Arabian Journal for Science and Engineering (2021) 46:11587–11600
https://doi.org/10.1007/s13369-021-05992-y

REVIEW-MECHANICAL ENGINEERING

# Recent Advancements of Micro-Lattice Structures: Application, Manufacturing Methods, Mechanical Properties, Topologies and Challenges

SakshiKokil-Shah[1] · Anirban Sur[1] · Sanjay Darvekar[2] · Mohanish Shah[1]

Received: 22 November 2020 / Accepted: 1 July 2021 / Published online: 2 August 2021


**Abstract**
Micro-lattice structure is a modern concept in cellular materials, which merges valuable mechanical attributes of material with smart geometrical directions. It is light in weight and consists of high energy absorption capacity, high strength and less vibration than other cellular materials. The micro-lattice structure is another type of cellular solid's materials containing slender lattice parts known as strut and is categorized according to their cell arrangement. Due to the above properties nowadays, it is very popular for industrial applications like medical and bioengineering, aviation, automation and robotics. There are various techniques available for manufacturing micro-lattice structure. The simple, rapid and scalable fabrication of micro-lattice structure is achieved using additive manufacturing. Even geometrically intricate parts, complex assemblies can easily accommodate this lightweight technology. This paper presents an overall view of the micro-lattice structure concerning different topologies, various manufacturing methods, and different materials used. This paper also discusses how the variation of the above parameters can perk up the micro-lattices working notably, from a mechanical and application outlook. The attributes of micro-lattice structures and the foremost later finite element analysis models developed by different researchers for analyses of different properties have been also discussed here. This paper surveys the challenges confronted by various researchers and proposes future insight about micro-lattice structures required to progress their utilization in lightweight applications.

**Keywords** Lightweight structures · Additive manufacturing · Micro-lattice structure · Topologies · Materials · Application · Future aspect

## 1 Introduction

Cellular materials are porous compared to solid material. Using substantial porosity in the solid material, cellular materials are obtained. In comparison with the solid materials, better functional characteristics are possessed by cellular materials. Cellular solids containing many members of the lean lattice known as strut are classified by monotonous construction. Cellular structures also depend on boundary arrangement and loading conditions. The micro-lattice structure is another type of cellular solids materials containing slender lattice parts known as strut and is categorized according to their cell arrangement.

The micro-lattice structures are three-dimensional open-cell structure, composed of one (Fig. 1) or more repeating unit cells (Fig. 2); struts diameter dimensions are in micron. The characteristics of micro-lattice structures are mainly depending upon cells orientation; the number of cells; strut distance; material and manufacturing processes [1]. The resistance of a micro-lattice structure to the applied force is a property of its micro-construction and can be measured by the amount of stress-energy accumulated in a broad lattice after the application of force by a single member. Cellular materials developed by micro-lattice structure are not only extremely light in weight, durable, but it also has a high capacity for energy absorption and recovery.

A team constituting researchers from the University of California at Irvine, HRL Laboratories and the California

✉ Anirban Sur
anirban.sur@sitpune.edu.in

1 Symbiosis Institute of Technology, Symbiosis International (Deemed University), Pune, Maharashtra, India

2 Gaytri Vidya Parishad College of Engineering, Vishakapatnam, Andhra Pradesh, India

**Fig. 1** Micro-lattices structure with different topologies

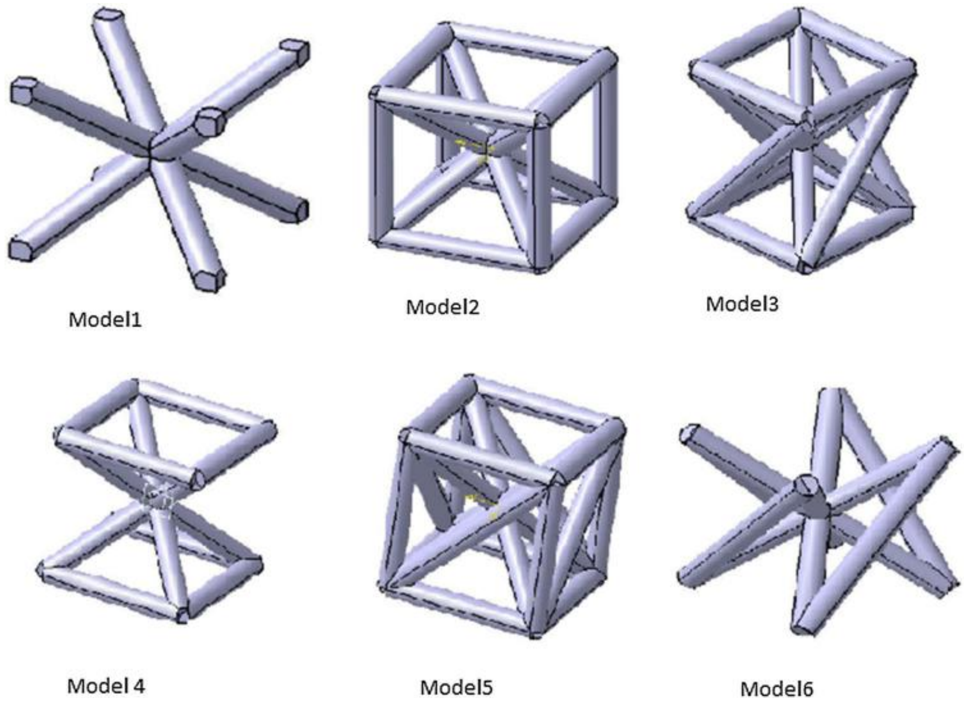
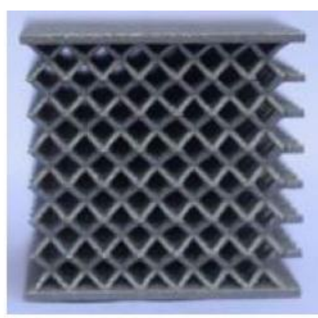
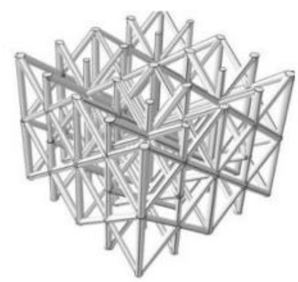


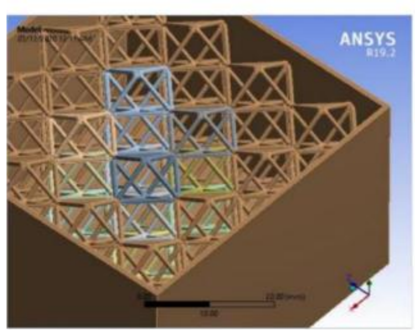

**Fig. 2** Different types of micro-lattice structure



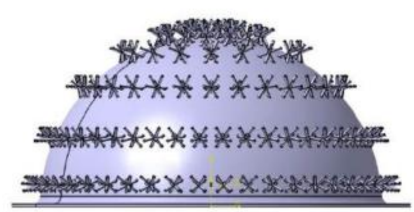
Metal Micro-lattice structure developing composing repeating BCC unit cells



Three-dimensional micro lattice structure open-cell structure, composed repeating unit cells [2]




4×4 cell micro-lattice sandwich structure



4axis BCC micro-lattice structure uses for inner cell (sandwich between inner and outer cell) of light weight helmet

Institute of Technology, are the pioneer in developing micro-lattice structure. The performance of these materials under compressive, tensile, cyclic, and impact loading is acceptable. Researchers claimed that micro-lattices structures are one of the lightest material structures [2]. For micro-lattice structure, it has been observed that changes in topology give major changes in mechanical properties. Variation in the relative density of lattice structure can be easily obtained by changing the topology, without changing the material.

