DESIGN AND DEVELOPMENT OF CELLULAR STRUCTURES FOR ADDITIVE MANUFACTURING

Biranchi Narayan Panda

Thesis to obtain the Master of Science Degree in

Mechanical Engineering

Supervisors: Prof. Marco Alexandre de Oliveira Leite
Prof. Bibhuti Bhusan Biswal

Examination Committee

Chairperson: Prof. Luís Manuel Varejão de Oliveira Faria
Supervisor: Prof. Marco Alexandre de Oliveira Leite
Members of the Committee: Prof. Luís Filipe Galrão dos Reis

July 2015

ACKNOWLEDGEMENTS

First and foremost, I sincerely express my deep sense of indebtedness and gratitude to Prof. B.B.Biswal and Prof. Marco Leite for providing me an opportunity to work under their supervision and guidance. Their continuous encouragement, invaluable guidance and support have inspired me for the successful completion of the thesis work.

It is the Erasmus Mundus Heritage scholarship programme that made it possible for me to join Instituto Superior Tecnico (IST) Lisbon for one academic year and carry out my master's thesis work. I am grateful to the Heritage programme committee and all the organizers for awarding me with such a great opportunity.

I am also thankful to Prof. S. S. Mahapatra (Department of Mechanical Engineering, NIT Rourkela), Prof. Alok Sathpathy (Department of Mechanical Engineering, NIT Rourkela), Prof. André Carvalho (Department of Mechanical Engineering, IST Lisbon), Prof. Arlindo Silva (Department of Mechanical Engineering, IST Lisbon), Prof. Relógio Ribeiro (Department of Mechanical Engineering, IST Lisbon) for providing me with all sorts of help and paving me with their precious comments and ideas. I am indebted to all of them.

In addition, I would like to thank all the staff members and labmates associated with me during the entire course of study, especially, Mr. M V A Raju Bahubalindruni, Mr. Bunil Balabantaray, Ms. Pallavi Pushp, Carlos Diogo and Bruno Soares for their useful assistance and cooperation.

Last but not the least; I am thankful to my parents and my brother for their unending love and emotional support. I love them so much and I would not have made it this far without them.

Thank You All!!!!

----------Biranchi Panda

Abstract

The demand for shorter product development time has resulted in the introduction of a new paradigm called Additive Manufacturing (AM). Due to its significant advantages in terms of cost effective, lesser build time, elimination of expensive tooling, design flexibility AM is finding applications in diverse fields in the industry today. One of the recent applications of this technology is for fabrication of cellular structures. Cellular structures are designed to have material where it is needed for specific applications compared to solid materials, these structures can provide high strength-to-weight ratio, good energy absorption characteristics and good thermal and acoustic insulation properties to aerospace, medical and engineering products. However, due to inclusion of too many design variables, the design process of these structures is a challenge task. Furthermore, polymer additive manufacturing techniques, such as fused deposition modeling process which shows the great capability to fabricate these structures, are still facing certain process limitations in terms of support structure requirement for certain category of cellular structures. Therefore, in this research, a Computer-aided design (CAD) based method is proposed to design and develop hexagonal honeycomb structure for fused deposition modeling process. To validate the robustness of the method, a resin transfer molding (RTM) mold internally filled with honeycomb is designed and tested instead of the regular aluminum mold. Results show that our proposed methodology has the ability to generate cellular structures efficiently while reducing the expensive build material (Mold) consumption to near about 40%.

Keywords

Computer-aided design (CAD), Cellular structures, Resin Transfer Molding (RTM), Design for Additive Manufacturing (DFAM)

Resumo

A procura de um menor tempo de desenvolvimento do produto resultou na introdução de um novo paradigma chamado o fabrico aditivo (AM). Devido às suas vantagens significativas em termos de custo, menor tempo de fabrico, eliminação de ferramentas e flexibilidade no *design*, procura-se com o fabrico aditivo procura encontrar aplicações em diversos campos da indústria.

Uma das possibilidades de investigação mais recentes nesta tecnologia envolve o fabrico de estruturas celulares. As estruturas celulares permitem um *design* customizado aplicando mais material onde é mais necessário para o desempenho de uma aplicação específica. Em comparação com materiais sólidos, essas estruturas podem oferecer uma elevada relação resistência-peso, boas características de absorção de energia e boas propriedades de isolamento térmico e acústico para produtos na indústria aeroespacial ou na medicina, por exemplo. No entanto, devido ao aumento da complexidade com inclusão de muitas variáveis de projecto, o processo de criação dessas estruturas é um desafio. Para além disto, as técnicas existentes de fabricação aditiva de polímeros, como o processo de modelação por deposição fundida (FDM), ainda que tenha grande capacidade de fabrico deste tipo de estruturas, apresenta algumas limitações na exigência de estruturas de material de suporte em alguns tipos de estruturas celulares.

Deste modo, procura-se nesta dissertação propor um método, auxiliado por técnicas de CAD que se propõe a projectar e desenvolver estruturas de ninho de abelha para processos de fabrico aditivo em FDM. Para validar a robustez do método, foi projectado e testado um molde composto internamente por ninho de abelha, para fabrico de uma peça em material compósito utilizando o processo de RTM. Os resultados mostram que a metodologia proposta tem a capacidade de gerar estruturas celulares de forma eficiente e eficaz e ao mesmo tempo reduzir o material consumido no fabrico do molde em cerca de 40%.

Palavras-chave

Computer-aided design (CAD), Estruturas celulares, Resin Transfer Molding (RTM), Design para a manufactura aditiva (DFAM)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

List of Acronyms

ABS Acrylonitrile butadiene styrene

AM Additive manufacturing

CLS Cellular lattice structure

CAD Computational aided design

CATIA Computer aided three-dimensional interactive application

DFAM Design for Additive Manufacturing

EBM Electron beam machining

FEA Finite element analysis

FDM Fused deposition modelling

RP Rapid Prototyping-

RTM Resin transfer molding

SLS Selective laser sintering

SLA Stereolithography

CHAPTER 1
INTRODUCTION, BACKGROUND AND MOTIVATION

1.1 Introduction

The demands for lighter, stronger, and more customizable parts have necessitated the research and development of new technologies, tools, and methodologies that can satisfy the new demands of the modern world. In this regard, the advent and continual improvement of one technology, additive manufacturing, has dramatically changed the way engineers pursue design and manufacturing. Additive manufacturing, once referred to as Rapid Prototyping (RP), has been used in many diverse field of industry for verifying the concepts (concept modeling) prior to production. However, with advancement of material science, this new and promising technology has eliminated many barriers to manufacturing and has allowed designers to achieve a level of complexity and customizability that is infeasible using traditional machining processes. As a result, most of the industries like Siemens, Phonak, Widex, Boeing and Airbus are now using this technology for producing their functional parts that are used in the final products. One such application of this technology is for manufacturing of customized, lightweight cellular structures. They have several advantages such as high strength-to-weight ratio and strong thermal and acoustic insulation properties. These types of structures are suitable for any weight-critical applications, particularly in the aerospace and automotive industries. This research will present a method for the design of these cellular structures for mold making application.

1.2 Background

1.2.1 Additive Manufacturing

Additive manufacturing (AM) is an additive fabrication process where a three-dimensional part is produced by stacking layers of thin 2-D cross sectional slices of materials one over another without use of tooling and human intervention. The process begins with a solid model CAD drawing of the object. The CAD model is then converted in to .STL file format and sent to an AM machine for prototype building [1]. The whole process of design to physical model through various intermediate interfacing stages is shown in Fig. 1. These steps are common to most AM systems but the mechanisms by which the individual layers are created depend on the specific system.

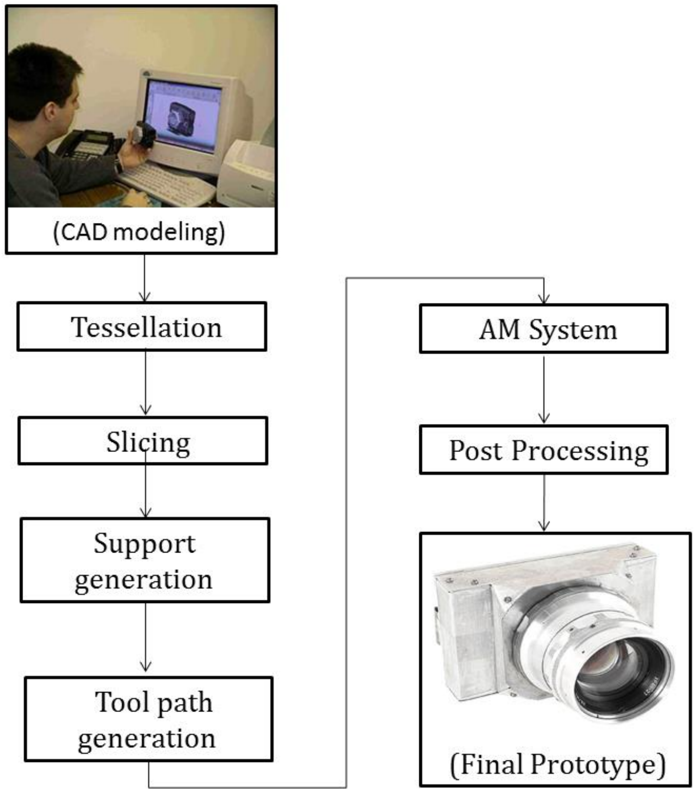


Fig. 1 CAD-Prototype intermediate stages

Currently, many technologies exist that into the broad definition of AM. These technologies are supported by various distinct process categories. These are: photopolymerization, powder bed fusion, extrusion-based systems, printing, sheet lamination, beam deposition, and direct write technologies [2,3]. Each of these processes has its own distinct set of advantages and disadvantages regarding characteristics such as surface finish, manufacturing speed and layer resolution. Of these different processes, three technologies are most commonly used: fused deposition modeling (FDM), stereolithography (SLA) and selective laser sintering (SLS). These three processes will be briefly outlined in the following sections.

1.2.1.1 Fused Deposition Modelling (FDM)

Fused Deposition Modelling (FDM) was introduced and commercialized by Stratasys, Minnesota, USA in 1991.FDM process builds prototype by extruding material (normally thermoplastic like ABS) through a nozzle that traverses in X and Y to create each two dimensional layer. As each layer is extruded, it bonds to the previous layer and solidify. The platform is then lowered relative to the nozzle and the next slice of the part is deposited on top of the previous slice. A second nozzle is used to extrude a different material in order to build-up support structures for the part where needed. Once the part is completed, the support structures are broken away from the part [4, 5]. Fig. 2 shows a schematic diagram of FDM Process, where blue color indicates the model material and red color points to the support material.

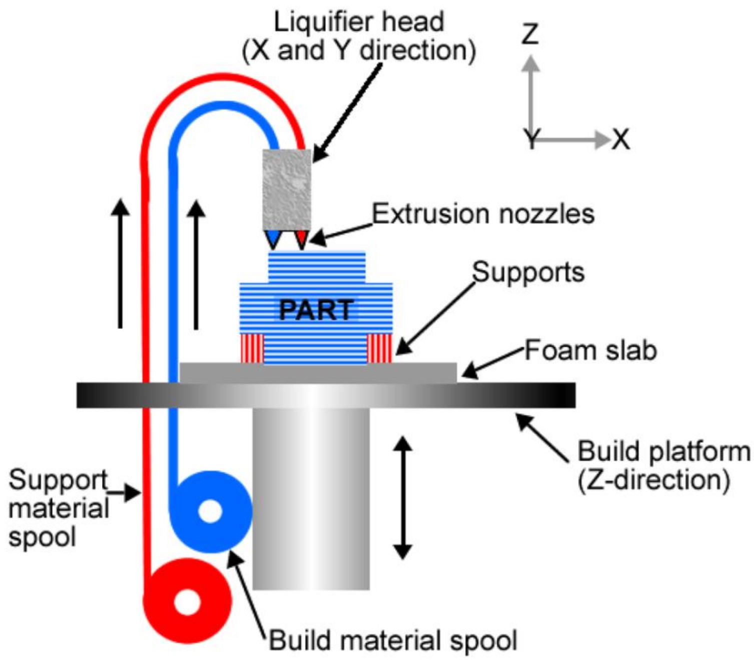


Fig. 2 FDM Process Flow [6]

Due to wide range of availability of material FDM can produce functional parts for various industrial applications including aerospace, automobile and medical sectors. BMW and Bentley Motors use FDM process to produce their automobile components which reduces their build time and cost up to 50 percentages compare to conventional CNC machining process.A carrier rack prototype build by FDM process is shown in Fig. 3.

Fig. 3 The prototype carrier rack [7]

1.2.1.2 Stereolithography (SLA)

Stereolithography (SLA) is the first fully commercialized AM process introduced in mid 1980s by 3D systems, California, USA. It fabricates part from a photo curable liquid resin that solidifies when sufficiently exposed to a laser beam that scans across the surface of resin. Once irradiated, the resin undergoes a chemical reaction to become solid called photo polymerization [8]. In SLA, there is a platform in a vat of liquid, photocurable polymer, i.e. epoxy or acrylate resin. After each cross-section is traced, the platform moves down an incremental amount and the laser cures the next cross-section. This process continues until the part is complete.

