STUDY OF FACTORS AFFECTING THE 3D PRINTING OF POLYLACTIC ACID ONTO TEXTILE FABRICS.

BY

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DECLARATION

DECLARATION BY THE STUDENT

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DEDICATION

I hereby dedicate this thesis to my lovely family. Thank you for never giving up on me and encouraging me towards my goals. If it were not for your love, encouragement, support and sacrifices, I would have never made it this far. I love and appreciate you.

ABSTRACT

The emergence of 3D printing has advanced industrial production processes. 3D printing or additive manufacturing is a technology that constructs objects in layers. It exhibits much saving in the design and manufacturing steps and has been applied in several fields including medical, aerospace and textiles. In recent times, textile substrates have been combined with 3D printed polymers to create multicomponent textiles. These structures have brought about the possibility of using polylactic acid (PLA), an environmentally friendly biodegradable polymer, as an alternative to dyes and pigments in decorative textiles. However, there has been a challenge with the adherence of the polymer to the textile substrate. The aim of this study was to design and produce a cotton/PLA structure through the Fused Deposition Modelling (FDM) 3D printing technique, to determine the effect of fabric parameters and 3D printing parameters on the adhesion and tensile properties of the structure as well as to characterize the mechanical properties of the structure. The printed PLA structure was designed using Solidworks, converted to a Standard Tessellation File (STL) and then sliced for 3D printing using the Cura software. 3D printing was done using an Athena FDM 3D printer. The printing was first done on 15 woven fabrics with different properties. Cotton woven fabric was used in this study since it exhibited the highest adhesion force for the 3D printed structures. The particulars of the fabric included 355.2 g/m^2, 50 Tex warp, 37 Tex weft and a thickness of 0.19 mm. A four-variable, five level Central Composite Rotatable Design was used for the optimization of extrusion temperature, printing speed, fill density and model height. The resulting cotton/PLA structures were tested for adhesion force before and after washing as well as tensile strength. The experimental data was used to develop regression models to predict the properties of the cotton/PLA structures. The model for adhesion force before washing yielded a coefficient of determination (R^2) value of 0.75, a P value of less than 0.05 and an optimum force of 50.06 N/cm. The model for adhesion force after washing had an R^2 value of 0.84, a P value of less than 0.05, an optimum force of 42.91 N/cm and showed a reduction in adhesion force after washing. Adhesion forces before and after washing, were both positively correlated to extrusion temperature. However, they reduced with an increase in printing speed and model height. Tensile strength yielded an R^2 value of 0.94, a P value of less than 0.05 and an optimum tensile strength of 346.22 MPa. From the results of this study it was concluded that the fabric parameters and the 3D printing parameters have an effect on the properties of the structures. Future work should study the effects of more fabric and 3D printing parameters and characterize more properties of the fabric/polymer structure. A cost analysis should also be done to compare the costs involved with costs of current textile decorative techniques.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABBREVIATION	DEFINITION
3D Printing	Three-Dimensional Printing
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
CCD	Central Composite Design
FC	Factor Contributions
FDM	Fused Deposition Modelling
NUST	National University of Science and Technology
PC	PolyCarbonate
PLA	Polylactic Acid
PTFE	Poly Tetra Fluoro Ethylene
PVA	PolyVinyl Acetate
SLS	Selective Laser Sintering
STL	Standard Tessellation Language
TPE	Thermoplastic Elastomers
VIF	Variance Inflation Factor

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND OF THE STUDY

3D printing or additive manufacturing is a production method that produces 3-dimensional objects from digital files by combining very thin layers of material until the object is formed (Gibson, Rosen, & Stucker, 2010). Unlike traditional production methods which are subtractive and result in huge material losses, 3D printing is an additive production method. This manufacturing method offers a freedom of design while reducing costs and lead times. It also has the advantage of being environmentally efficient as most of the material is used in the production process and there is very little that has to be disposed of. 3D printers have been in use since the 1980's and their impact in the industrial sector and in rapid prototyping has continued to grow (Chua, Leong, & Lim, 2003). There have been many adaptations to 3D printers as well as an increase in the availability of various software for use with them (Baumann & Dieter, 2017). The available types of 3D printers have diverse technologies that work in different ways to produce different types of models. 3D printers have therefore found diverse applications in several fields.

The use of 3D printing technology has been applied in several industries such as construction (Malaeb, et al., 2015), medical (Ventola, 2014) and aerospace (Yagnik, 2012). The use of this production method has been explored in the textile and clothing industry. There are some applications that have been used for the 3D printing of textile structures, that is, woven structures (Partsch, Vassiladis, & Papageorgas, 2015) and knitted structures (Melnikova, Ehrmann, & Finsterbusch, 2014; Beecroft, 2016). 3D printing has also been used to print fashion items such as shoes (Piper, et al., 2014;

Spahiu, et al., 2016) and garments (Valtas & Sun, 2016). However, although these structures exhibit the drape of textile materials, they have inferior flexibility and strength when compared to traditional textiles. The comfort of the 3D printed fabrics does not come close to that of natural fabrics like cotton. There still needs to be improvements in the manufacturing process to be able to produce flexible textile materials.

Researchers have combined the 3D printed forms with short fibres to create composites (Mahajan & Cormier, 2015). Research has also been done to combine 3D printed forms with textile yarns and fabrics in an effort to enhance the properties of the textile substrates (Korger, et al., 2016). Although this method has made it possible for new textile applications to be explored, there is still a challenge in the adherence of the 3D printed polymer to the textile substrate. Adhesion of the 3D printed polymer to the fabric is an important factor as it affects the end uses, durability and the quality of the product. Considerable efforts to improve adhesion have been done by varying the fabric, polymer as well as the printing parameters. Although the effect of these different factors has been studied and observed, there is still need for more research to be able to determine the optimum settings for the best adhesion. This study looks at the possibility of combining 3D printed polymers with textile fabrics as well as the effect of different parameters on the properties of the polymer/fabric structures.

1.2 STATEMENT OF THE PROBLEM

Decorative textiles are an important aspect of our textile needs. These have been produced using dyeing, printing and embroidery techniques. Although these methods have their own advantages, they are expensive, emit some pollution and waste during the process and may require a lot of space for storage of screens. The dyeing of textiles requires a lot of production time and costs and emits harmful chemicals at every stage of production. Environmental issues associated with dyeing have been discussed and attempts made to alleviate the problem (Gregory, 2007). The emergence of 3D printing as an effective process has led to the consideration of the production method for decorative textiles because of the possibility of the use of biodegradable Polylactic acid (PLA) instead of the conventional dyeing and printing chemicals. The use of 3D printing for decorative textiles involves the combination of polymers with textiles through 3D printing techniques. Although this method of decorative textiles has brought about the possibility for new textile applications, it has posed some quality challenges due to the adherence of the 3D printed polymer to the textile substrate. Studies have been done to overcome these challenges, but there are still other options that can be explored towards a solution to the problem. Hence the research investigated the effect of fabric and production parameters on the quality of the polymer/fabric structure in an effort to determine the most suitable parameters for a durable structure.

1.3 JUSTIFICATION OF THE STUDY

PLA is a biodegradable polymer therefore the 3D printing of PLA onto textile fabrics will enable the production of eco-friendly decorative prints. The use of 3D printing technology will allow more flexible and high-end products to be produced in less time and at a lower cost. This will also lead to the minimization of waste from textile production and reduced consumption of energy, water and chemicals. The 3D printed polymer could allow for the introduction of additional properties and will be a good alternative for screen printing and inkjet printing in decorative textiles. It will expand the pattern possibilities of decorative textiles as more unique designs with higher aesthetic qualities can be produced with 3D printing. The improved adhesion properties of the 3D printed polymer to the textile substrate will increase the durability of the composite even after undergoing the different kinds of stresses during the use of the product.

1.4 SIGNIFICANCE OF THE STUDY

Many challenges in current textile decorative methods are related to pollution, time and expenses incurred in dyeing and printing. The use of 3D printing, an additive manufacturing method, as an alternative method for printing and dyeing will minimize the use of water, chemicals and reduce the amount of waste thus improving the ecological footprint and the productivity. The use of biodegradable PLA will also have a positive impact on the environment. Challenges have been posed in the adhesion of the polymer to the textile fabric. This research will therefore contribute to new knowledge by providing a better understanding of polymer to fabric adhesion in the deposition of PLA onto woven fabrics. The results will also serve as a valuable basis to apply 3D elements onto fabric with added functionalities and to expand the possibilities of decorative textiles. It is therefore anticipated that this study will generate a great deal of interest not only among researchers but to the textile industry at large.

1.5 OBJECTIVES

The main objective of the study was to determine the effect of fabric parameters, extrusion temperature, printing speed, fill density and model height on the quality of textile/PLA structures. To be able to accomplish this, the project was guided by the following specific objectives:

i. To investigate the properties of textile woven fabrics that affect adhesion of PLA on textile and to determine the fabric with the highest adherence to PLA.
ii. To produce a cotton/PLA structure through the FDM 3D printing technique.

iii. To study the effect of production parameters on the quality of the cotton/PLA structure.

iv. To characterize mechanical properties of the cotton/PLA structure.

1.6 SCOPE OF THE STUDY

This study focused on the use of a Fused Deposition Modelling 3D printer for the deposition of Polylactic acid (PLA) filament onto fabrics. The design that was printed was designed with the Solid Works software and customised for 3D printing using Cura Software. The fabric samples for the preliminary tests were purchased from Fabrix and the Zimbabwe Spinners and Weavers factory shop in Bulawayo, Zimbabwe. The fabrics were all woven fabrics with different properties. The fabric selected for the study of the effect of production parameters was one that exhibited the highest adhesion force to PLA. The 3D printing parameters that were varied during the printing process were extrusion temperature, printing speed, fill density and layer height. The textile/PLA structure was characterized in terms of adhesion force before washing, adhesion force after washing and tensile strength. Optimization and characterization were done using multiple regression analysis.

CHAPTER 2: LITERATURE REVIEW

2.1 THE 3D PRINTING PROCESS

The rise of the use of 3D printing technology has sparked interest in researchers to determine its viability in the textile industry. 3D printing enables the manufacturer to produce complex structures easier and quicker than conventional production processes. The 3D printing or additive manufacturing process involves the following steps (Chua, Leong, & Lim, 2003; Canessa,et al., 2013)

i. Digital modelling, that is, designing a 3D model of the object to be printed. This can be done with computer-aided design (CAD) software or reverse engineering techniques such as the use of an object laser.

ii. The CAD file is converted to a file format that is compatible with the 3D printer such as a Standard Tessellation Language (STL) file. This file contains the geometrical information to represent the digital modelling.

   Steps (i) and (ii) can be simplified by downloading a digital model from open source websites on the internet such as *Thingiverse* (Nilsiam & Pearce, 2017).

iii. The STL file is then sliced into layers using slicing software such as *Cura*. In this step the digital model is converted into a list of commands understood and executable by the 3D printer, usually called a *g-code*.

iv. The *g-code* file is then transferred to the 3D printing control software, for instance *Franklin or RepRap* and the machine is set up. The 3D printer which is controlled by a computer then builds the model one layer at a time.

v. The next stage is post processing. This can involve finishing, polishing, cleaning and painting. After that the structure can be removed from the machine.

Figure 2.1 shows the different stages of the additive manufacturing process from the CAD Model to the 3D Object. The 3D CAD Model is designed and converted into a STL File. The file is then sliced using the slicing software. The layer slices are transferred to the 3D printer for the additive manufacturing process (AM Process) and the final 3D object is printed.

Figure 2.1 : Generalized Additive Manufacturing Process (Campbell et al., 2011).

2.1.1 Categories of 3D Printing

There are different 3D printing techniques that vary in the method of layer manufacturing. The differences in the techniques are based on the material and technology used. According to the American Society for Testing and Materials (ASTM) group F42-Additive Manufacturing; the processes can be described in 7 categories as follows: Material Extrusion, Material Jetting, Binder Jetting, Vat Photopolymerisation, Powder Bed Fusion, Sheet Lamination and Directed Energy Deposition.

2.1.1.1 Material Extrusion

Material extrusion is an additive manufacturing technique whereby material is selectively dispensed through a nozzle or orifice. The extruded material is heated and then deposited in layers until the 3D object is formed. Fused Deposition Modelling (FDM) and Contour Crafting are some of the technologies used in material extrusion (Gao, et al., 2015). FDM is the most common material extrusion process and is used on many low-cost domestic 3D printers. In the material extrusion process the quality of the final model is influenced by several factors which when controlled successfully can lead to the production of quality prints (Loborough, 2016; Christiyan et al., 2016).

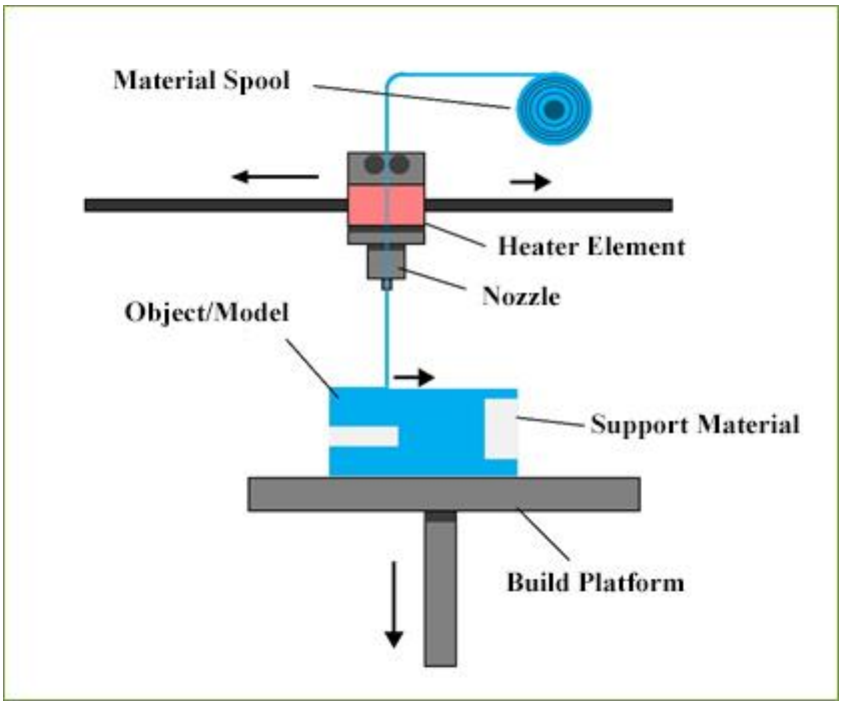

Figure 2.2 : Schematic Diagram of Material Extrusion Set-Up (Loughborough, 2016).

The material is supplied to the extrusion nozzle in filament form from a spool. The filament passes through a heater element that heats it to the set temperature before going through the nozzle in molten state (see Figure 2.2). The nozzle is moved along three axes, that is; x, y and z axes by a computer-controlled mechanism and deposits material where required thus forming the first layer. The next layers are added on top of the previous layers and the layers are fused together while the material is in molten state. The material immediately hardens after extrusion. These movements of the nozzle and pushing of the filament into the extruder are driven by stepper motors or servo motors (Canessa, Fonda,

& Zennari, 2013). Thermoplastics, metal pastes and ceramic slurries are some of the printing materials used in material extrusion (Gao, et al., 2015). FDM was developed by Stratasys and is the second most used 3D printing method after stereo lithography (SLT) (Ramya & Vanapalli, 2016).

The main advantages of the material extrusion technique are that there is no chemical post-processing required, there are no resins to cure and the machine and materials are less expensive resulting in a more cost-effective process. The disadvantage of the process is that the resolution on the z axis is low compared to other additive manufacturing processes, so if a smooth surface is needed a finishing process is required. It is also a slow process sometimes taking days to build large complex parts (Wong & Hernandez, 2012). This technique is mainly used in medicals and textiles.

2.1.1.2 Material Jetting

The method used in the material jetting technique is similar to that of a two-dimensional ink jet printer. Droplets of build material are deposited onto the build platform by means of an inkjet print head. The droplets of the material solidify and form the first layer of the object being fabricated. More layers are built over the first layer thus building the model layer by layer. The layers are either allowed to cool and harden or they are cured using ultraviolet (UV) light. Photopolymers and waxes are the commonly used materials for this process because of their viscous nature and their ability to form drops (Canessa, Fonda, & Zennari, 2013). Figure 2.3 shows the schematic diagram of Material Jetting whereby the build material is deposited in the form of droplets and then cured using UV light supplied by the UV Curing Lamp.

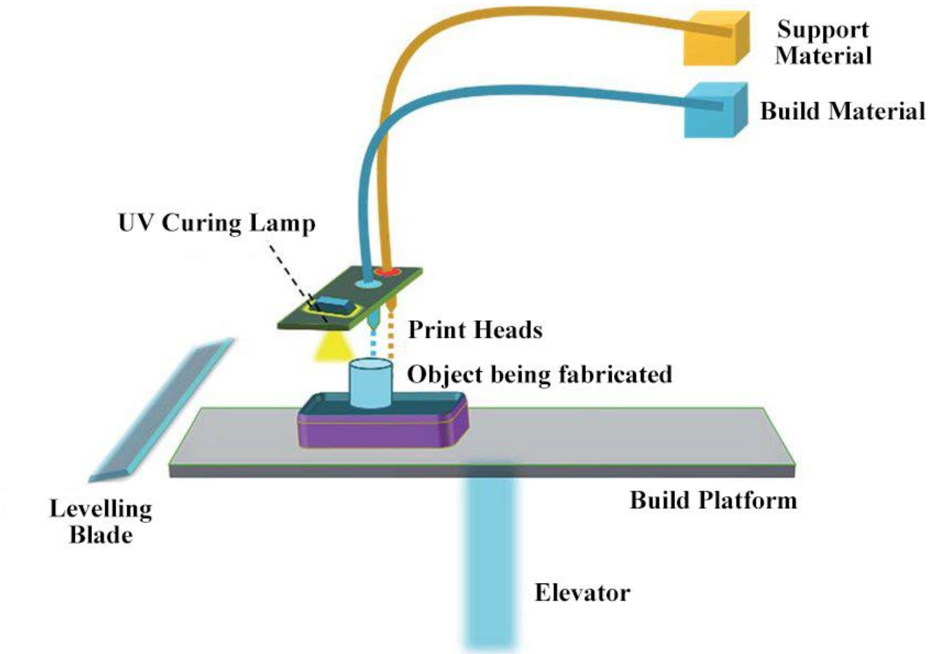

Figure 2.3 : Schematic Diagram of Material Jetting Set-Up (Loughborough, 2016).

The commonly used technologies are polyjet and inkjet printing. Multi-material printing is possible with material jetting and the fabricated objects have a high surface finish. The disadvantage of this technique is that it produces low-strength objects (Gao, et al., 2015).

2.1.1.3 Binder Jetting

This is an additive manufacturing method in which liquid binding agent is selectively deposited to join powder materials. In this method the model is built with polymer powder (plaster resin), ceramic powder or metal powder as the build materials and a liquid as the binder (Gao, et al., 2015). The powder is spread on the build plate by the use of a powder roller and the liquid binder is deposited in the cross-section of the part by use of an inkjet printhead (see Figure 2.4). The binder acts as an adhesive between the powder layers. The print head moves horizontally along the x and y axes of the machine and deposits alternating layers of the build material and the binding material. After each layer, the object being printed is lowered on its build platform (Gibson, Rosen, & Stucker, 2010).

The advantages of this technique are that full colour objects can be printed and a wide selection of materials can be used. The disadvantage is that the technique involves post processes such as de-powdering, curing, sintering, annealing, infiltration and finishing which may take long and incur costs (Gao, et al., 2015). The technology is often referred to as 3DP because of the similarity with the inkjet printing process that is used for two-dimensional printing in paper (Wong & Hernandez, 2012).

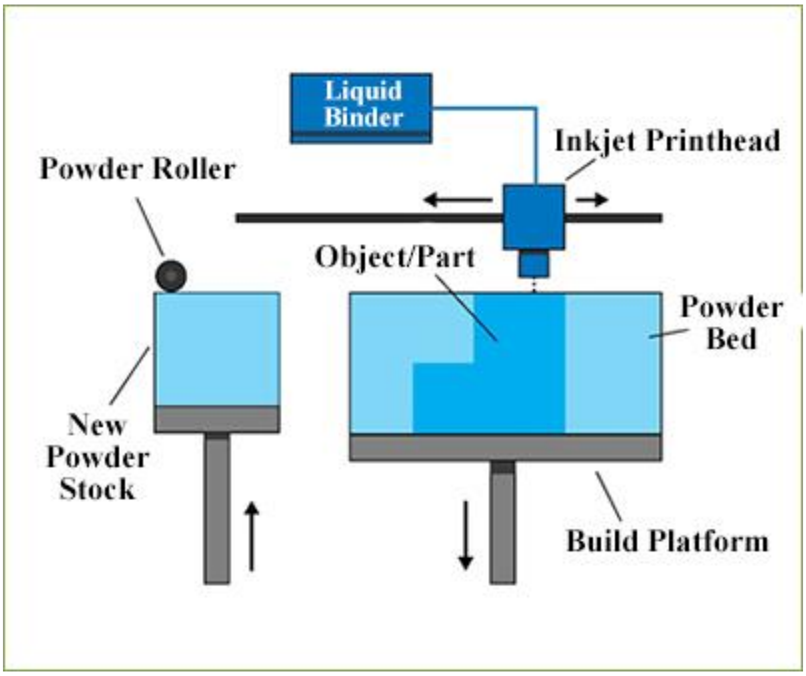

Figure 2.4 : Schematic Diagram of Binder Jetting Set-Up (Loughborough, 2016).

