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Metallic microlattice materials: A current state of the art on manufacturing, mechanical properties and applications

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ABSTRACT

Metallic microlattice is a new class of material that combines useful mechanical properties of metals with smart geometrical orientations providing greater stiffness, strength-to-weight ratio and good energy absorption capacity than other types of cellular materials used in sandwich construction such as honeycomb, folded and foam. Metallic microlattices consist of micro struts stacked in different arrangements and most of the volume is occupied by air voids. Relative density and strut stacking order are the prime design variables of this ultralight material and the mechanical properties could be engineered by controlling these parameters. The base metal i.e. stainless steel, titanium alloy etc. used in producing microlattices, obviously, would affect its behavior. A number of processes are reported in literature to produce metallic microlattices, which could significantly affect its mechanical properties. This paper presents an overview of manufacturing and processing of microlattices with the corresponding mechanical properties. Current techniques adopted for modeling its structural response are discussed herein. Possible future uses of microlattices and the demonstrated use of cellular materials analogous to applications of microlattices are also explored in this paper as practical applications are yet to be demonstrated for this innovative ultralight material.

1. Introduction

The application of sandwich structures is increasing in various fields including aerospace, automotive, marine, and defense industries. This growing demand has led to substantial amount of research on the improvement of existing materials as well as development of new sandwich structure components, e.g. skin, adhesive and core. Studies carried out in core materials of sandwich structure are mostly aimed to improving energy absorption capacity of the materials, which in turn improves the crash performance of the whole sandwich structure. Honeycomb, folded and foam are the most studied cellular materials to be used in sandwich construction as they offer high stiffness, high strength-to-weight ratio and good energy absorption property. Honeycomb and Folded cellular structures suffer from high cost associated with manufacturing and processing. They also suffer from trapped moisture in the core material when using in sandwich construction. Stochastic cell structures such as foam may enhance the mechanical properties of the structures, but their irregular structure results in overdesign due to high factor of safety consideration to account for defects and unreliable performance. Lattice materials are gaining traction as core material due largely to their highly hierarchical orientation and very high strength-to-weight ratio. With current development of various manufacturing techniques, especially the use of rapid prototyping manufacturing technology such as 3D printing, lattice materials with dimensions close to micrometer scale can be produced, and are called microlattice material. Fig. 1 shows the difference of physical appearance between folded, honeycomb, open-cell foam, and microlattice core structures.

Hasan [1] has identified four major factors that have to be considered when assigning appropriate cellular metallic materials for applications. Those are morphology, metallurgy, processing and economy. The most important factor morphology includes size and scale of porosity desired, type and amount of porosity needed and total internal surface area of cellular material required. A 'very open' cell is preferred for functional application such as for high rate fluid flow in heat exchangers, while a 'completely closed' cell is preferred for structural application such as for load-bearing components in aircrafts. The second important factor is the metallurgy, which deals with selecting suitable metals or alloys that can be manufactured according to a specific type of cellular structure. For example, lightweight alloys such as aluminum, magnesium or titanium foams are preferred for structural, load bearing parts applications. Finally, the manufacturing process and the relevant costs associated with it are also important considerations in selecting cellular metallic materials as the adopted technology could significantly affect the price of a finished product. Fig. 2a shows the type of porosity required for various application fields, whilst Fig. 2b shows the classification of cellular material based on openness and periodicity of cell.

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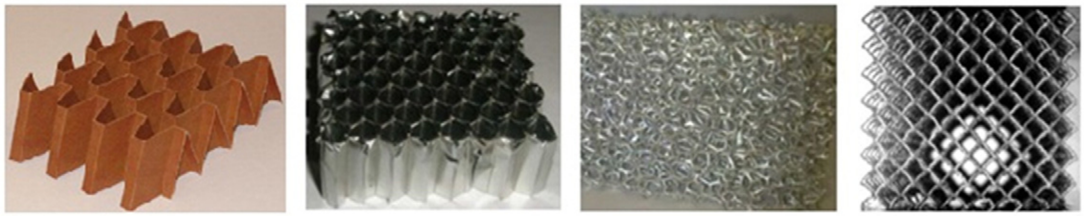


Fig. 1. Different physical appearance of cellular materials, from left: Folded, Honeycomb, Metal foam, Microlattice structure [1].

Luxner et al. [4] suggested that highly ordered lattices are stronger than other disordered types of cellular materials, but they are extremely sensitive to strain localization. In addition, they could accumulate high amounts of localized damage in certain strut orientation. Mullen et al. [5] also reported that randomization in cell structures enhance the mechanical properties of the structures by eliminating the natural fault planes that commonly occur in ordered structures. But Rehme [3] argued that better mechanical properties can be expected from regularly arranged cell structures than from stochastic formations, primarily because of the low connectivity of the joints due to a smaller number of cell walls or struts linked in respective edges or vertices. Microlattices are periodic open cell structure, where the lattice formation occurs due to interconnected struts.

Overall, open cell periodic microlattice structure has significant potential to be used as both structural and functional materials. Mechanical properties of microlattices, which are discussed later, complement its possible structural applications. Metallic microlattices, however, are at a very early stage to uncover its full potential for structural applications. Xiong et al. [6] recently reviewed microlattices produced from different materials such as composites, polymers and metals, but this paper focuses solely on in-depth analysis of metallic microlattices and its manufacture, mechanical properties, modeling and possible applications.

2. Manufacturing of metallic lattice structure

There are several manufacturing processes of metallic lattice structures [7], but only the proven methods are discussed in this section. Rehme [3], Sypeck [8] and Wadley et al. [9] previously reviewed earlier generation processes focusing on cellular materials, both metallic lattice and foam structures. Latest manufacturing processes along with the earlier generation processes focusing on microlattice materials are discussed herein.

2.1. Investment casting

Investment casting is one of the conventional methods to create cellular structures by injection molding or rapid prototyping methods where sacrificial truss patterns with attached face sheets is produced from a volatile wax or polymer such as polyurethane. In this process, a pattern is coated with ceramic casting slurry and dried with the help of a system of gating and risers. The wax or polymer is later removed by melting or vaporization and then the lattice material is produced by filling the empty mold with liquid metal. A range of cell topologies is possible with this method such as pyramidal, tetrahedral and 3D kagome [9,10]. Fabrication of complex, non-planar shapes featuring trusses with a high nodal connectivity is possible with this approach. However, it is difficult to fabricate structures with near-optimal, low relative density cores because of the metal pathways in the molds become prohibitively small and complex and subsequently suffers from increased susceptibility to casting defects. Alloys with high fluidity must be used which limits material choice [9]. This method is expensive and time-consuming, and the produced structures contained significant porosity. A core density of about 2% can be achieved by this method [11]. Deshpande and Fleck [12] manufactured aluminum/silicon and silicon/brass sandwich beams with tetrahedral cores and Deshpande et al. [13] manufactured octet-truss lattice material from aluminum alloy, shown in Fig. 3a, both using investment casting with injection molded polystyrene pre-forms. Wadley et al. [9] and Wang et al. [14] used rapid prototyped Acrylonitrile Butadiene Styrene (ABS) to manufacture a sacrificial pattern for investment casting using Cu–Be alloy, shown in Fig. 3b.

2.2. Deformation forming

Deformation forming is another method of producing periodic open-cell lattice structures by press forming operation. Using the forming and subsequent assembly process, cell sizes of millimeter to several centimeters can be obtained [9,15]. It utilizes sheet perforation and shaping techniques. Perforated metal such as stainless steel sheets with hexagonal or diamond shaped holes can be deformed at the nodes to produce sheets of tetrahedrons or pyramidal structure, as shown in Fig. 4a. The processed material requires annealing treatment in order to soften the strain-hardened struts. Lattice structure manufactured using deformation forming showed greater ductility than the investment casting process [9]. Relative densities between 1.7% and 8% can be achieved by varying the sheet thickness and the dimensions of the holes [16].

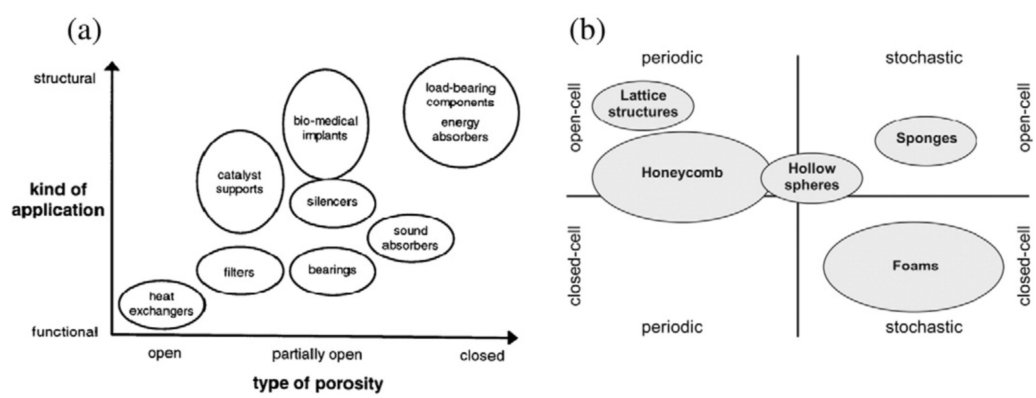


Fig. 2. (a) Applications of cellular metallic materials grouped according to type of porosity [2], (b) Classification of cellular materials [3].

