MANUFACTURING AND CHARACTERIZATION
OF ULTRA LIGHT BIO-INSPIRED
NANOCOMPOSITE
STRUCTURES

by

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Abstract

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The inner part of bones is spongy cell-type three dimensional structure called cancellous bone which is the major contributor in keeping the bone weight very low. Yet, bone can sustain body weight and reasonable impact loads implying bone is a naturally optimized light-weight but strong structure.This study demonstrates a novel approach to manufacture bone-like nanocomposite structure for weight saving structural applications. For this, Silicon Carbide (SiC)nano particles are dispersed in SC-15 epoxy resin (a two part liquid resin that solidifies when mixed together at room temperature). Using our novel 3D+ manufacturing technique we developed lighter but stronger nanocomposite structure. The compression test results showed an improvement in the strength and stiffness of epoxy polymer when a small percentage of SiC nano particles are dispersed in pure epoxy matrix. Using the same manufacturing process, new types of sandwich structures with polyurethane foam core were manufactured and bending tests showed higher stiffness with addition of polyurethane foam to regular honeycombed sandwich structure.

Table of Contents

List of Illustrations

List of Tables

Chapter 1

Introduction

Light weight structures play a significant role in aerospace and aviation industry since the reduction of structural mass translates directly into increment in energy efficiency. Moving a light vehicle is more fuel efficient since it takes less energy to move a lighter object than to move a heavier object. Ultra-lightweight structures and materials enable aircrafts to carry more fuel and payload. In military, these structures increase the mission duration and cruise time by decreasing fuel consumption in aircrafts. In commercial aircraft, they would reduce operational costs via better fuel efficiency. Developing lightweight structures can not only benefit aviation industry, but it is also advantageous to the automotive industry and marine industry, since fuel efficient cars and trucks are more economical and sustainable, and reducing the structural weight of ships can increase their cargo carrying capacity and their speed. For every 10% reduction in weight of the vehicle, fuel economy increases by 6-8%.So if we add that up over all the vehicles, massive amounts of energy can be conserved. Fuel efficiency is very important because it can reduce operational costs, oil dependence costs of the vehicles and increase energy sustainability as oil is a nonrenewable source and sustainability of life depends on the effective use of natural resources. In addition to fuel economy, light weight structures help reduce CO_2 emissions since the decrease in vehicle mass provide allowance to include emission control systems.

In order to resist the various forces that act on an airplane during its flight, aircraft structures must be strong, durable and stiff enough while being light. In designing an aircraft, it is very essential to find a compromise between high strength and low weight. Solid Aluminum alloy materials have been used in aircraft industry for decades. They are strong and fairly light weight and quite durable. However they are any applications where solid Aluminum is too heavy when strength to weight ratio is compared. Some of these applications include

- Cabin interiors structures
- Cabin floor panels

- Engine nacelle components
- Wing leading edge panels
- Cargo panels
- Aileron balance panels, etc.

One of the weight reduction strategies currently employed in aircrafts is to use sandwich panels instead of solid panels. The use of sandwich structures in aviation to reduce the weight dates back to 1940's[30]. They were used to replace conventional sheet and stringer or beam support approach and their use had been increasing ever since in commercial aviation because of their exceptional specific stiffness and strength properties. Sandwich structures are usually made up of two relatively thin and stiff skins, parted by a lightweight core as shown in figure 1-1. The partition of skins by the core increases moment of inertia of the panel without adding much weight generating an efficient structure that can resist bending and buckling loads.

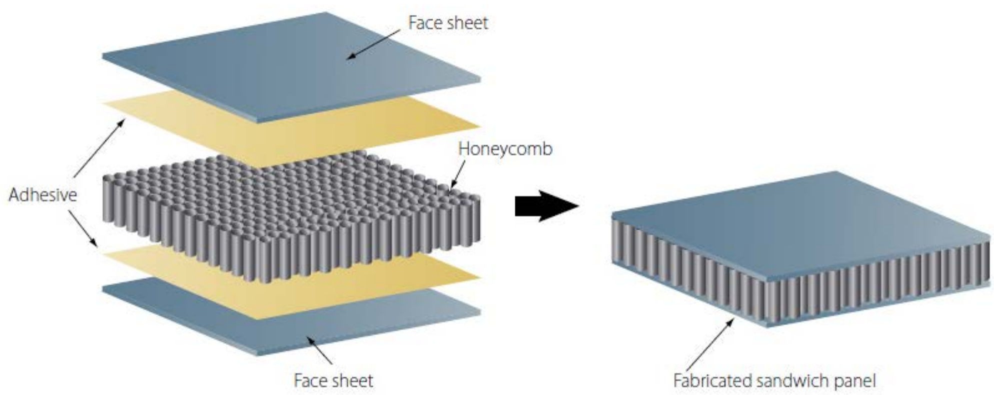


Figure 1-1 Sandwich panel [10]

1.1 The sandwich effect

The objective of making sandwich structures is to increase the bending stiffness of the beams without adding much weight [17]. The stiffness of a beam is given by the equation

$$\frac{F}{\delta} = \frac{48(EI)eq}{L^3}$$

$$EI = \frac{E_c b c^3}{12} + \frac{E_f b t^3}{6} + \frac{E_f b t d^2}{2}$$

If the face thickness is much less than that of the core i.e d/t >6 and if the face material is stronger than the core material i.e (E_f/E_c. $td^2/c^3 > 17$), then equation can be reduced to

$$EI = \frac{E_f b t d^2}{2}$$

From this equation, it is clear that the contribution of core material to the stiffness of the beam is negligible compared to that of face material. But the distance between the faces is the major contributor to the increase in stiffness. Figure 1-2 shows the values of bending rigidity for various types of beams neglecting the weight of core.

Figure 1-2 sandwich effect [9]

From the figure 1-2,it can be observed that by increasing the thickness, the stiffness of the structure increased 48 times and strength increased 6 times. Thus, the sandwich concept increases the flexural rigidity and stiffness of a beam without adding much weight. So, the application of sandwich structures is constantly increasing. Since, weight reduction is the critical factor in aviation, utilization of these sandwich structures for aircraft fuselage has been developing but the main challenge is to select an adequate core material for this purpose.

Currently, three different types of the cores are available: honeycomb, balsa or foam cores. Honeycomb cores are extensively used because of their better mechanical properties and fire safety properties. But these closed honeycombed cells can lead to accumulation of condensed water, which increases weight and reduces the properties. Another limitation of these sandwich structures is that they cannot resist the impact loads acting perpendicular to the surface to the structure due to thin faces and the core cannot withstand compressive loads effectively. The impacts are common for an aircraft in flight ranging from low velocity (e.g. tool drop) to high velocity impacts (e.g. bird strike, hail). The geometry and the properties of the face and core materials determine the mechanical behavior of sandwich panel. Most applications require some minimum stiffness; it should be able to withstand the loading during its service while being light. So, the following factors are to be considered while optimizing sandwich panels: core and skin thickness, core and skin materials and the core density.

1.2 Weight reduction approach

This study investigates a new core structure inspired from the cellular structures available in nature to develop strong, light weight structures and demonstrates a novel approach to manufacture those cellular structures by mimicking the composition of those structures with nanocomposites. The main factors that are to be considered while constructing a strong, light weight structure are:

1. Structural Geometry
2. The Material of the structure
3. Manufacturing of the structure

1.2.1 Structural Geometry

Soon after life began on earth, nature discovered and evolved low density cellular materials. Without these light weight cellular materials, our bones would not be able to support the weight of our body. These cellular materials configures as cores of columns and beams with strong outer surfaces. Bone, the material that makes vertebrates distinct from other animals, has advanced into a remarkable tissue over several hundred million years. It has the strength similar to cast iron while being as light as wood.

The front leg of a horse is able to withstand the loads generated by this 1500-pound animal while it is travelling at 30 miles per hour, the wings of the birds are able to keep them afloat for long time without landing; through entire migrations which sometimes can be over 10,000 miles, the antlers of deer undergo tremendous impacts during terrestrial clashes with other deer without fracturing because of these cellular structures.

Superficially, bones look like solid structures but most bones are intricate sandwich structures made up of a dense outer shell called cortical bone and internal to the cortical bone is cancellous bone which has an open honeycombed structure with needle like structures and flat pieces called trabeculae as shown in figure 1-3.This type of bone exists at the joints or at the extreme positions of long bones and in skulls. This configuration provides a large surface area to bear loads while minimizing the weight of bone. This design reduces the bearing stress on joints. In the skull, this type of sandwich core can take impact loads.

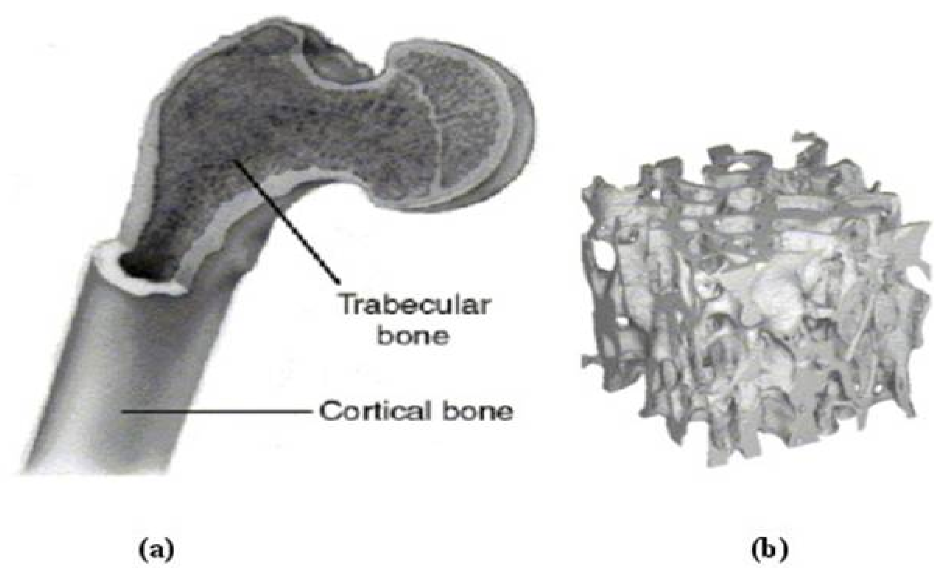


Figure 1-3 a) Cross sectional view of a head of the femur b) Magnified section of trabecular bone [15]

The cellular structure of trabecular bone as can be seen from figure 1-3 b) comprises of interconnected network of rods and plates. Low density cells are created by a network of rods, while the plates produce virtually closed cells with higher density. Generally, the relative density of trabecular bone varies from 0.05 to 0.7. Low density cells are open and like rods. They become closed and more like plates as density increases.