2.1.1.4 Vat Photopolymerisation

In this process a vat of liquid photopolymer resin is selectively cured/hardened with an ultraviolet (UV) light. The platform moves the model being formed downwards after the curing of each new layer. The model is built by lowering the platform one layer at a time (Hausman, 2014). In some machines a blade is used that comes between the layers to provide a smooth resin base for building the next layer. Once the model is built the vat is drained of resin and the object is removed (Gibson, Rosen, & Stucker, 2010). The commonly used techniques are stereo lithography (SLA) and digital light processing (DLP). In stereo lithography the vat of photo resin is cured using a laser and the object is formed (see Figure 2.5). Digital light processing uses a light source for the curing process (UOT, 2016). The advantages of vat photopolymerisation are that it has a high building speed and produces parts with a good resolution. The technique however has a high cost of materials and supplies (Gao, et al., 2015).

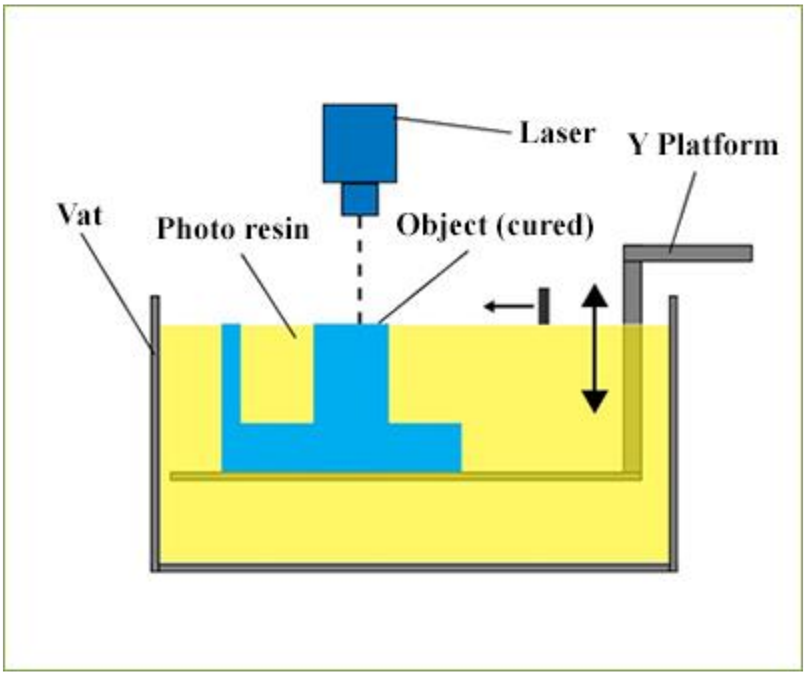

Figure 2.5 : Schematic Diagram of Photopolymerisation Set-Up (Loughborough, 2016).

2.1.1.5 Powder Bed Fusion

This method uses an energy beam, that is, either a laser or electron beam to selectively melt and fuse material powder together forming the first layer. Further layers are fused and added over the first layer until the entire model is created. The unfused powder remains in position; however, it is removed during post processing. There are several powder bed fusion technologies in use such as Direct Metal Laser Sintering (DMLS) and Selective Laser Sintering (SLS) (Gibson, Rosen, & Stucker, 2010). Powder bed fusion systems are the most used additive manufacturing production processes. The advantages of powder bed-based technologies are that the produced parts are fully dense, strong and have high accuracy and detail (Gao, et al., 2015). Figure 2.6 shows a schematic diagram of a Powder Bed Fusion technique that uses a laser to fuse the powder material together thus forming the object. This technique is commonly used in aerospace and medical orthopedics.

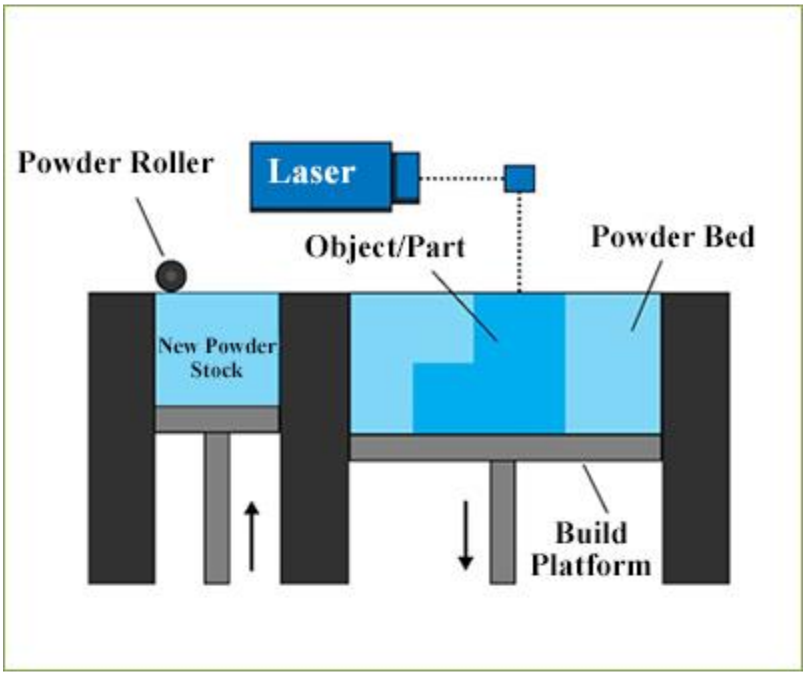

Figure 2.6 : Schematic Diagram of Powder Bed Fusion Set-Up (Loughborough, 2016).

2.1.1.6 Sheet Lamination

In sheet lamination sheets of material are bonded to form an object. The material, supplied by the material spool is positioned across the build platform in layers. The required shape is cut from the material layers using a laser knife and a set of mirrors (see Figure 2.7). Sheet lamination processes include ultrasonic additive manufacturing (UAM) and laminated object manufacturing (LOM) (Gibson, Rosen, & Stucker, 2010). The materials used in sheet lamination include ceramic tape, plastic film and metallic sheet. Objects made from this 3D printing technique have a high surface finish and can be produced at a low cost (Gao, et al., 2015).

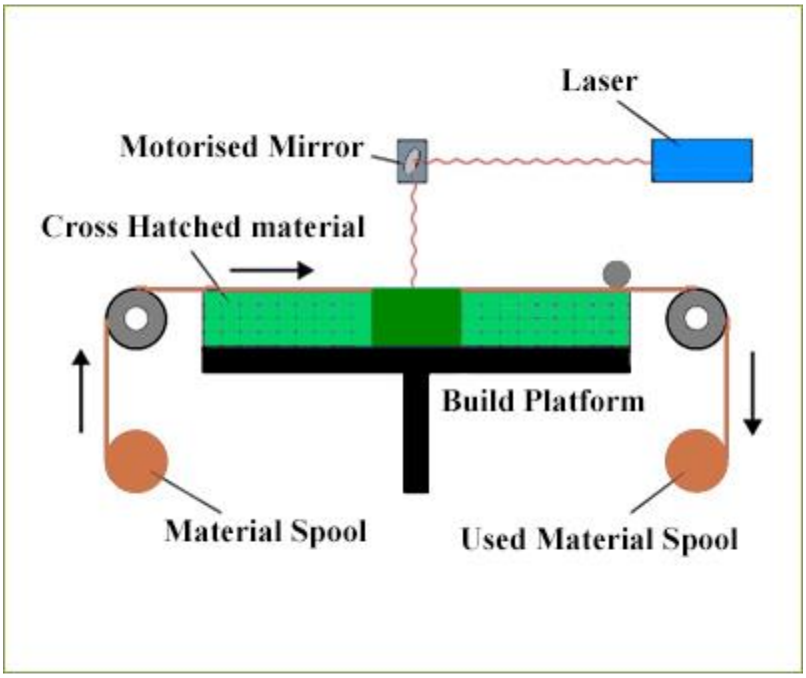

Figure 2.7 : Schematic Diagram of Sheet Lamination Set-Up (Loughborough, 2016).

2.1.1.7 Directed Energy Deposition

Directed Energy Deposition (DED) uses focused thermal energy to fuse materials by melting them as they are being deposited on the build platform. In Figure 2.8 as the material (metal wire) is being deposited on the build platform, thermal energy supplied by the electronic beam fuses the material together and the object is formed. Technologies of DED include electronic beam welding and laser engineering net shaping (LENS). This technique is commonly used to repair damaged or worn parts and to add additional material to existing components (Gibson, Rosen, & Stucker, 2010). The process can be used with polymers and ceramics but is typically used with metals, in the form of either powder or wire. The disadvantage of this technique is that it requires a post-processing machine (Gao, et al., 2015).

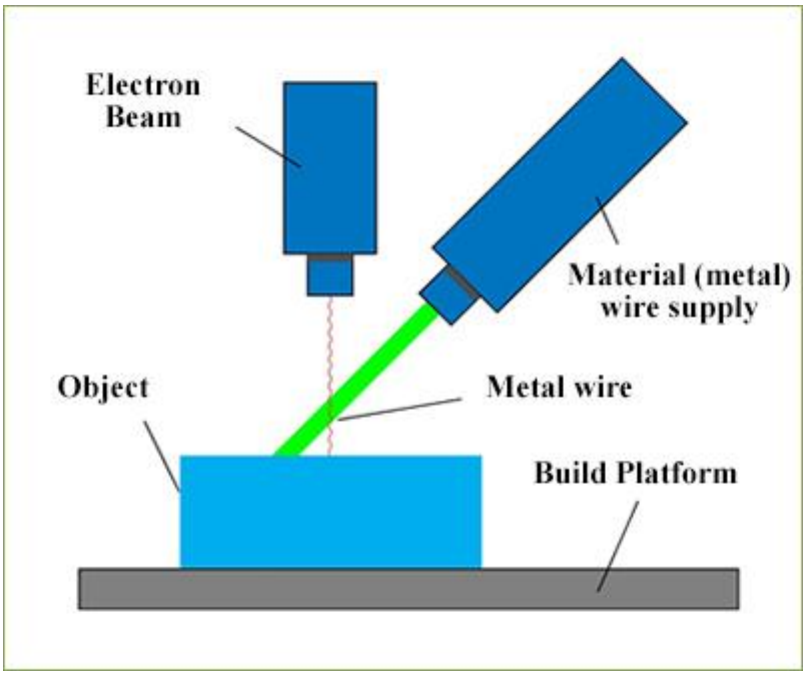

Figure 2.8 : Schematic Diagram of Direct Energy Deposition Set-Up (Loughborough, 2016).

2.1.2 Materials used in 3D Printing

The materials used in 3D printing depend on the additive manufacturing technique used. There are different 3D printing materials that exhibit different properties. The materials can be classified as plastics/polymers, metals, ceramics, composites as well as other materials such as food, concrete, papers and tissues/cells (Swetham, Reddy, Huggi, & Kumar, 2017). The most commonly used materials in 3D printing are Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), Polyvinyl Acetate (PVA) and Thermoplastic Elastomers (TPE). These materials are mainly produced as filaments with standard diameters of 1.75 mm and 3.0 mm. The 1.75 mm diameter filament is preferred because the smaller diameter makes it easier to push through the nozzle and is also easier to control during printing (Canessa, Fonda, & Zennari, 2013).

Table 2.1 summarises the properties, pros and cons as well as the extruded and print bed temperatures of the most commonly used materials. The most commonly used materials are PLA, ABS, Polyvinyl Acetate (PVA) and Thermoplastic Elastomers (TPE). PLA has an advantage over the other materials in that it is a bioplastic polymer and therefore has good environmental properties. It does not smell bad when printing and the fumes are not dangerous, therefore it does not require special safety precautions or forced ventilation. PLA works well with the printing bed at room temperature therefore there is no need to heat the printing bed. This makes it less expensive. It is also easy to use and is an ideal material for use in low-cost 3D printing.

Table 2.1 : Commonly used Materials in 3D Printing.

Material	Extruded Temperature	Bed Temperature	Properties	Pros and Cons
ABS	215°C - 250°C	80°C - 110°C	Durable Strong Slightly flexible Heat resistant	Pros: Great plastic properties, smooth finish, solidifies quickly, durable and difficult to break, ideal for mechanical parts. Cons: It is non-biodegradable, a heated print-bed is necessary, fumes, deterioration through sunlight.
PLA	170°C - 220°C	20°C - 55°C	Tough Strong	Pros: Bioplastic; it has good environmental properties, good smell when heated, non-toxic, no heated bed necessary, less warping or shrinking issues, ideal for small parts, hard or soft/flexible variants, less expensive, easy to print, can be used in low cost 3D printing. Cons: Slow cooling down, low heat resistance, easier to break than ABS, needs thicker walls than ABS.
PVA	160°C - 170°C	45°C	High tensile strength, flexible.	Pros: Biodegradable, recyclable, non-toxic. Cons: Expensive, deterioration due to air moisture, special storage necessary.
TPE	180°C - 230°C	20°C - 55°C	The properties of a soft rubber that make it very flexible and elastic.	Pros: Flexible Cons: Can produce parts that are rigid on the edges.

Source: (Kamran & Saxena, 2016)

PLA is an aliphatic polyester that is a derivative of renewable resources. It is a synthetic polymer based on lactic acid ($C_3H_6O_3$) and produced from the fermentation of agricultural resources (Aurus, Lim, Selke, & Tsuji, 2010).

The first stage in the production of PLA is the extraction of starch from plants such as corn, rice, wheat, rye or sweet potato or the extraction of sugar from whey, sugar beet or molasses. If the production starts with starch then the starches are converted to fermentable sugars like glucose and dextrose by enzymatic hydrolysis. The sugar is broken down by micro-organisms into lactic acid through fermentation (Avinc & Khoddami, 2009). The stages of production of lactic acid by fermentation in Figure 2.9 start with the conversion of renewable resources to fermentable carbohydrates. The carbohydrates are fermented to broth which is then converted to lactic acid.

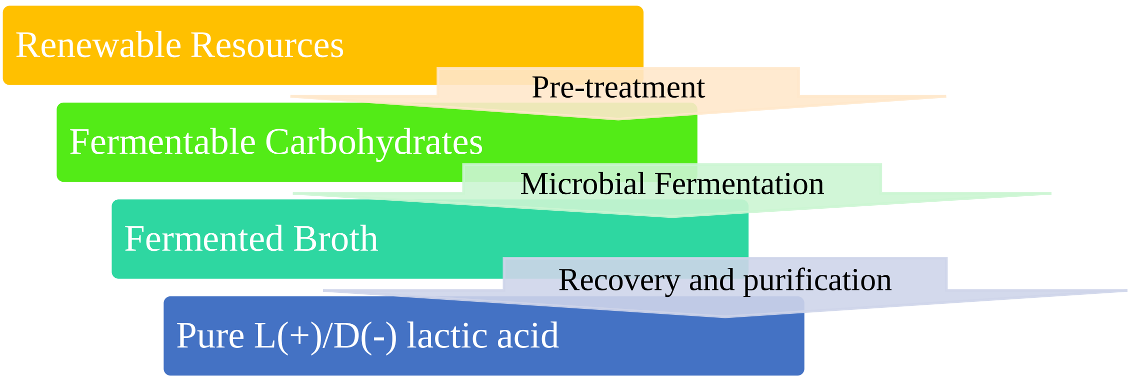

Figure 2.9 : Production of Lactic Acid from Renewable Resources (Ghaffar, et al., 2014).

The second step is the production of PLA from lactic acid (see Figure 2.10). This can be done by polycondensation of lactic acid, this process is carried out under high vacuum and high temperature and results in the production of a low molecular weight polymer (Swetham, Reddy, Huggi, & Kumar, 2017). A solvent is used to extract the water produced by ring-opening polymerisation of a cyclic dimer of lactic acid, that is lactide.

This method uses milder conditions and results in a higher molecular weight polymer (Avinc & Khoddami, 2009).

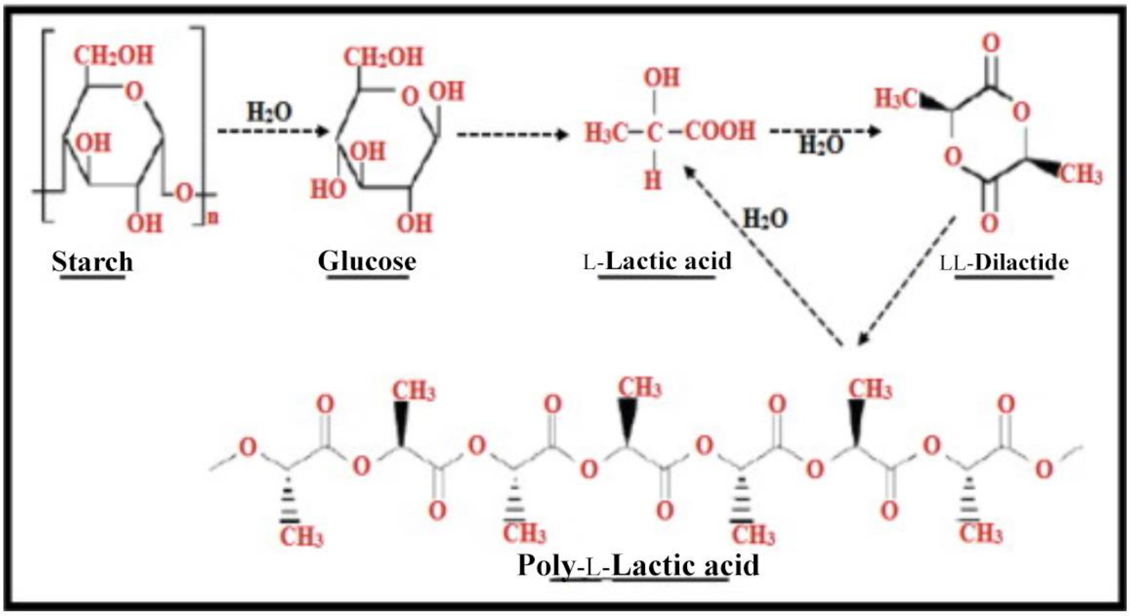

Figure 2.10 : Production of PLA from Lactic Acid (Ghaffar, et al., 2014).

Polylactic acid can be processed using several methods, that is, melt extrusion, film and sheet casting, injection moulding, thermoforming, injection stretch blow moulding and fibre melt spinning (Jamshidiam, Tehrany, Imran, Jacquot, & Desobry, 2010). This provides a wide range of materials for different purposes.

PLA is compostable, biocompatible and processable with most standard processing equipment. It is an environmentally friendly polymer whose raw material is both renewable and non-polluting (Ajioka, Enomoto, Suzuki, & Yamaguchi, 1995). Production of PLA requires 22-55% less fossil energy and 20-50% less fossil fuel resources than the production of petroleum-based polymers. PLA is available in many colours either solid or half-transparent and the resulting objects have a beautiful smooth surface (Castro-Aguirre, Iniguez-Franco, Samsudin, Fang, & Auras, 2016).

PLA has good mechanical properties (see Table 2.2) and can therefore substitute conventional polymers in several applications. It is attractive in many fields of industry because of its biodegradability characteristics in addition to its good mechanical and physiochemical properties.

Table 2.2 : Mechanical Properties of PLA.

Mechanical Properties	Value
Melting Point	About 180°C
Tensile Strength	50-70MPa
Tensile Modulus	3000-4000MPa
Elongation at Break	2-10%
Flexural Strength	100MPa
Flexural Modulus	4000-5000MPa
Glass Transition Temperature	50-60°C

Source: (Ajioka, Enomoto, Suzuki, & Yamaguchi, 1995)

PLA can be combined with a metal, wood or other materials to form composite materials for 3D printing. Tests have been done to combine PLA with magnetic iron and also with bronzefill. The tests showed that small metal concentrations can be embedded into polymer filaments resulting in conductive, magnetic, optic and other properties without altering important properties (Fafenrot, Grimmelsmann, Wortmann, & Ehrmann, 2017). Conductive polymer nanocomposites have also been created with PLA as the matrix and high structured carbon black (HS-CB) and multi-walled carbon nanotubes (MWNT) as the reinforcements for smart applications (Sanatgar, Cayla, Campagne, & Nierstrasz, 2017).