Figure 1 shows different topologies (orientation of struts) of micro-lattice structures. Model 1 has 4 studs, whereas model 2 consists of 16 studs, models 3, 4, 5 have 16 studs but in a different orientation. Models 5 and 6 contain 18 studs. Researchers observed the impact strength of a micro-lattice structure depends on its microscopic construction [1].

As each of the struts can move relatively independently, without failure, the micro-lattice can obtain significant amounts of energy. This elasticity of the strut means that the micro-lattice structure can be compressed to 50 percent of its size and fully reversibly recoil back. These features make the micro-lattice a great choice for aerospace applications, such as shock absorbance, where materials need to withstand and recover from significant impacts to sustain their function. After noteworthy compression, these micro-lattices are behaviourally like elastomers and regain their shape almost entirely. The mechanical properties of metallic lattices vary according to:

- Configuration of the material.
- Cell topology,

### 1.1 Fabrication Technique

A micro-lattice structure has great potential to be used as thermal insulation; dampening of acoustics, vibration or shock; absorption and recovery of energy.

Metal lattices have the following common applications:

- Lightweight physical ideas that can absorb the energy of audition, shock and vibration
- Aerospace fuselage sandwich structure and wing structures. In general, without bending, sandwich core morphologies show elongating and compression abilities [1].
- Flight recorder protection system: a micro-lattice coating covers the crash retention device [2]
- Impact as well as blast resistant buildings
- Permeable biocompatible assemblies
- The micro-lattice sandwich (micro-lattice structure has been placed between two thin solid layers) (Fig. 2) shows center topologies without bending during extension and compression. Due to these characteristic, micro-lattice structure is very popular for industrial applications like medical and biomedical engineering (different biomedical implants), aviation, filter and silencers, automation and robotics, electrochemical devices (electrode for dry cell), heat exchangers, impact attenuator, etc. As micro-lattice structure integrates energy on contraction and regain, they are mostly used for additive, impact, and vibration reduction. Some applications (multipurpose helmet, spacecraft, gasoline engine piston pin, connecting rod) of micro-lattice structures are shown in Fig. 3.

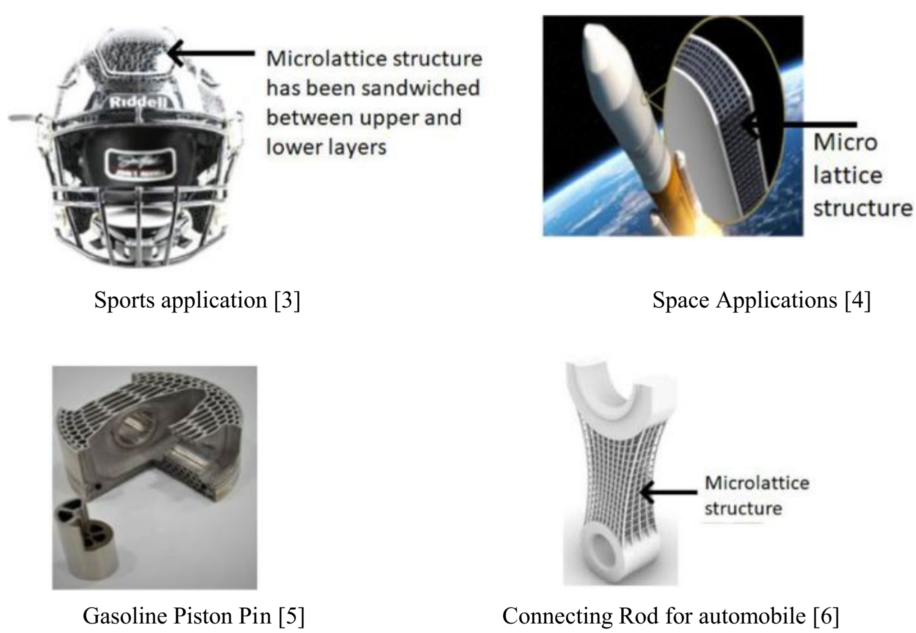



**Fig.3** Different applications of micro-lattice structure

## 2 Manufacturing Process for Developing Micro-Lattice Structures

Micro-lattice structures are three-dimensional solid structures composed of consecutively and repeatedly arranged interconnected cells. It is a porous material structure developed by interconnected struts and nodes in three-dimensional space. Developing of micro-lattice structure is not a very easy process and it is costly. In the last few years, researchers used several manufacturing techniques for developing micro-lattice structures using metal and polymers. Some conventional techniques were used by researchers like investment casting, metal sheet expansion, deformation forming process, metallic wire assembly, and snap-fit method [6] have been discussed here.

In the investment casting process, assemblies of patterns were immersed in a ceramic solution, which generated ceramic coating on the pattern. After that, patterns were dried, and de-waxing was done. The final product was obtained by removing the ceramic shell. This process has a limitation when alloys are used. In the expanded metal sheet process, solid stainless steel and hollow wires are pulled together using tools. Orientations are cluttered using a mechanism to form a lattice structure [7]. A complicated topology cannot be formed using this process.

In the snap-fitting method, the water jet cuts the desired topology of the lattice structure from the metal sheet, and then they are joined using brazing.

Due to high operational costs and huge material loss, above discussed conventional methods were not popular for commercial production for micro-lattice structure. Then researchers found that with the help of additive manufacturing, complex topologies of micro-lattice structures could be manufactured. In the deformation forming process, a laser is used to slice the mild steel sheet, and then it is stretched along the width to produce the mesh. The metal mesh is then transformed into a corrugated sheet by bending it into diamond shapes. Then the lattice was shaped by rotating shorter trusses by 120°.

Different additive manufacturing methods like selective laser sintering, selective laser melting, self-waveguide propagating technique, laminated object melting, electron beam melting have been also used by different scientists [8]. With the help of additive manufacturing processes, all types of material like polymers, metals, alloys can be used for developing micro-lattice structures [9, 10]. Complex topologies, hollow intricate parts, can be produced by those methods [11].

Researchers also proved that additive manufacturing processes are reliable, accurate, and consistent. The triply periodic minimal surface heat exchanger (shown in Fig. 3b) is exclusively manufactured using additive manufacturing and is the modern tool to optimize performance.

Table 1 shows a comparison between different additive manufacturing processes as per their application, overall efficiency, materials used, quality of finish, and requirement of post-processing.

**Table 1** Comparison between different additive manufacturing methods using for micro-lattice structure development

| Parameters | SLA (stereo lithography) | FDM (fusion deposition modelling) | SLS (selective laser sintering) | LOM (laminated object melting) |
|---|---|---|---|---|
| Material used | Semi-flexible materials, high temperature acrylonitrile butadiene styrene, Poly1500, protogen white, polylactide | Thermoplastic materials, photopolymer resin | Nylon glass-filled nylon, metals | Paper, plastic, metal |
| Finish product quality | Excellent surface finish | Standard finish | Standard finish | Wood like characteristics and can be treated similarly |
| Post processing requirement | Requires post processing to remove the support structure | Requires post processing to remove the support structure | Does not require support structure, less post processing requires | Polishing painting |
| Applications | Injection mold-like polymer prototypes; jewelry (investment casting); dental applications, hearing aids | Electrical housings; form and fit testing, jigs and fixtures, investment casting patterns | Injection mold-like prototypes, low run injection molds, medical models | Ideal for non-functional prototypes |
| Overall efficiency | accurate | Accurate | Accurate and reliable process | Slightly less dimensional accuracy |
| Finish product quality | Excellent surface finish | Standard Finish | Standard Finish | Wood like characteristics and can be treated similarly |

Figure 4 shows different types of additive manufacturing processes. In fused deposition modelling (FDM), the liquid thermoplastic material is protruded through an extrusion nozzle. This material is heated inside the extrusion head. The nozzle follows the path provided by CAD. Once the first layer is complete, the platform descends, and the process repeats. In laminated object melting (LOM), a sheet of material is supplied by roller. The desired shape provided by CAD software is cut with the help of a laser. Once the first layer is complete, the platform descends, and the process repeats.