At initial days, SLA was mainly used as a prototyping tool; however, several companies are now using SLA for production manufacturing. For example, Siemens, Phonak, Widex and other hearing aid manufacturers use SLA machines to produce hearing aid shell [9]. Align Technology uses SLA to fabricate molds for producing customized clear braces (Invisalign®)[10]. Fig. 4 shows examples of products manufactured using SLA machines.

Fig. 4 Siemens hearing aid manufactured using SLA process [9]

1.2.1.3 Selective Laser Sintering (SLS)

Selective laser sintering (SLS) uses a high-powered laser to selectively heat the grains of a powder to their melting temperature and then fuse them to form the cross-section of a part. During the SLS process, a roller spreads a thin layer of powder across the build platform. The SLS machine preheats the powder in the build platform to a temperature just below its melting point in order to minimize the laser power requirement. A CO2 laser scans the cross-section area generated from the 3D CAD model of the part and selectively fuses the powder. After each cross-section is scanned, the build platform is lowered by one layer, a new layer of powder is applied on top of the previous layer, and the fusion process is repeated. These steps are repeated until the part is complete [11].

SLS can build both plastic and metal components that include polymers such as nylons and polystyrene and metals i.e. steel and titanium. Boeing and it's supplier uses laser sintering to build over 80 separate components for their F-18 military jet [12]. An example of an SLS-manufactured exhaust manifold is shown in Fig. 5.

Fig. 5 Propeller made by SLS [13]

1.2.1.4 Advantages of Additive Manufacturing

Additive manufacturing has the potential to vastly accelerate innovation, compress supply chains, minimize materials and energy usage, and reduce waste. It has several key advantages over traditional material removal methods. These include:

- **Lower energy intensity:** These techniques save energy by eliminating production steps, using substantially less material, enabling reuse of by-products, and producing lighter products.
- **Less waste:** Building objects up layer by layer, instead of traditional machining processes that cut away material can reduce material needs and costs by up to 90%.
- **Agility:** Additive techniques enable rapid response to markets and create new production options outside of factories, such as mobile units that can be placed near the source of local materials. Spare parts can be produced on demand, reducing or eliminating the need for stockpiles and complex supply chains.
- **Customizability:** Additive manufacturing process allows customization of parts without modification of the manufacturing process and tooling. Only the CAD model of a part needs to be altered for the customization. Later modified part can be printed without disturbing the complete manufacturing process.

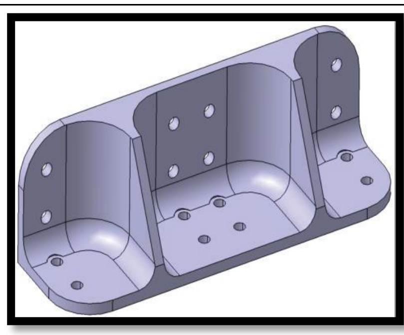
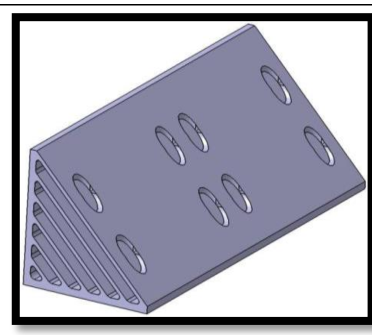
1.2.1.4 Limitations of Additive Manufacturing

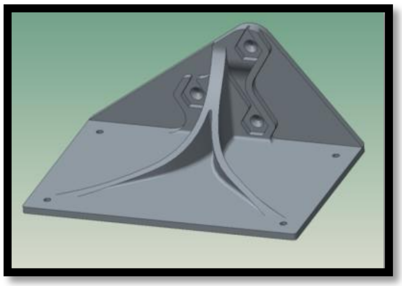
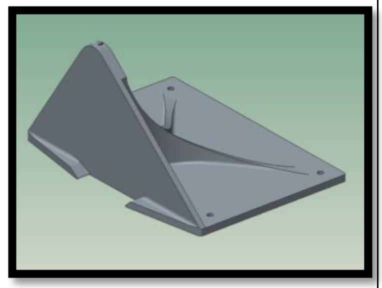
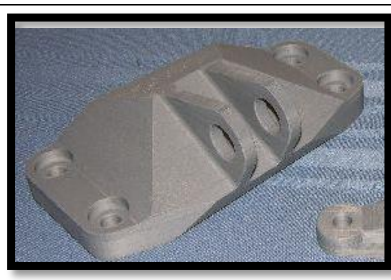
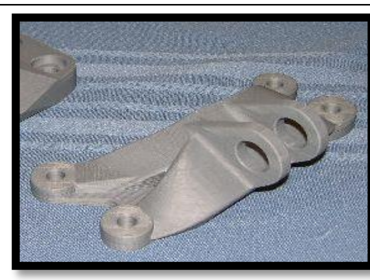
- **High production costs:** Sometimes, parts can be made faster using techniques other than additive manufacturing, so the extra time can lead to higher costs. Additionally, high-quality additive manufacturing machines can cost anywhere from $300,000 to $1.5 million, and materials can cost $100 to $150 per pound.
- **Requires post-processing:** The surface finish and dimensional accuracy may be lower quality than other manufacturing methods
- **Poor mechanical properties:** Layering and multiple interfaces can cause defects in the product
- **Considerable effort required for application design and for setting process parameters** – Complex set of around 180 materials, process and other parameters need to review for production of quality products.

1.2.2 Design for Additive Manufacturing (DFAM)

Design for manufacturing (DFM) has typically meant that designers should tailor their designs to eliminate manufacturing difficulties and minimize manufacturing, assembly, and logistics costs. The great potential of AM removes nearly all limits in the manufacturing of parts. However, because of the enormous freedom conferred by AM, the challenge of AM is not the manufacturing of the part itself, but the design of component. Traditionally, the design methods are mainly focused on mold-based production systems, they do not allow designers to benefit from the opportunities AM has to offer. However, in the DFM based workflow, the designer develops a customizable design by considering unique capabilities of AM process that enables improvement in product performance and lowers manufacturing costs. Table 1 shows some customized parts that are re-designed by design engineers to fully exploit the geometric freedom of AM.

Table 1 DFAM Examples

No.	Designer	Initial Design	Final Design	Remarks
1	Vayre et al.			The re-designed part proved to be lighter compare to its initial model. [14]

2	Thomas Wood			In the final design, holes are removed and the later drilled manually to save support material. [15]
3	EADS Innovation Works			The optimized Airbus A320 allowed to reduce raw material consumption by 75%.[16]
4	GE Aviation			The final design made plane engine 1,000 pounds lighter [17]

The aforementioned design examples reflect that AM can increase the sustainability of products on environmental and economic level by producing shape and material complexity parts. This research presents a design methodology that enables designers to take advantage of the shape complexity capability of AM processes. Specifically, we are focused on the design of periodic cellular structures for AM process.

1.2.3 Cellular Structures

Cellular structures with tailored mechanical properties are highly demanded in many areas of industrial applications such as thermal insulation, packaging, light weight structure, bone scaffolds etc. In recent years, AM processes have been found to be a promising technology, capable of producing such products with precise porosity and pore sizes. Advantages of these structures compare to their solid-body counterparts include good energy absorption characteristics, strong thermal and acoustic insulation properties, and, most importantly, a high strength over the low mass consumption. Some examples of cellular structures are foam, honeycomb, and lattice, etc. They are displayed in Fig. 6 [18, 19, and 20]

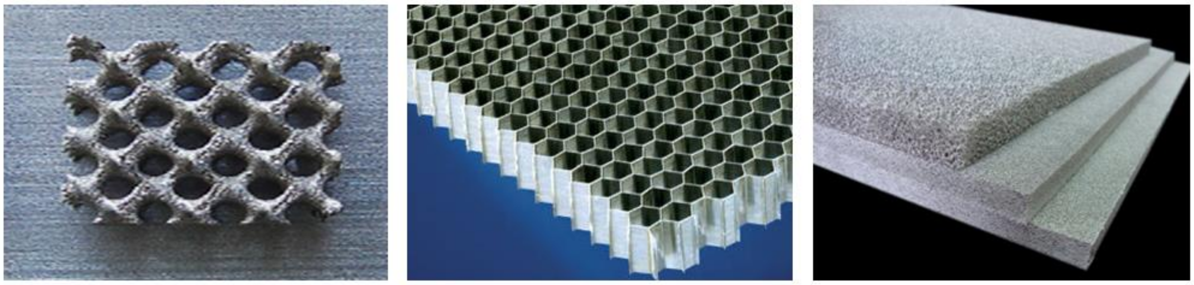


Fig. 6 Cellular lattice structure (left); hexagonal honeycomb (middle); aluminum foam (right)

These cellular structures are classified into two categories: those produced using stochastic processes (e.g. foaming) and those designed using deterministic processes (e.g. designed lattice materials). Deshpande et al. point out that foam's strength scales roughly to $\rho^{1.5}$, while the strength of lattice material scales to ρ, where ρ is the volumetric density of the material [21]. Therefore, a lattice material with a $\rho = 0.1$ is about three times stronger than a foam with the same volumetric density. The high difference in strength is attributed to the fact that foam deforms by cell wall bending while lattice elements stretch and compress [22]. Fig. 7 shows the detailed classification of these structures as per to their inbuilt topology [23].

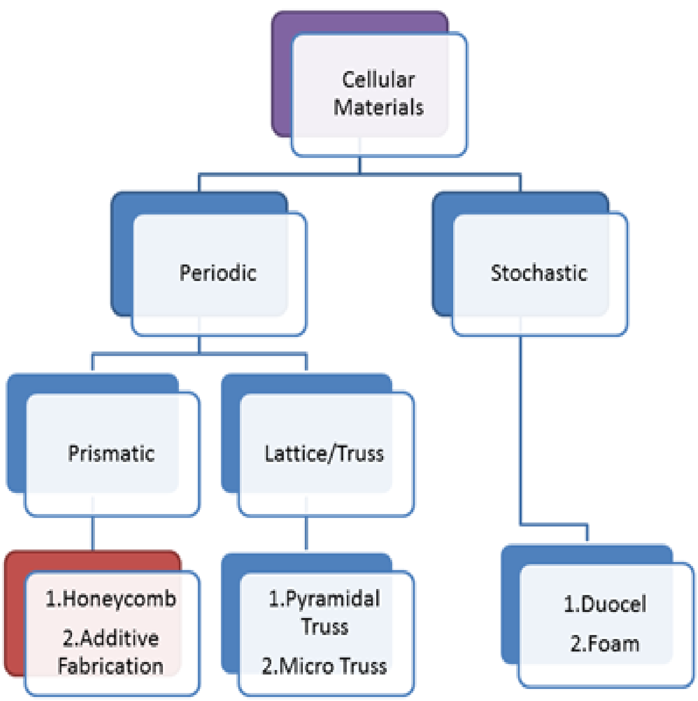


Fig. 7 Cellular structure classifications

]

1.3 Motivation

1.3.1 Design of Hexagonal Honeycomb Lattice Structures

Honeycomb is a two-dimensional periodic cellular material that is relatively strong and stiff along the normal to the microstructure but compliant and weak in-plane. This material is highly suitable for any weight-loading applications, particularly in the automobile and aerospace industries, which desire components with high strength-to-weight ratio. However, designing honeycomb structure using conventional machining process is a difficult and time consuming task. In this regard, AM seems to be an alternative solution due to it's design freedom capability and thus, it will be interesting to explore the ability of AM process, especially FDM, towards designing hexagonal honeycomb structures for any load bearing application. The motivation behind designing hexagonal honeycomb structure is it's self-supporting nature which in turn reduces support material volume in FDM process. Apart, it will save lots of expensive build material by putting the material where there is a need of it.

The biggest challenge associated with hexagonal honeycomb is not manufacturing of the part itself, rather the design of component. Although several approaches have been developed in the literature, there are significant limitations exist with these methods. These issues must be resolved in order for the method to be more effective and versatile.

1.4 Goals

The main goal of this thesis is to improve the material distribution inside a part body (RTM mold) with an aim to produce sustainable product that lowers part build cost and time without sacrificing it's mechanical properties. This will be achieved by developing a method for generation of cellular structures (Hexagonal Honeycomb) and improving it's performance subjected to given boundary condition. It should be easy to use, time-efficient, and provide a less manual construction of the model.

CHAPTER 2
LITERATURE REVIEW

In this chapter, a literature survey of relevant research is presented. Many studies are identified with respect to design improvement aspect of AM parts. Out of all, important and relevant research works are presented in Table 2. It summarizes the design approach: hollowing a part with uniform wall thickness, adopted by several researchers to save expensive build material while designing a part for aesthetic and ergonomic analysis.