2.1.3 Software used in 3D Printing

The 3D printing process requires the use of three different software. There is the designing software that is used to design the model, there is the slicing software that converts the model into instructions understood by the printer and then there is the printer control software that sends printing instructions to the 3D printer. The relationship between the different software is illustrated in Figure 2.11. The production of a printed object can either begin as a new project that needs to be designed using computer aided design software or as a design extracted from open source websites on the internet. The designs are converted to an STL format file and then sliced using software such as *Cura* which creates a G-code for printing. The G-code is then sent to the printer control software (Franklin software) which communicates that information to the 3D printer and the object is printed.

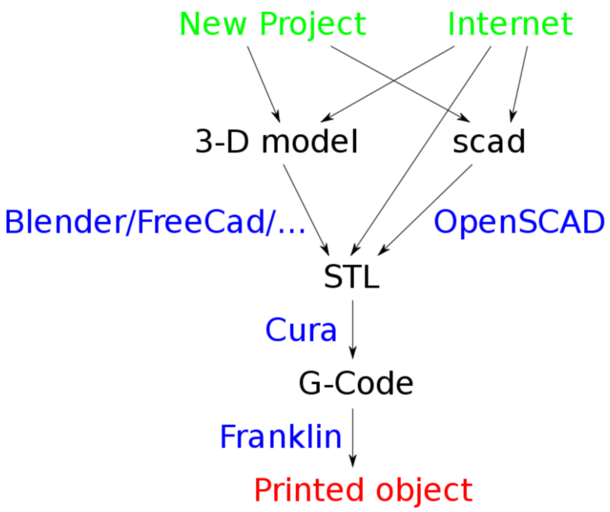

Figure 2.11 : Overview of Software used in 3D Printing and their Relationships (Wijnen B. , 2015).

2.1.3.1 Design and Modelling Software

The first stage in 3D printing is designing the model to be printed. This can be done in any 3D Computer Aided Design (CAD) modelling application such as *123D Design, Sketchup, FreeCAD, SketchUp, Onshape, TinkerCAD, OpensCAD, RepoCAD, Blender* and many other applications, some of which can be downloaded for free on the internet (Junk & Christian Kuen, 2016). These files have their own applications that enable the user to open, edit, save and export those files from the application. Once the model is designed it is saved as an STL file ready to be transferred to the slicing software. There are also pre-made and print-ready models available on sites such as *Thingiverse* and *Youmagine* that can be downloaded for free. These files have been designed and are usually already converted to STL format and ready to be imported directly into the slicing software (Jennings, 2017).

2.1.3.2 Slicing Software

Slicing software converts digital 3D models into instructions that can be understood by the 3D printer. The 3D model is cut into horizontal layers according to the predetermined user settings and calculates the amount of material required and also how long the printing will take (Gibson, Rosen, & Stucker, 2010). Slicer settings have an impact on the quality of the print. There are different 3D slicer programs available on the market; several of them are available for free download like *Cura* and *Slic3r* while others are available for purchase such as *Simplify3D* (Locker, 2018). Recently investigators have examined the advantages and disadvantages of different slicing software and have found the Cura software to be accurate and economical in filament consumption (Arrifin, Sukindar, Baharudin, & Ismail, 2018).

The slicing software is where the printing parameters are controlled. Some of the important parameters that can be controlled on the slicer software are extrusion temperature, printing speed, fill density, layer height, shell thickness, bottom/top thickness, filament diameter, nozzle size and retraction (Prusa Research , 2015).

Extrusion temperature is the temperature that is used for printing and is based on the filament being used. For PLA a value of 190 - 220°C is usually used (Trhlikova, Zmeskal, Psencik, & Florian, 2016). Printing speed is the speed at which printing happens. Fill density controls how densely filled the inside of the print will be. For a solid part a fill density of 100% is used and 0% for an empty part. The fill density will not affect the outside of the print and only adjusts how strong the part becomes, that is, a higher density gives a stronger part (Page, et al., 2017).

Layer height is the most important setting to determine the quality of your print. Every printer has a maximum and minimum layer height. The smaller the layer height the better the quality and the longer the printing time. It is important to set the layer height in such a way that the printing is quick without compromising the quality of the print. Shell thickness refers to the thickness of the outside shell in the horizontal direction. This should be an integer of the nozzle size. Bottom/top thickness controls the thickness of the bottom and top layers (Christiyan, Chandraselchar, & Venkateswarlu, 2016). Nozzle size is very important and is used to calculate the line width of the infill, and also the outside wall lines and wall thickness. (Rengevic, Fura, & Cubonova, 2016). Retraction is a feature which commands the printer to pull the filament back from the nozzle and stop extruding when there are discontinuous surfaces in the object being printed. Filament diameter is the diameter of the filament that will be used for 3D printing and should be recorded as accurately as possible (Jennings, 2017). The slicing software also has a function to set the dimensions of the model to be printed. The dimensions are set in the x, y and z directions where x is the width, y is the length and z is the height of the model. Once all the printing parameters have been set on the Slicing software the information is outputted as a *G-code* file which is sent to the 3D printer by means of the firmware.

2.1.3.3 Software for Controlling the 3D Printer (Firmware)

This is the software that is used for controlling the 3D printer and many other devices. It is a program that runs on the printer controller and serves the purpose of translating a g-code into action. It also deals with inputs and providing feedback to the user (Evans, 2012). The transfer of the g-code to the 3D printer can be done via USB, ethernet, SD card or Linux pipes depending on the type of firmware used. Firmware is a computer code that acts as the bridge between the hardware and software of a computer system. It is highly specialised to ensure the functioning of the 3D printer by controlling the motors, screen, temperature, time among other parameters during the 3D printing process (Bream, 2017). There are several types of firmware used in 3D printing, such as *Marlin, Sprinter, Teacup, RepRap, ImpPro3D, Smoothie, Sailfish and Franklin* (RepRap, 2018). Studies have shown that Franklin software has advantages over most conventional firmware in that it does not require technical knowledge and has good resilience with reliable hardware. It also has good integration in complicated systems. Franklin firmware can be set up and controlled entirely from a web interface. The software uses a custom protocol that allows printing to continue even when the internet connection is temporarily lost (Wijnen, et al., 2016).

2.1.4 Applications of 3D Printing in Textiles

3D printing techniques have been used in textiles because of the advantages the technique offers such as the creation of perfectly fitting customised designs with unique structures and patterns. It also reduces the production time and waste and is therefore likely to be a cheaper method of production of textiles (Perry, 2017). There have been many textile-like structures that have been produced using 3D printing technology. A variety of textile based structures such as fibres, woven structures, weft-knitted structures, layered structures and lace patterns have been created using the FDM and SLS technologies. These textiles have been designed using software such as Autodesk Inventor, Autocad Inventor and SketchUp. Different slicing software has been used including Repetier and Cura. Although the structures resembled the appearance of traditional textiles, they lacked their flexibility and mechanical properties.

2.1.4.1 Fibres, Soft Hair and Strands

Laput et al (2015) fabricated soft hair strands, fibres and strands using fused deposition modelling (see Figure 2.12). They ascertained that the technique was only suitable for printing straight hairs and fibres whose maximum length was equivalent to that of the printing bed. The results of the study are expected to enable users to explore hair components and fibre as a possible new design material for their 3D printed models (Laput, Chen, & Harrison, 2015).

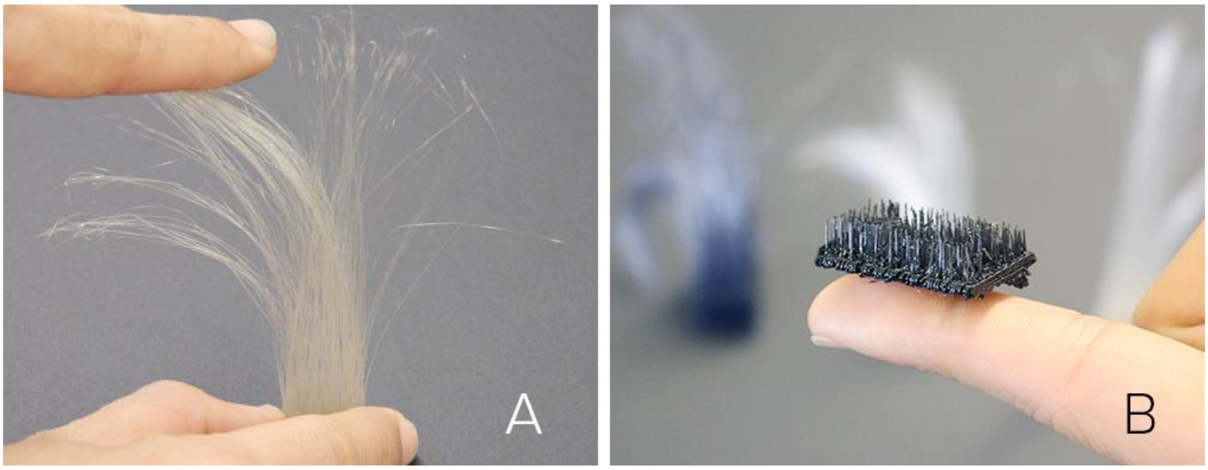

Figure 2.12 : (A) Fine Flowing fibres, (B) Bristles (Laput, Chen, & Harrison, 2015).

2.1.4.2 Woven Fabrics

Woven fabrics were printed using ABS and an FDM printer. Results showed the possibility to create structures with textile properties using 3D printing. The major challenge observed however was that the dimensions of the CAD model were not the same as that of the printed sample and there was also a change in resolution of the weft yarn (Partsch, Vassiladis, & Papageorgas, 2015). It was also observed through haptic means and mechanical measurements that warps and wefts stuck together making the sample inflexible and stiff (see Figure 2.13A). This was improved by increasing the yarn dimensions (see Figure 2.13B) and by incorporating a round shaped crimp in the weft (see Figure 2.13C).

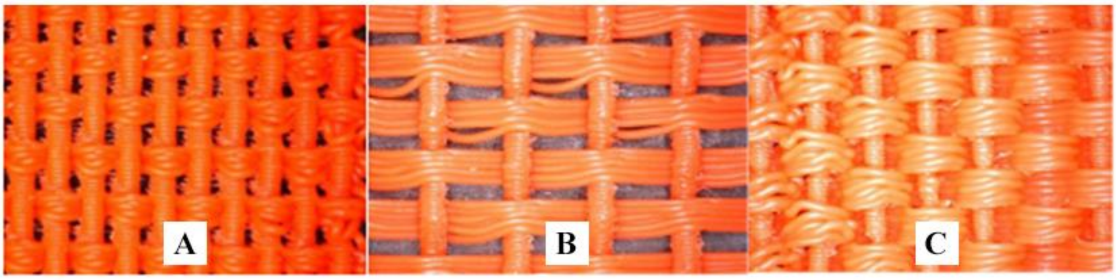

Figure 2.13 : Woven Textile Structures 3D Printed with ABS. (A) with Warps and Wefts Stuck Together, (B) with Increased Yarn Dimensions (C) with a Round Shaped Crimp in the Weft (Partsch, Vassiladis, & Papageorgas, 2015).

2.1.4.3 Knitted Fabrics

Melnikova et al (2014) created weft knitted structures using the SLS process and the FDM process. The model created with SLS (see Figure 2.14A) reproduced the look of a single-face weft knitted fabric but the lack of flexibility of the material led to different mechanical properties compared with knitted structures created from traditional textile yarns.

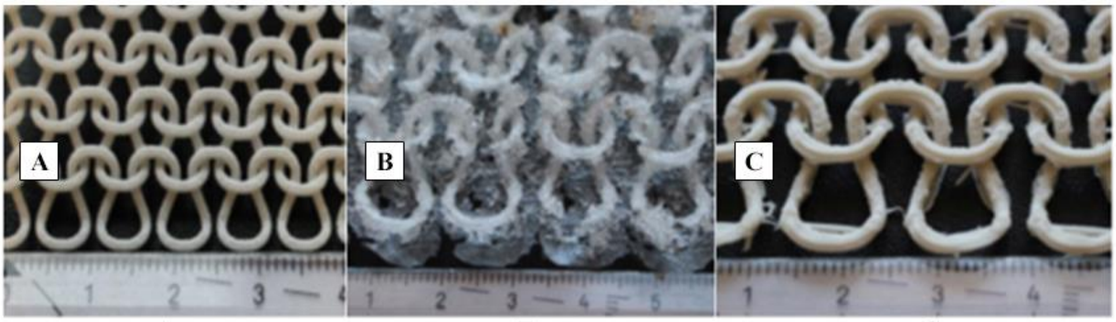

Figure 2.14 : Single-Faced Weft Knitted Fabric printed with (A) SLS and Nylon, (B) FDM and *Bendlay*, (C) FDM and Soft PLA (Melnikova, Ehrmann, & Finsterbusch, 2014).

For the FDM process *Bendlay* (a flexible, clear and transparent material that is a modification of ABS) was used and it required the use of support structures. The support structures were too fine to be produced by the printer as desired and they created clots which partly destroyed the model, as revealed in Figure 2.14B. The experiments showed that it is not possible to build a fine model by FDM.

The FDM process was also used with soft PLA. The process created a more flexible structure with significantly more similar properties compared to a textile knitted structure than for the design produced with SLS and Nylon. The surface of the soft PLA model (see Figure 2.14C) exhibits roughness on a macroscopic scale compared to the microscopic roughness of man-made or natural textile fibres.

Research has also been done to create flexible textile structures with the aim of creating textiles that are both flexible and rigid. Beecroft (2016) used the SLS method to print knitted structures with Nylon powder.

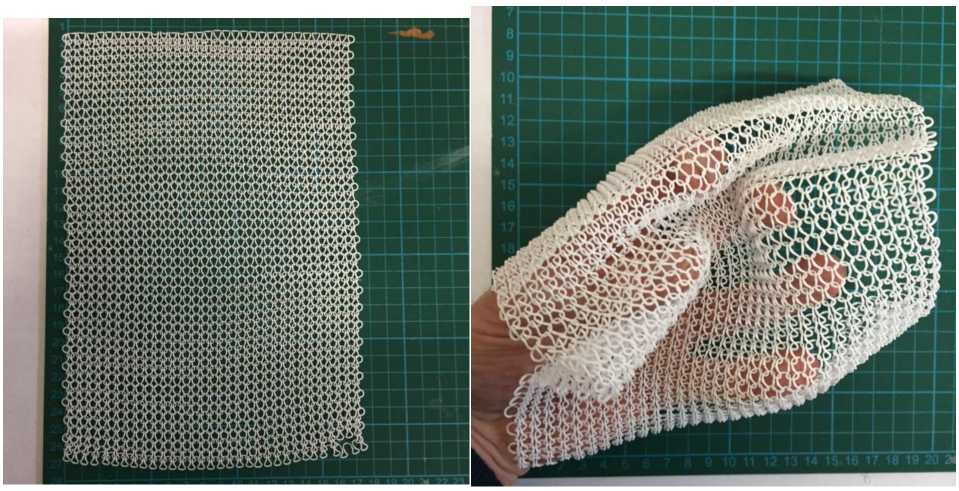

Figure 2.15 : 3D Printing of Weft Knitted Model (Beecroft, 2016).

Single-faced (see Figure 2:15) and interlock double-faced (see Figure 2.16) weft knitted pieces were printed.

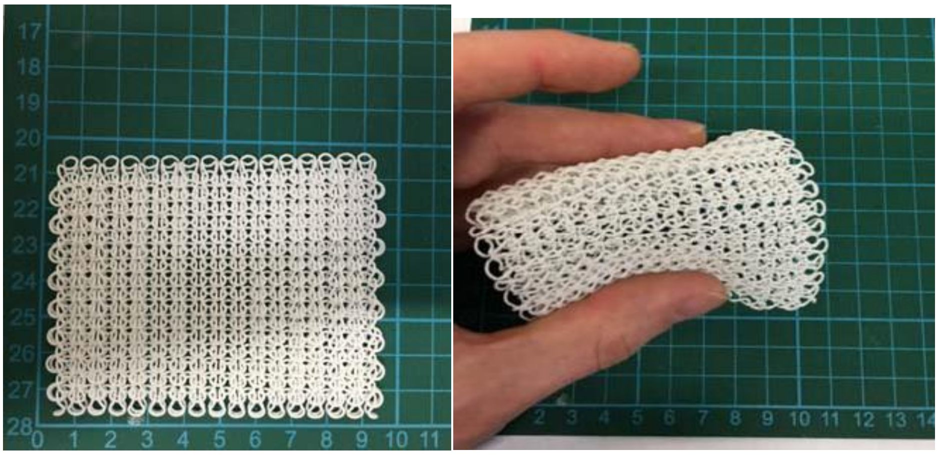

Figure 2.16 : 3D Printed Interlock Structure (Beecroft, 2016).

The pieces were strong enough to hold the knitted structure and flexible enough to articulate like a fabric. The pieces also exhibited stretch horizontally across the courses. These structures could be used in technical textiles. Further research with different printing materials can be used in future to create softer structures that can be used in the fashion industry (Beecroft, 2016).

2.1.4.4 Layered Structures

Melnikova et al (2014) created a model using FDM technology by depositing single strings on top of relatively open structures without any support structures. In Figure 2.17 structure A was combined with structure B and structure C to produce Structure D.

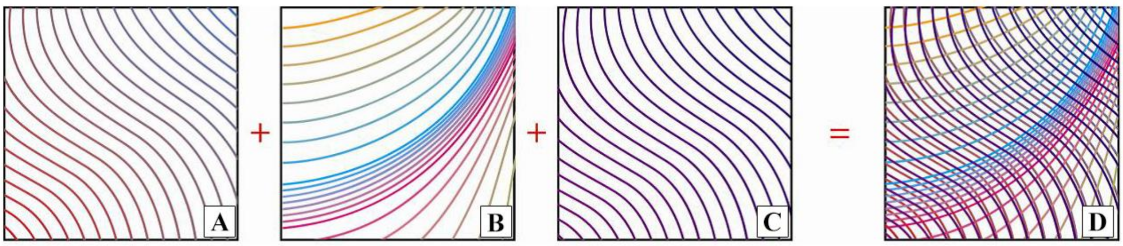

Figure 2.17 : Test Pattern for a Layered Structure, Composed of Three Stacked Layers (Melnikova, Ehrmann, & Finsterbusch, 2014).

The results in Figure 2.18 showed that the structures did not have sufficient strength and could result in the strings breaking.

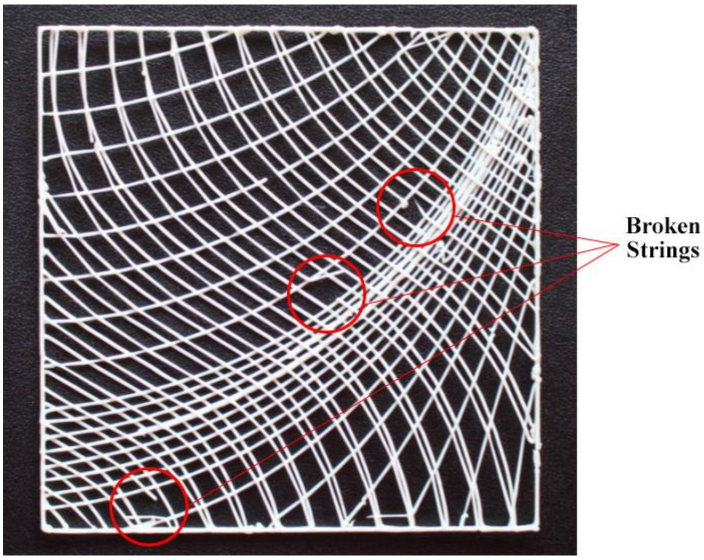

Figure 2.18 : FDM printed Three-Layer Structure with Broken Strings (Melnikova, Ehrmann, & Finsterbusch, 2014).

2.1.4.5 Lace Patterns

Lace models were created by Melnikova et al (2014) with FDM using soft PLA and LayTekks as shown in Figure 2.19. LayTekks is a hard filament that can be softened by placing in warm water after printing.

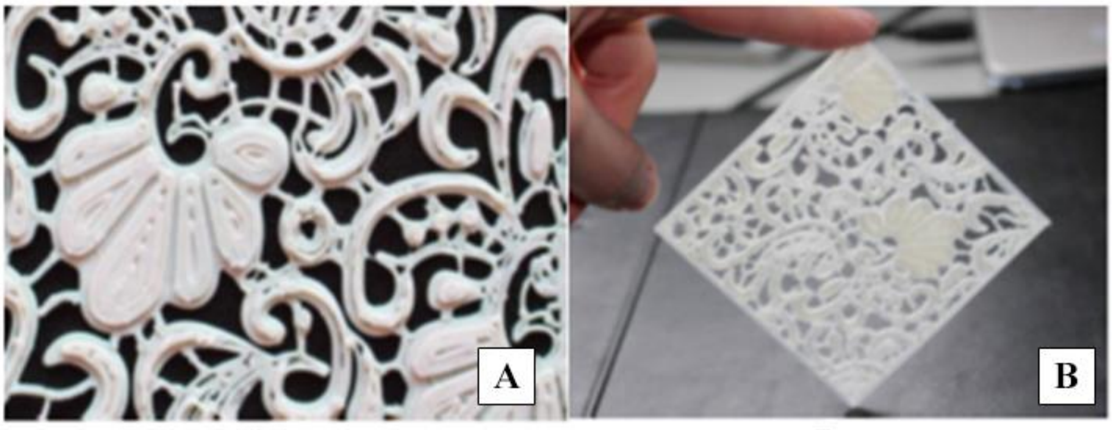

Figure 2.19 : Lace Pattern (A) Printed with Soft PLA and (B) Printed with LayTekks (Melnikova, Ehrmann, & Finsterbusch, 2014).

