Structural strength improvement of 3D printing parts from topology optimised design using anisotropic material modelling

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Abstract. Additive manufacturing (AM) offers diversity, customisability and creativity, making it an important tool to lead Industry 4.0. Reducing the cost of prototyping, bespoke, and small-scale production are some of the key advantages of 3D printing. Parts created by topology optimisation and generative design are usually easier to make by AM. Industrial sectors such as automotive, biomedical and manufacturing have begun to see AM as a cost-effective process for complex components. AM is not without its drawbacks, print failures, distortion, rough surfaces, anisotropic properties and lack of material data is limiting the quality assurance of this technology. It is known that the mechanical properties of the printed parts are sensitive to specific AM process parameters. e.g. the printing direction to the anisotropic property. In this study, the improvement of the prospective mechanical property of a topologically optimised design of a wheel was carried out. As the mechanical load of a wheel is crucial in its application, the prospective mechanical properties of the wheel to be made by AM are investigated by using simulation so that better outcome from AM may be predicted with the customised process planning.

Keywords: topology optimisation, additive manufacturing, 3D printing simulation, mechanical properties

1 Introduction

Formula Student [1] is a worldwide competition where students are tasked with designing and building a formula-style car to compete against other universities. It is an important and exciting curriculum for undergraduate engineering education. One of the objectives is to allow engineering students to learn and apply the latest technologies to design, build and test the components and systems of Formula Student cars. Smart design, smart manufacturing and smart operation are important themes in the context of Industrial 4.0 [2] [3]. Within the themes, computational aided Topology Optimisation [4], Generative Design (GD) [5] and Additive Manufacturing (AM) [6] play a crucial role.

1.1 Topology optimisation and generative design

Topology optimisation in structural design has been in constant development since it was first introduced in 1988 [4]. Since then, topology optimisation has been used to minimise the amount of material for a component whilst maintaining the required strength. Topology optimisation produces complex shapes which traditional manufacturing techniques would either take too long to manufacture or even would not be possible. Since the increase in the use of additive manufacturing, topology optimisation has been used to produce the optimal strength to weight ratio designs. Additive manufacturing can produce these complicated geometries but lightweight designs with little or no alterations required.

The initial computer-aided design (CAD) model taken into a topology study is the most basic design with the most material possible. With the proper definition of constraints (e.g. geometric, material strength, resonant frequencies *etc.*) and boundary conditions, topology optimisation can be applied to re-distribute the material layout in order to remove the regions with low stress and add more material to the high-stress regions. Popular algorithms include Solid Isotropic Material Penalisation (SIMP) and Evolutionary Structural Optimisation (ESO) [5].

With the availability of modern computer power, reliable computational mechanics codes, machine intelligence algorithms, and advanced manufacturing techniques, an integrated design framework, known as *generative design,* has become practical. One of the widely used concepts was defined by Shea *et al.* [7] *''generative design systems are aimed at creating new design processes that produce spatially novel yet efficient and buildable designs through exploitation of current computing and manufacturing capabilities.''*

Generative design is usually implemented in iterative optimisation approaches that have been implemented in a couple of commercial software such as AUTODESK® Fusion 360. The process takes user input boundaries, constraints, requirements and manufacturing capabilities. This results in a range of optimal designs which can be manufactured. The software uses cloud computing to run complex simulations and calculations, creating thousands of compatible designs. Components designed using generative design are not limited to additive manufacturing.

With the structural strength as the main objective, these are designs which minimise mass or increase stiffness. This can be done with the implementation of a factor of safety (FOS). The FOS is a multiplication of the maximum amount of force a component will be subjected to in its life cycle. Designing off the FOS gives engineers peace of mind when it comes to components which are safety-critical and are required to have a much higher FOS.

Combining the designs being produced with the best strength to weight ratio and additive manufacturing is hugely economical. This allows for manufacturing components with very little waste materials. Less material will result in shorter production times and less material costs, increasing the money saved per component.

