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Course Code: ENG5059P	Course Name: MSc Project
Name of **First** Supervisor: Professor Shanmugam Kumar	Name of **Second** Supervisor: Lecturer Paul Prentice
Title of Project: Performance Evaluation of Additive Manufacturing Enabled Thin-Walled Spinodoid Structures	

Declaration of Originality and Submission Information

I affirm that this submission is all my own work in accordance with the University of Glasgow Regulations and the School of Engineering requirements

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Date of Submission:19/08/2022

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Performance Evaluation of Additive Manufacturing Enabled Thin Walled Spinodoid Structures

Chandra Sai Kamal Nadendla

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MSc Project Report

ENG5059P

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Abstract

The complex cellular structures received a considerable attention because of their attractive properties, like high strength and stiffness. Fabricating these structures using conventional methods is difficult, this issue is addressed by using additive manufacturing process. The Performance of cellular structure with spinodoid can be investigated numerically and experimentally. Cahn-Hilliard equation (phase separation equation) is used to generate this type of spinodoid microstructures, whereas in this project they are generated directly by predefined geometry visualization of Gibbon tool box. Spinodoids with two different axis-orientations and surface wall thicknesses are investigated. The considered axis-orientations of spinodoids are [90 0 0] ([X Y Z]) and [45 0 0] ([X Y Z]) and selected surface wall thickness for spinodoid are 0.40 mm and 0.48 mm. In all cases, spinodoid characteristic features and relative densities are investigated. These spinodoid are fabricated using fused filament fabrication (FFF) 3D printer, using multi walled carbon nano tubes reinforced PEEK (MWCNTs/PEEK). The mechanical behaviour of these printed spinodoids is investigated by subjecting to compression test and piezoresistivity is investigated by collecting the resistance data with respective strain during compression test. These data set obtained from the test are analysed to know the effects on spinodoid due to change in axis-orientation and surface wall thickness. The change in resistance data is used to create model to predict deformations and damages of spinodoid structures in future. It is shown that relative density affects the stiffness and with change of orientation the relative densities can be altered. It is observed from the results presented in this report that the spinodoids with axis-orientation of [90 0 0] (X Y Z) is showing superior mechanical behaviour than other spinodoid topology.

Acknowledgment

I would like to thank my supervisor's professor Shanmugam Kumar, lecturer Paul Prentice for their guidance throughout this project. Thank you to school of engineering of University of Glasgow for their regular updates on the project format and deadlines. I would like to thank Alejandro Triay (PGR) and Johannes Schneider (PGR) for providing continuous support and guidance in lab.

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1.Introduction

This project focuses on investigation of performance of metamaterials whose architecture is built on repeating cellular structure.

1.1. What are Metamaterials?

Term metamaterial is the combination of Greek word “Meta” (beyond) and a Latin word “Materia” (matter), was given by Rodger M. Walser, University of Texas at Austin, in 1999. Metamaterials are originally defined as macroscopic composites with synthetic, periodic cellular architecture, three-dimensional designed to develop an optimized combination, not present in nature [1].

After proper analysis of metamaterials, it’s defined as the periodic or non-periodic structure, functions due to both the cellular architecture and chemical composition. Repeating patterns are usually observed in the arrangement of metamaterials, at scales that are smaller than the wavelength. In general, electromagnetic waves interacts [2] with inclusions (including electrical and magnetic moments), which affect the macroscopic effective electrical primitivity and magnetic permeability of the bulk composite “medium”. As metamaterial properties are derived from the newly designed structure and the size, orientation, geometry and arrangements provides the ability to manipulate the electromagnetic waves.

These metamaterials consist of multiple individual elements referred as meta-atoms, smaller than wavelength and there are microscopically built from conventional materials such as metals and dielectrics like plastics and few examples of available metamaterials are negative index materials, photonic metamaterials, etc. Some of these materials have unit cell of few millimetres as they operate at microwave frequencies, due to their subwavelength nature and the materials that operate at visible part of the spectrum have unit cell of few nanometres. They are also inherently resonant, i.e., absorb light at certain nano range frequency which can block or absorb a particular colour in spectrum [3].

Optical filters, sensor deduction, medical devices, infrastructure monitoring, remote aerospace applications lenses for high-gain antennas are some potential applications of metamaterials.

It’s interdisciplinary research, involves fields of material science, electrical engineering, electromagnetic, solid-state physics and semi-conductor engineering

1.2. Metamaterial properties and applications

The metamaterials are artificially synthesized materials, manufactured to give properties that are not readily available in nature [4]. These materials derive their properties from their structure rather than composition, by the use of small inhomogeneities inclusion to exhibit effective macroscopic behaviour.

1.2.1. Classification of Metamaterial

The macroscopic parameters permittivity and permeability of metamaterials describes their properties. The classification based on these properties are illustrated in Figure 1.

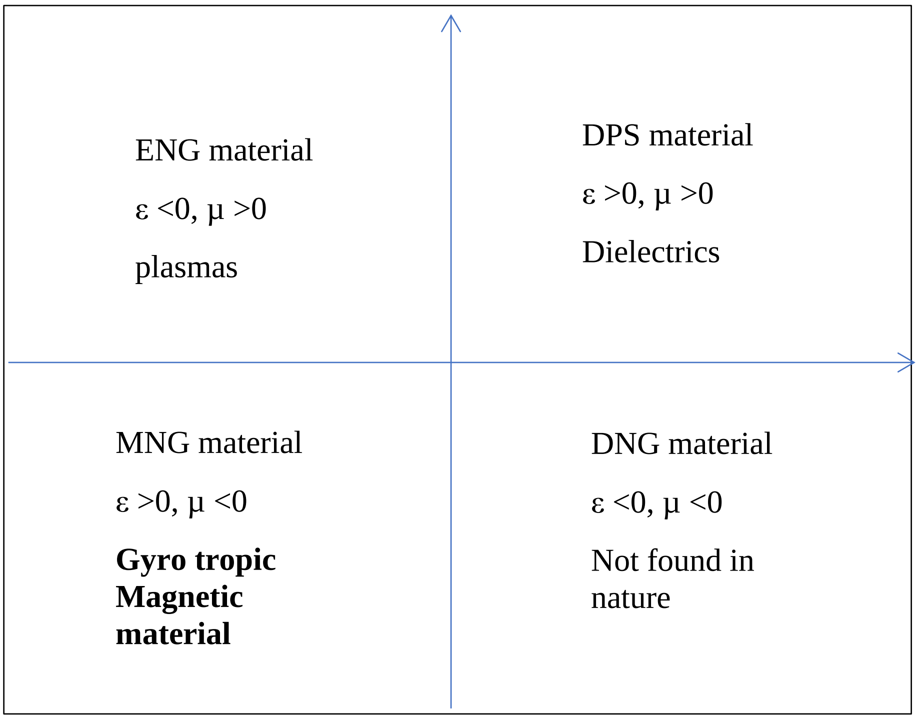


Figure 1:Metamaterial Classification

When both permeability and permittivity is higher than the zero value ($\varepsilon > 0$, $\mu > 0$) are called as double positive medium or DPS medium. The most happening media (e.g., dielectrics) comprise this designation.

Whereas permeability higher than the zero value ($\varepsilon < 0$, $\mu > 0$) and permittivity is below zero are called as Epsilon negative medium or ENG medium. In specific frequency regimes many plasmas exhibit this characteristic.

In the same way when both permittivity greater than zero & permeability but zero ($\varepsilon > 0$, $\mu < 0$) are called as Mu negative (MNG) medium. In certain frequency regimes some gyro tropic material exhibits this characteristic.

Similarly, when permeability and permittivity are below zero ($\varepsilon < 0$, $\mu < 0$) then it is called as Double negative medium or DNG medium. This stage of materials has only been demonstrated with synthetic constructs.

1.2.2. Various types of Metamaterials

I. Electromagnetic Metamaterials

a) Negative Refractive Index

b) Single Negative metamaterials

c) Electromagnetic bandgap metamaterials

d) Double Negative metamaterials

e) Chiral metamaterials

f) Bi-isotropic and Bi-anisotropic metamaterials

II. Non-linear metamaterial

III. Photonic metamaterial

IV. Terahertz metamaterial

V. Tunable metamaterial

1.2.4. Application of Metamaterials

- Metamaterial Super lens
- Metamaterial Clocking Devices
- Acoustic Metamaterial
- Metamaterial Antennas
- Wireless chagrining with Metamaterials
- Metamaterial as Absorber
- Metamaterial sensors
- Metamaterial Phase compensator

1.3. Spinodoid Metamaterials

Spinodoid metamaterials are metamaterials that have non-intersecting, smooth and surfaces which are bi-continuous, avoids points of stress concentration. These are created naturally by self-assembly process and are close approximations of microstructures during spinodal phase separation.

Conventional metamaterials are light weight cellular solids with engineered strength, energy absorption or stiffness, along with those these metamaterials suffers with the detrimental stress concentration which leads to less recoverability and poor strength. Whereas Spinodal topologies offers many advantages over conventional metamaterials. As they exhibit high scaling of strength and stiffness with respect to density [5]. These are considered as shell networks and as solid networks, covers mechanical properties of seamless and extreme range of anisotropic.

The non-periodicity of spinodal network, gives the creation of functionally graded materials with spatial varying properties effortlessly.

- The spinodoid microstructure's computational design depends on simulation of the phase separation process by phase field methods and its kinetics are modelled by Cahn-Hilliard-type evolution equation.
- It is proven that the spinodal topology exhibit better stiffness to relative density
- Spinodoids exhibit significantly improved mechanical behaviour over plate and truss metamaterials
- They void stress concentration at beam or plate junctions
- They are not sensitive to symmetry breaking defects and fabrication-induced imperfections.
- It can act like a good energy absorber and protection from the heat exchange

1.3.1. Various types of spinodoid metamaterials

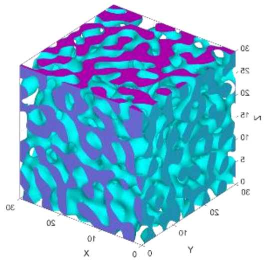
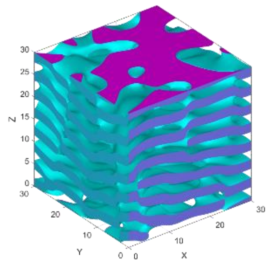
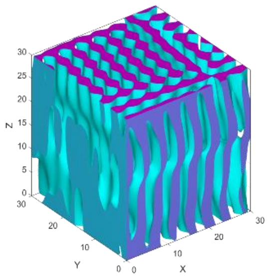
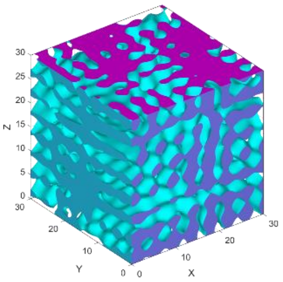
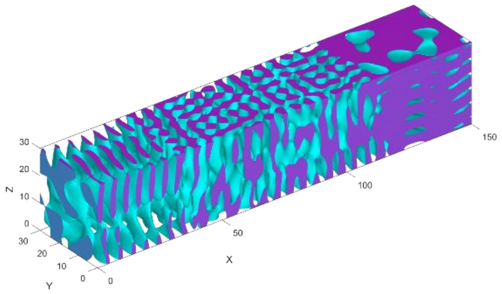
Name of Spinodoid	Structure of Spinodoid
Isotropic Spinodoid	
Lamellar spinodoid	
Columnar spinodoid	
Cubic spinodoid	
Spatially-graded spinodoid	

Table 1: Spinodoid Topologies

1.4. Self-Aware Metamaterials.

In general, self-sensing or self-aware metamaterials are composites that rely carbon fibres of different forms as sensing module. The latest self-sensing metamaterials are designed in such a way that under pressure, contact-electrification occurs between its dielectric layers and conductivity, generating an electric charge that relays information about condition of metamaterials and naturally inherits the mechanical properties of the conventional metamaterials.

