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Design Inputs for Fused Filament Fabricated Non-Pneumatic Tires

Manuel Sardinha[a*], Marco Leite[a], Tânia R. P. Ramos[b], M. Fátima Vaz[a], and Luís Reis[a]

[a]IDMEC-IST, Universidade de Lisboa, Av. Rovisco Pais, 1049-001, Lisboa, Portugal
[b]CEGIST, Universidade de Lisboa, Av. Rovisco Pais, 1049−001 Lisboa, Portugal
[*]Corresponding author: manuel.r.sardinha@tecnico.ulisboa.pt

Abstract

Airless or non-pneumatic tires (NPTs) can operate without internal fluidic pressure, offering a promising low-maintenance and environmentally friendly alternative to their pneumatic counterparts. These new tire concepts open a wide range of design possibilities, which has resulted in a diverse array of proposed solutions. Existing NPT concepts in literature often pursue intricate functional designs that can be challenging to manufacture. Taking advantage of the design freedom offered by additive manufacturing technologies, techniques such as fused filament fabrication (FFF) have recently been used to produce NPTs for diverse applications. In this study, the authors explore NPTs design features within the context of FFF tires made with thermoplastic elastomers, with a focus on bicycle-sized wheels. Following an analysis of the current state-of-the-art of FFF NPTs, the authors propose a processing workflow that helps identify how process-related parameters and design methodologies might interact with different stages of the tire development process. Above all, the authors believe that the early consideration of manufacturing constraints and design for additive manufacturing inputs allows a faster prioritization of initial design proposals. This analysis aims to elucidate suitable design decisions for developing NPTs using FFF and accelerate the study and adoption of these newly proposed products.

Keywords: FDM, Elastomer, 3D printing, Design for.

Introduction

Conventional pneumatic tires were developed in the late 19th century and have been dominating vehicle application fields since then. Non-pneumatic tires (NPTs), also termed airless tires/wheels, are regarded as a potentially more sustainable and low-maintenance alternative to traditional tires, primarily due to their ability to operate without the need for internal air pressure, which implies they will not leak air over time, puncture, or suddenly burst [1], [2]. To replace the air pressure, these airless structures typically use a combination of elastomeric material and intricate geometrical shapes, designed according to functional requirements. While certain NPTs are already present in commercially available products such as wheelchairs, lawn mowers, and small electric scooters, the introduction of innovative designs increases the complexity of decision-making in the initial stages of product design [3], [4].

Additive manufacturing (AM), also termed 3D printing, refers to a group of technologies where material is sequentially deposited or consolidated, usually in a layer-by-layer manner [5]. Recent scientific developments emphasize that the geometrical design freedom offered by AM technologies potentiates the feasibility of geometrically complex constructions such as those found in NPTs [6], [7]. In contrast to conventional manufacturing, AM allows the development of tailored products while minimizing waste and production costs [8]. Within the extensive list of AM methods, fused filament fabrication (FFF) stands out as one of the most broadly employed to process polymers. While it might be recognized that FFF technologies can bypass the need for extensive design for manufacturing requirements [9], design guidelines can still help improve production aspects such as time, cost, and the manufacturability of parts [10], [11].

This work explores the design of fused filament fabricated tires made with thermoplastic elastomers (TPEs), with a focus on bicycle-sized wheels. By evaluating the process workflow, the authors demonstrate how process-related parameters and design decisions might impact aspects such as functionality, manufacturability, costs, and end-of-life.

Fused Filament Fabricated NPTs

NPTs may offer obvious benefits such as puncture-proofing and reduced air pressure maintenance needs, but one of their most acclaimed advantages lies in their potential to reduce rolling resistance and, consequently, lower the energy consumption of the vehicle [12], [13]. Various NPT designs are oriented towards enhancing passenger comfort and delivering unique shock absorption capabilities [14]. Moreover, due to the absence of air, certain designs maximize the available space within the tire, which might facilitate the integration of components like brakes or electric motors. A highly flexible tire can also replace the suspension system of a vehicle, simplifying its complexity, assembly, and maintenance tasks [15], [16]. The application of 3D printing to the development of NPTs has been steadily gaining momentum, attracting growing interest from scholars and technology enthusiasts alike [17].