For example, in the wheel design of a Formula Student vehicle, as shown in Fig 1 (a), the input forces and obstacle regions may be used to produce a coarse convex hull as an initial volume. A level-set method topology optimisation then uses the volume to produce a shape. A hexahedral element-based Finite Element Analysis (FEA) is run to ensure the geometry produced is meeting the constraint conditions set up at the start of the study. The topology optimisation runs through multiple iterations to produce a minimised volume. To produce the beam shapes seen in many generative design studies. A beam network optimisation was used to create and connect nodes, all whilst varying thicknesses, as shown in Fig 1 (b). The algorithms [8] produce iterations to check whether the model is fully constrained.

1.2 additive manufacturing

3D printing, also known as additive manufacturing(AM) [9], is the "*fabrication of a physical, three dimensional part of arbitrary shape directly from a numerical description, typically a computer-aided design (CAD) model by a quick, totally automated, and highly flexible working process without any tooling*" [6]. AM was first developed in the 1980s by Charles W.Hull. A stereolithography technique which focused ultraviolet (UV) light to cure a photopolymer resin was used. This may be done in successive layers to produce a 3D model. Within this study, fused deposition manufacturing (FDM) was the chosen AM technique. This is one of the most used processes in 3D printing. A filament is melted and extruded through a nozzle, building up layers to make the required shape.

The use of 3D printing within the industrial sectors has allowed more companies to conduct rapid prototyping [10]. This process allows for designers who have produced a 3D model using CAD to ensure that it will fit without conflicting with any of the other components. Rapid prototyping permits the production of a full-scale real-life part quickly and economically. The cost of a print varies greatly. One main factor affecting price is infill density. It is the percentage of the interior parts of the 3D printed model that contains material as opposed to space. This can be used to reduce print time and material usage. Another condition that can be altered is the material choice. During rapid prototyping, the geometric shape of the component is usually more important than the material used. For this reason, a "cheap" material such as Acrylonitrile Butadiene Styrene (ABS) can be used as an alternative. This material is widely used for AM and is recyclable [11] [12].

There are a number of issues of Additive Manufacturing including print failures, distortion, rough surfaces, anisotropic properties and lack of material data that is limiting the quality assurance of this technology [13] [14] [15] [16]. For example, it is known that the mechanical properties [17] of the printed parts are sensitive to specific AM process parameters [18] [19]. e.g. the printing direction to the anisotropic property.

Without stringent testing of printed parts, the uses of AM are present in only a handful of real-life applications. Print failures are a common occurrence with AM processes and can be caused by a large range of factors. There are many failures across each AM method or material, but very few common across all [20].

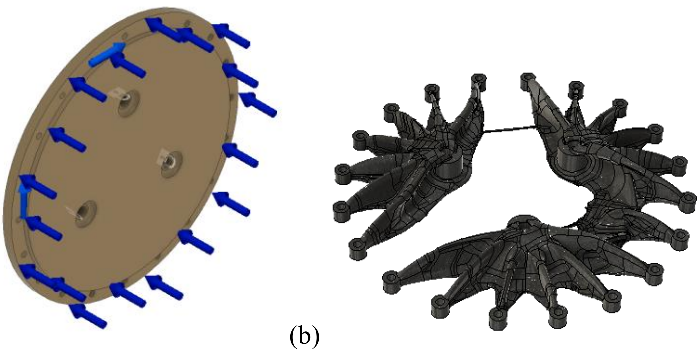
Print predictive technologies [21] [22] [23] may be achieved by using multi-physics simulation. e.g. distortion prediction and compensation due to thermal stress effect [24] [25]. Printing simulation may also help to prevent print failures by analysing a computer-aided design (CAD) model and correct issues with the mesh. Automated Process Monitoring [26] [27] [28] [29] can be used to detect defects produced during the print, allowing the user to repair or restart it depending upon the severity of the defect. However, this technology is currently limited and requires many print failures to gather the required data. This must be done for each different model, printer and material [30].

In the following sections, the improvement of the prospective mechanical property of a topologically optimised design of a wheel was carried out. As the mechanical load of a wheel is crucial in its application, the prospective mechanical properties of the wheel to be made by AM are investigated by using simulation so that better outcome from AM may be predicted with the customised process planning.

