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Propulsion and Power Research 2018;7(2):103–119

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ORIGINAL ARTICLE

Light-weighting in aerospace component and system design

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Received 19 January 2018; accepted 22 March 2018
Available online 6 June 2018

KEYWORDS

Light-weighting aviation;
High performance lightweight materials;
Numerical structural optimization;
Advanced manufacturing

Abstract Light-weighting involves the use of advanced materials and engineering methods to enable structural elements to deliver the same, or enhanced, technical performance while using less material. The concept has been extensively explored and utilised in many industries from automotive applications to fashion and packaging and offers significant potential in the aviation sector. Typical implementations of light-weighting have involved use of high performance materials such as composites and optimisation of structures using computational aided engineering approaches with production enabled by advanced manufacturing methods such as additive manufacture, foam metals and hot forming. This paper reviews the principal approaches used in light-weighting, along with the scope for application of light-weighting in aviation applications from power-plants to airframe components. A particular area identified as warranting attention and amenable to the use of light-weighting approaches is the design of solar powered aircraft wings. The high aspect ratio typically used for these can be associated with insufficient stiffness, giving rise to non-linear deformation, aileron reversal, flutter and rigid-elastic coupling. Additional applications considered include ultralight aviation components and sub-systems, UAVs, and rockets. Advanced optimisation approaches can be applied to optimise the layout of structural elements, as well as geometrical parameters in order to maximise structural stiffness, minimise mass and enable incorporation of energy storage features. The use of additive manufacturing technologies, some capable of producing composite or multi-material components is an enabler for light-weighting, as features formally associated with one principal function can be designed to fulfil multiple functionalities.

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Peer review under responsibility of National Laboratory for Aeronautics and Astronautics, China.

1. Introduction

Light-weighting design is an extensively explored and utilised concept in many industries, especially in aerospace applications and is associated with the green aviation [1] co-opted concept. The contribution of aviation to global warming phenomena and environmental pollution has led to on-going efforts for the reduction of aviation emissions. The international civil aviation organization target is to reduce aviation emissions by 50% by 2050 [1,2]. Approaches to achieve this target include developing clean energy such as solar power, as well as increasing energy efficiency. An effective way to increase energy efficiency and reduce fuel consumption is reducing the mass of aircraft, as a lower mass requires less lift force and thrust during flight [3]. For example for the Boeing 787, a 20% weight saving resulted in 10%–12% fuel efficiency improvement [1]. In addition to reduction of carbon footprint, flight performance improvements such as better acceleration, higher structural strength and stiffness, and better safety performance, could also be achieved by lightweight design [1,4] as well as economic benefits. Light-weighting optimization of a solar powered unmanned aerial vehicle (UAV) is an example of using both clean energy and lightweight structures to achieve green aviation operation. Current solar powered UAV designs face challenges such as insufficient energy density and wing stiffness. Lightweight design is essential for ultralight aviation; as an example an empty weight (less than 115 kg) with limited fuel capacity (19 L) can be necessary [5]. Lightweight design enables longer flight duration and other improved performance parameters. Light-weighting is also necessary in rocket design.

The principle of lightweight design is to use less material or materials with lower density but ensure the same or enhanced technical performance. A typical approach to achieve lightweight design for aerospace components and systems is to apply advanced lightweight materials on numerically optimised structures, which can be fabricated with appropriate manufacturing methods. As such, the application of advanced lightweight materials can effectively achieve both weight reduction and performance improvement. Although metal materials especially aluminium alloys are still the dominant materials in aerospace application, composite materials have received increasing interest and compete with aluminium alloys in many new aircraft applications. Structural optimization is another effective way to achieve light-weighting, by distributing materials to reduce materials use, and enhance the structural performance such as higher strength and stiffness, and better vibration performance. Conventional structural optimization methods are size, shape and topology optimization. Lattice structural optimization enables multi-scale optimization. Manufacturability is a crucial constraint in the

advanced metal forming not only enable the application of advanced materials, but relax constraints, enhancing the flexibility of multi-scale structural optimization.

Many examples of lightweight design have been successfully applied in the design of lightweight aircraft. Figure 1 (a) [8] illustrates the SAW Revo concept aircraft, produced by Orange Aircraft, which is an ultralight aerobatic airplane with carbon fibre reinforced composite wings and a topologically optimised truss-like fuselage. The empty weight of this 6 m wing span aircraft is 177 kg [8]. Figure 1(b) [9] shows a high altitude pseudo-satellite solar powered UAV from Airbus [9]. The Zephyr 7 currently holds the world record for the longest absolute flight

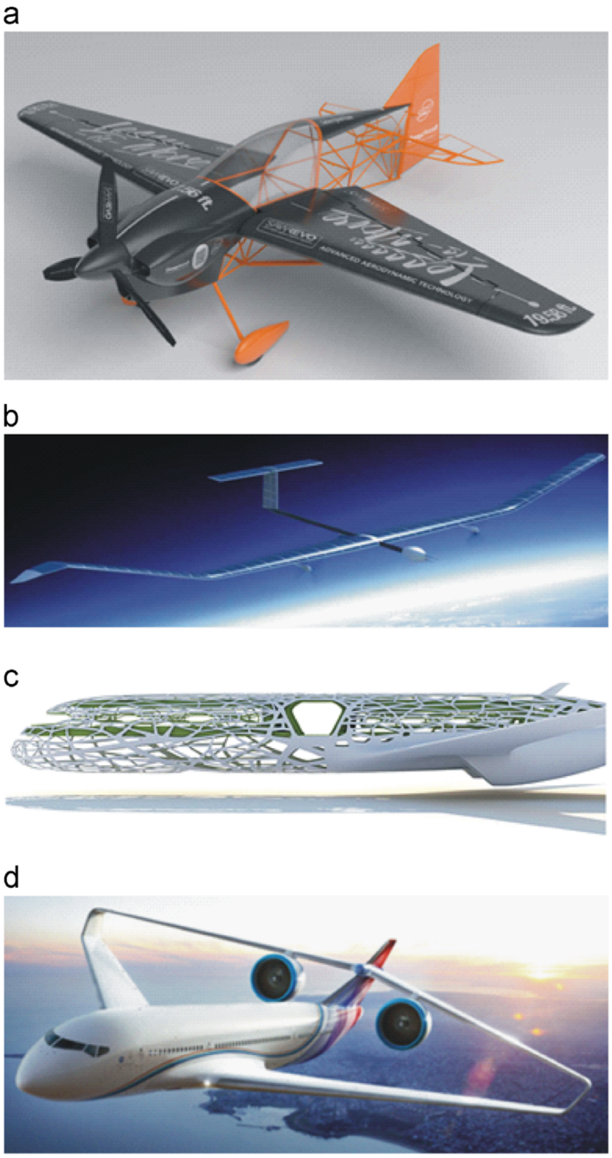


Figure 1 Light-weighting design example: (a) SAW Revo manu-

duration (336 h 22 m 8 s) and highest flight altitude (21,562 m) for UAVs, partly benefitting from increased energy efficiency by light-weighting [9]. Figure 1(c) [10] shows a model of a future concept lightweight airplane for 2050 from Airbus, inspired by a bird skeleton [10,11]. Figure 1(d) [12] demonstrates a concept design of a box wing aircraft where shape optimization is employed in the wing design [12]. Structural efficiency could be increased by using a box wing structure, i.e. higher stiffness and lower induced drag force result from the box wing compared with conventional wing structures [1].

