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Article

Applications, Manufacturing and Thermal Characteristics of Micro-Lattice Structures: Current State of the Art

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Abstract. Micro-lattice structures are emerging as multi-functional devices. They possess excellent heat transfer capabilities, energy absorption abilities, vibration control abilities, etc. The higher surface area to volume ratio of micro-lattice structures makes them suitable for heat transfer applications where compact and lightweight heat transfer mechanism is necessary such as in case of space and transportation. The heat transfer and mechanical load-bearing properties of micro-lattice structures can be tailored by altering several parameters such as the lattice strut angle, node-to-node spacing, the diameter of the strut, etc. In this paper, micro-lattice structures, their manufacturing methods, applications are reviewed and a passive heat transfer mechanism consisting of micro-lattice heat pipe is proposed for the battery thermal management system in electric vehicles.

Keywords: Multi-functional micro-lattice, additive manufacturing, heat transfer, energy absorption, light-weight structures.

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1. Introduction

Metallic micro-lattice is relatively a new material that can be utilized for multi-functional applications such as heat transfer, energy absorption, electrochemical devices etc. With the recent developments in the field of digital manufacturing processes like 3D printing, producing micro-lattice structures having dimensions in the range of micro-meters has become possible. It is possible to tailor the Mechanical properties of micro-lattice structures with various geometrical configurations. Lattice members are arranged in particular order called as stacking order. Parameters such as relative density, lattice stacking order, size and shape of unit cell, mechanical properties of parent material are the key design variables to impart mechanical properties to the material [1]. Micro-lattice structures are of two type i.e. Open cellular and Closed cellular. Open cellular structures are suitable for heat exchanger applications where higher fluid flow rates are desired and closed cellular structures are suitable for structural applications such as energy absorption. Various processes have been developed to manufacture micro-lattice materials such as Additive manufacturing (3D printing, Selective Laser Melting (SLM), Electron Beam Melting (EBM)), Rapid prototyping, woven metal lattices, non-woven metal lattices, self-propagating photopolymer waveguides, etc [2].

2. Materials

Pyramidal micro lattice structures of low density made from carbon fibre reinforced composites by laser beam cutting have been recently developed which are shown in Fig. 1 and a truss core formed by spreading the pyramidal unit cell in two directions is shown in Fig. 2. The applications/multi-functionality of these periodic structures can be found in reinforcing components for extreme light weight construction and obtaining protection from explosion [3]. These lattice structures can be manufactured by processes like hot press moulding, interlocking and textile techniques. Investigations show that these low-density structures exhibit higher compressive strength to their precursor [3].

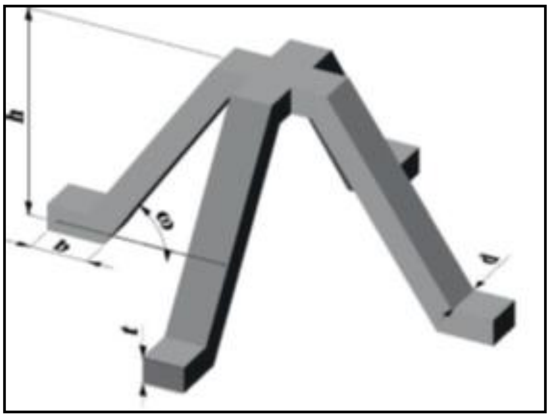

Fig. 1. Sketch of Pyramidal unit cell [3].

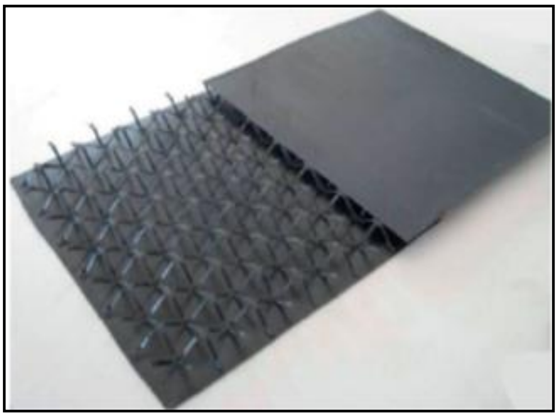

Fig. 2. Sketch of Pyramidal unit cell truss core [3].