Fused Filament Fabrication

In FFF, machines usually operate an extrusion system composed of a feeder, a hot end, and an extruder outlet (nozzle). The feeder system guides the filament into the hot end, where the polymer is heated until it reaches a molten state and is then selectively deposited onto a build platform or onto previously deposited material [18]. FFF uses thermoplastic materials which, unlike rubber, are more easily recyclable [19]. While FFF technology has witnessed significant advancements over the past decade, numerous challenges persist. These include reducing defects and enhancing the mechanical properties of parts, the prediction and simulation of these properties, and the scaling of the technology to deliver the promise of mass customization of consumer products. Mechanical properties are closely tied to both material characteristics and process parameters. FFF thermoplastics exhibit viscoelastic behaviors, they are either shear-thinning, shear thickening or yield stress fluids, and are greatly influenced by temperature-dependent flow field dynamics and polymer rheology [20]. Printed parts often exhibit signs of residual stresses due to the exposure of the polymers to shear and compression forces while extruding, and a non-uniform thermal history [21]. At higher deposition rates, the filament experiences higher forces in the feeder and inside the heating chamber, resulting in pressure fluctuations. These can lead to an oscillating extrusion rate, which adversely impacts the final geometric accuracy of the parts [22].

Interlayer strength of components is one of the most important characteristics of FFF components [23]. Interlayer bonding between the adjacent layers is a coalescence process resulting from phenomena such as surface wetting, neck growth, and interfacial polymer chain diffusion and entanglements [24]. Generally, when printed parts are tested perpendicular to the print direction, their mechanical properties are notably inferior compared to testing with the load applied parallel to the print direction. For this reason, build direction and infill parameters such as raster angle should be carefully considered in the design stage of a product [9].

Considering the amount of proposed TPE-based tires, it is necessary to address some of their processing challenges. TPEs can be understood as hybrid materials, displaying a combination of rubber-like elasticity (recoverable strains above 100%) and the processability commonly associated with thermoplastics. However, due to their soft nature, TPEs can suffer even more unpredictable and severe viscoelastic deformations during extrusion than most FFF materials, which makes it particularly difficult to control their flow during the extrusion, which also justifies why they often require the use of very slow and constant material deposition speeds [25]. Machine modifications such as smaller or adaptable nozzles and longer print heads might alleviate this issue. Figures 1a to 1c show some of the most common problems associated with 3D printed TPEs. To avoid printing issues such as stringing effects and over-extrusion, strategies relying on the tuning of filament retraction and cooling can help. Furthermore, a direct drive extruder configuration is preferred, and it might be adequate to force the travel movements to be within the previously deposited material paths [26].

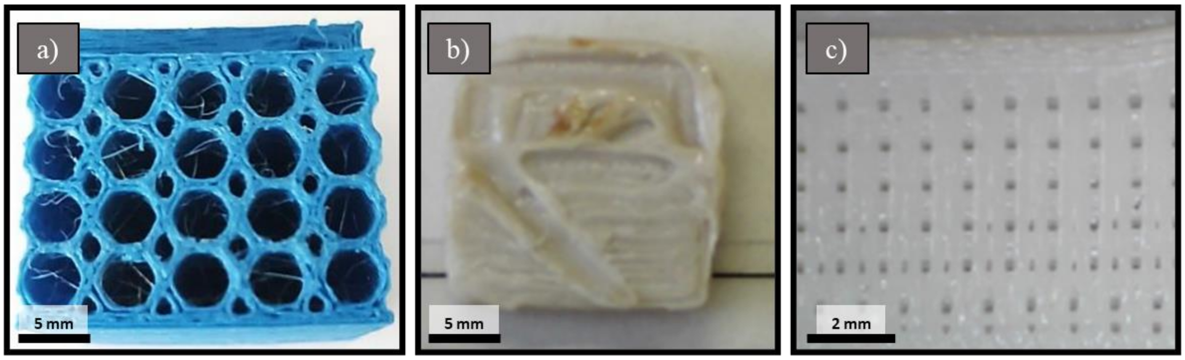

Figure 1: Examples of common issues with FFF TPEs. a) Stringing in the segment of a NPT with a honeycomb-based grid design; b) Over-extrusion associated with excess temperature; and c) Gaps in-between extruded rods due to under-extrusion.

