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Additive Technology of Soluble Mold Tooling for Embedded Devices in Composite Structures: A Study on Manufactured Tolerances

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ADDITIVE TECHNOLOGY OF SOLUBLE MOLD TOOLING FOR
EMBEDDED DEVICES IN COMPOSITE STRUCTURES:
A STUDY ON MANUFACTURED TOLERANCES

By

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This thesis is dedicated to the memory of my talented grandmother Leena Maitra, a smart woman whom I still miss everyday.

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ABSTRACT

Composite textiles have found widespread use and advantages in various industries and applications. The constant demand for high quality products and services requires companies to minimize their manufacturing costs, and delivery time in order to compete in general and niche marketplaces. Advanced manufacturing methods aim to provide economical methods of mold production. Creation of molding and tooling options for advanced composites encompasses a large portion of the fabrication time, making it a costly process and restraining factor. This research discusses a preliminary investigation into the use and control of soluble polymer compounds and additive manufacturing to fabricate sacrificial molds. These molds suffer from dimensional errors due to several factors, which have also been characterized. The basic soluble mold of a composite is 3D printed to meet the desired dimensions and geometry of holistic structures or spliced components. The time taken to dissolve the mold depends on the rate of agitation of the solvent. This process is steered towards enabling the implantation of optoelectronic devices within the composite to provide sensing capability for structural health monitoring. The shape deviation of the 3D printed mold is also studied and compared to its original dimensions to optimize the dimensional quality to produce dimensionally accurate parts of up to 0.02% error.

CHAPTER 1

INTRODUCTION

With rapid development in aerospace and automotive industries, the proper choice of structural materials have become an essential aspect for state-of-the-art designs. These industries have always been seeking ways to reduce the cost and weight of materials used in their production. Due to increased fuel prices, weight saving has become an important factor and hence composites have been introduced into such applications [1-3]. Fiber reinforces composites are ideal for part and device integration for example, on and within aircrafts. However the manufacturing process can be tedious, expensive and time consuming [4]. Moreover, the process of demolding can be relatively difficult and troublesome [5].

According to a survey conducted by Christman, there is a strong need to control and reduce costs of molds to compete with the declining prices, profit margins. He also observed the increase in demand for reducing the mold manufacturing times [6]. To be competitive in the modern industry, European companies were forced to switch to mass production of short series of customized products with added value. Additive manufacturing (AM), also known as rapid prototyping (RP) is a powerful tool that allows higher flexibility and greater efficiency to meet all the requirements of today's productions [7, 8]. Most RP technologies were developed to produce prototypes and models. However, some of the current RP technologies are geared towards the manufacturing of tooling and production parts.

Creation of molding and tooling options for advanced composites encompasses a large portion of fabrication time, making it a costly process and a restraining factor [9]. Therefore, the use of AM with a soluble compound enables manufacturers to reduce post-machining and secondary wear composites. This can be used for structronic (structural-electronic) parts and integration of devices [10, 11], such as micro-sensors, while providing easy part removal and dexterity [12]. Structronics involves the production of intelligent 3D. These can be produced containing sensors and electronic components to create self-sensing and adaptive structures.

1.1 Motivation

Composite textiles have found widespread use and advantages in various industries and applications. The constant demand for high quality, low cost products and services requires companies to minimize their manufacturing costs, and delivery times. This is essential for the companies in today's world to compete in general and niche marketplaces. Creation of traditional molds for composites requires a substantial amount of time and in turn becomes an expensive affair. Advanced manufacturing methods aim to provide economical methods of mold and tooling production. Composite structures are often exposed to harsh environments. With the increased use of composites in military and aerospace structures, it is important to study the failure modes of composites, which are quite different from that of metals. Damage in composites typically initiates between the laminates, which is often times, invisible to the naked eye. Hence, structural health monitoring (SHM) in composite materials is a necessity in high-performance composite structures for the detection and quantification of delamination, matrix cracking and fiber degradation in order to improve reliability. The use of fiber optic sensors in composites provides the ability for in-situ damage sensing and SHM that would be difficult to achieve by other means. The use of a dissolvable mold for composite parts will allow easy incorporation of opto-electronic sensors and integrable devices while ensuring quick and effortless mold removal.

Embedding of sensors not only provide SHM, but also provide integration of various performance attributes in the given structure, such as cure monitoring sensors, strain sensors, multifunctional chemical vapor sensors, etc.[13-15]. State of the art research in composites seeks to incorporate one or more functions to create robust composite systems. However, the process of embedding these sensors is non-trivial. Factors such as the aspect ratio (ratio of the size of the sensor to the size of the composite), placements, tooling, matrix curing conditions, fiber-matrix ratio, etc. play a crucial role in maintaining the integrity of the composite.

Molding/tooling options for composites calls for long undesirable fabrication processes. Tooling of composites has not changed quite significantly within the last quarter of the century [16]. Besides fiber placement and out-of-autoclave processing, composite tooling solutions have not seen tremendous research growth [16]. The demand for high quality products and services in today's companies requires them to minimize manufacturing costs and times. The use of AM technologies in making soluble molds could potentially address these issues by replacing

traditional mold material with a soluble thermoplastic. This can also provide custom complex shapes and structures for composite processing.

Additive manufacturing processes involve the use of thermoplastic polymers that are heated to their melting point, extruded into the desired shape and rapidly cooled down. The fluctuating temperature in and around the 3D printer causes the 3D printed part to cool down irregularly resulting in shrinkage and warpage. The production of good quality, accurate composite parts depends on the quality and dimension of the mold. Performing a dimensional analysis on a 3D printed mold will account for discrepancies in the dimensions, which will be compensated for in the CAD drawing to produce parts with the desired dimensions.

1.2 Research Objectives

Additive manufactured parts are susceptible to different errors during their fabrication process leading to geometric inaccuracies. It is essential for tooling and production parts to guarantee the accuracy of geometric dimensions within the acceptable tolerance as well as repeatability. Thus, dimensional analysis will be performed on the additive manufactured parts produced for this research to maintain its dimensional accuracy to produce consistent and error-free molded parts.

This research is aimed to study and demonstrate a novel molding/tooling technique, i.e., a soluble mold to produce composite parts with integrable devices. This will be done in two stages (1) process capability (2) application specific study (described below) in order to perform SHM in composites

Process capability

1. Perform a dimensional analysis on the additively manufactured mold and determine the sources of variation, such as, effect of temperature, material properties, extruder positioning, etc.
2. Digital comparison of the mold to that of original CAD drawing
3. Optimize/minimize dimensional errors in these molds

Application specific study

1. Use additive manufacturing to print a soluble mold with embedded sensors
2. Optimize placement of sensors to minimize delamination

The use of soluble polymer compounds and AM to fabricate a soluble mold can reduce the processing steps thus, resulting in a faster manufacturing process. Also, the soluble mold is a one-time use mold. This helps in eliminating the waiting time as required in other traditional molding techniques for the reusability of the same mold. The soluble mold allows in-process tooling and implantation of devices such as optical fibers within the composite. Optical-fiber sensors are ideal sensors for smart materials and structures, because they are small, light weight, immune to an electrical interface, and environmentally more stable [13].

In this study, to demonstrate the aforementioned approach and application, i.e., the soluble mold technique sensing elements for SHM will be integrated within a processed composite. The sensing element, in-situ optical fiber (ITOF) comprises of a plastic optical fiber with a triboluminescent coating. The triboluminescent coating contains Zinc Sulphide Manganese (ZnS:Mn) crystals which emit light when stressed or fractured [17]. Past studies have shown the use of ITOF for damage detection in engineering structures and in-situ structural health monitoring [3].

1.3 Outline of Thesis

This thesis comprises of an extensive literature review on the state of the art molding and tooling options for composites and additive manufacturing methods in Chapter 2. Chapter 3 discusses the proposed research methodology for the estimation of the different types of errors in additive manufactured parts. Chapter 4 contains the application of the proposed methodology in the fabrication of a mold for a composite sample. The future work and conclusions of this research are discussed in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

This chapter discusses the various composite molding and tooling methods while emphasizing on the advantages and disadvantages of each method. A short discussion on the factors considered in mold making is also included. It also explores the possibility of using additive manufacturing in fabrication of molds for composite structures.

2.1 Composite Molding and Tooling Methods

A mold is a structural shape, usually rigid, on which a composite part is formed [18]. Molds are special tools functioned to fabricate composite components. The tooling, also known as a mold, is a custom designed platform or support for a certain part to be produced on. A tool or mold supports and/or shapes the composite part in its formation [19]. For instance, injection molding allows the making of complex and intricate shapes. However, the challenge is to fabricate a mold that has the same geometry as the desired part tolerance and also allows for easy part removal [20]. There are a number of molding methods that have been used for shaping composite structures over the years [19, 21, 22]. Resin transfer molding (RTM) and its variants such as vacuum assisted resin transfer molding (VARTM) have been some of the most promising composite manufacturing methods as compared to pre-impregnation technology [18, 22].

The choice of processes for molding composite parts depends on a number of factors. Some of the factors are:

- The complexity of the part (flat/simple or 3D/intricate)
- Required annual production rate
- Type and nature of positioning reinforcement
- Constraints on the finished part price
- Acceptable tolerances by the finished parts
- Mechanical, thermal, chemical and other conditions of part use.

2.1.1 Molding and Tooling

A tooling determines the surface quality and geometry on the outside of the part, and inside, if the part is hollow. Traditional tooling are utilized to cast metals and plastics. Tooling for composite structures is a fairly mature technology, but has not progressed in recent years [16]. With a rigid mold, it is always necessary to draw the geometry in a way to allow placement of fibers and easy removal of the part. Generally, complex mold structures can require two or more primary tool segments, resulting in more than one parting plane, making the process of sealing the mold more difficult [22]. It is possible to accommodate undercut surfaces within the mold to support the complex geometry while allowing clamping and proper sealing, but at the cost of a longer cycle time. Thus, the design and manufacture of molds play a crucial role in composite manufacturing and can cost up to \$0.5 million. This takes up six to nine months for process development before it can actually be used for the production of parts [23]. Taylan et al. discusses the advantages of producing a single reusable mold over one-time use molds [23]. The factors he considered were surface finish, durability and reusability. However, he did not consider the high production costs and time wasted while waiting to reuse the mold.

The molds used for forming composites, are made from a variety of materials, such as robust metals for high production rates at increased temperatures [18, 24]. For molds that are not exposed to high temperature, materials such as wood, fiberglass, high-density foams etc. are used. The cost and complexity of the molds increases with the increase in part performance, requirements and the production rate. High-rate production molds are made of strong metals that can withstand repeated cycles of high temperature and pressure while maintaining dimensional accuracy and good surface finish. These molds are made of metals, ceramics, monolithic graphite, carbon fiber/epoxy, etc. and each material has its own advantages and disadvantages. For example, CTE mismatch between the mold material and the composite is a major concern. During heated cure, CTE mismatch is often too extreme to use with high precision composite parts. Certain metal alloys, such as Invar offer closer CTE matches but require expensive initial tooling processes. Epoxy and graphite molds do not meet the high temperature requirements and is also non-durable making it unsuitable for repeated or multi-use. A major concern with ceramic molds is their large thermal mass requiring high heat input to achieve the desired temperature for composite cure. This also causes the vacuum bag and other sealant materials used in manufacturing, to degrade. Metals such as steel, nickel and aluminum are widely used for tooling

but their biggest disadvantage is their high CTE [19]. Table 1 shows a comparison of the properties of different materials used for composite tooling.