In selective laser sintering (SLS), a bed of powder material is provided. The laser follows the desired path and that laser affected part gets solidified. Once the first layer is complete, the platform descends and the next layer is supplied by a roller mechanism.

In stereolithography, a liquid resin solution is treated using a laser beam. Laser light cures and solidifies parts it hits.

Figure 4 shows the following processes—stereolithography, fluid deposition modelling, selective laser sintering, laminated object melting. Process capabilities of the mentioned manufacturing processes are satisfactory for metals

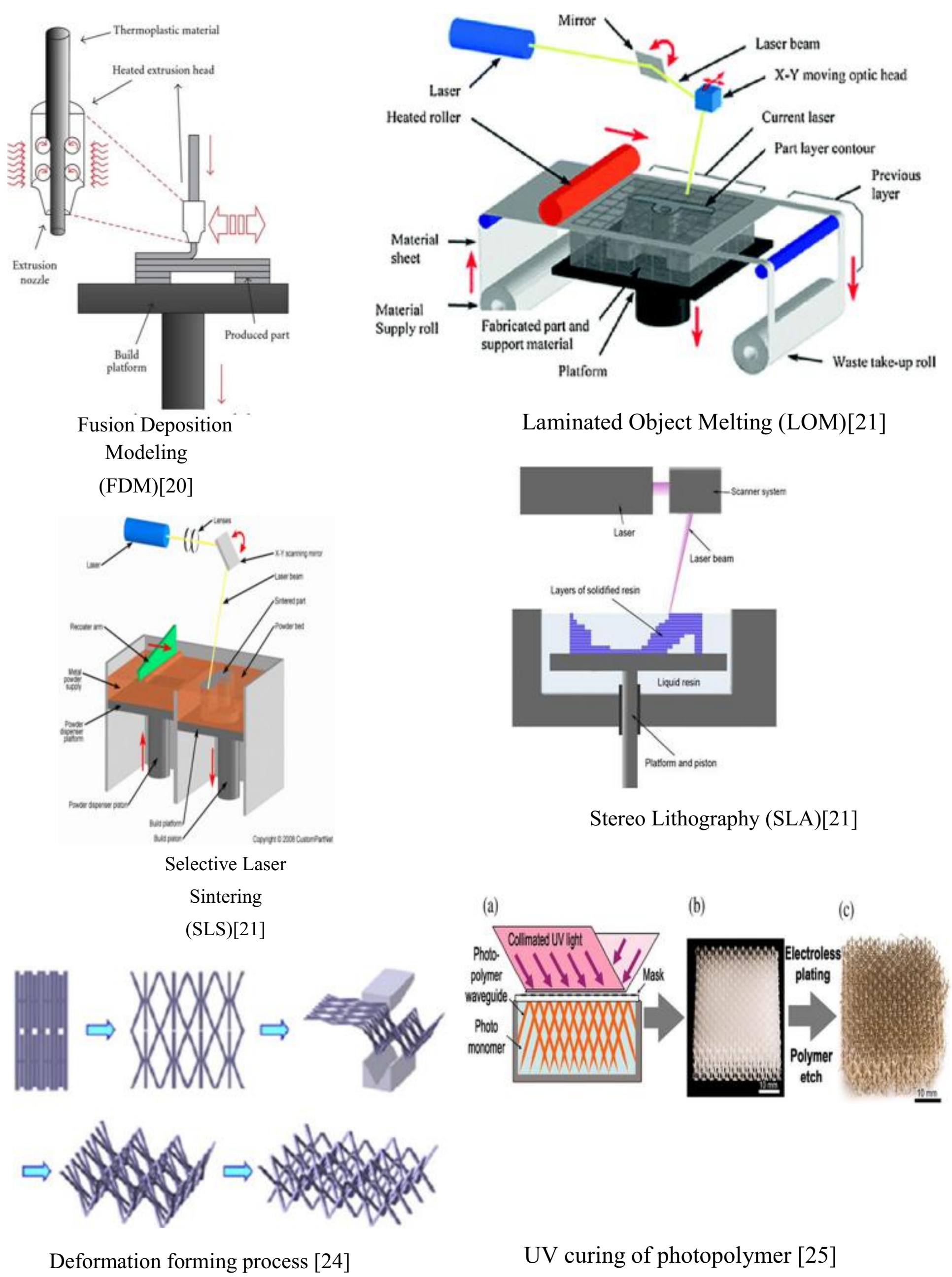



**Fig. 4** Different manufacturing processes used for micro-lattice structures development

and polymers. The polymer waveguide technique can be utilized to produce micro-lattice structures. When a pool of photo-monomer exposed to collimated UV light through a suitable photomask, polymerization begins at the exposure surface and causes the incident light to get trapped in the liquid photo-monomer. This self-trapping effect tunnels the light through the liquid photo-monomer. The self-propagating effect of the polymerized waveguides leads to the formation of lattice structures (lithography process). The choice of manufacturing process majorly depends on the type of material, the performance of the process, and applications.

Dinc Erdeniz et al. [12] presented the pack cementation procedure, which was utilized to convert Ni micro-lattice structure. It was made up using the self-waveguide propagating technique of material γ′-strengthened Ni-based super-alloys. It proposed a method based on deposition for the formation of lean layered nickel composed super-alloy micro-lattice arrangements that cannot be formed using other traditional approaches. Alloying electrodeposited Ni lattice structure with Cr, Al, and Ti enhanced their elevated capacities from a temperature point of view, and the procedure can be optimized to get constitution and microstructures within mechanical and physical characteristics.

Smith et al. [13] have observed micro-lattice structure behaviour, introducing porosity in solid elements. They showed how the additive manufacturing and rapid prototyping of lattice material on the micro-level became easy. Yong Liu [14] focused on the study of the effect of inertial stabilization, shock wave effect, and material strain rate hardening on dynamic energy absorption enhancement of electroplated Ni lattice structure. They developed a mathematical model to compute the abovementioned properties and validated them with FE analysis result.

Salari-Sharif et al. [15] reported manufacturing defects of Ni-based hollow octahedral topology micro-lattice structure using scanning electron microscopy imaging and CT scanning. They observed a reduction of compressive strength and instability of non-circular rods of a strut. They also observed the little deviation of UV rays during the manufacturing process affecting the dimensions of the micro-lattice. This indicated that by controlling the mechanized procedure of the lattice and by lessening the strut non-roundness, one can reach lattices with the best mechanical outcome.

Julia Kesslera et al. [16] investigated the limitations of the selective laser melting process. Microstructural analysis of circular struts with irregular spherical shapes was developed by them. The measured strut dimensions were less than the targeted values, and it was due to deformation in edges.

Manish Sharma et al. [17] reported studying the effectiveness of laser metal deposition of lattice on selective laser melting. The laser metal deposition method was used to make columnar and lattice samples of a 3-mm-thick medium. It successfully demonstrated that laser metal deposition can be utilized to form lattice arrangement by incorporating a columnar built-up technique by arranging spot welds.