Notably, most NPT designs require a production build volume of less than 1.0 m³. Even so, since elastomeric materials and cellular constructions tend to require the extrusion process to be slowed down, NPTs share some of the current limitations related to medium- and large-format FFF components. Since the production of larger components using FFF remains a challenging task in terms of production costs, time, and complexity, some authors have proposed solutions such as joining independently produced sections of a component [27] and using independent extrusion systems that cooperate to concurrently manufacture a part [28].

NPT Architecture and Design Proposals

NPTs have been proposed for a broad spectrum of applications, including wheelchairs, space probes, automobiles, trucks, and bicycles [1]. Whether composed of a single or multiple materials, incorporating independent and structural beam sections, or featuring a honeycomb grid extending from the outer to the inner radius, the architecture of these tires is variable. Nevertheless, it typically follows an annular concept, with three main components: core(s), shear layer/beam, and tread, as shown in Figure 2.

Among the variability of designs, spokes- and honeycomb-based solutions dominate. Honeycomb grids exhibit higher stiffness and strength in out-of-plane directions than in in-plane directions, which relates to the importance of tailoring cells to the lateral, longitudinal, and radial stiffness of tires [29]. But other designs featuring more intricate or functionally graded cellular structures, functionally compliant mechanisms (e.g., the integration of auxetic structures into shear beams), and bio-inspired characteristics have also been proposed [30], [31]. Research emphasizes the inherent adaptability of NPTs to pavement variability, application requirements, and manufacturing constraints [32], [33]. While comparing NPT designs, the research by Jafferson and Sharma [6] shows how some of them are very complex to produce.

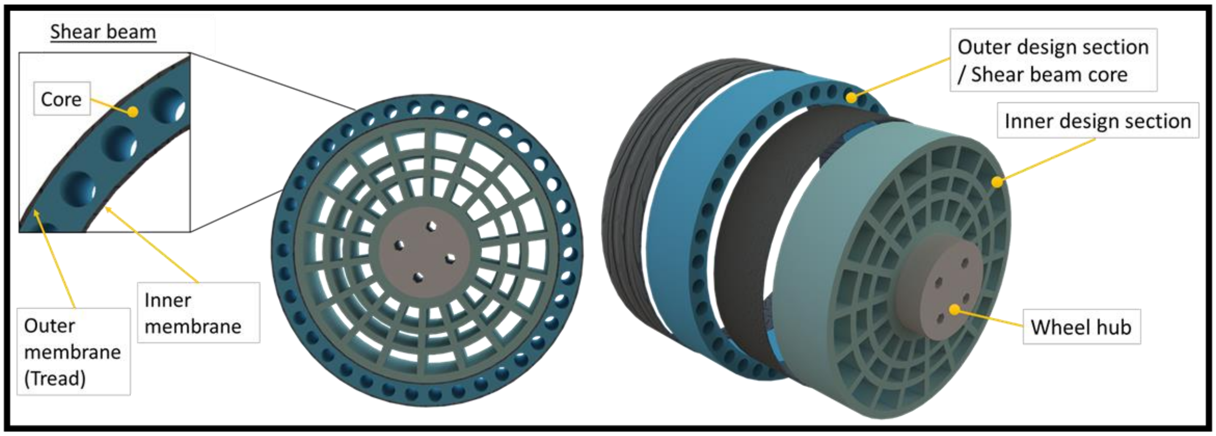

Figure 2: Schematic representation of the structure of a NPT, adapted from [1].

In recent years, various researchers have studied fused filament fabricated NPTs, namely their mechanical response, how they are affected by manufacturing parameters, or how to develop dedicated materials for their production [1]. In a previous research, authors debated the adequacy of different NPT designs for the FFF production technique [26]. Using experimental and numerical methods, Rugsaj and Suvanjumrat [34], [35], [36] investigated the appropriateness of the mechanical properties of FFF parts to produce spoke-based NPTs made with TPEs, confirming the feasibility of constructing intricate spoke shapes. Wang et al. [17] compared the experimental and numerically simulated stiffness of FFF NPTs made with TPEs subjected to biaxial tensile, flexural, and wear resistance tests. Dezianian et al. [15], [37], investigated the suitability of cellular structures for FFF NPTs made with rigid and TPE materials, with results pointing to the importance of the geometric design constraints due to manufacturing limitations related to the use of support structures. Andriya et al. [38] evaluated the processing parameters of FFF NPTs made with auxetic structures using TPE material. Montanini et al. [39] and Quattrocchi et al. [40] studied the stress and strain performance of an FFF NPT using non-contact techniques and confirmed the importance of material properties and geometric complexity in mechanical performance. Ma et al. [41] propose the production of multi-material wheels using a combination of FFF and resin moulding, and some authors have proposed the production of both a wheel rim and a tire using FFF [17], [42].