2. Lightweight materials

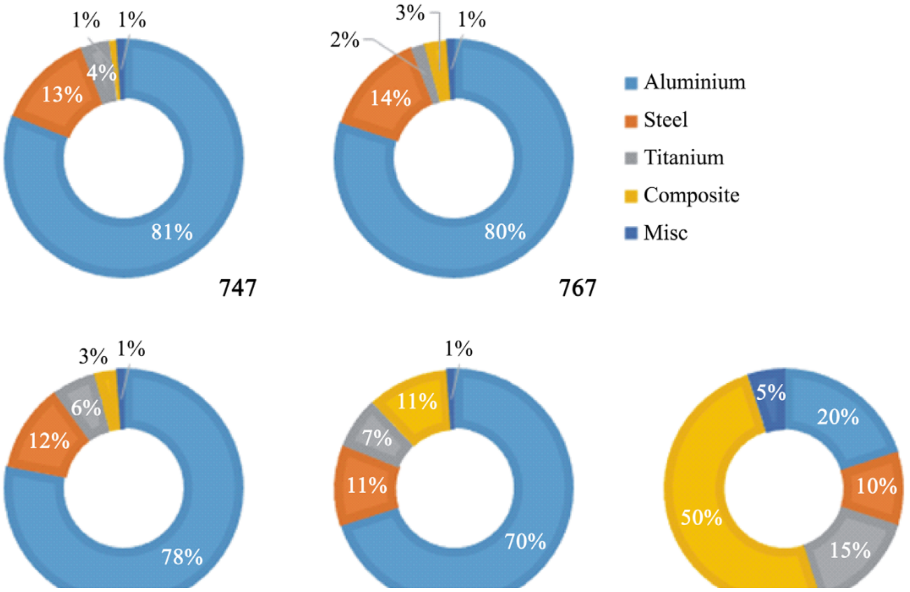
The selection of aerospace materials is crucial in aerospace component and system design cycles. It affects many aspects of aircraft performance from the design phase to disposal, including structural efficiency, flight performance, payload, energy consumption, safety and reliability, lifecycle cost, recyclability and disposability [13]. Aerospace structural material critical requirements include mechanical, physical and chemical properties, such as high strength, stiffness, fatigue durability, damage tolerance; low density, high thermal stability; high corrosion and oxidation resistance, as well as commercial criteria such as cost, servicing and manufacturability [14]. Apart from meeting the basic service requirements, the improvement of structural efficiency in aerospace structural design becomes increasingly critical because the application of lightweight structures brings benefits to aircraft performance, e.g. increased energy efficiency, acceleration performance, payload, flight endurance, and reduced life cycle cost and greenhouse gas emissions [15]. Previous studies have indicated that the most effective way to improve structural efficiency is reducing density (around 3 to 5 times more effective compared with increasing stiffness or strength), i.e. using lightweight materials [14,16,17].

The most commonly used commercial aerospace structural materials are aluminium alloys, titanium alloys, high strength steels and composites, generally accounting for over 90% of the weight of airframes [13,17]. From the 1920s until the end of the century, metal owing to its high strength and stiffness, especially aluminium alloy, has been the dominant material in airframe fabrication, with safety and other flight performance measures driving aircraft design decisions. Lightweight aluminium alloys were the leading aviation structural materials (accounting for 70%–80% of the weight of the most airframe of civil aircrafts before 2000 [13]) and still play an important role. Since the middle of the 1960s and 1970s the proportion of composites used in aerospace structures has increased due to the development of high performance composites. Figure 2 [17] illustrates the materials distributions for some different Boeing products [14,17,18].

2.1. *Aerospace metals*

2.1.1. *Aluminium alloys*

Although high performance composites such as carbon fibre are receiving increasing interest, aluminium alloys still make up a significant proportion of aerospace structural weight as demonstrated in the examples of materials distribution for some typical Boeing planes in Figure 2. The relatively high specific strength and stiffness, good ductility and corrosion resistance, low price and excellent manufacturability and reliability make advanced aluminium alloys a popular choice of lightweight materials in many aerospace structural applications, e.g. fuselage skin, upper and lower wing skins, and wing stringers, etc. The development of heat treatment technology



provides high strength aluminium alloys that remain competitive with advanced composites in many aerospace applications [17]. Aluminium alloys can offer a wide range of material properties meeting diverse application requirements, through adjusting compositions and heat treatment methods. The most extensively used aluminium alloys in aerospace industry are the Al-Cu alloys (2xxx series), Al-Zn alloys (7xxx series) and Al-Li alloys. [17].

2xxx series alloys are used where high damage tolerance and fracture toughness are the predominant criteria. AA2024 is one of the most commonly used Al alloys in fuselage structure due to its excellent damage tolerance at T3 condition. But its poor yield strength (345 MPa [19]) and fracture toughness ($K_{Ic} = 37\,\mathrm{MPa}\cdot\mathrm{m}^{0.5}$ [19]) restrict its application and it has been replaced by AA2524-T3 in the fabrication of many aircraft such as Boeing 777 aircraft, which has 15% to 20% improved fracture toughness resulting in 30% to 40% weight reduction [20–22]. AA2224 and AA2324 provide enhanced strength and are used in the lower wing skin. AA2026 is considered an excellent replacement of AA2024 because of its better damage tolerance and fatigue resistance, as well as higher strength [23].

The advanced AA7xxx series alloys are widely applied in the aerospace components where high strength is the driving requirement, including upper wing skins, horizontal and vertical stabilizers and wing stringers. AA7075-T6 has been used as an airframe material since the 1940s because of its relatively high specific strength (204 kN · m/kg [19]) and low price. However, the susceptibility to corrosion of this alloy reduced the life of the airframe components, which has led to its replacement by new AA7xxx series alloys in many applications [17]. For example, AA7475 has higher yield strength (490 MPa [19]) and a better combination of corrosion resistance and fracture toughness ($K_{Ic} = 33\ \mathrm{MPa}\cdot\mathrm{m}^{0.5}$ [19]), which makes it an ideal replacement for AA7075 [20]. Another high performance alloy AA7050 is used in fuselage frames and bulkheads as a form of thick plate (the best thickness ranges from 76 mm to 152 mm), and the sheet materials are used to fabricate wing skins [20,24,25]. The yield stress of AA7055-T7751 can reach 620 MPa with high fracture toughness and corrosion resistance. The application of this alloy in components in the Boeing 777 reduced the airplane weight by 635 kg [24].

Al-Li alloys are advanced heat treatable lightweight aluminium alloys that can decrease the density by up to 10% by including 1% to 3% of lithium. The introduction of lithium also enhances the elastic modulus of the alloys by 6% for each percentage of lithium added [17]. Al-Li alloys are lighter and stiffer than other aerospace aluminium alloys, such as AA2090, AA2091, AA8090 and AA8091 (1.9%–2.7% lithium) and are about 10% lighter and 25% stiffer than AA2xxx and AA7xxx series alloys. AA2199 toughness, higher strength (400 MPa [26]), better corrosion stress and exfoliation corrosion resistance than those made of AA2024)[17]. Extrusions of AA2099 could be an excellent replacement for conventional aerospace aluminium alloys for application to internal fuselage structures and lower wing stringers [27]. AA2050 could replace conventional Al alloys where medium or high strength and damage tolerance are required to offer better lightweight performance [28]. AA2198 could replace AA2024 and AA2524 for high damage tolerance applications (AA2198 can absorb 2 to 3 times of energy to fracture than AA2024) [29]. AA2060 and AA2055 alloys exhibit enhanced strength, fracture toughness and thermal stability that could replace the conventional aerospace aluminium alloys in fuselage and wing components applications. Application of AA2060-T8 reduced the structural mass by 14% in wing stringers and upper wing skin application, compared with that of the conventional material AA2024-T351 [17,30].