1.2.1.1 Stresses

Antonie Van Leeuwenhoek [18],an early microscopist observed the microstructure of trabecular bone in a human femur and in a bird wing and found a relationship between the structure and the internal forces acting on them. Some bones, for instance, the femur are subjected to a bending moment, and the structure and distribution of cancellous and cortical bone depend on the stresses produced by this bending moment.

In the femoral head, the trabecular bone comprises of two discrete systems of trabeculae. As shown in figure 1-4, one system follows the lines of maximum compressive stress. The second system intersects the first system perpendicularly and follows the lines of maximum tensile stress. This system of trabeculae, in general, is lighter than that of the compressive system.

The trabecular thickness at any point varies with the amount of stresses at that point. They are thicker along the paths of the principal tensile and compressive stresses which enable the structure to economically carry these stresses. Thus, higher strength can be achieved with less material. The compact bone in the shaft is also distributed in such a way that resists the stresses due to bending moment. Since the stresses are higher as we move away from the neutral axis, the bone should be harder and stronger in those areas. So, hard solid structure is developed as the outer part of the bone.

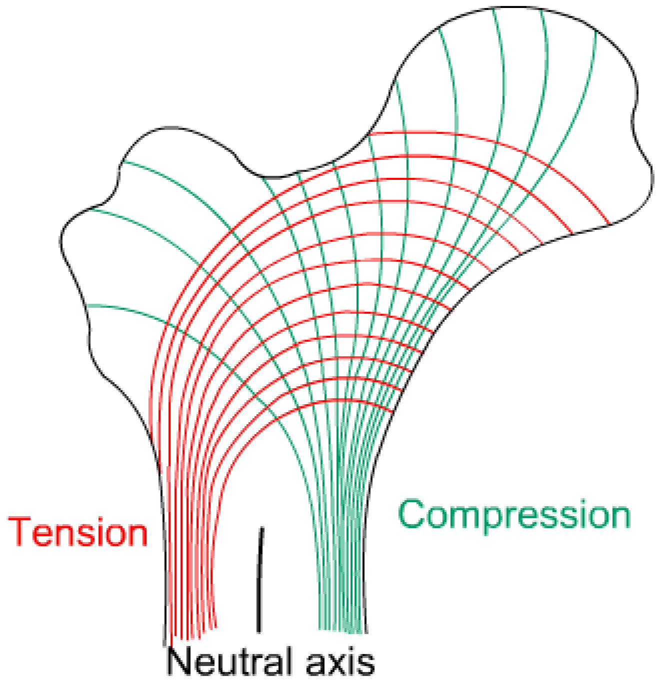


Figure 1-4 Diagram showing computed lines of constant stress from the analysis of various transverse sections[16]

1.2.1.2 The Material properties of cancellous bone

Bone is not made of a uniform solid material, but it is a composite made up of an inorganic mineral called calcium phosphate in the chemical arrangement named calcium hydroxyapatite which gives bones their rigidity and an organic mineral called collagen, an elastic protein which gives toughness. Thus, the strands of collagen provide bone its tensile strength, and the interspersed crystals of hydroxylapatite give bone its compression strength. These effects are synergistic. With the availability of new advanced materials, it is now possible to mimic the structure and material composition of the bone.

The inner spongy part of the bone called cancellous bone is the major contributor in keeping the weight of a bone very low. This structure exists everywhere in the nature. Tall trees are able to take bending loads due to high velocity winds because of this cellular structure. This structure provides efficient distribution of loads and has high compressive strength. It can also effectively absorb reasonable impact loads, thus making it a naturally optimized structure. So, this design was selected to manufacture light weight structure.

1.2.2 Material of the structure

The mechanical properties of a structure depend on the material with which the structure is made. It is possible to make very light, yet stiff materials and structures by using materials with a high elastic stiffness and low density, as are shown in the material property chart in figure 1-5.

The graph represents the strength of different materials against their density. It is clear from the graph that the materials that have high strength are heavy and the lighter materials are weak. The composites are as strong as the metals, but are less dense (low weight). Composites are materials, made from combining of two or more distinct materials with different properties in such a way that one reinforces the other and develops a new material with better properties. A composite has two phases: matrix which is continuous and dispersed phase which contains particles or fibers. The properties of composites are governed by the material properties of the phases, size and orientation of dispersed phase and the expanse of phase. While many materials can be used as matrix depending upon the application, the most commonly used composites to develop light weight structures are Polymer Matrix Composites (PMC). Thermosetting resins such as polyester, polyurethane, epoxy, vinyl ester, etc. can be used as the matrix in PMCs.

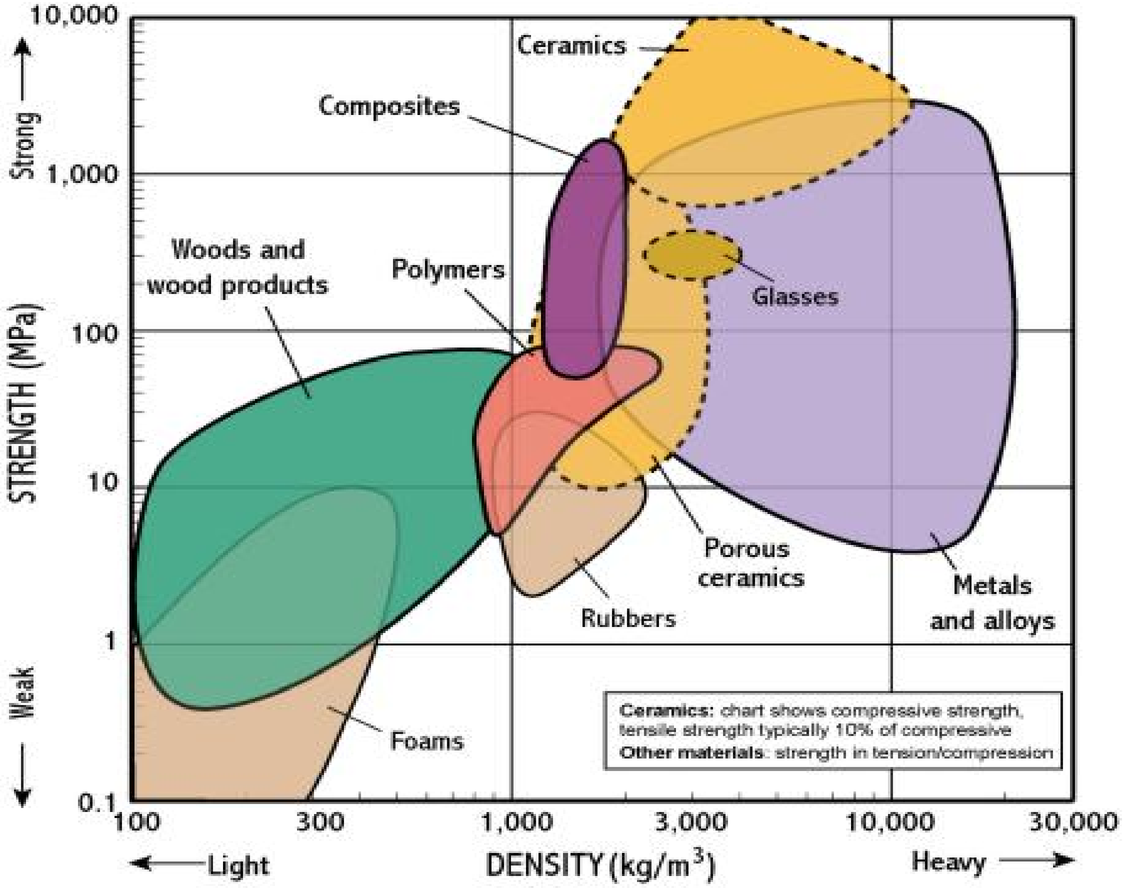


Figure 1-5 A material property chart comparing the compressive strength and density of engineering materials [19]

Epoxy resins have outstanding physical and mechanical properties among all the Polymer Matrix Composites (PMC).The epoxy has a ring structure which assists in absorbing thermal and mechanical stresses better than a linear structure thus improving the stiffness, fracture toughness, and heat resistant properties. Because of these properties, the epoxy resins are widely used as fiber-reinforced composite matrix in industrial and aerospace applications. Recent studies established that reinforcing polymer matrix with very small weight percentage of nanoparticle loadings improved the properties of the epoxy polymer. The nano particles increase the interactions among the atoms because of their larger surface to volume ratio. The nano particles modify the properties of the polymer at the atomic level and the molecular forces, bonding and interactions at this level dictate the overall properties of the materials. The nanoparticles act as fillers for the voids formed during the crosslinking of the polymer and reduces the defects in the polymer. As a result, the material properties are improved to develop a stronger and harder material. So, a study of properties of polymer composites is conducted by fabricating a bone with an epoxy polymer.

1.2.3 Manufacturing

Manufacturing is the most challenging part in developing a structure. Depending on the complexity of the part design, different manufacturing techniques are to be employed and all of them may not be cost efficient. Choosing an effective manufacturing process is very essential as it affects the final product cost.

Generally composites are manufactured by one of the following process: resin transfer molding (RTM), wet lay-up, vacuum assisted resin transfer molding (VARTM), pultrusion, autoclave processing, prepreg method, resin film infusion (RFI), fiber placement technology filament winding, etc. But owing to the complexity in designing the bone structure, a novel process called 3D + manufacturing was developed to manufacture trabecular structure. This final product obtained is ready to use and doesn’t require any further processing.

