Topology optimization of support structure for selective laser melting process

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TOPOLOGY OPTIMIZATION OF SUPPORT STRUCTURE FOR SELECTIVE LASER MELTING PROCESS

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School of Mechanical and Aerospace Engineering

A thesis submitted to the Nanyang Technological University

in partial fulfilment of the requirement for the degree of

Master of Engineering

2021

Statement of Originality

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ABSTRACT

As a kind of additive manufacturing technologies, selective laser melting (SLM) is widely used in various industries. In the three-dimensional (3D) printing process, support structure is often used to enhance the overhang structure and prevent the structure from collapsing. In addition, as the energy is highly concentrated during the printing process, it may cause a large temperature gradient, forming internal stress and warping deformation. Therefore, it is necessary to add support structures, which are usually generated excessively by the existing additive manufacturing technology, for avoiding warpage and enhancing thermal diffusion to reduce temperature gradient.

As such, this thesis mainly studies the support structure in SLM using topology optimization methods. The main contributions of this thesis are detailed as follows:

- 1) Optimization of support structure subject to mechanical load, based on structural topology optimization methodology. Modelling is presented for simulation of the support structure for SLM, based on structural topology optimization. This is performed to find the best distribution of structure materials with the objectives for minimizing compliance, and subject to certain volume fraction constraint.
- 2) Optimization of support structure subject to heat flux load, based on thermal topology optimization methodology. Similar to structural topology optimization, thermal topology optimization is conducted, in which the objective of the optimization is to minimize temperature, that is, to minimize thermal compliance, and subject to heat flux load generated during printing progress.
- 3) Optimization of support structure subject to thermo-mechanical coupled load, based on structural topology optimization methodology. For structural topology optimization with consideration of heat flux load, a thermal compliance is used as

an additional constraint in optimization, in order to obtain an optimized support structure subject to thermo-mechanical coupled load.

- 4) Optimization of support structure subject to thermo-mechanical coupled load, based on thermal topology optimization methodology. For thermal topology optimization, the present procedure is similar to that for structural topology optimization subject to thermal-mechanical coupled load. A structural compliance is introduced as an additional constraint in thermal topology optimization, for the support structures subject to thermal-mechanical coupled load.

Through the studies mentioned above, four kinds of support structures for a same printed part are generated optimally for comparison, namely (1) the uniform support structure, (2) the mechanical-loading support structure optimized by the structural topology optimization, (3) the heating-loading support structure optimized by the thermal topology optimization, and (4) the thermo-mechanical-coupled-loading support structure obtained by structural topology optimization. It is shown through comparisons that the optimized structures are more effective than the uniform structures for supporting the overhang structure and transferring heat. The printing efficiency is also improved and thus material consumption reduced.

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CHAPTER 1 INTRODUCTION

1.1 Background

3D printing is a new manufacturing technology based on 3D model data, unlike conventional methods through material reduction. It constructs the objects by stacking materials in layers, and it is also called additive manufacturing [1]. First, the 3D solid model of the part is discretized in the printing direction, and the cross-sectional data of the model is obtained. After that, the trajectory of the printing head is calculated, according to the characteristics of different additive manufacturing technologies. During the printing process, the printing head moves subject to the control of the computer to process the layer by layer. The layers are then stacked and connected until the end of printing. Additive manufacturing technology has been widely recognized by various industries and government departments in the global arena, since its inception in the late 1990s [2, 3]. A variety of materials, including plastics, metal powders, concrete, bioactive materials, food materials, ceramic powders, and biomedical materials, can be used in 3D printing for various purposes, such as printings of houses, cars, airplanes, animal organs and teeth, and these application fields continuously expand [4-7].

Selective laser melting (SLM) technology, as the most promising technology in laser additive manufacturing, started at Fraunhofer Institute for Laser Technology, Germany, in 1995. The technology uses high-power laser as energy input, selectively melting the solid powder layer by layer according to the 3D model data, and solidifies the molten layers to direct manufacturing high-performance parts with complex features. The porosity and pore shape may be controlled conveniently. Due to the direct irradiation of high-energy laser, the powder particles melt and solidify rapidly to form a very dense and fine microstructure. Usually the quality of printed part is superior to the casting part and close to forging part,

showing that the technology has outstanding advantages in the direct forming of complex and difficult work pieces. It also shows good application prospects in aerospace, automotive, mould and other fields. At the same time, the selection of materials is very extensive. Theoretically, any powder that is heated by laser to form an interatomic bonding can be used as the printed materials. At present, the research of SLM is mainly based on metal powder, including normal and stainless steels, cobalt-chromium alloy, aluminium and aluminium alloy, titanium and titanium alloy, copper, iron, nickel-based alloy and so on.

SLM technology has progressed tremendously. During the SLM printing process however, the laser acts directly on the surface of metal powder, which causes it to undergo rapid melting and cooling. This leads to various defects, such as spheroidization, pores, cracks, slag, over-burning, warping, etc. Although the surface quality of the printed part may be improved by post process, it is impossible to eliminate these defects only by post-processing methods for some complicated structures, such as overhang structure and complicated curved surface. Therefore, it is necessary to perform both the structural and process parameter optimizations before printing. In order to obtain a good quality of printed part, special attention is necessarily given to process parameters, scanning strategy and support structure, when the parts are printed with overhang structures and complex curved surfaces.

During the printing process of overhang structure, the thermal conductivity of the metal powder is much smaller than that of the metal body. Thermal energy cannot diffuse easily by heat conduction and thereby creates a molten pool. If there is no support structure added to the overhanging structure, the molten pool may sink into the powder due to its own gravity and capillary force, resulting in a dross phenomenon. In the case that the energy cannot be diffused in time, the overhang structure may cause the concentration of energy greatly. Temperature of the molten pool rises very fast, which may cause over-burning and poor quality of the surface of the printed part. In addition, it may cause a large temperature

gradient, forming internal stress and warping deformation, since the energy is highly concentrated.

In order to address the issues mentioned above, it is generally required to accelerate the dissipation of heat by adding support structure, since reasonable layout support structure may significantly improve the printing quality of the overhang structure. If the support is very dense however, it is difficultly removed after printing is completed, and then the printing surface may be destroyed. If the support is very thin, it is possible to cause defects, such as dross and excessive burning in the unsupported area. At present, the support structure generated by commercial software is usually a vertical bar connecting the overhang and the closest physical part under it. This type of support structure consumes more support materials than needed, and affects surface quality of the part when removing the support structure.

In order to reduce support structures during SLM, research has focused on minimizing the volume of support structures and interface between the part and support structures [8]. The volume of support structures directly affects material consumption and processing time. The interface is key to surface quality of finished part. Currently, there are two main ways to minimize support structures. The first is to optimize the part orientation, to avoid or reduce support structures [9-11]. The orientation of the part plays an important role in the SLM process because it affects the quality of the final part, manufacturing time and amount of support structures [12]. The second method is to use a better support structure to make it cost-effective. Various support types, such as lattice, unit cell, cellular support, are used as support structures to reduce the amount of support materials and shorten printing time [13-15]. In addition to the above two methods, some commercial companies have also introduced innovative technologies to reduce support structures. For example, the SupportFree system developed by Velo3D, through process simulation, geometry-based detection and closed-loop control of melt pool, can print parts with complex internal

geometries that don't need support structure. It can print parts with large horizontal holes without support structures, finished with a high-quality surface [16].

However, most of these optimization methods for support structures are based on geometric features. There are few studies on how to design lightweight support structures with consideration of the process characteristics of SLM. Therefore, it is really necessary to perform the optimization of support structure, in order to maximize the SLM processing capabilities while achieving the goal of lightweight design.

1.2 Objective and scope

Based on the background described above, this thesis aims to optimize the support structure by means of topology optimization method for reducing material waste and saving printing time. In order to achieve the objectives, the scope of this thesis is listed down below.

- (1) Theoretical analysis of the thermal-mechanical coupled problem during the SLM printing process.
- (2) Development of models for optimization of the support structure for SLM, based on structural and thermal topology optimization methodologies. The support structures are optimized systematically subject to the mechanical, heat flux, and thermo-mechanical coupled loads.
- (3) Comparison of various optimized support structures obtained by different methods.

1.3 Organization of the thesis

This thesis consists of five chapters, and each chapter is further composed of several sections for a better organization.

Chapter 1 introduces the background information, followed up by objective and working scopes of this thesis.

Chapter 2 provides a good literature review in details for the additive manufacturing, SLM, support structure in SLM, and followed up by optimization methods for support structure in SLM.

Chapter 3 introduces topology optimization methodology, including topology optimization for structural and thermal problems.

Chapter 4 describes how to perform the optimization of the support structure subject to mechanical, heat flux, and thermo-mechanical coupled loads through the structural and thermal topology optimization methodologies. Systematically case studies are carried out for comparison of the support structures optimized by different topology methods.

Finally, Chapter 5 draws several conclusions first based on the optimization studies detailed in Chapter 4, and then recommends several studies for the future works.

CHAPTER 2 LITERATURE REVIEW

2.1 Additive manufacturing

2.1.1 Classification

So far many 3D printing technologies have been developed, among which the differences mainly are the materials used and approaches for printing. According to ASTM International [17], namely American Society for Testing and Materials, additive manufacturing is classified to seven categories, (i) material extrusion, (ii) powder bed fusion, (iii) vat photopolymerization, (iv) material jetting, (v) binder jetting, (vi) sheet lamination, and (vii) directed energy deposition. An overview of these technologies is presented in Table 2.1 [17].

Table 2.1 Classification of additive manufacturing processes by ASTM International [4].

CATEGORIES	TECHNOLOGIES	POWER SOURCE
Material extrusion	Fused deposition modelling, Contour crafting	Thermal energy
Powder bed fusion	Selective laser sintering, Direct metal laser sintering, Selective laser melting, Electron beam melting	High-powered laser beam Electron beam
Vat photopolymerization	Stereolithography	Ultraviolet laser
Material jetting	Polyjet / Inkjet printing	Thermal energy / Photocuring
Binder jetting	Indirect inkjet printing	Thermal energy
Sheet lamination	Laminated object manufacturing	Laser beam
Directed energy deposition	Laser engineered net shaping, Electronic beam welding	Laser beam

Usually a process for printing a 3D model using a 3D printer starts with a virtual 3D model built by the computational 3D modelling software. After that, the developed 3D model is imported into the software that comes with the printer, and then the model is converted into

a series of layers, followed up by printing layer by layer. The printer can use viscous, powdery or silk-like raw materials. Finally, the cross-sections of the layers are bonded in their respective directions, eventually forming the whole object.