2.1.2. *Titanium alloys*

Titanium alloys have many advantages over other metals, such as high specific strength (e.g. the specific strength of Beta C titanium alloy, ca. 260 kN · m/kg, is around three times that of CoMo steel 4130 and 1.27 times that of high strength aluminium alloy 7075-T6), high stiffness, good fracture toughness and fatigue resistance, as well as very good corrosion resistance, heat resistance, cryogenic embrittlement resistance, and low thermal expansion (information on the material properties of Ti-6Al-4V can be found in Table 1). These advantages make titanium alloys an excellent alternative to steels and aluminium alloys in airframe and engine applications. However, the poor manufacturability and high cost (usually about 8 times higher than commercial Al alloys) result in the restriction of titanium alloys being extensively used. Hence, the titanium alloys are used where high strength is required but limited space is available, as well as where high corrosion resistance is required [14,31,32]. The current applications of titanium alloys in aerospace industry are mainly in airframe and engine components (overall comprising 7% and 36% of the weight respectively [31]).

Titanium alloys can, generally, be categorised as α-alloys, $\alpha+\beta$-alloys and β-alloys, according to the percentage of α-phase and β-phase in the alloy. In the alloys, the α-phase has lower density and the β-phase can improve strength [31]. Ti-6Al-4V ($\alpha+\beta$-alloys) is currently the most extensively used titanium alloy. Its applications include airframes structures such as windows frames, and gas turbine engine components such as discs and blades for the fan and compressor. Ti–3Al–2.5 V is an α-alloy that is used in place stainless steel in high pressure hydraulic tubing, saving 40% structural weight [31]. The β-alloy,

Table 1 Comparison of mechanical properties and cost of different classes of aerospace materials [18,19,46,47].

Material class	Example	Tensile strength/MPa	Elastic modulus/GPa	Density/10^3 (kg/m^3)	Specific strength /(kN · m/kg)	Specific stiffness /10^{-3}(GPa · m^3/kg)	Price
Al alloys	AA2024-T3	483	73.1	2.78	173.7	26.3	££
	AA7075-T6	572	71.7	2.81	203.6	25.5	££
Ti alloys	Ti-6Al-4V	1170	114	4.43	264.1	25.7	£££
Steels	AISI 4130	703	193	7.86	89.4	24.6	£
Composites	CFRP	1500	135	1.6	937.5	83.75	££££
	GLARE	1214	66	2.52	481.7	26.2	££££

*Note: The AISI 4130 is water quenched 855 ℃, 595 ℃ temper, 100 mm round; CFRP is carbon fibre reinforced epoxy resin (120 ℃ cure) reinforced by standard CF (carbon fibre) UD (0°); GLARE is glass fibre reinforced AA2024-T3 with unidirectional fibre orientation, 3/2 lay-ups of 0.25 mm layers.

γ-TiAl alloys are advanced titanium alloys that have only been applied in aerospace over the last 10 years or so. Compared with conventional titanium alloys, the main attractive properties of γ-TiAl alloys are their lower density (ca. 3.9–4.2 g/cm^3 [33]), high specific elastic modulus (ca. 40 × 10^{-3} GPa · m^3/kg [33]), better oxidation resistance (Al_2O_3 surface oxide), and retention of strength at high temperature (ca. 600–800 ℃ [33]). The major drawbacks are lower room temperature (below 20 ℃) ductility and toughness [14,31,33]. Hence γ-TiAl alloys are attractive in high temperature applications such as gas turbine engines, e.g. cast γ-TiAl blades have been used in the 'GEnX jet engine', produced by General Electric [33]. The application of the advanced γ-TiAl alloys in aircraft engines components results in about 50% improvement in specific stiffness compared to conventional engine materials, as well as higher creep and corrosion resistance [33].

2.1.3. High strength steel

Steel is the most commonly used structural materials in many industry applications, due to good manufacturability and availability, extremely high strength and stiffness in the form of high strength steels, good dimensional properties at high temperatures, as well as the lowest cost among commercial aerospace materials. However, high density and other disadvantages, such as relatively high susceptibility to corrosion and embrittlement, restrict the application of high strength steels in aerospace components and systems. Steels normally account for approximately 5% to 15% of structural weight of commercial airplanes, with the percentage steadily reducing. Despite the limitations, high strength steels are still the choice for safety critical components where extremely high strength and stiffness are required. The major applications for the use of high strength steel in aerospace are gearing, bearings [5a], and undercarriage applications [13,14].

2.2. Aerospace composites

High performance composites such as fibre reinforced polymer and fibre metal laminates (FML) have received increased attention in aerospace applications, competing metals at moderate temperatures (ca. −150 to 200 ℃). Mechanical properties of commercial carbon reinforced polymer can be found in Table 1. Other advantages of composites include improved fatigue resistance, corrosion resistance and moisture resistance, as well as the ability to tailor lay-ups for optimal strength and stiffness in required directions. However the higher cost of composites in comparison to metals is one of the major obstacles for the application of composites [13,14,18].

Carbon fibre reinforced polymer (CFRP), represents the most extensively used aerospace structural material apart from aluminium alloys, with the major applications being structural components of the wing box, empennage and fuselage, as well as the control surfaces (e.g. rudder, elevator and ailerons). Glass fibre reinforced polymer (GFRP) is used in radomes and semi-structural components such as fairings. Aramid fibre polymers are used where high impact resistance is required [13,14,18]. Fibre metal laminates (FML), especially glass fibre reinforced aluminium (GLARE), are other types of composites that have applications in aerospace industry (especially in the Airbus A380) due to enhanced mechanical properties such as reduced density, high strength, stiffness and fatigue resistance compared with monolithic metals. The main applications of GLARE are the fuselage skin and empennage [13,34,35].

The development of nanotechnology provides an opportunity to improve multifunctional properties (physical, chemical, mechanical properties, etc.) at the nanoscale. Unlike conventional composites, nanocomposites offer the opportunity to improve properties without too much trade-off of density increase, by only adding a small amount of nanoparticles (e.g. layered silicate, functionalized carbon nanotubes (CNTs) and graphite flakes, etc.) [36]. For example, to increase the oxidation resistance of composites, nanoparticles could be included, such as silicate, CNTs, polyhedral oligomeric silsesquioxane (POSS) that could form passivation layers. The addition of CNTs, silica and layered silicate into composite matrix could promote the energy dissipation on structural failure, hence increase the toughness of the composite, resulting in the potential approximate 1000 GPa) could improve the stiffness and strength of the composite. Reducing the thermal expansion coefficient of the composite could be achieved by incorporating low expansion coefficients and good matrix bonding nanofillers including CNTs, carbon nanofibres (CTFs) and silicate into resin matrix [36–38]. In summary, the development of nanocomposites offers the opportunity of redundancy elimination and weight reduction, which provides significant potential in promoting the properties of aerospace components especially in light-weighting.

Shape memory polymer composites (SMPC) are smart materials that could change their form from their distorted form to their original form as a result of a certain stimulus such as change of temperature, an electric or magnetic field, particular light wavelengths, etc., by releasing the internal stress (caused by viscoelastic deformation) stored in the material [39,40]. The applications of SMPCs in aerospace components and systems include the wing skin of morphing-wing aircraft, and the solar array and reflector antenna of satellites [39]. The advantages of SMPCs over the shape memory alloys includes lower density, higher shape deformability and recoverability, better processing and lower relative lower cost [39,40].

Self-healing composites have been developed to increase the damage tolerance of composite materials by incorporating the healing agents mosaicked in a microencapsulation system or microvascular network in the polymer matrix [41–43]. The self-healing mechanism is triggered by the micro-cracks propagating through the microcapsules or microvascular system, releasing the healing agents to the locations of micro-cracks through capillary action, after which the micro-cracks are bonded with the polymerised healing agents [41–43]. The application of self-healing mechanism could increase the damage tolerance and life of composites (including CFRPs, nanocomposites, etc.) with a modest sacrifice of material strength [41].