Tuomas Riipinenan [18] carried out printing and optimization of processing parameters of high-strength H13 stainless tool steel structures manufactured by selective laser melting. The numerical model was prepared for optimization of parameters like laser power, scanning speed. The numerical analysis was found to agree with microscopic analysis. This thermomechanical model can be explored in the micro-lattice structure for mechanical characterization in the future.

Ascari et al. [19] showed how to assess characteristics of weld components manufactured by selective laser melting. The AISI 316L samples were prepared by varying laser parameters like laser power and velocity and were subjected to tensile testing. They observed that the grater ultimate tensile strength was obtained for no HT selective laser melting component than HT selective laser melting component.

Donghua Dai et al. [21] used selective laser melting and the re-melting of the formerly hardened coating utilizing the constant two layers 900 rotate scan strategy which was carried out on AlSi12 material. The impact of the re-melting performance and scan approach, precision in geometry, microstructure attribute, tensile properties, microscopic sliding manners and the rupture system are investigated under tensile loading. It stated that the shortcomings, such as the part deformation, de-lamination and cracks, were removed which improved the strength of the lattice structure.

Theresa Juarez et al. [22] focused on a detailed assessment of numerous types of coatings and their features on polymer-based micro-lattice structure using aluminium, nickel, and titanium alloys. They reported that the ultimate tensile strength for the Al-coated strut was greater as compared to other coatings. They also observed that the Ti 6Al-4 V coating increased the specific stiffness of the polymeric cellular strut, while the Inconel 600 coating improved the specific strength of the micro-lattice structure.

Carluccio et al. [23] focused on the applicability of the selective laser melting process for biodegradable materials for bone scaffold application. A bone scaffold is used in the medical field for developing damaged tissues during fatal accidents. They studied the use of biodegradable material in selective laser sintering. They reported the strength of the scaffold was dependent on various factors like porosity, the geometry of porosity, stress concentration areas, biodegradation rate. Their work can be referred for future application in the direction of application of micro-lattice structure in a scaffold.

Li et al. [24] focused on the design and development of crash-proof structure, which can sustain crash for vehicle application. They focused on the different solutions of surrogate modelling as topology optimization also found some limitations. Multi-objective optimization was taken into consideration by observing the complexity of the design of the crash-proof structure.

Wooseok Ryu et al. [25] studied the use of prosthetic hands and their challenges while designing. The author designed an efficient prosthetic hand with the optimum weight, stiffness and strength which can retain thumb and another metacarpal. To fabricate frames, nylon was used along with 3D printing. This paper can be utilized for use of lattice in the weight optimization of prosthetic hands.

The focus of the above literature was on the choice of a manufacturing process for lattice structure in consideration, process parameters of manufacturing processes, error occurred due to manufacturing process and other factors. It has been observed that the above factors also had an impact on the quality of the micro-lattice structure. The above studies indicated that while selecting the manufacturing process for lattice structure, process parameters and errors of the manufacturing process should be considered well in advance.

Nelissena et al. [29] investigated the competitiveness of various Kagome-type topology for actuation out of which double Kagome showed satisfactory performance even though all structures were close to stretch dominated.

Francesco Rosa et al. [30] investigated the feasibility of micro-lattice structure for increasing damping capacity. Lattice structure possessed BCC topology (Fig. 5c)produced by selective laser melting.

Thomas Tancogne et al. [31] modeled an elastically isotropic strut lattices in such a manner that the strut member would respond as stretched dominated. Elastically isotropic micro-lattice structures were designed by analytical method. Micro-lattice structures with topologies like face-centred cubic (FCC), body-centred cubic (BCC) and simple cubic (SC) were studied. The combinations of topologies were done in such a way that elastic isotropic property is maintained. The analytical model was validated by the FEA model at different relative densities under compressive forces. They concluded that the elastic anisotropy has no effect on micro-lattice structure. SC-BCC micro-lattice structures were found to have peak strength as compared to other topologies. The lowest peak stress was attained by the SC-FCC micro-lattice structures.

Xiaoliang Geng et al. [32] examined the collapse mechanism of the three AlSi10Mg micro-lattice structures using finite element interpretation techniques (Timoshenko beam element). Tensile tests were carried out on rhombic dodecahedron (DOD) and body-centred cubic (BCC) to obtain stress–strain curve. They observed in DOD micro-lattice structures fracture process which was influenced by crack transmission, whereas for the BCC micro-lattice structures, the rupture initiated with the development of an exclusively fracture plane leads to complete failure. The diameter of the strut showed a great effect on the stiffness of the BCC construction, while had a minute effect on DOD lattice construction. DOD grid arrangements showed less stiffness for BCC lattice construction because they possessed small force bearing ability.

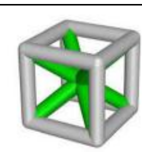
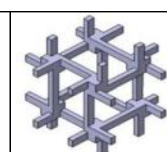
Hasan et al. [33] discovered a depth overview of grid arrangements, including aluminium, honeycombs and scaled-down truss depicting the different strategies for manufacturing.

Tankasala et al. [34] studied deformation mechanism micro-lattice structure made up of thermoplastic polyolefin with triangular, Kagome, hexagonal and diamond topologies. The flexibility of triangular and Kagome lattices was independent of the preference of average tensile strain or local tensile strain norm. It was because of the grid walls predominantly extended. On the other hand, the flexibility of the bending-dominated hexagonal and diamond lattices depends on the preference of local tensile strain or cell thickness-average collapse strain. For the average tensile strain collapse norm, the most elevated ductility was shown by the hexagonal lattice.

Mohammad Sadeq Saleh et al. [35] focused on the electrolytic capacity of a silver electrode made up of a micro-lattice structure.

Micro-lattice structure had octahedral topology manufactured using Aerosol Jet 3D printing which was compared with solid blocks. An electrochemical impedance spectroscopy trial was conducted on the micro-lattice structure and bulk unit to know about the result of micro-lattice

**Fig. 5** Different lattice Structures

| | | | | |
|---|---|---|---|---|
|  |  |  |  |  |
| a)Strut arrangement F2CCZ [25] | b)Hollow Spherical [25] | c)Modified BCC [26] | d) Octahedral lattice structure [27] | e) Open cell lattice structure [28] |

construction on the battery outcome. The result showed that the lattice electrode improved the transport of lithium ions, which substantiates the discussed result.

Sebastian et al. [36] performed relaxation experiments on two micro-lattice structures to study their outcome. Micro-lattice structures were fabricated using direct laser writing, and compression tests were carried out on both the lattices. Sebastian developed a stress relaxation experiment to learn stress relaxation in the lattice structure, to obtain time-dependent elastic modulus. Also, elastic modulus and loss factor were plotted against relative density. Lattice was meshed using ABAQUS tetrahedral elements. The stretch-dominated lattices confirmed collapse provoked by the buckling of the perpendicularly allied strut elements when the compression load was applied. Bending-dominated lattices fail chiefly at the nodes; it was the prime spot of the peak stress cohere happen.

Jianhang Shi et al. [37] elevated the quality and strength of lattice structure by using nickel and phosphorous. A different method was employed for creating a structure using composite electroplating and template etching along with rapid prototyping. By applying compressive load, mechanical attributes were investigated which indicated that the use of different integrated manufacturing methods attained elevated efficiency.

Diab W. [38] introduced a lattice structure with a completely different topology named Neovius lattice. This was a surface-based lattice structure with the absence of a node. They investigated the compressive mechanical properties of lattice structure enhanced by alumina coating. The micro-lattice structure failed due to buckling and plastic yielding in a single plane. Due to the absence of node, cause of stress concentration was eliminated.