2.1.2 Advantages and applications

3D printing technology provides numerous benefits for both individuals and businesses. The mainly significant benefits are briefly listed as follows [18-21].

(1) Complexity and diversification of products are achieved at a lower cost.

Manufacturing of products with complicated shapes by conventional methods often incurs higher manufacturing costs. At the same time, conventional manufacturing equipment has very few or even single function. Hence, the shape of the processable product is limited. However, a 3D printer is able to print a wide variety of shapes, regardless of complex or simple shape of the object. The complexity of the product does not have a significant impact on its manufacturing costs. Machining or prefabrication of mould is not required if 3D printing technology is used. Therefore, the difficulty of manufacturing complex products is reduced greatly and the development cycle is shortened.

- (2) Customization and personalisation of products. 3D printing manufactures on-demand productions, reduces the physical inventory of enterprises, avoids the waste of resources for large quantities of unsold goods in mass production, and is more environmentally friendly. Products are also printed locally on demand, and thus the logistics and transportation costs are reduced. These advantages make 3D printing ideal for rapid manufacturing of the following types of products: (1) products with complex structures, such as free-form surface blades and complex internal channels that are difficult to be manufactured by the conventional methods, (2) personalized and customized products, such as cultural creative products,

jewels, human organs and small batch products before mass production, and (3) high value-added products, such as products for aerospace and biomedical applications [22, 23].

- (3) Less manufacturing skill is required. Conventional workers need a few years to master the skills they need. Although skill requirement is reduced by mass production and computer-controlled manufacturing machines, skilled professionals are still required to make machine adjustments and calibrations, when using conventional manufacturing machines. Compared with conventional technology for the same complex products, individuals for 3D printing only need to intelligently design the products in computers, then convert the complex workflow into digital files and send them to the 3D printer for manufacturing. Throughout the process, users do not need to master a variety of complex manufacturing processes and skills, and thus the technical threshold of manufacturing is reduced greatly.

However, compared with the conventional machining, casting, forging, welding and moulding technologies, 3D printing has its disadvantages. Firstly, 3D printing technology differs from conventional technologies greatly in product dimensional accuracy and surface quality. The post-processing of 3D printing is cumbersome, and the performance of the product cannot meet the requirements of many advanced metal structures. Secondly, it is relatively slow in manufacturing speed and inefficient for mass production. Finally, the costs of 3D printing equipment and consumables is higher. For example, the cost of metal powder-based printing is much higher than by conventional manufacturing.

2.1.3 Selective laser melting (SLM)

Selective laser melting (SLM) technology is one of additive manufacturing (AM) methods that use a high-energy laser beam to melt metal alloy powder on two-dimensional (2D)

sections, which are sliced from a 3D model. It prints solid parts layer by layer from bottom to top [24]. A schematic illustration of the SLM system is shown in Figure 2.1 [25], and the main processes are detailed as follows [25].

- (1) Use CAD software to design a 3D CAD model.
- (2) Slice the 3D model into a series of thin layers and make a plan for the scanning path.
- (3) Import the processed data of the 3D model into the SLM printer.
- (4) Import the sliced data layer by layer, and the high-energy laser beam is used to melt metal powder selectively to complete the processing of one layer of the product.
- (5) After the melting of one layer of the product is finished, the piston is lowered by one sliced layer, then the powder feeder spreads the metal powder over the powder bed.
- (6) Repeat the above Steps (4) and (5) until all the layers are printed.
- (7) Remove the printed product from the substrate and perform post-processing.

Figure 2.1 Schematic illustration of the SLM system [25].

Compared with conventional manufacturing methods, SLM technology has advantages as detailed below.

- (1) The high-power density laser processes metal parts with high dimensional accuracy and good surface roughness.
- (2) The printed parts have metallurgical bonding characteristics. For example, the relative density of the parts reach nearly 100%, and the mechanical properties of the parts are comparable with castings and forgings [26, 27].
- (3) The final metal product is printed directly from the 3D model, which eliminates the intermediate steps and saves the time for making mould.
- (4) SLM technology is suitable for manufacturing workpieces with various complex shapes, such as products with complex internal cavity structures and personalized products in the medical field, which may not be manufactured by conventional methods.

SLM technology manufactures complex products, shortens product development cycles, reduces costs, and makes product development more convenient. At present, it is mainly applied to the rapid development of new concept products and the manufacture of small batch products to shorten the cycle times. It is mainly used in biomedicine, aerospace, industrial mould, automobile manufacturing and other fields, and gradually developed in the directions of individualization, lightweight and customization [28-30].

SLM technology is used more and more widely with the increasing demand for precision and personalization in the medical industry. It is gradually used to manufacture orthopaedic implants, customized prostheses, and personalized orthodontic brackets. For example, Wang *et al.* [31] fabricated a 316L stainless steel spinal surgery template. Song *et al.* [32] designed and manufactured a personalized femoral component by SLM technology.

2.2 Support structure in SLM

2.2.1 Types of support structure

Support structures are required for both base surface and overhangs of the parts manufactured by SLM. The base surface refers to the first layer in the forming direction of the printed part. The support structure under the base surface lifts the printed part from the substrate for a certain distance, which facilitates the removal of the printed part after printing is completed. If there is no support structure connecting the part and the substrate, the base surface of the part may be damaged when the printed part is removed from the substrate.

According to the geometric shape characteristics, the overhanging structures are divided into surface, line and point overhangs. The surface overhang is further divided into flat and inclined surfaces. A schematic illustration of these common overhangs is shown in Figure 2.2 [33].

Figure 2.2 Schematic illustration of common overhangs [33].

The main types of support structures used in SLM include block, point, web, contour and line supports, etc., as shown in Figure 2.3 [34]. For example, block support structure may be used for small and thin parts. Cone support structure may be added to the part that needs to withstand a certain tension. In terms of the boundary walls of the support structure, it may be designed as diamond or tree-shaped holes to facilitate the pouring of the powder when printing is done. In addition, the connection between the support structure and the part is designed in a zig-zag shape, which provides support strength and facilitates easy removal of the support structure if printing is finished.

Figure 2.3 Different types of support structure [34].

2.2.2 Functions of support structure

Adding support structure is an essential part for the SLM process to form complex part with overhang. In the early stage of printing, it is important to select appropriate support structure in the SLM process, according to the geometric characteristics of the part. Based on literature review, the major functions of support structure are summarised below [35-37].

- (1) Avoid machining error of part caused by unevenness of the substrate. Since the top surface of the substrate may be uneven, the bottom surface of the printed part is also uneven, if the part is printed directly on the substrate. Usually a support structure is added between the part and the substrate to reduce machining error.
- (2) Separate part from the substrate conveniently. Currently the printed part manufactured by SLM is mainly separated from the substrate plate using wire electric discharge machining (WEDM). In order to ensure that the printed part

is not damaged during the cutting process, a block or solid support is generally added to connect the part and the substrate plate.

- (3) Support overhang structures. If there is no support structure under the overhang part, the molten pool collapses due to its own gravity and capillary force. In this case, a support structure is needed to support the forming of the overhang part.
- (4) Transfer energy during the printing process. The laser rapid prototyping process generates a large amount of heat due to energy accumulation. The support structure transfers the generated heat to the substrate rapidly, in order to reduce the deformation of the part due to thermal stress. Compared with the cases without support structures, good thermal conductivity of the support structure makes more uniform distribution of the temperature field, thereby reducing deformation due to thermal stress.
- (5) Avoid warpage and deformation caused by shrinkage stress. When the metal powder is melted and solidified during the printing process, there is warpage caused by shrinkage stress. After one layer is printed, the scraper lays the metal powder of the next layer, there is friction between the scraper and the solidified layer. If there is no support structure, the solidified part may be damaged, which affects the scraper spreading the powder continuously, and the machine may be damaged seriously. The support structure connects the formed and the unformed parts, thereby suppressing shrinkage effectively and maintaining the stress balance of the formed part.

In brief, the support structure used is to connect the formed and unformed parts, enhance strength, transfer heat, and maintain the stress balance of the formed part. Different types of support structures are added for parts with different overhang features. However, the support structure introduces some other challenges. The main disadvantages of support structure are summarized as follows [37, 38].

- (1) Waste of materials. Most of the support structure materials are not reusable and have to be discarded after removal.
- (2) Longer printing time is needed. When support structure is added to a part, the printing time is longer as support structure also needs to be printed.
- (3) Detrimental to the surface finishing when the support structure is removed. A few main surfaces of structural parts are not precise enough that may fail subsequent assembly and lead to insufficient mechanical performance.

2.3 Optimization methods for support structure

For the optimization of support structure in SLM, currently researchers mainly focus on development of algorithms of support structure or overall rules [13-15, 34, 35, 39-42]. This includes the minimum angle, at which the overhang structure is necessarily added, the effect of different support types on formation of printed parts, the usage of the lattice structure, and design and simulation for optimization of support structure.

For the forming angle of overhang structure [43, 44], researchers obtained the minimum overhang angle for support structure under different conditions. A large number of experiments showed that a self-supporting length of about 2 mm and an overhang angle of less than 45° are required for metal cantilever. The effect of the scanning strategy was also investigated on the formation of the overhang structure, indicating that reducing the scanning energy input forms the overhanging structure with a smaller tilt angle. It was also shown that the minimum angles required were different for different materials, and the angular limit of the overhang structure depended on the forming process.

For the research in support structure optimization, Calignano [34] divided support structures into two functional areas, contact area or teeth, and main support structure or support base. A detailed view of support structure is shown in Figure 2.4, labelling four key parameters that are tooth height, tooth top length, tooth base interval and tooth base length. Therefore,

support structure optimization is divided into contact area optimization and main support structure optimization.

Figure 2.4 Detailed view of support structure contact area [34].

2.3.1 Support structure contact area optimization

The effects of the varying contact area parameters were investigated. Calignano [34] studied the effects of varying six control factors on the warping of aluminium (AlSi10Mg) and titanium (Ti6Al4V) samples printed by SLM. The experiment adopted the Taguchi L_{36} method and used samples at dimension of $20 \times 10 \times 15$ mm. The results of the experiment showed that three factors of tooth height, fragmentation and hatching are significant to the warping of the aluminium part. Only two factors of tooth height and hatching are significant to the warping of the titanium part.

Järvinen *et al.* [45] studied the availability of web and tube support structures, and applied these two support structures to the mouldings of teeth and jewellery. Through their experiments, it was found that the removability of the mesh support was better than that of the tube support. The contact area was further optimized between the support structure and the part, in order to improve the surface quality of the part.