2.3. Selection of aerospace materials

The selection of materials for an aerospace system is based on the operating conditions of the specific component or system, such as loading conditions, operating temperatures, moisture, corrosion conditions, noise [44] in combination with consideration of economic and regulatory factors. For example, wings mainly sustain bending during service, as well as tension, torsion, vibration and fatigue. Hence, the main constraints for wing materials are stiffness, tensile strength (lower wing structures), compressive strength (upper wing structures), buckling strength and vibration modes [45]. Combustion chambers are subjected to high temperature and pressure operation, and associated fluid-structure interactions, and the materials selection constraints are principally thermal properties and usually have much higher specific strength and stiffness than metals, which makes composites an attractive choice for light-weighting design for many aerospace components and systems. However, metals have the advantage of ease of manufacture and availability, as well as much lower cost, making them still extensively used in many aerospace applications.

3. Computer aided structural optimization

The structural optimization of a product or a component is usually carried out to enhance the performance, such as promoting the strength, stiffness and vibration performance of the structure, or reducing the weight, peak stress and displacement, and reducing cost. The conventional approach to optimization (i.e. analytical optimization) generally relies on the intuition and experience of the engineers based on experimental outcomes and consequently, a design could require extensive studies and time in order to achieve the desired results [48].

The development of numerical methods such as finite element analysis and computer aided engineering technologies, have provided approaches to overcome the challenge of structural optimization design. In numerical structural optimization an approximate model is created and optimised at each design cycle. Afterwards, the design solution of the approximate optimization is used to update the finite element model to perform a full system analysis in order to create the next approximate model. The sequence of design cycles continues until the approximate optimum design converges to the actual optimum design. Figure 3 [49] illustrates a typical flow chat for a computational topology optimization process [49,50].

The general mathematical description of the optimization problem with continuous design variables can be presented as follows [51–55]:

$$\begin{cases} \min\limits_{x} f_i(x, y(x)),\ i = 1, 2, \ldots, l \\ \text{s.t.} \begin{cases} g_j(x, y(x)) \le 0,\ j = 1, 2, \ldots, m \\ h_k(x, y(x)) = 0,\ k = 1, 2, \ldots, n \\ x \in [a, b] \end{cases} \end{cases} \tag{1}$$

The formulation states the design responses of design variables and state variables. The design responses could be set as objective functions or constraints.

- Objective functions $f_i(x, \boldsymbol{u}(x))$: The objective functions are used to classify designs, each of which returns a number that indicates the goodness of the design (l is the number of objective functions). Usually, the optimization problem is to minimise the f_i, which frequently represents weight, strain energy, displacement, cost, etc [51–53].

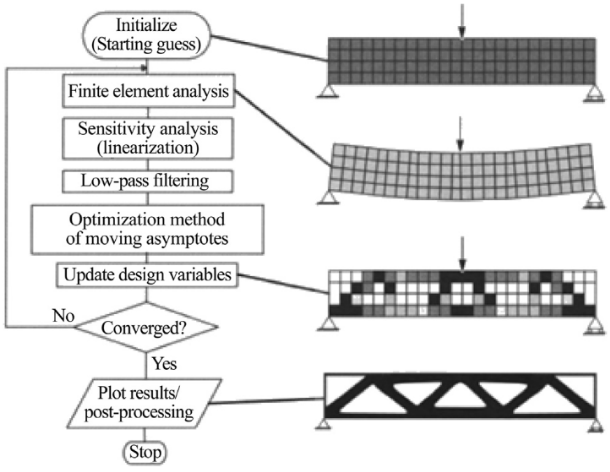


Figure 3 Flow chat of a computational structural optimization process [49].

the area of a cross section), the choice of material, etc [51–53].
- State variable $\boldsymbol{y}(x)$: For a given structure, i.e. for a given x, the state variable is a vector or function that represents the response of the structure. For a mechanical structure, the response could be displacement, stress, strain or reaction force (in general the state variable represents structural displacement matrix $\boldsymbol{u}(x)$) [49,51–53].
- Constraints: Typically, three kinds of constraints are applied to the structural optimization functions [49,51–53]:
  (1) Inequality constraints, which are constraints on the ranges of design responses, generally presented as $g(x,\boldsymbol{y}(x)) \le 0$;
  (2) Equilibrium constraints, which constrain the design responses with equations. The general form of equilibrium constraints on structural optimization problems is $\boldsymbol{K}(x)\boldsymbol{u}(x) = \boldsymbol{F}(x)$, where $\boldsymbol{K}(x)$ is stiffness matrix, $\boldsymbol{u}(x)$ is displacement vector, $\boldsymbol{F}(x)$ is force vector.
  (3) Design variable constraints, which are applied on a design variable x, e.g. $x \in [a,b]$, where a and b are the minimum and maximum value of x.
  (4) In real cases, the objective function could be more than one, i.e. $l > 1$. This then becomes a multiple criteria problem. Generally, $f_i(x,\boldsymbol{u}(x))$ cannot be minimized for the same x and $\boldsymbol{y}(x)$. Instead, one therefore typically tries to achieve Pareto optimality (making any one individual or preferred criterion better off without making at least one individual or preferred criterion worse off). The most common way to obtain a Pareto optimality is to form a scalar objective function [48,51]:

$$\sum_{i=1}^{n} w_i f_i(x,\boldsymbol{y}(x)), \tag{2}$$

3.1. *Conventional numerical structural optimization*

According to the design flexibility, conventional numerical structural optimization methods can be broadly categorised into sizing, shaping and topology optimization.

Sizing optimization: Sizing optimization is the most fundamental method that determines the optimal dimensions of the structure. The design variables could be the thickness, width and length of the objectives. In this process, the section properties of a given part are modified to meet a specified target, which could be stress, displacement or other criteria [51,56].

Shape optimization: Shape optimization focuses on the shape of the structures, such as their outer boundaries and the shapes of holes. It is commonly used to design the shape of the boundaries of the structure by modifying the location of grids. However, the connectivity of the structure is not changed in the process of this type of optimization [51,57].

Topology optimization: Topology optimization is a type of structural optimization used to find the optimal material distribution or material layout within the design domain. Topology optimization allows topological changes including increasing the number of holes in the design domain, in addition to changing the shape of the structure. The basic idea of topology optimization can be described as extending the design domain to a fixed design space and replacing the optimization problem by a material distribution problem, by using the characteristic function that could be simply represented as a value of '1' in material domain and '0' in void domain [49,58].

A wide range of algorithms have been developed to as approaches to structural optimization, such as solid isotropic material with penalization (SIMP) [59], bidirectional evolutionary structural optimization (BESO) [60], genetic algorithms [58] and level set methods [61].

Optimization examples: Numerical structural optimization has been extensively applied in the design of aerospace and automotive components and systems, as well as lightweight bicycles, architecture, etc. For instance, Zhu et al. provided a topology optimised model of an engine bracket that could be manufactured by casting [62]; Krog, L. et al. gave an example of optimised main wing box rib for Airbus, using the combination of sizing, shape and topology optimization methods [63]; the Alfred-Wegener-Institute designed a lightweight bionic bicycle where the topology optimization approach with the inspiration of natural lightweight structures were applied and 60% weight reduction achieved [64]; Whiting et al. studied

Figure 4 [63] illustrates an example of a design cycle for an optimised plate component with a combination of topology, sizing and shape optimization, in order to improve the stiffness and reduce the weight of the component [63]. Firstly, the objective model was optimised using a topology method according to the applied boundary conditions. The redundant material was removed from the model to reduce the weight. However, the topology model can be an idealised model with poor manufacturability. Hence the model obtained was refined using geometry extraction to build the improved model for sizing and shape optimization processes. Subsequently, the thickness distribution and ribs height were optimised during the sizing optimization, and the shapes of the void area were optimised on the shape optimization model as well, in order to modifying the optimised model to meet the manufacturing constraints. The final design with the combination of topology, sizing and shape optimization methods, achieved the lightweight and enhanced stiffness requirements with acceptable manufacturability [63].