Another material for light weight structures is polymer micro-lattice. To manufacture a polymer micro lattice, a liquid photopolymer reservoir is exposed to UV light through a 3D mask which results in an array of self-propagating waveguides forming a polymer lattice structure. With this process, fabrication of ordered open cellular materials is possible which can be compared with stochastic micro-scale foams. For multi-functional applications, Micro-lattice structures made up of carbon fibre are desired because optimization is possible for applications like internal fluid transport and simultaneous mechanical load bearing. This ability is highly necessary for applications involving heat transfer phenomena [4].

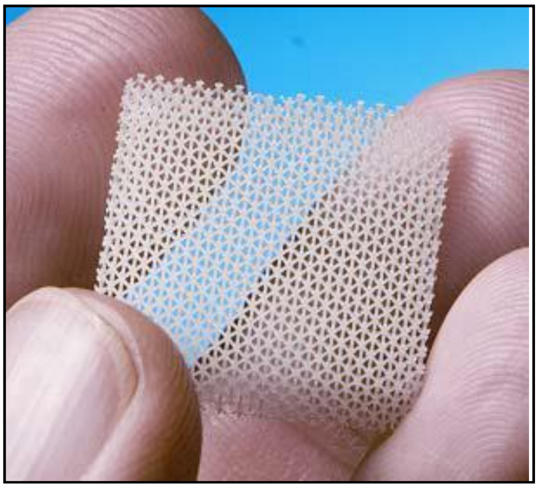

Fig. 3. Polymer Micro-lattice structure formed by self-propagating waveguides technique [4].

In addition to carbon fibre reinforced composites and polymers, different metals have been tested by researchers to manufacture micro lattice materials for ultra-light weight applications. Researchers have studied and investigated mechanical properties, crushing behaviours, and impact behaviour of stainless-steel micro-lattices manufactured by SLM [5]. To enhance the compression stiffness and strength properties of SLM stainless steel micro-lattice, it is coated with Ni-P. But authors have not specified the effect of coating thickness on the mechanical properties of the micro-lattice material. Coating can give number of multi-functional properties to the micro-lattice such as corrosion resistance, wear resistance, and improved structural performance.

Ti-6Al-4V Metal is another metal used for fabrication of metallic micro-lattice. It shows highest structural performance as compared to stainless steel as the specific strength of its parent material is higher than stainless steel [6]. Because of highly reactive nature of Ti-6Al-4V powder, it becomes difficult to process it. As a result, variation in the final micro-lattice structure can be seen. Computerised X-ray method is used to quantify morphological properties of micro-lattice like, porosity, pore size, strut size, interconnectivity, surface area which result in improved mechanical properties of Ti-6Al-4V micro-lattice [7].

Like SLM, attempts have been made to manufacture metallic micro-lattices with similar process called Electron beam melting (EBM). Working of EBM process is similar to that of SLM process, but unlike the use of a laser in SLM, EBM uses an electron beam that is generated by heating a tungsten filament as a power source which melt layers of the powder. But in EBM preheating of the base metal plate and powder is required before scanning the electron beam. Structural performance of micro-lattice structures manufactured using EBM is sometimes poor than that of micro-lattice structures manufactured using SLM, because of slight shifting of beams from one layer to another [8].

Alloys such as Nickel can be used to manufacture metallic micro-lattice structures by electroplating nickel on a polymer based micro-lattice structure obtained from self-intersecting photopolymer waveguides described earlier. These Nickel based micro-lattice structures were first manufactured at HRL (Hughes Research Labs) laboratories, Malibu, California. Compression experiments were carried out on micro-lattice samples to measure Young's modulus and strength, and density scaling is determined [9].

Not much consideration has been given in to develop cellular materials made up of Magnesium alloys. [10] Manufactured and investigated magnesium alloy micro-truss structures and found that they exhibit higher structural efficiency when compared to Magnesium foams because of their stretch dominated nature. Because of Magnesium's lower density, lower latent heat and lower heat capacity, lot of difficulties needs to be faced while casting Mg micro-truss structures by modified lost foam casting process [11].

3. Methods of Manufacturing Micro- Lattice Structures

In past few years, number of methods have been developed to manufacture micro-lattice structures. The potential methods are discussed in the following section.