Poyraz *et al.* [46] studied the support structures for Inconel625 (IN625) parts, which were manufactured by direct metal laser sintering (DMLS). As shown in Figure 2.5 (a), a part with an overhang was adopted. Two sets of experiment were conducted to test the effect of different block support and hatch parameters on the support structures. The parameters of

hatch distance, fragmentation, tooth top length, and Zoffset were evaluated, as shown in Figure 2.5 (b) and (c). The experiments discovered that lower hatch distance reduces the distortion of the part and the top length with lower value leads to weaker support attachments.

Figure 2.5 Designed part and dimensions for experiments, a) part dimensions, b) block support parameters, and c) tooth parameters [46].

Liu et al. [47] researched the distortion of three same parts with different support structures. The tooth base interval, tooth base length and tooth height were the same for all the three parts. As shown in Figure 2.6 (a), the tooth top length for Part I, Part II and Part III was 0.3 mm, 0.3 mm and 1 mm, respectively. Uniform support structure with hatching at 2 mm was added to Part I and Part III while non-uniform support structure with 1 mm hatching at two sides and 2 mm in the middle was added to Part II. The parameters of three parts are listed in Figure 2.6 (a). Part II has the same tooth top length with Part I but smaller hatching at

two sides. Part III has the same hatching with Part I but larger tooth top length. Part II and Part III were manufactured without warping as shown in Figure 2.6 (b).

No. item	Aspect ratio	Support parameters			
		Interval + length	Tooth height	Tooth top length	Hatching
Part I	10	2 mm	1 mm		
Part II	10	2 mm	1 mm		
Part III	10	2 mm	1 mm		

(a)

(b)

Figure 2.6 Comparison of warping of support structures, a) support parameters, and b) experiment results [47].

2.3.2 Main support structure optimization

In terms of optimization of main support structure, Yan *et al.* [39] studied the lattice structure with considering the influence of the geometric parameters of the unit cell, in order to obtain an easily removable support structure with a minimum volume fraction. Hussein *et al.* [48] explored the potential of using cellular structures to support overhang structures

of metal parts in SLM. As shown in Figure 2.7, the two types of unit cells, namely Schoen gyroid and Schwartz diamond, were used to generate support structures for the experiments, in which support structures generated from these unit cells were useful to support the overhang structures of metal parts. After that, it was further understood that the structure type, volume fraction and cell size had significant influence on the manufacturability, support quantity and printing time of the lattice support structures [14]. The volume fraction of the lattice support structures may be as low as 8%, which greatly saved the amount of material used and printing time of the support structures.

Figure 2.7 Unit cells and lattice support structures [14].

Strano *et al.* [13] proposed a method to optimize the cellular support structure. This method used 3D implicit functions to design the cellular support structure, which changed the density. Since the implicit function method was used to design the geometric shape by pure mathematical formulas, the method was very suitable for constructing and designing support structure. Through this method, various cellular structures were easily defined and optimized, especially in the case with different support requirements to produce different cellular structures. Two examples of optimized cellular structures are shown in Figure 2.8.

Figure 2.8 Examples of cellular support structures [13].

Calignano [34] designed a flow chart for support structure optimization and obtained optimized combined process by Taguchi orthogonal experiment. Zeng [40] optimized the algorithm for generating support structures in SLM using simulation software 3DSIM, LLC. The stress and thermal fields were simulated during the scanning process. A support structure was developed for the heat accumulation characteristic of the printing process from simulation.

Gan and Wong [41] at Singapore Centre for 3D Printing investigated three types of support structures, namely “Y”, “IY” and pin types. Through experiments, a thin plate with levelled surface was fabricated with only 25 contact points. It was shown in finite-element analysis that unequal spacing of the support structures changed the thermal field distribution, which resulted in thermal deformation of the thin plate. In addition, it was also shown that the angle should be greater than 90° between the support structure and shrinkage direction of the printing part to avoid upward warping.

Mirzendehtdel and Suresh [42] established a topology optimization framework to reduce the support structure by introducing sensitivity calculation methods and by constraining the volume of the support structure. Vaidya and Anand [15] proposed a method combining the shortest path algorithm and the use of a filled lattice structure to minimize the support structure. Kuo *et al.* [35] proposed a repulsion index (RI), considering cost and surface accuracy. As shown in Figure 2.9, an optimal support structure was obtained through multi-

objective solid isotropic material with penalization (SIMP) topology optimization method, in which the load due to self-weight of the printed part was assumed in the optimization.

Figure 2.9 Topology optimization of support structure [35].

2.3.3 Remarks

The current optimization methods of support structure are mainly based on geometric features. With development of metal additive manufacturing technologies such as SLM, the support structure has to consider thermal condition and external load. For the optimization of support structure, it is necessary to combine the simulation with other methods to determine optimal distribution of the support by considering the temperature and stress fields during the printing process. The simulation of the printed part with optimized support structure has to consider part distortion. Therefore, it is necessary to consider the combined effect of mechanical load coupled with heat in developing the optimization of support structure, which requires the optimization of support structure in the product design stage. In other words, it is necessary to combine the topological structure design with the optimization of support structure of the product for the product design.

CHAPTER 3   TOPOLOGY OPTIMIZATION METHODOLOGY

3.1 Structural problem

Structural optimization aims to achieve a better performance by changing the design variables of the structure under given constraints. Similar to other optimization problems, structural optimization also includes three factors, namely the objective function, design constraints, and design variables. Among them, the objective function is used to characterize the performance of a certain structure. The design variable is structural parameters that may be optimized and adjusted in structure. The design constraint is additional conditions attached to the design variables. The goal of structural optimization is to find the optimal value of the design variables for a certain structure, and to obtain the optimal objective function satisfying the given design constraints.

According to different design variables, structural optimization is divided into size, shape and topology optimizations [49]. Size optimization mainly refers to the optimization of the dimensional parameters of the structure to improve the performance of the structure while maintaining the topology and shape of the structure unchanged. Shape optimization refers to changing the shape of the design domain while maintaining the structural topological relationship or boundaries, in order to find the optimal shape and boundary of the structure. Topology optimization is to find the optimal configuration of the structure layout, topology connection relationship, number of holes and location and so on in a certain design domain, such that certain performance indicators of the structure are achieved. An example of topology optimization for a 3D cantilever beam is shown in Figure 3.1 [50].

Figure 3.1 Topology optimization for a 3D cantilever beam [27].

At present, many different optimization methods were proposed. They may be roughly divided into (1) density-based methods such as solid isotropic material with penalization (SIMP) method, (2) boundary variation methods such as level set method (LSM), and (3) hard-kill methods such as evolutionary structural optimization (ESO) method [51, 52].

Bendsøe [53] proposed the density-based method in 1978, introduced a material unit with variable density that does not exist in reality. The density of this material unit is considered as a continuous variable with a variation ranging from 0 to 1. On this basis, this variable density is used as a topological design variable, and the functional relationship is constructed between the density of the assumed material unit and the physical property of the material. Topological optimization is turned into optimal distribution problem of material density, and then optimization criterion or mathematical programming method is employed to solve the problem. The density-based method is one of the most widely-used and most successful structural topology optimization methods.

SIMP method [54, 55] is one of the most widely-used density-based methods. A power index p is used to punish the density variable, such that the density value of the material during the optimization process is as close as possible to both ends, i.e. "0" or "1".

In this way, the topology optimization with continuous density as the optimized variable is approximated well to the optimization problem with discrete variable.

In present study, topology optimization is carried out using SIMP method. The elastic modulus of the solid material in the SIMP method is expressed by a density variable as

$$\begin{aligned} E(\rho_e) &= \rho_e^p E_0 \\ 0 &\leq \rho_e \leq 1 \end{aligned} \quad (3.1)$$

where $E(\rho_e)$ is optimized elastic modulus, ρ_e is density variable, p is penalty factor and E_0 is initial elastic modulus of elements. A curve for material density function is shown in Figure 3.2 for different penalty factors. From top to bottom, the density curve of $p = 1$ to 5 is in order. It is shown in Figure 3.2 that, if the penalty factor is larger, the more intermediate density tends to $\rho = 0$ (void material). Through such processing, continuous variable optimization is brought closer to the discrete variable optimization.

Figure 3.2 SIMP interpolation curve [56].

Let K_e^0 and K_e be the initial and optimized stiffness matrices of structural elements, respectively, then Equation (3.1) is re-written as [57],

$$K_e = \rho_e^p K_e^0 \quad (3.2)$$

In general, topology optimization model for continuum structure based on density-based method takes the minimum compliance of the structure as optimization goal, and the material consumption of the structure (volume fraction) as constraint. The optimization model is thus expressed as

$$\begin{aligned} \text{Minimize } C(\rho_e) &= F^T U = U^T K U = \sum_{e=1}^N \rho_e^p u_e^T k_0 u_e \\ \text{Subject to: } &\begin{cases} \frac{V}{V_0} \leq f \\ K U = F \\ \rho_{min} \leq \rho_e \leq 1 \end{cases} \end{aligned} \quad (3.3)$$

where $C(\rho_e)$ is objective function, the compliance of the structure, F is structural load vector, U is the overall displacement vector of the structure, K is the overall stiffness matrix of the structure, N is the total number of elements in the design domain, ρ_e is the design variables, the relative density of materials, p is penalty factor, u_e is the displacement vector of element, k_0 is initial stiffness matrix of element, V is the volume after structural optimization, V_0 is the initial volume of structure, f is given volume fraction, and ρ_{min} is minimum relative density.

3.2 Thermal problem

The topology optimization for thermal structure is quite similar to the structural topology optimization. For heat transfer structure, the properties of a material are described by the thermal conductivity λ . By replacing the elastic modulus E in Equation (3.1) with the thermal conductivity λ , the functional relationship is thus established between thermal conductivity and density of materials, as shown in Equation (3.4) below,

$$\begin{aligned} \lambda(\rho_e) &= \rho_e^p \lambda_0 \\ 0 &\leq \rho_e \leq 1 \end{aligned} \quad (3.4)$$

where $\lambda(\rho_e)$ is optimized thermal conductivity, ρ_e is density variable, p is penalty factor and λ_0 is initial thermal conductivity. Accordingly, K_e^0 and K_e in Equation (3.2) are treated as initial and optimized thermal conductivity matrices, respectively.