Printing with FDM showed no problems because of the absence of free-floating areas and also because the connection lines had large enough diameters. The structures are however still not flexible and comfortable enough for use in clothing.

2.1.4.6 Chainmail-Like Structures

SLS and FDM methods were used to 3D print chainmail-like structures. The structures were printed using the SLS printing technology and polyamide material. The printed samples had links in the chain which were separate after printing and did not stick together. This resulted in a structure that is flexible and has textile-like mechanical behaviour. The samples (see Figure 2.20) had good drape and bending properties (Gurcum, Borklu, Sezer, & Eren, 2018). Figure 2.20A shows the draping properties of the chainmail structure while Figure 2.20B shows the bending properties of the structure and Figure 2.20C shows how the structure wrinkles. These properties have shown that the chain-mail like structures can be used to produce textile-like structures. Improvements will need to be made in the material used to be able to produce structures with good comfort properties.

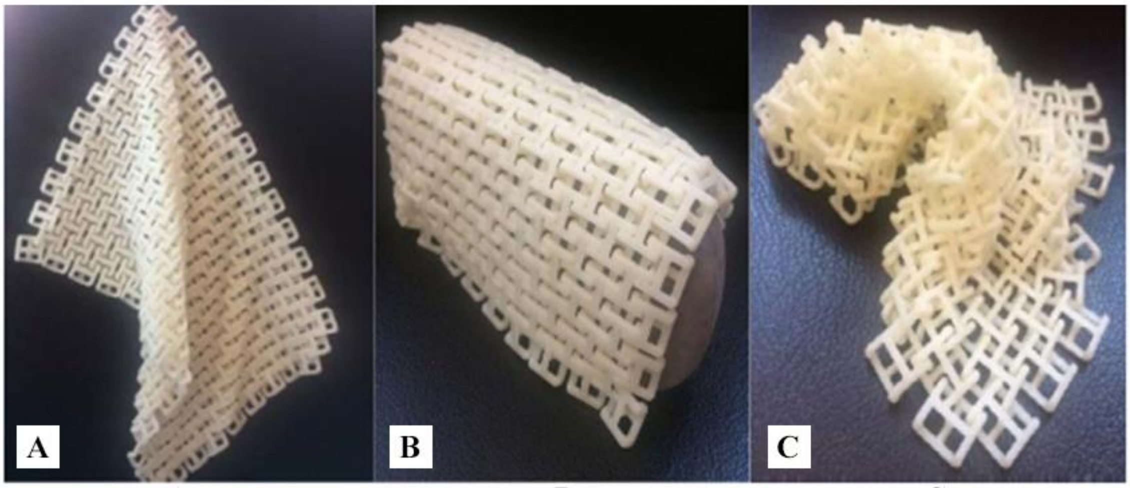

Figure 2.20 : Chainmail-Like Structures (A) Draping (B) Bending and (C) Wrinkling (Gurcum, Borklu, Sezer, & Eren, 2018).

2.1.4.7 3D Printed Textiles for Garments

3D printed textiles have also been created for garments (Figure 2.21). A lady's corselet was made from polylactic acid using the FDM printing technique. Different shapes were printed for the two parts of the corselet; a hexagonal pattern for the round-shaped bra cups and a square pattern for the rest of the garment. The different shapes ensured that the garment fit well with an increase in skin comfort. This could be a possibility to make custom-made diagrams that can differ according to the needs of the user. However, these textiles still needed improvement in the softness of the material and also in tear resistance (Lussenburg, Velden, Doubrovski, Geraedts, & Karana, 2014).

Figure 2.21 : Garment made from 3D Printed Textiles (Lussenburg, Velden, Doubrovski, Geraedts, & Karana, 2014).

2.1.4.8 Combination of Textile Substrates with 3D Printed Polymers

Although the 3D printed textile-like structures have opened doors for new opportunities the speed of modern 3D printing is still not fast enough to compete with the conventional textile production methods such as weaving and knitting. There is also the challenge that the 3D printed textiles do not compare to traditional textiles in terms of comfort, flexibility and strength. Research has been done to improve the mechanical properties of fabric while maintaining the drape and functionality of the textiles by direct deposition of polymers onto textile fabrics using 3D printing techniques. Direct 3D polymer deposition has been defined as a technology concerning the building of 3D polymers onto a surface in a programmed way (Brinks, Warmoeskerken, Akkerman, & Zweers, 2013).

These structures have been used to try and introduce braille onto textile care labels (Kreikebaum, Lutz, Doerfek, Finsterbusch, & Ehrmann, 2016). They have also been created for the possible use of the 3D printing technique as a novel finishing method (Grimmelsmann, Kreuziger, Korger, Meissner, & Ehrmann, 2017). Researchers have also used the technique with conductive material to contact electronic components in an effort to introduce electronics to textiles (Grimmelsmann, Martens, Schäl, Meissner, & Ehrmann, 2016). Patterns have also been 3D printed onto fabric for the introduction of decorative features onto textile fabrics (see Figure 2.22). This has affirmed the possibility of using 3D printing techniques for decorative textiles (Sabantina, Kinzel, Ehrmann, & Finsterbusch, 2015).

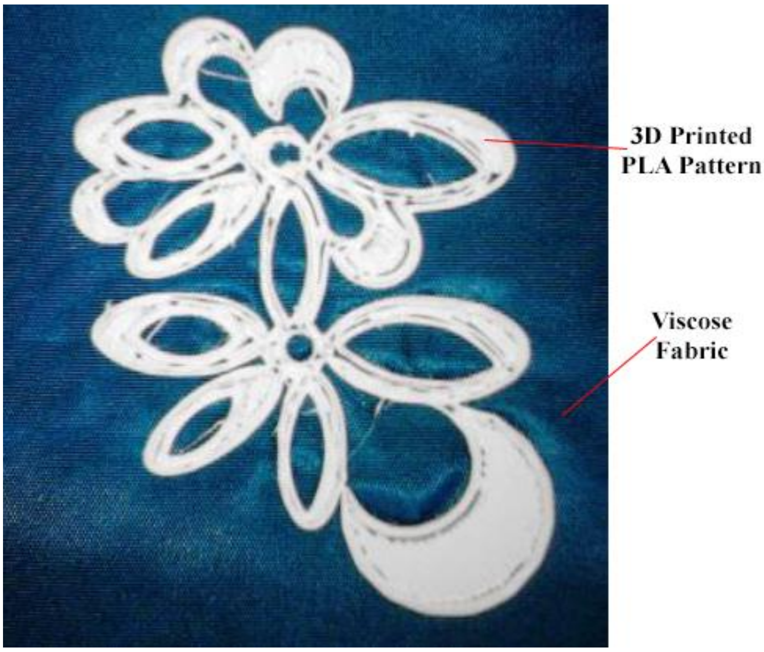

Figure 2.22 : Floral PLA Pattern Printed on Viscose Fabric (Sabantina, Kinzel, Ehrmann, & Finsterbusch, 2015).

The combination of 3D printed polymers with textile fabrics allows the creation of rigid objects with embedded flexibility and also the production of soft materials with additional functionality. Previous research has shown how the stretchability, flexibility and aesthetic qualities of textiles enhance rigid printed objects and how functional properties can be enabled to textiles by the use of 3D printing techniques. In Figure 2.23 a watchband was made by 3D printing a rigid polymer onto a flexible textile fabric. 3D printed snaps have also been printed on textile fabrics, this shows how accessories such as fasteners could be added to textiles using 3D printing techniques (Rivera, Moukperian, Ashbrook, Mankoff, & Hudson, 2017).

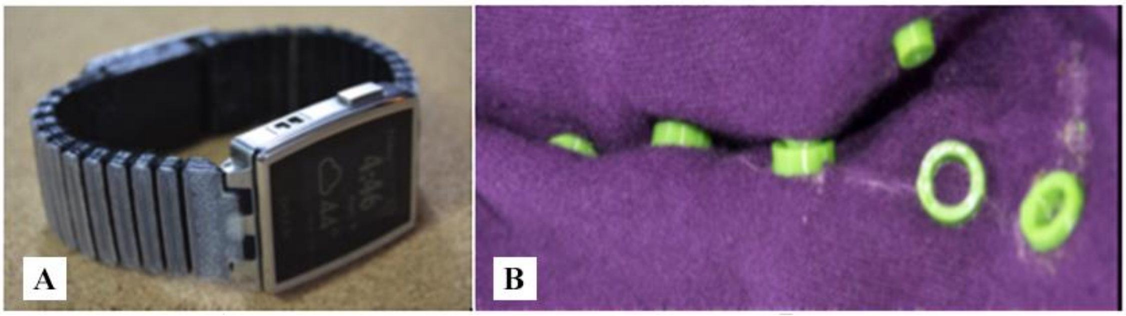

Figure 2.23 : (A) Functional Watchband Printed on a Polyester Mesh, (B) 3D Printed Snaps Printed on a Fabric (Rivera, Moukperian, Ashbrook, Mankoff, & Hudson, 2017).

The main 3D printing technique that has been used for this is FDM with the most common polymers being PLA, ABS, NinjaFlex, FilaFlex, PA66 and Nylon. Different fabrics have been used both knitted and woven.

Direct deposition of polymers onto fabric is done by laying the fabric on the printing bed and then 3D printing the polymer onto the fabric. The laying of the fabric has been done in different ways. Pei, Shen, & Watling (2015) used securing clips to ensure the fabric is firmly held onto the printing bed as illustrated in Figure 2.24.

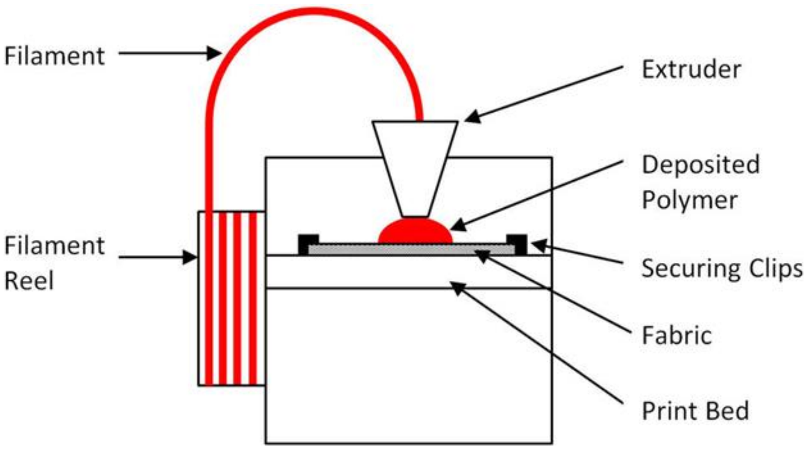

Figure 2.24 : Set-up of Fabric Laying and Securing with Clips on a 3D Printer (Pei, Shen, & Watling, 2015).

In their research Martens & Ehrmann (2017) fitted the samples on the printing bed using double-faced tape at the borders and sand paper in the printing area, that is, the middle area. The sand paper was to ensure that the textile fabric did not slip during the printing process. A similar method was also used by Neub et al (2016) and Dopke et al (2017).

Researchers have also identified problems with the direct deposition of polymers onto textiles such as shifting, sagging and tilting of the fabric during 3D printing. These problems affect the quality of the 3D print (Rivera, Moukperian, Ashbrook, Mankoff, & Hudson, 2017). For good quality prints the stability of the fabric during printing is an important factor. Attempts to solve this have been done through the use of adhesive tape. The shifting problem can be solved by fixing the fabric to the print bed using adhesive tape on its edges, sagging can be solved by making the fabric taut and then attaching it to the sides of the print bed using adhesive tape and tilting can be solved by using double-sided tape between the print bed and the fabric close to the problem spots (see Figure 2.25).

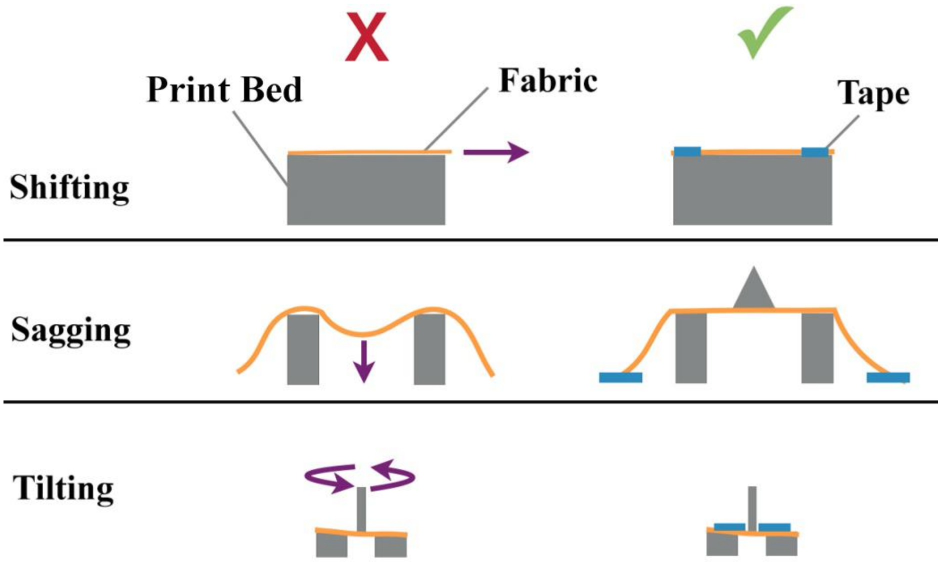

Figure 2.25 : Stabilization Problems and Solutions in 3D Printing of Polymers onto Textile Fabrics (Rivera, Moukperian, Ashbrook, Mankoff, & Hudson, 2017).

2.2 ADHESION OF POLYMERS TO FABRICS

Adhesion is the tendency of unlike surfaces to cling to one another due to the intermolecular and interatomic interaction of the two surfaces at the interface. There are different theories of adhesion based on the surface characteristics of the materials involved. These are diffusion theory, electrical interactions, mechanical interlocking and chemical interactions (Awaja, Gilbert, Kelly, Fox, & Pigram, 2009). The theory that is applicable to polymeric adhesion is the diffusion theory. According to this theory the adhesion to polymers is based on the inter-penetration or diffusion of the polymer across the interface. This is affected by parameters such as the temperature of the polymer, the contact time, the physical form and the weight of the polymer (Mittal, 1977; Lee & Wool, 2000; Awaja, Gilbert, Kelly, Fox, & Pigram, 2009). Studies on polymer to fabric adhesion have highlighted the importance of understanding the binding process of the polymers with the textile fabric as well as factors that influence the flow of the polymer. They determined that for better adhesion, the polymer should be able to penetrate into the fabric. This can be done by reducing the viscosity for high viscosity polymers or by adding pressure for better adhesion, (Brinks, et al., 2013). The study of these parameters is therefore important in the improvement of the adhesion force between polymers and fabrics.

Adhesion of the polymers to rough surfaces is based on the mechanical interlocking theory. This is based on the polymer keying into the rough surface. Researchers have hypothesized that if there is mechanical interlocking between the polymer and the substrate the adhesion force is increased. Research has also shown that roughening of the surface provides higher adhesion (Awaja, Gilbert, Kelly, Fox, & Pigram, 2009).

Adhesion to textile fabrics depends on the nature of the fibre surface and is affected by the presence of additional treatments on the fabric as well as impurities. Textile fabrics undergo a lot of chemical and physical treatments during use and this in turn leads to failure of the adhesive joint (Holme, 1999). It is therefore important to improve the adhesion forces so that they can withstand any form of chemical and physical treatments. Adhesion of polymers to fabrics is also affected by cohesion of the macromolecules of the polymer. The difference between adhesion and cohesion is that in adhesion the adhesive forces cause two different surfaces to cling to one another whereas in cohesion the cohesive forces cause similar surfaces to cling to one another (see Figure 2.26). If the adhesive forces are less than the cohesive forces adhesion strength between the polymer and the fabric decreases. This is affected by the speed at which the polymer is deposited onto the fabric (Sanatgar, Cayla, Campagne, & Nierstrasz, 2017). It is therefore important to determine the most appropriate speed to achieve a good adhesion strength between the fabrics and polymers.

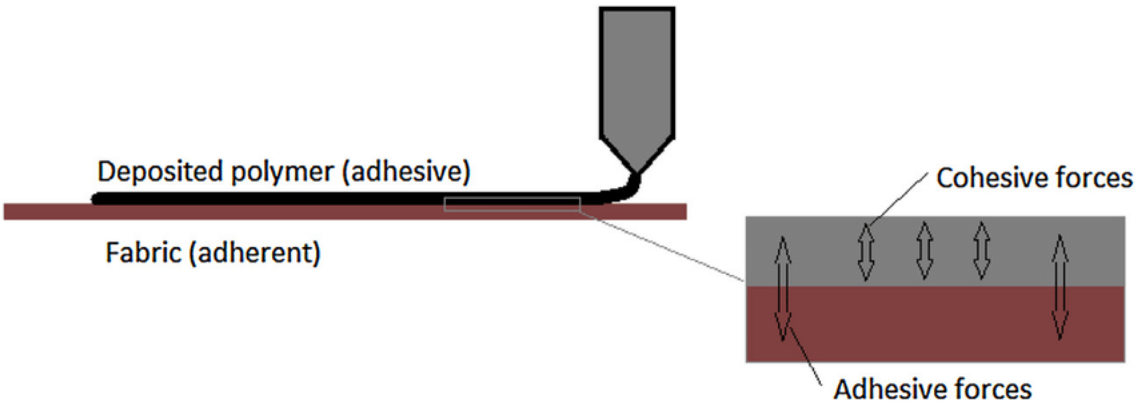

Figure 2.26 : Adhesive and Cohesive Forces in the Deposition of the Polymer (Adhesive) to the Fabric (Adherent) (Sanatgar, Campaigne, & Nierstrasz, 2017*)*.

2.2.1 Methods of Measuring Adhesion Force

Researchers have tested the printed fabric for adhesion using different methods. Pei, Shen, & Watling (2015) examined the quality of adhesion between the polymer and the fabric through visual and surface inspection. However, this method did not provide quantitative insights about the bond strength. In their research, Malengier, Hertleer, Cardon, & Van Langenhove (2017) used the perpendicular tensile test, the shear test and the peel test to characterise the adhesion of 3D printed shapes on different textile substrates. The tests were applied to determine if the differences in fabric construction had an influence on the adhesion properties. In the perpendicular test (see Figure 2.27) a pawn shaped object with a height of 24 mm was printed onto the fabric and both were clamped onto a tensile frame. The maximum force required to detach the object from the fabric was measured and recorded as the adhesion force. The shear test and peel test measured the maximum force required to detach a rectangular plate from a fabric. The sample is placed in the tensile frame with the lower clamp holding the textile and the upper clamp holding the printed plate (see Figure 2.28). The study concluded that the perpendicular tensile test was the best for the determination of overall adhesion strength as it is less likely to rupture the fabric before the test finishes (Malengier, Hertleer, Cardon, & Van Langenhove, 2017).

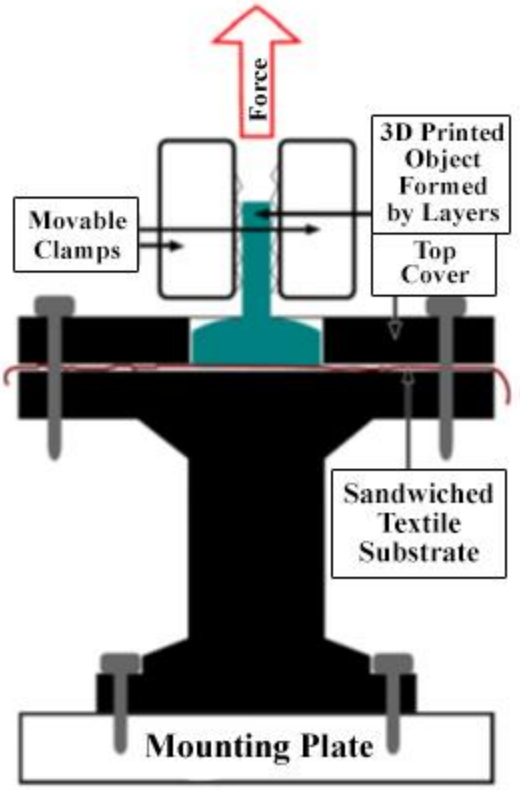

Figure 2.27 : Set-up of Perpendicular Test for Testing of Adhesion Force (Malengier, Hertleer, Cardon, & Van Langenhove, 2017).