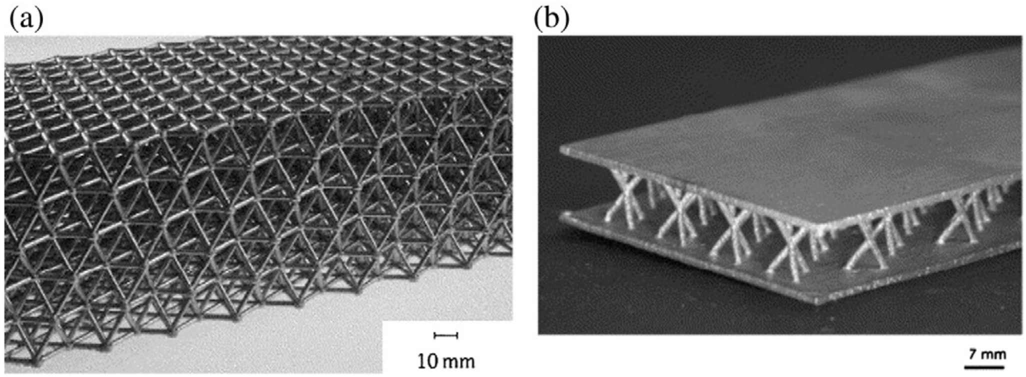


Fig. 3. Investment casting process — (a) octet-truss lattice material produced from cast aluminum alloy [13], (b) 3D Kagome core sandwich panel produced from Cu–1.8%Be alloy [9].

Another technique adopted in deformation forming process involves shearing and expanding metal sheets. Lim et al. [18] conducted a study where low carbon steel sheet was cut by laser, and expanded widthwise to form a metal mesh. The metal mesh was later bent along the lines connecting the longer ends of the diamond shapes, forming a corrugated sheet. Then the shorter struts were rotated by a 120° angle, and a quasi kagome truss was produced. Fig. 4b illustrates the shearing, expanding and corrugating processes. Corrugated shapes or egg box topologies can be formed by a simple press forming operation on solid sheets, made from high formability alloys. Corrugated and prismatic structures can also be manufactured using a slotting technique. This method has been used to produce square honeycomb cores and diamond prismatic cores [9,11].

2.3. Woven metal textiles

Woven metal textile approach is a simple method of weaving, braiding and sewing of wire drawn from metal alloy to produce an open-cell woven structure. The wire orientation is possible to be arranged in any angle, Fig. 5a shows 0°/90° orientation and Fig. 5b shows 45° orientation where plain weave structure and pyramidal truss structure is shown at the top and bottom respectively. Multifunctional uses are limited, as the wires are not bonded together in normal practice. This process offers a host of options as virtually all metals can be used to produce wires and variety of truss arrangements available [11]. Relative densities of around 10% can be achieved with this method [19].

2.4. Non-woven metal textiles

Non-woven metal textile approach produces textiles by layering wires and tubes made of metal such as stainless steel and subsequently joined together by brazing [19]. Square and diamond cell structures with relative densities between 3% and 23% can be produced by this method. The structures can be processed further by bending the layers to form pyramidal structures. Examples of non-woven metal textiles are shown in Fig. 6.

2.5. Selective Laser Melting

Selective Laser Melting (SLM) belongs to the group of additive manufacturing techniques. The principle of SLM process is based on that the metal powder is applied in very thin layers on a building platform, which is later completely melted using thermal energy induced by a laser beam [3]. The cross-section area of a part is built by melting and re-solidifying metal powder in each layer, then a new layer of powder is deposited and leveled by a wiper after the building platform is lowered. The laser beam can be redirected and focused across the powder bed following a computer-generated pattern by scanner optics in such a way that the powder particles are possible to selectively melted where desired. Schematic of SLM process is shown in Fig. 7. This method avoids wastage of material, which is the prime advantage of additive manufacturing technique. Although this advantage is currently overshadowed by the difficulty and high cost associated with the preparation of metal powders i.e. gas atomization and narrow particle size distribution, that the costs for built parts typically exceed the effect of the materials efficiency. Various types of metal powders can be used in SLM process including stainless steel, copper, nickel, chromium, titanium and super-alloys. Though freeform fabrication processes are capable of building any arbitrary shape, the SLM process has some limitations. It is difficult to produce overhanging geometries because of poor heat conduction in the powder bed below the newly laid exposed powders. It is also difficult to produce horizontal struts [20]. It was observed that the build angle of the truss has significant effect on the mechanical properties [21,22]. The most acute build angle possible is approximately 25° to the horizontal. Also the strut diameter increases by 50% at angles of 45° compared to vertical struts [23]. Larger amount

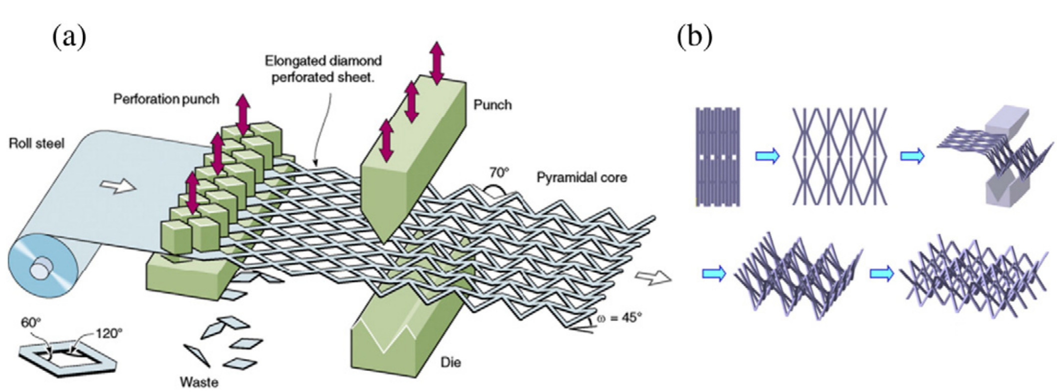


Fig. 4. (a) Deformation forming process [17], (b) processes in producing a quasi kagome truss [18].

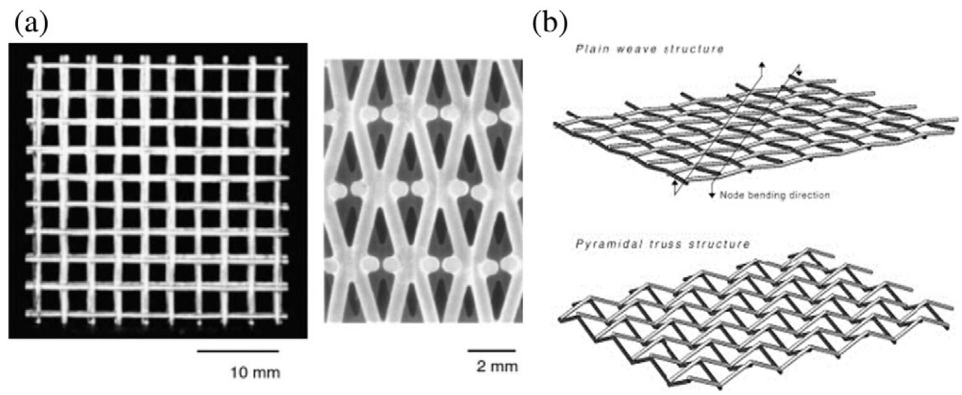


Fig. 5. Woven metal textiles [9] — (a) A 0°/90° orientation of Inconel textile from front and side view, (b) pyramidal truss can be produced by shearing a plain weave fabric and bending the node at 45° orientation.

of material gets deposited at nodes, so the properties may be different at those points [24].

2.6. Electron beam melting

There is an advanced process similar to SLM but instead of using laser, electron beam is used as the energy source of this method to melt layers of metal powders in vacuum, and the process is called Electron Beam Melting (EBM). Cansizoglu et al. [25] studied the fabrication of non-stochastic lattice structure using EBM. A schematic of EBM process is shown in Fig. 8a. First, a tungsten filament is heated to generate the electron beam and the electrons are accelerated to the build table onto the metal powder using an accelerating voltage of 60 kV. Electromagnetic coils are used to focus and deflect the electron beam for controlling purpose. Similar to SLM, the EBM also manufacture 3D objects by following layer-by-layer build, until the structure is completed. But unlike SLM, the base metal plate and the powder bed need to be preheated prior to electron scanning in the EBM [1]. Cansizoglu et al. [26] reported the effect of build angle on manufacturing of Ti–6Al–4V lattice structure. It was observed that each layer of thin beams built at an angle, consists of a relatively small cross-section that is slightly shifted from one layer to the next, shown in Fig. 8b and c, hence affecting its structural stiffness. EBM is fast and cost effective process than SLM, but the surface quality of built components is relatively uneven [27].

2.7. Self-propagating photopolymer waveguide technique

Metallic microlattices have been realized based on thiol-ene polymer templates [29]. This technique was used to produce microlattice with hollow tube, allowing for this structure to be ultralight, 0.9 mg/cm^3 [30]. Fig. 9 shows the steps involved in this technique. A template using a polymer had been created with the required repeating cell structure. The polymer starts as a liquid that hardens when ultraviolet light shines on it. A “patterned mask” which is similar to a stencil was used to shine the ultraviolet light through the open areas of the mask onto the liquid polymer, which results in hardening of the areas of liquid polymer that are exposed to the ultraviolet light. A 3D array

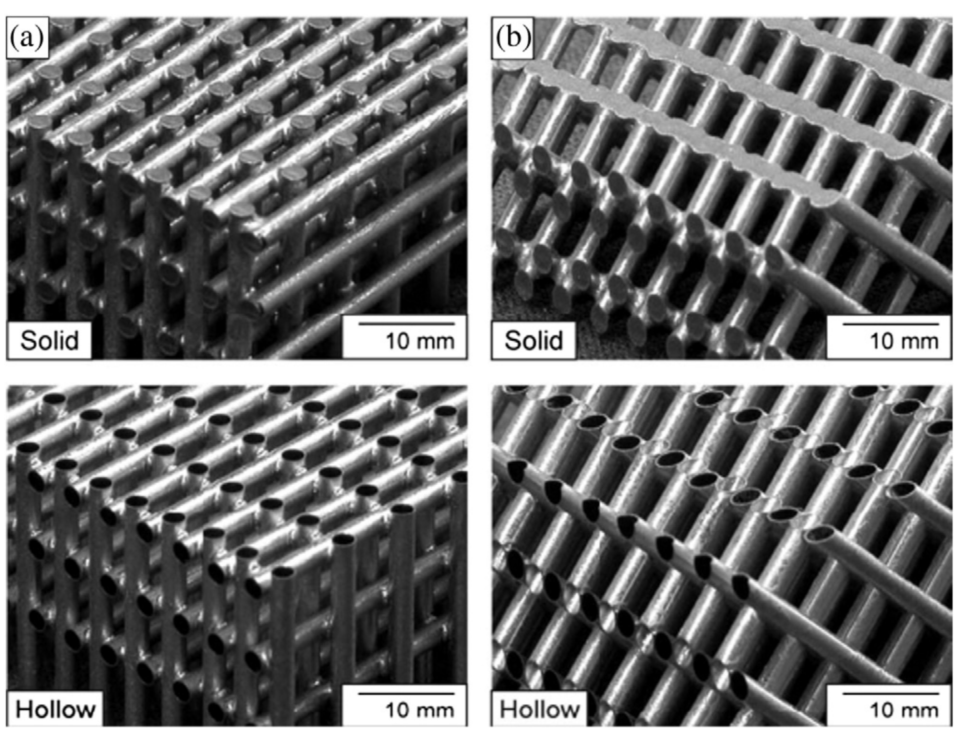


Fig. 6. Non-woven metal textiles, solid and hollow micro truss [19] — (a) square orientation (0°/90°), (b) diamond orientation (±45°).