The topology optimization model for continuum heat transfer structure based on density-based method takes the minimum thermal compliance of the structure as optimization goal, and the material consumption of the heat transfer structure (volume fraction) as the constraint. The optimization model is expressed as

$$\begin{aligned} \text{Minimize } C(\rho_e) &= Q^T T = T^T K T = \sum_{e=1}^N \rho_e^p t_e^T k_0 t_e \\ \text{Subject to: } &\begin{cases} \frac{V}{V_0} \leq f \\ K T = Q \\ \rho_{\min} \leq \rho_e \leq 1 \end{cases} \end{aligned} \quad (3.5)$$

where $C(\rho_e)$ is objective function, the thermal compliance of the structure, Q is heat generated, T is the overall temperature vector of the thermal structure, K is the overall thermal conductivity matrix of the structure, N is the total number of elements in the design domain, ρ_e is the design variables, the relative density of materials, p is penalty factor, t_e is the temperature vector of element, k_0 is initial thermal conductivity matrix of element, V is the volume after structural optimization, V_0 is the initial volume of structure, f is given volume fraction, and $\rho_{\min}$ is minimum relative density.

3.3 Remarks

This chapter describes the two optimization methods for structural and thermal problems, namely the structural and thermal topology optimizations. First, the structural topology optimization method is introduced for the structure subject to mechanical force, while the thermal topology optimization method described for the structure subject to thermal force. Structural topology optimization method is essentially the same as the thermal one, such

that either structural or thermal topology optimization method may be chosen for thermo-mechanical coupled problems.

CHAPTER 4   OPTIMIZATION RESULTS AND DISCUSSIONS FOR SLM

4.1 Structural topology optimization subject to mechanical load

In this section, the support structures are optimized for SLM, based on structural topology optimization subject to mechanical load, in which two types of load are considered, namely uniform and non-uniform loads.

4.1.1 Uniform load

As the most typical specimen with overhang structure, usually a single or twin cantilever is considered for experiment and simulation [14, 36, 58-61]. For example, the single or twin cantilever is chosen for experiment verification [14, 58-60], while single cantilever is generally chosen for simulation purpose [36, 59-61] because a twin cantilever is a symmetrical structure, in order to save computational cost.

Due to the printing capacity of the printer, SLM250 is considered here as an example, which is the smallest printer of SLM Solutions, with the smallest build envelope of $50 \times 50 \times 50$ mm. To follow the dimensions approximately, a printed part is drawn for the optimization of the support structure, as shown in Figure 4.1. The dimension of the vertical bar of the printed part is 15.5×1.0 mm, and that of the horizontal bar is 26.0×0.5 mm.

Figure 4.1 Geometry of printed part for structural topology optimization.

As shown in Figure 4.2, the design domain is defined as the space under the overhang of the part and displayed in green colour, while the non-design domain on top in grey colour remains unchanged even after optimization. There are two kinds of 2D basic element shapes, namely Quad and Tri elements, in the commercial software Hypermesh. Quad element is preferred in presented work. 2D meshing is done in the design domain, in which 2D Quad element is used with size of 0.25×0.25 mm. In addition, the element thickness of 1mm is considered. PSHELL is selected as Card Image under property definition.

Figure 4.2 Design and Non-design domains with meshing.

Material property is an important aspect for simulation. The elastic modulus and Poisson's ratio used in simulation are 0.7×10^{11} Pa and 0.3 respectively. These values correspond to aluminium alloy AlSi10Mg, which is a commonly used material in parts produced by SLM. Material property details are listed in Table 4.1.

Table 4.1 Details of material properties used in optimization.

Item	Value	Unit
Elastic modulus	0.7×10^{11}	Pa
Poisson's ratio	0.3	
Density	2.7×10^3	Kg/m ³

The rectangular design domain is ready for optimization after all meshing, material and property selections are completed. Loads and boundary conditions are imposed on the design domain after all the steps are done. As shown in Figure 4.3, all the nodes at bottom surface are chosen and Dof1 to Dof6 are ticked, such that the bottom surface is fixed as the boundary condition, as shown in Figure 4.4.

Figure 4.3 Setup of constraints for structural topology optimization.

The mechanical loads acting on the support structure include the weight of the overhang and the thermal stress that is generated in the process of printing. The generation of thermal stress is elaborated in Section 4.4.2. This section studies the impact of the weight of the overhang to support structure. For the setting of the loads, the nodes on the top edge of the design domain are chosen, on which the load is applied in the negative Z-direction. The view of load in Hypermesh is shown in Figure 4.4.

Figure 4.4 Load and boundary condition for structural topology optimization.

Several parameters are set in the commercial software Hypermesh, which are design variable, response, constraint and objective. Material is defined using the density-based method in software. The density of each element is used directly as a design variable and varies continuously between 0 and 1, in which the elements with the zero density are

completely deleted. The elements with density ranging from larger than 0 to less than 1 represent the fictitious intermediate material. The stiffness of the material is assumed as a function of the density. The setup of the design variable in the commercial software Hypermesh is shown in Figure 4.5.

Figure 4.5 Setup of design variable for structural topology optimization.

After the design variable is defined, the design responses are then defined. Two responses are defined for structural optimization, namely the volume fraction and compliance. The setups of the optimization responses are shown in Figure 4.6 (a) and (b). In this optimization, the volume fraction value of 0.3 is set as the constraint, as shown in Figure 4.6 (c), which represents the material fraction of the total volume in the design domain. The minimum compliance is chosen as the objective, as shown in Figure 4.6 (d), and all the settings of optimization parameters are summarised and shown in Figure 4.7.

Figure 4.6 Setup of parameters for structural topology optimization, (a) response of volume fraction, (b) response of compliance, (c) constraint and (d) objective function.

Design variables	* Density
Optimization responses	* Volume fraction * Compliance
Design constraints	* $0 \leq \text{Volume fraction} \leq 0.3$
Objective	* Minimize compliance

Figure 4.7 Summary of parameters for structural topology optimization.

Based on the settings described in Figure 4.2 to Figure 4.7, structural optimization is conducted using the commercial software Optistruct. The result obtained is shown in Figure 4.8, in which the unneeded material is removed from the design domain with the volume fraction value of 0.3. As a result, the remaining material is around 30 percent of the design domain. Red colour indicates the elements with a density of 1, while blue colour indicates the elements with a density of 0, and the remaining colours indicate the elements with a density between 0 and 1.

Figure 4.8 Result for structural topology optimization with uniform load.

4.1.2 Non-uniform load

For structural topology optimization, the loads acting on the printing support structure are the weight of overhang and the thermal stress caused by uneven heating during the printing process. For the case study mentioned above, the weight of the horizontal bar is a uniformly

distributed load, and the thermal stress is described in Section 4.4.2. For the supported and printed parts with different geometrical shapes, there are different weights and thermal stress distributed. For fully understanding of important parameters, several case studies are conducted with the differently defined loads, in order to optimize the support structures. These loads include the linear load, un-linear load, sinusoid load, and cosine load. The optimal results of support structure are shown in Figure 4.9 to Figure 4.25, based on topology optimization method with assumed loads. The simulated results obtained from the present case studies definitely are useful for future work.

It is shown in Figure 4.9 to Figure 4.25 that, the optimal support structures are quite similar to tree-like structures. The "tree" starts with a few small branches on the upper that become larger as they get closer to the substrate plate. In nature, these geometries can be found in plant leaf veins and roots [62]. Current optimization results as well as studies stated in the literature show that tree-like structures constitute a promising approach to support structures that can withstand mechanical and thermal loads [63-65]. Some findings from Figure 4.9 to Figure 4.25 are listed below.

- (1) Optimized support structures have 2 trunks, except support structures subject to two-step load (Figure 4.9) that have 3 trunks. The printed part is asymmetric with a vertical bar on the left side. The vertical bar also acts as a support, i.e., the "trunk", to withstand loads. Therefore, there is barely any support material besides the vertical bar. The diagonal support at the upper left corner acts as a branch of the vertical bar, connecting the vertical bar and the horizontal bar. However, the diagonal support in some optimization results is not obvious, i.e., the density of material less than 1, such as the support structures shown in Figure 4.12 and Figure 4.21. This is because the load on the left side near the vertical bar is very small or equal to 0.

- (2) Since the volume fraction is set at 0.3 in all cases, the material consumption of each obtained support structure is the same and equals 30% of the design domain. The distribution of support materials is directly related to the loads. Subject to the distribution of loads on the overhang, the optimized support structures are different in the position and size of the branches and trunks.
- (3) When the load is notably greater at a certain position than other places, such as the load on the left in Figure 4.20, there is more support material under it, and a longer contact interface between support structures and overhang. On the contrary, a smaller load requires less supporting material. As shown in Figure 4.11, the load in the middle is zero and results in no support material in the middle position.
- (4) For loads with similar curves, the obtained support structures are parallel. The V-shape load shown in Figure 4.15 and the single-wave-cosine load shown in Figure 4.25 are symmetric with the centre line of the top plate as symmetry line. The maximum load occurs at both ends. The load gradually decreases from the maximum on the left to 0, and then increases to the maximum on the right. The material distribution of the obtained support structures is alike with materials mostly distributed at both sides and no material in the middle.

Case study of two-steps load

Figure 4.9 Case study of two-steps load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of three-steps load

(a)

(b)

(c)

Figure 4.10 Case study of three-steps load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of dual-constant load

Figure 4.11 Case study of dual-constant load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of positive-linear load

(a)

(b)

(c)

Figure 4.12 Case study of positive-linear load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of negative-linear load

Figure 4.13 Case study of negative-linear load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of inverse-v-shape load

(a)

(b)

(c)

Figure 4.14 Case study of inverse-v-shape load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of v-shape load

Figure 4.15 Case study of v-shape load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of positive-constant-bilinear load

(a)

(b)

(c)

Figure 4.16 Case study of positive-constant-bilinear load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of constant-negative-bilinear load

Figure 4.17 Case study of constant-negative-bilinear load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of constant-positive-bilinear load

(a)

(b)

(c)

Figure 4.18 Case study of constant-positive-bilinear load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of first-dual-positive-linear load

Figure 4.19 Case study of first-dual-positive-linear load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of second-dual-positive-linear load

(a)

(b)

(c)

Figure 4.20 Case study of second-dual-positive-linear load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of non-linear load

(a)

(b)

(c)

Figure 4.21 Case study of non-linear load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of half-wave-sinusoidal load

(a)

(b)

(c)

Figure 4.22 Case study of half-wave-sinusoidal load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of single-wave-sinusoidal load

(a)

(b)

(c)

Figure 4.23 Case study of single-wave-sinusoidal load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of half-wave-cosine load

(a)

(b)

(c)

Figure 4.24 Case study of half-wave-cosine load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

Case study of single-wave-cosine load

Figure 4.25 Case study of single-wave-cosine load, (a) load distribution on printed part, (b) load setting in Hypermesh, and (c) optimization result of support structure.