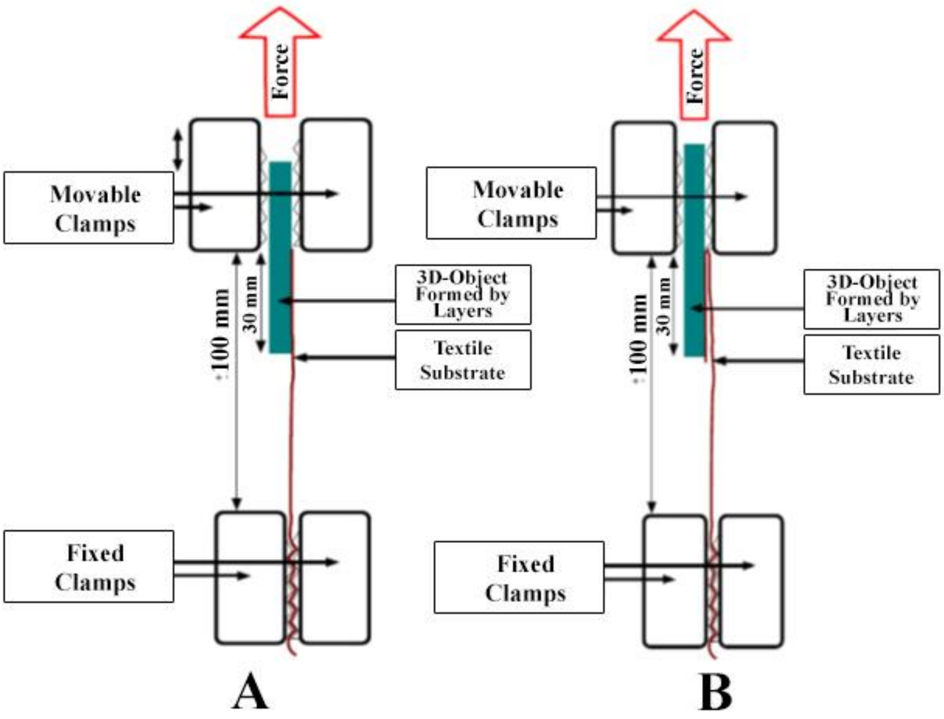

Figure 2.28 : Set-up of (A) Shear Test and (B) Peel Test for Testing of Adhesion Force (Malengier, Hertleer, Cardon, & Van Langenhove, 2017).

However, the perpendicular test is not suitable for very thin layers of polymer printed on the fabric as it would not be easy to attach it between the movable clamps. Researchers have therefore carried out adhesion tests according to standard test method ISO DN 53530 using a tensile tester, (Korger, et al., 2016; Sanatgar, et al., 2017). This method uses the principle of the peel test (Figure 2.28B) and allows for 3D printed objects of a height of less than 1 mm to be measured for adhesion force.

2.2.2 Effect of Fabric Properties on Adhesion Force

Studies of deposition of polymers onto different fabrics have shown that fabric parameters such as thickness, roughness and fabric density could have an effect on adhesion force (Sabantina, et al., 2015; Korger, et al., 2016; Malengier, et al., 2017). Textile structures have been observed to have a significant effect on adhesion force as shown in the adhesion of PLA to woven knitted and non-woven Tencel fabrics. The study showed that the knitted fabrics had the highest adhesion force to PLA (Burn, Vettese, & Shackleton, 2016). Different polymers have been printed on several woven fabrics with the conclusion that the adhesion was more dependent on the fabric than on the polymer used for printing (Korger, et al., 2016). The research also observed that if cotton is washed before printing the adhesion increases as it becomes more hydrophilic. On the other hand, when polyester fabrics were washed, they became more hydrophobic hence the reduction of wettability and surface energy. This led to a reduction in adhesion strength (Korger, et al., 2016).

Researchers have used different types of fabrics for direct deposition of polymers. Different structures were printed using ABS, PLA and nylon on eight different types of synthetic and man-made fabrics. The research showed that woven cotton, woven polywool and knit soy had excellent adhesion when the three polymers were deposited.

Among the three polymers, PLA showed the best results when printed on the eight different types of fabric with little warp, high quality of print and good flexural strength. The research also showed that the fabric with a rougher surface had better adhesion (Pei, Shen, & Watling, 2015).

Other studies have also shown that surface roughness has an effect on adhesion force with a small difference in surface roughness affecting the adhesion force (Cheng, Dunn, & Brach, 2002). Roughened or hairy fabrics and nets had better adhesion as observed in rough cotton, polyester net and wool samples. Thicker fabrics also have better adhesion. (Korger, et al., 2016; Sabantina, et al., 2015; Grimmelsmann, Kreuziger, Korger, Meissner, & Ehrmann, 2017). These results were based on visual observation of the surface roughness of the fabric. It is therefore necessary to carry out subjective or objective tests on the roughness of the fabrics to be able to give an accurate analysis of its effect on adhesion force.

A later study showed than PLA deposited on hairy textiles like wool proved to be unsuitable as a 3D printing substrate using FDM printing because during printing the protruding fibres were flattened by the nozzle and then returned to their original shape afterwards. In their research PLA was deposited on cotton fabrics with different weave patterns and weft densities. Their study showed that the weave pattern and the weft density influence adhesion of the polymer to the textile substrate, (Malengier, Hertleer, Cardon, & Van Langenhove, 2017).

In the deposition of polymers onto knitted fabrics the pore area, print area ratios, fabric characteristics are important factors in determining polymer-textile adhesion. Studies have shown that the adhesion between the polymer and the knitted fabric is controlled more significantly by mechanical effects than chemical. Particularly, a higher pore area gives better adhesion force (Narula, et al., 2018).

2.2.3 Effect of Varying 3D Printing Parameters on Adhesion

In a previous study researchers investigated the adhesion properties of direct 3D printing of polymers and nanocomposites on textiles by varying the printing process parameters. In their findings they concluded that varying different 3D printing parameters like platform temperature, printing speed and extrusion temperature can have significant effect on the adhesion force of polymers to textile fabrics in direct 3D printing (Sanatgar, Campaigne, & Nierstrasz, 2017). Another study also showed that 3D printing parameters like printing speed and extrusion temperature have a significant impact on the adhesion force while nozzle diameter and first layer height had no effect on adhesion force (Spahiu T. , Grimmelsmann, Ehrmann, Piperi, & Shehi, 2017). Work has been done on the deposition of polymers onto knitted fabrics and the results showed that there were differences in adhesion force for different distances from the printing nozzle (Döpke, Grimmelsmann, & Ehrmann, 2017). These studies however did not explore the influence of the different parameters on adhesion force when combined with other parameters. For the determination of the most appropriate parameters it is also important to establish the optimum settings for adhesion force.

2.2.4 Effect of Pretreatment and Post Treatment Fabric Processes on Adhesion

Pretreatment and post treatment processes have been shown to have an effect on the surface tension of the fibre and therefore altering the adhesion force (Holme, 1999). Sabantina et al (2015) did several tests using high temperature treatments to increase the adhesion strength of the printed fabric. They used a VEIT Kannegiesser fixation machine and a VEIT HP 2003 industrial steam iron. The combined pressure and temperature treatment enabled a slight increase in adhesion.

Research has also been done to study the effect of washing the 3D printed polymer/textile structure on the adhesion force. Although the research carried out by (Spahiu T. , Grimmelsmann, Ehrmann, Piperi, & Shehi, 2017) showed that washing had no effect on adhesion force, other studies have given different results. Martens & Ehrmann (2017) printed ABS objects on cotton and polyester woven fabrics and also on polyester knitted fabrics. After washing the objects stayed fixed but could be pulled apart by stronger mechanical forces as shown in Figure 2.29. After three washing cycles there were several broken and lost parts (see Figure 2.30). They also printed filaflex on knitted PES fabric and it was not altered after washing.

Figure 2.29 : ABS Objects Printed on Different Textile Fabrics after 1 Washing Cycle (Martens & Ehrmann, 2017).

Figure 2.30 : ABS Objects Printed on Different Textile Fabrics after 4 Washing Cycles (Martens & Ehrmann, 2017).

In another study of PLA printed on knitted polyester, washing of the fabric before printing reduced the adhesion force of the PLA to the fabric. This could have been attributed to the fact that the washing reduced the area of the pores through fabric relaxation thus reducing the amount of diffusion of the polymer into the fabric (Narula, et al., 2018).

Pre-treatment and post treatment processes have been shown to have an effect on adhesion force. These tests have been done through visual and haptic assessment and there have been no tests that produced quantitative results of adhesion force and hence achieve a detailed comparison of adhesion force with or without pre-treatments and post treatments.

2.3 CHARACTERISATION OF THE 3D PRINTED POLYMER/TEXTILE STRUCTURE

Tests that have been carried out on fabrics combined with 3D printed polymers include the Martindale abrasion test. A PLA model was printed on polyester net fabric and tested for abrasion according to standard ISO 12947-1. The pattern was not affected by the Martindale test but the polyester net fabric was destroyed. This showed that the connection between PLA and the fabric was stronger than the fabric itself (Sabantina, Kinzel, Ehrmann, & Finsterbusch, 2015).

Tests have been done to determine how 3D printing of PLA on polyester fabric affects the drape properties of the printed fabric. Different shapes were printed on the polyester fabric using a self-built drape tester according to the standard EN ISO 9073-9. A comparison was made between the drape of the pure textile fabric and the fabric printed with the 3D pattern (see Figure 2.31). The fabric drape was greatly affected by the 3D printed shapes.

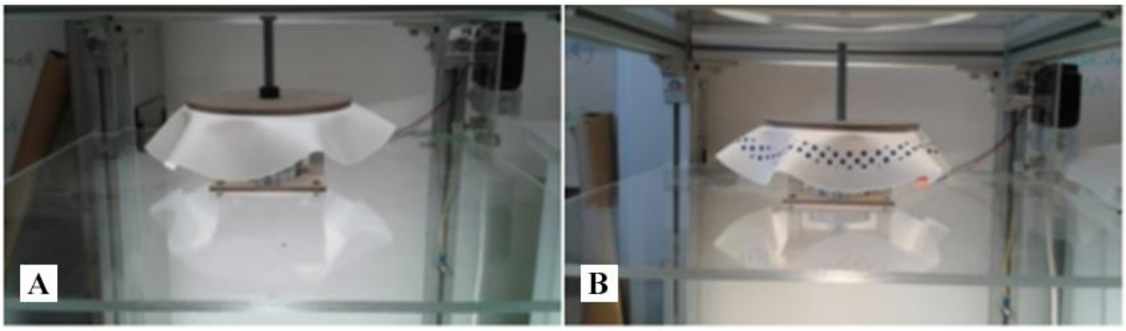

Figure 2.31 : Drape Test of (A) Pure Textile Fabric and (B) Fabric with a 3D-imprinted Pattern (Spahiu, et al., 2017).

Tests were also done on a flared skirt (see Figure 2.32). The drape profiles showed regular folds but differed in fold dimensions and numbers (Spahiu, et al., 2017).

Figure 2.32 : Flared Skirt with 3D Printed Patterns (Spahiu, et al., 2017).

The different tests carried out on the textile/polymer structures have shown that the deposition of polymers onto fabrics has an effect on the textile structure. The functionality of textile structures is affected by different properties such as air permeability, water absorption, tensile strength, bursting strength among other properties. It is therefore important to determine how the deposition of polymers onto fabrics affects these properties. However, there is no literature to show of any such tests being carried out on 3D printed polymer/ textile structures. Polymers have been coated onto textile fabrics for the production of coated fabrics. This has been shown to change the fabric properties such as bending rigidity, tensile strength, flexibility, tear strength, shearing and stretching and has thus shown the importance of such tests on polymer/textile structures (Ambroziak, 2015).

Tests have been done to determine the tensile strength of coated fabrics according to the standard ASTM D751 and the results have shown that the tensile strength is affected by the strength of the polymer that is used for coating the fabric (Masteikaite & Saceviciene, 2005). The tensile strength of 3D printed polymers has been studies and results have shown that 3D printing parameters such as layer height, shell thickness, printing speed have an effect of the tensile strength (Sukindar, Baharudin, Jaafar, & Ismail, 2017; Rajpurohit & Dave, 2018; Aw, et al., 2018). These studies therefore show the importance on mechanical tests to characterize the properties of the 3D printed polymer/ textile structures. They also show the importance of varying the 3D printing process parameters. More process parameters than the ones already studied could also be investigated to determine the required parameters for the desired properties.

2.4 SUMMARY OF KEY RESEARCH GAPS

The major challenge that has been observed in the deposition of polymers to fabrics is the adhesion of the polymer to the fabric. Studies have been done to improve the adhesion of polymers to fabric but the results have shown that there is still need for more research to achieve that. Research has been done to determine the fabric to polymer combinations with good adhesion force. However, these studies have looked at the use of different polymers on different fabric types and have not explored the deposition of one polymer onto different fabric types. These results make it difficult to determine how the fabric properties affect the adhesion force independent of the polymer type and the 3D printing parameters. Although research has been carried on the adhesion properties of different fabric to polymer combinations, no detailed study has been done on the effect of the different fabric properties on adhesion force.

The literature has shown the effects of varying 3D parameters on the adhesion force. These studies have looked at some and not all the 3D printing parameters. They have also not optimised the different 3D printing parameters for the optimum adhesion forces. Statistical analysis and optimization are therefore important to create models and to optimize adhesion force. Although studies have shown that mechanical properties are affected by the deposition of polymers onto fabrics as shown in coated textiles, there are however few mechanical tests that have been carried out to characterize the polymer/textile structures such as abrasion tests. Other tests such as tensile strength, shear strength, air permeability and bursting strength could also be carried out.

CHAPTER 3: EXPERIMENTAL METHODS

3.1 DIRECT DEPOSITION OF PLA ONTO WOVEN FABRICS

The direct deposition of polymer onto fabric was done in two phases: the preliminary tests to determine the best fabric for adhesion and the tests based on the experimental design to study the effect of printing parameters on the fabric. The direct deposition of the polymer onto the fabric began with the customization of the design for the 3D printing process. The next stage was the setting up of the Athena 3D printer. The fabric for printing was then laid on the 3D printer for printing.

3.1.1 Customization of Design for 3D Printing

The model for 3D printing was designed using Solid Works design software and then converted to STL format. The design was a rectangle which had a length 150 mm and a width 25 mm. The design was then customized for 3D printing according to a method outlined by Jennings (2017). The design was transferred to the Cura Software where the STL file was translated into a format that the printer understood. The file was sliced into layers for the 3D printing process and *Cura* worked out how those layers would be placed onto the print bed. The printing parameters were edited according to the requirements of the final model to be printed as shown in *Cura* Software interface in Figure 3.1. Once all the settings were prepared the file was saved as a G-code ready for printing. The G-code is a set of instructions for the printer to follow for every layer and is saved as a *.gcode* file.

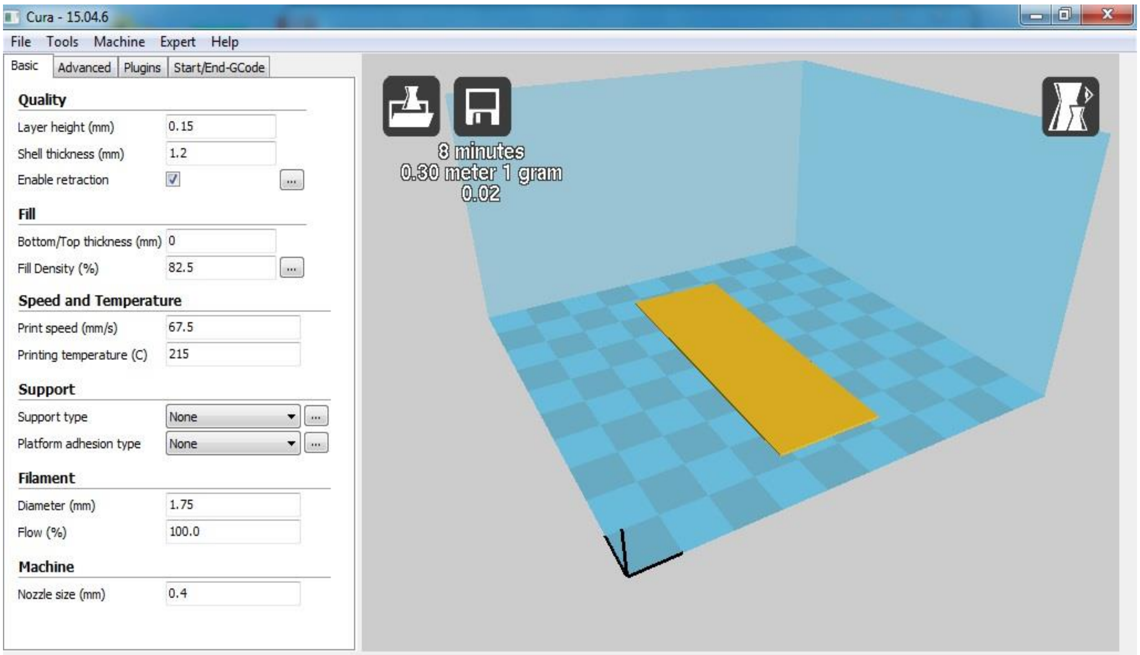

Figure 3.1 : *Cura* Software Interface for Slicing the Model for 3D Printing.

3.1.2 Setting up of the 3D Printer

The setting up of the printer involved loading the *.gcode* file to the software for 3D printing and inserting the filament into the 3D printer. The machine used for the 3D printing process was the Athena 3D printer which uses the Fused Deposition Modelling (FDM) 3D printing technique. The front and top view of the Athena 3D printer are shown in Figure 3.2. The PLA filament is supplied in spool form to the extruder through the Poly Tetra Fluoro Ethylene (PTFE) tubing. The pushing of the filament into the extruder is controlled by the motor. The printer works with the Franklin Software (Wijnen B. , 2015).

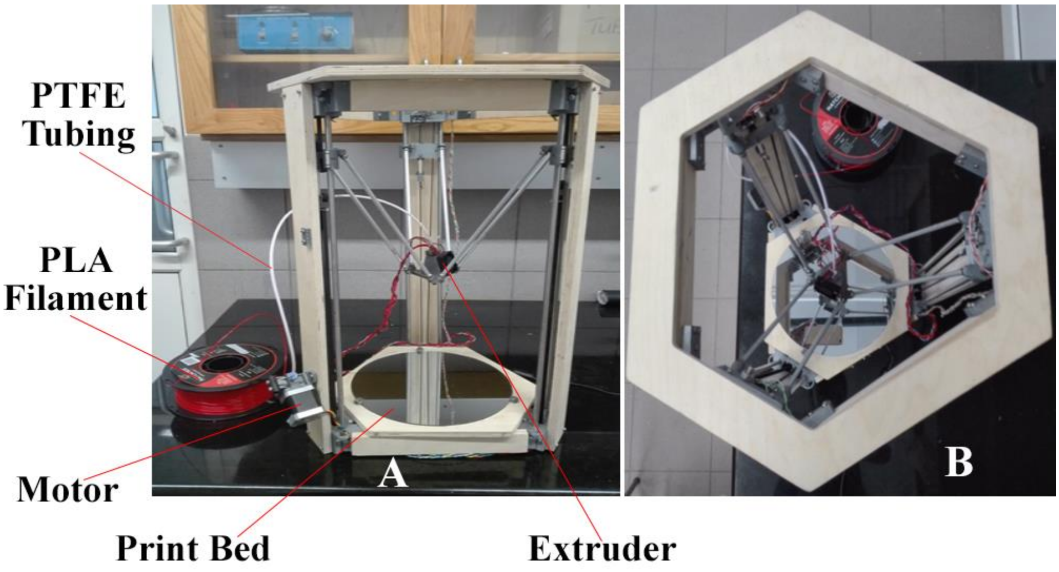

Figure 3.2 : Athena 3D Printer/ (A) Front View and (B) Top View.

The polymer used for the 3D printing process was Polylactic acid (PLA) and was acquired from Hatchbox, United States of America. The filament was purchased from the company's online shop at http://hatchbox3d.com. The filament was red in colour and had the properties shown in Table 3.1.

Table 3.1 : Properties of PLA Filament.

Property	Value
Elongation at break	4%
Tensile Modulus	1968 MPa
Diameter	1.75 mm
Extruder Temperature Range	180°C - 210°C
Melting Temperature	155°C
Density	1.27 g/cm^3
Solubility in water	Insoluble

The computer used for 3D printing was connected to the 3D printer using an ethernet cable. The computer had to have an internet connection to set up the Franklin Software for controlling the 3D printer on the computer. This was set up from the webpage, http://192.168.76.2:8000/admin. A web page with the Franklin software appeared on the computer screen for the operation of the 3D printer (see Figure 3.3). The filament was then inserted into the 3D printer ready for printing using the Franklin software. This was done by increasing the recorded length in the extrude text box and pushing the filament into the extruder. This was done continuously until the motor made a grinding sound, the sound indicated that the filament was now fully loaded onto the machine (Wijnen B. , 2015).