Chapter 2

Overview of 3D+ manufacturing

2.1 Introduction

The efficacy of advanced composites lies in the fact that they can be tailored. From the vast spectrum of available matrix and reinforcements, properties of composites can be optimized for a specific application. The factors that make the nanomaterials superior to other materials are quantum effects and relatively high surface area. For some nanocomposites, the improvement in properties may be due to the interfacial interactions and for others,it may be due the quantum effects related to nanodimensional structures. The basic step in manufacturing a nano-phased structural polymer composite is to choose the best fabrication method.

But these methods are not suitable to manufacture a complex structure such as bone because it is very different to prepare a mold and to remove it after polymer resin infusion. So, a novel manufacturing process called 3D+ manufacturing is developed. This process involves fabrication of molds with 3D printing technology. With this technique, it is now possible to manufacture any part as a whole without the need for manufacturing separate parts and assembling them later. Three-dimensional ("3D") printing is a rapidly evolving technology field providing individuals with the ability to produce 3D objects quickly and cheaply relative to other methods. It creates the objects by placing molten thermoplastic resin layer upon layer. Once the CAD models are designed for molding the object, various process parameters can be defined on the computer to adapt the CAD files for 3D printing of the molds. The object can then be physically created using injection molding processes utilizing the physical molds.

2.2 3D+ manufacturing process

The 3D+ manufacturing process starts with obtaining mold for the object to be manufactured. It can be designed using any CAD software or inverting the 3D digital image of the object. The mold is printed by a dissolvable material called HIPS using a 3D printer.Then the object is created by resin injection into the mold and finally the mold is removed by dissolving in D-limonene.

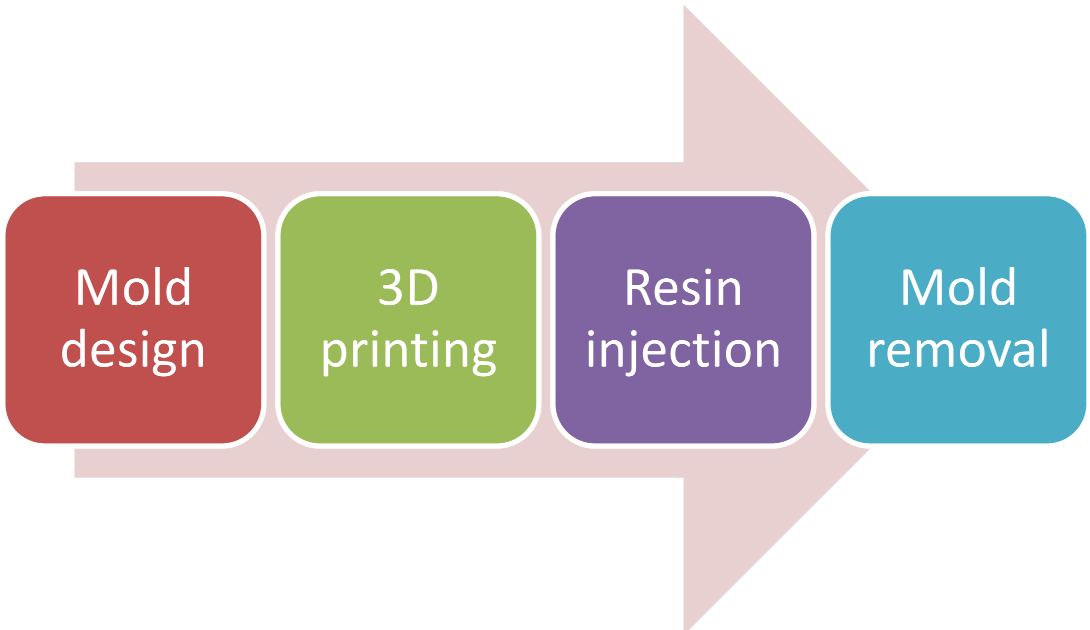


Figure 2-1 Stages of 3D + manufacturing process

The manufacturing process consists of four main stages:

1. Designing the mold
2. 3D printing the mold
3. Resin injection into the mold
4. Mold removal

2.2.1 Mold design

Mold is a structure that contains a hollow cavity of the desired shape where liquid resin is poured and allowed to cure. The molds are fabricated with molten thermoplastic resin that extrudes from the nozzle of 3D printer. The molds are designed and build as a single part unlike in most conventional casting processes where mold contains to two or more sections. With the advancements made in 3D printing technology, different types of plastic filaments are made available along with a dissolvable material called high impact polystyrene (HIPS)which dissolves completely in a liquid called D-limonene.

Two outstanding advantages of 3D printing molds over casting steel/aluminum molds are significant reductions in cost and both lead-time. Generally, it takes several weeks to months to build steel/aluminum tooling molds. However, a usual 3D-printed mold may be printed in a matter of hours. Besides, for metal molds, any defects in the mold design may become apparent only after machining, and manufacturing a suitable sound mold is time-consuming.

The mold can be designed using CAD software or inverting an available digital image of the object to be manufactured. The digital file of the mold should be saved in .STL format. STL is also known as Standard Tessellation Language. This file format is first created by 3D systems and is now supported by many other software packages; it is widely used for rapid prototyping and computer-aided manufacturing. The STL files contain only the surface geometry of a 3D object as a mesh of triangles. They can be saved either in binary or ASCII format. Binary files are more compact (usually by a factor of 6), so they are most commonly used. The accuracy of printed curved surfaces depends on the number and size of the triangles. While converting a CAD image into .stl file format, the following parameters can be adjusted to control the number and size of the triangles. They are

1. Chordal Tolerance / Deviation

It is the maximum distance between the surface of the actual design and the triangulated surface.

2. Angle Control

It is the allowed angular deviation between adjacent triangles. It can be adjusted to increase triangulation for surfaces which have small radii. (Smaller radii need more triangles to fully define the curvature).

So a fine triangulation will give a smoother surface of the final build as shown in figure 2-2. Thus the more detailed stl file has larger file size and it also affects the build time.

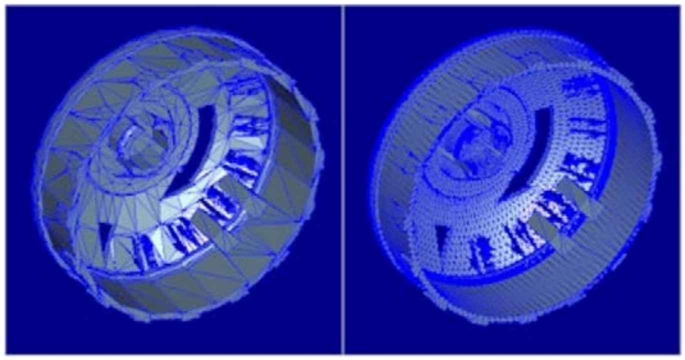


Figure 2-2 Effect of changing chord -height parameter during stl generation [22]

2.2.2 3D printing

3D printing is an additive manufacturing process, where a three dimensional object is created from a 3D digital model by consecutive layering of material through computer control. It is also called a rapid prototyping, a mechanized method that builds a 3D object on a platform of a machine that is connected to a computer, which contains the blueprints of that object.3D printers produce physical models of objects that are either designed using Computer Aided Design (CAD) program or plain digital camera and photogrammetry software or a 3D scanner. The designed model is then sliced digitally into layers and converted into a file that is readable by the 3D printer. The 3D printer then processes the material and deposits it layer by layer according to the design. In this way, objects with intricate shape can be created which otherwise cannot be produced by conventional method. Also this revolutionary method of creating 3D objects saves a lot of money and time. It eliminates the need to design, produce individual parts and combine them together. This technology is now being used in several industries like aerospace, automotive, architecture, defense, education, dental and consumer products among many others. These 3D printers can build objects ranging from nanoscale to objects that are as high as 10 feet and 4 feet wide. In recent years, affordable 3D printers are developed for desktop use.

2.2.2.1 *History of 3D printing*

The 3D printing technologies were first developed in 1980's.Charles Hull obtained a patent in 1984 for his technique named as Stereo lithography, in which layers of photo-hardened polymers are added successively and are cured by Ultraviolet lasers. He designed .stl file format that is extensively acknowledged by 3D printing software. After Stereo lithograph other technologies like Selective Laser Sintering (SLS) and Fused Deposition Modeling (FDM) were introduced. Today several additive processes are available such as selective laser sintering (SLS), selective laser melting (SLM),fused filament fabrication (FFF) and fused deposition modeling (FDM).In these processes, the material is melt or softened to produce layers. But some of the other processes cure liquid materials using highly sophisticated technologies, e.g. stereo lithography (SLA).Different 3D printers employ different technologies that process different materials in different ways. Each technology has its own advantages and limitations. Some printers process materials (nylon, plastic, metal, ceramics) which utilizes a heat /light source to sinter/fuse/melt the material together in defined shape, while some process liquid polymer resin that cures in ultrathin layers. But currently, the most common and widely recognized process is the deposition. Many basic 3D printers are using this technology. In this process, filaments of thermoplastic resins(ABS, PLA, HIPS, and PVA etc.) are extruded through a heated extruder on a heated platform to form layers on after the other until the required shape is obtained.[24,25,26].

2.2.2.2 Manufacturing process of 3D printer

MakerBot 2X replicator is used in the manufacturing process. This 3D printer employs Fused Deposition modeling (FDM) technology for the manufacture of 3D objects. This technology was first developed by S. Scott Crump in late 1980’s [24] and later it was commercialized by Stratasys. The 3D printer comprises of main parts such as

1. An extruder that feeds the plastic filament.

2. One or two nozzles which are independently controlled by Computer Aided Manufacturing (CAM) software.

3. Motors to move the head and control the flow.

4. Material spool to which the plastic filament is wound.

5. A build platform where the model is built.

6. A USB port and SDSC port to input the model.

The plastic filament is unwound and feed into the extruder or nozzle head through a feeding mechanism that can control the flow and can turn it on and off. The nozzle is heated to melt the plastic and the motion of the nozzle is controlled by a CAM package running on a microcontroller. The nozzle can move horizontally, vertically and diagonally to trace any type of contour. The nozzle is moved by stepper motors. These relatively small motors permit extremely small movements close to a fraction of a millimeter so that it can trace almost every shape with a reasonable accuracy. The part is produced by extruding the filament through a heated extruder which hardens immediately to form layers.