4.1.3 Remarks

In this section, modelling of the support structure for SLM based on structural topology optimization is presented to explain how to use the structural topology optimization method to generate optimal support structure for a given printed part. A printed part of a single cantilever is used for optimization. An optimized support structure is obtained with the objective with minimized compliance, subject to certain volume fraction constraint of 0.3 and weight of the overhang. Besides, for the supported and printed parts with different geometrical shapes, several case studies are conducted with differently defined loads, in order to optimize the support structures, and they are finally summarized in Table 4.2.

Table 4.2 Summary of differently defined loads.

Figure No.	Load type	Load shape
Figure 4.9	Two-steps	
Figure 4.10	Three-steps	
Figure 4.11	Dual-constant	
Figure 4.12	Positive-linear	

Figure No.	Load type	Load shape
Figure 4.13	Negative-linear	
Figure 4.14	Inverse-V-shape	
Figure 4.15	V-shape	
Figure 4.16	Positive-constant-bilinear	
Figure 4.17	Constant-negative-bilinear	
Figure 4.18	Constant-positive-bilinear	
Figure 4.19	First-dual-positive-linear	

Figure No.	Load type	Load shape
Figure 4.20	Second-dual-positive-linear	
Figure 4.21	Non-linear	
Figure 4.22	Half-wave-sinusoidal	
Figure 4.23	Single-wave-sinusoidal	
Figure 4.24	Half-wave-cosine	
Figure 4.25	Single-wave-cosine	

4.2 Thermal topology optimization subject to heat flux load

In this section, a simulation model is presented for the support structure subject to heat flux load, based on thermal topology optimization methodology.

A twin cantilever is considered for the printed geometry. If an experiment verification is carried out in the future, the printing time is affected greatly by the height of the printed part, such that the height of the selected printed part has to be appropriate. If the printed part is very high, there is a long printing time. However, if the height of the printed part is very small, the generated support structure is too small in the design domain, and thus the structure cannot work well for its objective. For the horizontal bar of the printed part, an appropriate thickness of 2 mm is selected. If the thickness of the bar is very large, the deformation becomes very small and thus it cannot be measured experimentally. If the thickness of the bar is very small, the deformation may collide with the powder scraper. For the length of the horizontal bar, an appropriate length of 105 mm is selected. It is unnecessary if the length of the horizontal bar is very large. If the length of the horizontal bar is very small, the support structure becomes too small. Finally, the dimension of the vertical bar of the printed part is designed as 48×5 mm, and that of the horizontal bar designed as 105×2 mm, as shown in Figure 4.26.

Figure 4.26 Geometry of printed part for thermal topology optimization.

The printed part is geometrically symmetrical, so half of the part is chosen for optimization. A zero horizontal displacement is imposed on the boundary of the vertical bar to simulate the symmetry condition. As shown in Figure 4.29, the corresponding design domain is defined as the geometry volume and displayed in green colour in the commercial software Hypermesh. Modelling has taken the vertical bar of the printed part into account as it plays an important role in heat transfer in the process of printing. 2D meshing is done in the design and non-design domains, in which the 2D quad elements are used with size of 0.5×0.5 mm.

Figure 4.27 Definition of design domain.

Aluminium alloy AlSi10Mg used in this case study adopts the same settings for the structural topology optimization elaborated in Section 4.1. The setups of elastic modulus,

Poisson's ratio and density are the same with that listed in Table 4.1. Additionally, thermal conductivity of 110 W/(m°C) is set in the optimization.

During the printing process, the heat generated by laser scanning is transferred through support structure to a substrate, such that constant temperature is set at the bottom edges of the design and non-design domains, representing the temperature condition of the substrate. The adiabatic condition, that is, zero heat transfer, is imposed on all the remaining edges of the domain. These thermal boundary conditions are shown in Figure 4.28.

Figure 4.28 Thermal boundary and load conditions for thermal topology optimization.

Laser is commonly used as a moving heat source to melt powders in the SLM process. The Gaussian heat source model [66, 67] is most widely used, and its expression is

$$q = \frac{2AP}{\pi r_0^2} \exp\left(\frac{-2r^2}{r_0^2}\right) \quad (4.1)$$

where q is the heat flux, A is the absorption coefficient of the metal powder, P is the laser power, r_0 is the laser spot radius at which the laser energy reduces to $1/e^2$, and r is the radial distance from the laser beam spot centre to a point on the powder bed surface. In the modelling, each element layer represents 12.5 real layers. The laser beam melts about three real powder layers [68], so the volume heat source can be simplified to surface heat source. Equation (4.1) then can be written as [69]

$$q = \frac{2AP}{\pi r_0^2} \quad (4.2)$$

The parameters used in the optimization include the absorption coefficient A of 0.2, laser power P of 250 W, laser spot radius r_0 of 75 μm , scanning speed v of 800 mm/s, and thickness of 40 μm for each printing layer, which are summarized in Table 4.3. Based on these parameters, heat flux q of 5659 W/mm² is obtained by Equation (4.2).

Table 4.3 Process parameters used in the optimization.

Item	Value	Unit
Absorption coefficient (A)	0.2	
Laser power (P)	250	W
Laser spot radius (r_0)	75	μm
Laser travel speed	800	mm/s
Layer thickness	40	μm

Heat flux load is imposed on the design domain after meshing is completed. The first layer of the overhang connecting supporting structures provides foundation for subsequent layers, so it plays an immense role in dictating print success. Its deformation causes partial size loss or print failure. When printing the subsequent layers, the bottom layers of the overhang are completely solidified, so the laser heat is transferred to the substrate through the first layer and the vertical bar. The key function of the support structure is to support the overhang [41]. Therefore, the uniform heat flux is only imposed on the first element layer of the overhang in this study, as shown in Figure 4.29.

Figure 4.29 Setup of heat flux load for thermal topology optimization.

Same as structural topology optimization method, several parameters are input in the commercial software Hypermesh, including design variable, constraint and objective. The setup of the design variable is shown in Figure 4.5.

After the design variable is defined, the next step is to define design responses. Two responses are defined for thermal optimization, namely volume fraction and thermal compliance. The setups of design responses are shown in Figure 4.30 (a) and (b). The design variable and responses are constrained with the allowed minimum and maximum values. The volume fraction is the material fraction of the designable volume, which is chosen as maximum 0.15 in this optimization, as shown in Figure 4.30 (c). Topology optimization is performed to find the optimal material placement. In this study, minimizing thermal compliance is chosen as the objective, which is shown in Figure 4.30 (d). As a summary, all the optimization parameters are shown in Figure 4.31.

Figure 4.30 Setup of parameters for structural topology optimization, (a) response of volume fraction, (b) response of thermal compliance, (c) constraint and (d) objective function.

Design variables	* Density
Optimization responses	* Volume fraction * Thermal compliance
Design constraints	* $0 \leq \text{Volume fraction} \leq 0.15$
Objective	* Minimize thermal compliance

Figure 4.31 Summary of parameters for thermal topology optimization.

For the problem described in Figure 4.31, thermal topology optimization is completed via the commercial software Optistruct. The result obtained from the optimization is shown in Figure 4.32, in which red colour indicates the elements with density equal to 1, blue colour the elements to be removed with zero density, and the remaining colours the elements with a density ranging between 0 and 1. Besides, iteration history of the optimization process is shown in Figure 4.33.

Figure 4.32 Optimization result of thermal topology optimization.

Figure 4.33 Iteration history of thermal topology optimization process.

As shown in Figure 4.32, the optimal support structure has a few of the material on the top left-hand corner. Most of the material is on the right-hand side. Because most of the heat generated from the middle of the overhang passes through the vertical bar to the substrate, a little material is needed around the vertical bar on the left. This also proves the importance of considering the vertical bar in the modelling.

In this section, optimization of support structure for SLM based on thermal topology optimization is conducted by the commercial software Hypermesh. A printed part formed in the twin cantilever is used for the optimization. An optimized support structure is obtained with the objective with minimized thermal compliance, subject to certain volume fraction constraint of 0.15 and uniform heat flux imposed on the first element layer of the overhang.

4.3 Topology optimization subject to thermo-mechanical coupled load

In this section, optimization of support structure is presented, subject to thermo-mechanical coupled load for SLM. The coupled thermo-mechanical problem is solved by two methods, namely structural and thermal topology optimizations. For the structural topology optimization, compared with Section 4.1, an additional constraint of thermal compliance is added, in order to consider the thermal environment in the optimization. Similarly, for the thermal topology optimization, compared with Section 4.2, an additional constraint of structural compliance is introduced to include the mechanical load.

4.3.1 Optimization with thermal compliance constraint

It is usual to only consider mechanical load in structural topology optimization. To carry out the optimization subject to thermo-mechanical coupled load, the study adds a constraint of thermal compliance. Thus, two constraints, volume fraction and thermal compliance, are set in the optimization. The volume fraction is set at 0.15. The settings of the coupled optimization are listed in Figure 4.34.

Design variables	* Density
Optimization responses	* Volume fraction * Compliance * Thermal compliance
Design constraints	* $0 \leq \text{Volume fraction} \leq 0.15$ * Thermal compliance
Objective	* Minimize compliance

Figure 4.34 Summary of parameters for structural problem with thermal compliance constraint.

In this study, the printed part used is the same as the one described in Section 4.2, which is shown in Figure 4.26. All the settings of parameters are also similar to those in Section 4.2. The loads acting on the support structure are the weight of the overhang and the thermal stress. The thermal stress is caused by uneven heating during the printing process that is generated from the heat flux of the laser. Therefore, in the coupled thermo-mechanical model, both the weight of the overhang and heat flux are considered for the loads input. As shown in Figure 4.35, the uniform structural load, that is, the weight of the overhang, is imposed on the upper boundary of the design domain, while the heat flux is applied on the lowest finite element layer of the overhang. The constant temperature is set on the bottom of the design and non-design domains to simulate the substrate temperature condition, while all the nodes of bottom are fixed as the boundary condition, which simulates the fixed effect of the printed part and support structure on the substrate.

Figure 4.35 Setups of Loads and boundary conditions for coupled optimization.