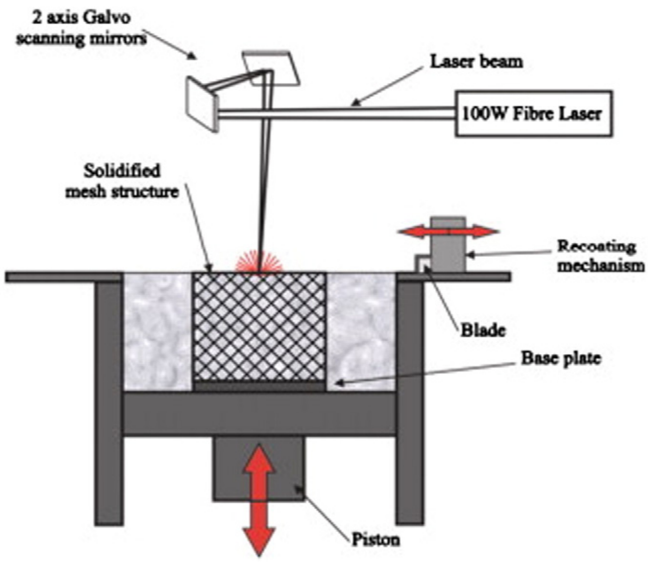


Fig. 7. Schematic of the SLM process [22].

of repeating cells were created using this technique. Later the polymer template was coated with metal, such as nickel phosphorous and finally the polymer template is removed by etching it out [31]. Microlattices with relative densities from 0.01% to 8.4% produced by this approach [32].

2.8. Discussion on production techniques

Aforementioned discussions give an overview on various methods available to manufacture periodic metallic microlattice structure. Table 1 summarizes the features of the discussed manufacturing processes, their corresponding advantages and disadvantages, and minimum observed relative density of produced microlattices. Conventional manufacturing methods of lattice materials have followed either casting in multiple steps or building by tooling approach. Nevertheless, only a small number of unit cells are possible through the core thickness as the strut size tends to be large [24]. In addition, the possible relative densities are high and the range of cell sizes is low. The methods are also unable to take advantage of topology optimization [3]. All these shortcomings can be overcome using advanced manufacturing techniques such as additive manufacturing and recent trend suggests a shift toward rapid prototyping as the primary manufacturing method of metallic microlattices. However, every method has their own strength and advantage in producing lattice structures that is suitable with different applications.

3. Mechanical properties of metallic microlattices

The mechanical properties of metallic microlattices depend on various factors such as the mechanical properties of parent material, size and shape of cell, periodicity and connectivity between cell walls or struts, type of strut i.e. solid or hollow, type of porosity, relative density of the materials etc. The ratio of the lattice density to the density of the parent material is defined as relative density (ρ^*) of the lattice structure [33]. The properties of lattice structure are strongly dependent on the manufacturing method used, as discussed in the previous sections.

3.1. Generalized stress–strain behavior

A typical general compressive behavior of cellular materials is shown in Fig. 10a. From the general compressive stress–strain curve obtained from uniaxial testing, it can be determined whether the material behavior is bending-dominated or stretch-dominated. Bending-dominated behavior is found in open-cell or stochastic materials, while stretch-dominated behavior is common in closed-cell or sometimes open-cell periodic materials. The modulus and initial yield strength of stretching dominated structures are much greater than those of bending dominated structures of the same relative density due to their different collapse modes and hence, are more weight-efficient for structural applications

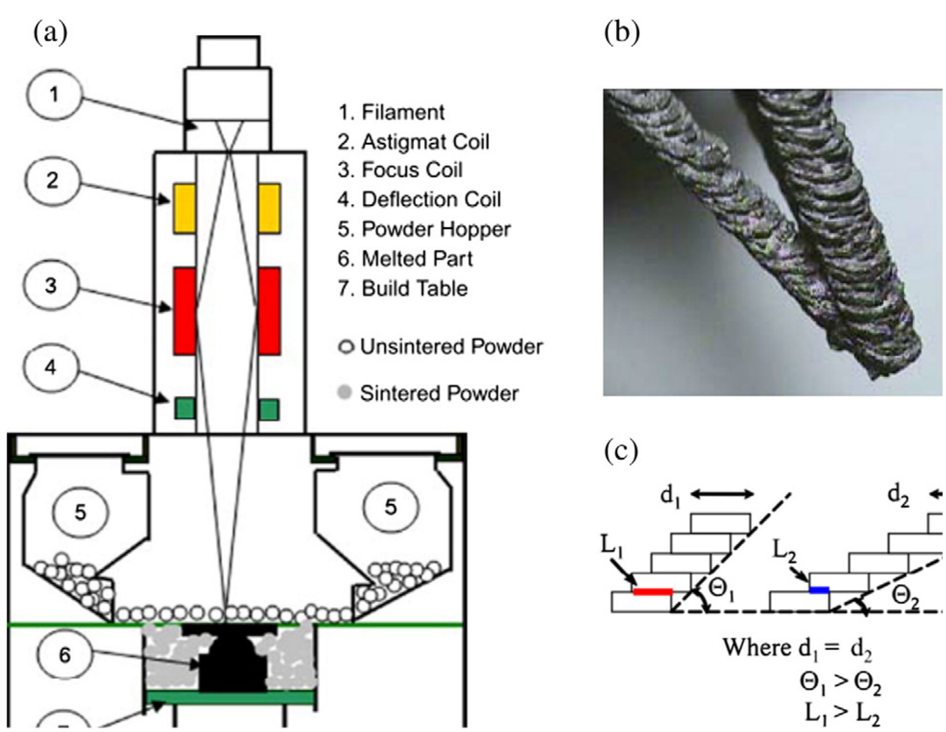


Fig. 8. (a) EBM process [28], (b) a thin beam (0.7 mm thick) manufactured at a low-angle using EBM [25,26], (c) effect of low-build angle on thin beam structure (0.1 mm layer thickness) [25,26].

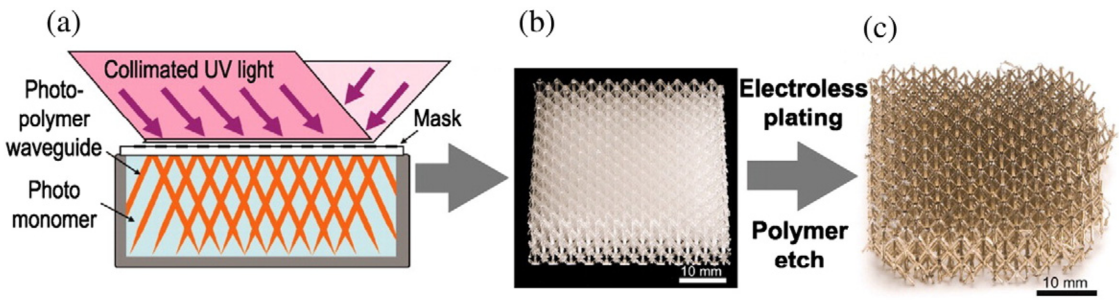


Fig. 9. Design, processing and manufactured ultralight microlattices [30] — (a) 3D array of self-propagating photopolymer waveguides used to fabricate polymer microlattice templates, (b) electroless plating of open-cellular templates with a conformal Ni–P thin film, later etch removal of the template is performed, (c) Ni–P microlattice fabricated.

[34]. Both types of structure often experience an initial settling period occurring due to broken cell edges from post processing, followed by a linear elastic region represented by the solid black lines. The bending dominated structures, represented by the dotted line, show a peak stress and failure, followed by a nearly constant plateau stress at a lowered stress level. The plateau continues as the strain increases until the relative density approaches unity and at that stage the stress level increases abruptly. The stretching dominated structures, represented by the dashed line, show failure initiation followed by linear stress increment with a slope much lower than the elastic region. Eventually the same densification process takes place and the stress increases rapidly. Deshpande et al. [13] observed that the octet-truss material produced by investment casting, are stretching-dominated comparable to corresponding properties of metallic foams. The performances of non-woven metal textiles with either solid or hollow trusses were assessed by Kooistra et al. [16] and Queheillalt and Wadley [19,35]. A similar study was carried out by Moongkhamklang et al. [36] on structures with carbon-fiber titanium composite struts. Fig. 10b shows the typical stress–strain curves from these types of structures and the form of the stress–strain curves is similar to a bending-dominated structure. The second moment of area is much greater for hollow trusses compared to solid trusses of same cross sectional area resulting in higher resistance to elastic and plastic buckling.