Xiaofei Cao [39] studied manufacturing induced defect in the lattice structure. The defects in lattices were lattice thickness variation, irregular surface of lattice strut, and strut porosity manufactured using selective laser melting. The defects are studied using X-ray tomography under quasi-static compression which was validated using the FE model. The ideal FE model which was based on no geometrical defects greatly differs from the experimental analysis. As the geometrical defects are introduced, it showed that defects played an important role in the mechanical characteristics of lattice structures. Strut porosity and strut surface roughness of lattice had a direct effect on ultimate strength and a compressive modulus. On the other hand, strut thickness had a direct effect on the energy absorption capacity.

An overview of the above studies indicates that the response of different topologies majorly depends on the stacking technique of strut and nodes, type of load applied, the strength of parent element, relative density and other factors. The comparison in experimental and numerical models of lattice structure has been studied and discussed in detail. The outcome of lattice structures whether stretch dominated or bending dominated played a key role in finalizing the scope of that particular lattice arrangement under consideration.

## 3 Optimization of Topologies in the Unit Cell of Micro-Lattice Structures for Predicting Mechanical Behaviour

Researchers used different simulations tools to predict the mechanical attributes of micro-lattice structures. Table 2 shows how different simulation tools have been used by different researchers for predicting mechanical behaviour of different topologies of microparticle structure unit cell and during analysis challenges faced by them. their results for fin. Also, during simulation different changes faced by the scientist have been discussed.

## 4 Effect of Different Factors on Mechanical Behaviour of Micro-Lattice Structures

The aforementioned discussions give an overview of other factors like heat treatment processes, alloying elements, etc., which influence the strength, stiffness or structural aspect of the micro-lattice structure.

Kun Yang et al. [44] manufactured Ti6-4Al-6 V micro-lattice structure using octahedral topology by selective electron beam melting. They compared compressive characteristics of micro-lattice structure annealed at 950 o C and micro-lattice structure annealed at 1050 o C. Micro-lattice structure annealed at 950 o C undergoes fragmentation at 15–29% strain, whereas in micro-lattice structure annealed at 1050 o C, strut fragmentation was not observed even after huge densification due to presence of β-phase.

Maryam Tabatabae et al. [8] created a steel-based micro-lattice structure using the laser-powder bed fusion method. This structure was compared with bulk materials under gradually applied compressive force. The numerical model was also generated using software that was validated by experimental outcomes. The software solution found to be quite matching with mechanical outcomes.

Yan Wu et al. [45] proposed a mathematical model using the matrix displacement method to determine the stress, displacement and stiffness of the micro-lattice structure. The effect on the fracture properties of the length of each strut (L), the opening angle (θ), wall thickness (t) and the number of unit cells (N) of both types of the cellular structure was investigated with the help of a mathematical model. It was observed that the relative density was proportional to the wall thickness. The fracture energy per volume of these two structures increased when the wall thickness increased.

**Table 2** Comparison between different topologies of unicell micro-lattice structure

| Type of topologies | Major findings | Limitation |
|---|---|---|
| Octahedron | The focus was on the investigation of the role of node cross-section on the stiffness of micro-lattice structure by FEA models using ABACUS [40]. For topologies like the Octahedron, octet, tetrakaidecahedron and pyramidal micro-lattice structures with a cross-section of node like circle, square, and star were created. Compressive tests showed star-node structures demonstrated more stiffness; the square-node showed medium and circular-node structures least stiffness | Reduced-order developed to simulate the lattice structure were later modified to higher-order (r/l). This is done to minimize the deviation from the result. This model was unable to categorize response as bending or stretch dominated |
| Cuboct | Different FE solution was presented to forecast the hyper-elastic attributes of ultra-light grid structure by Maryam Tabatabaei et al. [8]. The topology of the structure was made with a combination of cubical and octahedral. T-shaped and toggle frames with nonlinear rotational connections/supports were developed to solve the newly formed structure at the Massachusetts Institute of Technology material lab | The feasibility of this model for other than cuboct structures should be verified |
| Solid, intersected, graded, scaled lattice structures | Focused on the use of topology optimization (TO) for evaluating mechanical performance of micro-lattice structure[41]. A mathematical model was generated for solid, intersected, graded, scaled and uniform lattices using TO, strain energy was obtained. The scaled cross-section structure provided inferior (58%) strain energy than the symmetrical intersected and graded lattice structures. Lattice structures that incorporated TO outcomes (i.e. intersected/graded/scaled lattices) showed significantly (40–50%) advanced specific stiffness | Topology optimization is found to help predict lattice design strategies. Design to manufacturing discrepancies was achieved in most of the lattice structure except scaled structure |
| BCC | YilunLiu et al. [42] checked the response of hollow tube micro-lattice structure due to gradually applied loading, fluctuating and impact loading. They validated the experimental and numerical response of the micro-lattice structures focused on the vertical and inclined strut. It was concluded that, by improving the thickness and radius gradient of micro-lattice structure, energy absorption can be increased | The energy absorption density of a single 900 micro-lattice strut is larger than that of the 600 micro-lattice struts. In actual practice, the vertical strut is unstable in shear mode |
| BCC+ | F.Gillard et al. [43] formulated condition to depict elastic isotropy using empirical relations. Verification for selected micro-lattice structures of different orientations had been carried out by Finite Element analysis. Changes in length and angles in various specimens are accommodated to validate results after testing | This method had shortcomings when applied to thin long tube lattices as strut buckled easily |

The relative density decreased when the opening angle increased from 30º to 90º. On the other hand, the relative density increased when the opening angle increased from 90º to 150º.

Kevin J. et al. [46, 47] investigated copper, gold, silica, parylene micro-lattices, closed-cell foams, aluminium honeycombs under compressive strength with BCC topology. Aluminium honeycombs showed greater elastic modulus as compared to other micro-lattice structures.

## 5 A. Thermal Analysis of the Micro-Lattice Structure

Thermal Analysis plays an important role in the mechanical behaviour of the microlithic structure. In applications like a lightweight thermal regulator, heat exchangers need to function at much-elevated temperature. This can affect the failure mechanism of the micro-lattice structure. In this section, importance of thermal aspects of lattice structure has been discussed.

Hao ZHOU et al. [48] proposed the design of phase changing lattice cell which is applicable in lightweight thermal regulator arrangement. It was developed by DLS with pyramid topology by using AlSi10Mg material. Compared to the thermal regulator developed by the conventional method, the lattice-based regulator has increased the thermal ability by 50%.

Jin et al. [49] focused on the investigation of the lattice with twelve quarter-octahedral topologies in the matter of attributes of thermal expansion. The author constructed a mathematical model that can calculate the thermal expansion coefficient which is dependent on the strain in the lattice structure. The strains that were calculated were found to vary in direct proportion to the alteration in temperature. During the experiment, the constructed lattice underwent negative or zero expansion in the X, Y, and Z direction along the unit cell edge when it was subjected to a change in temperature. The author found it necessary to construct the panels which could withstand thermomechanical forces without undergoing thermomechanical failure.

After discussing the above literature, it can be concluded that both mechanical and thermal properties have to be considered while analyzing lattice structure when subjected to elevated temperature.

## 6 B. Mechanical Characteristics of the Micro-Lattice Structure Under the Application of Different Types of Loads

The mechanical behaviour of lattice structures is an important aspect as the application and feasibility of lattice structure are decided by mechanical behaviour. The response of lattice structure broadly categorized into stretch-dominated and bending-dominated structure. Depending upon the response of lattice structure, applications can be finalized.