In any FDM printer, based on the diameters of the extrusion nozzle and filament and the extrusion speed (flow rate), the software that controls the printer calculates the extrusion volume i.e. the volume of plastic that comes out of the nozzle, by rotating the extruder wheel and pushing a the filament through the hot extruder. So, it is very important that the filament diameter is uniform. Otherwise, extruder may fail and no plastic comes out of the extruder. Commercially filaments are available in two diameters: 1.75 mm and 3 mm .But 1.75 mm diameter is preferred because small filament besides printing faster allows for more precise plastic flow to obtain compact designs and also less force is required to drive the plastic in the extruder since pressure buildup is less in the nozzle.

2.2.2.3 Filament materials

Now that 3D printing technology is rapidly advancing, various materials are available as the filaments. Most commonly used are acrylonitrilebutadienestyrene (ABS), polycarbonate (PC), Polylacticacid (PLA), Highdensitypolyethylene (HDPE), polyphenylsulfone (PPSU) and high impact polystyrene (HIPS).One of the achievements in 3D printing is to develop a dissolvable filament (HIPS). The HIPS filament is similar to ABS but it can dissolve in a solvent called D-limonene. D-limonene is a nontoxic solvent made from orange reeds. It's common colorless, citrus scented solvent available anywhere. It is now possible to build structures that require supports using dual extruder to build supports with HIPS and they can be removed easily by dissolving instead of painstaking scraping process used earlier. Also this dissolvable material can be used to making molds for complex structures whose molds can't be manufactured by other methods. Once the molds are built, the object can be manufactured using any polymer. This is the basic strategy in 3D+ manufacturing.

.2.2.2.4 Creation of digital model

Before inputting the digital model of the object, it should be converted into a file that is readable by the 3D printer. The object either designed using CAD software or obtained from 3D scanner is converted into .stl file, which is used by most additive manufacturing systems. It is a triangulated representation of the surface of the CAD model. Triangulation causes faceting of the 3D model. Any design software supports this file format. Once the .stl file of the object is obtained, it is imported into MakerBot software. This is open source software, provided by MakerBot, which drives the MakerBot replicator. It takes the designed 3D models and prepares them for printing. It simulates the build platform of 3D printer and allows us to move, rotate and position our model on the platform. This software also allows us to scale the size of our model and build multiple objects at once. Once the model is positioned on the platform, other settings such as filament type, extrusion temperature and speed, platform temperature and the resolution of the print are selected. Usually, when a filament is selected, the software automatically updates the extrusion temperature and speed. They can be manually adjusted too. After selecting all the parameters, the file is exported by MakerBot software as a .3xg file .This is the file format supported by the 3D printer. It is uploaded in a SD card and connected to 3D printer .It reads the file and build the object .Figure 2-3 is a flowchart of this preprinting process of 3D manufacturing.

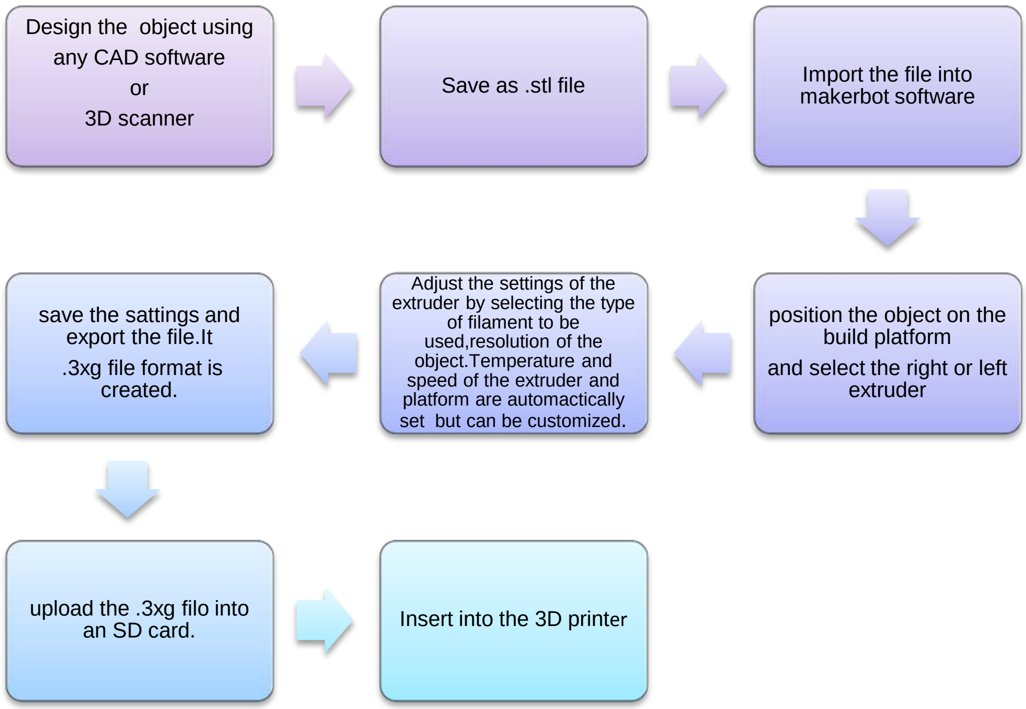


Figure 2-3 Flowchart representing the process of file conversion from .stl to .3xg

2.2.3 Resin injection

Resin injection is an open mold, pressure assisted injection process which employs constant rate industrial syringes. Once the mold is printed by the 3D printer, the liquid resin is injected into the mold which shapes the polymer into our desired shape. Both thermoplastic and thermosetting polymers can be injected into the mold by this process. Thermoplastic polymers soften on heating and harden on cooling. So, they are used for rapid prototyping. On the other hand, thermosetting polymers exist in liquid or viscous form and cures by irreversibly transforming into insoluble, infusible and hard polymer. The curing process alters liquid resin into hard plastic or tough rubber and it can be initiated by a catalyst or heat. During the curing process, the molecules react at chemically active sites and form chains through cross linking to create a rigid, 3-D structure, which has large molecular weight, thus increasing the melting point of the polymer.

In this process, the liquid resin is modified by adding the catalyst or hardener prior to injecting into the mold. The thermosetting polymers such as epoxy, polyesters, and polyurethanes are commercially available in two parts. The first part is the resin and the second part is the hardener, when added allows the liquid resin to cure. For the manufacture of nano composites, the nano composite mixture is prepared before injecting into the mold. The infusion of small amounts of nanoparticles into the polymer matrix dramatically improves the properties of polymers. The nano particles should be uniformly dispersed into the polymer matrix before adding the catalyst. Uniform dispersion of nanoparticles determines the properties of the nanocomposites depend on the size of the component phase and degree of dispersion. For uniform dispersion of nanoparticles, a variety of mixing techniques are available: shear mixing, magnetic mixing, ultrasonic mixing etc. In this study, process called ultrasonication is used to mix nanoparticles into polymer matrix, where high intensity ultrasonic waves are generated by the ultrasonic homogenizer. Those high pressure waves create microscopic bubbles called cavities which explode and generate high pressure and temperature which expedites the process of diffusion of nanoparticles into the matrix and also helps in uniform dispersion. Catalyst is added to the nano -phased polymer resin and it is injected into the mold by industrial syringe at a constant volume rate of cc/min and allowed to cure. The curing time and temperature varies for different polymers.

2.2.4 Removal of mold

Once the polymer is cured inside the dissolvable mold, it is immersed in a liquid called D-limonene, a common, colorless, citrus scented solvent. Depending upon on the size of the mold ,it takes about 8-24 hours to dissolve the material. The final product is clean and does not require further processing. This manufacturing process reduces the cost and time of manufacturing complex parts in small numbers. However, the cost efficiency in mass production is yet to be determined as new mold is to be build every time a new object is manufactured.

Chapter 3

Fabrication of trabecular bone structure using 3D+ Manufacturing

Bone is a sandwich structure comprising an outer compact shell called cortical bone and a porous inner structure called cancellous bone which has a spongy cellular structure .This configuration of bone provides large bearing surface while keeping its weight low .White house and his coworkers[12] studied the micrographs of human femur and found that the bones grow in response to stress applied on it and the shape and density of the bones depend on the loads which in a living animal, it has to support. The cells develop stronger in the direction where maximum load is applied. So, this structure is considered to be naturally optimized structure. In any structural applications, it is important that a structure should have stiffness and toughness along with the strength to resist various types of loads that act on it. This study attempts to mimic this naturally optimized structure with artificial composites to make this structure even stronger.

Many industrial and aerospace applications use epoxy resin as fiber reinforced composite matrix but recent advances in nanoparticles has led to research focusing on improving the polymer properties by using nanoparticles as reinforcements to the polymer matrix. Due to their large surface to volume ratios, the nanoparticles provide large interface in a composite. This attractive characteristic of nanoparticles makes them better than the conventional fillers. Slightest contribution made by the interphase greatly influences the properties of composites and provide diverse possibilities of performance tailoring. However the final properties of the composite greatly depend on the uniform dispersion of nanoparticles. Although the high surface to volume ratio is beneficial to the composite, it becomes difficult to achieve uniform dispersion because of the strong interactions among themselves. Moreover, attraction due to Vander Walls forces tends to form clusters among themselves.

This study investigates the mechanical properties of this trabecular micro structure by manufacturing with SiC/epoxy nano composites and the properties of the microstructure is studied for different percentages of SiC in epoxy matrix.