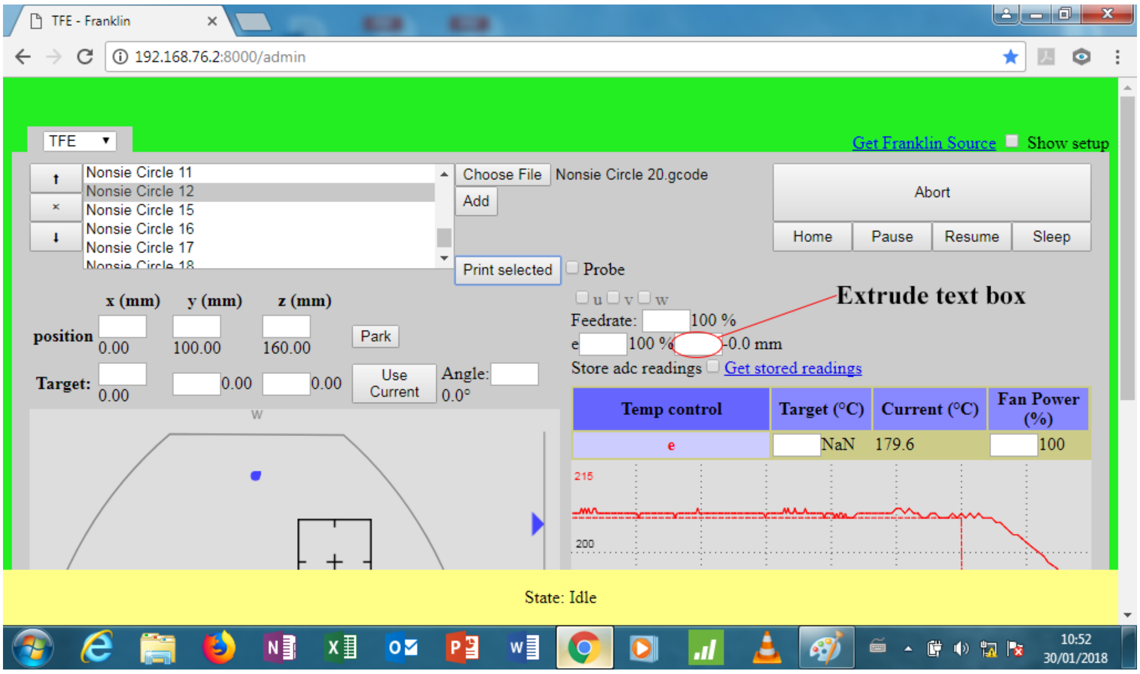

Figure 3.3 : Franklin Software Interface for Controlling 3D Printing.

3.1.3 Deposition of PLA onto Different Fabric Samples

The purpose of the preliminary tests was to determine the fabric with the highest adhesion force to PLA from a set of available fabrics. The PLA polymer and the 3D printing parameters were kept constant while the fabrics were varied. Statistical analysis was also done to ascertain the effect of the different fabric properties on adhesion force.

3.1.3.1 Fabric Selection

The fabric parameters can have an effect on the mechanical interlocking and the diffusion of the polymer into the fabric and hence affect adhesion. To be able to study the effect of fabric parameters on adhesion force; fifteen commonly used woven fabric samples (see Figure 3.4) were purchased from Fabrix and Zimbabwe Spinners and Weavers in Bulawayo, Zimbabwe. The fabrics differed in areal density, thickness, roughness, fabric weave density, yarn tex and fibre type. Tests were done to quantify the different parameters of the fabrics.

Figure 3.4 : Woven Fabric Samples for Preliminary 3D Printing.

3.1.3.2 Procedures for the Determination of Fabric Properties

The fabric weight of the fabric samples was tested according to ASTM D3776, Standard test method for mass per unit area (areal density) of fabric. The fabrics were conditioned and the length and width of each sample were measured. The samples were weighed in grams on a balance to the nearest 0.1% of the mass. The fabric weight was then calculated and recorded in grams per square metre (g/m^2).

The fabric weave density refers to the ends per inch and the picks per inch of the fabric. The ends per inch is the number of warp yarns per inch of woven fabric. The picks per inch is the number of weft yarns per inch of woven fabric. This was measured using a counting glass at different places according to the ASTM D3775 standard. The mean values were calculated and recorded in ends per inch and picks per inch.

Yarn tex is defined as the weight in grams of 1000 m. To measure the tex a strip of the fabric sample was cut to a length of 5 cm. A number of threads were then removed from the fabric sample. All the threads of one sample were weighed together on a sensitive balance and from their total length and total weight the linear density was calculated according to the ASTM D1059-01 standard. This procedure was repeated for all the fabric samples.

The thickness of the fabric sample was measured according to test standard ASTM D1777, Standard test method for thickness of textile materials. The fabric samples were each placed on the base of a thickness gauge and a weighed presser foot lowered. The displacement between the base and the presser foot was measured as the thickness of the specimen. The thickness was recorded in millimetres.

The fabric handle was measured using the subjective assessment of fabric handle as described by Kawabata & Niwa (1989). This method was also used by Tuigong & Xin (2005) in the assessment of commercial fabrics. In their research their panelists had some background textile knowledge and were first trained respondents prior to testing. Tomovska, Jordera, & Zafirova (2016) used the same method to determine the perception of different assessors on the contributions of different texture properties of knitted fabrics to their aesthetic properties. In this study a total of 6 male and 6 female postgraduate students were trained for the subjective testing method. The panellists were selected from individuals who use textile fabrics on a day to day basis. They were experts in different non-textile fields and were from different countries (Table 3.2).

Table 3.2 : Details of Subjective Assessment Panellists.

Gender	Nationality	Area of Specialization	Current Level of Study
Female	Kenya	Publishing	Masters
Female	Uganda	Library and Info Science	Masters
Female	Kenya	Media Studies	Masters
Female	Kenya	Publishing	Masters
Female	Tanzania	Sociology	PhD
Female	Tanzania	Linguistics	PhD
Male	Burundi	Economics	Masters
Male	Bangladesh	Information Technology	Masters
Male	Burundi	Linguistics	PhD
Male	Rwanda	Technology Education	PhD
Male	Burundi	Information Technology	Masters
Male	Zambia	Energy Studies	Masters

In the subjective assessment of fabric handle, the assessor usually strokes the fabric with one or several fingers and then squashes the fabric gently in the hand. The assessments are based on the sensations of smoothness or roughness, hardness or softness as well as stiffness or limpness (Hu, 2008). The terms smoothness and roughness were explained to the panellists in detail before they began the assessment. They were also trained on how to handle and stroke the fabric. They were then able to judge the fabrics based on the sensations of smoothness or roughness. Their eyes were covered to ensure that judgement was not based on visual observation but entirely on the feel of the fabric on the hand (see Figure 3.5). They each had to grade the fabric on a scale of 1 to 5 where 1 was for a smooth fabric and 5 for a rough fabric. The average readings of the different fabrics were recorded.

Figure 3.5 : Subjective Assessment of Fabric Handle.

The fibre type was analysed according to standard AATCC20. Several tests were carried out until it was possible to make a satisfactory judgement on the fibre type. The tests that were carried out were the burning tests, microscopical examination and the solvent tests.

3.1.3.3 Fused Deposition Modelling Printing Set-Up

The randomly selected fabric samples were used for the preliminary tests to determine the fabric with the highest adhesion force for use in the main experiment. The different samples were prepared as shown in Figure 3.6A. The 3D printer and the fabric were set up according to the method used by Pei et al, (2015). The fabric sample was laid on the print bed and secured with clips to enable the direct deposition of the polymer on the fabric as shown in Figure 3.6B.

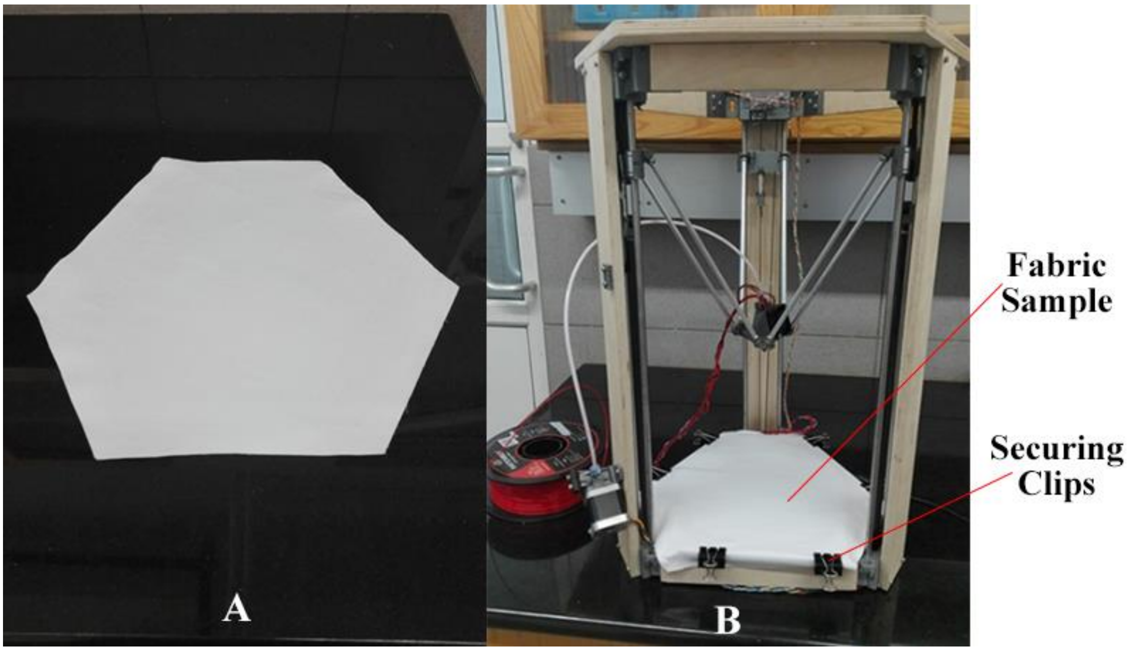

Figure 3.6 : (A) Preparation of the Fabric Sample for 3D printing, (B) Fabric Sample Attached to the 3D Print Bed with Securing Clips.

The purpose of this investigation was to keep the polymer and the printing parameters constant while varying the fabric structures and properties. For all prints the settings were maintained as shown in Table 3.3.

Table 3.3 : 3D Printing Parameters

Printing Parameter	Value
Layer Height	0.15 mm
Enable retraction	Yes
Support type	None
Platform adhesion type	None
Filament diameter	1.75 mm
Filament flow	100%
Nozzle size	0.4 mm
Fill density	65%
Printing speed	50 mm/s
Printing temperature	200°C
Model height	0.4 mm

3.1.3.4 3D Printing Procedure

After laying the fabric and securing it with clips on the print bed, the printing process was set to begin. The selection of files for printing and all other printing commands were performed on the Franklin software. The *.gcode* file from *Cura* was selected for printing by highlighting it and then clicking on the ‘Print selected’ button. Once selection was done the 3D printer began to heat and once it reached the printing temperature, printing began. During printing, the movement of the nozzle, the temperature and the printing time were shown on the computer screen. When the printing process was completed the ‘Home’ button was pressed to ensure that the nozzle returned to its original position and for easy removal of the printed model. The printed sample was then removed and the next fabric sample was prepared for printing. This procedure was repeated until 3D printing was performed on all the fabric samples.

3.1.3.5 Determination of Adhesion Force

The adhesion tests were carried out using the Testometric Micro 500 model tensile tester according to the standard DIN 53530. At one end of the composite the fabric and the PLA were separated to allow for them to be clamped on the Testometric Micro 500 model tensile tester. The sample was clamped onto the machine with the lower clamp holding the printed rectangle and the upper clamp holding the fabric sample (see Figure 3.7). During the test the upper clamps moved away from the fixed lower clamps at a separation speed of 100mm/min. The machine measured the maximum force applied before the specimen was destroyed. The adhesion force was then recorded.

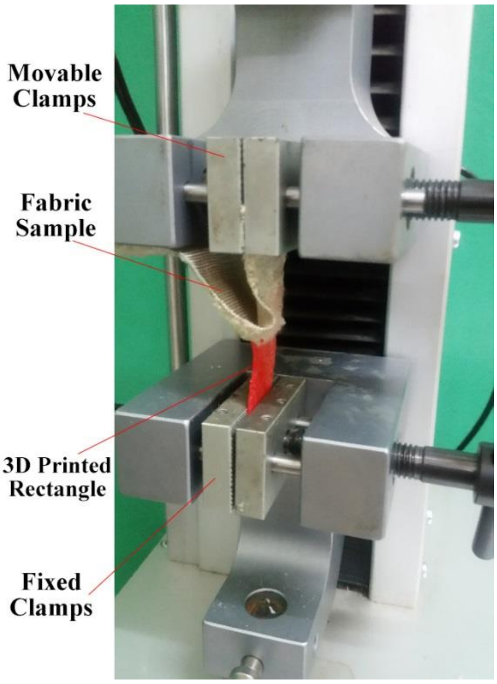

Figure 3.7 : Adhesion Test on the Testometric Micro 500 Model Tensile Tester.

3.2 STATISTICAL DESIGN OF EXPERIMENTS

The preliminary adhesion tests were done to study the effects of the fabric properties on the adhesion force and also to determine the fabric sample that exhibited the highest adhesion force to PLA. Sample 15 had the highest adhesion force to PLA and was therefore selected for the 3D printing process. In this experiment a four-factor inscribed central composite design was used to identify the relationship existing between the response functions and the process variables as well as to determine those conditions that optimised the responses. The central composite design (CCD) of experiments is a response surface method that uses a combination of statistical and mathematical methods to choose the best experimental methods to maximally reduce the number of experiments (Cavazzuti, 2013). In CCD the factors are tested at a minimum of three levels, that is, minimum, middle and maximum and are coded as – 1, 0 and 1. For a rotatable design, each experimental factor must be represented at the five levels of coded units, that is, - α, - 1, 0, 1, α (Table 3.4). This property ensures constant variance at points that are equidistant from the centre point and therefore provides equal precision of response estimation in any direction of the design (Montgomery, 2013). The value of α is calculated as shown in Equation 3.1.

$$\alpha = (2^k)^{0.25} = (2^4)^{0.25} = 2 \qquad \text{Equation 3.1}$$

Where, k is the number of factors.

The number of factors (k) is 4 hence an alpha (α) value of 2 was obtained. The independent variables studied were extrusion temperature, printing speed, fill density and model height. The extrusion of temperature range of PLA is between 190 °C and 220 °C (Ajioka, Enomoto, Suzuki, & Yamaguchi, 1995). Studies have however showed that adhesion of PLA to fabrics is weak at temperatures less than 200 °C (Korger, et al., 2016; Sabantina, Kinzel, Ehrmann, & Finsterbusch, 2015). In this study a temperature range of 200 °C to 220 °C was used. Previous research has shown that the effect of printing speed is significant at speeds of between 30 mm/s and 80 mm/s, therafter the results did not show a significant change in adhesion force (Sanatgar, Campaigne, & Nierstrasz, 2017). This printing speed range was therefore used for this study. For good quality prints in FDM, a fill density of above 30 % is recommended, therefore the range for this study was 30 % to 100 % (Jennings, 2017).

Table 3.4 : Factors and Levels for 3D printing Process.

Factors		Levels				
		-α	Low	Medium	High	+α
Coding		-2	-1	0	1	2
Extrusion Temperature (°C)	X_1	200	205	210	215	220
Extrusion Speed (mm/s)	X_2	30	42.5	55	67.5	80
Fill Density (%)	X_3	30	47.5	65	82.5	100
Model Height (mm)	X_4	0.3	0.35	0.4	0.45	0.5

Experimental responses of adhesion force before washing, adhesion force after washing and tensile strength were considered using regression analysis to predict the optimum and interaction effects. A randomized design created in the Minitab Software was used for the 3D printing. The design of experiments had 31 runs with 7 centre points as shown in Appendix A.

Optimal data values and sample points were generated with predicted response values closest to the optimal solution. The Analysis of Variance (ANOVA) and Variance Inflation Factors (VIF) were recorded and used to ensure the accuracy as well as the statistical significance of the model.

3.3 CHARACTERISATION OF MECHANICAL PROPERTIES OF THE 3D PRINTED PLA/TEXTILE STRUCTURE

The printed fabric was tested to determine its tensile strength, adhesion force before washing and adhesion force after washing.

3.3.1 Tensile Test

The tensile test was carried out using a Testometric Micro 500 model universal tensile tester. The test was carried out according to standard ASTM D751. The samples were preconditioned to standard atmospheric conditions. The fabric sample was then cut into a rectangle with the longer side parallel to the direction that is to be tested. This was done by cutting off the fabric parts around the 3D printed polymer and ensuring that the only parts that remained were those of the composite as shown in Figure 3.8. The sample was aligned into the grips and then loaded and secured into a pair of clamps. The speed of the testing was set at 100mm/min. The machine was then started with the fabric sample extended to break. The test was stopped as soon as the specimen broke. After the breaking of the specimen the results were saved on the computer and the machine returned to the starting position. The breaking force was recorded.

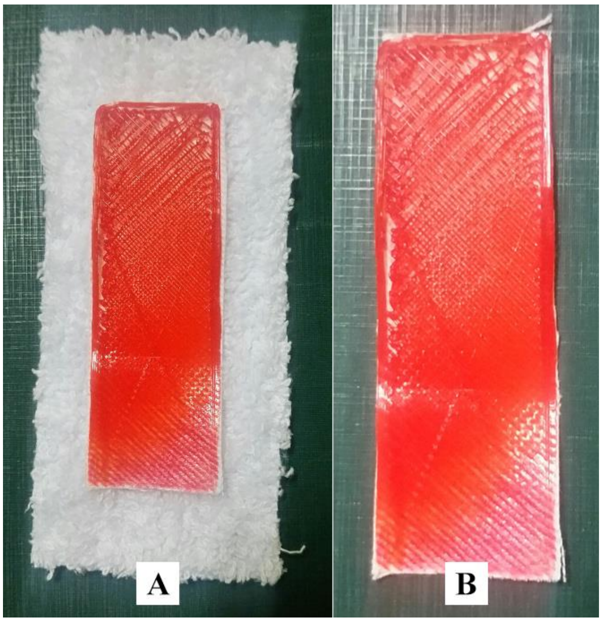

Figure 3.8 : PLA/Cotton Structure, (A) Before Cutting out the Fabric Parts Around the Composite and (B) Prepared for Loading on the Tensile Tester.

3.3.2 Adhesion Test

The adhesion tests were carried out using the Testometric Micro 500 model tensile tester according to the standard DIN 53530. At one end of the composite the samples were separated to allow for clamping them in the sample holders on the Testometric Micro 500 model tensile tester. The speed of separation was set at 100mm/min. The machine was started and was stopped as soon as the polymer and the fabric separated. The adhesion force was then recorded.

3.3.3 Adhesion Test After Washing

Washing was done using a M228 Rotawash according to the method outlined in standard ISO 105 C01. The composite samples were placed in steel containers with water and detergent (see Figure 3.9).

Figure 3.9 : Preparation of Composite Sample in the Steel Container for Washing.

The steel containers were then tightly closed and placed in the machine as shown in Figure 3.10. The machine was operated at a temperature of 40°C for 30 minutes. The shaft/container assemble was rotated at a speed of 40 ± 2 r/min.


Fig. 3.10 : Setting of the Steel Containers in the M228 Rotawash.

The samples were rinsed and excess water was extracted by squeezing them by hand. The samples were then air dried at room temperature. Adhesion tests were carried out on the washed samples as outlined in section 3.3.2.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 EFFECT OF FABRIC PROPERTIES ON ADHESION FORCE

The 15 woven fabric samples were characterized in terms of areal density, warp density and weft density, warp and weft count, fabric handle, fabric thickness and fibre type. Table 4.1 gives a summary of the measured properties of the fabric samples.

Table 4.1 : Properties of the Studied Fabric Samples.