The mechanical properties of lattice structures depend on factors such as constituent material, relative density, arrangement of strut and nodes, manufacturing method used, location of stress concentration, and failure mechanism. Literature review shows that different topologies have different deformation mechanisms. This deformation mechanism mainly depended on relative density, arrangement of lattice and sometimes porosity also.

Patrick Köhnen et al. [2] tested F2CC,z and hollow lattice structure under the action of tensile load and quasi-static compressive load. Under the action of compressive loading, F2CC,z showed better performance as compared to the hollow lattice structure. The author also observed that due to z strut, F2CC,z showed stretch-dominated behaviour.

Li [6] conducted the tensile test on BCC topology made of 316L SS. Their main focus was to note Young's modulus experimentally and to study the deformation mechanism using FE model. It was observed that failure was mainly due to the concentration of stresses at the intersection of struts.

Wahyudin P et al. [36] tested the impact capacity of BCC and modified BCC structures. The modification is achieved by changing the arrangement of struts. The modification of BCC caused an increase in the capacity of impact load and gradually applied compressive load. This showed that the mechanical attributes are also influenced by the arrangement of struts and nodes.

Liang Dong et al. [7]. tested different grades of stainless steel for octahedral topology under gradually applied compressive load. The compressive stiffness and strength of 316L stainless steel were superior to that of 17-7PH stainless steel. This was because 316L showed ductile behaviour, whereas cracks were developed on the surface of 17-7PH stainless steel.

Abigail Orange et al. [50] compared auxetic, octet, BCC, octahedral topology made of Ti6Al4v under the action of quasi-static compressive test and fatigue test. Under gradually applied compressive load, the auxetic structure showed greater energy absorption capacity. Octet structure was found to have versatile characteristic as it showed greater fatigue strength and greater compressive strength.

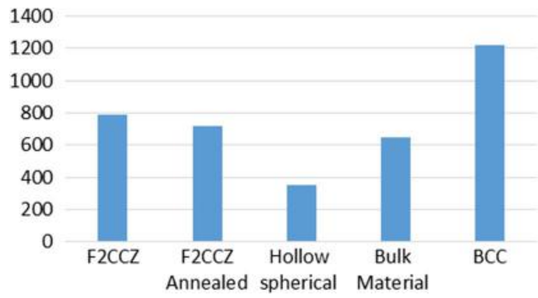



**Fig. 6** Comparison of UTS of 316L SS under Tensile load

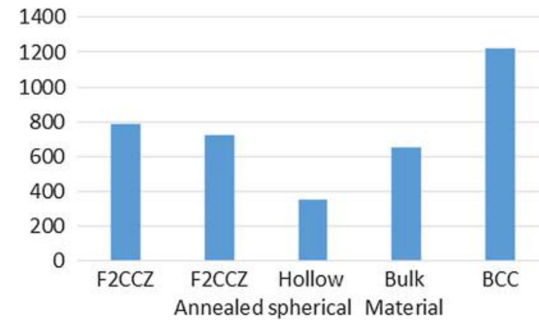



**Fig. 7** Comparison of Young's modulus of 316L SS under Tensile load

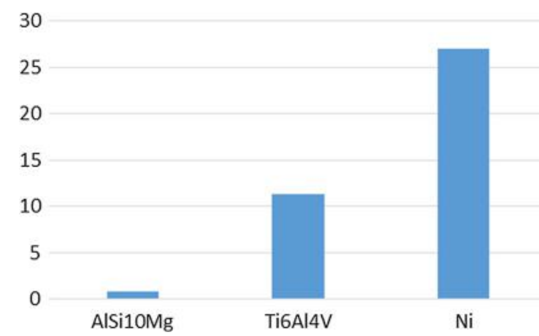



**Fig. 8** Comparison of BCC structure with different material under compressive load ( kN)

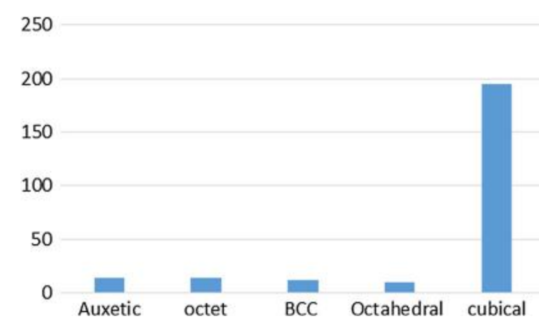



**Fig. 9** Comparison of different topology for Ti6Al4V under compressive load (kN)

Lena Huynh et al. [51] conducted tensile and fatigue test on nickel-based IN318 with BCC topology. BCC failed due to the initiation of crack at nodes. FE model confirms the result obtained by the experimental result.

Zefeng Xiao et al. [52] investigated compressive characteristics of VC, FCC and ECC topology made of 316L stainless steel. ECC due to the arrangement of struts showed higher energy absorption capacity.

Hongshuai Lei et al. [53] investigated compressive properties of multi-layer BCC, BCC-Z lattice structure made of AlSi10Mg. The focus of them was to investigate the deformation mechanism of the single- and multi-layered lattice structure. Single-layer lattices failed due to buckling of truss at the centre, whereas multi-layer lattices failed due to crushing of different layers. BCC-z had more strength due to the presence of the z strut.

Xingchen Yan et al. [54] tested compressive characteristics of Ti6Al4V lattice structure for cubical structure. They were more interested in the effect of porosity on the strength of lattice structure. They observed lesser porosity, less the chance to propagate the defect. So they concluded that the size of porosity does not affect the strength of lattice.

Chen Ling et al. [55] investigated standard grey resin and durable resin under the action of quasi-static and cyclic compressive load. In both cases, standard grey resin found to be superior to durable resin.

Chen et al. [56] investigated polymeric lattices under compressive load, at different densities. Density is found to be in direct proportion with yield strength of lattice structure.

Figures 6 and 7 show the comparison between different ultimate tensile strength and young's modulus of various topologies of 316L stainless steel respectively. Under tensile load, BCC topology was found to have more strength as compared to other topologies like F2CC,z, hollow structures. Heat treatment like annealing does not show much effect on the strength and Young's modulus of the lattice structure.

Figure 7 indicates a comparison of Young's modulus of 316L stainless steel material under compressive load. Topologies like ECC, VC, FCC and BCC were under consideration. ECC is found to have better performance as compared to VC and FCC due to ductile response.

Figure 8 shows a comparative analysis of the BCC lattice structure with different alloying elements. The addition of alloying elements like Al, Ni, Cr, V increased the compressive strength of lattices. Failure mechanisms of different lattice structures depended on alloying elements. Out of the AlSi10mg, Ti6Al4V and Ni-based IN718, Ni-based lattice structures found to have superior mechanical properties under the action of gradually applied compression load.

Figure 9 shows comparison of BCC, octet, octahedral, cubical, auxetic topologies for Ti6Al4V under gradually compressive load. Cubical is found to have superior compressive properties, whereas octet has medium compressive properties.

Figure 10 shows comparison of Young's modulus of 316L stainless steel of different topologies under compressive load. BCC structure shows highest Young's modulus.

Above figures also indicate along with the constituent material, arrangement of struts and nodes lays vital role in strength of lattice structure. Researchers also proved that various metals, polymers, alloying elements can be used for micro-lattice structure depending upon the application. Hence it can be said that the mechanical properties of lattice structures depend on many factors such as constituent material, relative density, arrangement of strut and nodes, manufacturing method used, location of stress concentration, and failure mechanism.

