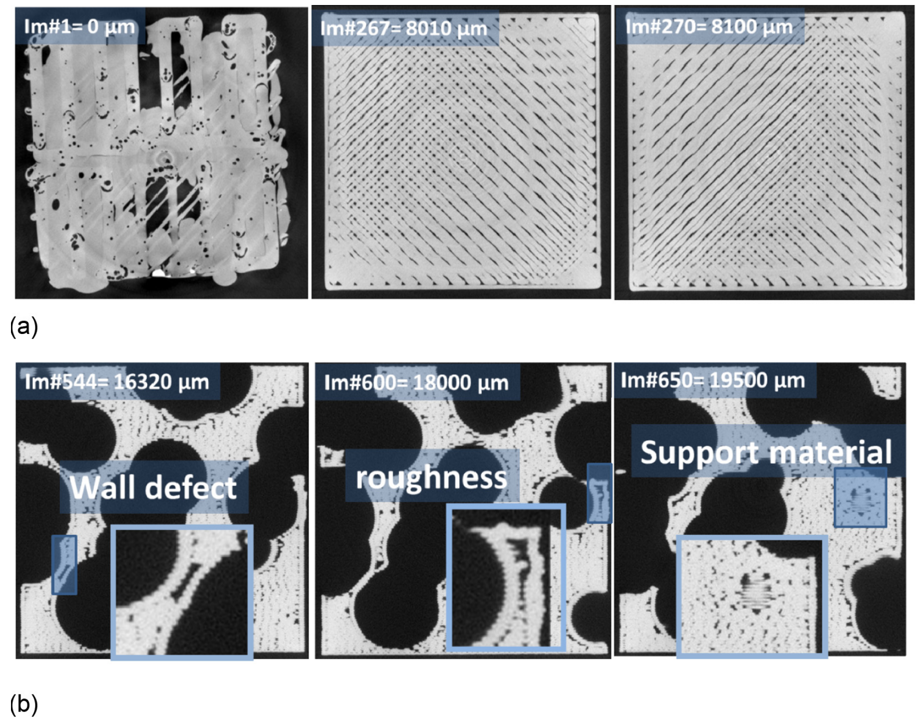

Figure 6. Microstructural defects in ABS polymer printed using FDM. Analysis is performed using X-ray micro-tomography. Two examples are shown one is (a) a dense ABS block and the other is (b) airy ABS materials exhibiting more than 60% of porosity.

which makes any deviation from the optimal virtual design a cause of failure. Numerical sizing in aerospace applications [128] is a typical example where such defects can be an issue to validate the final design in airframe development. In the second scheme (Figure 5b), the corrections introduced by the monitoring of the defects helps in guiding the optimisation tool towards the best realistic solution. This resolution is directly related to the AM tooling constrains, for instance the choice of the tip size. If the second scheme is used to consider appropriate selection for tooling options (like nozzle diameter), then such process parameter can be considered as a discrete variable. Optimal design can be searched in a larger space depending on the possibilities offered to select a certain number of available nozzles. Real-time control of AM like the optical tomography [129, 130], thermographic analysis [131] or ultrasonic monitoring [132, 133] helps in gaining valuable information about the structural defects that develop during AM processing and their direct consequence on failure of the designed part [73]. This is still a challenging issue as it appears that adequate non-destructive techniques are not yet fully available to evaluate properly AM part performance [52]. This situation can be improved through the development of standards which is still an ongoing process for the validation of testing techniques applicable to AM [134]. One of the most promising techniques to analyse microstructural defects in AM parts is X-ray micro-tomography [135]. This technique is able to provide precise information about the porous network induced by processing, surface roughness, part volume, amount of support material and any other microstructural defect [27]. As the technique relies on transformation of 2D projections into 3D image [136, 137], structural anisotropy effects can be quantified. Figure 6 shows two examples of defects revealed in ABS polymer printed using fused deposition modelling. Cross-section views refer to a dense block of ABS ($30 \times 30 \times 30$ mm^3) analysed using X-ray micro-tomography. This block is oriented at 0° in the printing plateau, but we notice clearly the crossing of filaments at an angle of 45° and the presence of bounding layer. In Figure 6a, the resolution of the image is $1077 \times 1062 \times 1059$ voxels, where a voxel is a graphical unit in 3D. The physical size of the voxel determines the accuracy of the structural defect evaluation. In Figure 5a, the voxel size is 30 µm. More information about the operating conditions can be found in reference [27]. Figure 5a shows the lack of cohesion between successive filaments and tendency to flattening because the filament diameter is tripled during the laying down of the fused matter. The subsequent porosity forms as a regular network of micro-sized defects, and appears to be highly connected. Also, residual support material can be found at the borders, which reveals difficulties of support material removal. The automatic cleaning process is generally followed by manual removal step to ensure that no residual support material is left behind. The second example highlighted in Figure 6b shows other imperfections that infiltrate the design of a two phase material. These imperfections are related to discontinuities of matter in the cell walls, the change of geometry due to design mismatch effects and the presence of support material trapped in closed pores of small size.