The compressive performance of woven metal textiles was assessed by Caulfield et al. [37] and Sypeck [8]. Stainless steel structures made from pre-crimped woven wire cloth were tested, with and without face-sheets. The structures were laminated together by transient liquid-phase bonding. Fig. 11 shows the collapse process and typical stress–strain curves of the structures, with and without face-sheets. The relative density of the core was 17%, in both cases. The response of both structures showed that the structures were stretching dominated and that the crushing response was affected by the presence or absence of the face-sheets which added constraints to the surfaces of the core causing shear-bands to form at the four corners of the specimen. This was referred to as 'global collapse'. The collapse of the structure without face-sheets was governed by local imperfections, which also caused shear bands to form, although these were not symmetrical. The structures showed potential for absorbing large amounts of energy while minimizing and controlling the stresses generated, which are key aspects of a good energy absorber. It was also observed that the linear behavior of structure produced by metal textile approach, performs better than low relative density open and closed-cell stochastic foams [8].

McKown et al. [38] investigated the performance of SLM built stainless steel octahedral, also known as Body Centered Cubic (BCC), and pillar-octahedral or BCC structure with vertical pillars (BCC-Z) having relative densities varying from 2.9% to 16.6%. Fig. 12 shows the typical stress–strain curves for the lattice structures and it is observed that the pillar-octahedral based structures (Lattices A and B) exhibited bending dominated responses, indicated by an initial peak stress. The peak for the high-density structure (Lattices A) was significantly less pronounced than the lower density structure. The response of the octahedral based structures (Lattices C and D) was also bending dominated, although there was no peak stress observed due to the stable nature of the collapse of the cell. It was reported that the pillar-octahedral geometry showing approximately 3.5 times higher yield strength compared to the octahedral geometry, at both low and high cell density. Tsopanos et al. [22] tested SLM produced stainless steel lattice structures in uniaxial compression. The lattice structures had a BCC unit cell structure with circular struts and relative densities ranging from 2.3% to 5.5%. The collapse of the structures was stable and bending dominated. It was observed that the plateau stress and elastic modulus scaled linearly with relative density.

Table 1
Comparison of metallic microlattice manufacturing processes.

Processes		Description	Features	Min. relative density, %
Conventional method	Investment casting	Truss pattern is produced by injection molding from a volatile wax or polymer, which is removed by melting or vaporization, followed by filling the empty mold with liquid metal.	Time consuming, expensive, wastage of sacrificial material, good surface quality.	2
	Deformation forming	Perforated metal sheets with hexagonal or diamond shaped holes deformed at the nodes and assembled.	Relatively faster, relatively expensive, wastage of material, good surface quality.	1.7
	Woven metal textiles	Metal wires are sewn; wire orientation can be of any angle.	Relatively faster, inexpensive, wastage of material.	10
	Non-woven metal textiles	Metals wires are layered and brazed together; limited wire orientation.	Relatively faster, inexpensive, wastage of material.	3
Advanced method	Selective laser melting	Layered metal powder is laser melted and re-solidified to produce the part; Properties governed by strut build angle.	Faster, expensive, avoids wastage of material, horizontal strut cannot be built.	-
	Electron beam melting	Similar to SLM but uses electron beam instead of laser; Properties governed by strut build angle.	Faster, expensive, surface quality is inferior than SLM.	-
	Self-propagating photopolymer waveguide technique	Array of repeating cells are formed by UV ray hardening liquid polymer, are subsequently coated with metal, and are removed from polymer template.	Faster, expensive, wastage of sacrificial material, good surface quality.	0.01

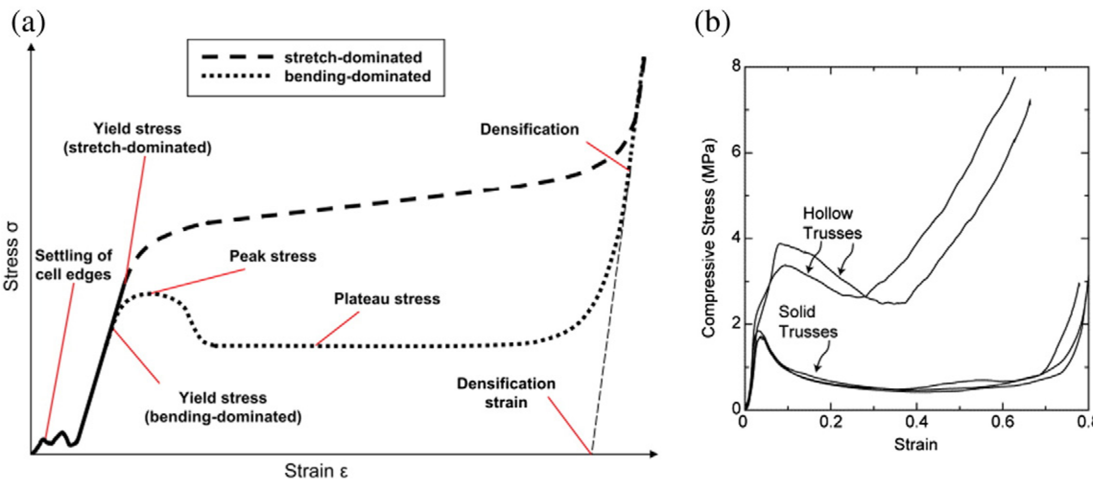


Fig. 10. (a) General compressive behavior of cellular solids [3], (b) typical stress–strain curves for pyramidal sandwich structures with solid and hollow truss [35].

3.2. Strength and collapse behavior

Fan et al. [39] studied several types of lattice truss materials with different periodic unit cells to compare the micro-failure mechanism and reported three main micro-failure mechanisms; tension yield, compression yield, and compression buckling of struts. Table 2 lists the mechanical properties of the studied 3D lattice materials. It was observed that diamond cell type is undesirable as sandwich core material since it has low uniaxial and shearing strength, and low stiffness. On the other hand, Pyramid cell type is a desirable core material for sandwich construction due to larger shearing strength than the uniaxial strength. It was suggested that the optimum design of lattice materials depend on two factors, the relative density (ρ^*), and the number and stacking order of struts. The relative density must be greater than a certain critical value for that lattice structure, otherwise the lattice structure will collapse early. According to Table 2, the arrangements of struts govern the mechanical behaviors. A uniform distribution of struts results in homogenous properties in all direction, whereas stacking the struts along a designed direction results in higher uniaxial strength and stiffness in that direction.

Mines [24] conducted review on the compressive collapse behavior for BCC, octet-truss, tetrahedral, and kagome structures in sandwich construction. It was reported that the compressive collapse of BCC cell is governed by plasticity at the strut nodal regions, tetrahedral trusses are good for plates, and octet-truss materials exhibit stretching dominated behavior but they are difficult to manufacture [12,13]. Wang et al. [14] reported that 3D kagome core produced by investment casting offers better performance than both tetrahedral and pyramidal cores, for similar core density. Moreover, the kagome core exhibits better isotropic properties and greater resistance to softening modes such as plastic buckling, over other types of lattice design. Compression and shear properties of sandwich structures with pyramidal lattice core produced from titanium alloy were investigated by Queheillalt and Wadley [40]. It was found that the stress–strain responses were similar to other lattice truss based materials during compressive and shear loading, and the peak strengths corresponded to the start of truss member buckling. The mechanism of strut failure determines the collapse strength of a lattice core, which depends on the cell geometry, material properties and failure mode of strut during loading such as plastic yielding, and elastic or plastic buckling. Doyoyo and Hu [41] studied the failure of metallic 3D warren truss lattice structure subjected to multi-axial loads. Fig. 13 shows the 3D warren truss that can be partitioned into a stretching-dominated octet-truss and a combined stretching and bending-dominated cubic truss. Parametric

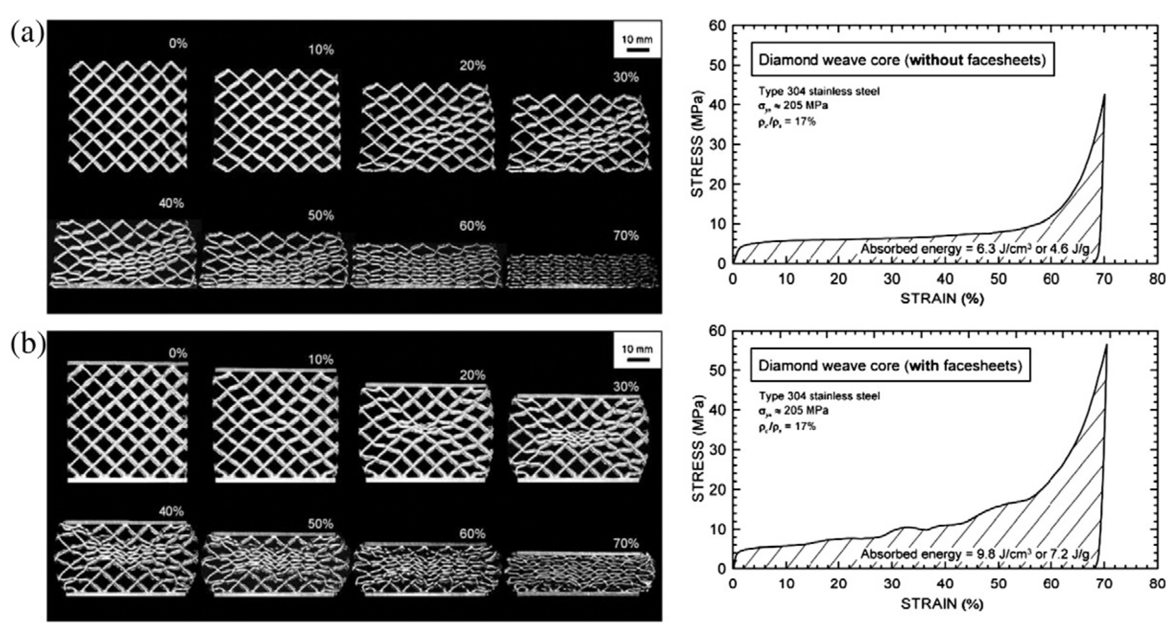


Fig. 11. Collapse process and stress–strain behavior of woven metal textiles [37] — (a) without face-sheet, (b) with face-sheet.