Table 1: Properties of materials used for tooling

Material	Accuracy	CTE (ppm/°C)	Life span	Cost
Invar	Accurate	1.3 Low CTE	Very long life	Very high cost
Carbon (Graphite)	Very accurate	2-4 Low CTE	Soft, but long life	Very high cost
Composite (GFRC)	Accurate	6.3 Low CTE	Soft, but long life	Fairly high cost
Metal (Steel/Al)	Very accurate	14.9-23.6 High CTE	Long life	Moderate cost
FDM polycarbonate	Less accurate	50-200 High CTE	Soft, short life	Very low cost

New technologies have evolved to compete with Invar's durability but at a fraction of its weight and cost [25]. One such technology uses a hybrid approach where in an easily fabricated base material is coated with a hard material to provide potentially better surface finish and durability. The parts are designed in a computer aided design (CAD) system and are converted to cutter paths for a computer numeric control (CNC) machine.

Gupta patented the invention of composite tooling for fiber reinforced high temperature composite manufacturing, which has an advantage over other tooling methods. Composite tools have a CTE close to the part CTE, helping the part maintain its dimensional accuracy during the cure. Shrinkage and thermal expansion of the part will be very similar. However, these molds are more susceptible to wear and tear and are typically used in low-volume. The composite tool is prepared on a master tool made of ceramic or monolithic graphite, which again consumes a substantial amount of time and money [19].

The required part accuracy is an important factor when making large-scale composite parts for industries. The aerospace industry follows the AS9100 standard [26] to ensure quality management for the production of high quality consistent parts. High accuracy requirements makes hand-made parts expensive and replication can be difficult. Thus, CNC machines having high accuracy, in the order of microns, are used to obtain parts with high precision [18].

Molds are also subjected to wear and tear from constant abrasion against dry fibers in composite or when other tools come in contact with the mold. The surface hardness and smoothness of the mold deteriorates with repeated use. Also, these molds are most often impacted during de-molding, which can cause the mold to deform, wear out, and contain perpetuating dents [18, 27].

Traditional metal molds are vulnerable to certain resins causing it to lose its durability. Metal molds are also prone to corrosion because of humid environmental conditions, which calls for further care to retain them in their pristine condition. The use of a release film prevents the resin from coming in contact with the surface of the mold; however, it requires replacement after each cycle and needs to be removed after the part is de-molded [18]. Such disadvantages calls for a one-time use mold that can be quickly manufactured and does not require any kind of maintenance to keep it in good condition to be reused.

2.1.1.1 Types of Molds

a) Male Mold: A protruding mold is referred to as a male mold or a positive mold. Since, the composite is layered on the mold as shown in Figure 1. The surface finish of the side of the composite in contact with the mold depends on the surface roughness of the mold itself. Although a male mold is easy to construct, it causes undesirable expansion of the composite part during the cure cycle. Due to this, their coefficient of thermal expansion (CTE) needs to be scrutinized to prevent the mold from damaging the composite part while curing. Thus, the molds are designed to be slightly smaller to allow the part to grow into the desired dimensions.

Figure 1: An example of a male mold

b) Female Mold: A female mold or a negative mold contains cavities, which makes it challenging for the fiber layers to be laid down in all the edges and corners, as shown in Figure 2 [28]. The outer surface of the finished composite part will have a smoother surface since it will be in contact with the mold and will also be more precise. The CTE of the mold, if made of metal, needs to be considered to prevent the mold from detaching itself from the part while curing due to expansion. While female molds are more costly to manufacture, they have a reduced post processing time as the part made in such a mold has a smooth outer surface.

Figure 2: An example of a female mold

c) Closed Mold: Closed molds contain both male and female molds that align together to form a closed structure within which the composite is laid. This ensure a smooth surface finish

on either side of the part, which means, the parts oftentimes will not require post processing. The fibers between the layers are impregnated with resin by injection. However, the male and female molds need to be machined with great precision. This is to ensure that the mating parts are uniform with respect to each other and are within the acceptable tolerance range. The cost of production of such molds thus increases with increased precision. The CTE is also a major issue as both parts of the mold may expand differently when exposed to heat, thus damaging the structure of the composite part inside [21]. Closed molds made of metals and ceramics are durable and able to withstand numerous production cycles. At the same time they are relatively heavy and expensive [25].

2.1.2 Mold Design Criteria

2.1.2.1 Shrinkage Allowance

Composite materials undergo a considerable amount of shrinkage during the curing process. The shrinkage during the chemical cure also affects the surface finish of the final composite part. It can lead to the formation of voids, delamination and warping [29]. Thus, shrinkage of the composite material needs to be taken into consideration while designing a mold. This helps to ensure that the final product is of the desired shape and dimensions and within the acceptable tolerance limits. The CTE of the mold material also plays an important role in composite manufacturing; however, it is not important for composites being cured at room temperature [30].

2.1.2.2 Part De-molding Considerations

Mold removal is a tedious and time-consuming process. Most often after a composite part is cured, it is left with no place to wedge under the part to apply any de-molding pressure. Particularly, thick or sandwich structures require a substantial amount of strategically placed force to remove the part without causing damage to the mold or the part itself. Molds are often slightly heated to allow easy part removal. However, temperatures above 55°C makes it uncomfortable for manual de-molding [18, 31]. The draft angle of the mold (angle of the sides of the mold with respect to the base of the mold) also plays an important role in the de-molding process. A mold with zero draft angles has sides perpendicular to the bottom as shown in Figure 3. In a mold with a positive draft, the sides are wider at the top than they are at the base.

Figure 3: Male mold with zero draft vs. positive draft angle

Figure 3 and Figure 4 clearly shows the difference between a zero draft and a positive draft angle mold. A mold with a positive draft angle makes it easier to de-mold parts. However, a mold with a negative draft is tighter at the top than at the bottom, making de-molding difficult or virtually impossible, especially for rigid materials [18, 32]. According to Dr. Mazumdar, a generous draft angle promotes better material flow, while minimizing warpage. He recommended a minimum inside corner radii of 2.032mm and minimum outside corner radii of 1.524mm [30].

Figure 4: Difference between positive and negative draft angle mold

2.1.2.3 Part Surface Characteristics

The surface finish of the molded composite part depends on the surface finish of the mold. The surface finish also affects the ease with which a part can be removed. A better surface finish makes the part resistant to resin attack, delay fiber strand and resin deposit build-up. Traditional methods of providing a smooth surface to the mold includes electro-less plating, electroplating, vapor deposition, etc. These coatings can be as expensive as the mold itself [18].

2.2 Components of Composite Materials

Composite materials or fiber-reinforced composites (FRCs) possess excellent stiffness and specific strength properties. This makes them perfect for use in various industries such as, aerospace, automotive, sporting goods, infrastructure, just to name a few [33, 34]. Although, FRCs are used in a large number of applications, there are certain issues that still need to be taken into consideration. FRCs consist of two or more distinct materials, each having their own unique properties. When these materials are combined and bonded together, the individual materials retain their physical and chemical properties. At the same time, their combination produces a set of properties that neither one of the constituents possess when acting alone. The fibers/reinforcements have a high strength and are bonded into a matrix/resin to form a composite. The fibers/reinforcements are the main load-carrying part of the composite. The matrix/resin provides protection from abrasions and environmental changes. It also acts as a structural medium for load transfer between the layers of reinforcement fabric [21]. Figure 5 shows a flow chart with the materials and processes involved in successfully creating a composite part from a design.

The flowchart lists the various raw materials such as, fibers, resin, fillers and additives, etc. that go into making a composite part. These materials are used in conjunction with specifically designed equipment such as molds and tooling. Once the fibers are correctly positioned in the mold, they are impregnated with resin and cured in a molding cycle. This is when the resin hardens with the fibers to take the shape of the mold.

Figure 5: Materials and processes used in composite manufacturing [35]

2.2.1 Delamination in Composites

Composite materials portray a relatively weak behavior under localized impact, thus limiting their use [36]. FRCs lack the ability to absorb energy from an impact and deform like metals. The impact energy is transmitted to the weaker interfaces between the composite layers which leads to a process called impact induced-delamination. Composites used in large aircraft structures are subject to low impact caused by hailstorms, birds and other unpredictable discrete events, causing it to gradually debilitate. These causes minor cracks in the matrix, separation between plies/layers of fabric, splitting between fibers, which are often completely invisible and thus undetectable [37]. To improve the performance and reliability of composites, it is necessary to be able to detect these damages as they occur [9]. The process of implementing a damage detection strategy for composite materials used in engineering is known as structural health monitoring (SHM) [38].

Although the use of an integrated device is aimed at improving the functionality of the part, the integrity of the host material is compromised. Its overall strength relies on the method of

layup used to embed the device. Parts with embedded devices produced by traditional layup methods portray lower mechanical properties compared to a part without embedded devices [39-41]. According to Hansen and Vizzini, the use of a structural technique called ‘interlacing’ which makes use of continuous and discontinuous plies at different locations throughout the laminate thickness delayed the onset of damage [42]. Their results for static tension and tension-tension fatigue tests showed that the specimen exhibited excellent damage resistance and displayed its first sign of delamination under loading values of 6.2 to 62kN after 188 cycles. It was also observed that there was no damage growth for cyclic loads up to 62kN. It was concluded that interlacing greatly improved the structural integrity of the embedded devices and delayed the occurrence of damage initiation.

Advanced composite structures are often used in harsh environments in many industrial areas. To ensure better performance, it becomes necessary to monitor the structural health of the composite when exposed to such conditions. In the past, a number of techniques had been developed to provide non-destructive evaluation such as shearography, ultrasonic scanning, vibration testing, sonics, radar, etc. [9]. But these techniques do not provide real-time evaluation. The importance of in-situ structural health monitoring is in high demand as they behave as real-time monitors for the health status of a composite and to detect any damage occurred within the structure [9].

2.3 Additive Manufacturing

Additive manufacturing (AM), also known as rapid prototyping (RP) is a powerful tool for manufacturing molds. It offers higher flexibility and greater efficiency while reducing cost and manufacturing time [7, 8]. AM processes based on the layer-by-layer technique, which is an effective procedure to overcome aforementioned challenges. The ASTM F42 Committee classifies AM processes into seven areas as listed below [43]:

1. Stereo lithography (SL)
2. Fused Deposition Modeling (FDM)
3. Ink Jet Printing (IJP)
4. Three Dimensional Printing (3D-P)
5. Selective Laser Sintering (SLS)
6. Laminated Object Manufacturing (LOM)

7. Selective Laser Chemical Vapor Deposition

Most AM systems make use of a single material to manufacture parts [44]. AM also allows the inclusion of embedded devices such as sensors, resistors, transistors and other electronic devices [45-51]. A company by the name of MarkForged implemented AM to embed electronic sensors in orthotics or insoles for shoes. The company prints custom insoles with reinforced fibers and embedded sensors to monitor a person's movements to make a new set of orthotics [52]. Since AM allows access to any point of interest during the fabrication process, it becomes possible to embed sensors and devices within the functional part. Traditional and subtractive manufacturing methods, such as machining, make it difficult to produce parts with complex geometry and intricate shapes. In such methods, the desired part is carved out of a block of the material, leaving behind wasted material chips that are often coated in oily cutting fluid making it inconvenient to recycle. Casting, forming, molding and machining are technologies that use subtractive techniques. The tools used during these manufacturing processes limit the complexity of final products (in terms of shape, structure, size, etc.). AM being a technology that builds products from the bottom up, adding one cross-sectional layer of material at a time, offers several advantages. For example, it provides the ability to build functional parts without the need of assembly while saving time and cost in the process [51]. Thus, the cost, time and effort taken to produce a part with a complex structure using AM is considerably less compared to other manufacturing processes.