Figure 5 shows an example of topology optimization for a cantilever beam, for the conditions given in Table 2. A 3D beam model was established in SolidWorks and the optimization process was operated with ParetoWorks, a plugin module. All degrees of freedom were fixed on the left end of the beam, while a concentrated force with a magnitude of 30 kN was applied on the right end of the beam in the direction demonstrated in Figure 5(a). The objective of this case was to achieve a weight reduction of 50% with the constraints listed in Table 2. Figure 5(b) shows the stress field of the initial model and Figure 5(c) shows the shape and stress field of the topology optimised model. The light-weighting optimised model appeared as a truss-like geometry feature with a 19.96% increase of maximum deflection and 23.63% of maximum von Mises stress, both of which have not reached the criteria.

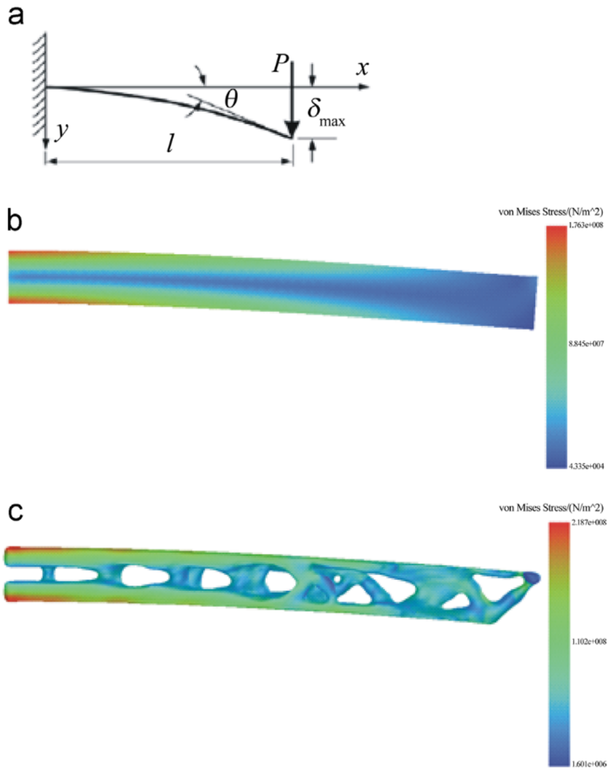


Figure 5 Cantilever beam optimization case study 1 by the author: (a) loading and boundary conditions, (b) von Mises stress field on initial model and (c) von Mises stress field on topological optimised model.

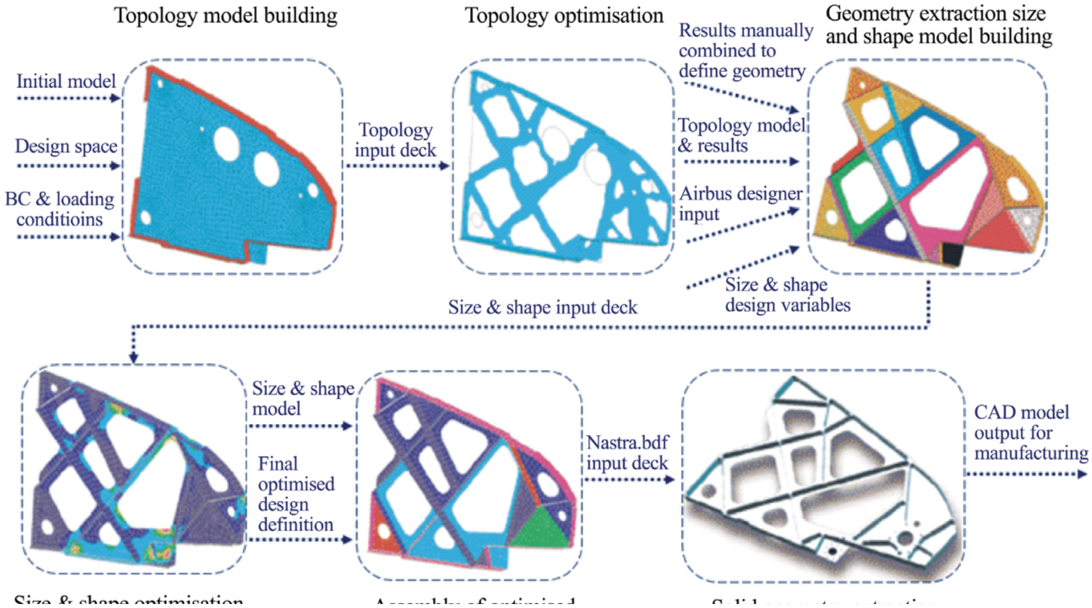


Table 2 Setup of a cantilever beam optimization case study.

Model setup	Beam dimensions/mm	Material			
		Type	Density/(kg/m^3)	Young's modulus/GPa	Yield strength/MPa
	100 × 100 × 1000	Alloy steel	7.7 × 10^3	210	500
Loading case	Boundary condition		Loading condition		
	$u_{x1} = u_{y1} = u_{z1} = 0$		$P = 30$ kN		
	$r_{x1} = r_{x2} = r_{x3} = 0$				
Optimization setup	Mesh		Objective	Constraints	
	Element number	49419	Weight reduction = 50%	Thickness ≥ 2 mm; Deflection ≤ 20 mm;	
	Element size/mm	5.94		Stress safety factor ≥ 1	

3.2. *Multi-scale optimization*

Models generated from the topology optimization are usually not manufacturable using conventional fabrication approaches such as casting, forming, stamping and machining, etc. The optimised model must be modified with strict manufacture constraints. However, the development of additive manufacturing (AM) significantly expands the flexibility of design freedom to realise designs with much more complex geometries than conventional manufacturing methods. AM provides better approaches to realise topological optimized deigns by fabricating parts layer by layer with certain lattice structures. The utilization of lattice structural material construction provides an opportunity for multi-scale structural optimization, i.e. topology optimization in macro-scale and lattice structural optimization in the meso-scale (0.1–10 mm). Additionally, structural elastic properties can be achieved with designed gradients by optimising lattice structures [66]. Hence, lattice structure optimization increases the freedom of structural optimization in the multi-scale, which provides the opportunity for further improvement of structural performance.

Figure 6 [67] illustrates an example of multi-scale structural optimization for a 3D cantilever beam studied by Robbins et al. [67]. Four types of lattice structures with cellular densities (CD) of 10%, 20%, 50% and 75% were used in this example. Different volume fractions (VF) of the cantilever beam calculated using topology optimization were applied with different cellular densities, resulting in the four combinations of multi-scale structures with the same weight reduction percentage (94%) compared with the original beam (1VF + 100% CD). Under the same loading and boundary conditions, the combination of 0.6 macro-structure volume friction with 10% cellular density indicated the maximum structural stiffness improvement, i.e. 59% deflection reduction was achieved [67]. Figure 6 also demonstrates the 3D mesh of the optimised beam and prototype fabricated with AM.

A design methodology for lattice structural optimization has been proposed by Tang et al. [66] and applied to a quadcopter arm design:

(1) The initial design was generated with macro-scale topology optimization as the input model of the lattice structural optimization design. The initial design was meshed and conducted with finite element analysis for the preparation of lattice structural optimization.
(2) The lattice frame was generated by selecting the array types of the lattice (uniform lattice or conformal lattice, as demonstrated in Figure 7(a) and (b) [68]) and then selecting the cell types from the established cell library. A conformal lattice can be adapted to better suit the boundaries of the macrostructure, avoiding poor struts connections along boundaries, hence it is generally used to fill the regions connected to functional faces and the remaining regions are filled with a uniform lattice [66]. Figure 7(c) [69] demonstrated an example of a cell library provided by Chang [69].
(3) The lattice structures are constructed with manufacturing constraints when the lattices are mapped and populated to the mesh of structure. The orientations of struts are optimised according to the manufacturing constraints to maximise self-supported struts and reducing supporting materials [66,68]. An artificial neural network (ANN) trained with experimental data could be used to obtain manufacturing constraints for each AM method [66].
(4) The thickness of each strut is optimised with BESO-based lattice structural optimization.