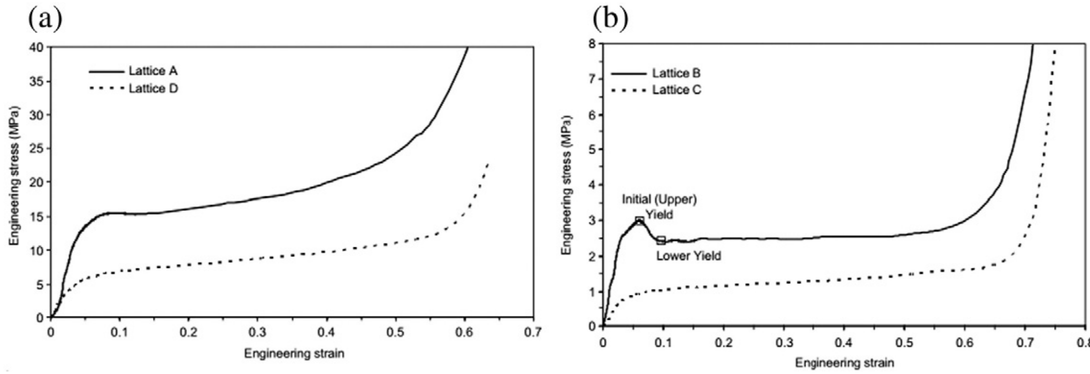


Fig. 12. Typical stress–strain curves [38] — (a) high relative density lattices A and D (13–16%); (b) low relative density lattices B and C (5–6%).

investigation was carried out on key design parameters related to the strut geometry, strut-level strengthening and slenderness ratio. The failure surfaces are found to be mainly linear for plastic yield, local and global buckling in biaxial longitudinal loading and shear-normal loading, and parabolic failure surfaces are observed for plastic yield under shear-normal loading.

Smith [11] combined variation of the compressive strength and Young's modulus of a range of cellular materials with their densities from McKown et al. [38] and Ashby et al. [42]. It was observed that of stainless steel lattice structures performed average against aluminum structures such as Alulight but this might be due to the difference in base material rather than the performance of the cell configurations. Gümrük et al. [43] compared the mechanical properties of steel microlattice structures to those of conventional cellular materials such as foam and honeycomb as shown in Fig. 14. The relative values for steel microlattice structures were obtained by dividing the experimental data by the values of parent materials. The steel microlattice structures give almost similar performance to that of metallic foams. However, it can be seen that they have low performances when compared with pyramids and honeycombs.

Shen et al. [44] tested sandwich panels with stainless steel lattice cores, under compression and bending. Similar mechanical properties were found for both the individual strands and the lattice structures after the tensile response examination of the individual lattice strands was conducted. The effect of adding face sheets to SLM built lattice structures was also investigate, which showed similar response to other cellular structures, where increased stiffness and strength was observed, due to the added constraints provided by the face sheets.

Lower density powders such as titanium and aluminum alloys can be used in SLM manufacturing but the process becomes more demanding as the laser melting process becomes more unstable with more reactive metal powder [24]. Initial work has shown the potential for titanium lattice structures in lightweight aero applications, as they compare favorably with aluminum based cellular structures, such as honeycombs and foams [45]. Brittle fracture was observed in titanium micro-struts, highlighting the need for heat treatment. The microstructure of titanium alloy lattice structures was characterized by Hasan et al. [46]. A simple heat treatment process was conducted which creates a uniform microstructure without causing excessive grain growth that would have detrimental effect on the mechanical properties. It was also pointed out that the mechanical properties of the structures may be affected by contamination of powder and this technology is not suitable for the equipment to be used with more than one powder.

Table 2
3D lattice materials and their Mechanical properties, taken from Fan et al. [39].

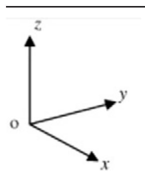
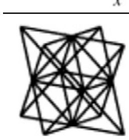
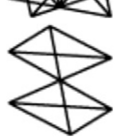
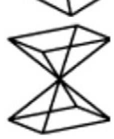
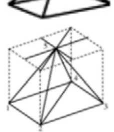
Lattice cell		Specific stiffness			Specific uniaxial strength			Specific shearing strength		
		x	y	z	x	y	z	xy	yz	zx
	Octet-truss cell	0.167 ρ^*	–	–	0.333 ρ^*	–	–	0.167 ρ^*	–	–
	Diamond cell	0.153 ρ^*	0.153 ρ^*	0.296 ρ^*	0.111 ρ^*	0.167 ρ^*	0.444 ρ^*	0.096 ρ^*	0.157 ρ^*	0.181 ρ^*
	Pyramid cell	0.15 ρ^*	0.15 ρ^*	0.2 ρ^*	0.1 ρ^*	0.1 ρ^*	0.2 ρ^*	0.2 ρ^*	0.283 ρ^*	0.283 ρ^*
	Block lattice truss cell	0.216 ρ^*	0.216 ρ^*	0.135 ρ^*	0.17 ρ^*	0.17 ρ^*	0.27 ρ^*	0.163 ρ^*	0.193 ρ^*	0.193 ρ^*

Fig. 13. 3D Warren truss formed by combination of octet-truss and cubic truss [41].

The indentation performance of SLM built lattice structures assessed by Mines et al. [47] and Shen [23]. Static penetration tests, performed on stainless steel lattice cores and sandwich panels, have shown (Fig. 15) that the SLM built structures are comparable to Alporas aluminum foam and that the performance could be further improved by changing the parent material or by optimizing the unit cell topology.

Schaedler et al. [30] investigated the compressive behavior of ultra-light metallic lattice structure by conducting multi-cycle compression test; result is shown in Fig. 16. A nearly complete recovery from strains exceeding 50% was observed in compression experiments on the as formed microlattices. Scanning Electron Microscopy (SEM) of the microlattices shows that cracks and wrinkles commenced mainly at the nodes during compression (Fig. 16g and 16h), which is responsible for the 1 to 2% residual strain observed after the first compression cycle and the drop in yield strength and modulus during subsequent compression cycles. The whole microlattice structure can deform through extensive rotations about remaining node ligaments after the formation of stable “relief cracks” at the nodes, no further fracture or plastic deformation is required because of negligible strain in the solid material. Reversible compressive behavior is observed due to this property (Fig. 16) and this deformation mechanism is facilitated by the extremely small wall thickness to diameter ratio. Excessive fracture and loss of recoverability happens with the increase of this aspect ratio (Fig. 16d). From Fig. 16a, the stress rises at strain of ~40% which is a result of increased interaction between lattice members after localized compression at the nodes. This should not be confused with densification, which in these samples occurs after the strains exceed 90% [30].

3.3. Strain rate effects

The mechanical properties, as well as the energy absorption capacity of the cellular structures increase at high strain rates. Lee et al. [48,49] investigated the response of stainless steel pyramidal truss structures under quasi-static and dynamic compressive loading. Quasi-static, intermediate strain rates and high strain rates tests were performed using a miniature loading stage, a kolsky bar apparatus and a light gas gun respectively. Compared to the quasi-static rate, an increase of approximately 50% and 130% to 190% in the peak stress was observed at intermediate (263–550 s^{-1}) and high strain rates (7257–9875 s^{-1}) respectively. The deformation of the structure was governed by a micro-inertia effect at intermediate strain rates but the inertia associated with the bending and buckling of the struts played a more significant role at high strain rates. Two factors facilitated the domination of inertia effect on the initial response of the truss core — (i) plastic wave propagation along the truss members, which delayed buckling of the member, and (ii) buckling induced lateral motion. The SLM built stainless steel lattice structures has shown a 20% increase in the yield stress from quasi-static to a strain rates of around $1 \times 10^3\ s^{-1}$ [38]. The collapse mechanisms under quasi-static and dynamic loading conditions, observed to be identical within the same type of unit cell structure. Fig. 17 shows damage mechanisms observed in sandwich panels subjected to drop weight impact tests, that is similar to the quasi-static tests (Fig. 15) [23,47].

Shen [23] also investigated the feasibility of SLM built Ti-6Al-4 V microlattice structure as the core material. Impact tests were done on sandwich panels with four different core materials, and the impact energies were normalized by their respective densities. The Ti–6Al–4V microlattice core was shown to be better than SLM stainless steel microlattice and Alporas aluminum foam core, although still outperformed by the aluminum honeycomb core. Fig. 18a shows the specific impact energy versus dent depth of four different core materials. Mines [24] identified five basic mechanisms that the core of sandwich structures undergoes during foreign object impact, (i) global elastic response, which represents the global stiffness and strength, (ii) local elastic response, which facilitates rise to skin core debonding, (iii) local crush response, which occurs during perforation, (iv) boundary response at connections or nodes, and (v) post-impact response. It was observed that graded microlattice cellular structures with finer cell nearer the skin and a coarser cell toward the center are beneficial in sandwich panels subjected to foreign object impact. The relative density of such structure varies through the thickness. Fig. 18b shows a graded lattice structure where the cell size is doubled at the center. Hasan et al. [45] also compared the impact performance of titanium lattice and aluminum honeycomb core sandwich panels. The resistance against impact of each panel was almost equal at high impact energies but the titanium lattice core showed a more localized damage area compared to the aluminum honeycomb. This is advantageous for structural applications, because damage areas to be of similar dimensions to the impactor and less replacement area needed for sandwich panels with titanium lattice core after damage occurs.