In several contributions, the red links in Figure 5b are ignored as if the approximate result of the optimisation is unavoidably accepted. More recent contributions tackle such links by suggesting corrections of the design based on manufacturability considerations [64]. This is performed, however,

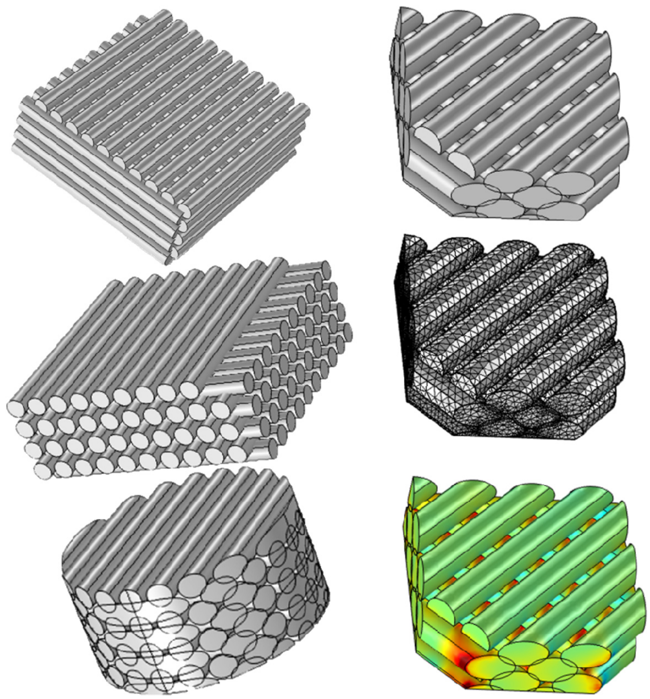

Figure 7. Towards modelling of AM process.

independently from the optimisation tool itself and does not involve defects induced by processing.

3 Challenges for AM topology optimisation

One of the important issues that topology optimisation needs to address is the pertinence of the constitutive laws representing the behaviour of the printed materials. Unfortunately, material law implementation is not yet fully revisited leaving an open area for research in this direction [138]. A typical research direction would be to explore interfacial effect in terms of limited load transfer and damage kinetics at the light of results achieved for composite materials [139, 140]. This direction is fully justified by the fact that lack of performance is more associated to the weak adhesion between filaments. Thus, failure mechanisms are likely to be affected by the arrangement of such weak regions [27].

Another concern is the embedding of the microstructural details in the topology optimisation. During the past decades, this opportunity to tune microstructurally the design was out of reach because of computation resource limitations. Now, this is accessible at the cost of using efficient paradigms that avoid unrealistic configurations and constrain the search volume to design-effective solutions. Recent experimental achievements show the potential of AM to tune locally the performance of multi-material parts [39]. The next realistic step would be to promote this kind of experimental attempts to fully automated procedures. The role of microstructural details can be even determinant in hierarchical structures. Indeed, previous studies show large possibilities of airy arrangement using hybrid optimisation strategies [141]. One can imagine the large possibilities of pore connectivity tailoring driven by AM if micro-porosity is considered.

Topology optimisation is not yet ready to provide systematic process error detection for AM. We know that AM processes are exposed to inaccuracy in terms of geometry imperfections, volume mismatch, and undesirable surface texture. All these drawbacks can be properly addressed by a tool that apprehends the limits of the AM processing. Realistic designs with acceptable defects are better than ideal designs with unmeasurable bias. Figure 7 shows some clues about how topology optimisation can achieve a higher sensitivity to defects in AM. A better understanding of the AM defects is a matter of scaling down the numerical model to the size of heterogeneities that are the birth sites of the process-induced defects. Explicit implementation of discontinuities can be handled as well as lack of bonding between layers or filaments. Also more elaborated constitutive laws can be considered in order to take into account anisotropies that are subsequent to the rapid cooling and stretching of the matter.

A straight-A learning paradigm is not also accessible for topology optimisation. The near future developments will meet substantial use of in-situ or in-line monitoring procedures for AM [16, 142]. Topology optimisation can integrate some of these procedures to learn from the design. This requires the combination with another class of algorithms that are derived from artificial intelligence [143]. As an end, the optimal design can be performed using optimal process parameters, which saves a considerable amount of time.

A bigger tool for higher perspectives is what process managers expect from optimisation tools. Topology optimisation can be part of it if other considerations are handled carefully like cost effectiveness with a large material catalogue, material saving logics, automated process selection, scenarios of durability, recyclability and projections of life time. Fully automated decision making processes can be then launched starting from the idea of design to the post-mortem step of the AM part.

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