Nguyen et al. [68] demonstrated an augmented size matching and scaling (SMS) method to construct and optimise lattice structures with efficient algorithms that simplify the multi-variable problem to a 2-variable problem with acceptable accuracy.

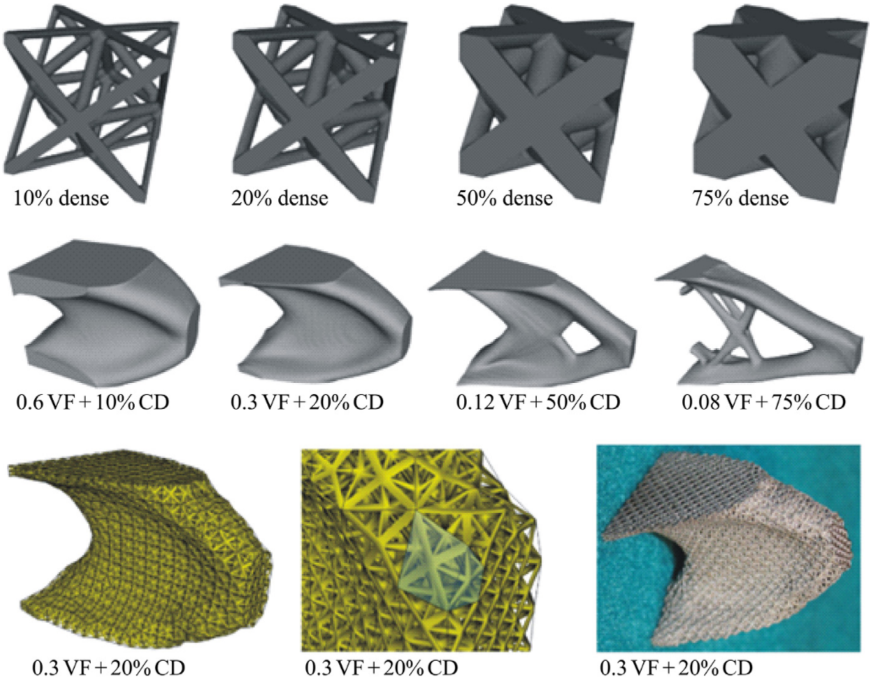


Figure 6 An example of multi-scale structural optimization and AM fabrication of a 3D cantilever beam [67].

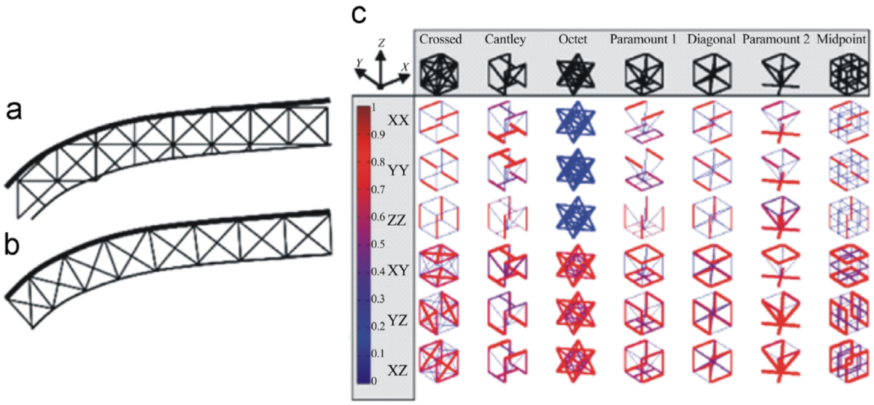


Figure 7 Illustrations of (a) uniform lattice structure [68], (b) conformal lattice structure [68] and (c) example of cell library [69].

Multi-scale optimization has been applied in many concept designs that show potential for weight reduction and performance enhancement. Figure 8 [72] demonstrates a bionic design for an Airbus 320 partition, where multi-scale optimization was enabled by additive manufacturing [72]. In this example, macro-scale topology optimization was operated on the base model, followed with the application of lattice structures in the meso-sale level to achieve further weight reduction and performance improvement. The concept design was enabled by additive manufacturing [72].

In addition to direct application on aircraft and associated components, lightweigting concepts are emerging across

and was fabricated with 3D printing [70]. Figure 9(c) shows a concept design of a 'bionic' automobile named Genesis, proposed by EDAG. Macro-scale topology optimization and lattice structure application such as sandwich shells with lattice cores have been combined in this design [71].

4. Advanced manufacturing methods

Manufacturability is a crucial constraint throughout the whole design process, governing the possibility of whether a design can be fabricated into real prototype or product [73]. Manufacturing constraints must be taken into con-

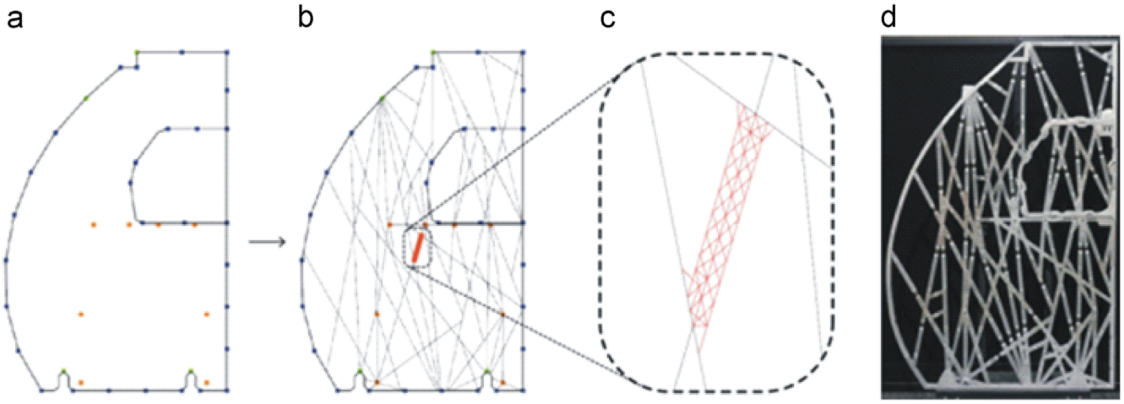


Figure 8 Bionic lightweight optimization of an Airbus 320 partition: (a) base model setup, (b) macro-scale optimization, (c) meso-scale optimization and (d) model fabricated by 3D printing [72].

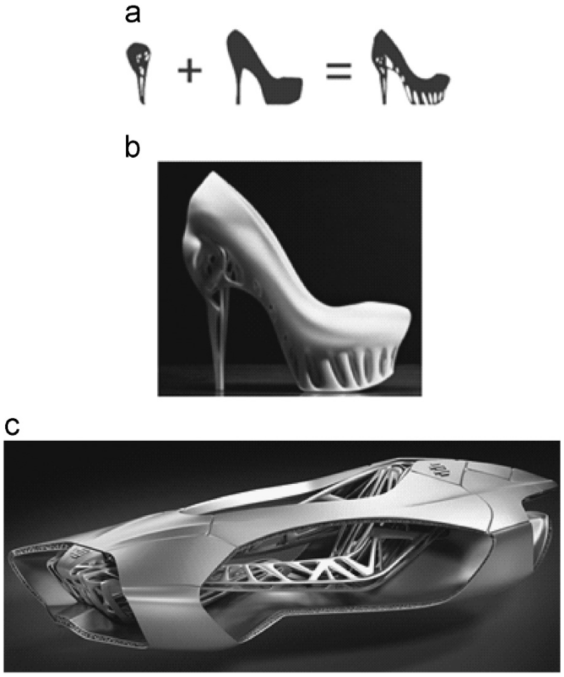


Figure 9 Lattice structures used in lightweight design from other domains: (a)(b) bionic lightweight shoes [70] and (c) concept design of 'Edag Genesis' automotive [71].