The responsive materials either in biology or engineering study are distinguish themselves by their ability to respond to external simulation.

1.5. Cellular Structures

Cellular structures, are more like bones of animals, trunks of tree, honeycombs, leaves and corals which occur naturally in the nature [6]. For many years, different natural cellular structures have been processed by human beings, like corks and another product which are made up with wood, for different applications or implementations, and have fabricated and utilized different synthetic cellular structures by replicating naturally available cellular structures. Structures which are based on polymer-foam, metal-based honeycomb, and truss structures are the commonly used cellular structures [7]. Polymer foams are commonly applied in applications such as packaging containers and insulations [8]. The structures like Metal honeycomb and truss are generally used as less weight structures and materials which are shock-absorbers in various industries, such as aerospace industry, architecture industry, automobile industry, and electronic industry [9].

Cellular structures which are three-dimensional (3D) are generally divided into two types

- Stochastic (foam) and
- Non-Stochastic (periodic)

structures depending on the way of arrangement of their unit cells, and each and every structure can be further divided or separated into closed-cell and open-cell structures (Figure 2) [10]. Open-cell foam structures have open cell walls, generally

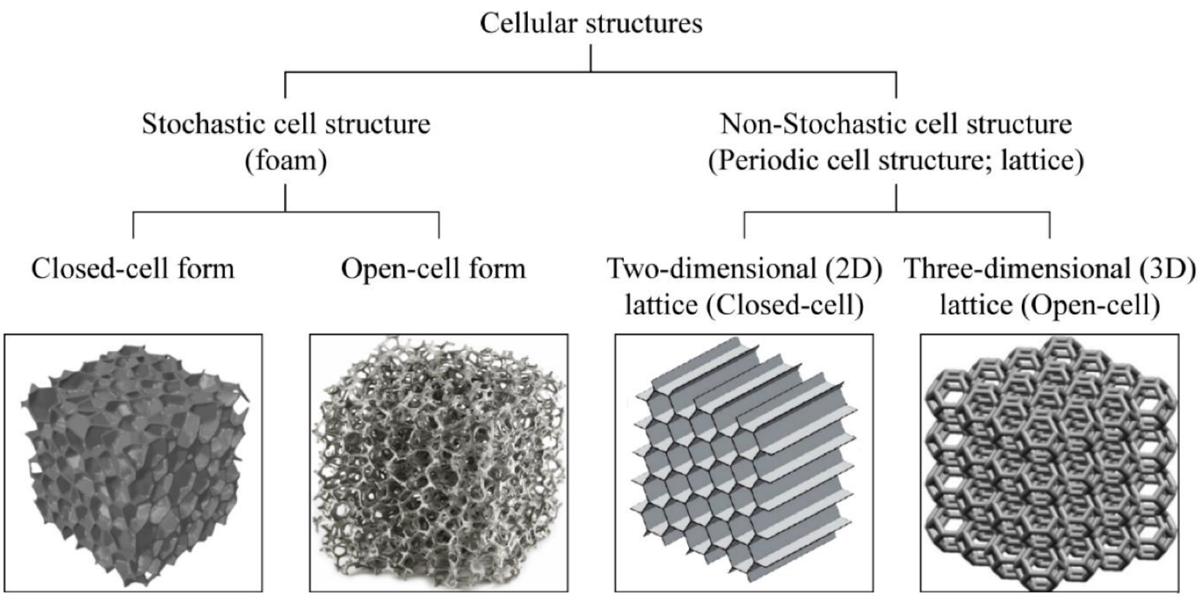


Figure 2: Categories of Cellular Structures [11]

synthesized during production by using an inflating agent which allows fluids and gases to easily pass through, by letting only the framework in place [12]. However, closed-cell structures have a wall structure with closed cell with intact membranes, making the closed-cell foam not to be porous and permeable. Generally stochastic cell structures include foams like non-metallic and metallic foams, which have sponge like structures [13]. The structures which non-stochastic are also called as periodic or lattice structures, in which the cells of unit size of a particular shape are repeatedly arranged, similar to the structures like honeycombs and trusses [14].

In specific, structures of lattice have received convincible attention because of their interesting mechanical behavioural properties like high strength and stiffness, weight which is very low, and the capability of absorbing an external impact force due to their internal structures [15]. materials which are solid (like steel and plastic) are typically used as structures in industries. However, solid materials reach design requirements of structures, various drawbacks persist, like wastage of material while production, design strategies become inflexible, and volumes with large structures. Now, the primary focus of industrial structural design is on reducing the weight and at the same time obtaining high performance of the components. To illustrate, considering an application related to aerospace [16], the design of structure aims to obtain excellent mechanical behavioural properties using materials which are light in weight, which generally allows the structures to be made at a very low expenses and with high performance. The reason for using lattice structures is it facilitates the production of structures with less weights and high strengths [17].

1.6. Piezo resistivity Effect

The electrical resistance changes of semiconductor or metal when mechanical strain is applied.

- It causes change in electric resistance, not in electrical potential
- Piezo resistive sensor is used for mechanical stress measurement

1.7. Mechanical Properties of Cellular Materials

The cellular materials exhibit unusual mechanical properties and cellular materials mechanical behavioural properties are related to their cell geometry.

- They have a capability of absorbing high amounts of energy and high range deflections

From the study on hexagonal cells, it is identified that these properties majorly depend on three factors

- Solid cell wall material property
- Geometric constant
- Relative Density of cellular material

1.8. Aim and Objectives

The aim of this project is to evaluate mechanical and piezoresistive performance of additive-manufacturing enabled thin-walled spinodoid structure using multi walled carbon nanotube (MWCNT) reinforced polyether ether ketone (PEEK).

Objectives

- Develop a thin-walled spinodoid structure and 3D print the designed model
- Perform Mechanical analysis on the model
- Evaluate results with different structures to understand model and material in detail

2.Background and Literature Review

2.1. Study on Past of Metamaterials and its Applications

2.1.1. Rapid Design for Metamaterials

The general composition of Metamaterials is sub-wavelength unit cells with spatially discrete, each of which is considered as a particle. The primary function of this rapid design for metamaterials is to obtain the optimized geometric parameters automatically and efficiently for every metamaterial particle of a complicated metamaterial system with inhomogeneous (or homogeneous) material parameters to be designed [18].

This rapid design's schematic process is illustrated by below figure

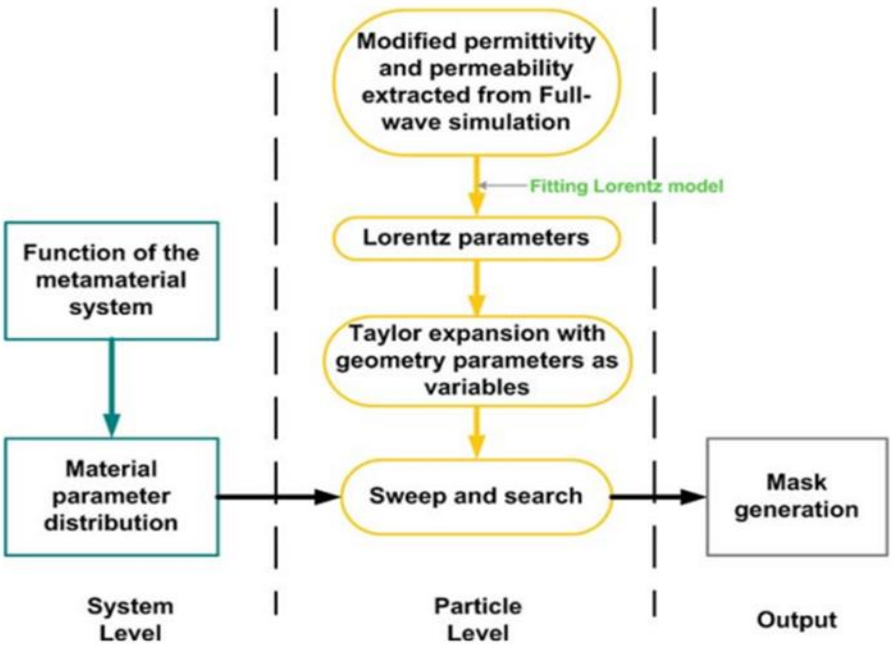


Figure 3: Flow Chart of Rapid design for metamaterials

In this study, authors addressed the increasing burden of large-scale metamaterial design [18]. According to authors the described rapid design for metamaterials is expected to boost the development of complex and inhomogeneous metamaterial system

2.1.2. Three-Dimensional Metamaterials

The metamaterial composites are designed rationally focusing at unique parameters of materials that go far beyond those of the materials which are ingredient. For better understanding, considering refractive index which is negative for metamaterials. These properties of metamaterial, like the coefficient of thermal expansion/Hall coefficient could be manufactured from constituents with parameters which are positive. In the similar manner, parameters of metamaterials with large values can arise from all-zero constituents, like an anisotropic from isotropic, magnetic from non-magnetic and chiral from achiral. This metamaterials field is raised from ranging from electromagnetic and linear electromagnetism around two decades ago and now addresses nearly all conceivable aspects of optical, solids, mechanical and acoustic to transport linear and nonlinear properties, reciprocal and non-reciprocal, monostable and multistable (programmable), active and passive, and static and dynamic [19].

2.1.3. Metamaterial Absorbers: Microwave to Optical

Metamaterials are devised by artificial means that contains its own specific features due to the way their geometries are designed and few characteristic properties are presented by them. The different properties like negative refractive index, left-handed behaviour, Doppler effect reverse, and Snell's reversal law. Metamaterials are applied in applications of myriad, containing perfect lensing, obscurity cloaking, sensing, and its precise absorption. In this study, the electromagnetic absorption characteristic shown by structures famous as metamaterial absorbers (MMAs) is debated. The MMA composite is containing many layers of patterns which are metallic divided by dielectric. This helps in achieving absorption of near-unity by various systems, that are examined in this study. The MMAs are divided based on their absorption features, to a tunability of polarization, operation of broadband, and absorption of multiband, indifferent regimes of frequency [20].

2.1.4. The Developing Trends on Metamaterials and their fabrication using Additive Manufacturing

In this study, the concept of metamaterials is discussed and according to this it's originated from the concept of negative refractive index of left-hand materials, succeeded by which, different kinds of metamaterial properties that cannot be easily available in materials which occur naturally, like Poisson's ratio with zero/negative, nature of electromagnetivity, effect of thermal cloaking, acoustic, etc., were come up with. The metamaterials are mainly divided into four divisions based on their application fields.

They are

- Metamaterials of Electromagnetic nature
- Acoustic Metamaterials
- Thermal Metamaterials and
- Mechanical Metamaterials

The theory of metamaterials function can be explained by their structural designs and arrangement of the distribution of materials with unique physical parameters. The flexibility of fabricating complex structures using technology of additive manufacturing (AM) provides a way more direct or straight forward and efficient way to obtain a piece of metamaterial and verification done experimentally. This study introduced the general metamaterials in various situations where they can be applied and their methods of design. This study focused more on the metamaterials manufacturing and the status of application of AM technology in them [21].

2.1.5. Metamaterials for Device Application

In this study, authors discussed about metamaterial's origin and stated as they are synthetically manufactured materials, that expose properties which are unobtainable naturally, in accordance to how their microarchitectures are manufactured. They exhibit exclusive effective properties which are also controllable and also includes permeability of magnetism also known as magnetic permeability and electric permittivity, the metamaterials have an important role in the development and progression of meta-devices. Hence, this study primarily concentrated on achieving tunable shifting, switchable, nonlinear, and sensing functionalities. In this study, authors concluded the recent development in terahertz, photonic metamaterials and micro-wave electromagnetic and their applications. The study also summarizes the importance of metamaterials in the improvement of microwave sensors, photonic devices, antennas, energy harvesting, and superconducting quantum interference devices (SQUIDs) [22].