## 7 Conclusion

This paper gives a detailed literature review on morphology, manufacturing process, mechanical properties, materials, and challenges of the micro-lattice structure. Structural properties of lattice structures are discussed in detail under the application of static, fatigue, and impact loading. Researchers observed that morphology plays an important role in the density of lattice structure which ultimately has an impact on the mechanical attributes of the micro-lattice structure. Change in morphology leads to changes in the mechanical output of lattices. The choice of the manufacturing process and their process parameters also influence the quality of the micro-lattice structure. More porosity or manufacturing induced defects affect the mechanical and thermal characteristics of the micro-lattice structure.

Till 2016 major focus was found to be on the structural analysis using BCC topology. Investigation on the failure analysis of struts of the lattice structure was the approach adopted by researchers. Failure analysis under quasi-static compressive load, tensile, impact and fatigue load was the focus of studies.

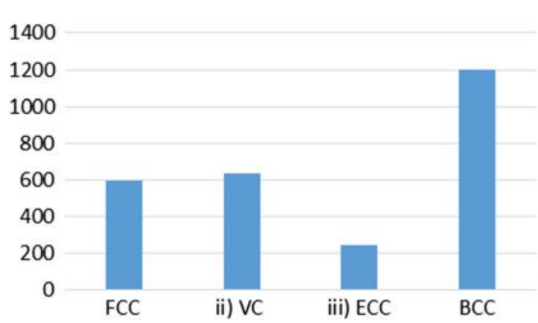



**Fig10** Comparison of Young's Modulus of 316L stainless steel material under compressive load

While carrying out the failure analysis, the effect of various loading conditions upon mechanical properties of micro-lattice structure such as yield strength, elastic modulus, energy absorption capacity under dynamic loading was explored. One of the important considerations to understand the critical nature of micro-lattice structure was the stress–strain response. Since the initial failure was observed at the nodal level, several researchers suggested various methods to improve the strength of the structure. Most researchers presented the significance of relative density on the mechanical properties of micro-lattice structures.

From 2017 onward, focus of the research was drawn towards an exploration of various other topologies such as octahedral, diamond-shaped, triangular Kagome, etc., with the intention to enhance specific mechanical properties. The research was carried out to realize the influence of relative density on the modulus of elasticity. Efforts were extended to study the effect of alloying elements, their manufacturing methods upon properties of the lattice structure. The relationship between manufacturing methods and manufacturing defects and their effect on the performance of micro-lattice structure was studied. Detailed failure analysis of unit cell along with its capacity to absorb energy and its stiffness was discussed from the point of view of its vibration isolation application.

In recent years, the study on different topologies was extended further to octet truss, F2CCz, VC, ECC, DOD, octahedral, etc. The response of advanced materials such as titanium, stainless steel with alloying elements under static, impact and dynamic loading on the performance of micro-lattice structures was further explored.

The finite element approach is a time-saving tool to locate the location and cause of the collapse of the micro-lattice structure. However, further investigation can be explored to increase the accuracy of the proposed FE model. FEA packages like ABAQUS can be utilized for predicting von Mises stresses, initiation of failure, and location of commencement of failure.

Researchers tried to refine the FE analysis with the help of new techniques such as micro-CT scan, which helps determine the modulus of elasticity and stiffness more precisely. The research was also found on certain materials like standard resin, durable resin, and alloying elements to study their effect on mechanical properties.

Further lattice structures can be explored for different structural applications. A study on the progressive failure of lattice structure is still being explored and can be studied in detail. More realistic lattice structure modelling and analysis can be done to avoid discrepancies in numerical and experimental results. Due to the versatility of lattice structure from strength and a weighted point of view, advances in the micro-lattice structure, especially in FE analysis, is the need of the era. Application-based load testing on lattice structures has the potential to become mainstream.

## References


1. Deshpande, V.S.; Fleck, N.A.; Ashby, M.F.: Effective properties of the octet-truss lattice material. J. Mech. Phys. Solids **49**(8), 1747–1769 (2001)
2. Köhnen, P.; Haase, C.; Bültmanna, J.; Ziegler, S.: Johannes Henrich Schleifenbaum, Wolfgang Bleck, "Mechanical properties and deformation behavior of additively manufactured lattice structures of stainless steel." Mater. Des. **145**, 205–217 (2018)
3. https://3dprinting.com/tips-tricks/3d-printed-lattice-structures/)
4. https://techxplore.com/news/2016-07-lattice-absorbs-vibrations.html
5. https://www.wardsauto.com/engines/iav-sees-huge-potential-3d-printed-pistons
6. Narkhede, S.; Sur, A.: Performance prediction of hollow microlattice cross-flow heat exchanger using a numerical approach. Int. J. Ambient Energy (2021). https://doi.org/10.1080/01430750.2021.1927835
7. Dong, L.; King, W.P.; Raleigh, M.; Wadley, H.N.: A microfabrication approach for making metallic mechanical metamaterials. Mater Des, **160**, 147−168 (2018)
8. Tabatabaei, M.; Atluri, S.N.: Ultra-light cellular composite materials with architected geometrical structure. Comp. Struct. **196**, 181–198 (2018)
9. QuanLaia, C.; Daraiob, C.: Highly porous MLS as ultrathin and efficient impact absorbers. Int. J. Impact Eng **120**, 138–149 (2018)
10. Clough, E.C.; Plaisted, T.A.; Eckel, Z.C.; Cante, K.; Hundley, J.M.; Schaedler, T.A.: Elastomeric microlattice impact attenuators. Matter **1**(6), 1519−1531 (2019)
11. Rosa, F.; Manzoni, S.; Casati, R.: Damping behavior of 316L lattice structures produced by selective laser melting. Mater. Des. **160**, 1010–1018 (2018)
12. Erdeniz, D.; Schaedler, T.A.; Dunand, D.C.: Deposition-based synthesis of nickel-based super-alloy MLS. ScriptaMaterialia **138**, 28–31 (2017)
13. Smith, M.: The Compressive Response of Novel Lattice Structures Subjected to Static and Dynamic Loading, PhD thesis, University of Liverpool (2012)
14. Yong Liu, Y.; Schaedler, T.A.; Chen, X.: Dynamic energy absorption characteristics of hollow MLS. Mech. Mater. **77**, 1–13 (2014)
15. Salari-Sharif, L.; Godfrey, S.W.; Tootkaboni, M.; Valdevit, L.: The effect of manufacturing defects on compressive strength of ultralight hollow microlattices: a data-driven study. Addit. Manuf., **19**, 51−61 (2018)
16. Kessler, J.; Bâlc, N.; Gebhardt, A.; Abbas, K.: Basic research on lattice structures focused on the strut shape and welding beads. Phys. Procedia **83**, 833−838 (2016)
17. Sharma, M.; Dobbelsteina, H.; Thielea, M.; Ostendorf, A.: Laser metal deposition of lattice structures by columnar built. Procedia CIRP **74**, 218–221 (2018)
18. Laakso, P.; Riipinen, T.; Laukkanen, A.; Andersson, T.; Jokinen, A.; Revuelta, A.; Ruusuvuori, K.: Optimization and simulation of SLM process for high density H13 tool steel parts. Phys. Procedia **83**, 26−35 (2016)
19. Ascari, A.; Fortunato, E.; Liverani, A.; Gamberoni, L.: Tomesani, "New Possibilities in the fabrication of hybrid components with big dimensions utilizing SLM." Phys. Procedia **83**, 839–846 (2016)
20. https://3dinsider.com/3d-printer-types/
21. Dai, D.: DongdongGu, Influence of scan strategy and molten pool configuration on microstructures and tensile properties of selective laser melting additive manufactured aluminum based part. Opt. Laser Technol. **99**, 91–100 (2018)
22. TheresaJuarez, AlmutSchroer; Schwaiger, R.; Hodge, A.M.: Evaluating sputter deposited metal coatings on 3D printed polymer micro-truss structures. Mater. Des. **140**, 442–450 (2018)
23. Carluccio, D. : Challenges and opportunities in the selective laser melting of biodegradable metals for load-bearing bone Scaffold applications. Minerals Metals Mater Soc. ASM Int. **51**, 3311−3334 (2020)
24. Schaedler, T.A.; Jacobsen, A.J.; Torrents, A.; Sorensen, A.E.; Lian, J.; Greer, J.R., et al.: Ultralight metallic microlattices. Science **334**, 962–965 (2011)
25. Ryu, W.; Choi, Y.; Choi, Y.J.; Lee, S.: Development of a lightweight prosthetic hand for patients with amputated fingers. Appl. Sci., **10**(10), 3536 (2020)
26. Patrick Köhnen, C.H.: Mechanical properties and deformation behavior of additively manufactured lattice structures of stainless steel. Mater. Des. 14 (2018)
27. source: https://www.researchgate.net
28. Liang Donga, W.P.: A micro-fabrication approach for making metallic mechanical meta-materials. Mater. Des., pp. 147–168 (2018)
29. Nelissena, W.E.D.; C. A. : Journal of mechanics and physics solids. Lattice Mater. Architect. Actuat. **2D**, 30472–30481 (2018)
30. Francesco Rosa, S.M.: Damping behavior of 316L lattice structures produced by Selective. Mater. Des., pp. 1010–1018 (2018)
31. Thomas Tancogne, D.; Mohr, D.: Elastically-isotropic truss lattice materials of re duce d plastic anisotropy. Int. J.Solids Struct. **138**, 24–39 (2018)
32. Geng, X.; Yahui, Lu.; Liu, C.; Li, W.; Yue, Z.: Fracture characteristic analysis of cellular lattice structures under tensile load. Int. J. Solids Struct. **7683**(19), 30015 (2019)
33. R. Hasan, R.M.: Comparison of the drop weight impact performance of sandwich panels with aluminiumhoneycomb and titanium alloy micro lattice cores. Appl. Mech. Mater., pp. 24–25 (2010)
34. Tankasala, H.C.; Deshpande, V.S.; Fleck, N.A.: Tensile response of elastoplastic lattices at finite strain. J. Mech. Phys. Solids **109**, 307–330 (2017)
35. SadeqSaleha, M.; LibParkbPanata, J.J.R.: 3D printed hierarchically-porous microlattice electrode materials for exceptionally high specific capacity and areal capacity lithium ion batteries. Addit. Manuf. **23**, 70–78 (2018)
36. Krödel, S.; Li, L.; Constantinescu, A.; Daraio, C.: Stress relaxation in polymeric MLS materials. Mater. Des. **130**, 433–441 (2017)
37. Shi, J.; Liu, L.: Creating hollow micro-lattice materials reinforced by carbon nano-tubes for improved mechanical properties. Mater. Lett. **240**, 205–208 (2019)
38. Abueidda, D.W.: Elhebeary, M.; Shiang, C.-S.A.; Al-Rub, R.K.A.; Jasiuk, I.M.: Compression and buckling of microarchitectured Neovius-lattice. Extreme Mech. Lett., **30059**, 1–25 (2020)
39. Cao, X.; Jiang, Y.; Zhao, T.; Wang, P.; Wang, Y.; Chen, Z.; Li, Y.; Xiao, D.; Fang, D.: Compression experiment and numerical evaluation on mechanical responses of the lattice structures with stochastic geometric defects originated from additive manufacturing. Compos. B **36513–8**, 1–31 (2020)
40. Portela, C.M.; Greer J.R.; Kochmann D.M.: Mechanical behavior of additively-manufactured polymeric octet-truss lattice structures under quasi-static and dynamic compressive loading (2019)