In order to obtain an appropriate value of thermal compliance for setting constraint in the coupled optimization, it must know the thermal compliance range when the part has different support structures. In Section 4.2, thermal topology optimization aiming to get the minimum thermal compliance is conducted, with which the settings of thermal boundary condition, heat flux load and volume fraction in this section are the same. So based on the thermal topology optimization in Section 4.2, the maximum thermal compliance of $33.7 \text{ s}^\circ\text{C}/(\text{N mm})$ that is also the initial thermal compliance, and the minimum thermal compliance of $13.1 \text{ s}^\circ\text{C}/(\text{N mm})$ are obtained from the iteration curve, as shown in Figure 4.33. In other words, when a heat flux load is imposed on the part and different support structures are set under the part, the obtainable minimum thermal compliance is $13.1 \text{ s}^\circ\text{C}/(\text{N mm})$, and the support structure has the best heat transfer efficiency at this moment. Therefore, the upper bound of thermal compliance may be set between 13.1 and $33.7 \text{ s}^\circ\text{C}/(\text{N mm})$ in the structural topology optimization subject to thermo-mechanical load. Obviously,

different optimized support structures are obtained with different settings of upper bound of the thermal compliance. In the section, five case studies are made with upper bounds of the thermal compliance at 13.1, 15, 20, 25, 30 and 33.7 $\text{s}^\circ\text{C}/(\text{N mm})$. The optimized support structures are shown in Figure 4.36.

Figure 4.36 Optimized support structure with thermal compliance of (a) 13.1 $\text{s}^\circ\text{C}/(\text{N mm})$, (b) 15 $\text{s}^\circ\text{C}/(\text{N mm})$, (c) 20 $\text{s}^\circ\text{C}/(\text{N mm})$, (d) 25 $\text{s}^\circ\text{C}/(\text{N mm})$, (e) 30 $\text{s}^\circ\text{C}/(\text{N mm})$ and (f) 33.7 $\text{s}^\circ\text{C}/(\text{N mm})$.

Figure 4.36 (a) shows the optimized support structure at thermal compliance of $13.1 \text{ s}^\circ\text{C}/(\text{N mm})$. It is alike that obtained from thermal topology optimization. Most materials are located at the right-hand side so as to transfer heat from overhang to substrate. In topology optimization, the iteration meets the constraints first, and then the optimization objective. If the thermal compliance constraint is set at $13.1 \text{ s}^\circ\text{C}/(\text{N mm})$, the optimized support structure ensures it below $13.1 \text{ s}^\circ\text{C}/(\text{N mm})$ in the first place. $13.1 \text{ s}^\circ\text{C}/(\text{N mm})$ is the minimum value that can be obtained in the thermal topology optimization subject to heat flux, so setting at $13.1 \text{ s}^\circ\text{C}/(\text{N mm})$ means fully considering the effect of heat flux and the obtained support structure is alike that obtained by thermal topology optimization subject to heat flux.

Figure 4.36 (f) shows the optimized support structure when the upper bound of thermal compliance is set at $33.7 \text{ s}^\circ\text{C}/(\text{N mm})$. It is the same with that obtained from structural topology optimization. If the thermal compliance constraint is set at $33.7 \text{ s}^\circ\text{C}/(\text{N mm})$, the optimized support structure ensures it below $33.7 \text{ s}^\circ\text{C}/(\text{N mm})$ in the first place. $33.7 \text{ s}^\circ\text{C}/(\text{N mm})$ is the maximum value at initial status before iteration starts. Obviously, all support structures can satisfy this constraint, which means $33.7 \text{ s}^\circ\text{C}/(\text{N mm})$ has no constraint at all. In this case, heat flux has no effect on the result of optimized structure and the obtained support structure is very close to that obtained by structural topology optimization subject to mechanical load.

Figure 4.36 (b) to Figure 4.36 (e) show the optimized support structures subject to coupled loads that may be regarded as the superposition of support structures subject to separate load cases, namely mechanical and heat flux loads. When the upper bound of thermal compliance gradually reduces from 33.7 to $13.1 \text{ s}^\circ\text{C}/(\text{N mm})$, the optimized support structure changes from that obtained by structural topology optimization to that obtained by thermal topology optimization. The support structure on the right-hand side gradually transforms from two pillars to a single pillar. If the upper bound of thermal compliance is set between 13.1 and

33.7 s°C/(N mm), the influence of both heat flux and mechanical load are considered at the same time. The closer the constraint value to the median, the more equal influence of heat flux and mechanical load has on support structure.

4.3.2 Optimization with compliance constraint

For thermal topology optimization, usually thermal load is considered only, to conduct the optimization subject to thermo-mechanical coupled load, an additional constraint is added, in order to consider the mechanical load in the optimization. Two constraints are used in the optimization, namely volume fraction and structural compliance. The volume fraction of 0.15 is chosen for the optimization. The setting of the coupled optimization is summarized as shown in Figure 4.37.

Design variables	* Density
Optimization responses	* Volume fraction * Compliance * Thermal compliance
Design constraints	* $0 \leq \text{Volume fraction} \leq 0.15$ * Compliance
Objective	* Minimize thermal compliance

Figure 4.37 Summary of parameters for thermal problem with compliance constraint

In this study, the printed part used is the same as the one described in Section 4.2, which is shown in Figure 4.26. All the settings of parameters are also similar to those in Section 4.2. The setups of loads and boundary conditions are the same as that in Section 4.3.1, as shown in Figure 4.35.

In order to obtain an appropriate value of compliance to set constraint in the coupled optimization, it must know the compliance range for the part with various support structures. Structural topology optimization is conducted to get the minimum compliance, with which this section has the same settings of boundary condition, mechanical load and volume fraction. An optimized support structure is obtained, as shown in Figure 4.38. The maximum

compliance of 2.79 mm/N that is also the initial compliance, and the minimum compliance of 0.69 mm/N are obtained from the iteration curve, as Figure 4.39 shows the variation of objective function with the iteration number. In other words, when a load is imposed on the part and different support structures are set under the part, the obtainable minimum compliance is 0.69 mm/N, and the support structure has the biggest stiffness to support the part at this moment. Therefore, the upper bound of compliance may be set between 0.69 and 2.79 mm/N in the thermal topology optimization subject to thermo-mechanical coupled load. Obviously, different settings of the upper bounds of the compliance result in different optimized support structures. Here, the case studies include six upper bounds of the structural compliance that are 0.69, 1.1, 1.5, 1.9, 2.3 and 2.79 mm/N. The optimized support structures are shown in Figure 4.40.

Figure 4.38 Support structure subject to heat flux by thermal topology optimization.

Figure 4.39 Iteration history for the thermal topology optimization process.

Figure 4.40 Optimized support structure with compliance of (a) 0.69 mm/N, (b) 1.1 mm/N, (c) 1.5 mm/N, (d) 1.9 mm/N, (e) 2.3 mm/N and (f) 2.79 mm/N.

Figure 4.40 (a) shows the optimized support structure at structural compliance of 0.69 mm/N. It is similar to that obtained from structural topology optimization, which is shown in Figure 4.38. Figure 4.40 (f) shows the optimal support structure when the upper bound of the structural compliance is set as 2.79 mm/N. It is very close to that obtained from thermal topology optimization subject to heat flux load. The reason for these similarities is the same as that described in Section 4.3.1.

It is shown in Figure 4.40 (b) to Figure 4.40 (e) that the optimized support structures subject to coupled loads may be regarded as the superposition of support structures subject to the separated load cases, namely mechanical and heat flux loads. When the upper bound of the structural compliance is gradually reduced from 2.79 to 0.69 mm/N, the optimized support structures change from that obtained by thermal topology optimization to that obtained by structural topology optimization. The support structure on the right-hand side gradually translates from two pillars to a single one.

4.4 Displacement analysis for part with different support structures

In this section, the optimized support structures obtained by structural and thermal topology optimizations are verified and compared through case studies.

Four different support structures are compared using Netfabb, which is a commercial software program for additive manufacturing produced by Autodesk. Netfabb Simulation is one component of Netfabb, with the ability of simulating the printing process for metal powder bed fusion and directed energy deposition, predicting part distortion, compensating for distortion, calculating residual stresses and simulating response after wire-cutting, etc. [70].

In Sections 4.1 to 4.3, the optimized support structures are obtained for the 2D printed part. Netfabb cannot perform the simulation with zero thickness, so a thickness needs to be set

for the printed part and support structures. Thickness affects printing time and material usage in an experiment verification, so an appropriate thickness is very important. A small thickness makes the part and support structures too weak and fails the manufacturing. A large thickness requires a long printing time and waste of materials. In this study, a thickness of 5 mm is chosen for the printed part and the support structures. The same printed part is used for topology optimizations and simulations of the printing process, which is shown in Figure 4.26.

4.4.1 Uniform support structures

In this section, printing process is simulated for a twin cantilever part with uniform support structures. The part is supported by 28 columns equally distributed as the support structures, with the cross section of $0.5 \times 5 \text{ mm}^2$ and the length of 48 mm. The total volume of material used for the support structures is thus equal to 672 mm^3 . The geometry of twin cantilever part with uniform support structures is shown in Figure 4.41 (a) and (b). A Cartesian coordinate system is defined in 3D domain, as shown in Figure 4.41 (c). The x -, y -, and z -axes are defined along horizontal, thickness and vertical directions, respectively. The positive x -, y -, and z -axes are labelled by x , y and z , respectively and the coordinate origin is located at the centre point of the bottom of the vertical bar. The building direction is along the z - axis.

The area of support structures is 672 mm^2 and the total area under the overhang is 4800 mm^2 , so the volume fraction of support structures is $672 / 4800 = 0.14$, which is reasonable. A smaller volume fraction may make the smallest size of the optimized support structures less than the minimum feature size that SLM can print and thus fail printing. A larger volume fraction generates a support structure too large to be easily removed in post-processing.

Figure 4.41 Geometry views of printed part, (a) Front view, (b) ISO view and (c) Cartesian coordinate system.

Before using the commercial software Netfabb for simulation, a geometric model including the printed part and the support structures is developed and saved in STL format. After that, the completed geometric model, including twin cantilever printed part and support structures, is imported into Netfabb. In other words, the model of the printed part is imported first, and then a substrate plate is added under the printed part. The substrate is considered

to make the simulation of the printing process close to reality. A large substrate requires greater computational effort, so a substrate with the same length of 105 mm and width of 5 mm as the printed part is adopted in the simulation to save cost. The height of the substrate is set at 25 mm to prevent deformation of the printed part and support structures during the printing process. Finally, the model of support structures is imported. The twin cantilever printed part, support structures and substrate plate are shown in Figure 4.42.