2.1.6. Imaging with Metamaterials

In this study, it is discussed that metamaterials at the subwavelength scale, enable precise tailoring of light–matter interactions, giving access to the complete range of electromagnetic responses that are encoded in equations of Maxwell and functioning across a large swath of the electromagnetic spectrum.

These specifications have, over two complete decades, increased fundamental metamaterials study which, in turn, has unveiled an interesting assemblage of applications which have great potentiality. Metamaterials Imaging is primary of these developments, using the capability of metamaterials to obtain arbitrary, particular and tunable scattering responses that are composed for integration with a host of materials and devices. Authors review the impact of metamaterials and meta surface on imaging science and technology from microwave to optical frequencies. The main concentration is on metamaterial-based imaging components and the associated imaging modalities that advantage from these advances [23].

2.1.7. Reconfigurable and Tunable Metamaterials

In this study, it is explained that metamaterials are now mostly used in the field of construction and improvement of various new devices over the electromagnetic spectrum. The restrictions of the metamaterial functional bandwidth and losses can be systematically mitigated by the incorporation of tunable elements into these devices of metamaterials. There are a large range of applications of metamaterials which have been progressed in the literature for incorporating reconfiguration to devices of metamaterials all the way from the RF through the regimes optically, whereas few techniques are useful only for specific bands of wavelength. A range of tuning techniques span from circuit which are active elements added into the resonant conductive metamaterial geometries to constituent materials that change electromagnetic properties under certain environmental stimuli. The presented survey in this study is for the improvement of reconfigurable and tunable metamaterial technology as well as of the applications where such these abilities are valuable [24].

2.1.8. Flexible Metamaterials and meta-Surfaces

The capability for bending, stretching, and rolling of devices of metamaterials on flexible substrates incorporates a unique dimension to aspects of manipulating electromagnetic waves and gives a new wave of device designs and functionalities. This overall procedure reviews terahertz and optical metamaterials given on flexible and elastomeric substrates, along with techniques and approaches to lend tunability to the devices. electromagnetic and mechanical substrate characteristics suitable for flexible metamaterials are concluded in this study, followed by manufacturing and processing techniques, and finally ideal applications used to-date to attain tunability. Future directions and emerging areas of interests are identified with these promising to transform metamaterial design and translate metamaterials into practical devices [25].

2.1.9. The Reshape and Rethink on Metamaterials

Metamaterials are like composite materials whose material features (electrical, acoustic, optical or magnetic.) are identified by their material structure, mainly the unit cells. The redefining of boundaries of materials continues by the improvement of metamaterials. In the area of electromagnetic study, these materials offer great design of flexibility accompanying their specialized features and their tunability when subjected to stimuli which occur externally [26].

2.2. Study on Additive Manufacturing and Fabrication of Complex Structures

From the study of metamaterials and cellular structures of materials, it is understood that the complex structures are easily fabricated using additive manufacturing technology rather than following conventional methods for manufacturing.

2.2.1. What is Additive Manufacturing?

The manufacturing or fabrication of desired shape by adding material, possibly by contoured layers staggering on top of each other is known as additive manufacturing. Therefore, it is also called layer (or layered) technology [27].

2.2.2. Methodology of Design for 3D printing of Complex Topology structures

It is a known information that most natural structures are complex topology structures with irregular surface morphology. These structures are very useful and these are used as porous scaffold, lightweight infill, energy absorber or micro-reactor. Now due to the immense advancement of 3D printing, the complex topology structures can now be precisely and efficiently fabricated by stacking layered materials. The ideal manufacturing technology and application background put forward new demands and challenges to the current design methodologies of complex topology structures. In this study, the development of recent complex topology structure design methods was discussed and also the limitations of existing methods and future work are also discussed [28].

2.2.3. Fabrication of Complex Polymer Structures by Additive Manufacturing

The two restrictions for the methods of additive manufacturing that arise due to layer-based fabrication as they are slow speed and geometric constraints (which poses bad surface quality). In this study, authors introduced a new volumetric additive fabrication paradigm that produces photopolymer structures with complex nonperiodic three-dimensional geometries on a time scale of seconds for overcoming these limitations. this approach is implemented by using holographic patterning of light fields, demonstrate the fabrication of a variety of structures, and study the properties of the light patterns and photosensitive resins required for this fabrication approach. The results indicate that low-absorbing resins containing ~0.1% photoinitiator, illuminated at modest powers (~10 to 100 mW), may be successfully used to build full structures in ~1 to 10s [29].

2.2.4. Fabrication using New Possible Techniques of Additive Manufacturing

In this study, authors explained that additive manufacturing is particularly used for fabricating complex geometry. Apart from that the material which are highly problematic for machine can processed with this technology. According to authors the 3D printing used to its fully potential when there is clear understanding on traditional machining and 3D printing. In this paper, it is pointed that material can be used where it is necessary rather than filling it completely and making component dense [30].

Techniques mentioned in this paper are listed below

- Improvisations for fused filament printers
- Change of extruder nozzle on a printer while it is hot to avoid solid plastic residues

- Tightening of replacement nozzle sufficiently without damaging its threads

2.2.5 Architected cellular materials

Additive manufacturing which are industrially-appropriate with high performance parts and components is reality today, mainly for additive manufacturing of metals. The complexity in design is now achievable which makes it particularly useful to increase variety of applications. Metal Additive Manufacturing is especially robust and is being applied for production of end-use responsibility-detracting parts. The next level concerning this development involves the use of purposely created porous metals - architected basic or mesh makeups. Cellular structures maybe planned or tailor-made for specific machine like or added act characteristics and have abundant benefits on account of their large surface region, depressed bulk, regular recurring construction and open pertain pore spaces. This is thought-out specifically beneficial for medical implants and for inconsequential automotive and aerospace elements, that are the main industry trainers now. Architected natural structure's function related to open container foams, which have erected many different technical applications to date, to a degree grinder panels for impact incorporation, radiators for warm administration, filters or catalyst fabrics, sound covering, among others. The benefit of additively made basic structures is the exact control of the data processing machine-design which enhances attainable. The enormous potential of these porous architected basic fabrics made by additive production is now restricted by concerns over their structural honour. This is a genuine concern, when taking everything in mind the complexity of the production process, and the only current development of metal supplement production electronics. Many potential manufacturing wrongs can happen, that have so far happened in a widely different set of results in the article for these types of structures, accompanying exceptionally weak fatigue properties frequently raise. These have upgraded over the years, corresponding the development and bettering of the metal preservative production processes. As the causes of errors and belongings of these on machinelike possessions are now better assumed, many of the latent issues may be removed or lightened. This form additively made cellular makeups a well genuine option for causing trouble new and enhanced modern products. This review paper confers the progress to date in the bettering of the fatigue acting of cellular makeups made by supplement manufacturing, particularly alloy-located, providing insights and a glimpse to the future for fatigue-open-minded additively made architected natural materials [31].

2.3. Study on various 3D Printers

The study on various 3D helps to use the material properly, cut costs, reduce time for fabrication of model and improves efficiency of printing.

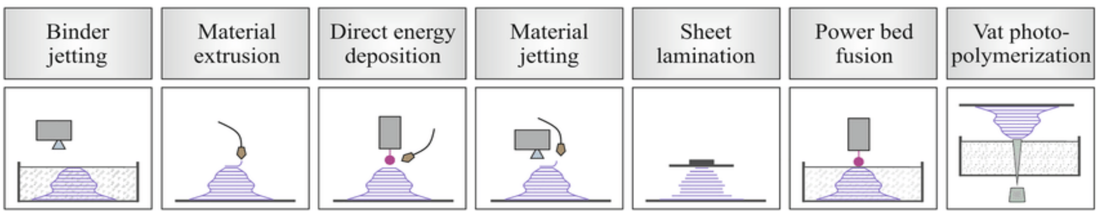


Figure 4:Classification of 3D Printing [32]

The various types of 3D printers are listed below

1. **Fused Deposit Modelling (FDM)**

    - It is the most popular 3D printer and affordable 3D printer
    - It was founded in 1980s, and developed by Scott Crump from Stratasys.
    - It is also called as Fused Filament Fabrication (FFF)
    - It is used for both operational prototypes and ready to use prototypes
    - The components printed with FDM can go in high performance and engineering-graded thermoplastic.

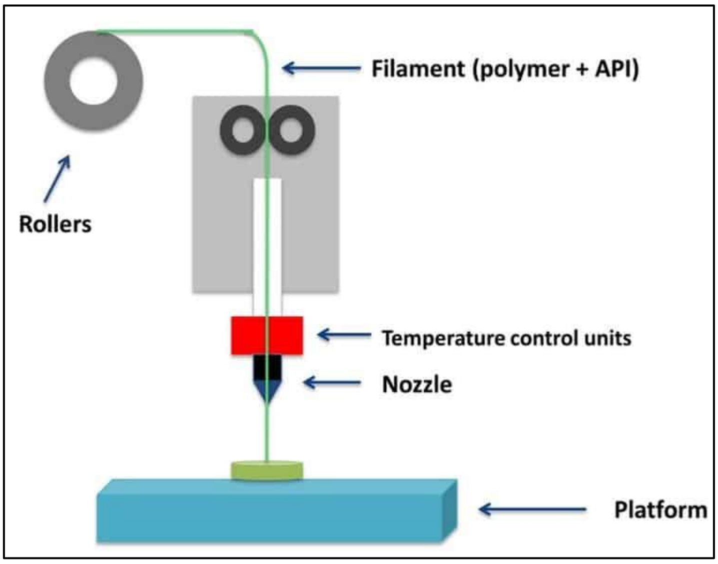


Figure 5: FDM 3D printer Schematic model [33]

2. **Stereolithography (SLA)**

    - It is the earliest 3D printing procedure and still in use
    - SLA 3D operates excess of liquid plastic that after a while hardens and forms to solid object [34]
    - The components printed in this printer usually have smooth surfaces

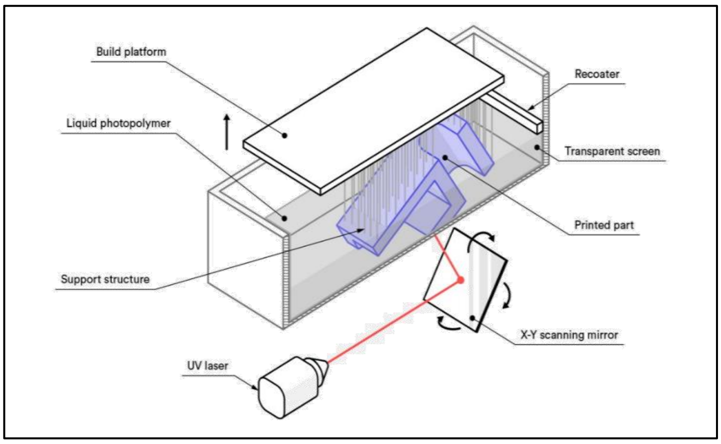


Figure 6: SLA 3D printer Schematic model [34]

3. **Selective Laser Sintering (SLS)**

    - SLS uses laser as power supply to fabricate strong 3D objects,
    - It was found in 1980s by Carl Deckard
    - The major difference between SLA and SLS is it uses powder materials rather than liquid resin