In addition, some aspects of cellular structure design including analysis and optimization methods are also discussed in section 2.2 and 2.3. It (this chapter) provides an overview of the various methods used for generating cellular structures (foam, honeycomb, lattice structure) subjected to different loading conditions.

2.1 Hollowing Approaches

Table 2 Summary of literature reviews

Sl. No.	Author(s)	Title	Summary of research	Remarks
1.	Yu and Li (1994)	Speeding up rapid prototyping by offset	This paper proposes to use solid offset to cut down the solid volume to be built. The background theory for obtaining the reduced-volume solid is negatively offsetting the CSG model.[24]	The approach is applicable to solids defined by constructive solid geometry (CSG)
2.	Ganesan and Fadel(1994)	Hollowing rapid prototyping parts using offsetting techniques	A simple effective method is presented here for creating (outside of the solid modeler) hollow CAD models of the object using offsetting techniques.[25]	This method is not suitable for creating hollow parts that have varying surface normals
3.	Koc and Lee (2002)	Non-uniform offsetting and hollowing objects by using biarcs fitting for rapid prototyping processes	This paper presents a new method of using non-uniform offsetting and biarcs fitting to hollow out solid objects or thick walls to speed up the part building processes on rapid prototyping (RP) systems.[26]	Offset STL model contains some triangular facets with overlaps and inconsistent orientations
4.	Qu and stucker (2003)	A 3D surface offset method for STL-format models	This paper presents a new 3D offset method for modifying CAD model data in the STL format. In this method, vertices, instead of facets, are offset. The magnitude and direction of each vertex offset is calculated	It works well for small offset values.

			using the weighted sum of the normals of the facets that are connected to each vertex.[27]	
5.	Sang C. Park (2004)	Hollowing objects with uniform wall thickness	This paper proposes a new algorithm that computes internal contours without computing the offset model. The proposed algorithm is efficient and relatively easy to implement, because it employs well-known 2D geometric algorithms, such as planar curve offsetting and tracing innermost curves.[28]	The proposed algorithm is efficient and relatively easy to implement, because it employs well-known 2D geometric algorithms, such as planar curve offsetting and tracing innermost curves.
6.	Zhengyu et al. (2004)	A new hollowing process for rapid prototype models	In this paper a new method of hollowing rapid prototype models based on STL models and their cross-sectional contours is presented to meet the demands of hollowed prototypes in casting and rapid prototype manufacturing. Offsetting along the Z-axis and cross sectional contour offsetting are employed to perform the hollowing operation.[29]	This method has been verified by practical case studies, and it is proved that this simplified hollowing operation can reduce the prototype build time and cost.

2.2 Cellular Structure Analysis

The main task involved in the analysis of cellular structures is to predict the mechanical properties and model their performance accurately. Several methods have been developed to analyze various cellular structures. For instance, Ashby et al. has conducted extensive research in the area of metal foams [22]. Murr et al. [30] measured the stiffness of Ti–6Al–4V open cellular foams fabricated by electron beam melting (EBM). Results are found to be in good agreement with the Gibson–Ashby model for open cellular foam materials Wang and McDowell have performed a comprehensive review of analytical modeling, mechanics, and characteristics of various metal honeycombs [31]. Campanelli and his co-authors [32] investigated compressive property of Ti6Al4V pillar textile unit cell made by selective laser melting. Assuming, struts in a lattice structure only undergo axial loading and that joints are pin-pin joints, Wallach and Gibson analyze sheets of lattices under axial loading conditions [33].Compared to experimental analysis, their framework reported errors ranging from between 3% and 27%. Chiras et al. extended this assumption to analyze similar structures undergoing bending and shear loading [34]. Johnson et al. provided a more comprehensive analytical model of the truss structure by considering each strut as a beam experiencing axial, bending, shearing, and torsion effects. He analyzed the octet-truss structure inside finite-element environment using a unit-truss model that consists of a node and set of half-struts connecting to the node [35]. Wang et al. also have applied this unit-truss method to design and represent lattice structure [36]. Considering a BCC-Z unit cell Ravari et al. [37] predicted the variation in struts' diameter of on the elastic modulus as well as collapse stress of CLS using both beam and solid finite element models. Chang et al. [38] proposed and deployed a new design approach called size matching and scaling (SMS) method for designing mesoscale lattice structures. Later this was improved in terms of unit cell types for generating conformal lattice structures [39]. Conformal lattice structures are the one among meso scale cellular structure that conformed to the shape of a part's surface and can be used to stiffen or strengthen a complex part where standard lattice fails to fulfill it.

2.3 Cellular Structure Design and Optimization

2.3.1 Size, Shape, and Topology Optimization

In order to understand optimization of structures, the definitions of three categories of structural optimization are explained below (Fig. 8). Literature reveals that the optimization of part geometry and topology of the structural lay-out has a great impact on the performance of the structures [40].

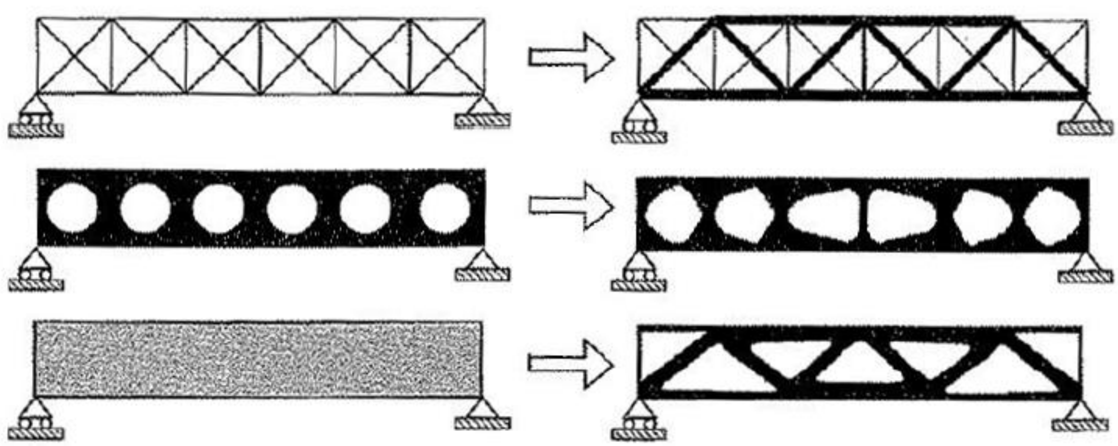


Fig. 8 Size (top), shape (middle), and topology (bottom) optimization [40]

A typical size optimization involves finding the optimal cross-sectional area of each strut in a truss structure [41]. Shape optimization computes the optimal form that defined by the boundary curves or boundary surfaces of the body [42, 43]. The process may involve moving nodes to change the shape of the structure; however, the element-node connectivity remains intact. According to Rozvany, topology optimization can be defined as determining the optimal connective sequences of members or elements in a structure. It consists of both size and shape optimization and has been used most frequently by design engineers to optimize their part structures for AM application (Section 1.2.2)

The topology optimization techniques used by the design are based on one of two approaches: the homogenization (continuum) approach and the ground (discrete) truss approach [44]. By using some continuous variables such as cross-sectional area, void sizes, these two approaches transform the discrete problem into a continuous one. The details of these two approaches are discussed in [45] [46].

2.3.2 Multivariable Optimization

Though structural optimization approach is used for the design, there is always a need for actual optimization routine. There are many different optimization algorithms depending on the applications such as mathematical programming techniques, stochastic process techniques, and statistical methods [47]. According to Rozvany and Zhou, these algorithms fall in two categories: direct methods and indirect method ([48], [49]). Direct methods (mathematical programming) consist of iteratively calculating the value of the objective function, its gradient with respect to all the design variables, and a change of design variables resulting in cost reduction until the local minimum of the objective function is found [50]. These methods are very robust, however, the calculation of gradients can be time-taking process, and sometimes can only optimize a limited number of design variables. On the other hand, indirect methods, such as optimality criterion, attempt to satisfy some design criteria of the structure instead of optimizing the main objective function. In many cases, such as uniform stresses, it has been found that direct method provides the same solutions as that of indirect methods [51]. Chu et al. compared the performance of three methods namely, Particle Swam Optimization (PSO), Levenberg-Marquardt (LM) and Active-set Programming while designing octet lattice cellular structures to achieve desired strength and stiffness [52]. Results show that LM is more efficient algorithms for this class of problems.

2.4 Summary

The aforementioned literature review concludes that much work has been done in the last decade related to the generation of truss type cellular structures. As per authors knowledge FDM is least used compare to SLA and SLS for generating these structures. This may be because of high grade material availability with SLA and SLS system. Both Computer-aided design (CAD) based geometrical modeling and mathematical modeling are addressed by many researchers for designing these cellular structures [53], In addition, recently developed SMS and Relative density methods by Rosen and his co-authors have promising performance for generating variety of cellular structures [54]. Regarding CAD modeling, a few authors stated that this is not a suitable platform for designing these complex structures; since it involves lot of design variable and takes lots of memory and time for processing operation. However, this problem can be tackled with the help of current advanced CAD toolbox and automation via macro programming. Therefore, in this research, a CAD based approach for generating cellular lattice structure (Hexagonal Honeycomb) is proposed and also evaluated for a real world load bearing application (Resin Transfer Molding). It provides a new way to generate precise cellular structure with less human error and computational time.

CHAPTER 3
DESIGN METHOD

In this section, a CAD based design method will be presented. The method will resolve the technical limitations of previous CAD based approach by utilizing an advance toolbox and automation setup. This design method will be able to efficiently design hexagonal honeycombs inside any complex shaped parts with reduced processing time and human error.

3.1 Method Description

Our methodology for generating honeycomb structures consists of two design phases. Phase 1 is related to the hollowing process with uniform shell thickness, while phase 2 facilitates reinforcement of the honeycomb structure inside the hollow part body, generated in phase 1. Considering the system (here FDM) potential/limitation in terms of material availability, dimension accuracy and the highly significant support generation strategy, honeycomb pattern is designed in this work among the wide range of cellular structures (shown in Fig. 9).

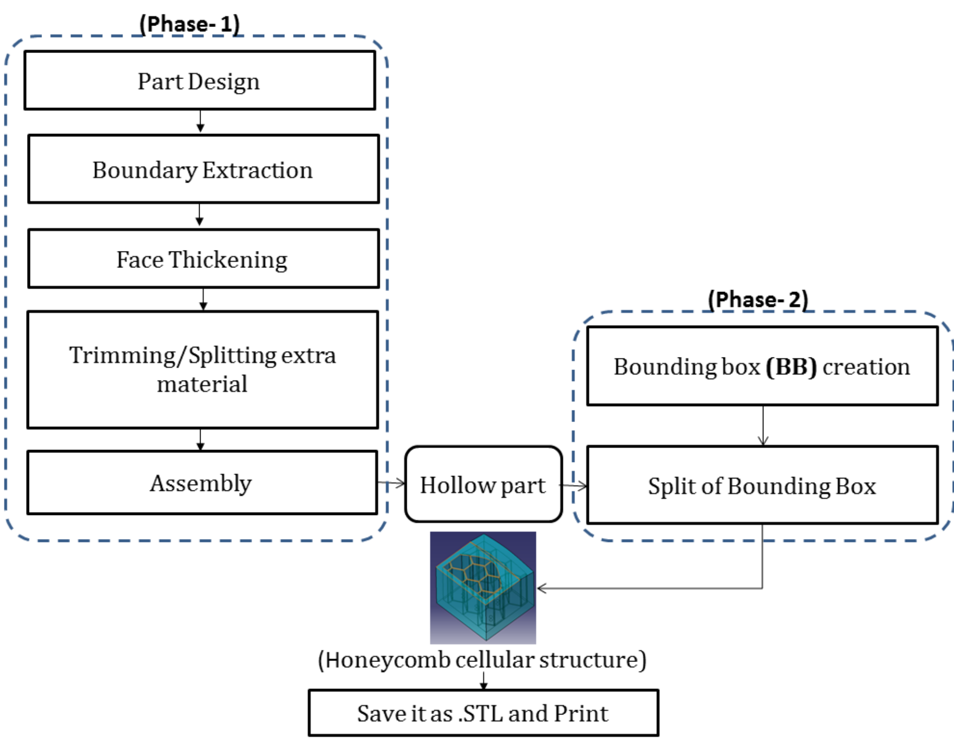


Fig. 9 Proposed Method

The following sections explain each step in Fig. 9 with graphical illustrations for better understanding of the complete process. The complete process is implemented in the work environment of a commercial CAD package, CATIA V5, used by most of design engineers for generating open porous structures.

3.2 Phase 1

3.2.1 Part Design

In the first step, a part is to be designed as per user requirements. Users can specify their requirements in terms of geometric features such as shape, size of the part along with different loading conditions (analytic feature) that are needed to perform stress analysis while designing cellular structures for it.