2 Design of a Formula student car wheel

The design, optimisation and production of the wheel are for a Formula Student vehicle. As shown in Fig 1(a), forces acting upon the wheels during the competition events were used to provide the boundary conditions for simulations. The maximum lateral force (acting perpendicular to the car) and longitudinal force (acting around the circumference of the wheel) were 2000N and 1777N respectively. To produce the forces acting upon the wheel, some assumptions were made. These were the assumption of optimal tyre operating temperature, thus producing maximum grip. A maximum mass of the vehicle and driver is 300kg and the effects of camber acting on the car being negligible.

As shown in Fig 1(a) below, the lateral force was applied to the area where the rim of the wheel would be attached. This is where the force acting upon the tyre during cornering would transfer to through the rim. At the same time, a moment was calculated using the maximum longitudinal force and the radius of the tyre. This provided a simulation of a "worse case scenario" which could occur during a spin-out when racing or testing. The constrained points of the simulation were the three bolt locations.



(a) (b)

Fig 1. (a) original wheel design; (b) a generative design

3 Topology optimisation of wheel design

Four stages of the topology optimisation process of the wheel are shown in Fig 2. The first image (a) shows a basic wheel design which was used in the study. Image (b) shows the mesh results of the topology study obtained from a SIMP algorithm. It may be seen that the boundaries are jagged because of the meshes. It may be better to smooth the edges, e.g. to reduce stress concentration, as shown in image (c). The FOS of the final wheel design, as shown in image (d), has more material on than required from the topology study. The initial mass of design (a) was 1.08kg, design (d) has a mass of 0.570kg.

The topology optimisation study was run to have a factor of safety (FOS) of 1.5. As the wheel is designed to be used in a motorsport application and therefore should be as light as possible, the smaller the FOS, the lighter the wheel. When creating the final wheel design, additional material was placed slightly external to the topology mesh. This resulted in a minimum FOS of 1.9 in the areas where the wheel would be bolted to the hub.