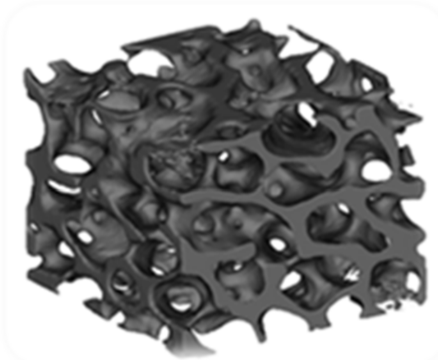


Figure 3-1 cross section of a human femoral joint

3.1 Manufacturing process

3.1.1 Obtaining the mold

The design of the bone structure was obtained from CT scan images of a 61 year old male human femoral neck. CT scan is a non-destructive way to obtain the cross sections of an object. Micro CT scan indicates the cross sections in micro scale. In biomedical imaging converting micro CT scan images into three dimensional models is robustly used. The trabecular part was separated from the CT scan and converted into a three dimensional solid volume mesh using a set of predefined processes. A software program called NRecon was used to correct the the long axis shift and grayscale. MIMICS, software used for Medical image processing was used to create a surface combining the corrected two dimensional images. Effective Region of interest was selected from the grey scale area and converted to 3D surfaces. The obtained surfaces are modified to generate an inverted print of the structure that define mold suitable to molding the object. The surface files were converted into stl format which contained the information related to surface of the geometry [31].

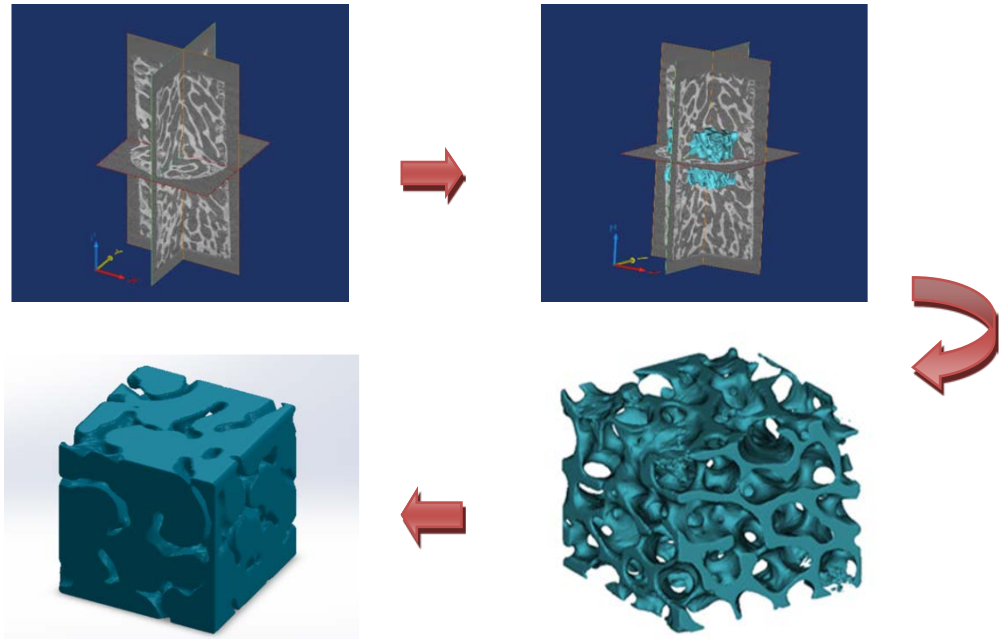


Figure 3-2 Process of selecting region of interest from merged cross sections of human femoral neck to obtain a mold for the trabecular geometry

3.1.2 Manufacture of mold using 3D printing.

The STL file of the mold for bone structure is imported into MakerBot software. Various process parameters such as speed and temperature of extrusion, temperature of build plate, resolution of the print are to be adjusted to print the mold. After importing the .stl file into MakerBot software, the mold is adjusted on the build platform and either the right or left the extruder is selected where the required filament is loaded. Since the mold is built using dissolvable material(HIPS), the inbuilt dissolvable filament is selected for the type of the filament. By selecting the dissolvable filament, MakerBot automatically adjusts the extrusion temperature of that filament and the build platform. The speed of extrusion is also automatically set but it can be adjusted manually if necessary. The settings are saved and the file is exported as .3xg and uploaded in an SD card which will be connected to 3D printer.

The print settings are as follows:

Resolution : Standard

Filament : MakerBot dissolvable filament (HIPS)

Temperature of extruder : 250^0

Build plate temperature : 110^0C

Speed while travelling : 150 mm/s

while extruding : 90 mm/s

HIPS filament with a diameter 1.75 mm is set in the extruder. The nozzle deposits molten HIPS to make a layer of mold and the process was repeated in layer by layer fashion until a complete solid mold was formed. The resolution of the print can be adjusted so we can get a strong and smooth mold surface.

3.1.3 Resin infusion into the mold

Two types of samples were prepared, one with neat epoxy resin and the other with nano particle infused epoxy resin. Introduction of SiC nano particles improves the strength of the epoxy matrix. After preparing the resin for both types of samples, it was injected into the mold and allowed to cure at room temperature.

3.1.3.1 Materials

The obtained trabecular microstructure was manufactured with SC-15 epoxy resin. This toughened epoxy resin system is two phased and cures at room temperature, obtained from Applied Poleramic Inc., Benecia, CA. The two phases are : Part A (mixture of: Diglycidylether of Bisphenol A, 60–70%, Aliphatic Diglycidylether,10–20% and epoxy toughener 10–20%)and Part B (hardener, cycloaliphatic amine 70–90% and polyoxylalkylamine 10–30%. Its viscosity is 300 cps at 70^0F.The mixing ratio for curing is 10:3 of part A and part B respectively.The nanoparticles used as fillers were SiC - β particles with 97% purity. They have a spherical shape with a diameter of 10 nm.

For the preparation of the mixture, 10 parts of part A is mixed with 3 parts of part B (hardener) and mechanically stirred for 10 min before poured into the mold.

3.1.3.2 Preparation of nanophased epoxy polymer

The process is carried out in two steps. In the first step, 1.5 % by weight of SiC particles were loaded into part A of SC-15 epoxy resin and the mixture was subjected to ultrasonicationat 20 KHz for about 30 min. The ultrasonic liquid processor generates high intensity acoustic waves which create cavitation and allows uniform dispersion of the particles in the resin. After 30 mins, dispersion appeared uniform. In the second step, part B (hardener) is added to the mixture and manually stirred with a mechanical stirrer for about 10 mins.

3.1.3.2.1Ultrasonic Mixing

While there were so many mixing techniques like solution mixing, shear mixing, ultrasonic mixing is one of the effective ways to disperse nano particles into the epoxy matrix. The ultrasonic processor contains an electric generator that converts 50-60 Hz voltage to high frequency (20kHz) electrical energy which is converted into mechanical vibrations. An ultrasonic probe amplifies the vibrations and generates high energy alternating pressure waves which creates microscopic bubbles in the liquid called cavities. These cavities are subjected to positive pressures in compression stage and become unstable and explode releasing high energy shock waves along with high pressure and temperature at the implosion sites. The collapsed cavities generate tiny particles of debris which further stimulates the cavitation. The development of cavitation facilitates acceleration of various physio-chemical processes such as heat and mass transfer processes allowing uniform dispersion of nano particles in the matrix.

3.1.3.3 Infusion procedure

The 3D printed molds were sealed on all sides by a sealing tape to close the inverted print of the bone microstructure. This could be easily removed after epoxy resin was cured in the mold. In the final step, both the neat epoxy mixture and nanoSiC / epoxy mixture were injected into mold through industrial syringes through the crevices in the top of the mold. Pressurized injection of resin into the mold ensures uniform filling of the resin in all the corners of the mold and prevents formation of air bubbles. The resin is injected until it completely fills the mold. Excess resin is allowed on the top to compensate for shrinkage of epoxy while curing. Then the resin is allowed to cure at room temperature for about 12 hrs. Cross linking occurred during the curing process transform the resin into a strong solid epoxy polymer.

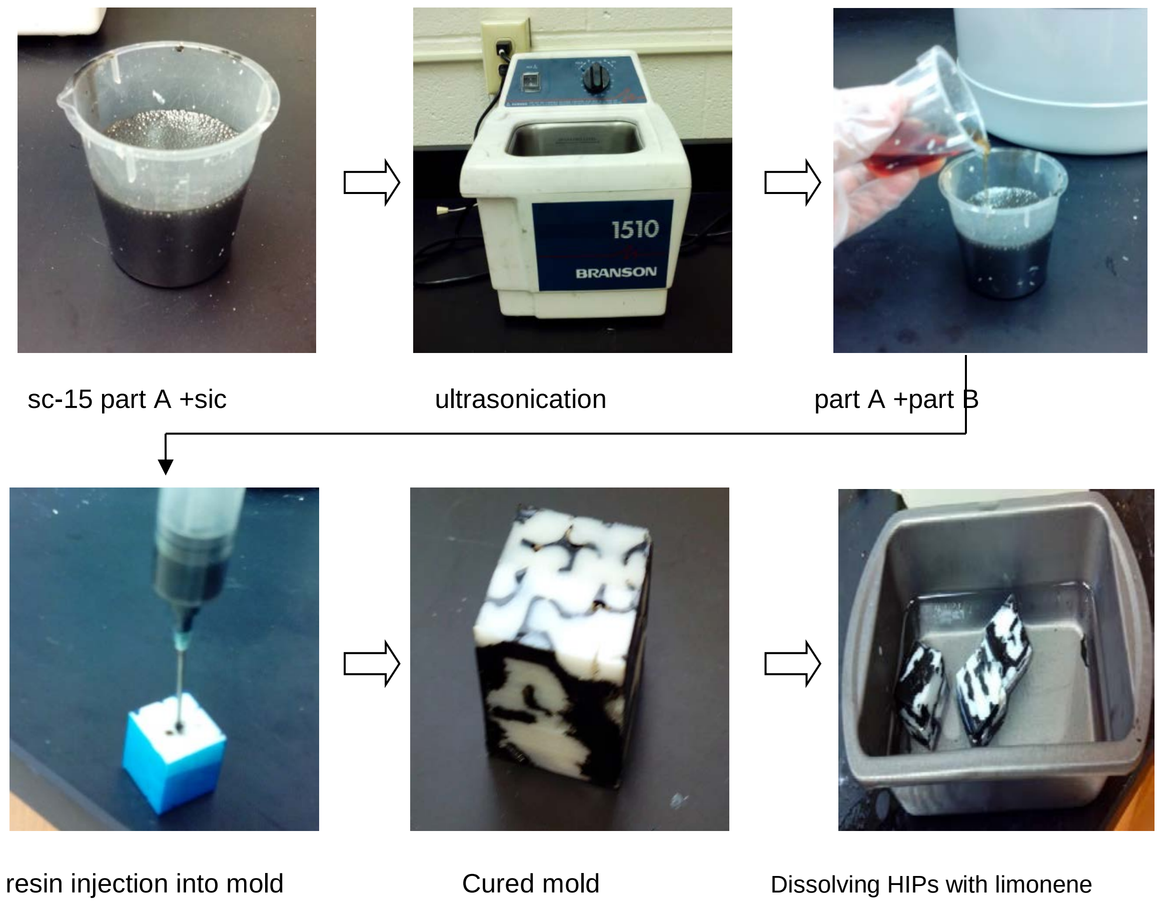
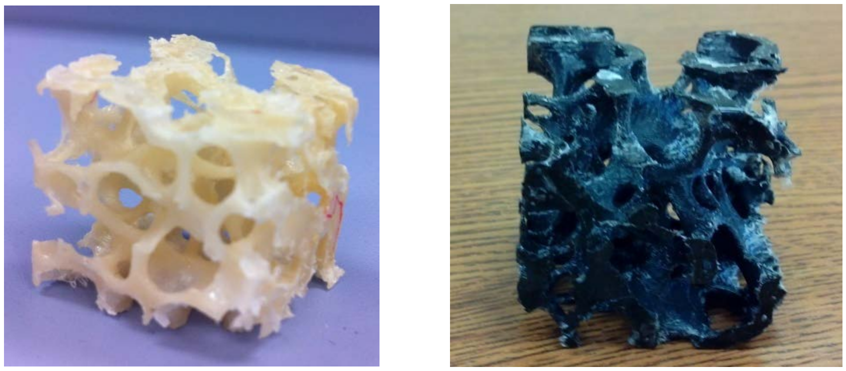