3.2.2 Boundary Extraction

Here, the boundary of part of the solid body is extracted into one or multiple faces with tangent continuity.Fig.10 represent a solid part and the extracted boundary with multiple surfaces is represented in Fig.11 as an exploded view.

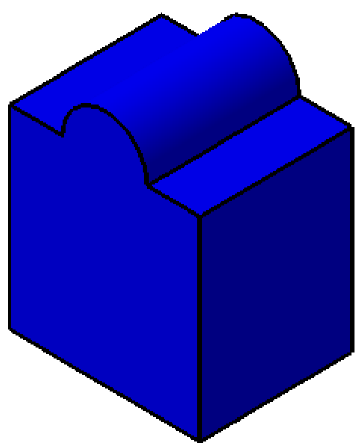


Fig.10 The 3D solid part

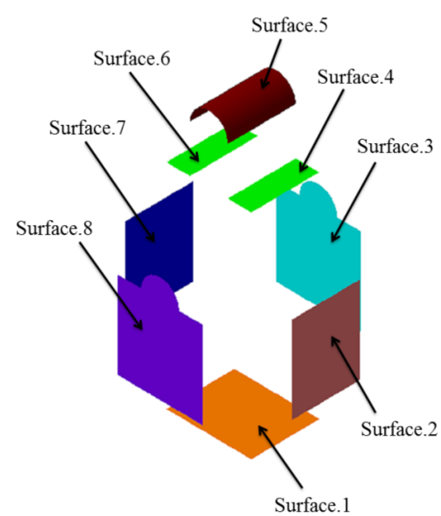


Fig.11 Exploded view of boundary surfaces

3.2.3 Face thickening

In this step, solid bodies are created by thickening each surface to a specified thickness normal to the surface towards material direction. Designers have the rights to change this value (thickness) as per their need for application. Fig.12 represents the surface normals towards the material direction for all surfaces (Surface8 is moved in the normal direction for clear representation). Fig.13 represents the thickened bodies (Surface8 and the respected thickened moved in the normal direction for clear representation).

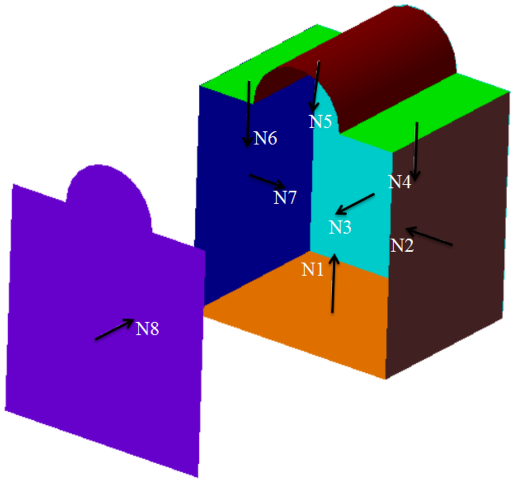


Fig.12 Direction of normal for each surface

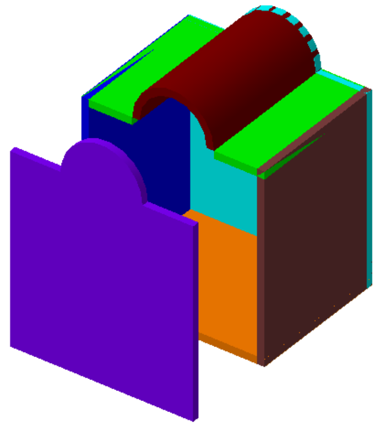


Fig.13 Thickened bodies

3.2.4 Trimming/adding the excess material

This step is not common to every solid part body, as it is a geometry dependent issue. In some case studies, it has been found that thickening surfaces result excess material or sometimes less material which is practically undesirable. Therefore if any thickened solid body crosses the boundary of the part, then the excess material will be trimmed with respect to the boundary. Fig.14 represents the excess material after thickening a face of the solid and the trimmed body with respect to the intersecting boundary surfaces is represented in Fig.15.

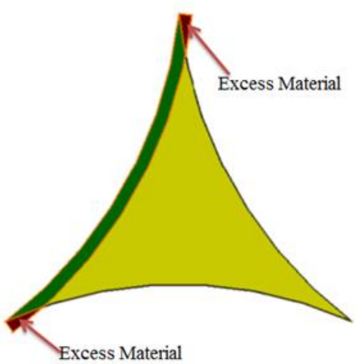


Fig.14 Excess material on thickened solid body

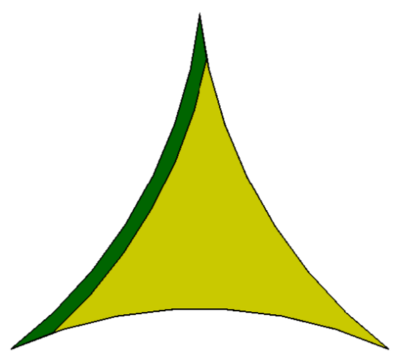


Fig.15 Trimmed body with respect to intersecting boundary surfaces

Similarly if there is a need of material, one of the surface can be extended up to the neighboring surface to maintain uniformity. Fig. 16 shows the gap (Need of material) when angle between the neighboring surfaces is convex. In order to generate a hollow uniform part body one of the surface should be extended in the opposite direction of material till it meets the other surface (Fig. 17).

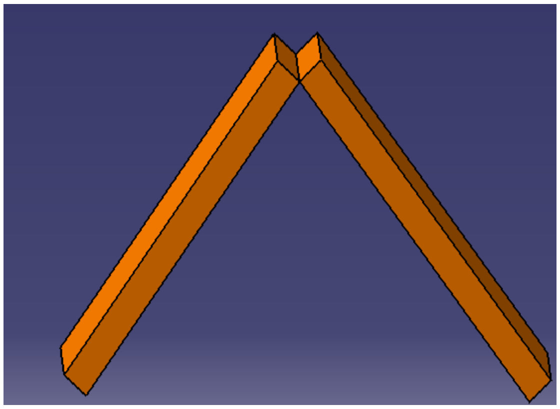


Fig.16 Gap on thickened solid body

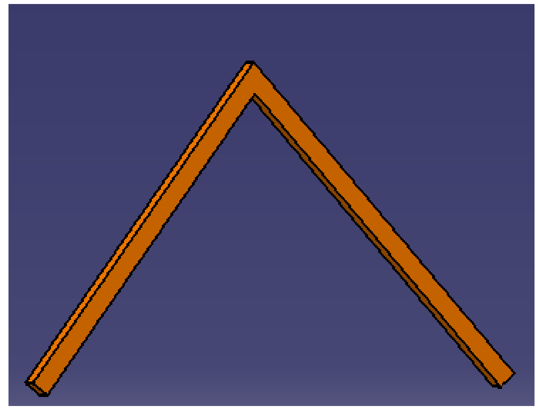


Fig.17 Extended thickened solid body

3.2.5 Assembly

All thickened bodies are assembled together to generate a part with internal hollow space without any deviation in the physical appearance. Fig.18 represents views of a 3D solid part, isometric view of the part, view from side and section cut to represent the internal configuration. Fig.19 represent the 3D hollow solid part created by using the proposed method, isometric view of the part, view from side with hidden lines and section cut to represent the internal configuration.

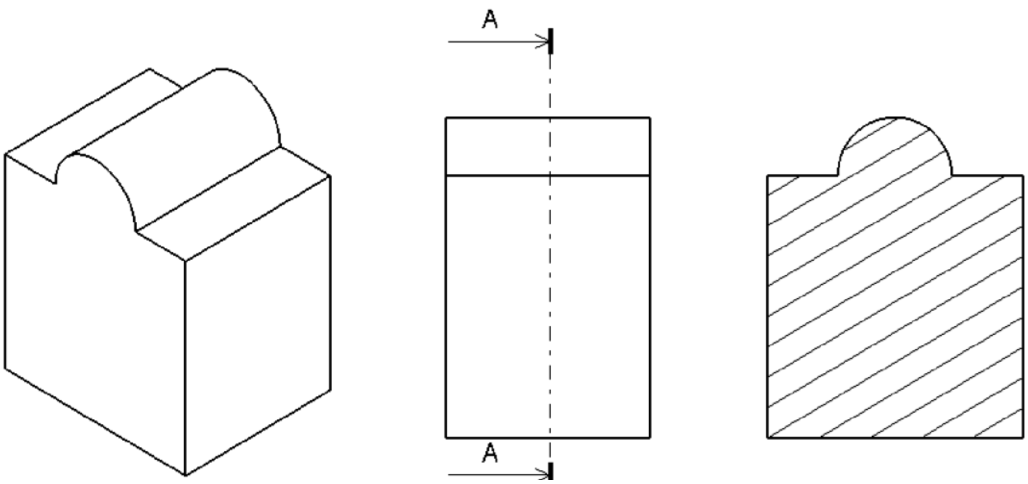


Fig.18 3D solid part views (Isometric view, View from side, Section Cut view)

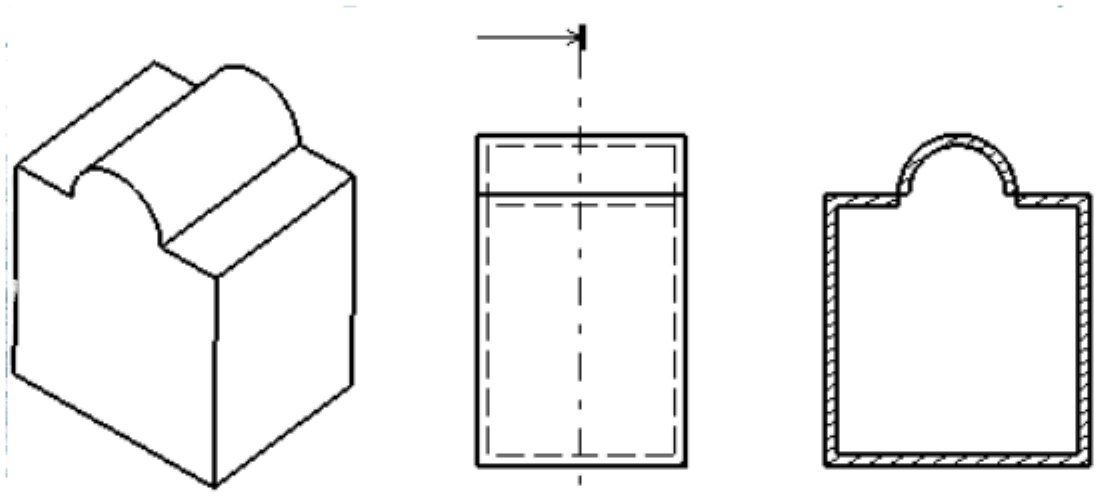


Fig.19 3D hollow solid part views (Isometric view, View from side, Section Cut view)

3.3 Phase 2

3.3.1 Bounding Box (BB) creation

Bounding box (BB), as the name refers; it is the minimum enclosing box surrounding the (hollow) part body. This BB creation is our preliminary step towards generating cellular structures inside any complex geometry part. With the help of advanced CAD tools, a minimum oriented BB full of honeycomb structure is created (Fig. 20) for the hollow part shown in Fig. 19. The cell sizes of these honeycombs are controlled parametrically, in order to generate BB of different infill densities.