AM being a high-speed process has the potential to reduce the time taken for a product to reach the market while allowing customization [11]. Compared to traditional manufacturing methods, AM only incorporates the required amount of material to construct the part, thus preventing the wastage of material and the production of scraps. According to Carol Tolbert, manager of the manufacturing Innovation Project at NASA Glenn Research Center, traditional methods used in manufacturing some of their equipment can take up to several months and involves a lot of measuring for it to be exact. The use of AM can drop the time between production iterations to weeks [11]. This is because the part can be 3D printed directly from a CAD drawing as opposed to having it machined in order to obtain accurate dimensions. Furthermore, AM allows the incorporation of negative drafts and free form enclosures.

All AM processes use the same series of steps in making a part. A CAD solid part of the component is designed on supporting software, which is transferred to the 3D printer in an STL

type format file. This file consists of a set of tessellations or triangular facets that describes the geometry of the solid model. The STL file is sliced into layers converting the solid 3D object into a series of 2D layers that can be stacked together to form the solid geometry [23].

FDM is one of the various existing AM methods that make use of thermoplastic material in the form of a filament. The filament is fed through a heater that raises the temperature close to the melting point of the plastic. The extruder nozzle then traces out the pattern of the 3D model while laying down a line of the molten plastic according to the 3D CAD model. The 3D CAD model is sliced into layers and also determines the path to be followed by the extruder to build the 3D model. After the first layer of material is laid down on a heated build tray, the tray moved down, in the Z-direction by a distance equal to the thickness of the layer. The second layer of material is traced over the first layer and the tray moves down again. The process continues until all the layers in the 3D model printed.

Figure 6 shows each individual layer laid down on the platform that moves down in the Z-direction. This layer-by-layer process produces a somewhat strong, native material but the layer lines may be visible on the finished part [53]. FDM is widely used because of its easy control operations and low cost of materials.

Figure 6: Manufacturing process of the FDM system

2.3.1 Additive Manufactured Tooling

The use of AM in making molds and tooling allows the ease of customization and flexibility in design making it free from geometrical manufacturing constraints. Commercially, several companies viz., Z Corporation, 3D Systems, Hoosier Pattern Inc., Humtown Products, and Stratasys are exploring manufacturing molds using AM methods. These companies mostly specialize in using AM techniques to make molds and cores for casting. Hoosier Pattern Inc. was the first commercial supplier of additively manufactured sand molds using the S-Max3D printer developed by the ExOne Company. Each layer of the part printed had a resolution of 0.2mm or 200 μ m producing dimensionally accurate and uniform molds and cores. The company claims that the use of the 3D printer has enabled them to build molds and cores that they had been unable to fabricate using a CNC machine [54]. Airbus has also reported to be expanding the use of AM in the manufacturing process of parts for aircrafts. The reason being, AM aids in the production of lighter parts in shorter lead times while consuming fewer materials. Airbus has already produced a variety of plastic and metal parts for the A350 XWB aircraft. They also started utilizing this technology for the fabrication of out-of-production spare parts on demand [55]. A company by the name of Linear Mold and Engineering is a leading manufacturer of prototype molds to serve a number industries such as automotive, aerospace, medical, military, etc. They have been using AM methods to fabricate tooling for injection molds, compression molds, and tooling required for processing of thermoplastic resins [56]. Some of their products include jet engine components, fuel circuits, robotic items, and interiors, exteriors, seating components, under-hood plastics for the automotive industry.

AM tooling can be classified into three types: (1) prototype tooling, (2) “bridge” tooling and (3) tooling for limited production runs, which is the most demanding application [23]. The need to produce quality parts in a short amount of time using a cost effective process has led to the production of a cheaper, less durable tools, which can be disposed after a single use. A new mold is printed every time a new production run is required. Altan et al., predicts that as the idea of using disposable molds becomes more popular and successful, industries such as the military and aerospace may be more willing to adopt such molds for their small batch of component production [23].

The process of making temporary molds using AM to create a plastic mold for injection molding was patented by Yeung et al. in 1997 [57]. Their system made use of CAD drawing to

produce a mold using acrylic or epoxy resin in Selective Laser Sintering (SLS). The inner surface of the mold was complementary to the outer surface of the desired molded part. The inner surface of the mold was coated with a 125 μ m thick layer of nickel so that the mold is completely contained inside the metal coating. The molds were then used in an injection-molding machine at relatively low pressures to produce fifty injection molded plastic parts. Manufacturing time for these molds using AM depends on their size, but is still under 24 hours, which is considerably less than weeks taken to produce a mold using traditional methods. Molding using this technique required up to 3 minutes, as compared to 30 seconds using traditional methods. The molding temperature was restricted between 200°C and 315°C and a pressure of 12,000 psi. However, the saving on cost to build the mold using this method was 80% as much as the cost to build one using conventional methods [57].

The 3D Systems (3DS) Company has helped the Bi-Link Corporation in reducing their mold development times and costs by producing 3D printed injection molds. This has given the Bi-Link Corporation a more flexible approach to their manufacturing process. The use of 3D printed molds has allowed them to perform rapid product iterations, create production parts within a day, and diagnose problems in manufacturability. The 3DS molds make use of SLS and multijet technologies to produce fast and accurate molds for injection molding.

Another complex AM method, called Layered Object Manufacturing (LOM) is being used in automotive industry to produce molds using RTV silicone and high temperature aluminum epoxy to produce parts with excellent surface detail [58]. Other direct methods of AM such as SLS are also applied to parts with good surface finish of 15 μ m or better [59].

3D Printing Systems took a different approach to mold making from 3D printed plastic prototypes. They made use of Polylactic Acid (PLA), which is a biodegradable thermoplastic material to 3D print their structure. The printed part was dipped into a tank of ceramic slurry and left to dry. After the ceramic had set, it was placed in a furnace at 150°C to melt the PLA. The molten PLA was poured out leaving behind a hollow mold of the printed part. This mold acts as a breakaway mold as it is cracked and removed away after the mold is cast with molten metal. They claim that this method of mold making is a great alternative to traditional methods as it is a faster, economical, and less tedious process and is ideal for short production runs [60].

A patent was published in the year 2000 for the production of additive manufactured water-soluble molds. A water-soluble polymeric material called poly (2-ethyl-2-oxazoline) or PEO was melt extruded and used in a fused deposition modeling (FDM) process. The advantages of using PEO is its high strength and relatively low shrinkage upon solidification as opposed to polyethylene oxide which shrinks about 15-20%. Due to crystallization of PEO upon solidification it induces interlayer stresses, which leads to warpage. PEO being highly water-soluble and environmentally non-toxic makes it a promising material for use in fabricating soluble molds. Their research tested the mechanical strength of the material and declared it to be 30% stronger and 2 to 3 times stiffer than most other water-soluble polymer materials such as, Polyox WSR-N80. However, they did not report on the solubility of the PEO and the time taken for it to disintegrate in water [61].

A recent method developed by Rosochowski et al., makes use of an inkjet technology to spray a binding agent onto layers of sand followed by a reactant added on selectively according to the slices from the STL file resulting in an accurate and rigid sand mold. This process is claimed to be ten times faster than SLS [62]. Brajliah et al. [63] describe manufacturing accuracy by the deviations between the finished part's dimensions and the dimensions of its corresponding CAD model. Since the process of AM builds layers on an X-Y plane up in the Z direction, dimensional errors can be expected in all three axes and can be denoted by:

$$\textit{Deviation } X = \text{dimension } X_{part} - \text{dimension } X_{CAD},$$

$$\textit{Deviation } Y = \text{dimension } Y_{part} - \text{dimension } Y_{CAD},$$

$$\textit{Deviation } Z = \text{dimension } Z_{part} - \text{dimension } Z_{CAD} \quad (1)$$

The ExOne company has developed a similar 3D printing technology called the 'binder jetter' that makes use of water soluble binder system which remains water soluble until 380°F [64]. At a higher temperature, the material's solubility is dramatically compromised. They made use of a silicate-based solution at higher temperatures with a variety of printing materials such as sand, carbon, ceramics, chromite, zircon and metals for the production of molds.

Figure 7: Schematic of binder jetter technology

The process involves the binder solution being printed over a thin layer of substrate. Once the binder is cured, the next layer is printed and the process continues. A schematic of the process is shown in Figure 7. The mold is also coated with base fill layers to improve the surface finish of the mold to provide a smooth surface for molding. The molds are porous because particles of material are held together using the binder material. A topcoat or sealant is utilized to prevent the resin from flowing into the mold. The ExOne Company used this technique to manufacture a mandrel and have declared that the final quality of the molded part was of very good quality. However, no quantitative data regarding the part quality was reported, as they did not require a high surface quality part.

Research conducted by Masood et al. [65], exhibits the use of a metal polymer composite material to successfully produce molds using FDM. The molds printed utilizing a composite material consisting of P301 polyamide thermoplastic as the matrix, and commercial grade iron powder as the strong, tough and conductive material. The molds were injected with ABS and the formed parts were found to be within an acceptable $\pm 0.05\text{mm}$ tolerance range [65]. FDM has also been used for the production of sacrificial molds using Acrylonitrile Butadiene Styrene (ABS), which was burnt off inside a furnace at 1000°C for one hour. The advantages of this method showed significant savings in terms of time and cost while providing parts with an

average ~1.5% dimensional error, while using an Aluminum alloy (A356 series) as the casting material [66].

High Impact polystyrene (HIPS) is a thermoplastic material very similar to ABS that dissolves in a solvent called limonene. HIPS is also dimensionally stable which means, it is more likely to retain its original dimensions when exposed to changes in temperature [67]. So far, there is no literature on HIPS being utilized for making sacrificial molds using AM. However, NASA scientists created a 3D model of a binary system of the second brightest star in the sky called Eta Carinae and made use of HIPS to print the support structures of their model which was later dissolved away using limonene [68, 69].

2.3.2 Dimensional Inaccuracy in Additive Manufacturing Processes

AM has various advantages over traditional subtractive manufacturing (SM) making it cost efficient for fabricating complex structures. Although this process enables the possibility of manufacturing intricate geometries without adding additional costs for tooling, it is challenging to achieve consistent and accurate planar results [70]. The advantages of SM are the direct machining to tolerance. Secondary machining and post-machining has been the standard and it incorporates high operating costs and times. AM processes involve laying down a layer of liquid or molten material, which is followed by another layer of the material once the previous layer, has solidified. This results in errors due to change in physical state of the material, thus causing it to shrink. The orientation of the build part on the build platform in relation to different axes can also affect the accuracy of the final printed part. Dr. Huang states that the major reasons for shape deviation are (1) material phase change (2) and inter-layer bonding effects [71]. In order to understand and minimize the effects of these changes, the effects of the major contributing factors were built into a predictive model and studied.

For FDM processes, the errors are classified into two types:

- Extruder positioning error before material deposition
- Processing error or material shrinkage due to rapid change in temperature after deposition.

An extruder in an FDM machine moves along the X and Y-axes as it prints thermoplastic material on a heated platform moving in the Z direction as seen in

Figure 6. Due to inaccuracy in motor drivers and belt tension, the home position of the extruder may not be aligned to the desired coordinates prior to the extrusion of material. Song et al. describes this process and considers the desired location of the extruder to be at a point ‘P’ and the actual physical position of the extruder is ‘P’ [71]. As the material is being melted and extruded, a phase change takes place from molten liquid plastic to the solidified plastic part that is being manufactured. This change in material phase inevitably leads to shrinkage and deformation of the part as it rapidly cools down. This depends on the physical properties of the printing material. The ambient temperature of the 3D printer’s surroundings also plays an important role [72]. Different cooling processes generate thermal stresses in the printed part causing undesirable warpage and change in shape.