Figure 3-3 steps in 3D+ manufacturing process



a) b)

Figure 3-4 Trabecular structures made with a)neat epoxy and b)nanoSiC/epoxy

3.1.4 Mold removal

After the samples were cured, the seal wrapped around the mold was removed .Due to the complex internal structure of the bone, removal of mold necessitated mold removal by dissolution. So, the sample was immersed in limonene until HIPS completely dissolves leaving behind the actual bone structure. Dissolving the material may take up to 8-24 hrs depending upon the size of the sample. Then the samples were allowed to dry and excess material on the mold was scraped.

3.2 Testing

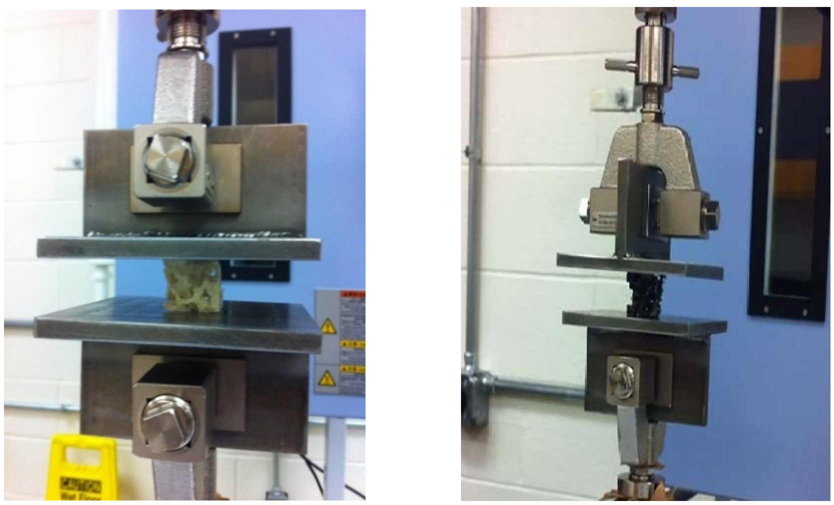
Five types of samples were prepared one with pure epoxy and four with SiC phase epoxy polymer. The weight percentage of SiC nano particles were varied in the four kinds of samples from 1.5 % to 7 %. The samples were tested in three directions, because the anisotropic behavior of the trabecular geometry varies the properties in all directions.

The trabecular structures manufactured from pure epoxy polymer and nanoSiC phased epoxy polymer and tested under compression load using Schimazdu Universal Testing machine having a capacity of 5000 N. The machine was operated at a speed of 1 mm/min. The size of the specimen was 1 ×1 ×1 in .Test was performed until the sample breaks. The UTM automatically generates stress-strain graphs from the forces applied and displacement of the crosshead. Stress is calculated from the force by

$$\sigma=\frac{F}{A}$$

$$\%strain = (\Delta L / L) \times 100$$

Where σ, F, A, L,ΔL are stress, force applied, cross sectional area of specimen, length of specimen, change in length of specimen respectively.



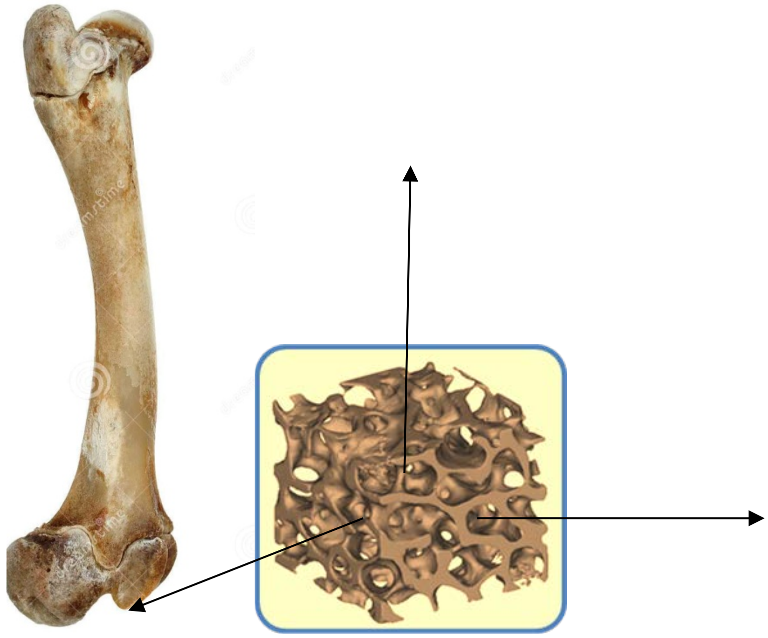
a) b)

Figure 3.5 a) Compression test of pure epoxy and b)SiC epoxy

3.3 Results and discussion

The graph in figure 3-6 shows the specific compressive strength for different samples .From the graph, two observations can be made. The first is that the compressive strength of the structure depends on the direction and it is high in longitudinal direction because bones carry most of the loads in longitudinal loads, they are developed to have higher strength in that direction. The second observation is that incorporating SiC nano particles into the epoxy matrix has improved the strength of the pure epoxy polymer for 1.5 and 7 percent weight.

As described earlier, bone grows in response to mechanical loading and the trabeculae are oriented along the directions of the principal stress. So, they are stronger in the direction of higher stresses and weak in the direction of low stresses. Trabecular bone in human vertebrae is



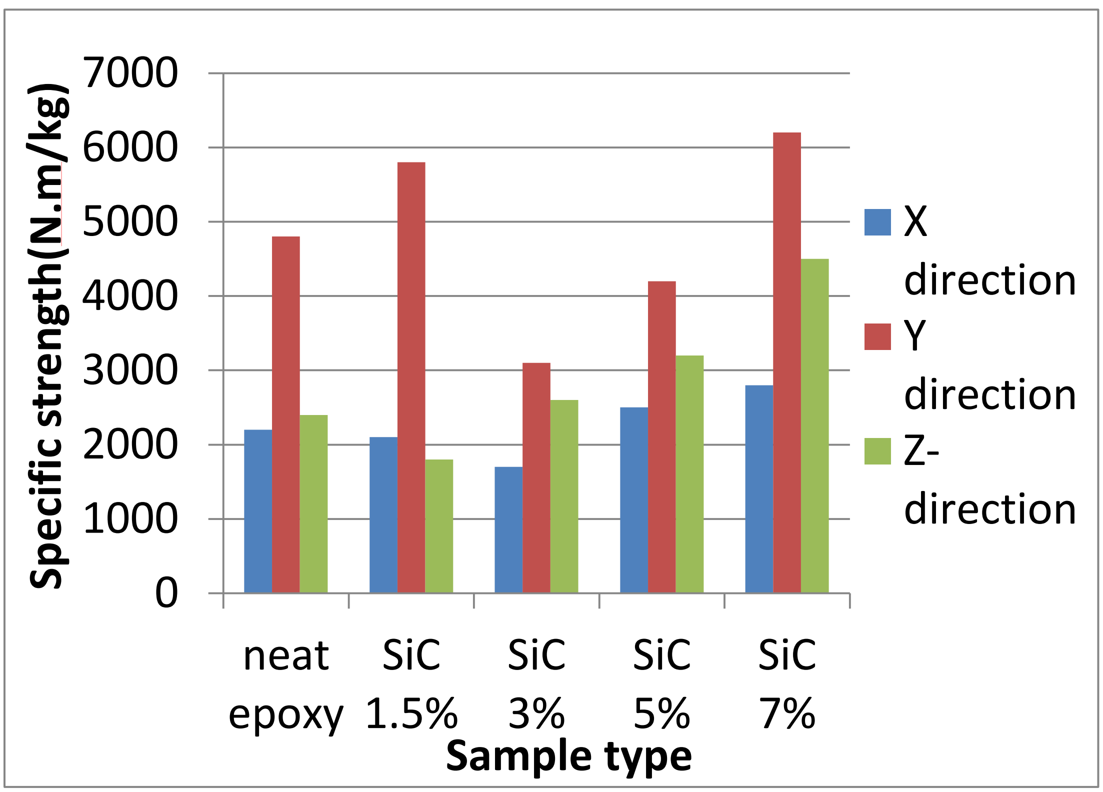


Figure 3-6 Graph showing the specific strength for all types of samples

loaded primarily along the length of the spine. This explains the behavior observed from the results. The femoral bone is subjected to compressive loadings in longitudinal direction, so the graph shows higher strength in only one direction

In the graph, specific compressive strength is used to compare all the samples. This is because each specimen has different weight percentages of SiC particles .So, density varies for each sample. In order to eliminate the dependence of compressive strength on the density of the sample, we divide the obtained compressive stresses of samples with their densities. It can be seen from the figure that samples with 1.5 % and 7% SiC nanoparticle infusion have higher compressive strength and stiffness when compared to other systems. The nano particles act as fillers for the voids that are created during crosslinking of the polymer and thus improve the strength of the polymer. With higher particle loading, the strength of the composite was improved naturally as large number of particles contributes to the load bearing. But with the increase in nano particles, the interactions between the particles become higher than the particle-matrix causing reduction in the mobility of the polymeric chain thus increasing the viscosity of the polymer matrix. Hence it became difficult to manufacture this thin and intricate trabecular microstructure with further increasing particle loading.