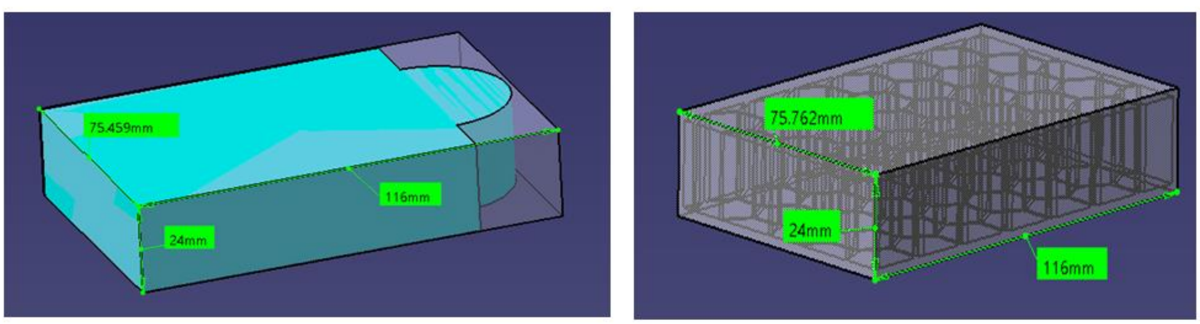
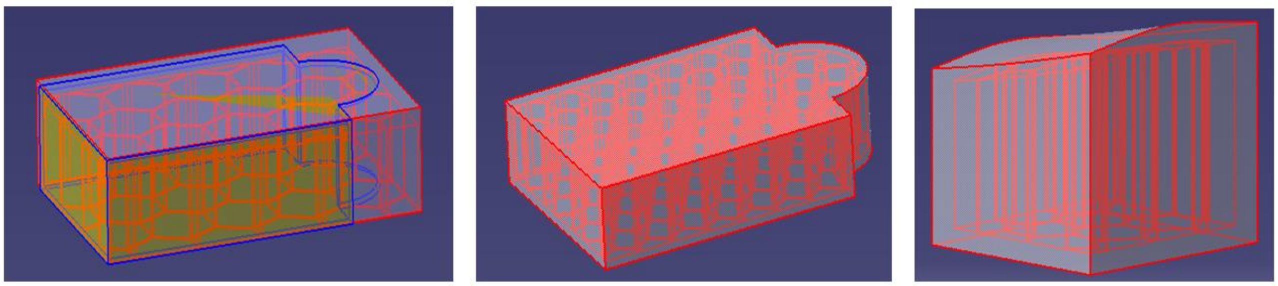


Fig.20 Bounding Box

3.3.2 Splitting of BB

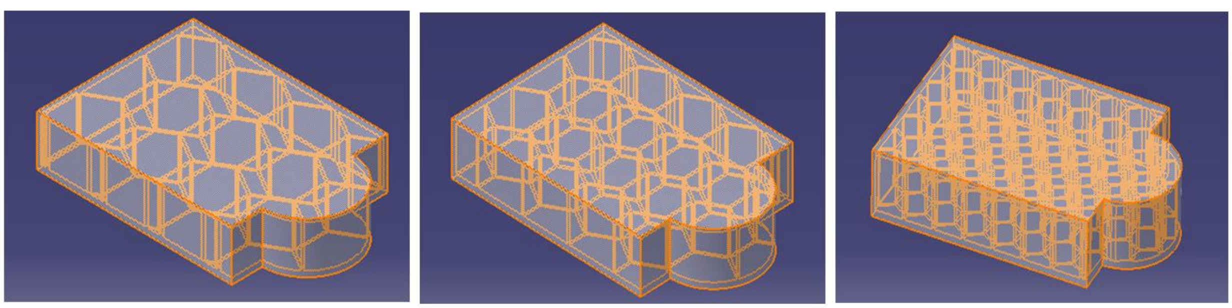
This step produces internal honeycomb cellular structures for any complex shape part by splitting the BB with respect to internal contour (marked in blue) of the hollow part. Fig. 21(a) and (b) represents the splitting operation carried out to obtain internal honeycomb structure. In fig 21(c) (another part), the internal honeycomb structure is found to be a conformal one since it perfectly adapts to curve surface of the part body. This adaptive nature of the honeycomb structure will be verified and discussed later in this paper by analyzing it’s micrograph image.



(a) (b) (c)

Fig.21 Splitting and Generating Hexagonal Honeycomb

Since the complete process seems to be lengthy and complicated, a macro program (using VB script) is written to minimize computational time and human errors while designing the part. Users can run it just by assigning some values to wall thickness and cell size of their model as per the need of applications.



(a) (b) (c)

Fig. 22 Hexagonal Honeycomb with infill (a) 25 (b) 30 (c) 35 percentage

Fig 22 shows, CAD models of three honeycomb cellular structures with different volume fractions such as 25%, 30%, 35% created using this program. Volume fraction is defined as the volume percentage of the solid material in the cellular structure. It is clear from this images that our proposed program is able to generate internal honeycomb structure for any complex part based on the values of wall thickness and cell size.

CHAPTER 4

MICROSTRUCTURAL AND MECHANICAL CHARACTERIZATION

In this chapter, the microstructure and mechanical properties of hexagonal honeycomb cellular structures is thoroughly investigated with a wide range of cell size (5–15%) and wall thickness (1 &3 mm).

4.1 Experimental Material and Methods

The CAD model of hexagonal honeycomb cellular structures with different cell size and wall thickness are initially generated using our proposed design method, explained in chapter 3. Five different cell sizes such as 5mm, 7.5mm, 10mm, 12.5mm, 15mm and two different wall thicknesses of 1mm and 3mm are chosen for this purpose. The designed CAD model of the honeycomb structure with the cell size (5–15%) with wall thickness of 3.0 mm is shown in Fig. 23.

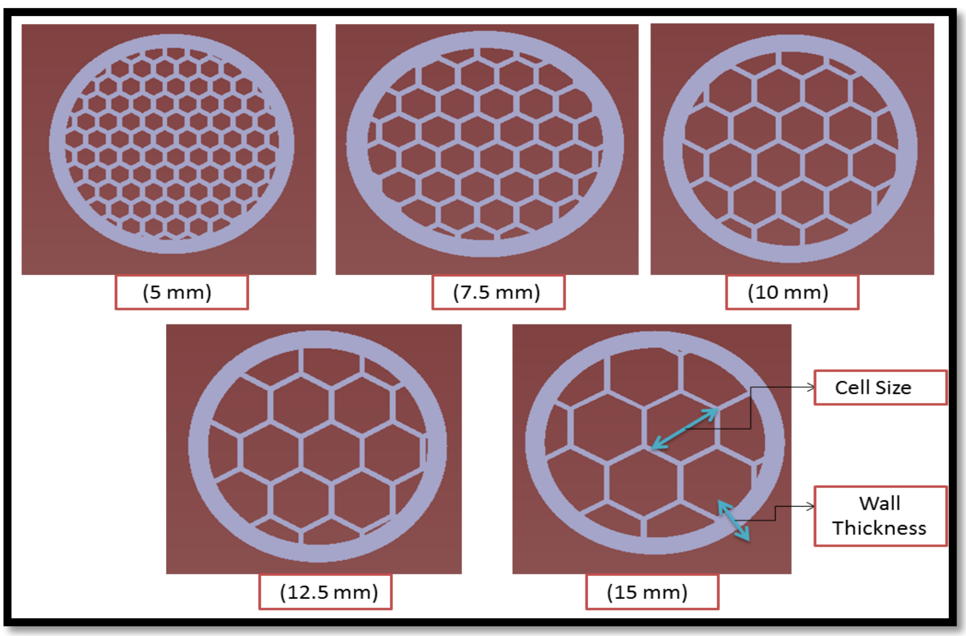


Fig. 23 CATIA modeled honeycomb cellular structure

These CAD models are then sent to Stratasys® FDM (dimension sst 1200es) for fabrication. ABS P400 is used as model material while keeping all the default processing parameters constant (Layer Thickness: 0.234mm, Raster angle: 45 degree, Orientation: 0 degree).

4.2 Measurement

The densities (= Density per unit volume) of the solid structures were measured by dividing mass of structure with it's volume .Similarly relative density was calculated by the ratio of the density of the honeycomb structures to the density of fully dense ABSP400 material, taken here to be 0.98g/cm3. In real world, density of full dense ABSP400 is near about 1gm/cm3 (APENDIX A), however due to layer deposition nature of FDM process, experimentally it is found to be 0.98g/cm3.

Uniaxial compression tests are carried out using Instron 5582 at 1.0 mm/min loading rate. All the tests, done for measuring the compressive strength, are conducted in accordance with ASTM D1621 standards. A sample during the test along with loading direction is shown in Fig. 24

Fig. 24 – A specimen during compression testing

For microstructure analysis, a part having curve surface is cross-sectioned parallel to the building direction and an optical microscope with 400X resolution is employed to scan the surface. The optical microscope used in this study and the part is displayed in below Fig. 25.

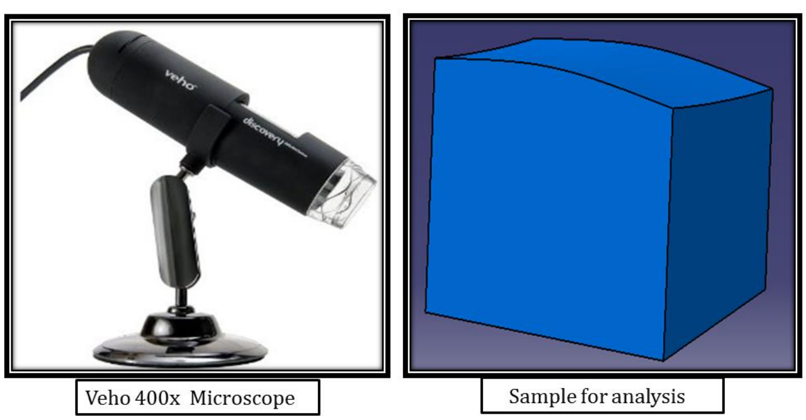


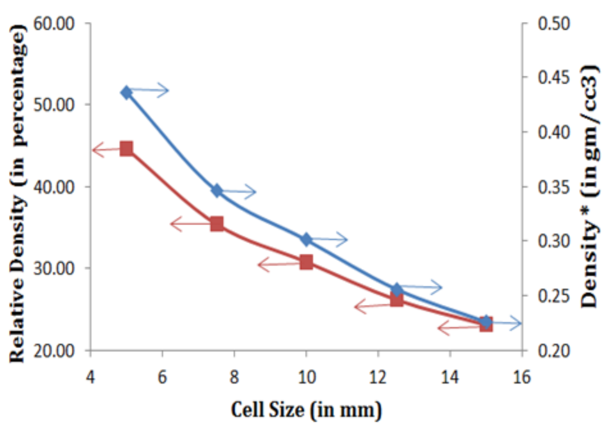
Fig. 25 Microscopic and Test sample

4.3 Result and Discussion

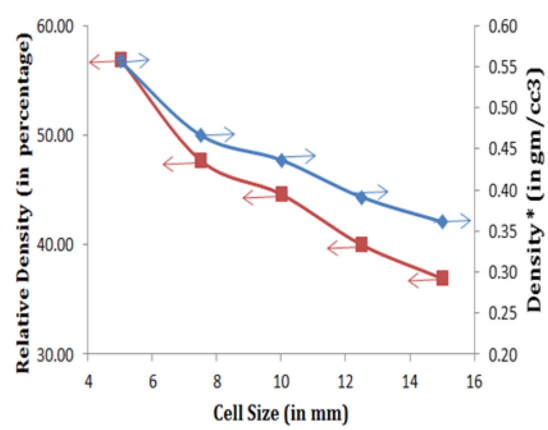
4.3.1 Mechanical properties

4.3.1.1 Effect of unit cell size on the density

The relative densities and densities of the honeycomb cellular structures with different unit cell sizes are shown in Fig. 26 (a) and (b). The density as well as relative density of both wall thickness 1 and 3 mm decreases with increasing unit cell size. The honeycomb structure with the unit cell size of 5 mm has a relative density of 56%, which is higher than the relative density of the struts within the 15 mm cell size lattice structure, 36% (for 3 mm wall thickness). It is also noticed that the values of densities of 3 mm are higher than that of 1 mm thickness. This increasing trend may be the result of increase in material content for 3 mm thickness honeycomb structure in a defined volume.



(a) Wall thickness = 1 mm



(b) wall thickness = 3 mm

Fig. 26 Variations of the relative density and density of cellular structure with cell size and wall thickness

4.3.1.2 Effect of unit cell size on the compressive properties

It is well known that the porosity, which equals to relative density, mainly determines the mechanical properties of cellular materials. Usually, higher relative density results better mechanical properties. Fig. 27 shows the compression strength of the honeycomb cellular structures as a function of cell sizes at the different wall thickness. It can be that at a fixed wall thickness, compressive strength increases with increase in cell, consistent with the Gibson–Ashby model [55].

$$\frac{\sigma}{\sigma_o} = C_1 \left(\frac{\rho}{\rho_o}\right)^{1.5} \qquad \text{………….. (1)}$$

Also at a fix cell size, Wall thickness = 3, offers more strength (16 MPa) than that of 1 mm thickness (13 MPa). This can be explained by computing amount of material inside the fixed geometry. Since 3 mm wall thickness contains more material (37 gm), it can sustain more load than 1 mm thickness (29gm) sample, thus more compressive strength.

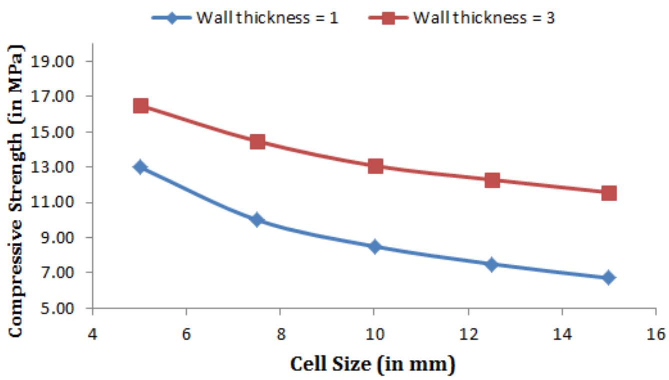


Fig. 27 Variations of the compressive strength with cell size at different wall thickness

4.3.1.3 Optical microscope observation

The optical microscope an image of the cross-sections of honeycomb cellular structure is taken along the build direction (z axis) is shown in Fig. 28. It can be concluded from the micro image that the honeycomb structure made by FDM are conformal to the part curve shape and they have a good geometric agreement with the original CAD model.