Figure 8: Flowchart of FDM process modeling [71]

As seen in Figure 8, the flowchart depicts the two types of errors involved in the FDM process. Due to inaccuracies of the motor drivers and the tension in the belt that moves the extruders in the X-Y plane, the actual input shape may be shifted from the actual shape in the CAD drawing. This is termed as the ‘extruder positioning error’. As the shape is being printed the thermoplastic material cools down from its molten state. This causes it to shrink or deform due to changes in temperature resulting in residual stresses between the printed layers. This is termed as the ‘processing error’. The deformation seen in the final printed part is the resultant of

the extruder positioning error and the processing error. Huang et al. successfully modeled the extruder positioning error in the Cartesian coordinate system and the shape deformation error in the polar coordinate system [71]. The polar coordinate system was used to describe edges of planar shapes using a single function (θ). The difference between the final product shape and the actual input design or computer-aided design (CAD) drawing gives the changes in dimension, which includes both errors. Each of these errors was individually recorded and calculated using Fourier series [71].

Sood et al. conducted a designed experiment study using the Grey-Taguchi method and considered orientation, layer thickness, raster angle, raster width and the air gap between rasters on the same layer as their factors. The dimensions of their samples were measured using vernier calipers and the percentage change in dimension was calculated using the following equation:

$$\% \Delta X = \frac{|X - X_{CAD}|}{X_{CAD}} \times 100 \quad (2)$$

In equation (2), X is the measured dimension, X_{CAD} represents the respective CAD model value and $\% \Delta X$ denoted the percentage change in dimension. Signal to noise (S/N) ratio was used to determine the source and its variation caused by each factor. Their study reports the shrinkage of the material along the length and width directions but an increase in dimension in the thickness of each layer [73]. This was determined to be due to inner stresses caused by rapid changes in temperature leading to distortion, dimensional inaccuracy and inner layer cracking or delamination [74]. However, their designed experiment showed a large number of conflicting factors, independently and in interaction affecting dimensional inaccuracy [73].

Wang et al. [74] proposed a three hypotheses approach to analyze warp deformation in FDM:

1. If the melting temperature of the thermoplastic is T_m and the glass-transition temperature is T_g , as the temperature drops from T_m to T_g , the thermoplastic is subjected to contraction. But if the cooling temperature ranges between T_m and T_g , the extruded material undergoes a larger deformation with less force. Thus, there is no built up stresses between the layers in spite of the contraction. The stress only occurs when the

temperature in the enclosed chamber of the printer drops below the glass-transition temperature T_g to the chamber temperature T_e .

2. The extruded thermoplastic cools rapidly and for ABS P400, it takes 0.55 seconds to cool from T_m to T_g and 1.20 seconds to reach T_e from T_g . However, it takes a longer time for the extruder to finish a layer of a 3D model than it does for the temperature of the thermoplastic to reach T_e . So, the temperature of the material being deposited is expected to be equal to the temperature of the previous layer to allow better bonding between the layers.
3. The side-by-side deposition of thermoplastic material in the X and Y direction and the layer-by-layer deposition in the Z direction results in warp deformation. It is assumed that the layers are closely deposited to avoid any gaps between stacked layers.

Based on these hypotheses, they proposed and experimentally validated a mathematical model for the determination of inter-layer warp deformation for the first time. Their mathematical model provides a scientific tool to control and adjust deformation by using different in-layer deposition strategies in FDM, and understanding the effect of ambient temperature.

Similar research conducted by Ziemian et al.[75] using a designed experiment study portrayed the dimensional inaccuracies in different geometric shapes using ABS filament for FDM as seen in Figure 9. The graph shows the accuracy levels in inches between the actual and predicted shapes for a cylinder, a rectangle and a prism fabricated using different nozzle tip sizes. Their accuracy results did not represent a strong relationship between the actual and predicted shapes and they claim that the predictive capabilities of their model were considerably better for the rectangular and cylindrical parts than for the prisms. Their study suggests that the most significant effect was the interior fill strategy. Further research and experimentation led to their understanding that accuracy depended on several other factors such as the location of the part on the X-Y plane and the airflow within the chamber. These were not included in their study [75]. Various other researchers [66, 71, 76, 77] have stated change in ambient temperature as one of the major contributing factors causing dimensional variation in the printed part.

Figure 9: Comparison of measured part accuracy to predicted accuracy from response surface model [75]

2.3.3 Surface Finish of Fused Deposition Modeled Parts

Surface finish is a major issue in fused deposition modeled parts requiring some form of post-processing for basic levels of part quality. Good surface quality leads to higher accuracy of dimensions, which in turn facilitates the fabrication of dimensionally accurate molded parts. Surface roughness is defined as the arithmetical mean of the deviations of the roughness profile from the central line along the measurement by the ISO 4287 standard [78]. Since the FDM process works by depositing thin fibers of molten thermoplastic, layer-upon- layer, it results in ridges between each fiber of thermoplastic due to which each layer can be distinguished and is called ‘stair-stepping effect’ [79]. Figure 10 shows the cross sectional view of the layers in the FDM process. A larger air gap leads to the formation of a rougher surface finish [80].

Figure 10: Definition of +/- air gap [80]

Stacking 2D layers of material over and over again forms the 3D physical models. Due to the spaces between layers, the 3D printed part suffers from axial weakness in the Z direction and fluctuating temperatures during the printing process leads to a rough surface. A significant amount of research has been conducted in this area and it was determined that surface roughness depends on the surface angle [79] as seen in Figure 11. As the surface angle increases from 0° , the surface roughness gradually decreases and progressively increases from around 95° to 180° . Surface roughness was seen to be minimum at an angle close to 90° and maximum at 0° and 180° .

Figure 11: Theoretical surface roughness curve for an FDM part [79]

Ziemian found that a chemical treatment is fast, economic and easier to use to achieve a better surface finish, than using state of the art techniques such as abrasive jet deburring [81], hot cutter machining (HCM), CNC milling machines, etc. [76]. Cyano acrylate resin and acrylic resin are some popular resins used for post processing and strengthening of AM parts [80]. Ahn et al.[80] also stated that the larger the air gap, the more the 3D printed part is likely to shrink at elevated temperatures.

CHAPTER 3

RESEARCH METHODOLOGY

The aim of this research is to fabricate an additive manufactured mold using soluble thermoplastic material, i.e. High Impact Polystyrene (HIPS). This mold will be used for the fabrication of a composite to enable the incorporation of embedded sensors within it. Implantation of sensors could be useful for integrating structural health monitoring systems into composites used in aerospace, marine and civil applications. Furthermore, a methodology has been established consisting of (1) experimental design and (2) variation analysis in fused deposition modeling (FDM) for the study of tolerances.

Due to discrepancies in parts produced using AM, both dimensional and shrinkage analysis will be performed for the extruder positioning and the printed parts. A modified experimental methodology established by Stopp et al. [82] and Huang et al. [71] have been used in this research. As such, a 3D printed product (mold) will be delineated as (i) product tooling/mold and (ii) product component part. A loss of tolerance is expected in the 3D printed part due to the variations. Because of the particular use in the aforementioned applications, this research is aimed towards achieving aerospace tolerance and will be characterized on this restriction. The AS9100 defines the part quality and tolerance requirements for aerospace industry with a tight tolerance range of $\pm 1\mu\text{m}$ [26]. The process capability will be documented to adjust to accuracy of the prints. Thus, the research work will outline these discrepancies and generate knowledge discovery to ascertain appropriate solutions.

3.1 General Procedure for Printed Mold and Part Analysis

The guiding framework for determining the errors involved in procuring a dimensionally accurate composite part product from an additive manufactured mold is divided into two phases (Figure 12). Phase I describes the process of designing the mold to be 3D printed, and all the parameters that need to be kept in mind to fabricate a dimensionally accurate end-component part. This phase contains a Part I, II and III formulation for training experiments, deciphering errors and sources of variation, and method application for device integration, respectively, as emphasized in the variant geometry. Phase II comprises of performing visual capturing and

dimensional analysis on the 3D printed mold and molded component. The dimensions of the 3D printed mold will be compared to its dimensions in the original CAD drawing and the deviations will be analyzed. Ultimately, the accurate integration and placement of devices for composite fabrication is of interest. Which means, the completed composite part containing the sensor will be analyzed for its shrinkage within the mold and its effect on the placement of the sensor.

Figure 12: Research methodology flowchart

Figure 13 describes the general process of the molded part creation using the raw materials. A soluble material filament, HIPS will be used to 3D print a structured mold using fused deposition modeling technology on the MakerBot Replicator 2X as shown in Figure 13. Once the mold is printed and cast, it will be dissolved in limonene and the solubility of the HIPS material will be studied and discussed under the factors of temperature and agitation in section 4.1.1.

Figure 13: Outlines the general procedure and process flow from raw materials to part creation

3.1.1 Determination of Extruder Positioning Error

As discussed in section 2.4.1, extruder-positioning error plays a major role in accuracy of the final printed part. Since the objective is to minimize dimensional inaccuracy of AM parts, the extruder positioning error needs to be assessed. Failure to accurately position the extruder of a 3D printer can lead to deformed or inaccurate prints.

It is important to determine the extruder positioning error in the X-Y plane. Such errors in the positioning of the subsequent print layers are primarily inherent due to the inertia of the motor as it changes directions and speeds during the printing process. The inaccuracy of the motor drivers of the printer also results in a positioning error of the extruder in the XY plane during the print. Therefore, each individual position on the heated platform is expected to have a distinct extruder positioning error.

Consider the desired input shape of the product part/mold or the original CAD to be, ψ_0 , and let the extruder positioning error be, $e(\psi_0)$. The input shape is defined as the original shape, dimensions and position obtained from the CAD drawing and is primarily viewed as a two-dimensional set. The actual shape can be obtained from the input shape, considering only the extruder positioning error, which is given by equation (3),

$$\psi^* = \psi_0 + e(\psi_0) \quad (3)$$

This excludes the inherent material shrinkage where, after material deposition, the actual input shape, ψ^* , changes to the final product shape, ψ , through a function of f . The actual shape is the feature and position where the thermoplastic material is deposited and is given by:

$$\psi = f(\psi^*) \quad (4)$$

To determine the extruder positioning error in the Cartesian coordinate system, the home axes of the extruder is aligned with the home axes of the coordinate system. If the extruder was programmed to extrude material at a point location of (x_0, y_0) , but it actually adds material at (x^*, y^*) , meaning that the error can be represented as:

$$(x^*, y^*) = (x_0 + e_x(x_0, y_0), y_0 + e_y(x_0, y_0)) \quad (5)$$

This procedure was proposed by Huang et al.[72] to measure the error in the X and Y directions. However, in this experimental process, we will also be measuring and taking into account the error in the Z direction. The Z direction is important due to factors that play a significant role in deposition, such as, raster width and the air gap between the layers of the print. The following illustration explains the procedure for creating a test grid, which is coupled to the build tray of the printer. To experimentally calculate the extruder positioning error, a 5×5 matrix of individual cross marks each of length 22.5mm, width 4.68mm and height 3.75mm with an offset of 30mm between the crosses, will be printed on the platform of the 3D printer.