Concerning bicycle FFF tires, Ramadhani et al. [42] conducted research comparing various designs of NPTs made of TPEs. Additionally, BigRep, a manufacturer of large-format 3D Printers, showcased a project involving a non-pneumatic bicycle tire in a promotional video [43]. On a social media platform, technology enthusiast Brendan Carberry shared an FFF NPT made from ten identical segments connected with tie-wraps to form the complete tire [44]. These examples can be seen in Figures 3a to 3c. Other notorious examples of NPTs for bicycles are the Airfree tire concept by Bridgestone and the foam-based tires from Tannus® tires.

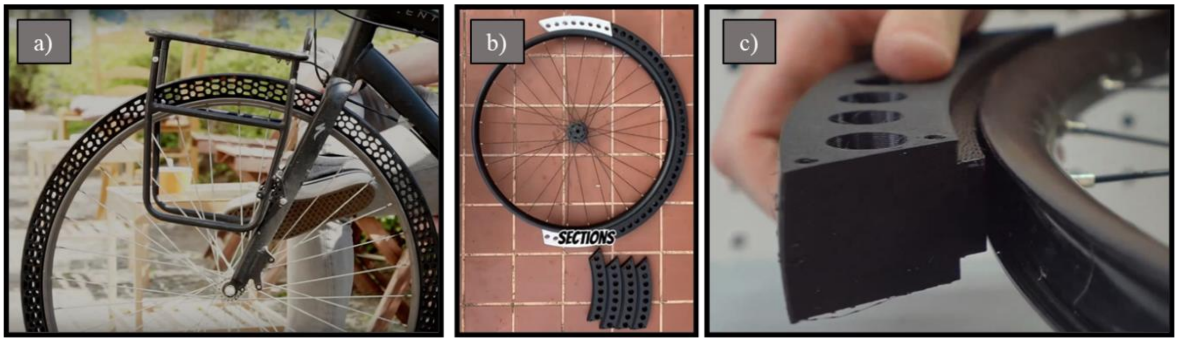

Figure 3: Examples of bicycle NPTs. a) NPT advertised by FFF machine manufacturer BigRep, adapted from [43]. b) Tire segments mounted on a bicycle wheel; and c) Single NPT segment, presented by an Instagram account, adapted from [44].

Design for Manufacturing Methodologies

In product design, methodologies that encompass functionality and production context expedite development and efficiency. These approaches introduce previously unforeseen requirements that help to define design space, and early exploration of enhancements by designers maximizes potential positive impacts on life cycle performance.

Design for X is a sum of holistic methodologies in which, for each possible X domain, there are guidelines that aim to facilitate the application of technical knowledge to address challenges encountered during the development cycle. Within these methodologies, design for manufacturing can be described as a structured framework of rules and guidelines aimed at aligning product designs with manufacturing capabilities, which requires a deep understanding of the capabilities of the manufacturing process. Therefore, Design for Additive Manufacturing (DfAM) methodologies are essential tools to fully exploit the potential of AM technologies [45], [46]. To effectively harness all the capabilities of AM technologies, it is imperative to perform the redesign of parts rather than retain designs intended for conventional manufacturing that take into consideration the limitations of conventional processes. Designing components for FFF may imply the consideration of constraints related to slicing parameters, toolpath generation, build orientation, support structures, and post-processing requirements [9]. Furthermore, within the context of designing FFF parts, other tools, such as concentrating on simplifying component assembly time (design for assembly) and sustainable-based methodologies, are fundamental. Life cycle assessment methodologies assess the environmental impacts of a product, covering its life cycle from raw material production to end-of-life considerations [47]. Together, all these methodologies aim to enhance product manufacturability and optimize the overall production life cycle.