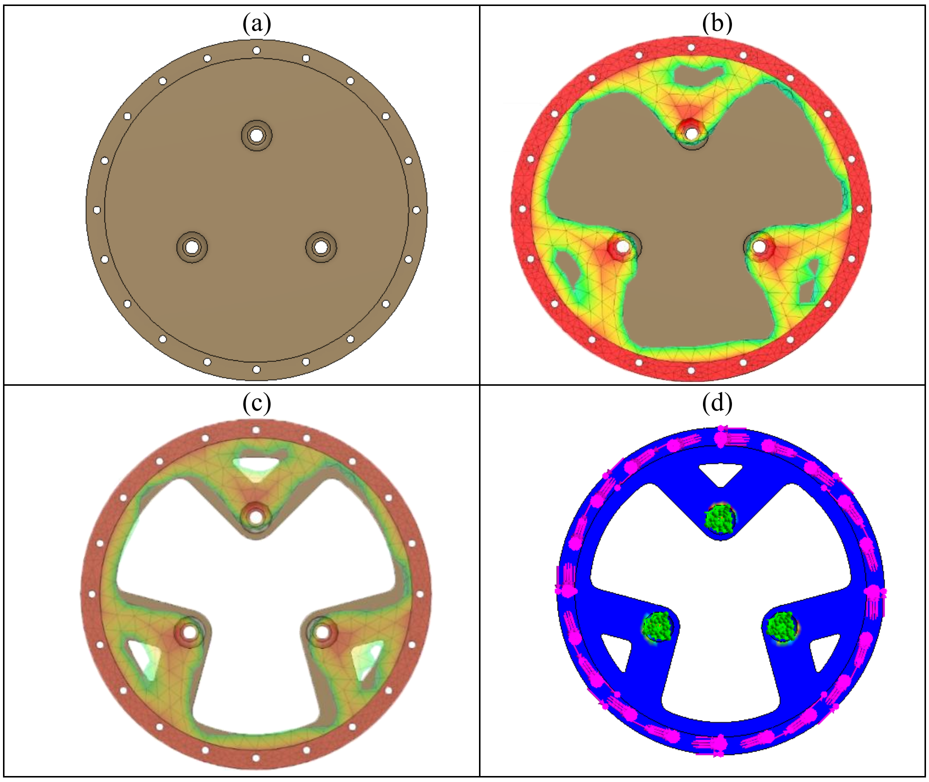


Fig 2. topology optimisation process of the wheel

The topology optimisation was carried out using the Solid Isotropic Microstructure with Penalisation [31] [32] algorithm in which the material assumption of isotropy and homogeneity was made. However, it is known that in the physically printed parts, such assumptions are usually invalid. A number of experimental studies [24] [33] [34] [35] [36] [37] have shown the effect of the process parameters to the outcome and quality of the printed parts in the perspective of mechanical characteristics. The specimens used in these studies are in the standard shapes. In practice, it is crucial that the results from the standard testing can be applied to the real applications of part design. In the next section, the printing process planning of the topologically optimised wheel is investigated. The main factor we considered is the anisotropic properties due to the raster deposition directions [10] [13] [19]. It is aiming to improve the strength of the printed wheel by customised the deposition directions based on the internal loads of the structure.

4 DFM process planning to improve strength

As shown in the literature [17] [38], the strength of a 3D printed part is significantly affected by the process parameters such as build orientation and raster angle in FDM. The anisotropic properties in the printed parts may be modelled by the transversely isotropic material constitutive behaviour [12], as expressed in equation (1).

$$\begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix} = \begin{bmatrix} 1/E_p & -\nu_p/E_p & -\nu_{pz}/E_p & 0 & 0 & 0 \\ -\nu_p/E_p & 1/E_p & -\nu_{pz}/E_p & 0 & 0 & 0 \\ -\nu_{pz}/E_p & -\nu_{pz}/E_p & 1/E_z & 0 & 0 & 0 \\ 0 & 0 & 0 & 1+\nu_p/E_p & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/2G_{pz} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/2G_{pz} \end{bmatrix} \begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{xz} \end{Bmatrix} \tag{1}$$

where $\sigma_{..}$, $\tau_{..}$ and $\varepsilon_{..}$, $\gamma_{..}$ are stress and strain components, respectively; E_p and E_z are the elastic moduli of the planar directions (x-y plane in Fig 3) and the principal direction (z-direction in Fig 3), respectively; ν_p is the Poisson's ratio in the planar directions; ν_{pz} and G_{pz} are the Poisson' ratio and shear modulus between the principal direction and the plane. A set of experimental values of these constitutive parameters of ABS using FDM were estimated by Zou *et al*. [12], and will be applied in this study. The strength in the principal direction is slightly stronger than the transverse directions [12] [33]. Thus, this would help to plan the deposition directions during the printing process.

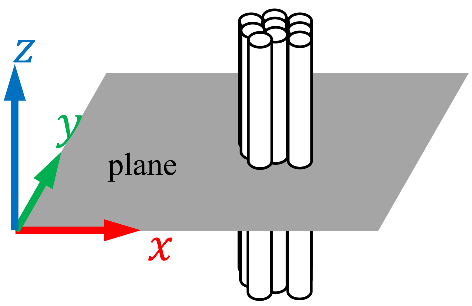


Fig 3. schematic diagram of a transversely isotropic material model

The initial study of structural analysis showed that the applied moment/torque mainly contributes to the stress along the circumferential direction, and the applied lateral force mainly contributes to the stress along the radial direction. The two main stress directions may help in planning the deposition directions. It may be helpful to align the principal direction of the transversely isotropic material model to the main stress directions. It is proposed, as shown in Fig 4, that the wheel is sectioned into the front and back plates. For the front plate, the principal direction of the transversely isotropic material model is aligned to the circumferential direction of the wheel as shown in Fig 4(a), which may improve the structural strength to resist the applied moment. For the back plate, the principal direction of the transversely isotropic material model is aligned along with the radial directions, as shown in Fig 4(b), so that the structural strength may be improved to resist the applied lateral force. Furthermore, the circular deposition pattern may be applied to the three holes that are closed to the centre of the wheel, as shown in Fig 4(c).