3.1. Additive Manufacturing

Additive manufacturing offers several benefits such as design freedom, minimization of the waste, manufacturability of complex structures. Applications of the components manufactured using additive manufacturing processes include aerospace, automobile, biomedical, protective structures etc. It offers wide range of material selection such as polymers, ceramics, concrete, and metals and metal alloys [12].

3.1.1. Stereolithography

Stereolithography is an additive fabrication process which allows manufacturing of parts from CAD data. It is based on the principle of photo-polymerization of liquid resin by controlled solidification to fabricate 3D objects. A computer-controlled laser beam illuminates a pattern on the surface of resin. Because of this, the resin gets solidified in the shape of the pattern and up to the specified depth. This solidified pattern gets adhered to the support platform [13].

3.1.2. Selective laser melting

Selective laser melting (SLM) is a type of powder bed fusion technique and is commonly used in industry. Metal powder is melted and fused together by utilizing the laser power. Melting and fusing operation is done with the help of CAD data input [14-16]. To fabricate a part without any imperfections or defects, several process parameters have to be adjusted which have been explored in literature. Laser power, laser scan speed, hatch speed, hatch overlaps, hatch style etc. are the parameters which have significant effect on mechanical assets of the manufactured parts [17-19].

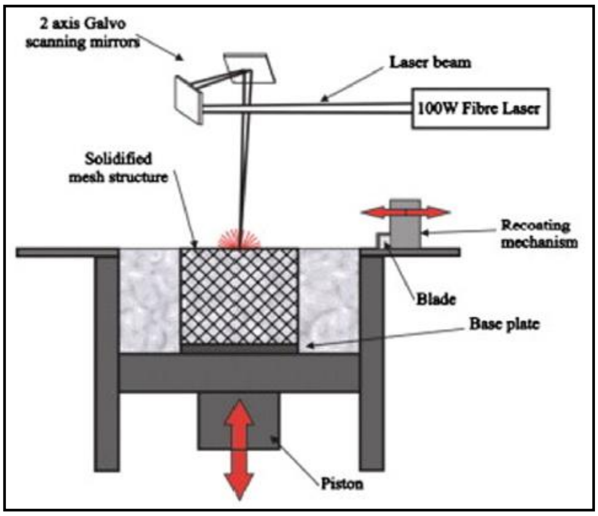

Fig. 4. Schematic of SLM process [20].

SLM is the most versatile process as it has the ability to process a large variety of materials such as Al-based alloys, Ti-based alloys, Fe-based alloys, Cu-based alloys, Co-based alloys, and Ni-based alloys as well as their composites. Also, SLM has the ability to produce amorphous materials [21]. While processing high temperature and brittle materials, substrate plate is generally heated for the sake of reducing the cooling rate to avoid the chance of cracking during solidification [21].

3.1.3. Electron beam melting

Electron beam melting also known as EBM is similar to that of SLM process explained above with some differences. Unlike laser beam, use of an electron beam is made to melt and fuse the powder. Optimization of process parameters is more difficult in EBM as compared to SLM as the EBM process contains a greater number of process parameters than that of SLM process. This is the reason why only limited number of materials can be processed with EBM. The slower nature of EBM process makes the parts more expensive.

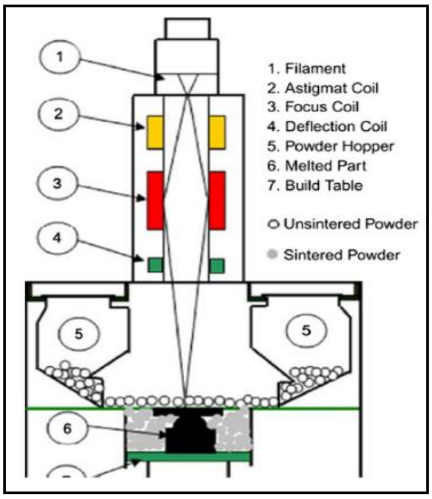

Fig. 5. Schematic of EBM process [22].

While manufacturing lattice structures with EBM, unit cell size is limited that is the smaller sized cells cannot be manufactured. Brittle materials that SLM cannot process can be processed with EBM. Powder bed temperature is suitably chosen, to avoid solidification cracks in brittle materials [21].