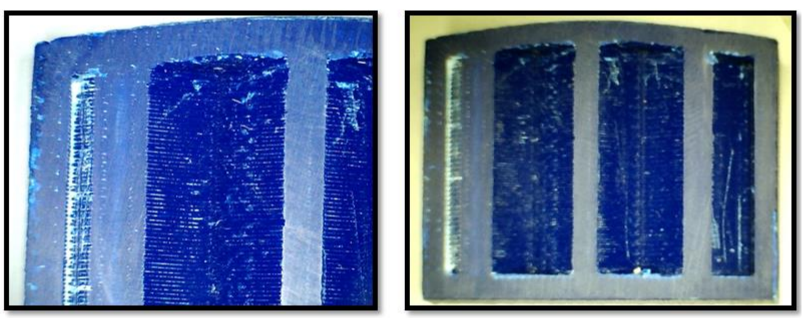


Fig. 28 Optical microscope image

In addition, these digital images indicate no defects or broken cells within the structures, confirming the ability of FDM to manufacture honeycomb cellular structures, which are very difficult or impossible to be manufactured by conventional manufacturing methods. Furthermore, they are well suited to the FDM's capabilities and can be constructed in a broad range of cell sizes. This verification would allow future development of even more advanced and functional cellular lattice structures.

CHAPTER 5
DESIGN EXAMPLE

In order to validate the proposed design methodology, it will be applied toward a design example of varying complexity. Here, we have considered the design of resin transfer mold (RTM) for composite fabrication.

5.1 Resin Transfer Mold (RTM)

The Resin Transfer Molding (RTM) is one of the most promising technology available today for composite manufacturing. In this process, a reinforcement matrix is formed to the geometrical shape of the part to be produced. This preform is placed in a mold determining the final shape of the part. The dry preform is impregnated with a liquid matrix resin, injected at either one or several gates. After the curing of the resin, the part is de-molded (Fig. 29).

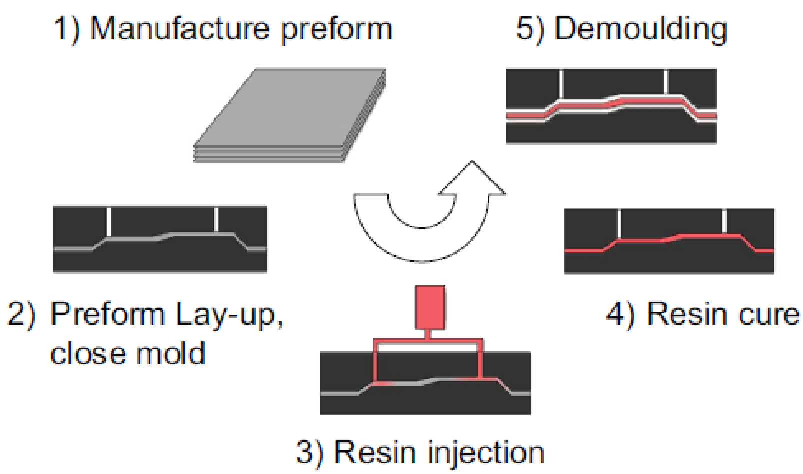


Fig. 29 Resin Transfer Molding Process [56]

RTM processes are capable to manufacture high geometrical complex parts and due to the comparably low cost of the raw materials and preforming technologies, it is applicable for medium size manufacturing series. However, for successful composite fabrication in RTM process, proper mold design should be done prior to processing. Moreover when mold is in complex in nature, it is much more critical to fabricate it within demand deadline by employing traditional manufacturing process. In this regard, AM seems to be a potential technology by offering customers a wide range of design freedom while designing their part.

Also availability of variety high grade materials along with low build cost now made this technology possible for RTM mold application.

Though it (AM) is capable to produce low cost(complex shape parts are cheaper to produce by AM, compare to conventional machining process)RTM molds in short time duration, introduction of cellular solids instead of bulky solid material, may further improve it's design since they offer good mechanical and thermal properties over low material consumption.

In this chapter, hexagonal honeycomb structures are made with the help of our proposed method for RTM application and evaluated in terms of manufacturing cost with the standard aluminum mold.

5.2 Resin Transfer Molding (RTM) Setup

The RTM system used in this work, consists of two separate components, which optionally may or may not be used together for composites production:

- A heated press unit (model PRESSE 3508 SERIES – 15 kW): acquired from ISOJET Equipments (France). It consists of two heated plates of 500 x 500 mm with the maximum temperature of 200°C and the maximum pressure of 14 bars assisted by a pneumatic system (Fig. 30);

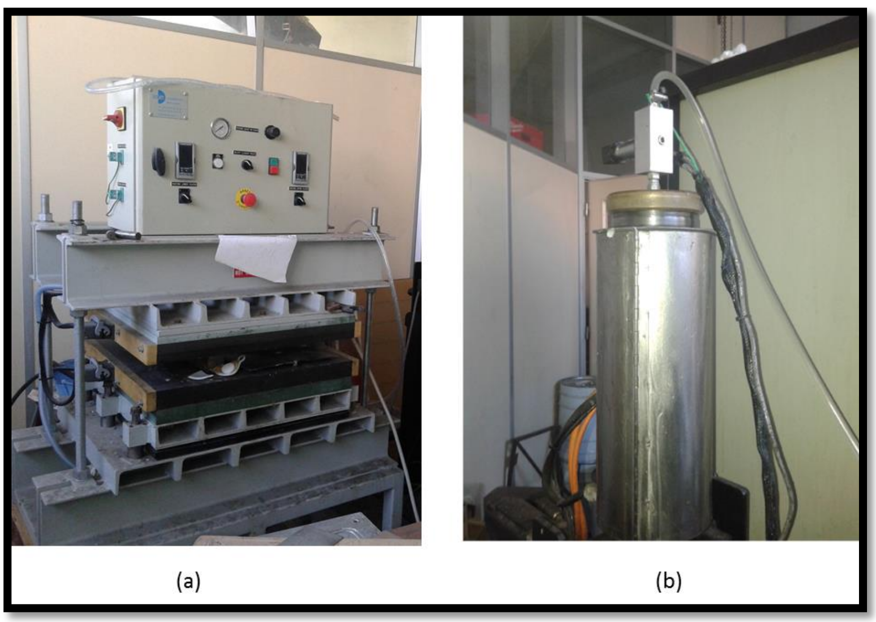


Fig. 30 Resin Transfer Molding (RTM) Setup

5.3 Materials and Methods

Stratasys FDM (dimension SST 1200es) is used in this study, with default ABSP400 material, to make RTM mold for an oar paddle application. Oar is a long stick with a wide flat blade at one end, used for rowing a boat (Fig. 31).

Fig. 31 Boat Oar Paddle

CAD models for the paddle's mold is designed in CATIA V5 and then it's scale down model is fabricated considering the FDM process capabilities and guidelines. The CAD modeled mold is shown in Fig. 32

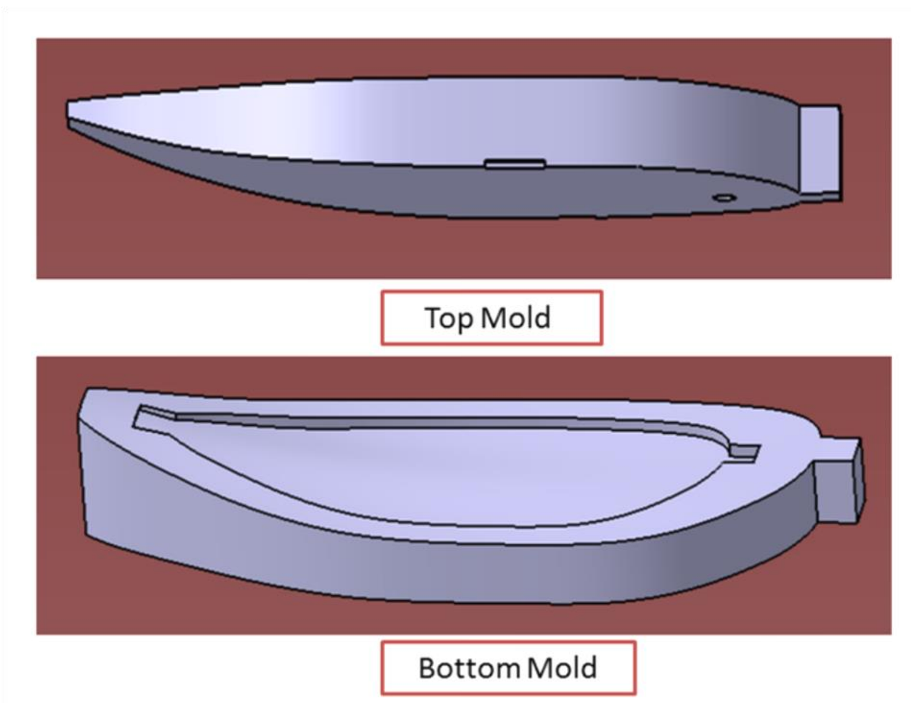


Fig. 32 Mold for Paddle

Before putting the ABS made mold in to use for RTM, we tested chemical stability of the ABSP400 with epoxy resin, used in molding (Fig.33). Staying stable for some long hours, it (ABS) finally proved it's inertness for the epoxy resin.

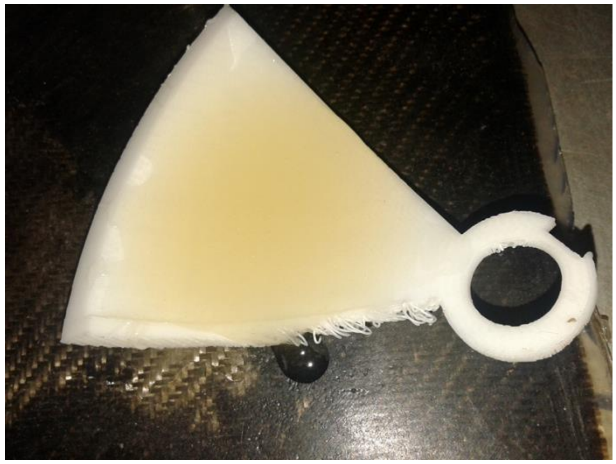


Fig. 33 FDM test specimen with epoxy resin

At first, we did a trail test by printing solid mold instead of the cellular mold for the oar paddle. The complete descriptions about this RTM test along with associated materials and machinery is explained below:

Step 1: Mold Making

In this step, solid mold for the Oar paddle is prototyped from the CAD model using stratasys FDM process. Proper inlet and outlet are designed in the mold for smooth flow of resin inside it. 4 mm width groove is also provided so as to prevent the spreading of resin when injected in the mold at high pressure. The complete FDM printed mold is shown in Fig. 34

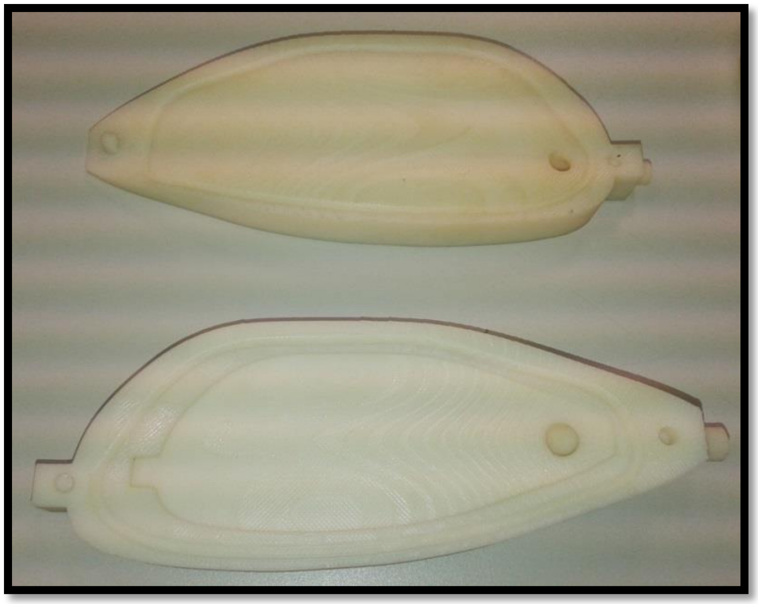


Fig. 34 FDM Printed Mold

Step 2: Reinforcement Selection

For oar paddle application, glass fiber reinforcement is selected due to it’s good moisture resistance and high strength-to-weight properties. As per the desired size of paddle, it (3 pieces) is cut out from the bundle of fiber and then placed in between the molds (Fig. 35). The detail property about this glass fiber is attached as APPENDIX B.