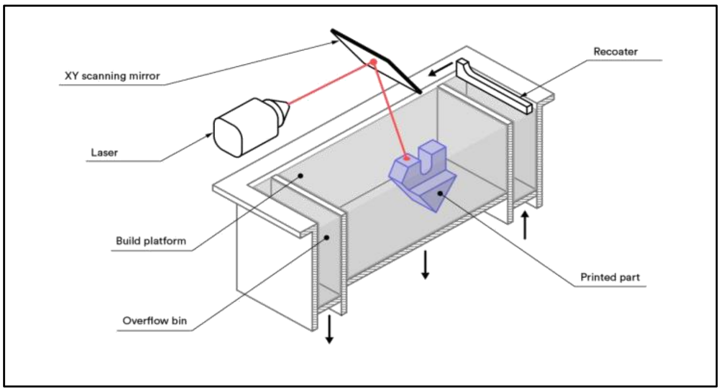


Figure 7: SLS 3D printer Schematic model [35]

4. Material Jetting

- It is one of the fastest and accurate 3D printing technology
- It was founded in late 1990s and patented under the PolyJet
- The objects fabricated by this printer are comparatively weak than SLS
- It is a slow printing process
- It is an ideal technology for both prototyping and tooling
- It delivers full-colour and multi-material with high dimensional accuracy

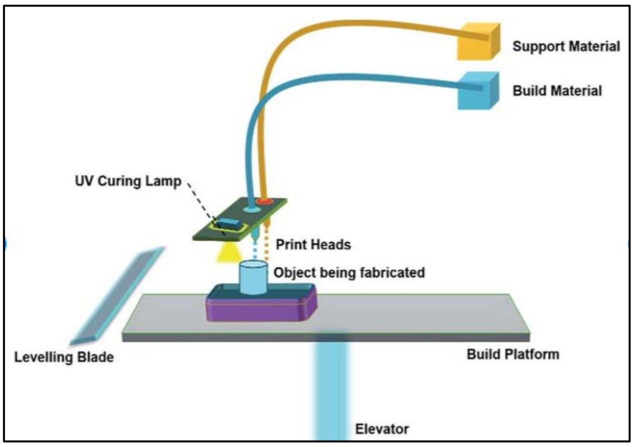


Figure 8: Material Jetting 3D printer [36]

5. Binder Jetting

- The selective deposition of binder onto the powder bed and bonding the areas together to form a solid part one layer at a time.
- It was invented in 1989 by sachs et al.
- The materials commonly used in this are metal, sand and ceramics
- It is used for fabrication of full-colour prototypes and sand molds

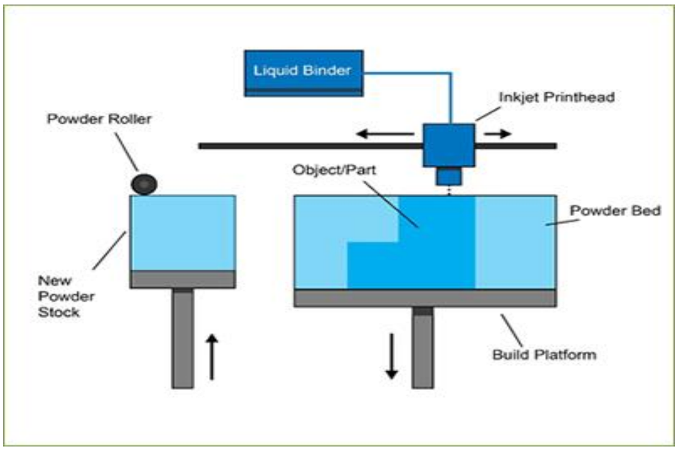


Figure 9: Binder Jetting 3D printer Schematic model [37]

6. Selective Laser Melting (SLM)

- It uses high power-density laser to fully melt and fuse metallic powders to fabricate net-near shapes
- SLA automatically fuses materials using high-powder laser, whereas SLM fuses powder materials together by heating them until they reach a melting point.
- It was invented by Wilhelm Meiners, 20 years ago.

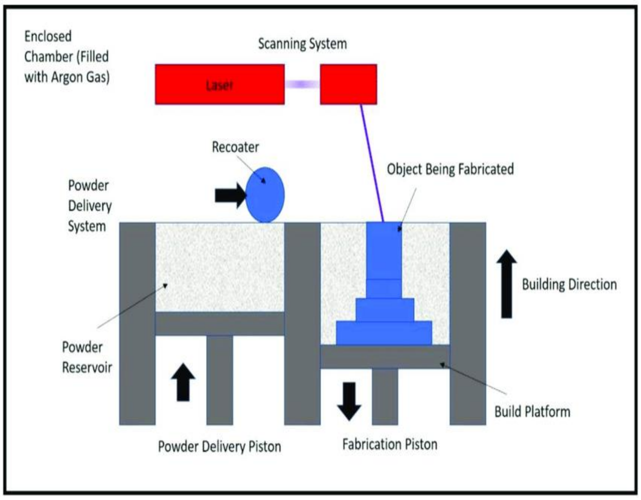


Figure 10: SLM 3D printer Schematic model [39]

2.4. Apium P220 3D printer

- It is a PEEK-ready industrial 3D printer developed by Apium
- It is a FFF type printer
- Manufacturer based in Germany known as Indmatec
- It is a closed-frame 3D printer which enables high performance polymers 3D printing
- The materials available for this printer are PEEK, carbon PEEK (30%), PVDF, PP and POMC

Features of Apium 3D printer

- It controls temperature within the parts and offers ability to control properties of material at voxel level
- It has integrated controlling software on touch screen
- It enables change of material in 2 minutes
- It is specially used for 3D printing of high-performance engineering materials
- It emits low noise and weighs around 65 kg

Figure 11: Apium P220 3D printer [39]

2.5. Various Filaments or Materials used in Additive Manufacturing

There are different types of 3D filaments used for high quality manufacturing processes and are useful in the creation of detailed models of the product and so much more. So, choosing proper filament for the particular product is very important.

These are some 3D printing filaments and the features of each filament.

PLA Filaments

PLA (Polylactic acid) filaments are most popular among 3D materials on the market. The main objective of creating this filament is its strength. The filament is high in durability and comparatively easier for printing than other varieties.

- It has lower printing temperature (helps in protecting it from shrinking or warping during printing)
- It has less flexibility (This is reason it isn't used for products which meant to be bend)

PETG Filaments

PETG (Polyethylene Terephthalate Glycol) is second most popular filament, if PLA is considered to be the first.

- It has high durability and strength like PLA
- It is comparatively more flexible than PLA

Note: If it exposed to moisture, it can cause surface to deteriorate.

TPU Filaments

TPU (Thermoplastic Poly Urethane) is a rigid material when it is in raw state, which makes it easier to print in various printers. But it becomes soft and stretchable when it got crafted and hold up against all kinds of physical stress.

- It has high durability and flexibility
- The texture of TPU is like rubber (helps in maintain its elasticity in colder temperature)

Nylon Filaments

Nylon-based series is another type of 3D printing filament which combines well with a plethora of other materials which includes glass, carbon fibre and Kevlar. This results in materials having diverse range of uses in many industrial and crafting industries.

- It offers good strength and flexibility
- It acts as durability base during with other materials
- It has low friction

Polycarbonate (PC)

It is the strongest filament with extremely durable and resistant to both physical impact and heat. This filament which has a capability of withstanding up to 110°C.

- It offers good strength and flexibility
- It is hygroscopic, absorbing water from air

Note: PC filament should be stored in cool and dry place

2.6. Carbon Nanotubes (CNTs)

Carbon Nanotube which are like tube are made up of carbon whose diameter is typically measured in nanometres [40].

CNTs are majorly classified into three types, SWCNTs, DWCNTs, MWCNTs.

2.6.1. Single-Wall Carbon Nanotubes

The single-wall carbon nanotubes (SWCNTs), which was founded in 1993, with a around 1 nm diameter and a tube length of the orders of centimetres. The SWCNT structure can be known as a perfect graphene sheet, graphene being the same polyaromatic monoatomic layer made of a hexagonal display of sp^2 hybridized carbon atoms, and wrapped in a one-atom-thick layer of graphene as a seamless cylinder [41].

2.6.2. Double-Wall Carbon Nanotubes

The Double-wall carbon nanotubes (DWCNTs) have related features and form as that of SWCNTs, except that they have significantly higher resistance compared to available chemicals. This property is specifically lively when performance should to increase new features to the nanotube. As distinguished to SWCNTs and MWCNTs, DWCNTs own higher thermal and electrical stability and flexibility, as they are an artificial blend of two together SWCNTs and MWCNTs. Any structural defect in SWCNTs can change their mechanical and electrical characteristics and in functionalized form, they are more exposed to damage. On the other hand, only the outside wall of DWCNTs is improvised thus by maintaining its internal properties. DWCNTs could be applied widely in dielectrics, gas sensors, and in technically demanding applications like nano sensors, nanocomposite materials, and field-emission displays [41].

2.6.3. Multiwall Carbon Nanotubes

The Multiwall carbon nanotubes (MWCNTs) are made of different layers of graphite wrapped around one another in a structure which is a tube-shaped with an interlayer dispersing of 3.4 Å. The two models that can be utilized to illustrate the structure of MWCNTs are the

- Russian Doll model and
- The Parchment models.

the graphite sheets are arranged in concentric cylinders in Russian Doll model, , whereas they are like a single sheet of graphite which is wrapped around itself in Parchment model, just like a rolled-up newspaper [41].

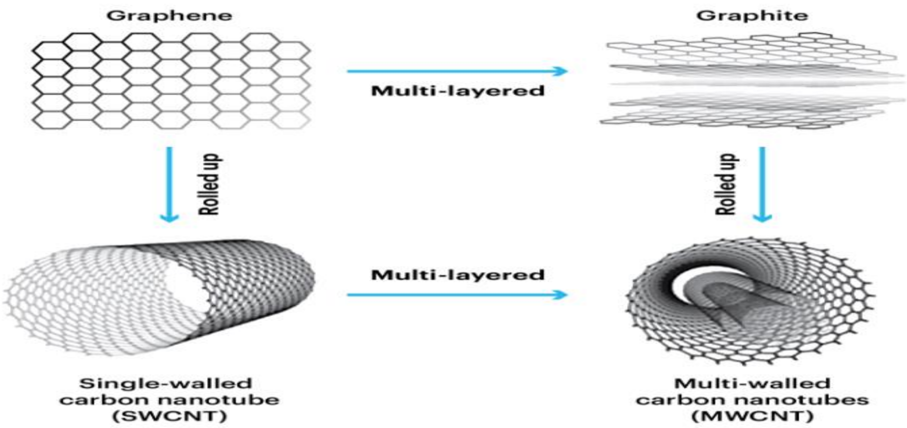


Figure 12:Classification of CNTs [42]

2.7. Discussion on PEEK/MWCNTs Composites.

Polyether ether ketone (PEEK) is applied in various applications of engineering, like piston parts, high performance liquid chromatography (HPLC) columns and so on. The PEEK's widespread application attribute is due to excellent mechanical properties and chemical resistance [43]. In developing the application fields of PEEK composites, incorporation of suitable fillers is an effective method to improve the mechanical properties or bring in the tribological properties for improvement [43].

PEEK is a thermoplastic semicrystalline with great chemical and mechanical resistance features that are reconfigured to high temperatures. The functioning conditions used to a PEEK mold can deviate the crystallinity, and therefore, the mechanical properties. The Young's modulus is 3.6 GPa and its tensile strength 90 to 100 MPa. PEEK has a transition of glass temperature of around 143 °C (289 °F) and melts around 343 °C (662 °F). Some grades have a useful operating temperature of up to 250 °C (482 °F). It is highly resistant to thermal degradation as well as attack by both organic and aqueous environments. It is attacked by halogens and strong acids as well as some halogenated compounds and aliphatic hydrocarbons at high temperatures. It dissolves completely in concentrated sulfuric acid at room temperature.