The response of cellular structures to blast and shock loading is also of interest as these types of structures are being increasingly used for blast protection [42,50]. It is beneficial to attach a faceplate having high unit weight and hardness to the front of the energy absorber as the blast impulse imparts a momentum to the faceplate accelerating it to a certain velocity with an associated kinetic energy. Heavier faceplates result in a lower velocity and hence a lower kinetic energy for the absorber to dissipate.

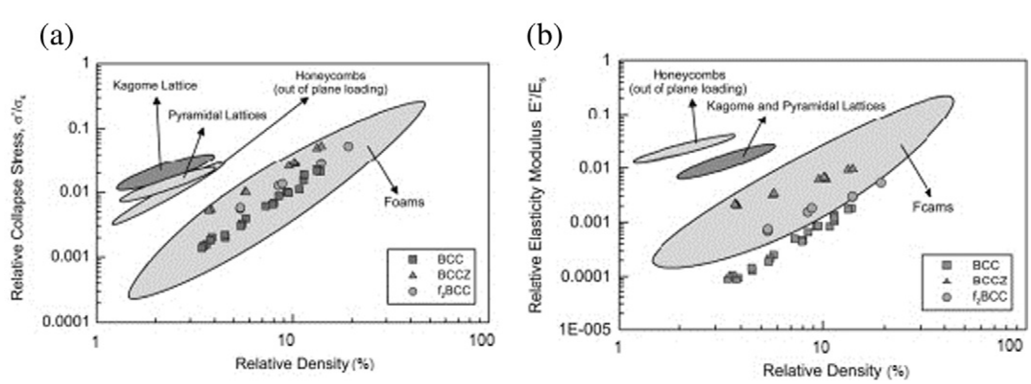


Fig. 14. Comparison of general mechanical performances of steel microlattice structures and conventional cellular materials in terms of [43] — (a) relative collapse stresses and (b) elasticity modulus versus relative density.

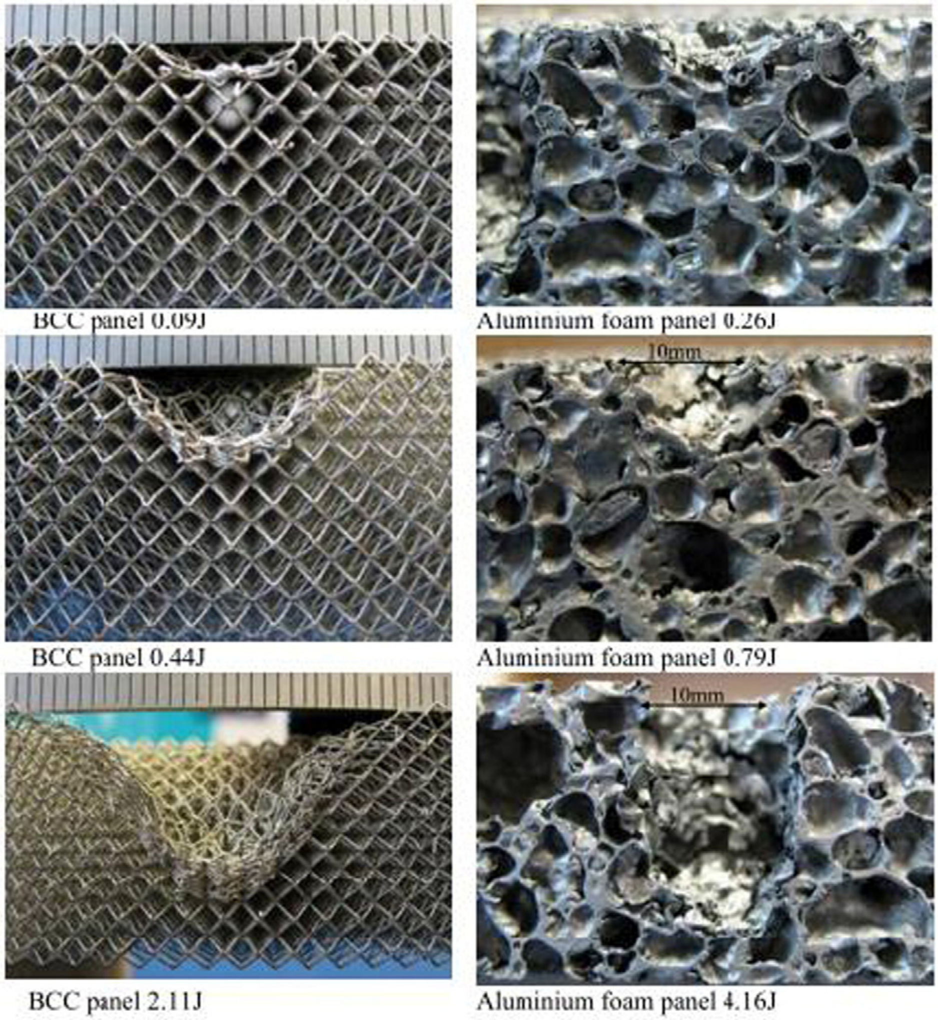


Fig. 15. Cross-sections at various penetration energies [47].

3.4. Summary on mechanical properties

Mechanical properties of metallic microlattices are affected by various factors including mechanical properties of the parent material, cell geometry and their connectivity, relative density, and the manufacturing technique. Metallic microlattices predominantly demonstrate bending dominated stress–strain response showing a significant stress plateau followed by a peak stress when subjected to uniaxial compression. Orientation of micro-struts dictates micro-failure mechanisms with pyramidal configuration being the most favored; three failure types are observed such as tension yield, compression yield and buckling of struts. Albeit limited experimental data are currently available on the behavior of metallic microlattices subjected to impact and blast loading i.e. high strain loading cases, this new class of material shows promising potential for application in high impact scenarios. High strain experimental schemes, to date, have looked at microlattices as a block but comprehensive investigation is required at the unit cell level for appropriate characterization of material response.

4. Modeling of metallic microlattices

Microlattices are not new materials, rather a new form of geometry at micro scale level. Finite element method has been used to develop several modeling approaches in recent years. Most of the modeling was done in continuum scale, which is essentially a macroscopic approach that attempts to capture the microlattice response at the macroscopic level using continuum scale. The strut members of lattice structure assumed to have uniform mechanical properties and microstructure in numerical modeling. In reality, the individual struts are subjected to variations in microstructure and defect sizes, that may affect the local properties. To overcome this, investigation of individual struts is needed to obtain individual data as input for numerical simulation analysis [1]. Lee et al. [48] simulated the response of pyramidal truss structures using finite element method, under quasi-static and dynamic compressive loading. Geometric imperfections in the trusses were introduced and strain rate effect was investigated by running simulations with and without the strain rate contribution in the Johnson-Cook constitutive model. Labeas and Sunaric [51] predicted the quasi-static response and failure of lattice core structures using linear static and nonlinear elastic–plastic FE analysis. Luxner et al. [52] predicted the linear elastic response of lattice structures using several FE modeling concepts, with different unit cell geometries. Mines [24] highlighted a problem associated with the progressive collapse modeling of large microlattice structures. With the increase of size of the lattice structure, the number of elements becomes extremely large which makes modeling of large lattice structures computationally expensive. Several other

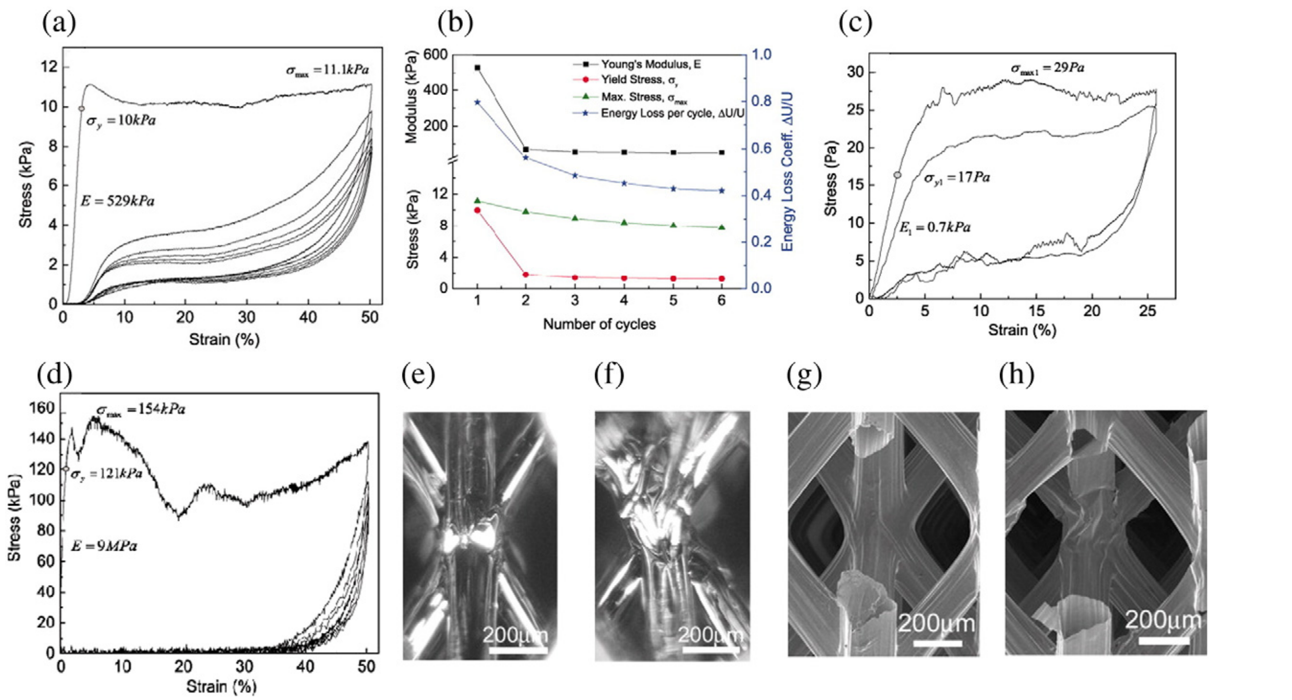


Fig. 16. Cyclic compression test of nickel microlattices [30] — (a) stress–strain curves of a microlattice (density = 14 mg/cm^3) exhibiting recoverable deformation; (b) history data during the first six compression cycles shown in (a) for Young's modulus, yield stress, maximum stress, and energy loss coefficient; (c) stress–strain curves of a microlattice (density = 1.0 mg/cm^3) exhibiting recoverable deformation; (d) stress–strain curves of a microlattice (density = 43 mg/cm^3), the response is similar to metallic cellular materials; (e) optical image of unloaded unit cell; (f) buckling of node under compression; SEM image of node — (g) before testing, (h) after six compression cycles at 50% strain.

researchers have also modeled microlattices in continuum scale [1,11, 53–59].