Figure 4.42 Imported part and uniform support structures in Netfabb.

A set of the input parameters are required by the commercial software Netfabb, such as material properties, process parameters, heat treatment, properties of build plate, and operating conditions, etc. Aluminium alloy AlSi10Mg is chosen as the printing material for the simulation. The key processing parameters are listed in Table 4.3. Pre-heating is not considered for the substrate. Zero-displacement is set at the bottom of the substrate to simulate the real boundary condition. A uniform heat loss coefficient of $2.5\text{e-}5 \text{ W}/(\text{mm}^2 \text{ } ^\circ\text{C})$ is set as the thermal boundary condition. The ambient temperature of $25 \text{ } ^\circ\text{C}$ is set in the simulation.

There are four options for mesh accuracy setting, namely the “fastest”, “fast”, “accurate” and “most accurate” options. Obviously, different settings of accuracy have influence on the accuracy of the final results. When the accuracy is set at “fastest”, the meshed elements are large and the number of elements is low, and thus the simulated results become worse. If the accuracy is set at “most accurate”, the meshed elements are small and number of elements is high, and thus the simulated results become best. In present simulation, the option “fast” is chosen for setting of accuracy.

Meshing is carried out automatically once the parameters are set. The printed part, support structures and substrate are discretized with 207062 nodes and 112163 elements, as shown in Figure 4.43. Part of meshing detail is shown in Figure 4.44 for comparison of the meshing result with the original geometric model, in which the size of the meshing elements in some locations is larger than the geometric model. This may affect the computational accuracy.

Figure 4.43 Meshing result of part and uniform support structures.

Figure 4.44 Meshing details of part and uniform support structures.

After the setting of meshing details is completed, the program is executed and various results are displayed for each computational step, such as the displacement, principal stress, principal stress direction and temperature distributions, etc. A lot of computing resources are required to simulate every real layer, so Netfabb combines multiple layers into one computational layer. There is a total of 24 computational layers for the printed part. The first 23 layers are the vertical bar and support structures and the last layer is the overhang. With a layer thickness of $40\text{ }\mu\text{m}$ for the printed part and support structures, a computational layer corresponds to around 52 real printing layers.

The simulation of each computational layer is typically separated into two steps. In the first step, the computational layer is instantaneously activated in a molten state. When the computational layer cools and contracts after a specific time, it starts the second step. The time between each computational layer (increment 2 & 3, 4 & 5, and so on) is short to simulate a near steady state response from the end of one layer to the start of the next.

Several steps in printing order are shown in Figure 4.45. The printing process of vertical bar and support structures is simulated from steps $i=1$ to $i=46$. The activation and cooling of the overhang, that is, the last computational layer, are at step $i=47$ and $i=48$, respectively. A short time of 0.24 s between step $i=48$ and $i=49$ simulates a near steady state response. The temperature of the whole model cools down to the ambient temperature of $25\text{ }^{\circ}\text{C}$ at step $i=50$.

The substrate together with part and support structures are dismantled at step $i=51$. The part and support structures are removed from the substrate at step $i=52$, and the support structures are removed from the printed part at step $i=53$. It takes 13782 s to simulate the whole printing process.

Figure 4.45 Simulation steps in Netfabb.

The simulation result of displacement at step $i=53$ is shown in Figure 4.46. The minimum displacement of 0.0134 mm occurs at the bottom of the vertical bar, and the maximum displacement of 0.14698 mm at both ends of the horizontal bar. During the SLM processing,

the laser source generates high thermal intensity. The rapid melting of metal powder is followed by a rapid solidification. This solidification causes the area of the scanned layer to expand or contract, and generates residual stress. The residual stress may cause geometric deformation or warping of the part [71, 72]. Since there is a support structure under the part, the support structure connects the part to a fixed substrate, thereby forcibly fixing the geometric shape in the proper position. Therefore, the deformation or warping is not evident during the printing process. When the support structures are removed, the residual stress releases and causes two ends of the part to warp upward. Therefore, the displacements of both ends are the largest. The bottom of the vertical bar connects to a fixed substrate, so heat is transferred to the substrate through this area during the printing process, where the cumulative residual stress is the smallest. Therefore, when the part is removed from the substrate, the displacement at the bottom is the smallest.

Figure 4.46 Simulation result of displacement of part with uniform support structures .

4.4.2 Non-uniform support structure subject to thermal stress

In the structural topology optimization, the mechanical loads acting on the support structure are the weight of the overhang and the thermal stress generated in the process of printing.

In Section 4.1.1, an optimized support structure is obtained by structural topology optimization, subject to the weight of overhang. However, the typical forces imposed on the support structure during the printing process are usually thermal loads rather than gravity loads [73]. Therefore, in the structural topology optimization of the support structure, the influence of thermal stress is more important than that of overhang weight. In this section, the support structure is optimized subject to thermal stress by structure topology optimization.

Since the thermal stress exists throughout the printing process, it is necessary to simulate the entire printing process to obtain the desired thermal stress. As illustrated in Section 4.4.1, the simulation of the printing process is already done in Netfabb for the printed part with a uniform support structure. Therefore, thermal stress can be obtained from the simulation results in Section 4.4.1. It is used as the design load in structural topology optimization to obtain the optimized support structure subject to the thermal stress. A similar method can be found in other papers [8, 73].

The first layer of the overhang is activated from step $i=47$, which means the support structure starts to support the overhang at step $i=47$. The support structure is removed from the part at the last step $i=53$. Therefore, it is enough to consider the thermal stress generated during the process from step $i=47$ to step $i=52$. To do this, the lower edge of the overhang, that is, the upper edge of the design space, is divided into 50 equal parts and the thermal stress on 51 points to be obtained from the simulation results. For the specified points on the part-support interface, the thermal stresses at specified points changes constantly at different stages. The maximum thermal stress needs to be considered for every specified point to ensure the optimized support structure can withstand the forces over the entire manufacturing process. All stages have to be checked to determine the maximum thermal stress as they may not appear at the same stage. Figure 4.47 shows the maximum stresses at each specified point obtained from simulation results.

Figure 4.47 Maximum von Mises stresses at the specified points along the part.

It is shown in Figure 4.47 that the maximum thermal stress along the bottom edge of the printed part ranges from 20.2 to 61.0 MPa, with an average value of 35.1 MPa. The maximum thermal stress at a specific point may not occur in the process of “printing”. It may occur after printing when cutting the part and support structures from the substrate or removing support structures from the part. For example, the maximum thermal stress at position 54 mm occurs at the simulation step $i=52$ when the part and support structure are removed from the substrate.

The maximum stresses at specific points are then used as the design load in structural topology optimization as described in Section 4.1.1. Figure 4.48 shows the optimized support structure obtained from the optimization.

Figure 4.48 Optimized support structure subject to thermal stress.

Figure 4.49 Generated geometry for part and support structure subject to thermal stress.

It is shown in Figure 4.48 that most of the material is on the right-hand side with a small part on the top left-hand side. The vertical bar at the left-hand side plays a role in withstanding thermal stress, so fewer supports are needed on the left. The surface of support structure obtained by optimization is uneven, which is unsuitable for the final optimal geometry. Apart from that, some elements are not connected to each other, and thus a final CAD model is necessarily generated based on the material distribution. In the commercial

software Hypermesh, the Ossmooth tool is used to convert the optimal model into a geometry. A threshold for the density of elements is selected, such that all elements with a density larger than the threshold are selected to generate a geometry, and elements with a density less than the threshold are deleted. After the geometry is generated in Ossmooth, it is exported and saved as a IGES format file, as shown in Figure 4.49. There are small geometrical errors, such as tiny holes resulted from missed elements and disconnected segments. The file is then imported into a CAD software, such as Solidworks and Rhinoceros 3D. Finally, an optimal geometry is obtained by rebuilding of lines that eliminates those errors, as shown in Figure 4.50. The area of the half support structure is 336 mm^2 that is the same as that of the uniform support structures as described in Section 4.4.1.

Figure 4.50 Printed part and support structure (a) Front view; (b) ISO view.

After the final geometries of the printed part and support structure are modelled, the printed part is imported into Netfabb first, as shown in Figure 4.51. Then, support structure is imported and added to the printed part, as shown in Figure 4.52. Using the same setting as described in Section 4.4.1, the meshing result of printed part and support structure is shown in Figure 4.53. More meshing details of support structure is shown in Figure 4.54. After executing the program, the result of displacement at the last simulation step is shown in Figure 4.55.

Figure 4.51 Imported printed part in Netfabb.

Figure 4.52 Imported printed part and support structures in Netfabb.

Figure 4.53 Meshing result of part and support structure subject to thermal stress.

Figure 4.54 Meshing details of part and support structure subject to thermal stress.

Figure 4.55 Simulation result of displacement of part with support subject to thermal stress.

4.4.3 Non-uniform support structure subject to heat flux

In this section, the optimal support structure (Figure 4.32) subject to heat flux is chosen for the printing process simulation by the commercial software Netfabb. After the optimal geometry of the support structure is generated in Ossmooth, it is exported and saved as an IGES format file. The file is imported to a CAD software and a final geometry is obtained by rebuilding the lines, as shown in Figure 4.56. In the commercial software Netfabb, the printed part is imported. Then, support structure is also imported and added to the printed part. Using the setting same as described in Section 4.4.1, the meshing result of the printed part and support structure is shown in Figure 4.57. More meshing details of the support structure and printed part is shown in Figure 4.58. After executing the program, the simulation result of displacement at the last step is shown in Figure 4.59.

(a)

(b)

Figure 4.56 Geometry of printing part and support structure (a) Front view; (b) ISO view.

Figure 4.57 Meshing result of part and support structure subject to heat flux.

Figure 4.58 Meshing details of part and support structure subject to heat flux.

Figure 4.59 Simulation result of displacement of part with support subject to heat flux.

4.4.4 Non-uniform support structure subject to thermo-mechanical coupled load

In Section 4.3, several optimal support structures are obtained subject to coupled load, with different values of constraint. In order to consider the influence of weight and heat flux on the support structure as equally as possible, the constraint close to median is selected. In this study, the optimized support structure shown in Figure 4.36 (c) is chosen for the printing process simulation. It is obtained by structural topology optimization with thermal compliance constraint at $20 \text{ s}^\circ\text{C}/(\text{N mm})$. A geometry of support structure is then generated using the component Osmooth in the Hypermesh, as shown in Figure 4.60.

Figure 4.60 Generated geometry of part and support subject to coupled load.