Because of its robustness, PEEK is used to fabricate items used in demanding applications, including bearings, piston parts, pumps, HPLC columns, compressor plate valves, and cable insulation. It is one of the few plastics compatible with ultra-high vacuum applications. It is extensively used in the aerospace, automotive, and chemical process industries.

Applications

- High Vacuum plant
- Chemical industries
- Nuclear environments
- High pressure valves
- Oil & Geothermal wells
- Food processing equipment

As carbon nanotubes (CNTs), became most interesting area of research due to their unique structure and excellent mechanical and electronic properties [43] and making it a suitable candidate for enhancing the properties.

2.8. What is ESD?

Electrostatic-Dissipative materials are created by incorporating the combination of plastics which are insulative and metals that are conductive, materials of electrostatic-dissipative accepts electric charges to go slowly from the material while reducing the energy output parallelly to avoid electrostatic discharge.

Particularly in the approach, electrostatic-dissipative materials could ground built-up static energy without taking the risk of channelling the sensitive of charging or equipment vulnerability and materials.

This static electricity can easily be neutralized and grounded by controlled environment which is created by materials of electrostatic-dissipative. Even when a single or sample of equipment which is sensitive were to come in contact with the material, that would not distribute the electrostatic charge at lower levels of energy than conductive or insulative materials released by esd workbenches

Electrostatic-dissipative materials are also divided as ‘anti-static’ which means that they decrease the chance of occurring and storing of electrostatic energy.

Applications of Electrostatic-Dissipative Materials

- Static electricity can be applied in many scientific, controlled and technical environments. sensitive electronics and Magnetic data could easily damage with the transfer of electrons, which is why many facilities handling vulnerable equipment and technology choose electrostatic-dissipative materials when designing their furniture.
- Electrostatic-dissipative tables, countertops, and chairs channel unwanted static electricity away from sensitive equipment, flammable chemicals, and magnetic data, grounding and neutralizing the charge through a controlled path. Gone are the days of needing to worry about how dry your facility gets, how worn your surfaces are, or whether you’ll receive a shock each time you put a hand on your desk
- Similarly, educational environments, labs, and medical facilities storing liquids which flammable and often materials opt for materials which are electrostatic-dissipative when selecting their storage and furniture.
- Investing in preventative features like electrostatic dissipative laminate can help you to create a safer, more efficient environment, and save you money down the line.

2.9. Discussion on the results from the article “Preparation of PEEK/MWCNTs composites with excellent mechanical and tribological properties” [43].

2.9.1. PEEK/MWCNTs composites’ thermal Properties

PEEK is like a semicrystalline thermoplastic and due to its mechanical and tribological properties, it is closely related to the molecular chain structure and can be interacted with polymer chains due to the incorporation of fillers and change its crystallization and melting behaviour, which effects the PEEK composites. Therefore, in the article of “Preparation of PEEK/MWCNTs composites with excellent mechanical and tribological properties” authors used DSC to investigate the effect of contents and different lengths of MWCNTs on the thermal properties of PEEK/MWCNTs composites.

The below figure shows the thermal properties gathered by the authors in the above-mentioned article

Sample	T_g (°C)	T_c (°C)	T_m (°C)	X_c (%)
PEEK	148	296	340	24
$0.5–2\ \mu m^{-0.1}$	149	294	341	26
$0.5–2\ \mu m^{-1}$	149	297	340	25
$0.5–2\ \mu m^{-2}$	149	297	341	25
$0.5–2\ \mu m^{-4}$	149	298	339	23
$10–30\ \mu m^{-0.1}$	148	296	341	25
$10–30\ \mu m^{-1}$	148	297	340	25
$10–30\ \mu m^{-2}$	148	298	340	24
$10–30\ \mu m^{-4}$	148	299	340	23
Approximately $50\ \mu m^{-0.1}$	149	293	340	28
Approximately $50\ \mu m^{-1}$	148	295	340	26
Approximately $50\ \mu m^{-2}$	147	296	341	26
Approximately $50\ \mu m^{-4}$	147	296	340	25

T_g: glass transition temperature; T_m: melting temperature; T_c: crystallization temperature; X_c: crystalline; MWCNTs: multiwalled carbon nanotubes; PEEK: polyether ether ketone.

Figure 13: Thermal properties of the PEEK/MWCNTs composites [43]

2.9.2. PEEK/MWCNTs Composites' Mechanical Properties

The effect on mechanical properties of MWCNTs/PEEK composites due to MWCNTs loading and different lengths of MWCNTs, is shown in Figure 14 which is retrieved from the above-mentioned article

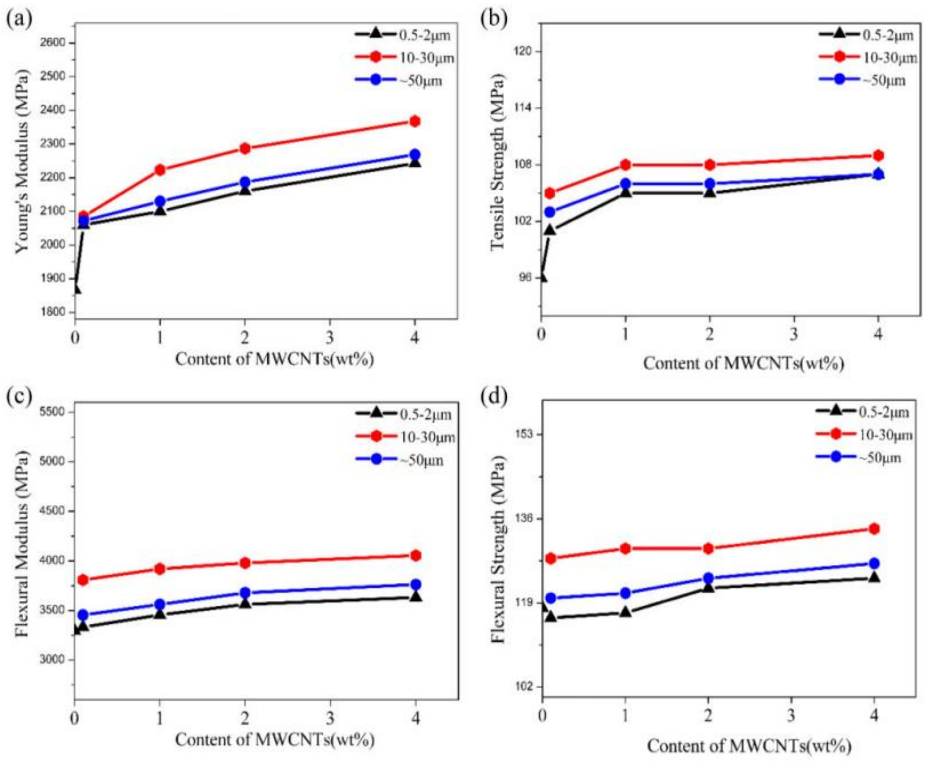


Figure 14: PEEK/MWCNTs composite's Mechanical properties of: (a) Young's modulus, (b) tensile strength, (c) flexural modulus, and (d) flexural strength. MWCNTs: multiwalled carbon nanotubes; PEEK: polyether ether ketone [43]

These results explains that the mechanical properties of PEEK/MWCNTs composites can be increased significantly with the incorporation of MWCNTs.

2.9.3. PEEK/MWCNTs Composites Tribological Properties

The two important factors, coefficient of friction and wear rate characterizes the tribological performance.

In the above-mentioned article, the analysis was done on MWCNTs loading and different lengths of MWCNTs, which are shown in Figure 15

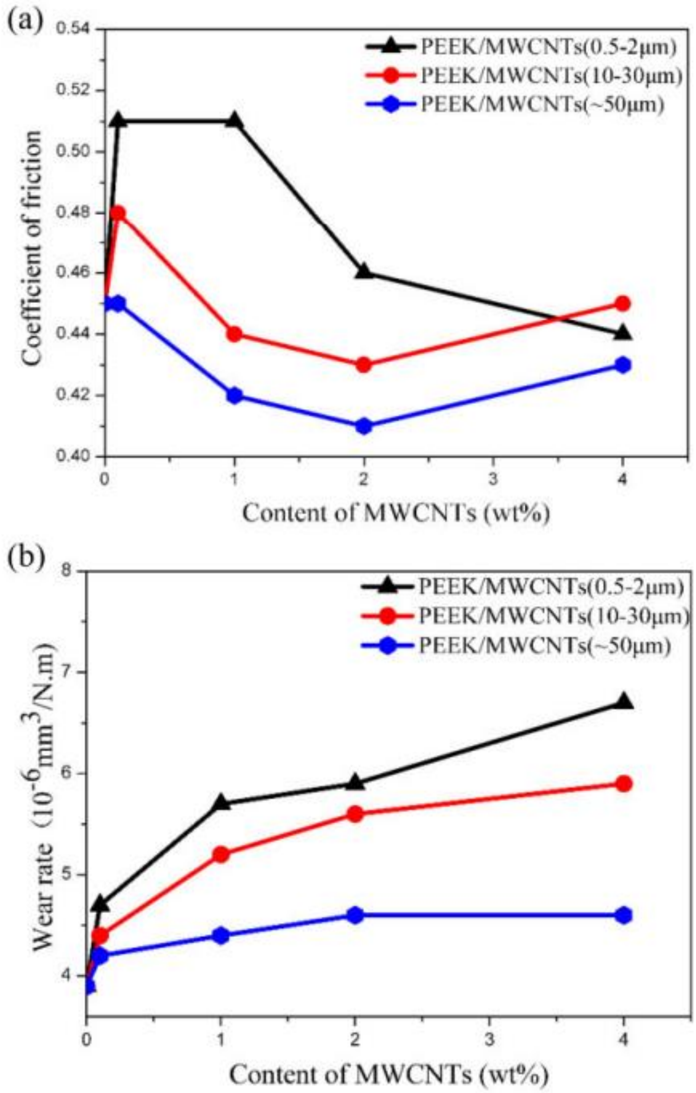


Figure 15: PEEK/MWCNTs composite's Tribological properties: (a) coefficient of friction and (b) wear rate. MWCNTs: multiwalled carbon nanotubes; PEEK: polyether ether ketone [43].