Fig. 35 Glass Fiber Reinforcement

Step 3: Resin Preparation

A standard thermosetting liquid resin, with the commercial brand name Quires 406 PA is used in the matrix in the form of orthophthalic unsaturated polyester (UP). It is acquired from the company MR-Dinis dos Santos (Lisbon, Portugal) and its characteristics are presented in the APPENDIX B. Peroxide Methyl-Ethyl-Ketone (PMEK), also bought from same location, is mixed and stirred with the resin (10mm per 1 liter resin) properly as the curing agent of matrix (Fig. 36)

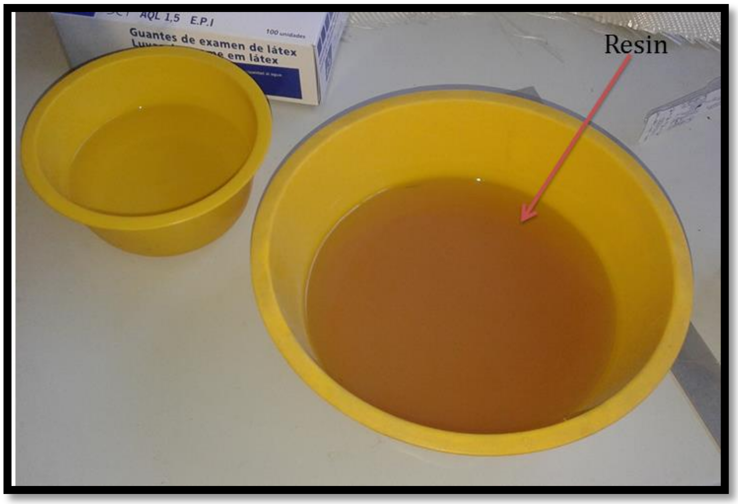


Fig. 36 Resin Preparation

Step 4: Injection

The mixture of resin and curing agent is injected at 20cc^3/min flow rate and 3 bar pressure into the mold; through RTM injection unit setup (Refer Section 5.2), till it comes out from outlet of the mold (Fig. 37). This confirms proper impregnation of resin with the reinforcement.

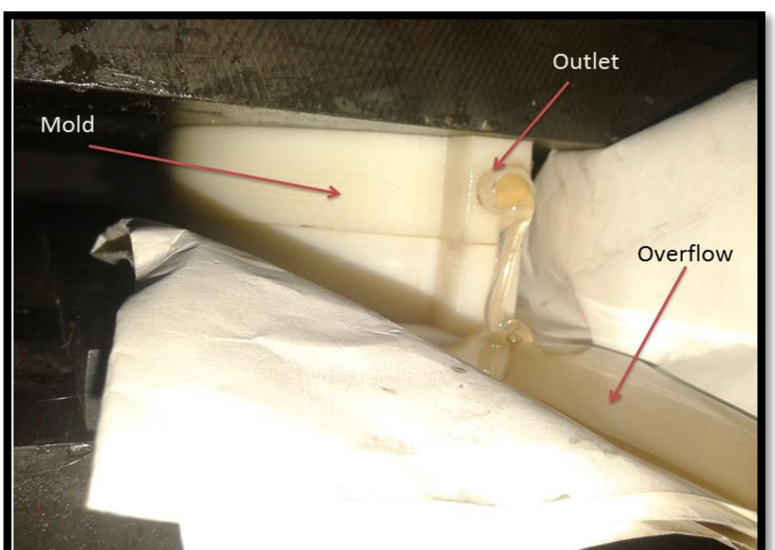


Fig. 37 Resin overflowing from the mold

Step 5: Curing

After injection, mold is kept under heated plates of the RTM machine for some hours (24 to 36)* for curing operation. Then it is taken out and composite is removed from the mold. The below Fig. 38 shows our glass fiber reinforced composite obtained directly from the mold.

Fig. 38 Glass fiber reinforced composite

Precautions:

- Mold is pre-heated for 30 minutes before performing the RTM test. This allows proper curing of resin, which results high strength composites.
- In order to get better surface finish in composite material, the mold surface is coated with a thin layer on resin before it's use.
- For easy removal of composite from the mold, we used a mold release agent (Honey Wax) before putting the glass fiber in to the mold.

The FDM printed solid mold was successful for composite manufacturing accounting 336 gm of material. In order to reduce material content, we printed and tested the sparse infill mold, using the default setting in the machine.

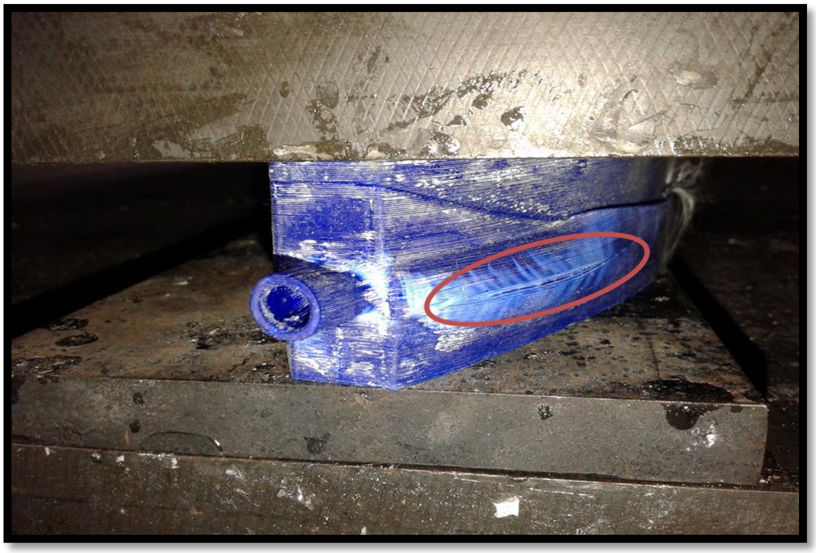


Fig. 39 Crack deformation in the sparse filled mold

It has been noticed by printing the sparse filled mold (using default setting in FDM setup) that when the pressure (about 3 bars) is applied on the mold, maximum deformation occurs at edges of mold and minimum at inner zone (Fig. 40). Therefore we designed our cellular mold by considering 10 mm wall thickness and 10 mm honeycomb cell size.

5.4 Cellular Mold

Since cellular structures show good performance at comparatively low volume of material, in this section we designed and tested our hexagonal honeycomb for the mold in finite element analysis (FEA) by virtually creating the similar RTM environment for it. FEA modeling is carried out by CATIA V5 structural analysis unit for the honeycomb filled RTM mold shown in Fig. 39. We used 10 mm cell size and 10 mm wall thickness to design the mold.

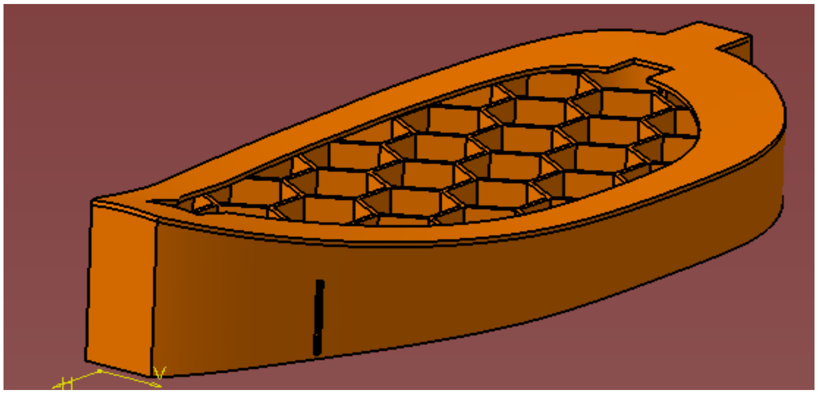


Fig. 40 Internal layout of honeycomb filled mold

We used Von Mises stress criterion to check our design under a given load (RTM) of 3 bar pressure. "*If the induced von mises stress is less than yield stress of material and there is minimum deformation in the mold under the given load, then our design is safe for the testing*".

For the analysis, we created and assigned ABS material to the mold with the defined properties given in APPENDIX A. Two steel plates are then attached to the mold that serves as RTM pressure plates during the analysis (Fig. 41). A distributed pressure of 3 bar is applied over the top face of the mold whereas bottom face is made fixed to the one of the steel plates and simulation started. The results of the simulation is discussed in the "Result and Discussion" Section.

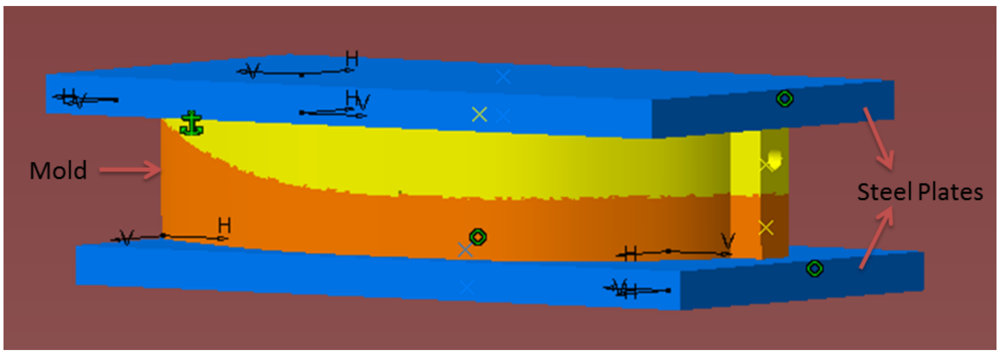
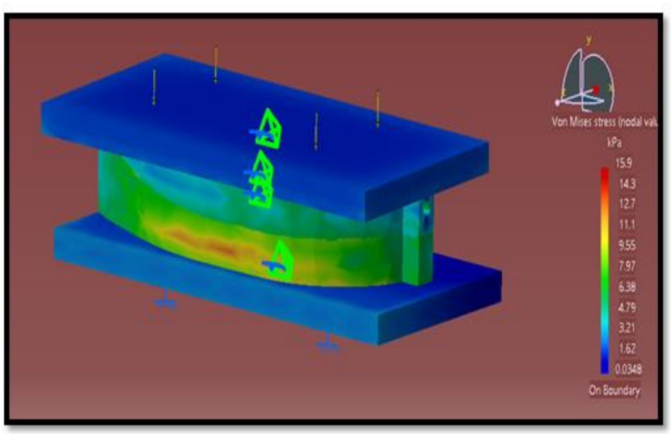


Fig. 41 Cellular mold for FEA analysis

5.5 Result and Discussion

Structural analysis report of the cellular mold is shown in Fig. 42 (Stress analysis report). It can be noticed that the obtained von mises stress at peak point (marked in red) is around 15.9 MPa, which is less than yield strength of the material.



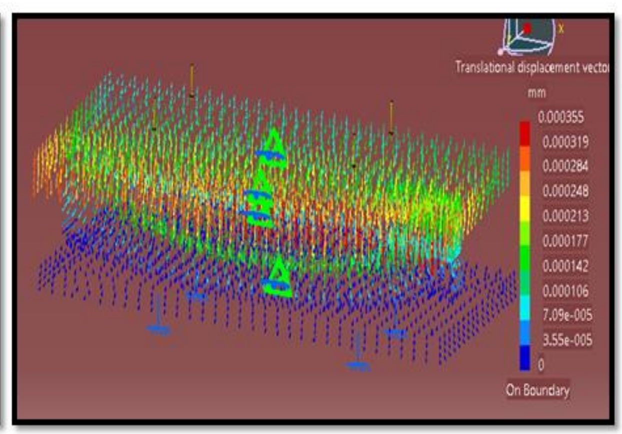


Fig. 42 FEA stress analysis

Fig. 43 FEA displacement analysis

Similarly, from the displacement analysis (Fig. 43) of the mold, a maximum deformation of 0.000335 mm is recorded which can be ignored compare to height of the mold.

$$\text{Safety Factor (SF)} = \frac{Yield\ strength}{Von\ mises\ strength} = 2.78$$

From the above discussion, it can be concluded that our cellular mold design is safe and it can be tested for production of composite via RTM process. This test also confirms the potential of FDM process to create end use cellular solids without using of any tool and human interventions.

It has been also noticed that compare to solid (336gm) and sparse (104gm) mold, our designed honeycomb mold behaves well and good at 182 gm material. Thus, the potential of FDM made cellular structure has been proved with our RTM case study and in future this approach can be extended to other load bearing application for saving expensive build material without sacrificing the mechanical strength.

CHAPTER 6
CLOSURE

6.1 Summary

Advances in additive manufacturing technologies have revolutionized the manufacturing and design domain as a whole. Designers now have access to a greater design space in which they can re-design and manufacture their customizable products by considering the greatest capabilities of AM.

In this regard, **Chapter 1** provides an overall overview by introducing the concept of “Design for AM”. Various cellular structures are also focused with regard to their application for light-weight and high strength structures.

Chapter 2 covers all the relevant research including design, analysis of cellular structures, and also the approaches for optimization of these structures.

Chapter 3 presents a novel method for designing periodic cellular structures using advanced tools of CAD. The method is able to generate honeycomb structures of different cell sizes and wall thickness for various industrial applications.

Chapter 4 explains the microstructure and mechanical property characterization of these cellular structures of varying cell sizes and wall thicknesses. Impact of relative density and wall thickness on compressive properties of these structures are also studied by conducting repeated experimentation.