Figure 14: Original positions of crosses according to CAD

Figure 14 is an illustration of the original position of the test grid as displayed in the user interface. It has been noted that the physical build tray is slightly tilted, which can be seen by the naked eye. As seen in Figure 14, the front of the printer is aligned with the X-axis of the printer platform. This orientation will be maintained through the discussions in Chapters 3 and 4. This represents the ideal grid with equidistant spacing and separation between crosses. A departure from this control would indicate that the prescribed printer inherently succumbs to location error. The uniformity of the error is of concern, as well as the nature of drift of the individual printed components in the entirety.

Figure 15 shows the (a) printer schematics, (b) orientation of the grid on the print bed and (c) flowchart for the process. As seen in Figure 15(a), the High Impact Polystyrene filament is fed through the feeder, which guides it to the heater. The HIPS material melts to a semi-solid state in the extruder nozzle at 250°C. A thermo graphic analysis (TGA) was performed and it was observed the HIPS material started to liquefy at 237°C and gradually disintegrated as the

temperature reached 400°C. A thermal analysis using a differential scanning calorimeter (DSC) was also performed to observe the glass transition temperature (T_g) of HIPS.

Figure 15: (a) Schematic of an FDM extruder (b) Position of the 5x5 grid on the build plate of the MakerBot (c) Flowchart representing the sequence of tasks to calculate the extruder positioning error

The molten thermoplastic is extruded through the nozzle and is laid down one layer at a time on a heated bed. Once a layer is printed on the heated bed, it solidifies before the next layer is printed on top of it. This process continues to build the model from the bottom up. The thickness of each layer of thermoplastic depends on the gap between the extruder nozzle and the

previous layer. All the crosses in the grid were printed at the same time to account for their respective shifts in positions from the original CAD. It is necessary to ensure an optimal gap between the nozzle head and the heated bed before beginning any print. Inaccuracy in the gap between the nozzle and the bed can lead to two problems.

1. A large gap between the two prevents the extruded plastic from sticking to the heated bed (greater than $\sim 0.8\text{mm}$). Since the first layer of the plastic will form the foundation for the rest of the printed model, it is essential that this layer is in good contact with the platform at all times.
2. If the gap between the extruder nozzle and the heated bed is too small, there is a possibility of the opening of the nozzle being clogged due to the lack of space (less than $\sim 0.3\text{mm}$).

The platform is therefore positioned with respect to the nozzle in such a way that a gap of 0.4 - 0.7mm is maintained throughout the surface of the printer bed. This is achieved by sliding a gauge (i.e. piece of cardstock paper) between the nozzle and the printer bed while adjusting the bed height to ensure there is some resistance. The MakerBot user manual recommends this method. However, since the MakerBot Replicator 2X 3D printer is equipped with three leveling screws under the heater bed, which must be manually adjusted to level it, it is highly problematic to achieve a correctly leveled heater bed for every print. This results in errors in the Z-direction of the build. In addition to that, the thermoplastic material shrinks as it solidifies when it cools down from its molten state. Thus, there is a need to calculate the printer errors in the Z-direction separately from the errors in the XY plane. Figure 16 shows the CAD drawing of the experimental grid and the expected errant drift. This process is performed to isolate the extruder positioning error or error in the XY plane from the material shrinkage error or Z-direction error. The matrix of crosses will enable the determination of the change in their position compared to the CAD. Each of the crosses as well as the spaces between them will be measured in the X and Y directions to record their dimensions to establish the positioning error. After the matrix is printed, the coordinate points of the crosses are expected to shift from the desired location as noted in the CAD drawing in Figure 16. The gray crosses in Figure 16 represent the original position from the CAD drawing and the dotted black lines illustrate the expected positions of the 3D crosses from the printed bed.

Figure 16: CAD drawing of a 5x5 grid of crosses for calculating the extruder positioning error

This method of error estimation has been successfully utilized to adjust the dimensions of the CAD drawing so as to print any 3D structure without extruder positioning errors [72]. The adjustment made in this study will take into account the Z-height and decipher if any skewedness exists across the platform.

3.1.2 Determination of Shape Deformation

The shape deformation error of the 3D printer will be verified using a digital measurement system. The shape deformation error is calculated separately from the extruder positioning errors as described in section 3.1.2. The shape deformation error accounts for the shrinkage of the printer material, i.e., HIPS, and the height of each layer in the Z-direction. The measurements will be performed on 10 samples of additive manufactured rectangular blocks of

dimension $80\text{mm} \times 70\text{mm} \times 8\text{mm}$ using HIPS material. Figure 17 shows the steps followed in the determination of shape deviation for the specific printer.

Figure 17: Process flowchart of shape deformation determination

The rectangular blocks were fabricated using the MakerBot Replicator 2X and 1.75mm diameter HIPS filament (MakerBot, Inc.). The extruder was heated to a temperature of 250°C and the heated platform was maintained at a temperature of 150°C . The printed block was allowed to cool on the platform until the temperature dropped to 30°C , to avoid any stresses on the printed blocks while removing it from the heated bed. The temperature of the printer bed was monitored using the inbuilt temperature indicator of the 3D printer. Five samples or rectangular blocks were fabricated with the use of an external infrared heater lamp to maintain an elevated ambient temperature of approximately 50°C within the printer chamber to prevent any sudden changes in temperature that could cause warpage or delamination. The temperature inside the chamber of the 3D printer was observed using an infrared temperature gun. Five more samples were printed without the infrared heater lamp, at room temperature, with regular printer temperature settings. This was used to check for changes in dimension of the blocks due to changes in within the printer chamber.

The additive manufactured blocks were scanned using the Nikon iNEXIV VMA2520 measuring microscope to obtain the coordinate points associated with the surface geometry of the mold. The data obtained from the microscope was later visually compared with the dimensions of the original CAD drawing. The deviations in dimensions were saved in terms of coordinate points and were displayed on a color-map ranging between the minimum and

maximum points of inconsistency. These dimensions were plotted against the known CAD drawing dimensions using a MATLAB program.

The blocks were measured along the edge in the X and Y directions to account for any waviness or unexpected deformations. Since the digital microscope is also capable of measuring the height of an object, the height of the rectangular block will be measured in a systematic manner across the entire surface to record the changes in Z height. The red points in Figure 18, denote the points of measurement across the surface of the rectangular block. Each of the five samples from the heated and non-heated category was measured using this technique.

Figure 18: Points of measurement for recording variation in Z height across the sample

A physical measurement system will also be implemented to study the Z-heights of the blocks. A Heidenhain thickness-measuring gauge (Messtativ MS 200, D-83301) will be used to measure the heights of the blocks along the surface at the same points as marked in Figure 18, to

ensure consistency. The data points obtained from the Heidenhain will be compared to the data obtained from the VMA2520 to check for accuracy between a digital and a mechanical measuring system.

The data obtained from measuring the rectangular blocks will be utilized to perform a Measurements System Analysis (MSA) using MiniTab software to observe any variations or discrepancies that may have been caused in the measurement system of the digital microscope.

3.1.2.1 Material Shrinkage

A sample of the HIPS filament will be tested to deduce the properties of the material and the percentage shrinkage. A section of the filament used for AM will be measured and then heated to 200°C in an oven. The material will then be allowed to cool to room temperature and its dimensions will be measured once again using a measuring microscope to calculate the shrinkage. The aim is to mimic the temperature conditions of the 3D printer during a print to observe the percentage shrinkage of the material.

Another test will be performed to test the shrinkage of the HIPS material. A total of 30 samples will be 3D printed for this test. Ten lines of lengths ranging from 20mm to 65mm in increments of 5mm will be printed. Three samples of each length were made to ensure the collection of statistically correct data. The samples will have a width of 1mm and height 4mm. This set of lines will be printed both in the X and Y directions separately to account for shrinkage. It is understood from literature review that a shrinkage in the material is observed when a new layer of plastic is extruded onto an existing layer that has already cooled down. Thus, these printed lines will be measured its topmost layer to observe the shrinkage as compared to the defined CAD dimensions. This will help in designing the mold while accounting for its shrinkage so as to produce a dimensionally accurate mold.

The measurements obtained from the samples will be plotted against the original CAD dimensions and a simple 1D equation will be derived to calculate the error.

$$s = mx + c$$

or

$$\left[\begin{array}{c} \text{Required CAD dimensions} \\ \text{or} \\ \text{Shrinkage compensation} \\ \text{error} \end{array} \right] = m \times [\text{Measured dimensions of the sample}] + c, \quad (1)$$

where, m is the slope of the line from the measurements plot and c is the added error.

3.1.3 Final Error in Dimension

The extruder positioning error and the determined shape deviation/processing error are combined together to obtain the final deformation error as seen in equation (7). The final deformation error is a combination of the change in dimension due to the extruder positioning error, shrinkage of the material and the ambient temperature of the 3D printer. The study from the position of the grid of crosses will help analyze the error in the XY plane. The measurements of the rectangular block and the shrinkage of the material will account for the error in the Z-direction. Since some of the rectangular blocks were printed in the presence of a heater lamp to maintain a constant elevated temperature within the chamber. The extruder positioning error points representing the cuboid are added to the points of measurement on the CAD drawing, which should give the same result as the points measured in the physical samples.

$$\left[\begin{array}{c} \text{Final deformation} \\ \text{error} \end{array} \right] = \left[\begin{array}{c} \text{Extruder positioning} \\ \text{error} \end{array} \right] + \left[\begin{array}{c} \text{Material shrinkage} \\ \text{error} \end{array} \right]$$

$$\left[\begin{array}{c} \text{Final deformation} \\ \text{error} \end{array} \right] = \left[\begin{array}{c} \text{New coordinate points} \\ (x *, y *) \end{array} \right] + \left[\begin{array}{c} \text{Shrinkage error} \\ 's' \end{array} \right] \quad (7)$$

3.1.4 Part Tolerances

The tolerance of the 3D printed mold will be compared with the tolerance of the molded part to meet the aerospace grade requirements in Chapter 4. Since the product part is an impression of the mold/tooling, the source of variation is limited to process variations in the experimental printer.

3.2 Selection of Digital Measurement System

Optical or digital measuring systems are widely used in industrial applications for their benefits such as, non-contact measurement techniques. Samples measured using a digital image-capturing machine is expected to give more accurate results than a touch probe measuring system. A digital system is preferred, as full shape scans are desired to analyze and interrogate as one build. Several different digital measurement systems were used to try to capture accurate data from the 3D printed samples. Due to limited resources, various digital systems were tested involving the Coherix ShaPix 1500, Konica Minolta VIVID 910 3D laser scanner with Geomagic, Keyence VR-3000 series and the Excel VMA2520.

Figure 19: Example of a successful scan using Coherix Shapix

Our first attempt at scanning the samples was performed using the Coherix ShaPix 1500 Metrology solution (located at HPMT). The ShaPix is a high definition laser holographic technology utilized to measure profiles, flatness and waviness of surfaces with micron level accuracy to produce high definition 3D images of scanned surfaces and their coordinate points of reflective surfaces [83]. Since the samples used in this experiment were additively manufactured using HIPS, which is a white opaque thermoplastic material, the samples were not reflective enough for the ShaPix to capture any accurate data points. The non-reflective samples were unsuitable for obtaining accurate measurements with the ShaPix.

An alternate method of using a thin layer of metallic paint was experimented with, to observe if the reflective metallic paint made it easier for the ShaPix to capture the surface of the sample. The metallic paint made the surface of the 3D printed samples reflective enough for collection of data points. However, it did not prove to be very consistent. Some of the samples that were scanned were accurate, but for some of the samples the ShaPix was unable to capture enough points to create a scan, as seen in Figure 19 and Figure 20.