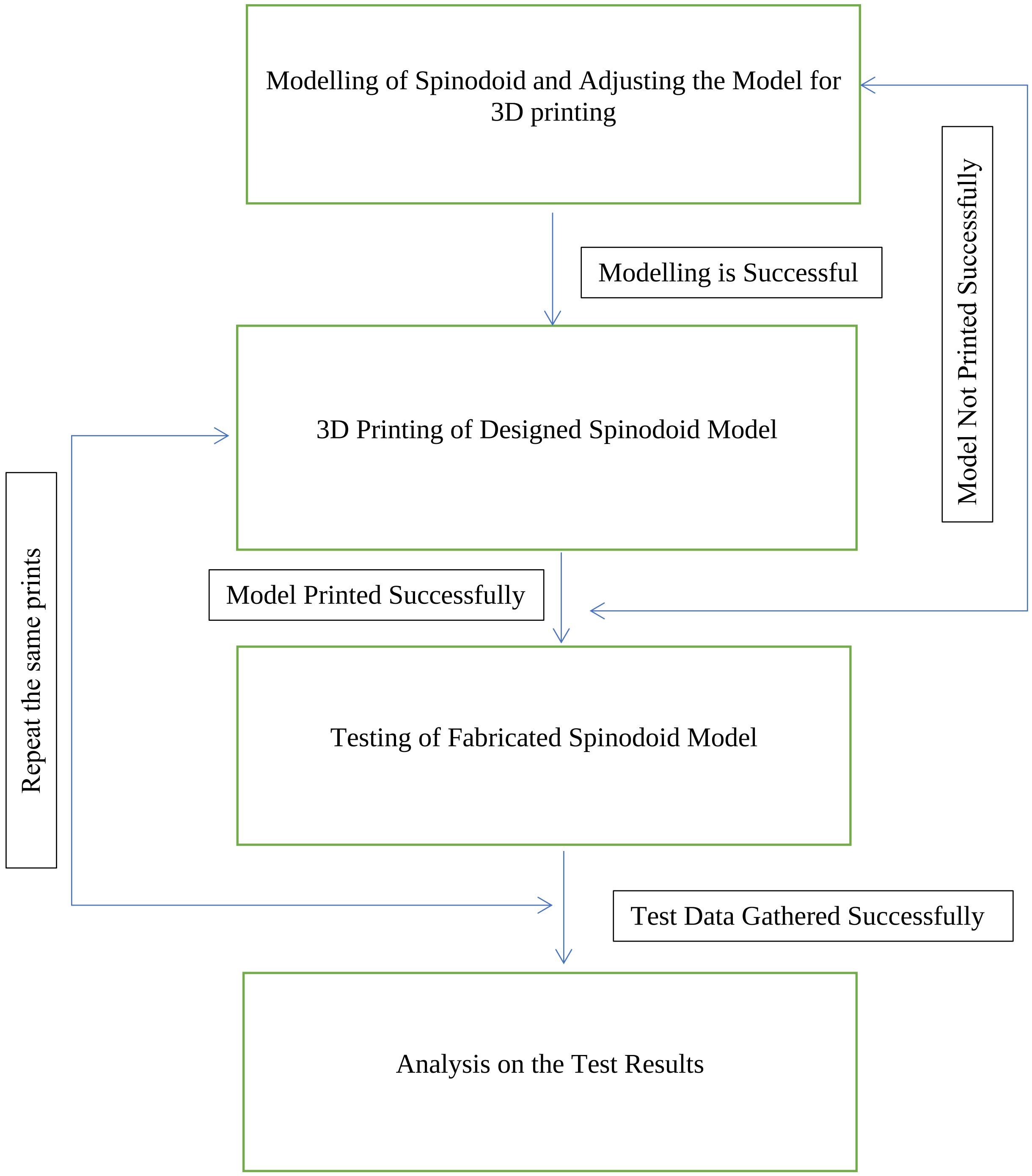
2.9.4. Conclusion Provided in the article

This article systematically investigated the effect on the thermal, mechanical, and tribological properties with different lengths of MWCNTs. When PEEK composites are incorporated with 10–30 mm length of MWCNTs exhibited the best mechanical properties. The approximately 50 mm MWCNTs can effectively decrease the adhesive wear, which was a benefit of forming a thin transfer film, thereby effectively decreasing the coefficient of friction and improving the wear resistance [43].

3.Methodology

The process to understand the mechanical and electrical behaviour of the spinodoid model fabricated with PEEK/MWCNT is divided into four levels

These levels are showed in below flow



4.Modelling of Spinodoid Using MATLAB

Spinodoids are bi-continuous surfaces which are indeed complicated structures to design and orientation of surfaces varies for these structures. This is the reason the Gibbon Toolbox of MATLAB [45] is used to develop random spinodoid structures.

This image-based bioengineering and geometry (GIBBION) is an open-source toolbox developed by Kevin M. Moerman.

This toolbox includes

- Array of image and geometry processing and visualization tools
- These tools are interface with software such as TetGen, FEBio.
- These software gives highly flexible image-based modelling environment

This application highlights are listed below

- Computer Aided Design (CAD) tools
- Volumetric meshing
- Lattice structure
- Finite element analysis
- Visualization
- Surface meshing
- Segmentation

4.1. Detail Explanation of Design of Spinodoid Structure in MATLAB

- rng: It is a random number generated is to produced controlled random number sequence every time. This is used to in the code to produce set of random number or random seed while designing
- The predefined spinodoid function in used to generate the spinodoid structure.
- The gpatch is used to plot the figure in MATLAB for visualizing the modelled spinodoid
- Sample MATLAB code for generating spinodoid structure

```
Spinodoid_structure.isocap=true; % option to cap the isosurface
Spinodoid_structure.domainSize=1; % domain size
Spinodoid_structure.resolution=75; % resolution for sampling GRF
Spinodoid_structure.waveNumber=15*pi; % GRF wave number
Spinodoid_structure.numWaves=1000; % number of waves in GRF
Spinodoid_structure.relativeDensity=0.5; % relative density: between [0.3,1]
Spinodoid_structure.thetas=[90 0 0]; % conical half angles (in degrees) along xyz
Spinodoid_structure.R = eye(3); % Rotate the GRF, R must be SO(3)
[F,V,C]=spinodoid(Spinodoid_structure);
groupOptStruct.outputType='label';
[G,~,groupSize]=tesgroup(F,groupOptStruct); %Group connected faces
[~,indKeep]=max(groupSize); %Index of largest group
F=F(G==indKeep,:); %Trim faces
C=C(G==indKeep,:); %Trim color data
[F,V]=patchCleanUnused(F,V); %Remove unused nodes
 cFigure; gpatch(F,V*30,C,'none');
 axisGeom; camlight headlight; colormap parulaicolorbar;
 gdrawnow;
```

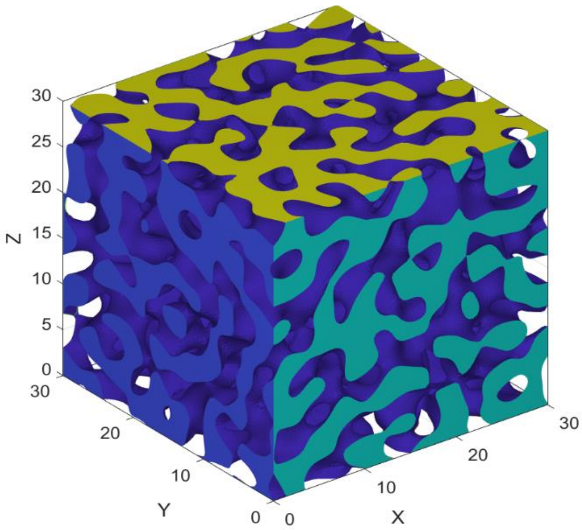


Figure 16: Generated Spinodoid Model

As we can see the above obtained spinodoid structure is without any specific wall thickness, to achieve this surf2solid MATLAB extension is used provide the required wall thickness.

- The one of the objects of this project is to evaluate the thin walled spinodoid, So the wall thickness provided for desired spinodoids is estimated to be 0.48mm and 0.40 mm
- MATLAB code for thin walled spinodoid structure

```
[~,~,~,GRF_A,X,Y,Z,levelset_A] =spinodoid(Spinodoid_structure);
[F,V]=isosurface(X,Y,Z,GRF_A,levelset_A);
FV =surf2solid(F,V*30,'triangulation','delaunay','thickness',0.48);
cFigure; gpatch(FV.faces,FV.vertices,S);axisGeom; camlight headlight;
new = [0 0 0  1 0 0  0 1 0 0 0 1 1 1 1];
colormap(new);
icolorbar;
gdrawnow;
```

- Generated thin wall model

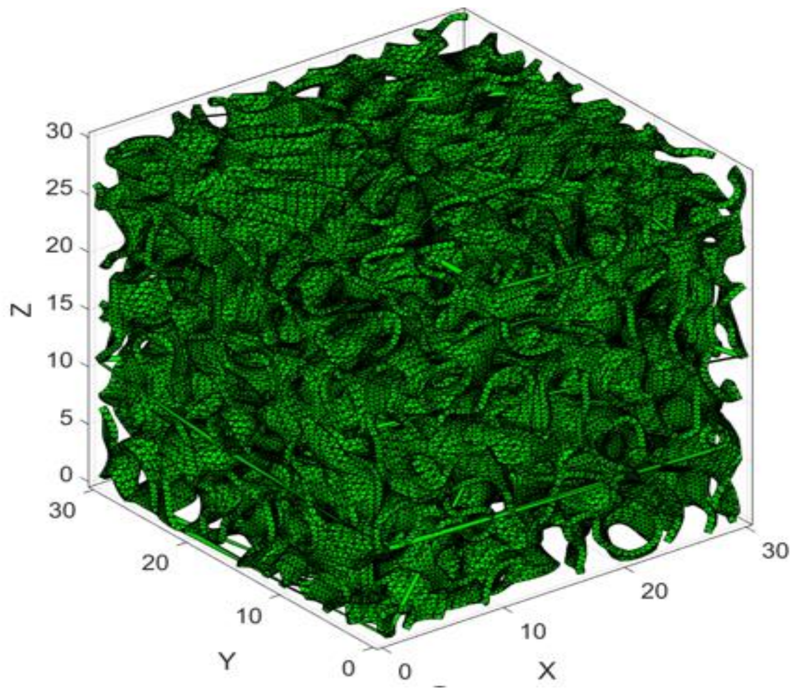


Figure 17:Generated Thin-wall Spinodoid Model

- The obtained model is converted to STL file to use it in other software for further analysis and 3D printing for that STL write file extension is used.
- MATLAB code for converting it into STL file

```
stlwrite ('Spinodoid.stl’, FV,'mode','binary');
```

5.Specification of Spinodoid Models

5.1. Specifications of Designed Spinodoid Models

Spinodoid Model	Surface Orientation [X Y Z]	Surface Wall Thickness (mm)	Length (mm) X breadth (mm) X height (mm)
Spinodoid A	[90 0 0]	0.40	30 X 30 X 30
Spinodoid B	[90 0 0]	0.48	30 X 30 X 30
Spinodoid C	[45 0 0]	0.40	30 X 30 X 30
Spinodoid D	[45 0 0]	0.48	30 X 30 X 30

Table 2: Specifications of Designed Spinodoid Models

5.2. Specifications of Spinodoid Model after Printing

5.2.1. Set 1 of four spinodoid models

The designed spinodoids are printed using Apium P220 printer with material PEEK and below table shows the change in specification after printing

Spinodoid Model	Surface Orientation [X Y Z]	Surface Wall Thickness (mm)	Length (mm) X breadth (mm) X height (mm) and weight (g)
Spinodoid A	[90 0 0]	0.40	30.39 X 30.41 X 30.7 and 12.8
Spinodoid B	[90 0 0]	0.48	30.09 X 30.56 X 30.46 and 15.6
Spinodoid C	[45 0 0]	0.40	30.61 X 30.5 X 30.36 and 10.3
Spinodoid D	[45 0 0]	0.48	30.48 X 30.43 X 30.77 and 16

Table 3: Specifications of Set-1 Spinodoid Model after Printing

5.2.2. Set 2 of four spinodoid models

The designed spinodoids are printed using Apium P220 printer with material PEEK and below table shows the change in specification after printing

Spinodoid Model	Surface Orientation [X Y Z]	Surface Wall Thickness (mm)	Length (mm) X breadth (mm) X height (mm) and weight (g)
Spinodoid A	[90 0 0]	0.40	30.46 X 30.79 X 30.79 and 12.8
Spinodoid B	[90 0 0]	0.48	30.4X 30.62 X 31.01 and 15.3
Spinodoid C	[45 0 0]	0.40	30.46 X 30.68 X 30.69 and 10.3
Spinodoid D	[45 0 0]	0.48	29.93 X 29.79 X 25.63 and 9.6

Table 4: Specifications of Set-2 Spinodoid Model after Printing

5.2.3 Specifications of Random Spinodoid Models

The complex structures like spinodoid may not print perfectly in first few trails and below table show the specifications of spinodoid models which were not fabricated as expected.