3.1.4. Multi jet fusion

Multi jet fusion (MJF) can build parts with high dimensional accuracy, high quality, functionality that to at much faster rates than SLM and EBM processes discussed above. Unlike other 3D printing techniques, mechanical properties of parts manufactured by Multi jet fusion process doesn't depend on the build orientation that is they are isotropic in nature [23]. A self-explanatory schematic of MJF process is shown in Fig. 6, which explains the building process, application of fusing agent, detailing agent and fusing energy and how the reactions between agents and materials takes place to selectively fuse and lead to formation of the part.

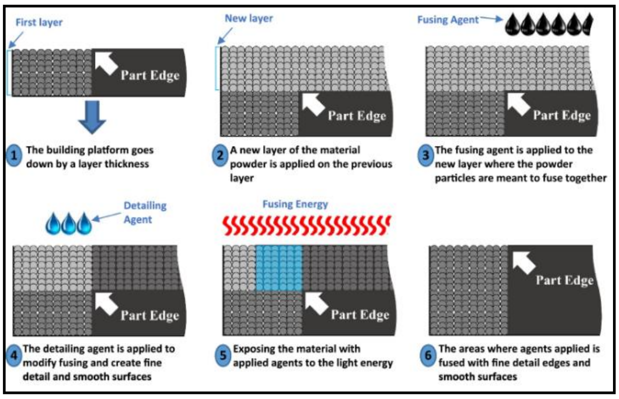

Fig. 6. Schematic of Multi-jet fusion process [23].

3.2. Wire-Woven Cellular Metals

Wire woven metals are manufactured using metal wires as raw material as shown in Fig. 7. When metal wires are woven in cellular fashion as 3D truss elements, it forms wire woven material. To achieve multi-layered fine cell lattice structures, wire woven materials are a practical choice. They are generally classified as Single layered wire woven metals which are used in sandwich panels as low-density cores and Multi-layered wire woven which are used in applications such as vibration and sound damping, to provide buckling resistance and their high surface area makes them suitable for their use in heat transfer applications [24].

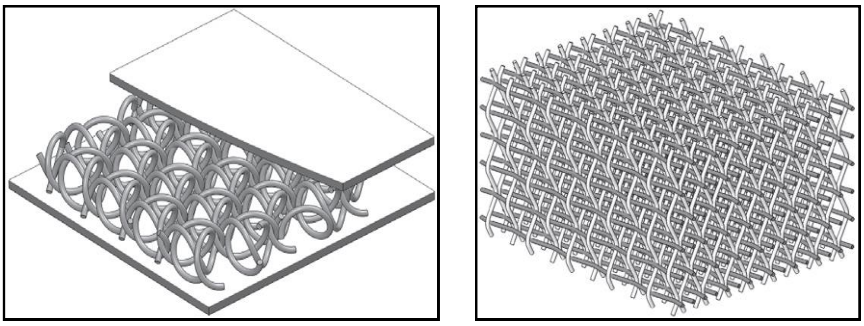

Fig. 7. Schematic of Single layered circular spring kagome and multi-layered woven metal [24].

3.3. Self-Propagating Photopolymer Waveguide

Self-propagating photopolymer waveguide is relatively a new technique to manufacture micro-lattice structures. It is developed by a team of scientists at HRL Laboratories, California. A lattice structure is created by 3D array of interconnected self-penetrating photopolymer waveguides. The lattice structure is formed by exposing a pool of liquid photo monomer to a collimated UV light through a two-dimensional mask having circular apertures. By changing the mask pattern as square, hexagonal distinctive unit cell architectures with different symmetry are possible. Amongst all the rapid prototyping processes, this process of manufacturing ordered open cellular structures with micro-lattice feature is the fastest of all and it is dependent on single two-dimensional mask through which the liquid monomer is exposed to the UV light. The schematic of the process is shown in Fig. 8 in the next section [4].