Figure 19 is an example of one of the successful scans of metallic spray painted 3D printed part using the ShaPix. The reflective metallic spray paint allowed the Shapix to capture even the slightest deformation on the surface of the sample due to the honeycomb pattern underneath. Figure 20 however, displays a scan of the same 3D printed spray painted part on a different day. The scanner settings were ensured to be the same while taking measurements, yet the Shapix was unable to capture all the data points accurately. This made the data capturing process non-repeatable, and thus non-reliable. Figure 20 (b) shows a graph of cross sectional surface of the mold. However, this graph was not a reliable source of data due to the erroneous scans obtained using the machine.

A comprehensive software package known as Geomagic was utilized. Geomagic originally paired with the Konica Minolta VIVID 910 3D laser scanner (located at HPMT). However, the technology is out-of-date and proved cumbersome for this examination. The Konica Minolta allows for a 360-degree scan and profile. The data output allows for a CAD comparison in Geomagic Control.

(a)

(b)

Figure 20: (a) Surface data captured from a 3D printed part with a layer of metallic spray paint using the ShoPix (b) Graph showing the surface waviness of a cross sectional area of the scanned part

The scans made with this equipment provided incomplete figures, meaning that the scans of the parts were scattered with holes, or regions of no data. The software of the scanner allows the user

to smooth out the scan, compensating for any of the regions with not enough data points. The software takes an average of the data points surrounding the area with the missing data to create an approximated surface to cover the hole. This method proved to be unfeasible because of the fictitious data points. Figure 21 shows a scan of the 3D printed part with missing data regions or holes covered up by calculating the average of the position of the surrounding data points.

Figure 21: A scan of a 3D printed part using the Minolta VIVID 910 scanner, after the missing data points were smoothed out by averaging the surrounding data points

The data points obtained from some of the successful ShaPix scans of the spray painted samples were also exported in the form of coordinate points to compare the points of deviation from the original CAD drawing using Geomagic Control software. Since the ShaPix metrology solution is originally meant for measuring reflective metal parts, some of the measured points

from the samples were visibly inaccurate. Figure 22 displays a color map of the points of deviation of a scanned mold from the dimensions specified in the CAD. Due to the uneven surface of the 3D printed part, the metallic spray point did not offer a smooth reflective surface, causing the scanner to collect unreliable data points, particularly in the central part of the mold.

Figure 22: Comparison of ShaPix scan to original CAD in Geomagic Control

Keyence VR-3000 series, a 3D digital measuring microscope produced scans concerning the study. The scans reveal a high-resolution imagery of the position error method as highlighted in section 3.1.2. This would have been an appropriate choice for measuring, as it is able to scan a large field of view, with which it was able to capture most of the printed grid. Figure 23 shows a scan of a part of the 5x5 grid that was used for determining the extruder positioning error of the printer. The heights of the crosses were supposed to be at 3.75mm according the CAD. From the scan, with the help of the color bar, it can be observed that the heights of the crosses lie between 3 and 4mm.

Figure 23: Scan obtained from the Keyence VR3000 series microscope

The 5x5 grid for the calculation extruder positioning error was measured using the iNEXIV Excel VMA2520 (Nikon) measuring microscope/digital CMM as the ShaPix and the Minolta VIVID were unsuitable to take accurate measurements. The VMA2520 was programmed to measure the edge along the X-axis, the edge along the Y-axis and the Z height for each individual cross on the grid and the measured values were exported to a CSV file. The data was later used for calculating and plotting the error in all three axes. Since the Nikon VMA2520 makes use of surface and contour illumination, paired with a 10x optical zoom, it has proved successful in the accurate measurement of intricate parts and surfaces of the 3D printed samples.

The above CMM study revealed that the Nikon system is acceptable to collect topology and measurement data. The Excel VMA2520 will be used to describe methods and application measurements in Chapters 3 and 4.

3.2.1 Measurements System Analysis

A Measurement System Analysis (MSA) was performed of the Nikon iNEXIV VMA2520 digital measuring microscope to analyze the adequacy of the measurement system. The output from any measurement system can be subject to two types of variations:

1. Part-to-part variation
2. Measurement system variation

A Gage R&R study was performed to estimate the variation in the measured data due to the measurement system. The R&R stand for repeatability and reproducibility. The analysis was set up to be calculated using ten samples and two operators in MiniTab. On each occasion, two sets of data were collected. The measurements of ten identical 3D printed rectangular blocks were taken in the same location of each sample to avoid variation in height.

From this study it was inferred that the Nikon VMA2520 digital microscope allows repeatable and consistent data collection and can hence be used for the collection of accurate data from the samples. Due to time-constraints MSA was not conducted for the other viable CMM measurement systems.

3.3 Dimensional Analysis

The 3D printed crosses and molds for the CT specimens were digitally measured using a Nikon VMA2520 measuring microscope/ Digital CMM to collect measurements and coordinate points of the 3D printed samples.

3.3.1 Extruder Positioning Error

During preliminary prints, it was observed that the size and position of the printed parts did not conform to the dimensions of the input data file/CAD drawing. The errors also seemed to be directionally dependent; meaning the location of the print on the print bed affected the positioning and dimensions of the print. An experiment was conducted to analyze the positioning error of the extruder. A 5x5 grid of crosses was printed using HIPS at an extrusion temperature of 250°C and print-bed temperature of 150°C. A sheet of G-10 glass epoxy composite material was cut to match the size of the printer bed and covered in green masking tape to make the removal and measurement process easy and undistorted. The print bed was leveled using a

carpenter's level to ensure a uniform print. The bed was allowed to cool before the parts were removed from the printer to avoid any sudden changes in temperature. The crosses were measured to determine the original print positions and the error in positioning in the X, Y and Z directions. The dimensions of the crosses are given below and are illustrated in Figure 24.

Table 2: Dimensions of the grid of crosses for estimating extruder positioning error

Length	Width	Height	Offset distance between crosses in X and Y directions
22.5mm	4.68mm	3.75mm	30mm

Figure 24: Dimensions and positioning of crosses in the grid

These dimensions were chosen because this was the largest size of the crosses that the printed bed could accommodate so as to cover a larger surface area to assess the error across the entire printer bed. Each cross was measured across ten points each in the X and Y directions as denoted by the red lines for X and blue lines for Y in Figure 25.

Figure 25: Measurements taken from each cross on the grid. An average value was calculated from the measured points and their respective coordinate points were recorded. The measurements were made with a Nikon VMA2520 measuring microscope/ digital CMM.

The following 3D plots in Figure 28, Figure 29, Figure 30 display the X edge error, Y edge error, and Z height error measurements in their corresponding positions with respect to the print bed orientation respectively. The Z height or each square on the plot represents the error along each of the axes. The color bar for each plot represents the range of deviation.

Figure 26 shows a typical 3D surface and dot plot that was generated using the data from the digital CMM to represent the length error in the X-axis over the entire build area of the printer. Each vertex of the squares in the plot represents a measured point. The plot is divided into four quadrants for ease of understanding. It is noted that the error in the first quadrant appears to be higher than the rest of the points on the platform. Meaning that, the crosses were longer in the X direction in the first quadrant region of the printer platform.

Figure 27 shows a 3D plot that was generated using the data from the digital CMM to represent the length error in the Y-axis over the entire build area of the printer. Each vertex of the squares in the plot represents a measured point.

Figure 26: Surface and dot plot of the error along x-axis of the grid, where the X-axis of the plot represents the printer X-axis, the Y-axis of the plot represents the printer Y-axis and the Z-axis of the plot shows the actual edge measurement along the X direction of the printer bed.

According to the plot and the color bar seen in the figure, the yellow regions denote a value higher than zero and blue regions represent values lower than zero. The green squares on the plot denote data points closer to a zero value, or areas with the least error. Quadrants I and III seem to have some brighter yellow squares which explains the increase in length of the squares in the Y direction in those particular regions.

Figure 28 shows a 3D plot that was generated using the data from the digital CMM to represent the length error in the Z-axis over the entire build area of the printer. Each vertex of the squares in the plot represents a measured point. The color in this plot displays a large range of variation. It is observed that the regions that are green are closer to the nominal value, where as the yellow regions show an increase in length in the Y direction and the blue areas show a decrease in length in the Y direction. However, the error in the Z axis also consists of the shrinkage error of the HIPS material.

Figure 27: Error along y-axis of the grid, where the X-axis of the plot represents the printer X-axis, the Y-axis of the plot represents the printer Y-axis and the Z-axis of the plot shows the actual edge measurement along the Y direction of the printer bed.

The mean and standard deviations for the measurements were calculated for all three axes. The grid was printed using the printer's standard resolution settings. The average measured X-axis measurement at 22.26mm is considerably lower than the theoretical value of 22.5mm while a standard deviation of 0.06mm denotes a small variation between the measured values. A higher standard deviation is observed in the Y-axis measurements although the mean measurement is closer to the nominal value of 22.5mm. Note the Y-axis and key indicate larger values of deposition corresponding to the machine resolution (MakerBot Replicator 2X, resolution: 100 μ m). A higher variation was expected in the Z-axis due to the shrinkage of the material as well as air gap between the printed layers. The nominal Z height of the crosses was set at 3.75mm and the average measured height of the crosses was 2.67mm, thus revealing a significant amount of shrinkage of the HIPS material.

Figure 28: Error in z-axis or height of the grid, where the X-axis of the plot represents the printer X-axis, the Y-axis of the plot represents the printer Y-axis and the Z-axis of the plot shows the actual edge measurement along the Z direction or height of each of the crosses.

As mentioned in section 2.3.3, larger air gaps result in a higher rate of shrinkage of the part. The error in the Z-axis is also dependent on the leveling of the build plate of the printer. It is understood that, since the build plate is manually leveled, the errors in the Z-axis for a machine such as a MakerBot is inevitable. The measured values in the X-axis shows a strong position dependency in the X direction.

From the plots and the standard deviation calculations, it is observed that the error in the X direction is slightly larger than the error in the Y direction. It is noted that the deviation in the X-axis is 0.06mm and is 0.10mm in the Y-direction.

Table 3: Result of the measurement of the 5x5 grid

	X(mm)	Y(mm)	Z(mm)
Mean	22.26017	22.46727	2.67427
Standard Deviation	0.06152	0.10159	0.30128
%Error	1.0659111	0.14546667	28.6861

However, the standard deviation of 0.3mm in the Z direction shows a large range of variation across the print bed of the printer and a percentage error of 107.573. Applying equation (1),

$$Deviation\ X = \text{dimension } X_{part} - \text{dimension } X_{CAD}$$

$$\text{i.e., Compensation in X direction} = 22.5\text{mm} - 22.26017\text{mm}$$

$$\text{Compensation in X direction} = 0.23983\text{mm} \quad (8)$$

To compensate for the error in the X direction, adding the following value to the CAD measurement will adjust the dimensions of the actual printed dimensions of the crosses:

$$\text{Length} = 22.5\text{mm} + 0.23983\text{mm (in the X direction)} = 22.73983\text{mm}$$

$$\text{Width} = 4.68\text{mm} + 0.23983\text{mm (in the X direction)} = 4.91983\text{mm}$$

The error observed in the Y direction was negligible compared to the errors in the X and Z directions. The Y direction errors are calculated as:

$$Deviation\ Y = \text{dimension } Y_{part} - \text{dimension } Y_{CAD}$$

$$\text{Compensation in Y direction} = 22.5\text{mm} - 22.46727\text{mm}$$

$$\text{Compensation in Y direction} = 0.03273\text{mm} \quad (9)$$

The new dimensions in the Y direction would be:

$$\text{Length} = 22.5\text{mm} + 0.03273\text{mm (in the Y direction)} = 22.53273\text{mm}$$

$$\text{Width} = 4.68\text{mm} + 0.03273\text{mm (in the Y direction)} = 4.71273\text{mm}$$

A large error of 28.68% was observed in the Z direction. However, the Z error includes the shrinkage of the HIPS material as well as the thickness of each layer in view of the nozzle-platform gap. The material shrinkage will be isolated from the layer thickness and the Z error will be further studied in section 3.3.2 in the calculation of shape deformation using rectangular blocks. It was also observed that the Z error in the MakerBot predominantly depended on the leveling of the build plate with respect to the extruder nozzle. Since the platform is calibrated manually with the help of three screws provided underneath it, it is highly susceptible to human error. This makes it difficult to achieve a perfectly level build plate every time.