Spinodoid Model	**Surface Orientation [X Y Z]**	**Surface Wall Thickness (mm)**	**Length (mm) X breadth (mm) X height (mm) and weight (g)**
Sample 1	[45 0 0]	0.40	30.68 X 30.74 X 30.76 and 20.3
Sample 2	[45 0 0]	0.48	30.45X 30.93 X 22 and 8.9
Sample 3	[45 0 0]	0.40	30.48 X 30.44 X 27.05 and 10.3
Sample 4	[45 0 0]	0.48	30.49 X 30.92 X 26.4 and 9.1
Sample 5	[45 0 0]	0.4	31 X 30.52 X 30.82 and 20.2
Sample 6	[45 0 0]	0.4	30.38 X 31.03 X 30.5 and 20.3
Sample 7	[45 0 0]	0.4	30.63 X 30.73 X 30.44 and 15.6
Sample 8	[45 0 0]	0.4	30.48 X 30.73 X 30.44 and 20
Sample 9	[45 0 0]	0.4	30.32 X 30.79 X 14.57 and 11.2
Sample 10	[45 0 0]	0.4	31.21 X 30.27 X 18.09 and 9.1
Sample 11	[45 0 0]	0.4	31.5 X 30.24 X 15.98 and 9.8

Table 5: Specifications of Spinodoid Model with improper printing

6.Calculations

6.1. Calculation of Density of Material

Sample Model	Length (cm) X breadth (cm) X height (cm)	Mass (g)	volume(cm^3)	Density (g/cm^3)
Sample 1	1.03 X 1.041 X 1.014	1.28	1.091	1.172
Sample 2	1.031 X 1.037 X 1.01	1.26	1.079	1.166
Sample 3	1.037 X 1.047 X 1.004	1.3	1.090	1.192
Sample 4	1.035 X 1.04 X 1.008	1.27	1.085	1.170
Sample 5	1.031 X 1.033 X 1.01	1.27	1.075	1.180
Sample 6	1.04 X 1.05 X 1.007	1.28	1.099	1.164

Table 6: Measured Values of Solid Spinodoid

The relative density of material is calculated by printing a solid block with 100% infill and measuring its volume and mass to obtain the measured relative density of PEEK material.

Therefore, average of densities of above table results in the approximate material density .

Thus, the measured density value of PEEK material is 1.174 g/cm^3.

6.2. Calculation Relative Densities Spinodoid Models

6.2.1. Desired Relative Density of Spinodoid models

The desired relative density is calculated by finding the ratio volume of the spinodoid and volume of solid cube.

Spinodoid Model	Surface Orientation [X Y Z]	Wall Thickness (mm)	Surface Area of designed model (mm^2)	Volume of Spinodoid (mm^3)	Volume of the cube (mm^3)	Relative Density
Spinodoid A	[90 0 0]	0.40	32390.6	12956.24	27000	0.47
Spinodoid B	[90 0 0]	0.48	32550.3	15624.144	27000	0.57
Spinodoid C	[45 0 0]	0.40	30968.1	12387.24	27000	0.45
Spinodoid D	[45 0 0]	0.48	31116.6	14935.968	27000	0.55

Table 7: Desired Relative Densities of Modelled Spinodoids

6.2.2. Measured Relative Density after printing

- The density is the ratio of mass and volume
- The calculated density of material is 1.174 g/cm^3

Spinodoid Models Of Set 1	Surface Orientation [X Y Z]	Wall Thickness	Density Of spinodoid (g/cm^3)	Relative Density
Spinodoid A	[90 0 0]	0.40	0.45	0.38
Spinodoid B	[90 0 0]	0.48	0.55	0.47
Spinodoid C	[45 0 0]	0.40	0.36	0.30
Spinodoid D	[45 0 0]	0.48	0.56	0.47

Table 8: Measured Relative Densities of set-1 Spinodoids

Spinodoid Model Of Set 2	Surface Orientation [X Y Z]	Wall Thickness	Density Of spinodoid (g/cm^3)	Relative Density
Spinodoid A	[90 0 0]	0.40	0.443262195	0.37
Spinodoid B	[90 0 0]	0.48	0.530042745	0.45
Spinodoid C	[45 0 0]	0.40	0.359132809	0.30
Spinodoid D	[45 0 0]	0.48	0.420092963	0.35

Table 9: Measured Relative Densities of set-2 Spinodoids

Note: The height of the spinodoid D in set 2 is 25mm, whereas other spinodoids are 30mm

7.Results and Analysis of Compression Test on 3D printed Spinodoids

7.1. Study on Compression Test

The compressive strength and elastic modulus are critical parameter for many structures.

A compression test is a type of mechanical test in which a component responds to forces that crush, compress, squash, push and flatten the test specimen [44].

It is similar in nature to tensile and bend tests [44].

It helps in measuring the component strength and stiffness under applied crushing loads [44].

This compression test is typically conducted by applying compressive pressure to a component using platens or specialized fixtures with a testing machine that produces compressive loads [44].

7.1.1. Compressive Response of Polymeric Cellular Materials [45]

In this study, compression test performed under various high performance light weight cellular materials which are conventionally used for energy absorption applications.

In the above-mentioned paper ("Compressive Response of Polymeric Cellular Materials"), authors conducted series of compressive tests, were performed over range of strain rates with a universal testing machine.

The compression test was divided into two level in this paper

1. Quasi-Static Compression Test
2. Dynamic Compression Test

From this compressive test, authors observed that compressive behaviour depends on relative density and mechanical properties of the cellular structure.

7.2. Compressive test on Spinodoid Model

The printed spinodoid models are subjected to compression test through which the force, displace and time of UTM machine are collected. A multimeter is connected to the platens of UTM machine with which the resistance and time reading are noted.

The Force vs Displacement curves of spinodoid are plotted below

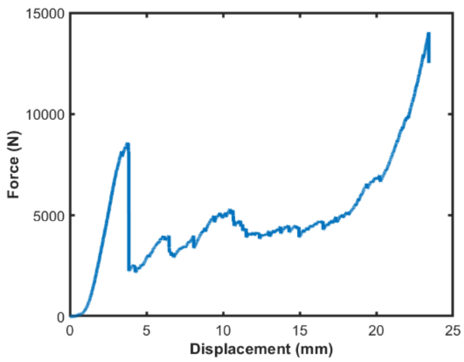


Figure 18: Force vs Displacement of Spinodoid A

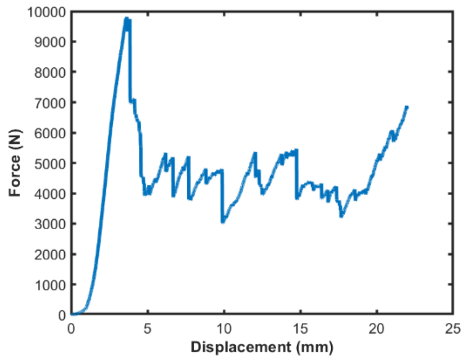


Figure 19: Force vs Displacement of Spinodoid B

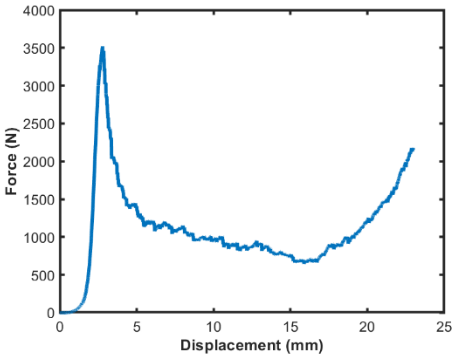


Figure 20:Force vs Displacement of Spinodoid C

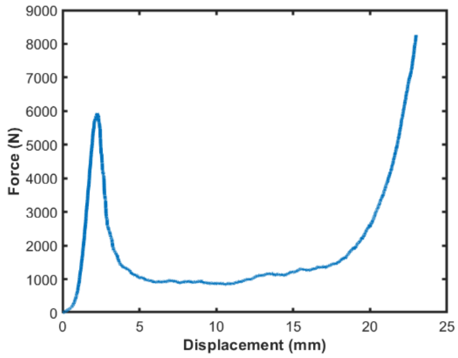


Figure 21: Force vs Displacement of Spinodoid D

7.2.1. Mechanical Analysis of Spinodoid Models

Stress: It is defined as the external force acting on the cross-sectional area.

Strain: It is defined by the change in dimension of the component to the original dimension.

Spinodoid Model of Set 1	Cross-Sectional Area (mm^2)	Original Dimension (mm)
Spinodoid A	924.1599	30.7
Spinodoid B	919.5504	30.46
Spinodoid C	933.605	30.36
Spinodoid D	927.5064	30.77

Table 10: Measured Dimensions of set-1 Spinodoids after Printing

Spinodoid Model of Set 2	Cross-Sectional Area (mm^2)	Original Dimension (mm)
Spinodoid A	937.8634	30.79
Spinodoid B	930.848	31.01
Spinodoid C	934.5128	30.69
Spinodoid D	891.6147	25.63

Table 11: Measured Dimensions of set-2 Spinodoids after printing

The stress vs strain curves of spinodoids are plotted below

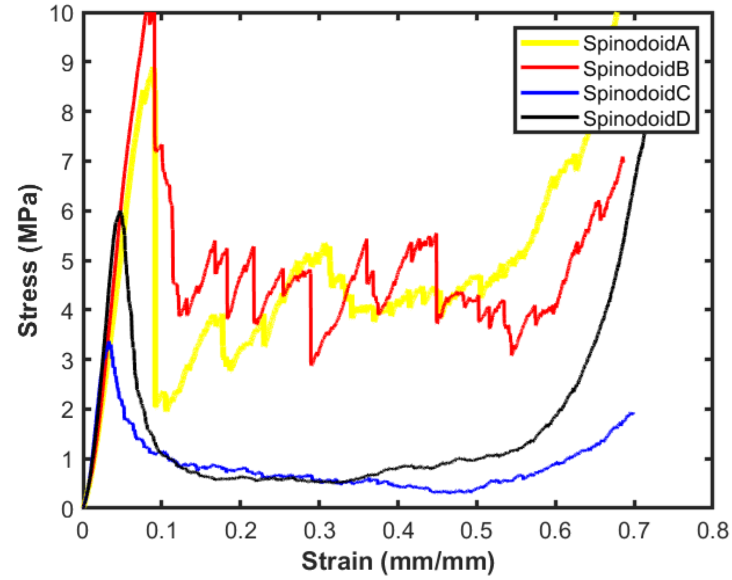


Figure 23: Stress vs Strain curves of Set 1 Spinodoids

Spinodoid Model of Set 1	Standard Deviation of stress data	Standard Deviation of strain data
Spinodoid A	2.9638	0.2255
Spinodoid B	1.7946	0.2095
Spinodoid C	0.7112	0.2280
Spinodoid D	2.0595	0.2470

Table 12: Standard deviations of set-1 Spinodoids

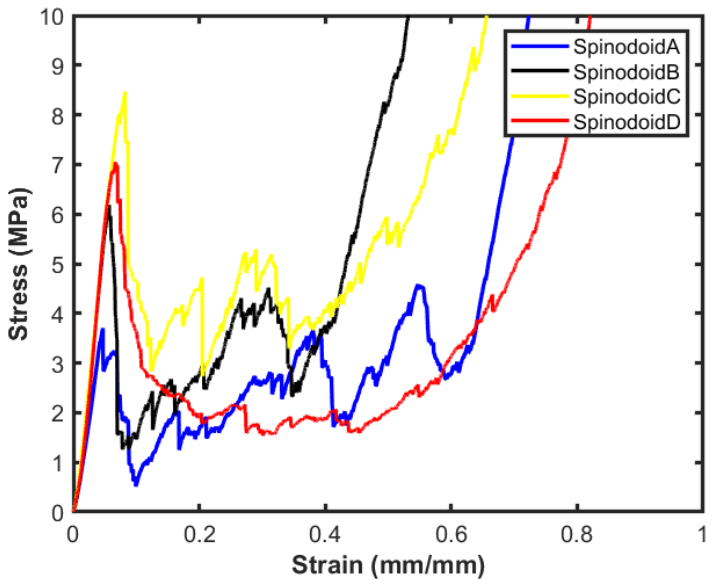


Figure 22: Stress vs Strain curves of Set 2 Spinodoids

Spinodoid Model of Set 2	Standard Deviation of stress data	Standard Deviation of strain data
Spinodoid A	5.4409	0.2343
Spinodoid B	6.2510	0.2950
Spinodoid C	4.2212	0.2470
Spinodoid D	5.0863	0.1880

Table 13: Standard deviations of set-2 Spinodoids

The above curves explain about the two similar sets of spinodoids stress with respect to strain during compression.