4. Thermal Applications of Micro-Lattice Structures

4.1. Micro-Lattice Heat Exchangers

Micro-lattice structures offer higher area density. This makes them suitable for use in heat transfer applications such as heat exchangers, heat sinks, and thermal storage devices etc. Scientists at HRL laboratories, California developed a process called self-propagating photopolymer waveguides for the fabrication of micro-lattice structures [4]. Figure 8 shows the schematic of the process used for manufacturing polymer lattice structures. These structures were utilized to make a cross flow micro heat exchanger. By electroplating the outer periphery of polymer struts and itching out the polymer structure lead to hollow micro-lattice structure. Compact arrangement of hollow micro-strut elements leads to enhanced heat transfer as area density increases. It has been claimed that the process is faster and accurate than LIGA and serial micro-milling techniques for manufacturing micro-lattice structures. Micro-lattice heat exchangers manufactured using the technique mentioned above are tested under compression and reported to be excellent energy absorbers and justify their multi-functional ability [25].

4.2. Micro-Lattice Structures as Heat Dissipation Media

Micro-lattice sandwich panel truss cores having higher area density are useful where simultaneous heat dissipation and structural support is desirable. Such structures are also known as lattice frame materials. Convective heat dissipation and pressure drop characteristics of compact heat sink made up of aluminium lattice frame material of triangular topology are investigated [27]. It is reported that orientation of LFM has strong influence on the pressure drop which is because of anisotropy of the structure which causes flow blockage effects. Heat removal with LFM is about six to seven times that of empty channel. [28] Studied LFM with tetrahedral ligament configuration to assess the effect of porosity by changing the ligament diameter. Overall surface efficiency is calculated by applying analogy of cylindrical fins, as LFMs exhibits similar thermal characteristics as that of cylindrical fins. 3D woven lattices possess the potential for higher thermal performance because of their higher specific areas, higher thermal conductivity of the wire material, and periodic structure of weave. Thermal and hydraulic performance of 3D weaves can be tailored by changing flow patterns like axial, full bifurcated, focus bifurcated and selecting the configuration of weaves as standard or topology optimized.

Table 1. Summary of manufacturing processes for producing micro-lattice structures.

Process	Explanation	Features	Minimum feature size
Stereo-lithography [13]	Photopolymerization of liquid resin with the help of laser beam through controlled solidification	Comparatively Faster process as that of conventional process, prototypes are strong enough to undergo machining; costly process, careful handling of photopolymer is required	10 μm
Selective laser melting [14-19, 21]	Metal or polymer powder is spread in layers and is selectively melted as per input from CAD file with the help of a laser beam and resolidified; strut build angle has strong influence on properties of structure	To optimize the process, limited number of parameters are to be considered; capable of processing large number of metal powders	40 - 200 μm
Electron beam melting [21]	Similar operation to that of SLM but the laser beam is replaced by an electron beam, capable of processing brittle materials.	Process parameters are difficult to optimize as the process involves a greater number of parameters; only a limited number of material powders can be processed; relatively fast and cost effective than SLM but surface quality is inferior than SLM	100 μm
Multi Jet Fusion [23]	A bed of nylon powder is selectively applied with fusing and detailing agents with the help of inkjet array; which are then fused together in solid layers by heating elements.	Offers high dimensional accuracy, high quality surface finish without post-processing, Properties of parts build doesn't depend upon build orientation; parts are isotropic in nature.	500 μm
Wire Woven Metals [24]	Metal wires are used as raw material and are woven in different fashion, wires can be oriented at any angle	Offers high surface area and hence suitable for heat transfer and energy absorption applications; inexpensive process, single layer and multi-layers are possible	NA
Self-propagating photo-polymer waveguides [4]	A pool of liquid monomer is exposed to Collimated UV light through 2D dimensional mask having specific apertures	Relatively new to all the manufacturing processes, faster than all the rapid prototyping processes,	10 μm