Design Inputs for FFF NPTs

As demonstrated, recent advancements in FFF technology have pushed the research and development of innovative tire designs, but the feasibility of intricate geometrical arrangements such as the ones found in most NPTs can be difficult to achieve. In this section, the authors outline a process workflow (Figure 4) for FFF and highlight key factors to consider during the design of NPTs. After a fruitful concept generation, manufacturing constraints allow designers to validate and prioritize design proposals (phase 1). In addition to the influence of a direct drive extruder configuration (preferred for working with TPEs), extruders capable of higher flow rates can significantly reduce tire production time. Due to the typically slow print speeds achievable by most 3D printers when working with TPEs, even a small increase in print speed can have a substantial impact on overall production time. Moreover, common small-scale 3D printers have a build volume of less than 1 m^3 [48] and cannot accommodate most bicycle tire sizes. Therefore, designing section-based tires for small-scale printers becomes almost inevitable. Even so, articulated designs (similar to what are commonly known as flexi 3D prints) printed in a geometrical configuration different from a tire mounted on a rim are theoretically feasible.

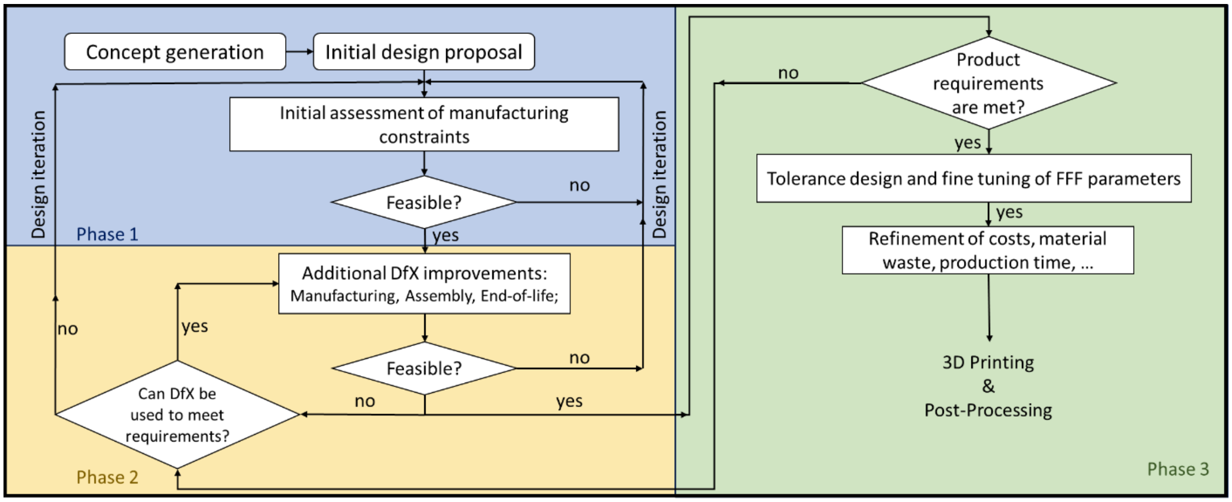

Figure 4: Proposal of design methodologies interaction with the process workflow of FFF parts.

The proposed workflow assumes that, during the development of a product like an FFF bicycle tire, design iterations that involve revisiting previous design stages are expected. Generally, the number of iterations returning to previous phases should be minimized, as this can increase costs and development time. If possible, iterating through small design adjustments within each phase enables faster validation of features and prevents major revisions to previously validated concepts. In such scenarios, the early establishment of a well-structured DfX framework can help minimize the impact of each design iteration on the development process. Furthermore, process parameters often function as valuable inputs for design methodologies (Phase 2). To properly consider manufacturing requirements and their influence on a new tire concept, the designer should envision the stages ahead. In FFF, these typically include the tessellation and slicing of models, understanding machine limitations during the printing process, and assembly or post-processing requirements, as represented by the scheme of Figure 5. Once product requirements are fulfilled, fine-tuning process parameters, such as speed and machine trajectories, can help optimize production efficiency (phase 3).

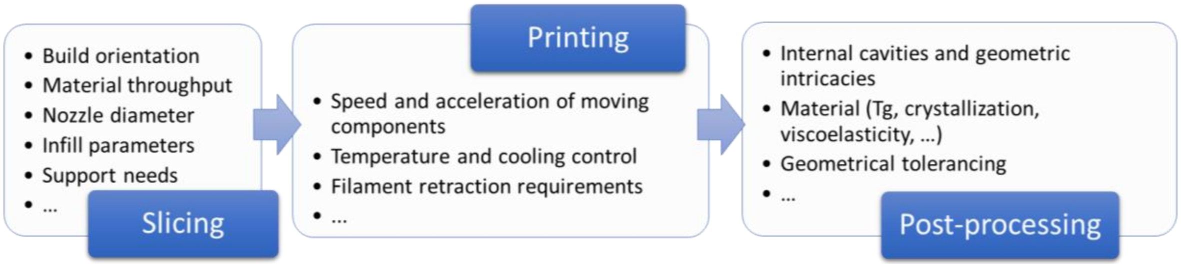

Figure 5: Relation of FFF process parameters along different production stages, in line with the proposal by Steuben et al. [9].