Aforementioned modeling approaches followed a generalized FEA approach. Models were developed using solid elements as well as beam elements but use of beam elements would offer computational efficiency. The approach consists of using an isotropic elastic–plastic constitutive model, either as a rate-dependent or as a rate-independent model. Generally, isotropic yield criterion is used and defined by uniaxial yield stress as a function of uniaxial equivalent plastic strain. Isotropic hardening is used to define the post-yield response of the material in lattice structures. An isotropic material has a yield surface that (yield stress) increases evenly in all directions as plastic strain occurs. Isotropic hardening is defined by yield stress with respect to plastic strain and is inputted in a tabular form. The value of yield stress is interpolated from the data table for any given value of strain, and remains constant when it exceeds the last given value in the table. Finally, a nonlinear FE analysis is conducted due to the presence of three sources of nonlinearity that are included in the FE models; material nonlinearity, boundary nonlinearity, and geometric nonlinearity. Material behaves linearly for smaller strains, but material nonlinearity has to be taken into account for large strain problems in post yield scenario. Strain rate dependency, temperature and material failure are also forms of material nonlinearity. Varying boundary conditions during analysis results in boundary nonlinearity, it is common in analysis involving contact. Boundary nonlinearities are extremely discontinuous; and the response of the structure changes instantaneously to a large degree when contact occurs during a simulation. Geometric nonlinearity occurs due to changes in geometry during the analysis, also affecting the response of structure. This can be caused by large translational or rotational deflections, presence of pre-stress within a structure and snap-through effects.

Nevertheless, continuum scale approaches offer a simplistic technique in materials modeling but has limitations; such as the absence of a fundamental failure criterion and the lack of capability to predict defects such as dislocations, grain boundaries etc. from the structural and dynamic point of view [60]. A number of continuum mechanical properties of materials begin to break down as sample dimensions are reduced. At small scales where sample sizes begin to approach the grain size of a material, amorphous metals exhibit ductility instead of their natural brittleness [61], single crystalline metals and ceramics demonstrate large increases in strength and polycrystalline metals show weakening effect [62]. Being small scale, microlattices may exhibit size effects on material and structural behavior. Continuum scale is also limited in replicating both structural and materials size effects in a structure.

It has been observed that continuum scale numerical simulation approach has various limitations, especially when simulating microlattices. The geometry of the lattice structures has either been drawn up in CAD software or more recently, obtained from Computed Tomography (CT) [63,64]. In both cases the internal structural defects lacks thorough attention in simulation, considering the extreme fine resolution required for the simulation of defects and failure modes investigation. To overcome these limitations, multiscale modeling approach is needed which is essentially a microscopic approach where an infinite sample reduces to a numerical problem of a unit cell with appropriate boundary conditions. It allows estimating material properties at one level by using models or information from another level. There are four different levels, and a physical phenomenon is addressed by each level over a specific window of length and time [65,66]; quantum mechanics level includes information about electrons, molecular dynamics level includes information about individual atoms, mesoscale or nanoscale level includes information about groups of atoms and molecules, continuum mechanics level includes information about classical mechanics. Simulation of microlattices in multiscale FE approach is vital to obtain accurate material response at failure. Further experimental evidences at unit cell level are required to develop reliable FE models to explore the potential application opportunities of metallic microlattice structures.

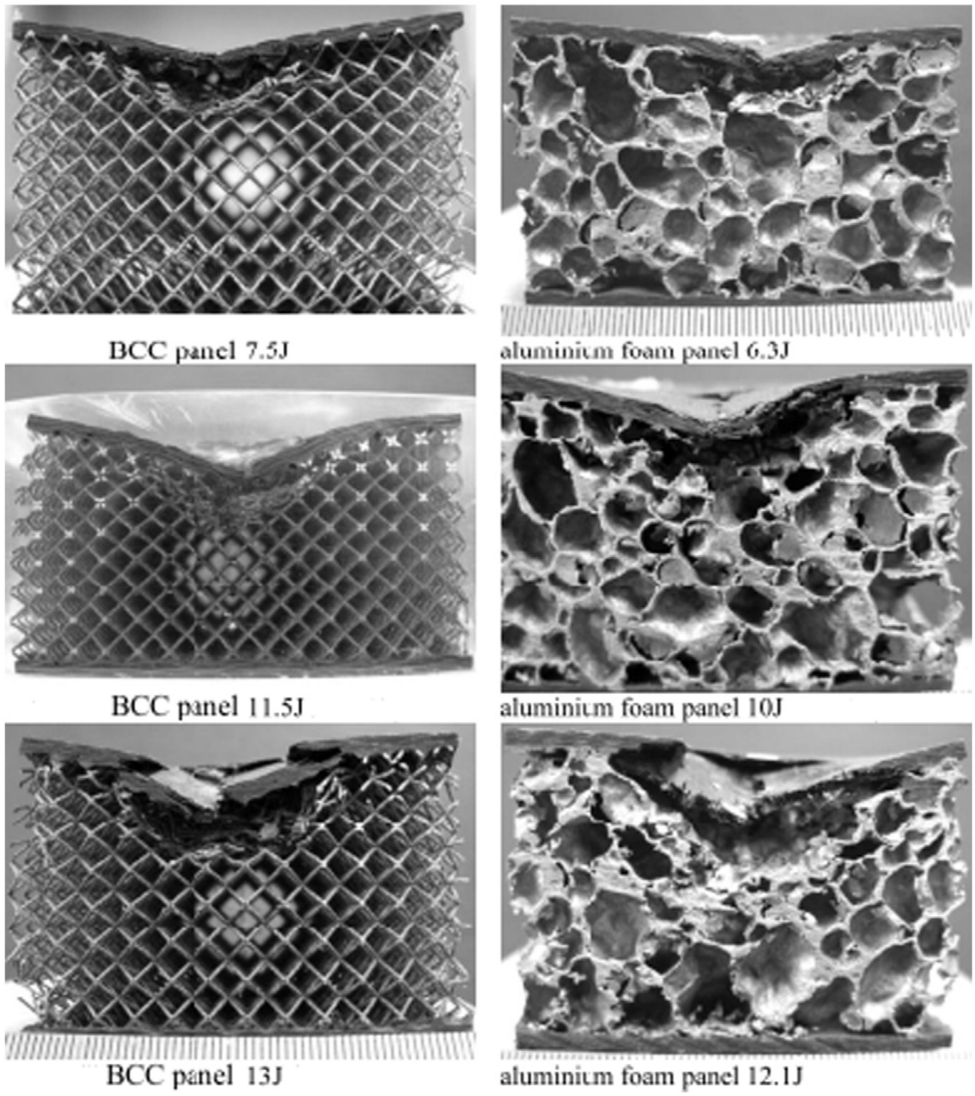


Fig. 17. Cross-sections at various impact energies [47].

5. Applications of metallic microlattices

Currently, ultralight cellular materials are being researched for applications such as thermal insulations, absorption or damping of vibration energy, sound energy, thermal energy, battery electrodes. Metallic microlattice materials hold new possibilities. They may still be used for all the current applications of an ultralight material, and perhaps other applications such as filtration and separation, supports for

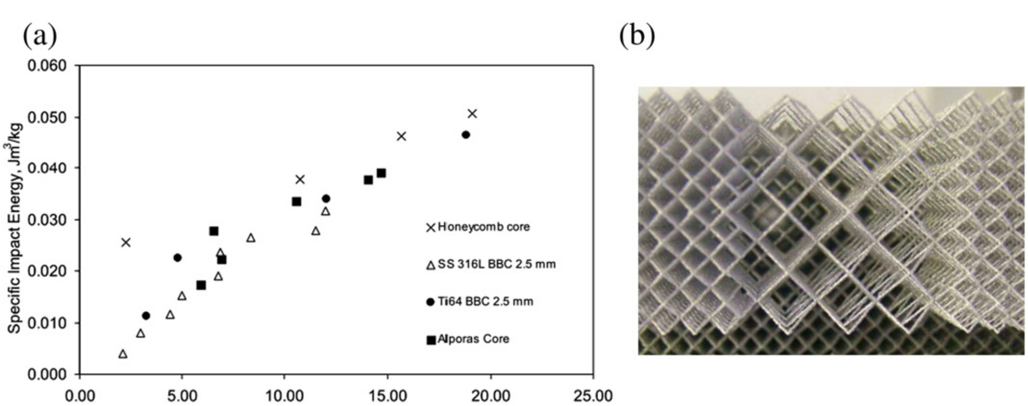


Fig. 18. (a) Comparison of performance for sandwich panels with four different types of core materials [23], (b) A graded lattice core manufactured using the SLM process [24].

catalysts, storage and transfer of liquids, fluid flow control, silencers, purification, acoustic control, flame arresters etc. Microlattices has the potential to absorb greater amount of energy [67], they are also suitable for use in spring-like energy storage devices because of the ability to return to the original state after being compressed. The automotive and aerospace industry can benefit highly from the shape regaining property in impact scenario and yet be lighter than the materials currently used. Microlattices have higher thermal and electrical conductivity, are highly structured and can handle high temperatures. These materials could be applied in aerospace structures such as satellites, space telescopes, and airplanes [31]. The following sections outline some of the potential applications offered by sandwich structures based on metallic microlattice cores.