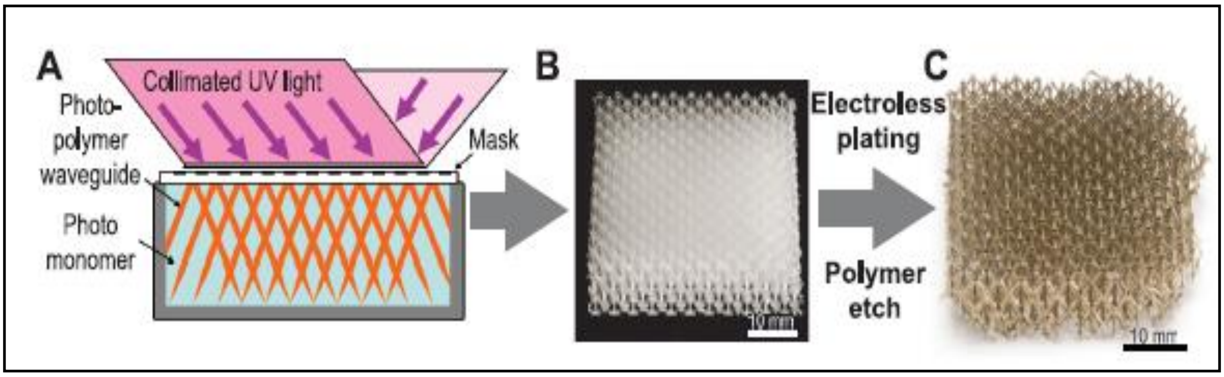

Fig. 8. Schematic of the process for manufacturing nickel plated lattice structures [26].

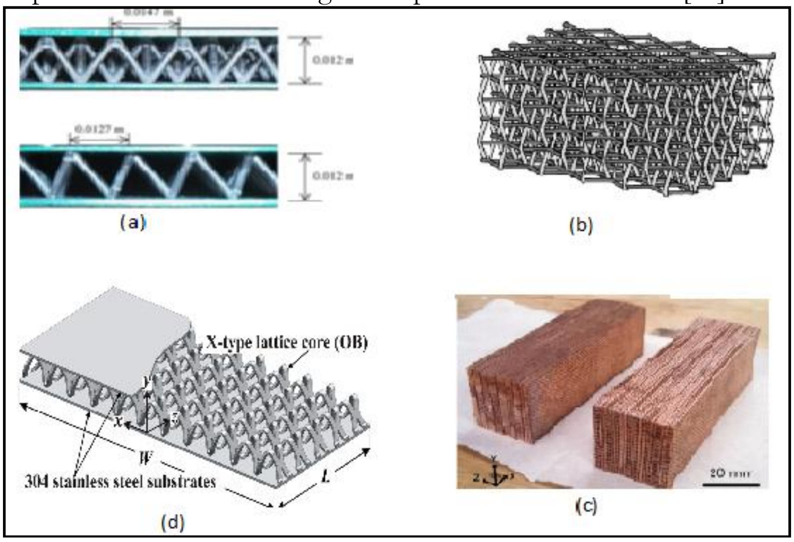

Fig. 9. (a) triangular micro-lattice sandwich structure [27], (b) schematic of wire woven lattice structure [24], (c) Fabricated woven Cu-lattices with standard and optimized topologies [28], (d) X-type lattice [29].

3D weaves show capability for higher heat dissipation and uniform temperature distribution which is extremely useful for cooling of high-power laser diodes [28]. [29] Experimentally and numerically investigated convective heat dissipation capabilities of X-type lattice structures manufactured using metal sheet folding method. X-type lattice core provides higher overall Nusselt number than the tetrahedral lattice structure. Whereas average Nusselt number for X-type lattice structures is inferior to that of tetrahedral lattice core. This is because formation of transverse and longitudinal vortices at the brazed joints and the less turbulence in X-type lattice structures.

4.3. Micro-Lattice Heat Pipes

Sandwich panel heat sinks are well studied and reported in literature as mentioned in the earlier section. To further improve the performance of these heat sinks by utilization of evaporation-condensation of working fluid. Tian et al., fabricated sandwich panel heat sink with inbuilt heat pipes. The structure is fabricated in such a way that cylindrical and triangular tubes are arranged perpendicular to each other as shown in Fig. 10. The sealed vertical triangular tubes contain methanol and their corners have wicking ability and hence are heat pipes. Whereas the horizontal tubes are not heat pipes. It is reported that heat transfer performance of heat sinks with embedded heat pipes is much more than that of sandwich panels with wire screen meshes even though the surface area available with former is around 40% less as compared to the latter. This is attributed to improved effective thermal conductivity of the sandwich panel structure as a result of embedded heat pipes [30]. Heat exchangers resulting from 3-Dimensional micro-lattice structures as described in section 3.1 require external power source, which increases weight of the system. Roper modelled sandwich panel micro-truss heat pipe and optimized [31]. Pareto optimal design surfaces are determined using multi-objective optimization to compare thermal and structural performance of sandwich panel micro-truss heat pipe. Objective functions were formulated for density, compressive strength, compressive modulus, and maximum heat flux. It is reported that heat pipes provide higher effective thermal conductivities than material having higher thermal conductivities such as copper and aluminium.