The generated optimal geometry is then exported from Hypermesh and imported to a CAD software, and a final geometry is obtained by rebuilding the lines, as shown in Figure 4.61. For the simulation in commercial software Netfabb, the printed part and support structure are imported from CAD software. Using the setting as described in Section 4.3.1, the meshing result of the printed part and support structure is shown in Figure 4.62. More meshing details of the support structure and printed part is shown in Figure 4.63. Finally, the simulation result of displacement at the last step is obtained, as shown in Figure 4.64.

(a)

(b)

Figure 4.61 Geometry of printing part and support structure (a) Front view; (b) ISO view.

Figure 4.62 Meshing result of part and support structure subject to coupled load.

Figure 4.63 Meshing details of part and support structure subject to coupled load.

Figure 4.64 Simulation result of displacement of part with support subject to coupled load.

4.4.5 Comparison of displacements for part with different support structures

In this section, four kinds of support structures are studied and compared each other for printing the same part with different optimization methods, namely (1) the uniform support structures without optimization for purpose of comparison, (2) the support structures optimized by the structural topology optimization subject to thermal stress, (3) the support structures generated by the thermal topology optimization subject to heat flux, and (4) the support structures obtained by the structural topology optimization subject to thermo-mechanical coupled load. The same volume fractions of 0.15 are used in all the optimizations. In other words, the volume of material is around 15 percent of the design domain for these four kinds of support structures. The printing process of parts with different support structures is simulated via the commercial software Netfabb.

For the simulation results of displacement of printed parts shown in Figure 4.46, Figure 4.55, Figure 4.59 and Figure 4.64, the displacement of the vertical bar is close to zero, and the

largest displacement occurs at both ends of the overhangs. The twin cantilever printed parts are geometrically symmetrical, so only the right half part is considered. To compare the displacement of the overhangs, each overhang is divided into 10 equal sections. There are 11 points on each overhang. With displacement values of the points obtained from the simulation results, the displacement curves of overhangs are drawn, as shown in Figure 4.65.

Figure 4.65 Displacement of overhangs after wire-cutting.

It is shown in Figure 4.65 that all the displacement curves are similar. The overhang presents an uplifted shape, which is consistent with other research findings [14, 74]. This deflection is due to the accumulation of residual stress during the printing process. When the part is removed from substrate and support structure, the release of these residual stresses causes the deformation. In practice, all parts undergo a heat treatment process to release residual stress before being removed from the support structure. The inappropriate release of residual stress through the heat treatment process will deform the part when it is removed from the substrate and support structure. The maximum displacements of each printed part are summarized in Table 4.3 for further discussion.

Table 4.4 Summary of the maximum displacement for different support structures.

Support structure type	Max. displacement (mm)
Uniform (Support_1)	0.147
Non-uniform optimized by structural topology optimization subject to thermal stress (Support_2)	0.137
Non-uniform optimized by thermal topology optimization subject to heat flux (Support_3)	0.141
Non-uniform optimized by structural topology optimization subject to coupled load (Support_4)	0.134

As shown in Table 4.4, Support_1 represents the uniform support structure with the maximum displacement of 0.147 mm, Support_2 represents the non-uniform support structure optimized by structural topology optimization with the maximum displacement of 0.137 mm, Support_3 represents the non-uniform support structure optimized by thermal topology optimization with the maximum displacement of 0.141 mm, and Support_4 represents the non-uniform support structure optimized by thermal topology optimization with the maximum displacement of 0.134 mm. Some findings from Table 4.4 are listed below.

- (1) The printed part with Support_1 has the highest maximum displacement compared with the other three support structures, suggesting that uniform support structures are worse than non-uniform structures to support overhang and transfer heat.
- (2) The printed part with Support_4 has the lowest maximum displacement, meaning that its material distribution transfers heat better during the printing process, and reduces distortion when the printed part is removed from the substrate plate.
- (3) The maximum displacement of part with Support_2 is in between as the load imposed on it is based on the simulation results of part with Support_1. It reflects that the iterative method used in the optimization is an effective approach.

- (4) The maximum displacement of part with Support_2 is smaller than that of part with Support_3. This is because the thermal stress is obtained from simulation results which is caused by heat flux. The thermal stress is imposed directly on the support structure during the printing process. This shows that the support structure optimized subject to thermal stress is better than that subject to heat flux.

4.5 Remarks

In this chapter, the optimization results of support structure for SLM are presented and discussed in detail. Simulation of the support structure is presented in Section 4.1 by structural topology optimization subject to mechanical loads, in which uniform and non-uniform loads are considered for the simulation. Thermal topology optimization method is employed in Section 4.2 to generate the optimal support structure for a given printed part, subject to uniform and non-uniform generated heats. Topology optimization subject to thermo-mechanical coupled load is investigated in Section 4.3, in which thermal compliance and displacement constraints are considered for the optimization. Four support structures are simulated in Section 4.4 via the commercial software Netfabb, in order to compare the displacements of the printed part after cutting from substrate. They include (1) the uniform support structure, (2) the support structure generated by structural topology optimization, (3) the support structure generated by thermal topology optimization, and (4) the support structure obtained by topology optimization subject to thermo-mechanical coupled load. It is shown through comparison that the printed part with the fourth support structure achieves the smallest displacement, such that considering both heat and mechanical loads simultaneously in topology optimization is critically important.

In terms of the topology optimization methods, a good optimized result means that the generated support structure is manufacturable. First, the size of the support structure shall be larger than the minimum size that SLM can print. Currently, the minimum printable

feature size by SLM is 40-200 μm [75]. In this study, the smallest element size is 0.25×0.25 mm that meets the minimum size requirement and ensures the structure is printable. Second, the generated support structure itself does not need any support. The critical angle of the overhang shall be around 45° to realize self-support [44, 76, 77]. In this study, most obtained support structures meet this requirement. A few that fail, such as the overhang of the support structure near the vertical bar in Figure 4.61 with the angle only at 26° , can be solved by adding AM filters in the topology optimization, which makes structures self-supported [78].

In this study, only the optimization of the main support structure was considered, which is directly connected to the overhang. This brings great difficulties to remove the support structure in post-processing. In order to reduce post-processing costs and improve surface quality, one solution is to add a design constraint in the topology optimization to generate comb-like patterns at the interface between the support structure and the overhang, so that the support structures can be easily removed [35]. Another solution is to replace the upper continuous connection area of the support with a comb-like pattern, so that the part is connected to the support by multiple "teeth" that can be easily separated. These solutions only alter the interface between the part and the support which requires a little change of material amount. The conclusion of the comparison of several support structures in Table 4.3 remain unchanged.

CHAPTER 5   CONCLUSIONS AND FUTURE WORK

This chapter summarizes the research work that has been completed so far. In particular, major conclusions are made, based on the research work discussed in Chapter 4, followed by several studies proposed for future work.

5.1 Conclusions

This thesis has mainly studied the optimizations of support structure for SLM by topology optimization methodologies. Based on past research work in open literature, the support structures are optimized by two optimization design methods, considering the heat and mechanical loads in the SLM printing process. The printing efficiency is thus improved, and the consumption of materials reduced. The main research contributions of this thesis are summarized as follows.

- (1) Optimization of support structures subject to mechanical, heat flux and thermo-mechanical coupled loads. The commercial software Optistruct is utilized for optimization of support structures subject to various loads, based on structural and thermal topology optimization methodologies. This study's results show that the topology optimizations are indeed suitable to derive these support structures.
- (2) Displacement analysis for a part with different support structures. The support structures optimized by structural and thermal topology optimizations are verified and compared with case studies. Four kinds of support structures for a same printed part are studied and compared. The printing processes of parts with different support structures are simulated by the commercial software Netfabb, and the displacements of printed parts are studied. It is shown by simulation results that material distribution of the support structure optimized by topology optimization subject to

thermo-mechanical coupled load offers better heat transfer during the printing process, and reduces distortion after the printed part is removed from the substrate plate.

The present study has made good progress in researching the topology optimization of support structure in SLM. However, this study still has some limitations, as described below.

- (1) The support structures obtained in the present study are based on a given volume fraction. In practice, experience is required to choose an appropriate volume fraction, which limits the application of the current method.
- (2) The strength of the support structures is not considered in the topology optimizations. In the optimization, if the volume fraction is set too small, it may result in a sparse, elongated support structure with a relatively small contact interface on the substrate, which may cause printing failure. To solve this problem, an additional stress constraint can be added during topology optimization to ensure sufficient strength of the generated support structure.
- (3) There are some unsupported surfaces in the overhang. For example, in the support structure obtained by thermal topology optimization subject to heat flux load (Figure 4.32), all the support materials are on the right side, and only a small part of the overhang is supported. This problem can be solved by introducing an overhang constraint in topology optimization [78].
- (4) For the displacement analysis for parts, Netfabb Simulation is used for the simulation of the printing process. Netfabb Simulation makes meshing automatically whose element size cannot be changed manually, which may affect the accuracy of the simulation results. Therefore, it is necessary to choose other simulation software to do more simulations to observe the accuracy of the results.

5.2 Future work

With the continuous development and popularization of 3D printing technology, the 3D printing process of parts with complex structures attracts significant attention from researchers. For SLM printing technology, the support structure is important for part with overhang, and it is necessary for more research work in this direction. In this thesis, the optimizations of support structure are carried out by structural and thermal topology optimization methods. The future work is thus recommended as follows.

- 1) It should be noticed that only 2D regular printed parts have been studied in this thesis. Therefore, the study of 3D irregular printed parts via topology optimization is recommended systematically through case studies.
- 2) In Chapter 4, the support structures are optimized by considering different loads and using different topology optimization methods. In order to verify if these support structures have greater stiffness and smaller thermal compliance compared with conventional support structures, simulations of the printing process have been conducted, and displacements of the overhang have been compared, for the same printed part with different support structures. It is demonstrated that the optimized support structures have better performance, compared with conventional support structures. However, the results from simulation may not be accurate enough. Therefore, it is necessary to conduct experiments for verification of the performance of the optimized support structures.
- 3) For the topology optimization methodologies used in this thesis, the steady-state heat conduction is assumed in the optimizations. However, practical printing is a complex transient process. During the SLM manufacturing process, the support structure and printed part are significantly subject to transient thermo-mechanical coupled load. In order to consider the transient effects of the thermo-mechanical

coupling environment in the optimization of the support structure for the overhang, a topology optimization methodology considering transient thermo-mechanical coupled load is recommended for further study.

- 4) In order to achieve more accurate support structure subject to thermo-mechanical coupled load, more printing-process parameters should be considered, such as printing scanning strategy in optimization for the future work.

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