The decrease in strength with other load percentages like 3% and 5 % could be due to the weak bonding between the nanoparticles and the matrix. Also, formation of clusters due to non-uniform dispersion in the matrix may have decreased the properties because the clusters act as defects rather than filling the voids. The factor that influences the compressive strength of the composite is that the reinforcing particles increase the strength of the material by transferring the load, which depends on the bond integrity at particle/matrix interface and by impeding dislocation motion.

Many experimental results showed variations in the properties of the composites. Some researchers found improvements in properties while some reported degrading effects after particle inclusion. However in most of the studies, the properties tend to decrease after reaching a maximum after particle loadings of about 5 -10 %. These anomalies in the properties of composites are due to the quality of dispersion of nanoparticles in the matrix. Uniform dispersion of nanoparticles is the primary issue to exploit the advantage of nanoparticle reinforcement but ironically, it becomes even more difficult to achieve well dispersion due to reduction of interparticle distance with higher particle loading.

Chapter 4

Sandwich structures

Sandwich structures are extensively used in aircraft and military applications since they have higher stiffness to weight ratio than solid structures. These structural members are made of two stiff faces with a lightweight core in between. The main purpose of the core is to reduce the weight and increase the shear properties of the structure. It cannot take tensile loads, thus these structures can be determined only by the shear and compression loads. The three main properties of the sandwich structures are flexural, shear and compressive properties. These structures may fail due to delamination, tensile failure, crushing failure, buckling and core shear failure. The structure should be designed to withstand all these failures.

4.1 Design considerations

Sandwich structures are to be designed in such a way that they carry structural loads throughout their design life. In addition, they should maintain structural integrity in their service environments. They should satisfy the following criteria

- The faces should have sufficient stiffness to carry tensile, compressive and shear stresses that occur due to different types of loads that are applied during its service.
- The core should be stiff enough to withstand shear stresses due to applied loads.
- The core should have sufficient shear modulus to prevent overall buckling of the structure under loads.
- To prevent the wrinkling of face sheets, the core should have stiffness and faces should have high compressive strength.
- The core cells should be small to prevent inter-cell buckling of face sheets.
- The core shall have high compressive strength to prevent crushing under compressive stresses due to flexure.

- Overall structure should have sufficient flexural and shear rigidities to prevent excessive deformation under loads.
- Most importantly, all the materials in sandwich structure should maintain structural integrity during in service environments.

Generally, in all the sandwich structures, the core and the faces are joined by an adhesive. But the integrity of the structure is compromised due to the presence of adhesive. Most of the adhesives are instable to heat and therefore limiting the use of sandwich structures in high temperature applications. Even in normal temperature applications, the properties of the bond may alter with long term use. There are many other disadvantages in using adhesive bonding. Cleaning and surface preparation is necessary before the application of adhesive on the surface. The adhesives have to meet specific requirements in order to use them in practical applications. Special clamping devices are needed to fix the joint.

With the 3D+ manufacturing, it is possible to manufacture the sandwich structure as a single part by combining faces and core. This integrity of the structures is improved eliminating the need for bonding. This technique greatly reduces the time and cost of production since no special surface treatments or devices is necessary to fix the joint.

4.2 Designing mold for sandwich structure using SolidWorks

Some of the important factors to be considered while designing a mold are

1. Optimal use of material
2. Uniform distribution of resin
3. Shrinkage allowances
4. Air bubbles

Designing a mold is very complicated and important part of resin injection process. The mold should be designed in such a way that allows the resin to flow into every corner of the mold. The mold was designed to be open on the top for these reasons.

1. Since the mold is to be dissolved later, it is very important to use as less material as possible. So, the top surface was left open to conserve the material

2. It allows the air bubbles to escape evenly throughout the length of the mold.

3. The flat section on the top acts as a reservoir of resin to compensate for shrinkage of resin while it is curing.

4. The air bubbles that try to escape from the top get trapped on the outer surface of the mold. So, extra tolerance was allowed for the height of top section so that the final part obtained from the mold can be polished to obtain a smooth outer surface without any defects.

Since it is necessary to manufacture the sandwich structure as a single part, the mold was also designed as a single part. The figure shows the mold designed in SolidWorks. The size of the sandwich structure to be manufactured was (140 × 25 × 12.5) mm. For that the mold is (142 × 27 × 16)mm. First the base was modeled as a hollow rectangular box of dimensions (140 × 25)mm with thickness of 1 mm on the outside using a rectangle tool. Then, using linear pattern tool, squares of area 1mm^2 are modeled in a pattern comprising 4 rows and 14 columns lengthwise and extruded as columns of (2×2)mm^2 cross sectional area. Another hollow rectangular similar to the base was drawn on the top of the columns but keeping the upper section open. Then, from the top section, (1×1)mm square holes are made into the columns, previously extruded from the base, until the top section of the base. Then the final mold modeled is as shown in the figure 4-1.The columns in the design act as the gating system for the resin flow in the mold. The resin was prepared and injected into the mold with the same procedure explained in the previous chapter.

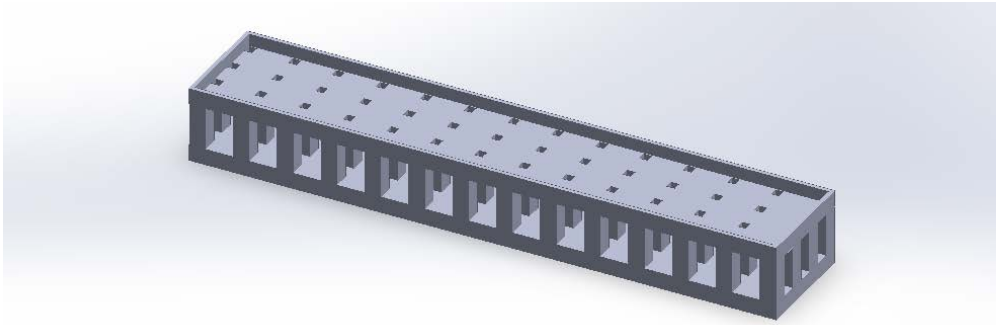


Figure 4-1 Mold designed in solid works

These sandwich structures are not like regular structures where cores are attached to the faces by adhesives .Eliminating the adhesives increases the bond integrity of the structure and failure due to adhesive bonding.

4.3 Manufacturing foam core sandwich structure

Some of the sandwich structures manufactured from the above process are filled with foam core to make it more strong and stiff. By the addition of foam core, the sandwich structures can be used as thermal insulators .Noise and vibration dampening is another advantage. Filling the hollow spaces in the structures reduces water ingression due to condensation which is the major problem associated with the use of honeycombed structures.

4.3.1 Materials

Polyurethane foam was used to fill in the hollow space of the sandwich structure. It is a two part liquid, 4 lb expanding urethane foam purchased from US composites. It is used in filling applications and it can take minor to moderate loads. The two parts have a mix ratio of 1: 1 by volume and it takes 45 seconds to start expanding. It can expand up to 15 times its liquid volume.

4.3.2 Preparation of sandwich structure.

Before filling the foam, the sandwich structure should be tightly sealed on all sides to contain the expanding foam. So, three of the open sides of the structures were sealed with a sealing tape leaving one side lengthwise open to pour the liquid foam. This side was also sealed with a plate immediately after filling with foam.

4.3.3 Process of infusion

Initially prepared sandwich structure was placed on a flat plate which was sprayed with a releasing agent called frekote to avoid sticking of excess foam onto the plate. Similarly the top plate that is to be clamped on the open side was also sprayed with releasing agent.

For filling the inside of sandwich structure which has a volume of 35 cubic cm, the volume of liquid needed to fill it was calculated as follows.

Since the foam expands 15X its liquid volume, volume to liquid needed to fill 35 cc volume is

Volume of liquid = Volume of filling space / 15

=35/15

=2.5 ml

So ensure the foam fills the spaces completely, a little more than 2.5 ml was used to fill the space. Part A and part B were mixed in equal parts and poured into the empty spaces of the sandwich structure within 45 seconds and the top surface was sealed tightly by clamping a plate on it. The plate should be clamped tightly because the expanding foam exerts an upward force on the plate and the plate tends to move. Also, this ensures uniform distribution of foam insides the spaces. It takes 5 min for the foam to fully expand and up to 20 min to become hard and rigid. Then the plate can be unclamped and the seals were removed.

a)

b)

Figure 4-2 Sandwich structure before (a) and after filling with foam (b)

4.4 Testing

Two types of samples were prepared one with neat epoxy and other with SiC/epoxy nano composite. Bending tests were performed on the sandwich beams made with and without foam core using 3 point bending test and failure modes were observed. The tests were conducted until the first break was observed. The failure mechanism in sandwich structure depends on geometry of the structure, material and type of loading.

4.5 Results and discussion

On the application of bending loads, it was observed that for the beams without foam core , the internal columns in the core failed at the column and face joint on compression side (i.e the top surface under compression load).This is due to the shear stresses occurred due to bending load. The stress concentrations are higher at the places where the central columns meet the faces. So, under the load, those columns that are weak failed first. But for the beams with foam core (figure 4-3), wrinkling was observed on the top surface and diagonal cracks were observed on the core. So, the failures indicate that faces carry the bending moment and the shear stress is carried by the foam core.