As with many FFF components, the most common initial DfAM consideration for fused filament fabricated NPTs is likely the build orientation. Tire build orientation imposes design limitations concerning feature size and shape and impacts relavant characteristics such as its mechanical behavior, overall cost, build time, surface quality, and the need for support structures. Considering the general mechanical properties of FFF parts, to promote radial stiffness of NPTs, radial spokes and cell walls are usually aligned with the plane of each built layer, i.e., tires are printed lying flat on the build surface. Additionaly, since the layered effect runs along the thickness of the tire, this positioning may help reduce noticeable oscillations during wheel rotation. In this sense, functionally efficient bi-dimensional (2D) or quasi-2D tires are the perfect fit for more reliable and accurate production. Nonetheless, three-dimensional designs can be functionally more interesting and certainly fully exploit the production capabilities of AM technologies. Notably, new approaches to slicing using variable line widths and non-planar slicing techniques might help to mitigate a significant number of manufacturing issues and will certainly impact how designers of FFF parts look at build orientation.

Designer freedom, design methodologies, and DfAM-related constraints can differ significantly between a traditional integral tire and one printed in segments. For NPTs, methodologies like design for assembly (DfA) can aid in developing specific features, such as mechanisms that ensure secure mounting between the tire and the rim. In theory, a segmented tire requires attaching each section individually to the wheel, which increases the number of assembly steps. However, experiments have shown that mounting a tire in sections may be significantly faster than mounting a full tire, as smaller sections offer less resistance to deformation. Figures 6a and 6b illustrate two iterations of the mounting mechanism for attaching a tire to a bicycle wheel rim. The first iteration (Figure 6a) shows a simple grooved design that positions the tire within the rim. As proposed in the scheme of Figure 4, functionallity and feasibility should periodically be evaluated. While optimized for manufacturability and material efficiency, this design exhibited issues under radial and lateral loads, causing some thin tire features to deform before the core, leading to twisting and partial slippage of the tire from the rim. In contrast to the previous iteration, the later design shown in Figure 6b incorporates an adaptive structure that deforms under radial loads, helping the tire maintain its position within the rim.

From a diferent perspective, design methodologies such as DfA can also aid in developing an attachment mechanism between tire sections. The example shown in Figure 6c demonstrates how the introduction of a simple locking mechanism can interfere with with the behavior of the NPT. In this example, the periodicity of the hexagonal cellular core structure is interrupted by the locking mechanism, which may lead to fluctuating tire stiffness and reduced driving comfort.

Ideally, the interlocking mechanism would be integrated into the walls of the honeycomb structure. Even so, accommodating such features may be constrained by the minimum size of the cell walls or of the locking mechanism itself. In addition to impacting mechanical behavior, incorporating such mechanisms is likely to increase production complexity and add weight to the final tire. Moreover, design uncertainties remain broad. Among the many variables to consider, the number of attachment points between sections can play an important role. More connections can increase assembly time, while larger, single-point connections may allow for more robust features and greater attachment strength, but they may lack redundancy, i.e., if one connection fails, the tire sections could separate. Conversely, smaller locking mechanisms might provide weaker connections but allow design space for additional connection points. Often, designers must balance functional performance with aspects such as manufacturability, production costs, or assembly time.