Thus, in order to achieve the actual dimensions of the CAD drawing, a value of 0.23983 mm was added to the original value in the X direction and 0.03273mm was added in the Y direction. For a better visualization, a comparison in terms of the physical build tray is needed to examine the relative machine error. If the stage or build tray exhibits a natural tilt along the planar surface, then one would expect errors to drift with the error in mechanized movement, and natural gap between nozzle and stage. To this effect the build tray is examined by splitting the stage into four spatial quadrants. Figure 31 is an example visualization technique for displaying the drift error along the entirety of the build tray in the XY plane.

A linear polynomial equation was derived using MATLAB for the best-fit curve for the extruder positioning error in the X and Y-axes. The equation is a function of x and y.

Let (x_0, y_0) be the original or desired coordinate points and (x^*, y^*) be the corresponding adjusted coordinate points due to the extruder positioning error. δx is the error in the X-axis.

$$\delta x = f(x_0, y_0) = a_1 + a_2x_0 + a_3y_0 + a_4x_0^2 + a_5x_0y_0 + a_6y_0^2 \quad (10)$$

Coefficients (with 95% confidence bounds):

$$a_1 = -0.3623 \text{ } (-1.286, 0.5615)$$

$$a_2 = 0.1082 \text{ } (-0.3856, 0.6021)$$

$$a_3 = -0.1286 \text{ } (-0.6214, 0.3642)$$

$$a_4 = 0.1764 \text{ } (-0.4281, 0.781)$$

$$a_5 = 0.0121 \text{ } (-0.4855, 0.5097)$$

$$a_6 = 0.1385 \text{ } (-0.4432, 0.7202)$$

Thus, the equation to calculate the corrected coordinate points to compensate for the extruder positioning error in the X direction is:

$$\delta x = -0.3623 + 0.1082x_0 - 0.1286y_0 + 0.1764x_0^2 + 0.0121x_0y_0 + 0.1385y_0^2 \quad (11)$$

$$= (x^*, y^*) = (x_0 + \delta x, y_0) \quad (12)$$

Figure 29 shows a 3D plot where the location of the marked blue points in the XY plane represent their position on the platform and their position with respect to the Z axis shows the magnitude of the positioning error in the X direction of the extruder. From the figure, it can be observed that the extruder positioning error in the blue region of the surface plot, representing the front of the printer platform has the least error and the yellow region representing the back of the printer platform shows a higher extruder positioning error in the X-axis.

A similar equation for the extruder positioning error in the Y-axis was derived with the following equation and coefficients:

$$\delta y = f(x_0, y_0) = a_1 + a_2x_0 + a_3y_0 + a_4x_0^2 + a_5x_0y_0 + a_6y_0^2 \quad (13)$$

Coefficients (with 95% confidence bounds):

$$a_1 = 0.2289 \text{ } (0.144, 0.3137)$$

$$a_2 = 0.02632 \text{ } (-0.01778, 0.07043)$$

$$a_3 = 0.1424 \text{ } (0.09825, 0.1865)$$

$$a_4 = 0.008248 \text{ } (-0.04555, 0.06205)$$

$$a_5 = 0.005304 \quad (-0.03971, 0.05032)$$

$$a_6 = -0.02214 \quad (-0.07594, 0.03166)$$

Figure 29: A curve fitted plot displaying the trend in the error in the X-axis. The X and Y axes of the plot represents the location of the measured point on the heater bed and the Z axis shows the magnitude of the error in the X direction with respect to the movement of the extruder.

Thus, the equation to calculate the corrected coordinate points to compensate for the extruder positioning error in the Y direction is:

$$\delta y = 0.2289 + 0.02632x_0 - 0.1424y_0 + 0.008248x_0^2 + 0.005305x_0y_0 - 0.02214y_0^2 \quad (14)$$

Figure 30 shows a similar trend in the extruder positioning error in the Y-axis. The plot shows a higher error in the back of the platform as compared to the front. The extruder positioning error could also be as a result of the inherent skewedness of the printer platform.

Figure 30: A curve fitted plot displaying the trend in the error in the Y-axis. The X and Y axes of the plot represents the location of the measured point on the heater bed and the Z axis shows the magnitude of the error in the Y direction with respect to the movement of the extruder.

The location of the marked blue points in the XY plane in the above figure represent their position on the platform and their position with respect to the Z axis shows the magnitude of the positioning error in the Y direction of the extruder. The platform seems to be tilted along its diagonal axis according to the observed data. The corner of the platform in Quadrant II is at a lower level, making the corner in Quadrant IV to elevate from its original position as seen in Figure 31. This may be the reason for a higher error in quadrant IV.

The grid of crosses displayed in Figure 31 is oriented to match the orientation of the build tray of the printer for ease of understanding. A CAD comparison was also performed on the software for the digital microscope and it was inferred that the error along the X-axis was more concentrated in the quadrant IV as seen in Figure 31. The software was programmed to compare the measured values of the crosses to the nominal values from the CAD within a tolerance range

of $\pm 0.5mm$. The output file was in the form of a report displaying the measurements that passed or failed with respect to the tolerance.

Figure 31: Extruder positioning error evaluation in quadrants

Hence, it was concluded that the errors in the X direction were higher and exceeded the range of tolerance although the errors in the Y direction showed more variation. However, it is still not understood if the tilt of the printed bed affects the dimensions of the parts in the XY plane.

3.3.2 Determination of Shape Deformation

3.3.2.1 Measurement Using Digital Measurement System

The additively manufactured rectangular blocks $80\text{mm} \times 70\text{mm} \times 8\text{mm}$ were used to measure the shape deformation error or the shrinkage of the material after the part was printed. Five samples were printed with the normal printer settings, i.e., with the nozzle at 250°C and the heated bed at 150°C . Each of the samples was measured at 16 locations using the Nikon VMA2520 measuring microscope as described in Figure 18. Their difference in heights from the original CAD was calculated and the error was displayed in a surface plot as seen in Figure 32. Each black dot on the plot was a point of measurement. The color bar of the plot shows that a darker blue region has the least error. Thus, it can be observed from the plot that the sample showed higher shrinkage along the front and left sides. The sample was measured in the same orientation that it was printed on the printer bed.

Figure 32: Z heights of the 3D printed blocks without the application of external heat using an IR lamp

Figure 33 shows a surface plot with the data obtained from a set of rectangular samples that were printed under different conditions. The printer temperature settings were unaltered, however, an external infrared lamp was used to increase the temperature around the temperature. The lamp was used to maintain the surrounding temperature at around 50°C, which was measured using an infrared digital thermometer. However, the surrounding temperature using the lamp did not seem to have a significant effect on the shrinkage of the part as the measured values were almost similar.

Figure 33: Z heights of the 3D printed rectangular blocks in the presence of a heater lamp

The Z height of the blocks may also be affected by the tilt adjustment of the printer bed. Since the printer bed has to be manually adjusted using three leveling screws under it, it is very difficult to achieve a level build plate every time. Since all the rectangular blocks were printed with the same printer settings and without any change in the tilt of the build plate, most of the error is observed in the front and left part of the printer bed.

Figure 34 shows the distribution of the Z height errors seen in the rectangular blocks. Quadrant I shows the least amount of error while quadrants II, III and IV show a higher range of errors in the height of the block. It is likely that the Z height error will be different if the same rectangular block was printed after readjusting the printer bed. This method draws attention to the errors in the X, Y and Z directions of the 3D printed part similar to research conducted by Stopp et al.[82] and Ziemian et al.[75]

Figure 34: Distribution of Z errors in different quadrant sections of the printer bed

3.3.2.2 Shrinkage Test of HIPS

A shrinkage test was also performed on the HIPS material to validate the error observed in the Z direction of the printed rectangular blocks. For this test, a small piece of the HIPS filament sample was used from the spool of filament. The cross sections of the sample of the filament was measured and verified to be approximately 1.743mm compared to the given factory dimensions of 1.75mm.

Figure 35: Extruder positioning error observed in X, Y and Z axes

The sample was heated in an oven to 200°C on a sheet of Teflon to prevent it from sticking to any other surface. Once the temperature was reached, the sample was taken out and allowed to cool before measuring. However, it was observed that the sample of the filament did not shrink as it rapidly cooled down to room temperature.

In a separate test, three lines of different lengths of 30mm, 40mm and 50mm were printed using the MakerBot printer at the standard printer temperature settings of the extruder nozzle at 250°C and the heated bed at 150°C. Each of these lines had a width of 1mm and height of 4mm. The samples were measured after they were allowed to cool down to room temperature. Each sample was measured at the topmost layer, where maximum shrinkage was expected. Table 4 shows the original CAD dimensions along with the average of the measured dimension for each length of the sample printed in the X direction and the Y direction respectively.

Table 4: Measurements of 3D printed samples for assessing HIPS material shrinkage

CAD Dimensions (mm)	X-axis measurements (mm)	Y-axis measurements (mm)
20	19.80666667	19.11
25	24.69666667	24.2
30	29.55	29.71666667
35	34.48333333	34.66666667
40	39.39666667	39.61333333
45	44.48666667	44.53666667
50	49.52	49.49
55	54.45666667	54.38666667
60	59.42333333	59.43
65	64.40666667	64.40666667

Figure 36(a) and (b) show examples of a 30mm and a 60mm sample respectively that were printed in the X direction for this test. It is visible that the top layer is has shrunken as compared to the bottom most layer. Since the 3D printer platform is heated, the bottom layer retains the correct CAD dimensions. As the part builds in height, it moves away from the heat of the platform, causing it to gradually shrink. It was also noticed that after about 20 layers of print, the length of the part starts to stabilize instead of further shrinking.

Based on the deviation in the measurement, a simple equation was modeled to compensate for the material shrinkage.

$$s = mx + c \quad (16)$$

where, s denotes the CAD measurement, x denotes the actual measured value of the sample, m is the slope of the line and c is the calculated shrinkage error. Thus,

$$m = \frac{(y_2 - y_1)}{(x_2 - x_1)} \quad (17)$$

Therefore, $m = 1.007$

Using this value of m , the value of c was calculated to be 0.182 in the X direction.

Figure 36: (a) and (b) show examples of a 30mm and 60mm 3D printed sample respectively, with the top layer considerably shorter than the bottom layer.

Thus, in order to obtain a print in the desired dimensions in the X direction, the following equation can be used to calculate the corresponding CAD dimensions:

$$\left[\begin{array}{c} \text{Required CAD} \\ \text{dimensions in X - axis} \end{array} \right] = 1.007 \left[\begin{array}{c} \text{Desired print} \\ \text{dimensions in X - axis} \end{array} \right] + 0.182 \quad (18)$$

Similarly, for Y-axis, $m = 0.9974$ and the c value was 0.6536.