5.1. Aerospace applications

Aerospace industries have a strong interest in lightweight structural concepts that can absorb acoustic, shock and vibration energy. Boeing 360 helicopter was partly manufactured using sandwich materials which resulted in weight saving, number of parts, tooling costs and manufacturing time reduction [68]. Microlattices can be used in sandwich construction of future aircraft fuselages and wing structures, offering higher performance per unit cost as microlattice materials are an excellent candidate to use as core material of sandwich panel construction, resulting in more weight-efficiency [23]. In general, stretching and compression without bending sandwich core topologies are the preferred types [34]. Miller et al. [69] proposed a new protection system for flight recorders where microlattice material layer protects the memory device against crash.

5.2. Automotive applications

Pingle et al. [70] argued that cellular materials are able to undergo plastic deformation within the core after the conversion of the kinetic energy of an impact event. Microlattices have excellent energy absorption capacity and this particular property is of special interest to automotive industry as it is mandatory to use energy-absorbing materials for protecting passengers from impact when designing a car or motor vehicle. It is important to keep the peak force transmitted through the structure below the limits that a human can withstand. The energy absorbing behavior of microlattices can be influenced within a certain range by varying the cell topology, alloy and relative density.

5.3. Impact and blast resistant structures

McKown et al. [38] and Smith et al. [71] investigated the collapse behavior under blast loading and found it similar to quasi-static loading conditions. Evans et al. [72] suggested a conceptual impulsive and blast load resistant structure shown in Fig. 19. Microlattices can sustain large plastic deformations at an almost constant stress level and are ideally suited for use as cores in sandwich panels or sacrificial cladding. Microlattice materials fit the definition of ideal energy absorber by having a stress–strain curve with an initial modulus and yield point followed by a long and flat plateau stress. Longer plateau stresses will absorb more energy than those reach the densification strain more quickly, for the same plateau stress level. The lattice structure collapses plastically under compression at a constant level [11,72].

5.4. Other applications

Wheeler et al. [73] suggested porous biocompatible foam to be used in dental implants. Microlattices as a variant of cellular material can be used in biomedical field as implant. Application in the medical field may have both the structural and functional purpose, which makes the case complicated. Titanium or titanium alloy microlattices can be used for biomedical implants because of their biocompatibility. Murr et al. [74] and Wauthle et al. [75] demonstrated the application of patient specific Ti–6Al–4V implants produced by EBM and SLM process respectively, both processes were also supported by Sing et al. [76] in their review on additive manufacturing of metallic implants. Microlattices have higher thermal conductivity. Open cell metal structures based on low cost aluminum or copper can be used in cooling machines and as heat exchangers. Fluids can be flown through the open celled structures while cooling or heating the structure at the same time, resulting in ability to add or remove heat [77].

6. Current issues and further work

6.1. Influence of imperfection sensitivities and parent material microstructure

A number of manufacturing processes have been highlighted, namely: investment casting, deformation forming, woven metal textiles, nonwoven metal textiles, selective laser melting, electron beam melting, and self-propagating photopolymer waveguide technique. The stiffness and strength of microlattices made using these processes will depend on the quality of the structure. This includes surface roughness, dimensional accuracy, geometric accuracy, strut imperfections, parent material microstructure and inclusions, and possible residual stresses. Investment casting depends on a pre-form, which may be 3D printed, and the surface quality will be dependent on the as cast process. Metal textiles tend to be extruded, and so should have good material structure and geometric properties. SLM and EBM are complex processes, and so will be most susceptible to imperfections in the form of inherent micro-voids due to the stacking-layered-fused nature of the metal powder [78–85], which introduces some level of anisotropy that is difficult to investigate due to stochastic nature of void distribution. Photopolymer waveguide techniques are often electro plated, and so quality should be good. From the general standpoint, surface roughness will influence Ultimate Tensile Strength (UTS) and rupture [86], dimensional and geometric accuracy will influence stress measurement from tensile tests [87], lack of integrity of struts will influence micro strut block properties

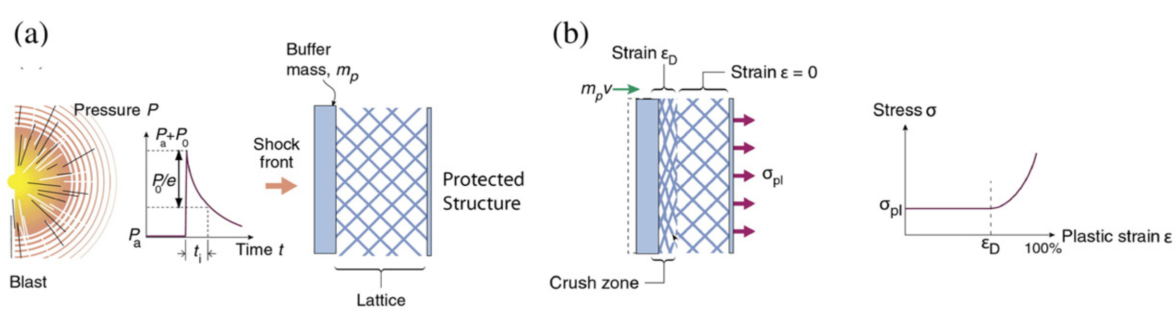


Fig. 19. Impulse and blast resistant structure [72] — (a) impulse from an air blast striking a solid buffer attached on top of a cellular medium, (b) the kinetic energy is converted to plastic deformation of the cellular medium and the resultant stress/strain response.

[88], microstructure and inclusions in parent material will affect all mechanical properties [89], as will residual stress [90]. Post processing using surface modification techniques, e.g. chemical etching and electrochemical polishing [91], or heat treatment [92], will also improve microlattice quality but will add to overall process cost.

6.2. Experimental study of microlattice structures

Fairly obviously, the structural behavior of discussed microlattice structures can be complex, especially if three dimensional progressive collapse is of interest [24]. Also, the ability to design parent material and cell topology allows the creation of structures that can be pre–specified, and hence controllable in structural response. Given the complexity of these issues, there is a need to experimentally study designed and realized microlattice structures. A number of full field experimental measurement techniques are becoming available, that include Digital Image Correlation (DIC), and Digital Volume Correlation (DVC) [93]. The latter uses micro-CT scans [94]. Important issues to address here are quality of basic CT data, which depends on scanner setup [94], as well as data conversion in DIC/DVC processing [93]. Such issues are also dependent on the parent material and size of component [94]. With these techniques, the deformation of micro strut elements can be tracked during block deformation, both on the exterior and in the interior. Gillard et al. [95] provided an up to date account of application of these techniques, and highlights the integrated use of experiment with microscale finite element analysis to fully investigate deformation behaviors.

6.3. Optimizing, tailoring and quality assuring microlattice structures

Most of the discussion in this review has concerned repetitive cell topology, with simple microlattice volumes with simple loading regimes. The next step with the technology is to develop methodologies to realize tailored and optimized lightweight structural solutions. In the context of this, additive manufacturing (SLM and EBM) have the greatest flexibility in realizing fully bespoke three dimensional solutions. Some issues here include conformal lattice structures, in which the lattice structures follow curved contours, and graded lattice structures, to fully optimize the distribution of structurally effective material. Yang and Zhao [96] reviewed additive manufacturing enabled design theory and methodology, and they discussed formal design methods for lattice structures. Given the complexity of the problem, formal optimization methods can only satisfy a restricted number of objectives, whereas a hybrid (heuristic) approach is necessary for lattice structures [96]. Interestingly, this methodology can be extended to lattice — solid optimized structures [97], and a major issue here is the behavior of the lattice solid interface [98].

As the use of microlattice structures as industrial components become more wide spread, not only is the quality of the final component of importance, but also the process used to realize the component is essential [99,100]. The latter is the difference between a laboratory based process and an industrially based process. Investment casting, deformation forming, selective laser melting, and electron beam melting, are all at a small-scale industrial level, whereas woven metal textiles, nonwoven metal textiles, and self-propagating photopolymer waveguide technique are still at the laboratory stage. It is proposed that the additive manufacturing processes of SLM and EBM have the potential to be general purpose [101], whereas the other processes are niche, e.g. ultrahigh performance (self-propagating photopolymer waveguides) or heavy structural duty (deformation forming).

7. Conclusions

An overview on the uniqueness of the metallic periodic open-cell cellular material known as microlattices compared to other cellular materials, its manufacturing and processing, mechanical properties, modeling techniques, future possible applications, current issues encountered and further work required in this field are presented in this paper. It should be noted that the manufacturing of microlattices is still a complex process and many methods are being suggested.

Key features of metallic microlattice manufacturing are:

- Additive manufacturing techniques are gaining traction as the preferred production process instead of conventional machining and tooling approaches, resulting in less wastage of material.
- The mechanical properties and quality of the metallic microlattice materials strongly depend upon the manufacturing method used and the control parameters of that method.
- Relative density of up to 0.01% can be achieved using latest additive manufacturing process.

It was reported that the progressive collapse of the lattice structures are non-optimal yet, but active research is ongoing in the analysis and optimization, with both the homogenization and the micromechanical approaches are being used. Use of multiscale modeling paradigm instead of continuum scale in simulating microlattices will be beneficial to capture the collapse behavior.

It is observed that lattice structures have predictable properties and can be used in structural applications. The quasi-static and dynamic collapse and damage behaviors are found to be of similar nature. The multiple degree hierarchical structure of microlattices go through complex deformation process of several orders which makes it suitable for energy absorption applications such as under impact and blast loading conditions.

Despite the appeal metallic microlattices hold in ultralight-weight constructions, there exist several key issues related to the internal structure of the finished part, microscale physical experimentation and quality assurance of the manufactured part. However, additive manufacturing techniques, especially SLM and EBM with the help of DIC/DVC techniques for microscale experimental observations, have the potential to become mainstream.

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