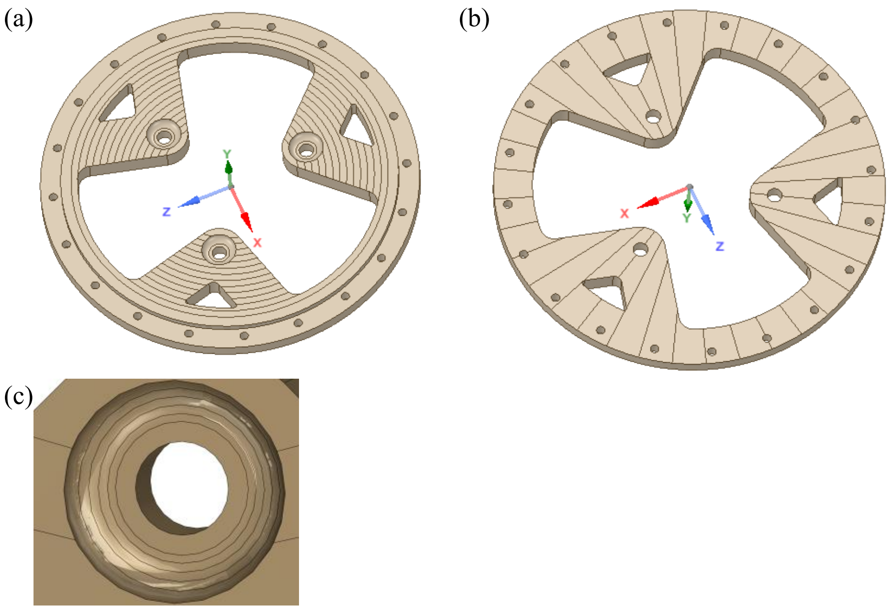


Fig 4. 'customised' printing process path for the deposition to potentially improve the strength; the black lines illustrate the deposition paths.

5 Results and Discussions

Results of stress analysis by ANSYS from different deposition patterns are shown in Fig 5. Two deposition patterns are considered with identical boundary and loading conditions. The equivalent stress of the first pattern from a rectangular deposition pattern is shown in Fig 5(a). While the results from the customised deposition pattern, as described in Fig 4, is shown in Fig 5(b).

It may be seen that the stress is more concentrated in Fig 5(a) whilst the high stresses are more spread around the holes in Fig 5(b). The maximum value of the equivalent stress in the wheel from the customised deposition pattern in Fig 5(b) is $\frac{6.7272-5.7513}{0.5\times(6.7272+5.7513)} = 15\%$ less than the other one in Fig 5(a). Therefore, it may be possible to improve the structural strength of a printed wheel by customising the deposition pattern based on the alignment between the principal direction of the transversely isotropic material model and the principal stress directions.

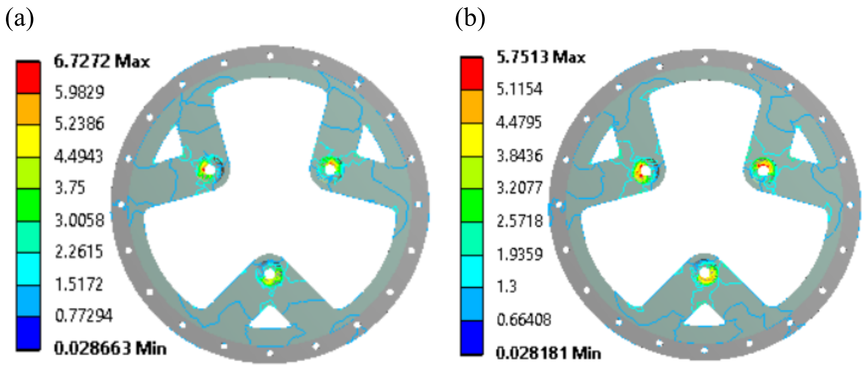


Fig 5. the equivalent stress distribution (MPa) of the wheel subjected to the design loads; (a) simulation from a rectangular deposition pattern; (b) simulation from a customised deposition pattern as illustrated in Fig 4.

6 Conclusions

In this study, a wheel design of a Formula Student car with computational aided topology optimisation was carried out for additive manufacturing. The uncertainty in additive manufacturing was briefly surveyed. The process influence on the mechanical properties of the wheel design was simulated by customising deposition patterns of the DFM process. It was found that aligning the principal direction of the transversely isotropic material model for DFM to the principal direction of stress may improve the strength of the printed part. Further work will be crucial to develop a mathematical formulation of this strength improvement approach with experimental validation.

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