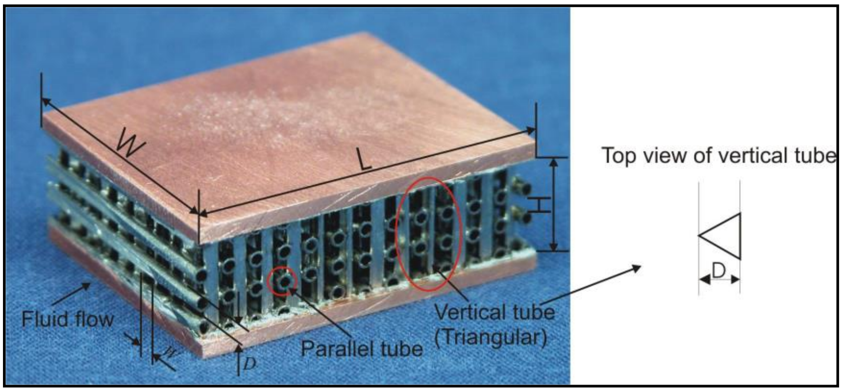

Fig. 10. Sandwich structure with embedded heat pipe [30].

4.4. Scope of Heat Transfer Enhancement at Micro-Scale

In case of the micro-channels, heat transfer and pressure drop are affected by the surface roughness of channel walls. In order to interpret the fluid flow and heat transfer performance of micro-channel heat exchanger, surface roughness is required to be accurately measured. Obtaining the optimal surface roughness of the tube walls of micro-heat exchanger can result in enhanced heat transfer rates. In the study carried out by Yu et al. [32] for different micro channels, Nusselt number is found to be weakly dependent on the Prandtl number in contrast to the conventional correlations. This indicates that micro-tubes have some different convective heat transfer mechanism when compared to conventional tube diameters [33]. Several influences of fluid flow and heat transfer on energy conservation and momentum transport are usually neglected at macro scale. These factors become important as the channel diameter reduces. This is the main reason behind the fact that results calculated by macro scale correlations and those obtained using experimental studies on micro channels deviate from each other [34]. Some of these factors whose consideration into calculations would help reduce the deviation of macro scale results and experimental results are viscous dissipation, compressible flow, fully developed flow, constant of variable wall temperature conditions, irregular distribution of flow in micro channels, temperature jump.

5. Structural Applications of Micro-Lattice Materials

Load bearing structures existing in nature are cellular solids and the reason for this is that the cellular materials offer simultaneous optimization of strength, stiffness and overall weight for given application. Stochastic cellular materials such as foams are extensively used in applications such as cushioning, insulation, load bearing, and packaging [35]. In the similar way, ordered cellular materials such as sandwich panels, micro lattice structures can be used in simultaneous load bearing and heat transfer applications thereby proving themselves to be multi-functional materials [36]. Cellular materials can be implemented for ultra-light materials, compact cooling equipment, energy absorption, blast protection, vehicle components, body implants. Evans et al. studied structural performance of lattice block material which is composed of pyramidal unit cell and octet truss material in which nodes are kept in face-centered tetragonal topology. They have developed methods to create cellular materials with various topologies. Even though the stochastic materials are inexpensive, they have material present at locations which contributes less to the improvement of structural performance of stochastic materials.