41. Panesara A.; Meisam Abdia, C.; Hickmana, D.; Ashcroft, I.: Strategies for functionally graded lattice structures derived using topology optimisation for Additive Manufacturing (2018)
42. Liu, Y.; Schaedler, T.A.; Jacobsen, A.J.; Chen, X :Quasi-static energy absorption of hollow MLS. Comp. Part B **67**, 39–49 (2014)
43. Gillard, F.; Boardman, R.; Mavrogordato, M.; Hollis, D.; Sinclair, I.; Pierron, F., et al.: The application of digital volume correlation (DVC) to study the micro-structural behaviour of trabecular bone during compression. J. Mech. Behav. Biomed. Mater. **29**, 480–499 (2014)
44. Yang, K.; Wang J.; Jia, L.; Yang, G.; Tang, H.; Li, Y.: Additive manufacturing of Ti-6Al-4V lattice structures with high structural integrity under large compressive deformation. J. Mater.Sci. Technol. (2018)
45. Yan Wu, L.Y.: Annual International Solid Freeform Fabrication Symposium (2018)
46. Zefeng Xiao, Y.Y.: Evaluation of topology-optimized lattice structures manufactured via selective laser melting. Mater Des, pp 27–37 (2018)
47. Maloney, K.J.; Roper, C.S.; Jacobsen, A.J.; Carter, W.B.; Valdevit, L. ; Schaedler, T.A.: MLS as architected thin films: analysis of mechanical properties and high strain elastic recovery (2013)
48. Zhou, H.; Zhang, X.; Zenga, H.; Yang, H.; Lei, H.; LI, X.; Wang, Y.: Lightweight structure of a phase-change thermal controller based on lattice cells manufactured by SLM. Chin. J. Aeronaut. (2018)
49. Jin, Z.-H.: A MSL material with negative or zero thermal expansion. Comp. Commun., pp. 48–51 (2017)
50. Abigail Orange, Y.W.: An investigation of the fatigue strength of multiple cellular structures fabricated by electron beam powder bed fusion additive manufacturing process. In: Solid Freeform Fabrication :Proceedings of the 29th Annual International (2018)
51. Huynh, L.; Rotella, J.; Sangid, M.D.: Fatigue behavior of IN718 MLS produced via additive manufacturing. Mater. Des. **105**, 278–289 (2016)
52. Zefeng Xiao, Y.Y.: Evaluation of topology-optimized lattice structures manufactured via selective laser melting. Mater. Des., pp. 27–37
53. Hongshuai Lei, C.L.: Evaluation of compressive properties of SLM fabricated multi-layer lattice structures by experimental test and μ-CT-based finite element analysis. Mater. Des. (2019)
54. Yan, X; Li, Q.; Yin, S.; Chen, Z.; Jenkins, R.; Chen, C.; Wang, J; Ma, W.Y.; Bolot, R.; Lupoi, R.; Ren, Z.; Liao, H.; Liu, M .: Mechanical and in vitro study of anisotropic Ti6Al4V lattice structure fabricated using selective laser melting. J. Alloys Compd., **782**, 209e223 (2019)
55. Ling, A.C.; Cernicchi B.A.; Gilchrist, M.D.; Cardiff, P.: Mechanical behaviour of additively-manufactured polymeric octet-truss lattice structures under quasi-static and dynamic compressive loading. Mater. Des., **162**, 106–118 (2019)
56. Chen, X.Y.; Tan H.: An effective length model for octet lattice. Int. J. Mech. Sci., pp. 279–287 (2018)
57. Sur, A.; Narkhede, S.V.; Darvekar, S.K.: Applications, manufacturing and thermal characteristics of micro-lattice structures: current state of the art. Eng. J. **23** (6), 419–431 (2019)