for lightweight design, but their application is restricted by the high production costs. Topological optimised designs tend to result in a complex geometry that cannot be fabricated by conventional manufacturing methods, such as casting and forming, without modification according to the manufacturing constraints such as drawing direction for a casing part. Hence, manufacturing methods have significant effect on the light-weighting design of aerospace components and systems. The development of advanced manufacturing technology, such as additive manufacturing, foam metal manufacturing and advanced metal forming,

4.1. Additive manufacturing

Additive manufacturing (AM), defined by ASTM, is a process that joins materials layer on layer according to 3D model data [74–76]. As discussed in the previous section, AM enables the fabrication of designs with complex geometries, and it relaxes the manufacturing constraints and increases the flexibility the structural design. AM provides the opportunity of realising multi-scale optimization (i.e. macro-scale topology optimization and meso-scale lattice structural optimization) of designs that could not be fabricated with conventional manufacturing methods [67]. The design flexibility enables part consolidation, i.e. assemblies with multiple components can be simplified to one whole piece of component for each assembly, which is favourable for light-weighting design [68]. Additionally, the geometry construction method of AM allows multi materials as well as multi fibre orientations of composites in component fabrication. For example, Sugavaneswaran et al. [77] established a model for randomly oriented multi material components using pure elastomer and randomly oriented plastic reinforced elastomer, with samples fabricated by 3D printing. Chen et al. [78] have demonstrated the potential to deposit multi-materials, with an electrochemical metal 3D printer. To sum up, the capability of fabrication of multi-scale optimization and multi materials components with multi-function enables designs with gradient properties to be realised by AM. Hence, AM has significant potential to enable light-weighting design.

The feasibility of AM enabling optimised design is demonstrated by many examples. Figure 10(a) shows the original and a topological optimised automotive bracket enabled by AM. Figure 10(b) demonstrates a 3D printed titanium seatbelt buckle used in airplane, designed by 3T RPD® Ltd. A weight reduction of 87 g was achieved for a single product (conventional steel and aluminium seatbelt weights are 155 g and 120 g

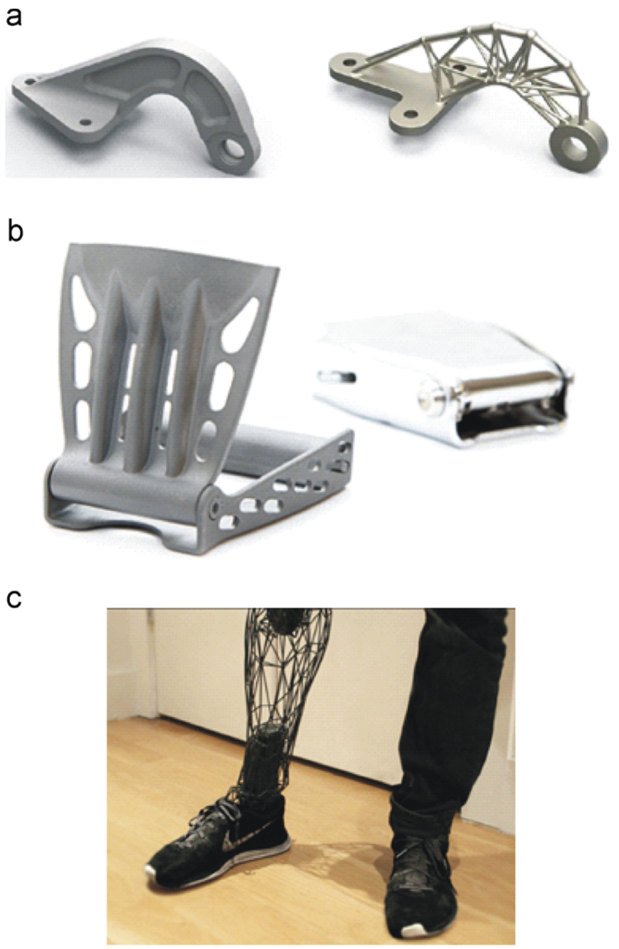


Figure 10 (a) Examples of optimised structures enabled by additive manufacturing: optimization of an automotive bracket [85], (b) a 3D printed lightweight titanium seatbelt buckle used in airplanes [86] and (c) a 3D printed lightweight titanium limb [87].

achieved by the application of selected types of lattice structures, enabled by AM. A flexible lattice structure (Figure 11(b)) was used for locations where the chair was in contact with the user and a rigid lattice structure (Figure 11(c)) used in supporting regions.

Significant potential for enhancing structural properties exists for the optimization of lattice structures at both macro-scale and meso-scale as discussed in Section 3.2. Figure 12 illustrates examples of complex lattice structures with inspiration from bionics, e.g. diatoms and conch, and mathematics, e.g. half of 120-cell and round Möbius strip, which provide the opportunity to realise multiple and gradient functional designs.

AM has been applied to many classes of materials from metals to composites. Multiple kinds of processes have been developed for different states of raw materials [75]. Lightweight aerospace materials including advanced aluminium alloys, titanium alloys and composites have been used

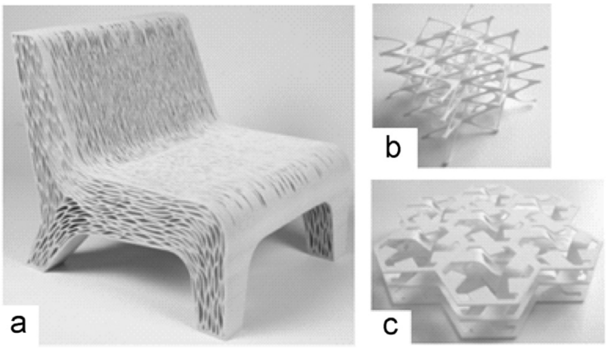


Figure 11 Example of gradient structural properties enabled additive manufacturing: (a) 3D printed chair (b) with flexible lattice structure and (c) rigid lattice structure [88].

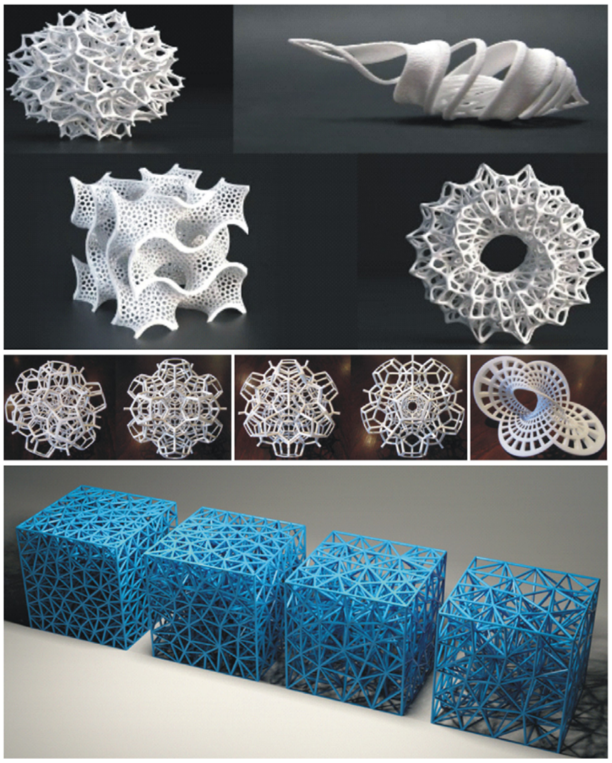


Figure 12 Examples of AM lattice structures with bionic and mathematic inspirations [89–91].