Chapter 5 demonstrates the capabilities of our proposed method by testing a cellular RTM mold for oar paddle application.

Chapter 6 summarizes the contributions, addresses the limitations, and provides the future work.

6.2 Contribution

The method developed in this thesis allows leveraging the advantages of additive manufacturing for designing periodic cellular structures (honeycomb). Using this, cellular structures can be generated for hydro form and injection molding application, to reduce expensive build material consumption and production time. As per the author’s knowledge, in future, the proposed method will have a greatest contribution towards sustainable and green product development. In addition, the design example presented here, would led the future design engineers for a low cost composite fabrication.

6.3 Limitations and Future Scope

In this research, only hexagonal honeycomb, designed by FDM is tested for RTM application. In future, other category of cellular structure such as truss, conformal lattice structure should be investigated to study their properties. Tool-path optimization should be focused to reduce build time of these complex cellular structures. Though we have designed honeycomb structure, optimization is not carried out yet for the given loading condition. It should be taken in to consideration for generating optimal part design. In addition, the complete process should be integrated with the existing CAD platform, through an add-on installation, for quick and an easy part (cellular) generation.

REFERENCES

[1] S. Upcraft and R. Fletcher, “The Rapid Prototyping Technologies,” *Assembly Automation*, vol. 23(4), pp. 318-330, 2003

[2] C. C. Kai and L. K Fai, “Rapid Prototyping: Principles and Applications in Manufacturing,” *John Wiley and Sons*, Singapore, 1997

[3] S.S. Mahapatra and B. N. Panda, "Benchmarking of rapid prototyping systems using grey relational analysis," *Int. J. Services and Operations Management*, Vol. 16, No. 4, pp.460–477, 2013

[4] R. Noorani, “Rapid Prototyping-Principles and Application,” *John Wiley & Sons*, New Jersey, USA, 2005

[5] S. H. Masood and W. Q. Song, “Development of New Metal / Polymer Materials for Rapid Tooling using Fused Deposition Modelling,” *Materials & Design*, vol. 25, pp. 587-594, 2004.

[6] "Image: FDM Process Flow," ed. http://chuansong.me/n/492448

[7] http://www.stratasys.com/industries/automotive

[8] P. F. Jabobs, "Rapid Prototyping & Manufacturing: Fundamentals of Stereolithography," TX: Mcgraw-Hill, 1993.

[9] "Image: Siemens hearing aid," ed. http://www.medical.siemens.com.

[10] "Image: Invisalign braces," ed. http://www.invisalign.com.

[11] D. W. Rosen, I. Gibson, and B. Stucker, "Additive Manufacturing Technologies," *Springer*, 2010.

[12] J. Wooten, "Aeronautical case studies using rapid manufacture, in Rapid Manufacturing (Hopkinson, N., Hague, R., and Dickens, P., eds.)," ch. 15, *John Wiley & Sons*, 2006

[13]"Image: Propellor," ed. http://www.steg.com.au/capabilities/additive manufacturing/metals/

[14] Vayre, Benjamin, F. Vignat, and F. Villeneuve, "Identification on some design key parameters for additive manufacturing: application on Electron Beam Melting," *Procedia CIRP,* Vol.7, pp.264-269, 2013.

[15] www.amrc.co.uk/wp-content/uploads/AMRC_DPG_CircuitBracket.pdf

[16] http://www.eos.info/eos_airbusgroupinnovationteam_aerospace_sustainability study

[17] http://www.geaviation.com/company/additive-manufacturing.html

[18] Yan, Chunze, et al. "Evaluations of cellular lattice structures manufactured using selective laser melting." *International Journal of Machine Tools and Manufacture*, vol.62,pp. 32-38, 2012.

[19] "Image: Honeycomb," ed. http://www.ec21.com/offer_detail/Sell_SSH-301_and_SSH-304_Stainless--23593211.html.

[20] "Image: Foam," ed. http://www.zhongweiaf.com/en/

[21] V. S. Deshpande, N. A. Fleck, and M. F. Ashby, "Effective properties of the octet-truss lattice material," *Journal of Mechanics and Physics of Solids,* vol. 49, pp. 1747-1769, 2001

[22] M. F. Ashby, A. G. Evans, N. A. Fleck, L. J. Gibson, J. W. Hutchinson, and H. N. G. Wadley, *Metals Foams: A Design Guide*. Woburn, MA: Butterworth-Heinemann, 2000.

[23] J. Chu, S. Engelbrecht, G. Graf, and D. W. Rosen, "A comparison of synthesis methods for cellular structures with application to additive manufacturing," *Rapid Prototyping Journal,* vol. 16, pp. 275-283, 2010.

[24] K.M. Yu and C.L. Li, "Speeding up rapid prototyping by offset, Proceedings of the Institute of Mechanical Engineers," *Part B: Journal of Engineering Manufacturing*, Vol. 209, pp.1-8, 1995.

[25] M. Ganesan, and G. M Fadel, "Hollowing rapid prototyping parts using offsetting techniques," *Proceedings of the 5th International Conference on Rapid Prototyping*, June 1994, University of Dayton Research Institute, Dayton, 1994.

[26] B. Koc, and Y. S. Lee, "Non-uniform offsetting and hollowing objects by using biarcs fitting for rapid prototyping processes," *Computers in Industry*, Vol. 47, pp. 1-23, 2002.

[27]X. Qu and B, Stucker, "A 3D surface offset method for STL-format models," *Rapid Prototyping Journal*, Vol.9 (3), pp.133-141, 2003.

[28]Park, and C. Sang, Hollowing objects with uniform wall thickness," *Computer-Aided Design*, Vol.37, pp.451–460, 2005

[29]Z. Zhengyu, D. Yucheng and H. Jun, A new hollowing process for rapid prototype models," *Rapid Prototyping Journal*, Vol. 10(3), pp. 166-175, 2004

[30] L. E. Murr, , et al. "Characterization of Ti–6Al–4V open cellular foams fabricated by additive manufacturing using electron beam melting." *Materials Science and Engineering:* Vol. *A* 527.7, pp.1861-1868, 2010

[31] A.J. Wang and D. L. McDowell, "Optimization of a metal honeycomb sandwich beam-bar subjected to torsion and bending," *International Journal of Solids and Structures,* vol. 40, pp. 2085-2099, 2002

[32] Campanelli, L. Sabina, "Manufacturing and characterization of Ti6al4v lattice components manufactured by selective laser melting." *Materials* Vol. 7.6,pp. 4803-4822, 2014.

[33] J. C. Wallach and L. J. Gibson, "Mechanical behavior of a three-dimensional truss material," *International Journal of Solids and Structures,* vol. 38, pp. 7181-7196, 2001.

[34] S. Chiras, D. R. Mumm, A.G. Evans, *et al.,* The structural performance of near-optimized truss core panels," *International Journal of Solids and Structures*, vol. 39, no. 15, pp. 4093-4115, 2002

[35] S. R. Johnson, M. Reed, H. V. Wang, and D. W. Rosen, "Analysis of mesostructure unit cells comprised of octet-truss structures," presented at the Solid Freefrom Fabrication Symposium, Austin, TX, 2006.

[36] H. Wang, "A unit-cell approach for lightweight structure and compliant mechanism," PhD Thesis, Georgia Institute of Technology, 2005

[37] Ravari, MR Karamooz, *et al.,* "Numerical investigation on mechanical properties of cellular lattice structures fabricated by fused deposition modeling,"*International Journal of Mechanical Sciences* Vol. 88,pp. 154-161, 2014

[38] Chang, S. Patrick, and David W. Rosen. "The size matching and scaling method: a synthesis method for the design of mesoscale cellular structures, *"International Journal of Computer Integrated Manufacturing* Vol.26.10,pp. 907-927, 2014.

[39] P. Chang, "An Improve Size, Matching, and Scaling Synthesis Method for the Design of Meso-Scale Truss Structures," Master's Thesis, Georgia Institute of Technology, 2010.

[40] M. P. Bendsoe and O. Sigmund, *Topology Optimization: Theory, Methods and Applications*. Berlin: *Springer*, 2003.

[41] M. P. Bendsoe, *Optimization of Structural Topology, Shape and Material.* . Berlin Heidelberg: *Springer-Verlag*,1995.

[42] G. Allaire, Shape Optimization by the Homogenization Method. New York: Berlin, 2002.

[43] P. Pedersen, "On optimal shapes in materials and structures," *Structure Multidisciplinary Optimization,* vol. 19, pp. 169-182, 2000

[44] G. I. N. Rozvany, Topology Optimization in Structural Mechanics, *Springer*, 2003.

[45] M. P. Bendsoe and N. Kikuchi, "Generating optimal topologies in structural design using a homogenization method " *Computer Methods in Applied Mechanics and Engineering,* vol. 71, pp. 197-224,1988.

[46] S. A. Burns, Recent Advances in Optimal Structural Design, *American Society of Civil Engineers*, 2002.

[47] S.S. Rao, Engineering Optimization: Theory and Practice. *John Wiley & Sons*, Inc., 4 ed., 2009

[48] S. C. Chapra and R. P. Canale, *Numerical Method for Engineers*, 6 ed., *McGraw-Hill*, 2010.

[49] G. I. N. Rozvany and M. Zhou, "The COC algorithm, Part I: Cross-section optimization or sizing," *Computer Methods in Applied Mechanics and Engineering,* vol. 89, pp. 281-308, 1991.

[50] B. Hassani and E. Hinton, "A review of homogenization and topology optimization III - topology optimization using optimality criteria," *Computers and Structures,* vol. 69, pp. 739-756, 1998

[51] P. Pedersen, "On optimal shapes in materials and structures," *Structure Multidisciplinary Optimization,* vol. 19, pp. 169-182, 2000

[52] Chu, Jane, et al. "A comparison of synthesis methods for cellular structures with application to additive manufacturing." *Rapid Prototyping Journal*, Vol. 16.4, pp.275-283, 2010

[53] Wang, Hongqing, Y. Chen, and D. W. Rosen. "A hybrid geometric modeling method for large scale conformal cellular structures." *ASME 2005 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers, 2005

[54] Alzahrani, A. Mahmoud , S. K. Choi, and D. W. Rosen. "Design of Truss-Like Cellular Structures Using Relative Density Mapping Method." *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers, 2014

[55] Gibson LJ, Ashby MF. Cellular solids: structure and properties. New York: Cambridge University Press; 1997.

[56] Luz, Felipe Ferreira, et al. "Resin Transfer Molding Process: Fundamentals, Numerical Computation and Experiments." Numerical Analysis of Heat and Mass Transfer in Porous Media. Springer Berlin Heidelberg, 2012. 121-151.

APPENDIX A

PROPERTIES OF ABS

Property	Extruded	Moulded	Unit
Physical property			
Density	0.350-1.26	1.02-1.17	g/cm3
Moisture Absorption at Equilibrium	0.150 - 0.200	0.000 - 0.200	%
Viscosity	155000 - 255000 (Temperature 240-260°C)	1.16e+6-1.52e+6 (Temperature 240-260°C)	cP
Linear Mould Shrinkage	0.00240 - 0.0120	0.00200 - 0.00900	cm/cm
Mechanical property			
Hardness Rockwell R	90.0 - 121	68.0 - 115	
Tensile Strength, Ultimate	27.0 - 52.0	28.0 - 49.0	MPa
Tensile Strength, Yield	20.0 - 62.0	13.0 - 65.0	MPa
Modulus of elasticity	1.52-6.10	1.00-2.65	GPa
Elongation at Yield	0.620 - 30.0	1.70 - 6.00	%
Flexural Modulus	1.20 - 5.50	1.61 - 5.90	GPa
Flexural Yield Strength	28.3 - 81.0	40.0 - 111	MPa
Charpy Impact, Notched	0.900 - 5.00	0.400 - 14.0	J/cm^2
Izod Impact, Notched	0.380 - 5.87	0.100 - 6.40	J/cm
Thermal properties			
Thermal Conductivity	0.150 - 0.200	0.128 - 0.200	W/m-K
Coefficient of thermal expansion, linear	68.0 - 110	0.800 - 155	µm/m-°C
Glass Transition Temperature	108 - 109	105 - 109	°C

APPENDIX B

MATERIAL DATA

RESIN

Characteristics	Quires 406 PA
Density	1.2
Viscosity at 25^oC (cPs)	600-800
Gel time at 25 ^oC (min)	14.5-15.5
Styrine content (%)	38-42
Acidity (mgKOH/g)	15-21

Reinforcement

Component Name	Glass fiber
Fiber Density	2600
Fiber Diameter	1.05E-04
Price	R$ 9,41

Catalyst

Component Name	BRASNOX
Density	1100
Price	R$ 9.3

Wax Blend for Industrial Mold Release

Product Name	Honey Wax
Physical State	Paste
Appearance	Yellow
Flash Point	40 ^oC
Boiling Point/Range	157-199 ^oC
VOC content	587 g/L
Specific gravity	0.78