SN	Areal Density (Gsm) X_a	Ends/ Inch X_b	Picks/ Inch X_c	Warp Tex X_d	Weft Tex X_e	Fabric Thickness (mm) X_f	Fabric Handle X_g	Fibre Type X_h
1	210.4	46	52	73	17	0.04	3.2	Polyester
2	218.4	32	111	50	10	0.003	1.7	Polyester
3	227.6	69	80	19	59	0.002	2.7	Cotton
4	126.0	48	68	26	31	0.002	2.7	Cotton
5	146.0	60	68	28	32	0.002	2.2	Cotton
6	246.8	75	54	20	72	0.04	3.0	Polyester
7	137.6	50	64	33	30	0.002	3.3	Cotton
8	132.4	22	25	75	72	0.03	4.5	Cotton
9	224.8	49	55	63	59	0.004	2.7	Polyester/Cotton
10	332.4	17	15	288	276	0.1	5.0	Acrylic
11	451.2	20	20	277	280	0.09	5.0	Acrylic
12	536.0	28	77	336	29	0.18	4.3	Acrylic
13	128.8	59	22	25	71	0.08	1.0	Cotton
14	282.3	42	32	60	42	0.12	2.5	Acrylic
15	355.2	24	38	50	37	0.19	3.3	Cotton

4.1.1 Effect of Areal Density on Adhesion Force

A second order model was formulated to predict the effect of fabric weight on adhesion force. Equation 4.1 gives the fitted regression model that described the relationship between adhesion force (Y_A) and areal density (X_a).

$$Y_A = 38.13 - 0.1914X_a + 0.000491(X_a)^2 \qquad \text{Equation 4.1}$$

The effect of areal density on adhesion force of PLA onto fabrics was also represented graphically in Figure 4.1. The coefficient of determination (R^2) was 0.7997 and the P value of 0.002 was less than 0.05 hence the model was significant. The relationship between adhesion force and areal density was therefore statistically significant and can be used to study the effect of areal density on the adhesion force. From the regression equation, after 200GSM the higher the areal density the higher the adhesion between the fabric and the PLA polymer. This may be due to the large contact area for bonding.

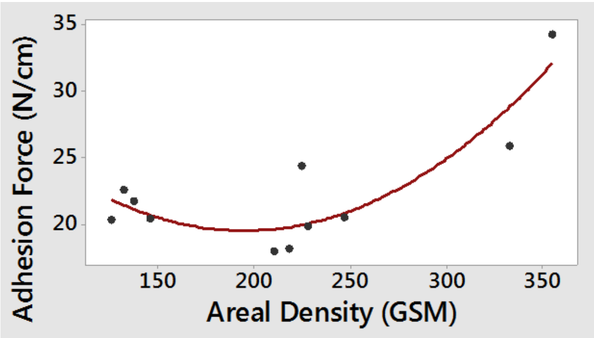

Figure 4.1 : Effect of Areal Density on Adhesion Force.

4.1.2 Effect of Ends/Inch and Picks/Inch on Adhesion Force

The effects of ends/inch (X_b) and picks/inch (X_c) on adhesion exhibited similar trends (Figure 4:2 and 4:3), where the adhesion force decreased as the ends and picks increased as shown in Equations 4.2 and 4.3.

$$Y_A = 26.74 - 0.09985X_b \qquad \text{Equation 4.2}$$

$$Y_A = 26.65 - 0.08240X_c \qquad \text{Equation 4.3}$$

The R^2 values for the ends/inch and picks/inch were 0.7303 and 0.7655 respectively.

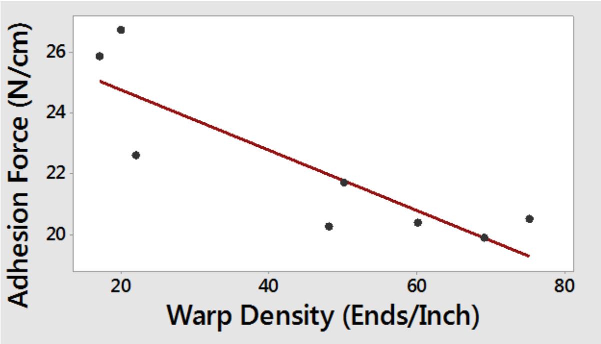

Figure 4.2 : Effect of Ends/Inch on Adhesion Force.

The two regression models also reported negative correlation with adhesion force of -0.86, which indicates that ends/inch and picks/inch are negatively correlated to adhesion force. This could be due to the fact that as the warp and weft density increases the fabric cover factor reduces. An increase in cloth cover factor reduces fabric pores and there is less diffusion of the polymer into the fabric. This reduces adhesion force. On the other hand, as the warp and weft density decrease there are more pores which allow the polymer to diffuse into the fabric. In their study Sabantina, Kinzel, Ehrmann, & Finsterbusch, (2015) concluded that fabrics with a lower warp and weft density had higher adhesion forces as seen in the adhesion force of PLA and open textile structures. This could be because of the increased mechanical connection generated by the PLA surrounding the single yarns. The results are also in line with those from other studies that revealed that an increase in ends and picks per inch reduced the adhesion force between the polymer and the textile fabric (Rivera, Moukperian, Ashbrook, Mankoff, & Hudson, 2017; Malengier, Hertleer, Cardon, & Van Langenhove, 2017).

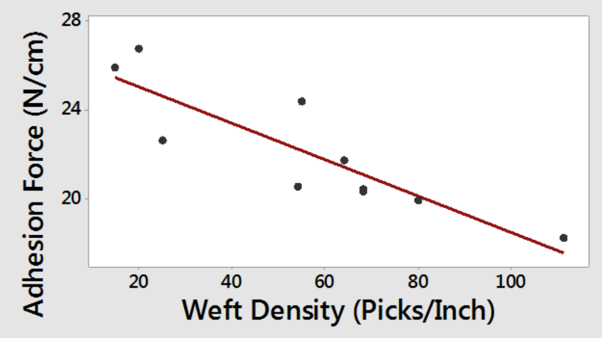

Figure 4.3 : Effect of Picks/Inch on Adhesion Force.

4.1.3 Effect of Warp and Weft Count on Adhesion Force

The effect of warp count (X_d) and weft count (X_e) measured using the Tex system, on adhesion force is given in Equations 4.4 and 4.5.

$$Y_A = 19.64 + 0.02373X_d \qquad \text{Equation 4.4}$$

$$Y_A = 17.50 + 0.09087X_e \qquad \text{Equation 4.5}$$

The effect of warp and weft count on adhesion force was also presented using graphs in Figures 4.4 and 4.5. The value of R^2 for warp and weft count were 0.7284 and 0.765 respectively, with both properties recording a positive correlation of over 0.8 with adhesion force.

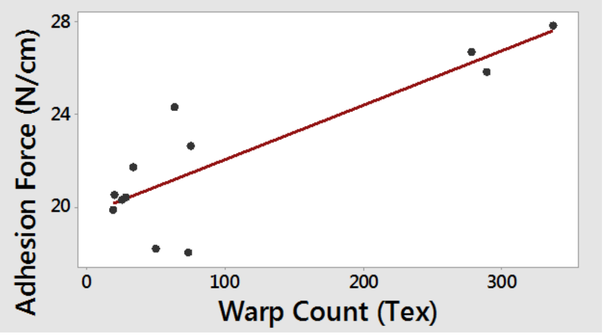

Figure 4.4 : Effect of Warp Count on Adhesion Force.

This could be an indication that an increase of warp and weft count increase yarn diameter hence increase the surface area where the polymer attaches to the fabric. These results are similar to those deduced by Sanatgar, Cayla, Campagne, & Nierstrasz (2017).

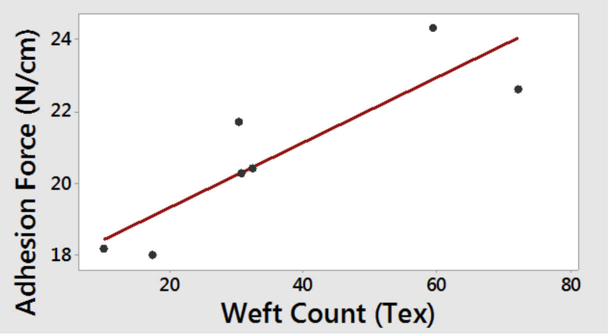

Figure 4.5 : Effect of Weft Count on Adhesion Force.

4.1.4 Effect of Fabric Thickness on Adhesion Force

A linear regression model was formulated to predict the effect of fabric thickness on adhesion force. Equation 4.6 describes the relationship between adhesion force (Y_A) and fabric thickness (X_f) as follows:

$$Y_A = 20.24 + 59.61X_f \qquad \text{Equation 4.6}$$

The value of R^2 was 0.8349 and the P value of 0.002 was less than 0.05 therefore the relationship between adhesion force and fabric thickness was statistically significant.

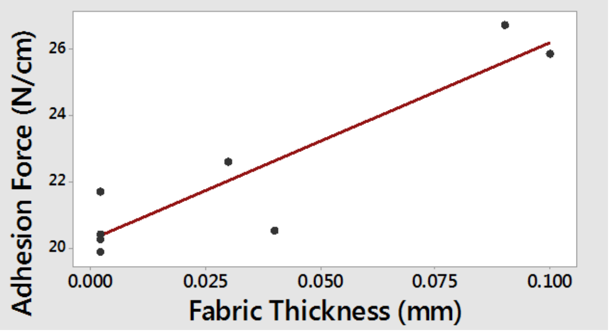

Figure 4.6 : Effect of Fabric Thickness on Adhesion Force.

The positive correlation of 0.91 indicates that when fabric thickness increases, adhesion force also tends to increase. Several studies have shown that adhesion force increases with an increase in fabric thickness (Korger, et al., 2016; Grimmelsmann, Kreuziger, Korger, Meissner, & Ehrmann, 2017; Martens & Ehrmann, 2017). A thicker fabric allows for deeper penetration hence leading to an increase of adhesion force as the fabric thickness increases. This also increases the connections inside textile structure offering sufficient areas for the polymer to penetrate inside the fabric.

4.1.5 Effect of Fabric Handle on Adhesion Force

A linear regression model was formulated to predict the effect of fabric handle on adhesion force. Equation 4.7 gives the quadratic model that describes the relationship between adhesion force (Y_A) and fabric handle (X_g).

$$Y_A = 14.43 + 2.315X_g \qquad \text{Equation 4.7}$$

The value of R^2 was 0.6029 and the P value of 0.003 was less than 0.05 therefore the relationship between adhesion force and fabric thickness was statistically significant.

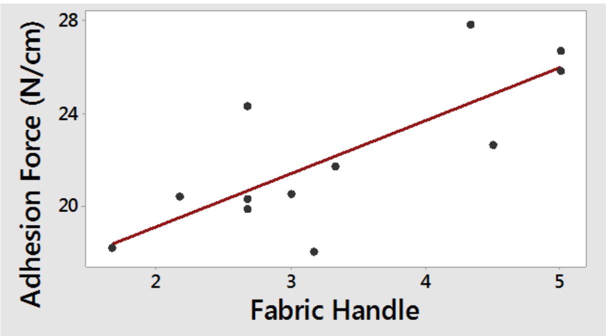

Figure 4.7 : Effect of Fabric Handle on Adhesion Force.

The positive correlation of 0.78 indicates that when fabric roughness increases, adhesion force also tends to increase as shown in Figure 4:7. Rougher fabrics have higher adhesion force due to the free-standing fibres that allow for an increase in mechanical interlocking between the polymer and the fabric. Researchers have also shown in their studies that rougher fabrics have higher adhesion force to polymers which agrees with these results (Pei, Shen, & Watling, 2015; Korger, et al., 2016).

4.1.6 Effect of Fibre Type on Adhesion Force

The results of the fibre tests showed that the fabrics had the following fibre types: Polyester (PET), Cotton, Acrylic and Polyester/Cotton blend. The average adhesion force for each fibre type was calculated, recorded and represented graphically in Figure 4:8. The graph showed that acrylic exhibited the highest adhesion force to PLA while polyester had the lowest adhesion force to PLA. Adhesion force has been observed to be affected by fibre type. In previous studies there have been no tests on acrylic but the adhesion force of polymers to polyester has been shown to be less than that of polymers to cotton (Martens & Ehrmann, 2017; Rivera, Moukperian, Ashbrook, Mankoff, & Hudson, 2017).

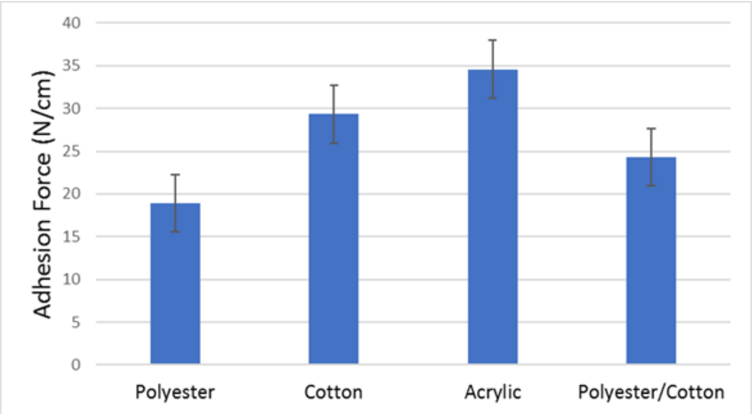

Figure 4.8 : Effect of Fibre Type on Adhesion Force.

4.2 3D PRINTING OF PLA ONTO WOVEN FABRICS

The tests to determine fabric properties affecting adhesion force showed that Sample 15 had the highest adhesion force. The sample was therefore used for the tests to study the effect of extrusion temperature, printing speed, fill density and model thickness on the adhesion force before and after washing. The fabric characteristics of the sample were as follows: 24 ends/inch, 38 picks/inch, 50 tex warp count, 37 tex weft count, 355.2 GSM and a thickness of 0.19 mm. Tests to determine the tensile strength of the printed fabric were also carried out.

4.3 CHARACTERISATION OF THE PLA/COTTON STRUCTURES

Statistical methods were used for the characterization and optimization of the mechanical properties of the printed fabrics. The mechanical properties (adhesion force before washing, adhesion force after washing and tensile strength) were taken as the response of the system while the four process parameters (extrusion temperature, printing speed, fill density, model height) were taken as input independent variables. The effects of extrusion temperature (X_1), printing speed (X_2), fill density (X_3) and model height (X_4) on the adhesion force before washing (Y_A), tensile strength (Y_T) and adhesion force after washing (Y_{AW}) were determined. These factors were monitored for the optimization of the mechanical properties.

A regression analysis was done for the relationship between the X and Y values. The result indicated that all the regression models were statistically significant with a P value of <0.05. The R^2 values were 0.7473 for adhesion force before washing, 0.7513 for adhesion force after washing and 0.9406 for tensile strength. R^2 shows how much the change in an independent variable affects the dependent variable.

4.3.1 Adhesion Force (Y_A) of the Printed Fabrics Before Washing

The adhesion force regression model (Y_A) shown in Equation 4.8 had an R^2 value of 0.7473. The ANOVA gave a P-value of 0.000 for the general model which was less than the Alpha (α) value ($P < 0.05$) and was therefore a significant model.

$$Y_A = -1054 + 4.113X_1 + 14.05X_2 + 864X_4 - 0.01737X_2X_2 - 1048X_4X_4 - 0.0584X_1X_2$$

Equation 4.8

The regression analysis showed that extrusion temperature (X_1), extrusion speed (X_2) and model height (X_4) had an effect on adhesion force while fill density had no significant effect thus it is not captured in the model.

The ANOVA, factor contributions and Variance Inflation Factors (VIF) for the adhesion force are shown in Table 4.2. The percentage contribution of the factors showed that extrusion temperature contributed 35.62% to the model for adhesion force while printing speed contributed 2.28% and model height 1.58%. The extrusion temperature X_1 had the highest percentage contribution of 35.62% while the combined effects of extrusion temperature X_1 and printing speed X_2 had the second highest contribution of 13.01%. The P values for the estimated coefficients, curvilinear and interaction effects were less than 0.05 and were therefore significant in the model.

Table 4.2 : ANOVA, Factor Contributions (FC%) and VIF for Adhesion Force

Source	ANOVA (P-Value)	FC (%)	VIF
Regression	0.000	74.73	
X1	0.000	35.62	1.00
X2	0.022	2.28	1.01
X4	0.029	1.58	1.01
X2*X2	0.003	10.02	1.02
X4*X4	0.004	12.21	1.02
X1*X2	0.004	13.01	1.00
Error		25.27	
Lack-of-fit	0.918	12.96	
Pure Error		12.31	
Total		**100.00**	

The combined effect of extrusion temperature and printing speed showed that as the temperature increased and the printing speed decreased there was an increase in the mean of adhesion force (see Figure 4:9).

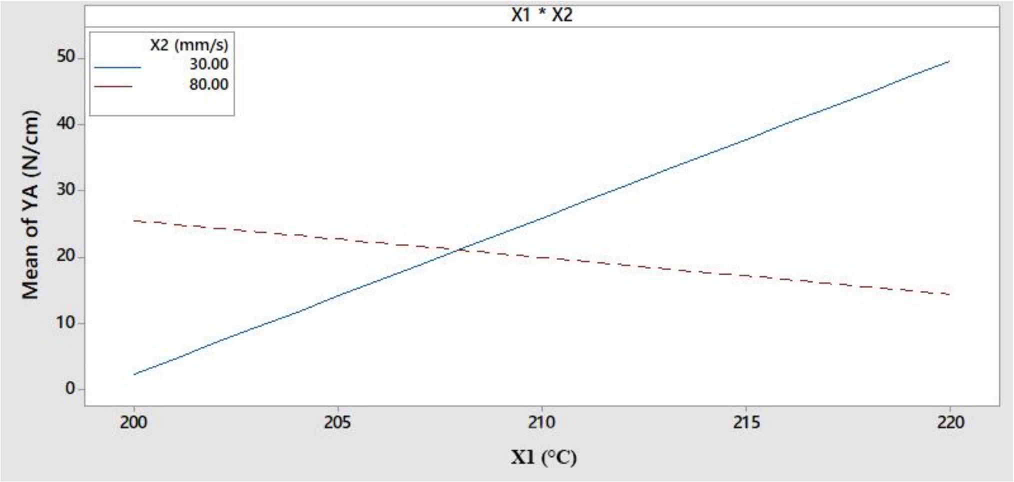

Figure 4.9: Combined Effect of Extrusion Temperature and Printing Speed.

The normal probability plot of residuals for adhesion force (see Figure 4.10) shows that the data points were normally distributed.

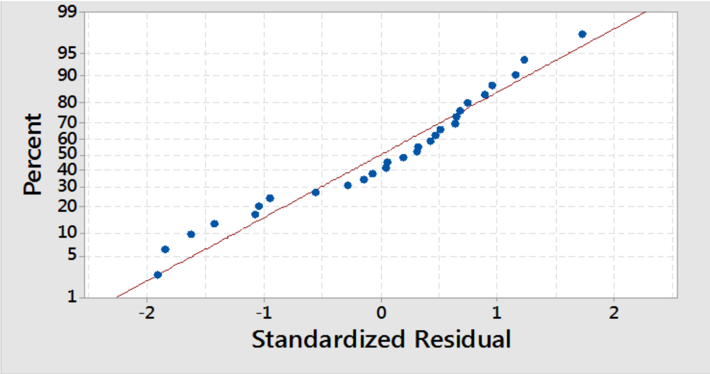

Figure 4.10 : The Normal Probability Plot for Adhesion Force.

The regression model was used to predict the optimal settings for a maximized adhesion force shown in Table 4.3. The optimal settings obtained were; extrusion temperature (X_1) of 220 °C, printing speed (X_2) of 34.55 mm/s and a model height (X_4) of 0.41 mm and a predicted adhesion force (Y_A) of 50.06 N/cm.

Table 4.3 : Predicted Values and Optimal Settings for Adhesion Force.

Goal: Maximized Adhesion (N/cm)		Solution: Optimal Settings
Predicted Adhesion Force (N/cm)	50.06	X_1 = 220.00°C
95% Predicted Interval	(37.05, 63.07)	X_2 = 34.55 mm/s
		X_4 = 0.411mm

X_1 = Extrusion Temperature *X_2 = Printing Speed* *X_4 = Model Height*

The top five values closest to the predicted optimum settings for adhesion force (Table 4.4) were also considered in case the optimum settings were not practicable.

Table 4.4 : Values Closest to the Predicted Optimum Settings for Adhesion Force.

X1(°C)	X2 (mm/s)	X4 (mm)	Predicted YA (N/cm)
220	55	0.4	42.7830
215	42.5	0.45	39.3309
215	42.5	0.35	36.8322
210	55	0.4	33.7513
215	67.5	0.45	29.0334

The optimum settings yielded maximum extrusion temperature of 220°C. An increase in extrusion temperature resulted in an increase in adhesion force (Figure 4.12). This is in line with the general trend in previous studies that shows that an increase in temperature leads to an increase in adhesion force. This is explained by the reduced viscosity of PLA at higher temperatures which then allows the polymer to penetrate deeper into the woven fabric (Spahiu T. , Grimmelsmann, Ehrmann, Piperi, & Shehi, 2017; Sanatgar, Campaigne, & Nierstrasz, 2017). Another study also showed that PLA adheres better to fabric when extruded at higher temperatures than the normal extrusion temperatures of between 180°C and 210°C (Rivera, Moukperian, Ashbrook, Mankoff, & Hudson, 2017).