Ideally both curves should look similar, whereas during the test there were few human errors due to which the compress on similar spinodoid slightly varied, where as to understand this properly only elastic regions are of spinodoids are considered for the study.

The mechanical properties such as strength, toughness, yield point, strain energy, elasticity, resilience and elongation during loading are obtained from the stress-strain graph

- The starting point of necking in stress-strain graph is the ultimate tensile strength which shows the maximum amount of stress a component can handle. Applying load more than this load may cause fracture or breaking
- The area under the stress-strain graph shows the toughness of the component. Area is directly proportional to the toughness of the component
- The slope of the elastic region of stress-strain graph gives the stiffness of the component. In general engineers consider y-intercept as the stiffness.
- The amount of energy absorbed by a material and still return to its original position

Spinodoid Model	**Young's Modulus (N/mm^2) for set 1**	**Young's Modulus (N/mm2) for set 2**
Spinodoid A	112.59	115.67
Spinodoid B	137.03	122.7
Spinodoid C	50.49	40
Spinodoid D	149.8	88.15

Table 14: Young's Modulus Values of Spinodoids

Note: The height of the spinodoid D in set 2 is 25mm, whereas other spinodoids are 30mm

Plotting the elastic region of stress vs strain graphs of spinodoid for better understanding.

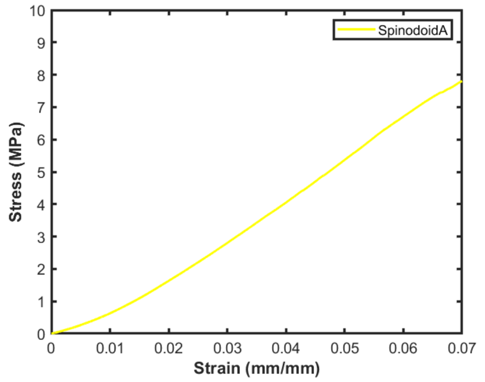


Figure 24: Stress vs Strain of Spinodoid A

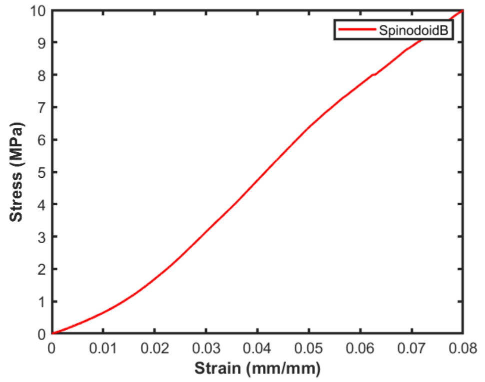


Figure 25: Stress vs Strain of Spinodoid B

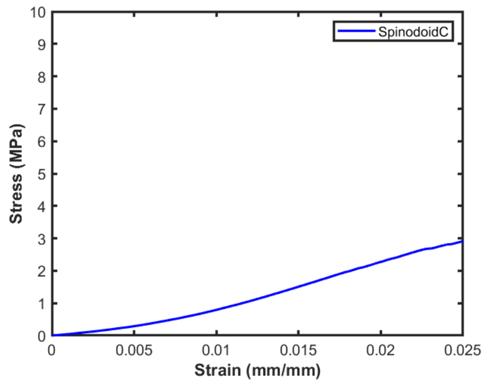


Figure 27: Stress vs Strain of Spinodoid C

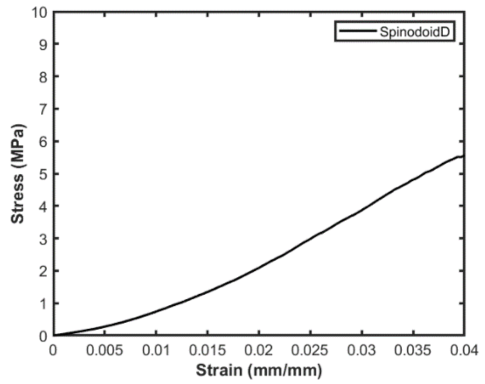


Figure 26: Stress vs Strain of Spinodoid D

7.3. Electrical Analysis of Spinodoid Models

The measure of difficulty of a current to pass through a component is known as resistance.

The Resistivity is a physical property of a particular substance or component which is having particular dimensions.

The relationship between resistivity and resistance is described below

R=ρlA

- Resistivity is denoted with ρ
- Length of conductor is denoted with l
- Cross-sectional area is denoted with A

  Therefore, resistance is directly proportional to resistivity

7.3.1. Results obtained from multimeter during compression test

The below shown figures are the raw curves of the data which consists human errors which are later corrected.

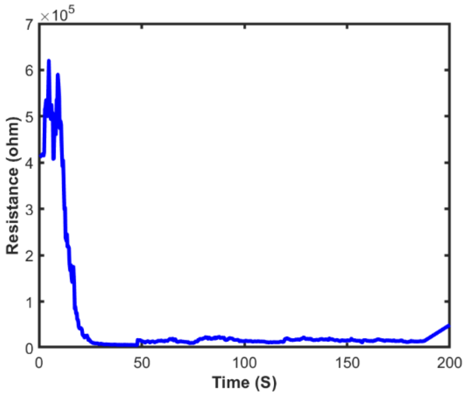


Figure 31: Resistance vs time of Spinodoid A

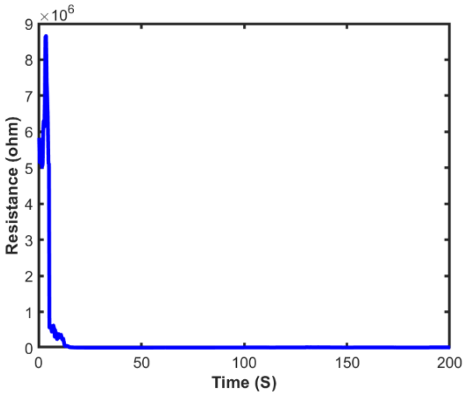


Figure 30: Resistance vs time of Spinodoid B

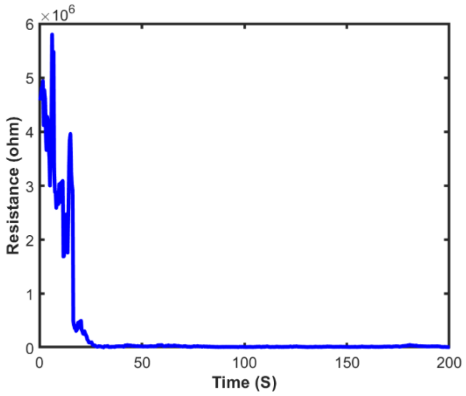


Figure 28: Resistance vs time of Spinodoid C

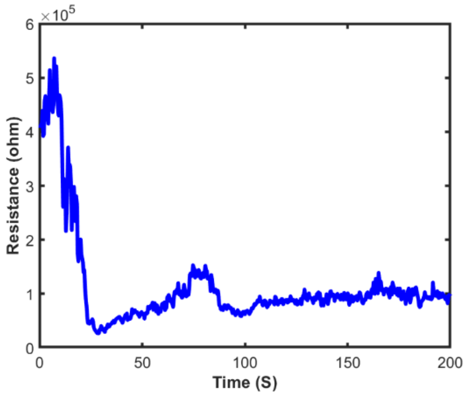


Figure 29: Resistance vs time of Spinodoid D

7.3.2. Normalized Resistance Change

Normalized resistance change is given by (R-Ro)/Ro where Ro is the base resistance and R is the resistance at time t.

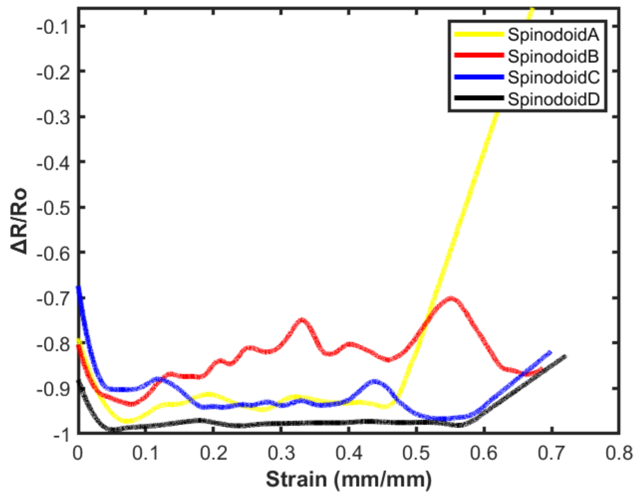


Figure 33:ΔR/Ro vs time of Spinodoids

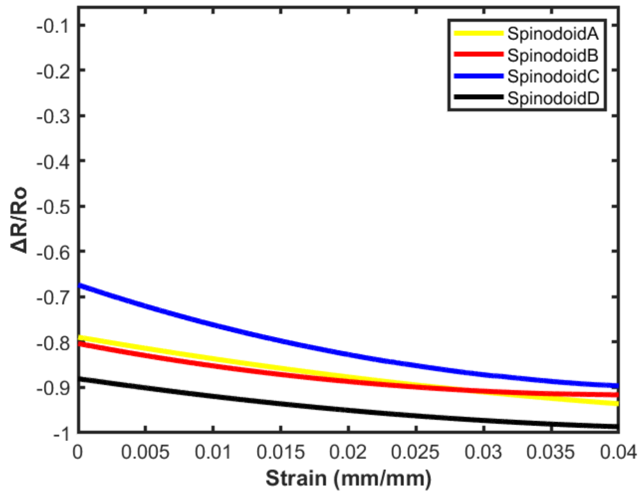


Figure 32:: ΔR/Ro vs time in Elastic Region of spinodoids

Therefore, this data of normalized resistance change with respect to strain can be used to create a data model, used to predict the deformation and damage of these type of samples fabricated with reinforced PEEK/MWCNT.

8.Conclusion

The performance of spinodoids is numerically investigated and experimentally evaluated. In this project Cellular structures of spinodoid are modelled using predefined geometry visualization of Gibbon tool box. Different spinodoid topologies were modelled and printed using fused filament fabrication (FFF) 3D printer. Apium P220 3D printer is specially used as it is the PEEK-ready 3D industrial print and the filament used to fabricate spinodoids in this project is multi walled carbon nano tubes (MWCNTs) reinforced PEEK. These spinodoid topologies are varied mainly by their axis-orientations and by the surface wall thicknesses. The considered axis-orientations and surface wall thicknesses are [90 0 0] ([X Y Z]), [45 0 0] ([X Y Z]) and 0.48 mm and 0.40 mm. Printed spinodoid are subjected to compression test to evaluate their mechanical behaviour and resistance with respect to strain data is measured using multimeter for piezoresistive analysis. The data of force and displacement change collected during compression stress is used to know the spinodoid's strength, stiffness and change in resistance with respect to strain data can be used to create a data model with which deformations and damages of similar type of materials can be predicted. From the results it is observed that the axis-orientation of [90 0 0] shows higher stiffness irrespective of surface wall thickness, whereas another axis orientation [45 0 0] is showing comparatively high stiffness when surface wall thickness 0.48 mm than 0.40 mm.

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