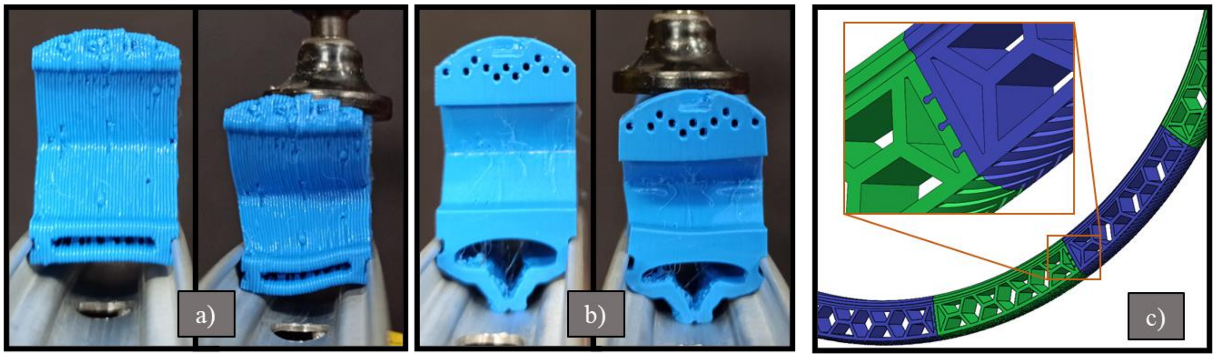

Figure 6: Examples of coupling mechanisms: a) Mounting between a simple tire section and the wheel rim; b) Mounting between a deformable tire section and the wheel rim; and c) CAD model of a connection between tire sections.

During the slicing stage of a FFF tire, a proper planning of the material volumetric flow rate is fundamental. Material flow requires accurate temperature control and is the result of its combination with printing speed, nozzle outlet diameter and layer heigh. For tires made with TPEs slow print speeds can be offset with larger outlet areas, which can be achieved using larger, variable, or adaptable nozzles, or other print head modifications. Even so, the outlet area directly impacts the minimum feature size capabilities of FFF machines and the mechanical properties of parts, which imposes new design limitations. Together with extrusion temperature and part cooling, flow rate predominantly governs the phenomenon of material diffusion between adjacent deposited rods/layers, influencing the mechanical strength of FFF parts like NPTs. Infill parameters like pattern, density, and orientation are usually not forgotten, but less commonly addressed parameters, such as the overlap between rods, can also have a significant impact on material diffusion.

Post-processing techniques such as polymer annealing might be valuable to promote the interdiffusion between extruded layers and rods within a NPT, diluting the anisotropic behavior typical of FFF parts, which might help to mitigate issues such as the ones detailed above. The existence of a post-processing stage typically imposes additional constraints which might impact the freedom of a designer such as its ability to build open/closed cellular structures since these might collapse under certain combinations of high temperature and pressure.

Lastly, multi-material tires or even multi-material wheels that combine TPE tires with rigid FFF-made wheels could drastically reduce assembly stages. Even so, the use of difficult-to-separate materials may negatively impact the recyclability of FFF tires.

Prospects and Future Work for FFF NPT

This work explores the design process of fused filament fabricated tires made with thermoplastic elastomers (TPEs). Following an analysis of the current state-of-the-art of FFF NPTs, the authors propose a processing workflow that helps identify how process-related parameters and design methodologies might interact with different stages of the tire development process. Above all, the authors believe that the early consideration of manufacturing constraints and DfAM inputs allows a faster prioritization of initial design proposals. The authors propose the application of the discussed contents in the following future research paths:

- Further explore the potential to produce a tire in individual segments, since most FFF machines do not allow the production of large-format parts.
- Explore and evaluate failure mechanisms of FFF NPTs. As an example, since tires are usually produced laid down on the build plate and layers are perpendicular to the riding pavement, encountering an obstacle (e.g., a nail or a rock) while rolling may lead to critical interlayer separation.
- Model the energy and production costs associated with NPTs production and understand most influencing factors.
- Evaluate how current slicing developments, such as non-planar slicing strategies, may help to address design limitations and enhance product performance.
- Assess the environmental impact of various tire characteristics and examine how implementing strategies like the use of multi-materials in different tire sections affects the life-cycle performance of NPTs, comparing these outcomes to traditional tires.
- Explore the possibility of replacing a vehicle suspension with soft materials or functionally graded cellular structures.
- Evaluate how the available space inside tires allows the integration of components like brakes and electric motors.
- Investigate how employing strategies such as compliance mechanisms can broaden the applicability of NPTs to unforeseen products by augmenting their functionality. An example includes a tire architecture that facilitates both rolling and bending, enabling capabilities like climbing stairs or adapting to sudden changes in pavement levels.

In conclusion, the authors would like to state that the debate carried out concerns the production of NPTs for bicycles, but most considerations can certainly be applied to similar-sized wheels for wheelchairs, autonomous robots, and other light mobility vehicles.

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