For instance, Li et al. [79] carried out a numerical study of the thermal behaviour of AlSi10Mg powder with selective laser melting (SLM); Xu et al. [80] investigated the formation and phase decomposition of Ti-6Al-4V powder under SLM; the effect of fibre quantity and length of carbon fibre reinforced thermoplastic for fused deposition modelling (FDM) manufacturing has been studied by Ning et al. [81].

much attention, challenges exist for AM to compete with conventional manufacturing methods, including:

- The quality of fabricated components is restricted by the complex thermal mechanics in the manufacturing zone and the printing resolution, which affect, for example, the mechanical properties, geometry accuracy and surface roughness of the components [82].
- The stability and reliability of AM depend on the in situ monitoring and closed loop control system, which would significantly affect the product quality [83].
- More powerful computer aided design tools are needed to suit the AM designs as most of current commercial CAD software are designed for conventional manufacturing approaches [84].
- The time consuming processes and relatively expensive raw materials restrict the use of AM in mass production applications compared with conventional manufacturing methods. Current AM technology remains favourable for small production runs [74].
- As a novel manufacturing technology, the standardization, qualification and certification are important for the mass production application of AM. The establishment of standards and protocols still remains a challenge for AM [74,83].

4.2. Foam metal processing

Foam metal is a cellular structure that contains solid metal filled with air voids that comprise a large volume fraction resulting in significant weight reduction. Generally, only 5%-25% of volume is occupied with base metal [92]. The porous structure of the metal foam material leads to tailored structural and non-structural properties. Improved specific strength and stiffness can be achieved with significantly reduced structural density, compared with the base metals [93]. The stochastic cellular distribution results in the constant structural reaction regardless of loading directions. The porous structure improves the energy absorption capability and vibration properties of the material, which results in higher impact toughness of metal foam than its base metal [92–94]. The increased specific surface area improves the heat transfer properties making metal foam a favourable material for heat exchangers application [94,95]. The controllable volume fraction of air voids provides high freedom for adjustment of structural properties. The tailored properties of metal foam make it a favourable material for extensive applications. Metal foam materials have much larger thermal exchange surface than the base metals, which makes the metal foam better choice for the heat exchanger and heat-sink applications with high thermal shock resistance [92]. The good impact energy absorption ensures the superior performance of the metal foam structures under shock wave loading condition [96], sandwich (AFS) is a typical application example that gives higher stiffness and lower density than dense material and higher tensile strength and fracture toughness than bare metal foam [97].

Open cell and closed cell are typical categorizations of metal foam materials, both of which could be processed with powder metallurgy, hollow spheres method and lotus type processing method, etc. [94]. Foaming agents and catalysis are usually used in foam metal fabrication. The common methodologies of foam metal processing includes casting with open celled polyurethane foam skeleton, directly air injection or foaming agent mixing with molten metal, etc. [94].

4.3. Advanced metal forming

Metal forming is extensively used to fabricate metal sheet components. However, the formability of lightweight metals, such as aluminium alloys and titanium alloys, usually have relatively low formability particularly at room temperature, i.e. they could be difficult to form especially for complex geometries after structural optimization. Some metal forming technologies have been developed to improve the formability of materials in order to fabricate the complex optimised structures.

HFQ®: Solution heat treatment, forming and in-die quenching is an advanced metal forming technology that can improve the material formability and increase the mechanical properties of the formed part as well. During the HFQ® process, the sheet material is firstly heated to its solution heat treatment (SHT) temperature and subsequently held at the SHT temperature for a sufficient period of time to dissolve all the precipitates into the material matrix. The ductility increases significantly after SHT because the homogenous microstructure is obtained. Afterwards, the material is transferred into a set of cold dies to be quenched and formed at the same time. Supersaturated solid solution (SSSS) is generated subsequently and the homogenous microstructure is reserved during the fast quenching process. Then the material is heated to its artificial ageing temperature to distribute the precipitates in a designed distribution, in order to take the advantages of precipitates hardening. To sum up, the HFQ® process can significantly enhance the material formability to form complex components, and reduce the spring back and distortion as well. This technology has been successfully used in aluminium alloys and high strength steels. For example, the HFQ® technology has been applied to fabricate complex vehicle beam using AA7075 with only single stamping process. Complex AA7075 components are difficult to fabricate using other processing technologies. [98,99]

Superplastic forming: SPF is a slow forming (the could not be formed using the conventional forming technologies. To achieve superplastic deformation fine grains equiaxed grain with average grain sizes typically around 5 μm are required. Additionally, to enable the diffusion process to occur, the temperature is excess of 50% of the melting temperature are required. At this state, the material shows high ductility with the elongation usually over 200% of the initial sample length. However, under these conditions, grain growth takes place by static diffusion controlled processes, which can be promoted by deformation. The grain growth causes material hardening and decreases the strain rate sensitivity, in turn decreasing the elongation to failure. This behaviour is obvious in two-phase systems, such as titanium alloys (e.g. Ti6Al4V), the presence of the low diffusivity alpha phase, tends to constrain the growth of the higher diffusivity beta phase, hence preventing uncontrolled grain growth. SPF can be achieved using particular processes, such as thermoforming, blow forming, and vacuum forming, etc. The major advantage of SPF is the complex shaped component can be formed without too much spring back and residual stresses. However, the slow processing speed and large energy consumption are the major drawback of this technology. [98,100]

5. Conclusions

Light-weighting represents an effective way to achieve energy consumption reduction and performance enhancement. This concept has been well accepted and utilised in many industries, especially in aerospace component and system design. Light-weighting design involves the use of advanced lightweight material and numerical structural optimization, enabled by advanced manufacturing methods.

Metal materials especially aluminium alloys have been the dominant aerospace materials for over a century and still account for the major fraction of airframe materials. Metal materials have many advantages as structural materials such as relative high strength and stiffness, good damage tolerance and fracture resistance, as well as good manufacturability, etc. The well-developed metal processing technologies and availability of raw material result in relatively low cost. With new heat treatment and metal processing methods, advanced lightweight metals such as new Al-Li alloys and γ-TiAl alloys are available for lightweight optimization of aerospace components and systems. Composites have become increasingly competitive and challenge the predominance of metal materials in aerospace applications. Much higher specific strength and stiffness makes composites the better choice than many metals in lightweight design considerations. CFRPs are the most extensively used composite materials in aerospace application, comparison with conventional materials. However, the much higher cost and poorer manufacturability comparing the metals restricts the wider application of composites.

Structural optimization can effectively improve the performance of aerospace components and systems by optimising the material distribution to achieve maximum weight reduction, and enhance structural performance such as strength, stiffness and vibration performance. Conventional structural optimization methodologies include sizing, shape and topology optimization. Computer aided software products have been developed to enable optimization. Lattice structural optimization enables multi-scale optimization that could further optimise the weight and performance of objects. One of the major challenges of numerical optimization approaches is the large number of variables. Efficient algorithms are needed to increase the efficiency of numerical optimization.

Manufacturability is an important constraint in both the process of material selection and structural optimization. Advanced manufacturing methods such as additive manufacturing, foam metal processing and advanced metal forming increase the freedom of both of the processes mentioned above. Materials considered with poor manufacturability and the complex structural geometries cannot be fabricated with conventional manufacturing methods, but the fabrication of which could be enabled by these advanced manufacturing technologies. However, the long manufacturing processes and high cost, as well as standard and protocol establishment, etc. still remain the challenges of additive manufacturing and foam metal process.

Acknowledgements

The authors are grateful for the sponsor from AVIC (Aviation Industry Corporation of China) the First Aircraft Institute and the China Scholarship Council. The strong support from the Aviation Industry Corporation of China (AVIC) the First Aircraft Institute (FAI) for this funded research is much appreciated. The research was performed at the AVIC Centre for Structural Design and Manufacture at Imperial College London.

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