The optimum settings yielded a value close to the minimum printing speed, that is, 34.5mm/s. The relationship between printing speed and adhesion force showed that as the printing speed increased adhesion force decreased (Figure 4:11). Previous research has shown that the adhesion force reduces with an increase in printing speed (Spahiu T. , Grimmelsmann, Ehrmann, Piperi, & Shehi, 2017). The penetration of the macromolecules of polymers into the fabric is slow at high printing speeds as a result the adhesive forces are less than cohesive forces hence the decrease in adhesion strength (Sanatgar, Campaigne, & Nierstrasz, 2017). As indicated in Figure 4.11, the adhesion force with an increase in model height to an optimal height of 0.411mm beyond which the adhesion force reduced. This could be due to the fact that as the height of the model continues to increase the print becomes easier to peel off the fabric hence the reduced adhesion force.

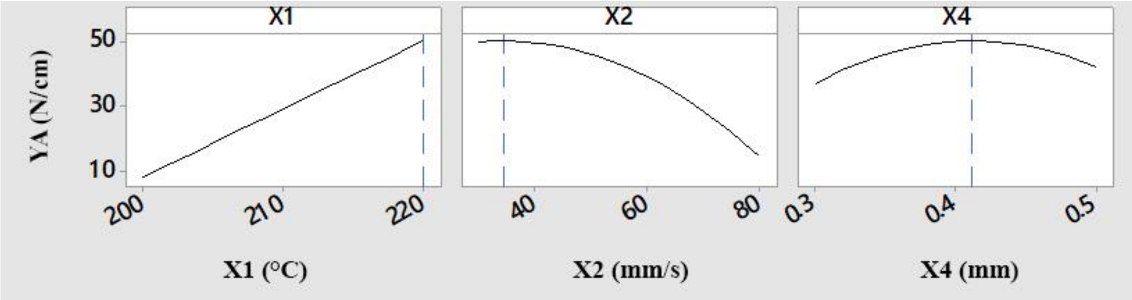

Figure 4.11: Settings and Sensitivity for Optimal Adhesion Solution.

4.3.2 Adhesion Force of the Printed Fabric After Washing (Y_{AW})

After washing the 31 samples, only 18 of the samples could be tested for adhesion. The PLA on the remaining samples was either already broken from washing or it broke while trying to test for adhesion force (Figure 4.12). It was observed that the PLA became too brittle during washing, hence the reason for it breaking during the adhesion tests. This could be due to the low glass transition temperature of PLA which is below 60°C (Ajioka, Enomoto, Suzuki, & Yamaguchi, 1995). The same challenge was experienced by Martens & Ehrmann (2017) when they printed ABS zip fasteners on polyester fabric. The mechanical forces during washing folded and broke the zip fasteners.

Figure 4.12 : Fabric Sample After Washing (a) PLA not Broken (b) PLA Broken.

4.3.2.1 Statistical Analysis of Adhesion Force after Washing

The adhesion force regression model (Y_{Aw}) shown in Equation 4.9 had a coefficient of determination (R^2) of 0.8337. The ANOVA gave a P value of less than 0.001 for the general model which was less than the Alpha (α) value ($P < 0.05$) and was therefore a significant model.

$$Y_{Aw} = - 459.7 + 1.233X_1 + 2.023X_2 + 873X_4 - 0.01902X_2X_2 – 1073X_4X_4$$

Equation 4.9

The regression analysis showed that extrusion temperature (X_1), printing speed (X_2) and model height (X_4) had an effect on adhesion force after washing while fill density (X_3) had no significant effect thus it was not captured in the model.

The ANOVA, factor contributions (FC%) and Variance Inflation Factors (VIF) for the adhesion force after washing are shown in Table 4.5. The percentage contribution of the factors showed that extrusion temperature contributed 57.56% to the regression model for adhesion force after washing while printing speed and model height contributed 1.07% and 1.04% respectively. The P values for the estimated coefficients, curvilinear and interaction effects were less than 0.05 and were therefore significant in the model.

Table 4.5 : ANOVA, Factor Contributions (FC%) and VIF for Adhesion Force after Washing

Source	ANOVA (P-value)	FC (%)	VIF
Regression	0.000	83.37%	
X_1	0.000	57.56%	1.03
X_2	0.048	1.07%	1.03
X_4	0.012	1.04%	1.05
$X_2 * X_2$	0.001	10.93%	1.05
$X_4 * X_4$	0.014	12.77%	1.09
Error		16.67%	
Lack-of-fit	0.637	10.79%	
Pure Error		5.84%	
Total		100%	

The normal probability plot of residuals for adhesion force after washing (Figure 4.13) shows that the data points were normally distributed.

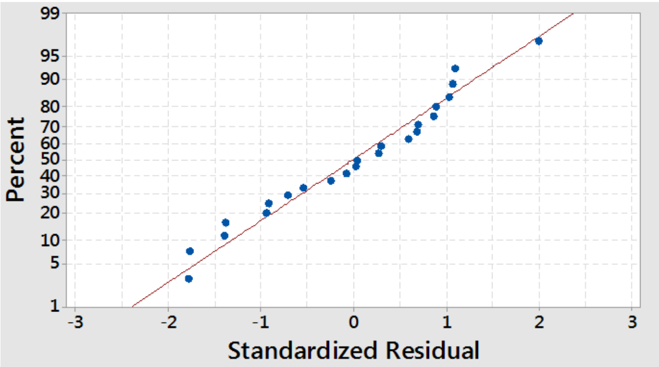

Figure 4.13 : The Normal Probability Plot for Adhesion Force after Washing.

The regression model was used to predict the optimal settings for a maximized adhesion force after washing (Table 4.6). The optimal settings obtained were extrusion temperature (X_1) of 220°C, printing speed (X_2) of 53.23mm/s and a model height (X_4) of 0.41mm to achieve a predicted maximum adhesion force after washing of 42.921 N/cm. This is less than the predicted maximum adhesion force before washing which has a value of 50.06 N/cm. This shows that the adhesion force is expected to reduce slightly after washing the sample.

Table 4.6 : Predicted Values and Optimal Settings for Adhesion Force after Washing

Goal: Maximized Adhesion after washing (N/cm)		Solution: Optimal Settings
Predicted Adhesion Force (N/cm) 95% Predicted Interval	42.921 (34.14, 51.70)	X_1 = 220°C X_2 = 53.23 mm/s X_4 = 0.41 mm

X_1 = Extrusion Temperature *X_2 = Printing Speed* *X_4 = Model Height*

The top five values closest to the predicted optimum settings for adhesion force after washing (Table 4.7) were also considered to be used in a situation where the optimum settings proved to be unfeasible.

Table 4.7 : Values Closest to the Predicted Optimum Settings for Adhesion Force after Washing.

X_1(°C)	X_2 (mm/s)	X_4 (mm)	Predicted Y_{AW} (N/cm)
220	55.0	0.40	42.8071
215	42.5	0.45	32.5952
215	42.5	0.35	31.1052
210	55.0	0.40	30.4794
215	67.5	0.35	29.3859

The optimal settings yielded a maximum temperature of 220°C. Figure 4.14 shows that as extrusion temperature increased, adhesion force increased. The optimum printing speed for adhesion force after washing is 53.23 mm/s. As the printing speed increased the adhesion force after washing increased until a speed of 53.23mm/s, thereafter the adhesion force started to decrease. The optimal settings yielded a maximum model height of 0.41mm. The adhesion force increased with an increase in model height to an optimal height of 0.41mm beyond which the adhesion force reduced.

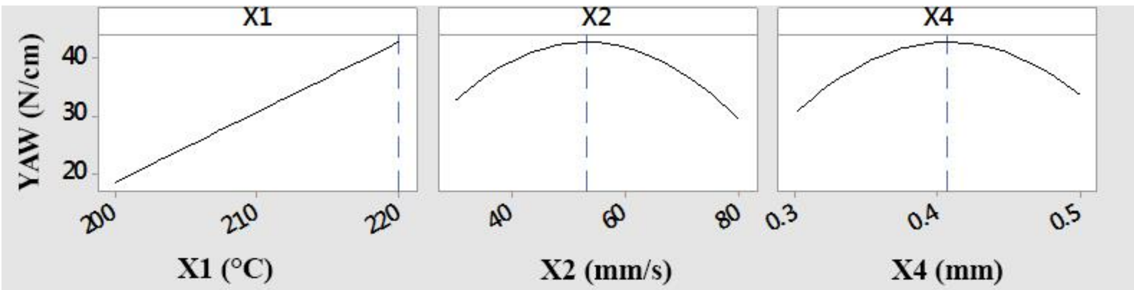

Figure 4.14 : Settings and Sensitivity for Optimal Adhesion after Washing Solution.

4.3.2.2 Comparison of Adhesion Force Before and After Washing

Adhesion tests were done for the 18 samples and a comparison was made between the adhesion force before washing and the adhesion force after washing as shown in Fig. 3. Previous researchers have suggested that there was no significant change in adhesion force after washing at 40°C when PLA was printed on polyester (Spahiu T. , Grimmelsmann, Ehrmann, Piperi, & Shehi, 2017). Figure 4.15 however shows that there was a slight decrease in adhesion force after washing for all samples. This is consistent with the tests carried out by Martens & Ehrmann (2017). In their study ABS was printed on cotton and polyester and the adhesion force reduced after washing at 30°C in the first washing cycle. No change was observed in cotton with more washing cycles but the adhesion force between polyester and ABS continued to decrease.

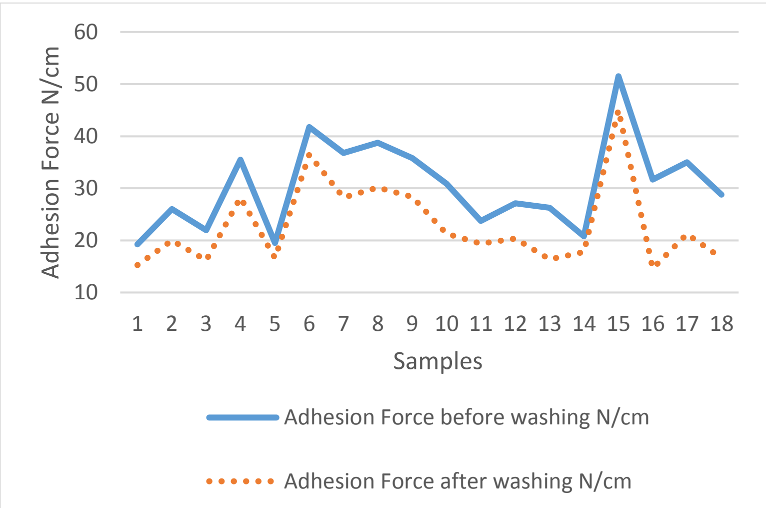

Figure 4.15 : Comparison of Adhesion Force Before and After Washing.

4.3.3 Tensile Strength (Y_T) of the Printed Fabric

The regression model for tensile strength (Y_T) is represented in Equation 4:10 with an R^2 value of 0.9406. The ANOVA gave a P value of 0.000 for the general model which was less than the Alpha (α) value ($P < 0.05$) and was therefore a significant model.

$Y_T = 43148 - 363.8X_1 - 1161\ X_2 - 77.77X_3 - 8334X_4 + 0.775X_1X_1 + 0.3561X_1X_3 + 28.7X_1X_4 - 0.0426X_2X_3 + 36.27X_2X_4$

Equation 4:10

The regression analysis showed that all factors, that is, extrusion temperature (X_1), printing speed (X_2), fill density (X_3) and model height (X_4) had an effect on tensile strength.

The ANOVA, factor contributions and Variance Inflation Factors (VIF) for the tensile strength are shown in Table 4:8. The percentage contribution of the factors showed that extrusion temperature contributed 4% to the model for tensile strength while printing speed contributed 1.02%, fill density 6.33% and model height 4.70%. The combined effect of extrusion temperature and fill density had the highest percentage contribution of 36.58%. The combined effect of printing speed and fill density had the second highest percentage of 21.83%.

Table 4.8 : ANOVA, Factor Contributions (FC%) and VIF for the Tensile Strength.

Source	ANOVA (P-Values)	FC (%)	VIF
Regression	0.000	94.06	
X1	0.000	4.00	1.11
X2	0.918	1.02	1.05
X3	0.052	6.33	1.04
X4	0.003	4.70	1.05
X1*X1	0.000	12.93	1.10
X1*X3	0.000	36.58	1.06
X1*X4	0.047	4.68	1.06
X2*X3	0.014	1.99	1.05
X2*X4	0.000	21.83	1.05
Error		5.94	
Lack-of-Fit	0.540	4.64	
Pure Error		1.30	
Total		**100**	

The normal probability plot of residuals for tensile strength (see Figure 4.16) shows that the data points were normally distributed.

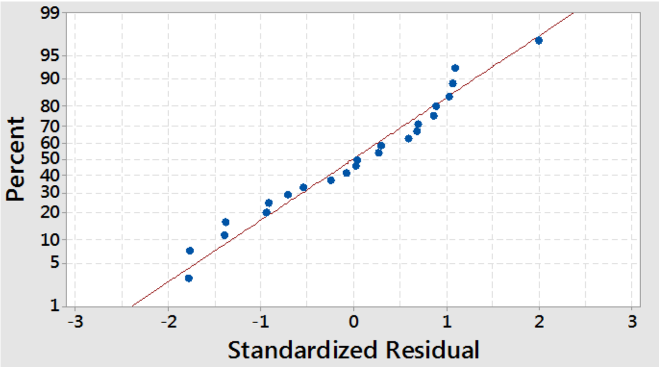

Figure 4.16 : Normal Probability Plot for Tensile Strength

The regression model was used to predict the optimal settings for a maximized tensile strength shown in Table 4:9. The optimal settings obtained were; extrusion temperature (X_1) 220 °C, printing speed (X_2), fill density (X_3) 100% and model height (X_4) 0.35 mm to achieve a tensile strength of 346.22 MPa.

Table 4.9 : Predicted Values and Optimal Settings for Tensile Strength.

Goal: Maximize Tensile Strength (MPa)		Solution: Optimal Settings	
Predicted Tensile Strength	346.22	X_1: 220°C	X_3: 100 %
95% Predicted Interval	(291.67, 400.77)	X_2: 42.5 mm/s	X_4: 0.35 mm

The top five values closest to the predicted optimum settings for tensile strength were also considered and presented in Table 4.10 in case the optimum settings were not possible.

Table 4.10 : Values Closest to the Predicted Optimum Settings for Tensile Strength.

X_1 (°C)	X_2 (mm/s)	X_3 (%)	X_4 (mm)	Predicted Y_T (MPa)
205	42.5	47.5	0.35	259.883
205	67.5	47.5	0.45	236.931
205	67.5	47.5	0.35	236.565
215	42.5	82.5	0.35	216.370
205	42.5	82.5	0.35	204.626

X_1= Temperature, X_2= Speed, X_3= Fill Density, X_4=Model Height

The optimum settings produced a maximum extrusion temperature of 220°C. Figure 4.17 shows that as extrusion temperature increased, tensile strength increased. Earlier results have shown that an increase in extrusion temperature results in an improved tensile strength with the best tensile strength achieved at a temperature of 220°C (Sood, Ohdar, & Mahapatra, 2012; Sun, Rizvi, Bellehameur, & Gu, 2008). This is because when there is higher temperature the polymer is less viscous and there is improved adhesion between the layers. The predicted optimum printing speed for maximum tensile strength is 42.5 mm/s. As the printing speed increased the tensile strength reduced. The optimum settings predicted a fill density of 100%. The graph for fill density versus tensile strength shows that as fill density increases, tensile strength increases. An increase in fill density means that there is more material in the specimen therefore the tensile strength is likely to increase (Fernandez-Vicente, Calle, Ferrandiz, & Conejero, 2016). An increase in model height resulted in a slight decrease in tensile strength.

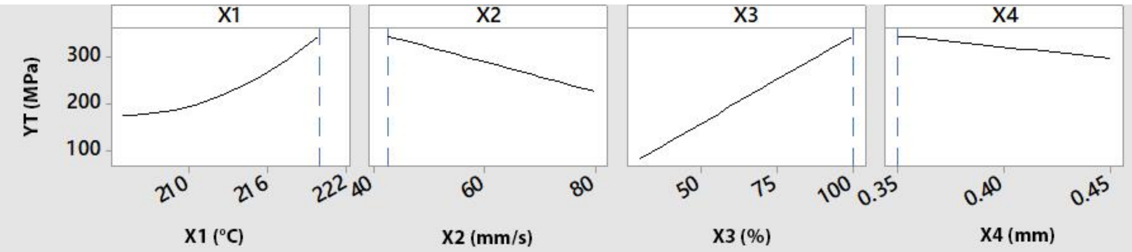

Figure 4.17 : Settings and Sensitivity for Optimal Tensile Strength Solution.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The current study was investigating the factors affecting the properties of 3D printing of PLA on textile structures. The printing was done by additively depositing biodegradable PLA onto textile fabrics using a 3D printer. The aim of this study was to determine the effect of fabric parameters, extrusion temperature, printing speed, fill density and model height on the properties of textile/PLA structures. Several conclusions are drawn from the study.

The study showed that 3D printed PLA can be deposited onto woven textile fabrics. The adhesion force of PLA onto textile fabrics depends on the fabric properties when the polymer and 3D printing parameters are kept constant. A positive correlation exists between adhesion force and fabric areal density, warp and weft count, fabric thickness and fabric roughness while a negative correlation exists between adhesion force and ends/inch and picks/inch. The tests showed that from the different fabric samples, the acrylic based fabrics displayed the highest adhesion force to PLA with polyester based fabrics showing the lowest adhesion force. The fabric sample that had the overall highest adhesion force was a cotton fabric weighing 355.2g/m2, with 24 ends/inch, 38 picks/inch, 50 tex warp, 37 tex weft and a thickness of 0.19mm. The fabric was used for the study of the effect of 3D printing parameters on adhesion force.

The study also showed that the 3D printing production parameters have an effect on the properties of the PLA/textile structure. The factors that affected both adhesion force before and after washing were extrusion temperature, printing speed and model height while fill density had no significant effect. Adhesion force before and after washing were both positively correlated to extrusion temperature and negatively correlated to printing speed and model height. The results also showed that the adhesion force reduced after washing. A positive correlation exists between tensile strength and temperature while a negative correlation exists between tensile strength and printing speed and model height.

5.2 RECOMMENDATIONS

Future tests should also be done on knitted fabrics and also a wider range of fibre types. Properties such as weave type, cover factor, yarn twist should also be considered for the determination of the fabric properties that affect adhesion force.

Research should be done to determine the best washing parameters to maintain a good adhesion force after several washing cycles. Parameters such as washing temperature, washing time, washing detergent and number of washing cycles could be studied. This would ensure a good adhesion and also prevent the breaking of the PLA parts during washing. Apart from adhesion force before and after washing as well as tensile strength, other tests can be done on the textile/PLA structure to be able to characterize the structure. Tests that can be done include air permeability tests, water absorption and bursting strength. This will help researchers identify other possible end uses for the structures based on the properties.

A cost analysis should be done comparing the costs involved in the manufacture of the textile/polymer structures to those involved in embroidery, dyeing and printing. This will aid in determining the viability of 3D printing techniques as an alternative for decorative textiles.

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APPENDICES

Appendix A: Parameter Settings for 3D Printing Process

	Factors			
Runs	X_1	X_2	X_3	X_4
1.	0	0	-2	0
2	0	-2	0	0
3.	-1	-1	-1	-1
4.	-1	1	1	-1
5.	0	0	0	-2
6.	1	-1	1	-1
7.	1	1	-1	1
8.	1	1	1	-1
9.	0	0	0	0
10.	-2	0	0	0
11.	-1	-1	1	1
12.	1	-1	1	1
13.	0	0	0	0
14.	0	0	0	0
15.	1	1	-1	1
16.	1	-1	-1	1
17	-1	-1	1	-1
18.	-1	1	-1	-1
19.	-1	-1	-1	1
20.	-1	1	-1	-1
21.	0	0	0	0
22.	0	0	0	0
23.	2	0	0	0
24.	1	-1	-1	-1
25.	0	0	0	2
26.	0	2	0	0
27.	0	0	0	0
28.	0	0	2	0
29.	-1	1	1	1
30.	0	0	0	0
31.	1	1	1	1

Appendix B: Publications

1. Mpofu, N. S., Mwasiagi, I. J., Nkiwane L., Njuguna D. (2018). 3D Printing of PLA onto Textile Fabrics, *Annals of the University of Oradea Fascicle of Textiles, Leatherwork,* 19(2), 73-78, ISSN 1843 – 813X.
2. Mpofu, N. S., Mwasiagi, I. J., Nkiwane L., Njuguna D. (2018). Effects of Washing on the Adhesion of PLA Polymer onto Cotton Fabric, *In Proceedings of Eleventh South African Conference on Computational and Applied Mechanics, SACAM 2018, Vanderbijlpark, South Africa, 17-19 September 2018*. 811-818. ISBN 978-1-77012-143-0.