On the other hand, periodic materials can be optimized for their multi-functionality by adding material only where it is required [37]. Kooistra et al. manufactured tetrahedral lattice structures from aluminium to test their compression behaviour. They found that peak compressive strengths increase with yield strength of parent alloy and relative density of core material. A model has been developed based on inelastic column theory which considers the effect of strain hardening. The model can predict compressive peak strength of lattice core, for different relative densities. From the comparisons of with similar media, it is found that the compressive strength of aluminium lattice structures is superior to that of aluminium foam and prismatic corrugations [38]. Jacobsen et al. fabricated polymer micro-truss structure by self-propagating photopolymer waveguides technique and conducted compressive experiments on it. Post curing cycle in air at high temperature was carried out to increase the solid polymer modulus which will simultaneously result in reduced buckling tendency of micro-truss material. During post cure cycle, surface oxidation occurs which resulted in increased modulus of polymer approximately by 40% thereby doubling the peak strength of the micro-truss material. The surface oxidation reaction on polymer micro-lattice structure also resulted in increased shear modulus and maximum shear strength [39].

Meza et al. [40] applied principles of hierarchical design and produced structural nanolattice materials from three different materials namely Polymer, Hollow Ceramic and Ceramic-Polymer composites. The concept of hierarchical design is used to minimize the use of material and optimize the structural integrity. The study revealed that the overall deformation behaviour of the metamaterials is strongly dependant on the materials used for their construction. Also, the topology of nanolattices strongly affects the failure within the beams of the structure and its recoverability. Authors concluded that the concept of hierarchical design can be applied to create materials of any order which offer high strength to weight ratio, negative poisons ratio, near infinite bulk to shear modulus ratios. However, the unique properties of micro-lattices such as high specific modulus, specific strength and energy absorption are restricted by the strength-recoverability compromise [41]. To overcome this strength-recoverability trade-off, Zhang et al fabricated three-dimensional architected nanolattices from composites. The polymer nanolattices are fabricated by two-photon lithography and coating of high entropy alloy is performed by magnetron sputtering [41]. Scanning electron microscope images of the compression tests performed on these nanolattices have shown that these nanolattices show a high specific strength and high energy absorption capability per unit volume. In-spite of having such superior properties, these nanolattices are found to display nearly complete recovery, and hence overcoming the strength-recoverability trade-off.

The ultra-low density of hollow metallic micro-lattice structures typically less than 0.2, along with the higher diameter-to-wall-thickness ratio, characteristically greater than 1000, strongly affects the compressive strength of the micro-lattice structures. In this context, Zheng et al. [42] presented hierarchically designed 3D scalable metamaterials formed from Nickel-Phosphorous, which possess higher strength even at very low densities. Manufacturing of these extraordinarily scalable materials is achieved by a relatively new additive manufacturing technique which is capable of producing miniaturized structures over large areas and has nanoscale post processing ability. The materials formed by this technique shows higher tensile deformation (approximately 20%) and compressive elastic deformation (greater than 50%), unlike most of the lightweight materials reported in the literature [26]. Recently an effort has been made to create lattice materials having octet and iso-truss topologies from pyrolytic carbon. Zhang et al. [43] utilized two-photon lithography succeeded by pyrolysis to produce octet and iso-truss lattices from pyrolytic carbon. The pyrolysis is performed in vacuum at a temperature of 900°C. Their analysis disclosed that, density values beyond 0.95g/cm^3 makes the nanolattices insensitive to manufacturing defects which allows them to achieve nearly the same strength as that of the parent materials. Such Nano-architected materials, which shows higher specific strength and deformability at low density, are desirable in harsh thermomechanical applications.

6. Conclusions and Future scope

A review on applications, materials and manufacturing processes of micro-lattice structures is carried out. Multi-functional ability of micro-lattice structures is explored i.e. micro-lattice structures can be utilized simultaneously as heat exchanger as well as an energy absorbing device. A detailed comparison of advanced manufacturing processes is tabulated along with their features. Looking at the advantages periodic micro-lattices offers over stochastic cellular materials such as foams, the future of Micro-lattice structures seems promising. Further studies can be carried out on incorporating micro-lattice structures in electric vehicles to improve thermo-electrical behaviour of batteries. As the proper thermal management of batteries in electric vehicles will lead to improved performance of the vehicle. Also, replacing traditional radiators in car by micro-lattice heat exchanger. This will prevent damage of radiator in case of minor car accident, because of the energy absorption capacity of micro-lattice structure. The topology of micro-lattice structure affects the fluid flow through it. Which influences the thermo-hydraulic performance of the micro-lattice heat exchanger.

Number of such applications can be found out and the topologies of micro-lattice structures can be tailored to meet the requirements of the particular application.

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