Thus, the compensation equation is given as:

$$\left[\begin{array}{c} \text{Required CAD} \\ \text{dimensions in Y - axis} \end{array} \right] = 0.9974 \left[\begin{array}{c} \text{Desired print} \\ \text{dimensions in Y - axis} \end{array} \right] + 0.6536 \quad (19)$$

Figure 37: Plot representing the measured dimensions of the measured prints on the X-axis and the CAD dimensions on the Y-axis. These samples were printed along the X direction

Figure 38: Plot representing the measured dimensions of the measured prints on the X-axis and the CAD dimensions on the Y-axis. These samples were printed along the Y direction

For example, if a part with 30mm length in the X direction of the printer were desired to be printed, the CAD drawing would have an adjusted length of 30.392mm, calculated using equation (18). Similarly, if the same part was to be printed with a Y-axis orientation, the CAD adjusted length would be 30.5766mm, which was calculated using equation (19). An error of 0.012% in the x direction and 0.018% in the y direction was calculated from this case study.

A similar study was performed to observe the error in the Z-axis. A series of 10 lines with heights ranging from 1.5mm to 6 mm were printed in increments of 0.5mm. The data obtained is shown in

Table 5: CAD height and measured height of samples for Z-axis shrinkage test. It is observed that the measured heights were greater than the height in the sample specified in the corresponding CAD. This may be due to the error in the adjustment of the level of the build platform of the printer, which in turn affects the air gap between the layers as studied by Sood et al.[73].

Table 5: CAD height and measured height of samples for Z-axis shrinkage test

CAD height (mm)	Measured height (mm)
1.5	1.79
2	2.13
2.5	2.66
3	3.09
3.5	3.62
4	4.01
4.5	4.59
5	5.01
5.5	5.58
6	6.05

Figure 39 shows the measured data along the X-axis and the CAD measurements on the Y-axis. The slope of the line, $m = 1.0412$ and the c value is -0.2616 . The c value is negative because of the expansion in the Z height of the printed samples as compared to the CAD. Thus the compensation equation for the error in the Z-axis is given by,

$$\left[\begin{array}{c} \text{Required CAD} \\ \text{dimensions in Z - axis} \end{array} \right] = 1.0412 \left[\begin{array}{c} \text{Desired print} \\ \text{dimensions in Z - axis} \end{array} \right] - 0.2616 \quad (20)$$

3.4 Final Error in Dimension

The obtained extruder positioning error along with the shape deformation or shrinkage of the HIPS material was used to calculate the final error. Using the aforementioned equations to calculate the error and deviation from the CAD drawing compensated this value obtained. The final deformation error is a combination of the extruder positioning error and the shrinkage error.

Figure 39: Plot representing the measured dimensions of the measured prints on the X-axis and the CAD dimensions on the Y-axis. These samples were measured along the Z direction

$$\begin{bmatrix} \text{Final deformation} \\ \text{error} \end{bmatrix} = \begin{bmatrix} \text{Extruder positioning} \\ \text{error} \end{bmatrix} + \begin{bmatrix} \text{Material shrinkage} \\ \text{error} \end{bmatrix} \quad (21)$$

$$\begin{bmatrix} \text{Final deformation} \\ \text{error} \end{bmatrix} = \begin{bmatrix} \text{New coordinate points} \\ (x^*, y^*) \end{bmatrix} + \begin{bmatrix} \text{Shrinkage error} \\ 's' \end{bmatrix} \quad (22)$$

Thus, the following equations will provide the final deformation error in the X and Y-axes respectively:

$$\begin{bmatrix} \text{Final deformation} \\ \text{error in X axis} \end{bmatrix} = \begin{bmatrix} 0.2289 + 0.02632x - 0.1424y + \\ 0.008248x^2 \\ +0.005305xy - 0.02214y^2 \end{bmatrix} + [0.993x - 0.1796] \quad (23)$$

$$\begin{bmatrix} \text{Final deformation} \\ \text{error in Y axis} \end{bmatrix} = \begin{bmatrix} 0.2289 + 0.02632x - 0.1424y + \\ 0.008248x^2 \\ +0.005305xy - 0.02214y^2 \end{bmatrix} + [0.9974x + 0.6536] \quad (24)$$

The error in the Z direction was mostly observed in the front and left edges of the printed platform from the sample in this study. This varies with the manual process of leveling the printer bed. Thus, the adjusted coordinate points as well as the shrinkage of the material can be taken into account while designing a CAD so as to obtain the desired dimensions after printing process.

CHAPTER 4

METHOD APPLICATION AND VALIDATION

The research methodology established in Chapter 3 will be used to fabricate 3D printed tooling/molds for creation of compact tension specimen. A soluble mold for a compact tension specimen was utilized to prepare a compact tension specimen with an embedded sensor to perform mechanical tests on the composite material part. The printed tooling serves as a device guide and stringer for accurate placement of sensors during the composite molding cycle. Because of the nature of composite post-processing and machining, the soluble mold procedure allows for minimal post processing. This will ensure the integrated device remains intact and is not pre-stressed during mold removal before testing. The process flowchart is shown in Figure 40.

Figure 40: Process of fabrication and analysis of CT specimen molds

4.1 Fabrication of Compact Tension Specimens

This section discusses the experimental setup and the materials used to fabricate the compact tension (CT) specimen sample using an additive manufactured mold. A CT specimen is a notched sample used to create a fatigue crack by applying cyclic loads to observe the fracture toughness of the material. The CT specimen sample in this experiment consists of an embedded optical fiber device. The ITOF (in-situ triboluminescent optical fiber) is an optical fiber coated with triboluminescent material utilized in damage detection of engineering structures and in-situ structural health monitoring [84]. Triboluminescence is the emission of light by solid materials when stressed or fractured [85]. The optoelectronic fiber is aligned and held in place, perpendicular to the compact tension (CT) impression and initial crack. The mold for the CT specimen geometry was designed in accordance to ASTM E647-00 [86]. The featured application is to integrated optoelectronic sensors during fabrication and infusion. The process flowchart is shown in Figure 41. The CAD for the mold was generated using dimensions from ASTM E647-00 and with the following parameters in mind:

1. Shrinkage of resin during cure
2. Shrinkage of additive manufactured mold
3. Aerospace grade tolerance ($\pm 0.001mm$)

Once printed, the optoelectronic sensors are strung through the designated opening in the mold to hold it in place. This provides for a hermetic type fit for the embedded device. The mold for the CT specimen was additively manufactured on a MakerBot Replicator 2X with FDM technology using HIPS filament. The HIPS material from the mold is expected to dissolve away in limonene leaving behind the CT specimen with an embedded ITOF sensor.

After the fabrication of the mold, the ITOF was inserted through the cavity in the mold and afterwards sprayed with a mold release agent. A mixture of Amorstar vinyl ester resin (VER) containing catalyst Methyl ethyl ketone peroxide (MEKP) 1.1% by weight of the resin was poured into the soluble mold. Figure 42 shows a mold with the sensor. The molded part was allowed to cure overnight. The soluble mold was dissolved in concentrated limonene (a colorless liquid hydrocarbon) at 30°C with an agitation of 900 rpm by magnetic stirring. A designed experiment was conducted to determine the optimal temperature and agitation to minimize the dissolving time. The de-molded sample was rinsed off and was ready to be tested.

Figure 41: Soluble mold preparation and de-molding process for CT specimens

Figure 42: (a) 3D printed soluble mold with triboluminescent crystal coated optical fiber (b) 3D printed mold with cured resin [89]

4.2 Compensation and Verification of AM Mold

The additively manufactured molds for the process of making CT specimens were measured using the Nikon VMA2520 to check for printing accuracy. The molds were measured

before the applied compensation and an average deviation of 1mm was observed in both X and Y directions of the mold. Figure 43 and Figure 44 represent the comparison between the CAD measurements of the mold and the actual measurements of the 3D printed product in the X and Y directions respectively.

Table 6: CAD dimensions and measured dimensions of the mold before error compensation

	Original CAD dimension (mm)	Measured mold dimension before compensation (mm)
X	60	~59.21
Y	62.5	~61.42

Figure 43: Graph comparing original CAD dimensions with the measured dimension of the mold in the X direction

Figure 44: Graph comparing original CAD dimensions with the measured dimension of the mold in the Y direction

The compensation equations from Chapter 3 were applied to calculate the adjusted CAD dimensions for the molds. The product-molds were again printed using the adjusted CAD dimensions and measured. The measurements of the new molds were observed to be much closer to the original CAD dimensions as seen in Table 7, Figures 45 and 46. The measurements of the new mold dimensions lies within a small error range of 0.02%, thus validating the compensation equations from the experimental component study of the previous chapter.

Table 7: CAD dimensions and measured dimensions of the mold after error compensation

	Original CAD dimensions (mm)	Measurements of error compensated mold (mm)
X	60	~59.998
Y	62.5	~62.513

Figure 45: Original dimensions and measured dimensions of error compensated mold in X direction

Figure 46: Original dimensions and measured dimensions of error compensated mold in Y direction

CHAPTER 5

CONCLUSION AND FUTURE WORK

Additive manufacturing methods have developed over the past 30 years and have evolved into a feasible manufacturing process for the production of parts. Many companies such as Boeing and Airbus make use of additive manufactured parts. Several mainstream publications such as Forbes and USA Today call it the ‘third industrial revolution’ and is expected to have a huge impact on the society in the near future by reducing cost and times of productions.

In the present work, a low-end 3D printer, a MakerBot Replicator 2X was tested for its capability to produce parts within an aerospace grade tolerance level of 1 micron. The effect of extruder positioning error and material shrinkage error of the printer were studied from which the dimensional accuracy of the printer was concluded. The original extruder positioning error equation modeled by Huang et al. [71] was modified to account for errors in the Z direction as well. The errors in the X, Y and Z-axes of the printer were studied and an equation was modeled to compensate for the total error due to the extruder position as well as the shrinkage of the 3D printing material itself. It was realized that the printer was capable of achieving prints within a tolerance of $\pm 0.5\text{mm}$, meaning that it was not suitable to produce accurate parts within the aerospace grade tolerance. A number of digital measuring systems were employed during the process of measuring the samples to obtain accurate measurements and coordinate points for the position errors in the samples. The samples were ultimately measured using a digital coordinate measuring machine and statistical study (MSA) was performed to check for the repeatability and reproducibility of the measurement system. Although the positioning error and shrinkage error were calculated for the MakerBot system, a thorough study on the effect of the skewedness of the Z platform is necessary. This type of procedure more than likely should be performed on most commercial printers. The future work includes understanding the reasons for the lack of a 100-micron accuracy as claimed by a majority of commercial systems as well as understanding the combined effect of the tilt in the platform and the extruder position.

Since the aim of this research was to produce soluble molds for composite parts with high accuracy levels or aerospace grade tolerance, a dimensional error study was necessitated. The error compensation deduced from the proposed model was applied to a soluble mold for a compact tension (CT) specimen mold to check for the accuracy in dimensions of the CT sample.

This soluble mold tooling was also equipped with a provision to embedding a sensor in the CT sample for eventual applications in structural health monitoring. It was observed that the mold enabled the fabrication of a CT specimen sample with the desired dimensions with the use of (1) mold material shrinkage compensation and (2) resin shrinkage compensation equations. The optical fiber sensor was also positioned at the desired location in the sample. The soluble mold was successfully dissolved away in limonene leaving behind the CT sample with the embedded sensor intact without causing any stress or damage to the printed tooling or during the demolding of the composite part.

It is inferred that in-depth experimentation and testing are necessary to monitor the damage, the point of excitation and the related TL performance. Further future work requires preparation and study of more complex mold geometry and integration of various structural sensors, while maintaining the overall strength of the composites. Such research work into additive technology provides a framework for multi-intelligent processing in composite production.

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BIOGRAPHICAL SKETCH

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