From the graph in figure 4-4, it can be seen that for the beams with foam core, the breaking strength doubled than that of beams without foam core. The SiC/epoxy beams have higher stiffness than neat epoxy beams.

Figure 4-3 Failure of sandwich beam with foam core

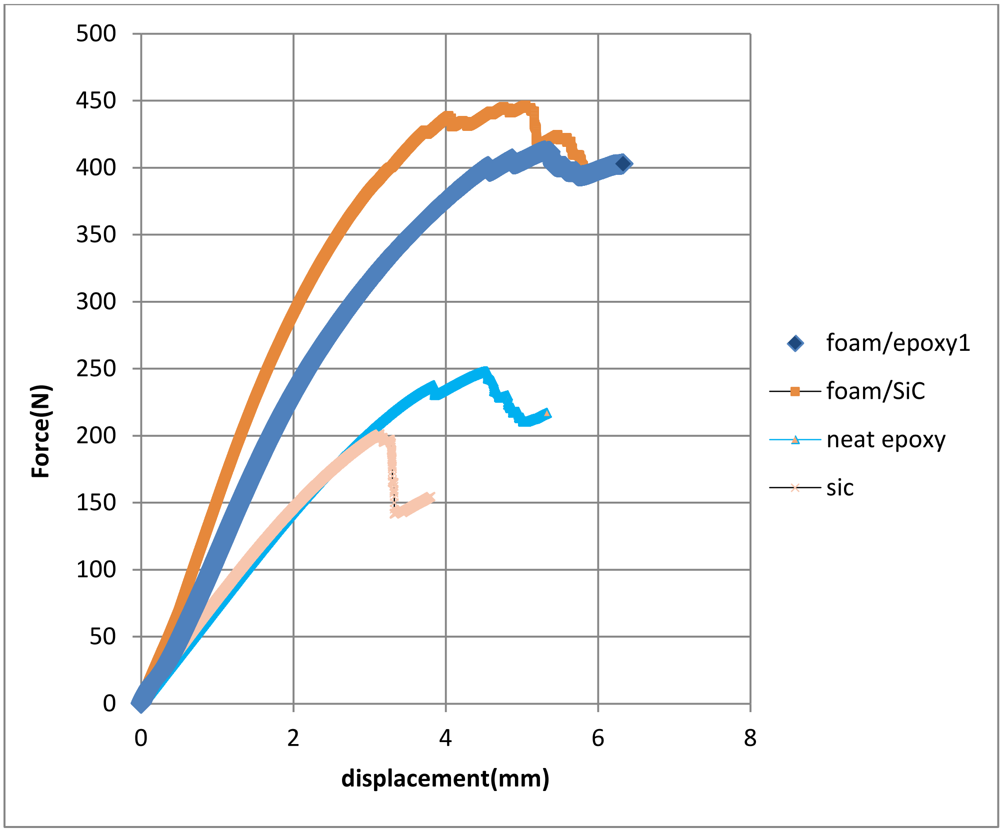


Figure 4-4 Force Vs displacement curve for all types of sandwich beams.

Table 4-1 List of bending rigidity and bending stiffness values of sandwich beams with and without foam core

SAMPLE TYPE	BENDING RIGIDITY(N.mm^2)	BENDING STIFFNESS(N/mm)
Neat Epoxy	661790.5	55.5
SiC	768530.9	64.5
Epoxy with foam core	926506.7	77.7
SiC with foam core	1067336	89.6

Table 4-1 shows the values of bending rigidity and bending stiffness for the beams with and without foam. The results show higher stiffness for SiC/epoxy beams than neat epoxy beams suggesting improvement in properties of neat epoxy after reinforcing with SiC nano particles. Addition of foam core increased the stiffness and rigidity of the structure even more.

So these sandwich structures have high stiffness and structural integrity and more importantly, they are light. This new design of sandwich structure greatly reduces the cost and manufacturing time and ensures structural integrity. These smart sandwich structures can be used as structures where high stiffness is required along with another critical property i.e saving weight

The applications of this sandwich structures are increasing from as other industries like automotive and construction are now focused on developing light weight structures for fuel consumption and emission control

Chapter 5

Conclusions

Rapid increase in technology demands lightweight materials and structures in many Engineering applications. Light weight structures play an important role in aviation, marine and automotive industry since they increase the fuel efficiency of the vehicles reducing the operational costs.Nature has evolved natural strong and lightweight structures such as cellular materials. This type of structure is present in most of the living things .Tall trees are able to withstand high speed winds, birds are able to fly easily keeping their weight minimum and bones are able to carry the weight of our body because of this cellular structures.

Human bones support the entire weight of our body but their weight constitutes of only 15% of the total body weight. The microstructure of bones is developed in such a way to carry the loads optimally without adding much weight. Most of the bones in human body are not solid, but they are sandwich structures comprising of hard outer layer called cortical bone and inner spongy structure called trabecular bone. The trabecular bone is present at the ends of long bones and at the joints where stresses are maximum. The bones develop according to the internal forces acting on them. The trabecular bone has rods and plate like structures. They form plate like structures along the direction of maximum stresses and thin rod like structures where stresses are low. Since they are subjected to compressive loading due to the weight of the body, they develop thicker and stronger in vertical direction, increasing strength and stiffness in that direction.

This study attempts to mimic this naturally optimized structure in structural applications to develop strong and light weight structures with nanocomposites since bone itself is a composite material made up of inorganic calcium phosphate which is rigid and organic collagen which has an elastic property to develop a stronger and stiffer material which can withstand the applied loads while being light.

Now-a-days, with recent advances made in nano technology, many attempts are made to improve the properties of a material at nano scale i.e. from the atomic level where the, interactions between the interfaces and physical phenomenon such as the defects etc and molecular forces and bondingat this level dictate the overall properties of the material. Recent studies show that reinforcing PMCs with very small percentages of nanoparticles improved the mechanical and thermal properties of a pure polymer using only conventional processing techniques. These composites find applications in many areas such as electronics, aerospace, automotive,marine,packing, coating etc. The attractive feature of the nanoparticles is their high surface to volume ratios which creates large interface in a composite. High surface area provides even distribution of loads.

In this present study, a novel, low cost but reliable manufacturing process called 3D+ manufacturing was developed to fabricate the microstructure of trabecular bone in human femur with SC-15 epoxy polymer reinforced with SiC nanoparticles. Using this 3D+ manufacturing, sandwich structures,used in aircraft and marine structural applications as weight reducing structure, were manufactured. The sandwich structures usually consist of two thin faces and a light weight but thick core in between and they are bonded together by an adhesive. This type of structure has high bending rigidity due to high moment of inertia by adding thick core (honeycombs, foams etc) in between the faces, which in turn gives high stiffness without adding much weight. In this study, the sandwich structures were fabricated in a non-conventional way which eliminates the need for bonding the faces and the core with adhesive. The cellular core and the faces were designed as a single structure and these structures have high structural integrity than those bonded by an adhesive. Finally, this cellular core is filled with polyurethane foam to make it stiffer and to increase the shear strength of the structure.

5.1 Summary

- To fabricate the trabecular structure, the mold was obtained from CT scan image of a 61 year human male femoral joint. A portion of the cross section was selected and using software called mimics, the threshold of the CT scan images were reverted,so that it could be used as a mold. Then the inverted part was converted to .stl format and imported into 3D printer(MakerBot) software where it can be scaled to required size which is a cube of volume 1"×1"×1".

- After adjusting the settings in MakerBot software, the mold was printed using MakerBot replicator2X with a dissolvable filament called HIPS, which dissolves in a solvent called D-limonene. The printed mold was sealed on three sides before the resin wasinfused. SC-15 epoxy resin was reinforced with SiC nanoparticles and infused into the mold and allowed to cure for 12 hrs and then it was dissolved in limonene for another 12 hrs to finally get the trabecular structure.
- Different types of samples were made by increasing the percentage of SiC nanoparticles in epoxy matrix from 1.5 % to 7 % and a neat epoxy and compression tests were performed. The results showed improvement in compressive strength of the structure for 1.5 % and 7 % addition of nanoparticles than that of neat epoxy. The reduction in strength of 3 % and 5 % particle infusion may be due to the improper dispersion of nanoparticles in the epoxy matrix .Also, the structure displayed high strength in one direction suggesting that the bones are stronger in the direction of maximum stress.
- The mold for the sandwich beam was designed using SolidWorks and manufactured by using 3D+ manufacturing process. Two types of samples, one with neat epoxy and other with 1.5 weight percentage SiC nanoparticles in epoxy were prepared and some of them were filled with polyurethane foam as a core.
- 3 point bending test conducted on sandwich beam showed high stiffness for beams with foam core. Also, SiC/epoxy composites showed improved properties than neat polymer. The breaking strength increased twice than that of beams

without foam core. The foam cores increase the stiffness of the beam and also increases the shear strength to support loads in bending.

5.2 Future Scope

- In the present study, a simple rectangular unit cell structure was considered for core structure in the sandwich beam but the main idea was to use trabecular bone structure as a core for sandwich beams or panels since the trabecular structure has so much potential as a lightweight core with high stiffness and compressive strength. If the trabecular structure could be replicated with a structure that exist in strongest direction, that structure could be used as a core with the manufacturing technique described in this study.
- In this study, the trabecular bone was taken from a 61 year old male with osteoporosis which makes the bone less dense and weak. In the future study, younger bones and bones of different animals can be studied to find a structure which is stronger than this.
- In this study, only compressive tests were performed on the bone structure. Fatigue tests could be performed to see the performance of the structure under cyclic loads.
- Sandwich beam can be tested in different directions to study the failure mechanisms of beams under different types of loading.

Appendix A

Nomenclature

F	Force applied
$\boldsymbol{\delta}$	Strain
E_f	Elastic modulus of facing material
E_c	Elastic modulus of core material
t	Thickness of a facing
b	Width of the beam
d	Distance between facing centroids
c	Core thickness
EI	Bending rigidity
σ	Stress
A	Area of cross section
L	Length of the beam/specimen
ΔL	Change in length

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