GÖKHAN BÜRGE

OPTIMIZATION AND ANALYSIS OF PLA
IMPLANT PRODUCED BY 3D PRINTER

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A THESIS SUBMITTED TO THE GRADUATE SCHOOL OF APPLIED SCIENCES OF NEAR EAST UNIVERSITY

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In Partial Fulfillment of the Requirements for the Degree of Master of Sciences in Mechanical Engineering

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Approval of Director of Graduate School of Applied Sciences

Prof. Dr. Nadire ÇAVUŞ

We certify this thesis is satisfactory for the award of the degree of Master of Sciences in Mechanical Engineering

Examining committee in charge:

Assist. Prof. Dr. Ali Evcil — Supervisor, Department of Mechanical Engineering, NEU

Assoc. Prof. Dr. Hüseyin Çamur — Committee Chairman, Department of Mechanical Engineering, NEU

Assoc. Prof. Dr. Kamil Dimililer — Department of Automotive Engineering, NEU

I declare that all of the material found in this paper has been collected and transmitted in compliance with scientific and ethical laws. I also declare that ı has thoroughly cited and referenced all material and findings which are not original of this research, as provided by these rules and behaviour.

Name, Last name: Gökhan Bürge
Signature: 

Date: 02/10/2020

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To my family…

ABSTRACT

The aim of this study is to produce polymer-based polylactic acid (PLA) material, which is used as an alternative to materials with high production cost, such as metal, ceramics, etc., used in implant production, and to make mechanical tests of the samples to be tested using additive manufacturing (3D printing) with Taguchi method. In order to reach the best analysis and optimization of parameters larger the best signal noise ratio analysis and ANOVA variance analysis were used. Tension test and 3-point bending test experiment specimens designed in computer aided design program called SolidWorks and produced from polylactic acid (PLA) which is a polymer-based material by using 3D printing technology. In the stage of designing of samples 4-factor and 3-level L9 orthogonal array experimental design technique used to decrease the number of specimens used in tensile and compression tests. Taguchi's orthogonal index, Signal / Noise (S/N) ratio, and variance analysis were used to find out which sample is the most effective parameter in strength resistance and optimum levels in production. Verification test results with optimum levels of control parameters were examined using the 3D printer molding process and the suitability of implant production using the Taguchi Method.

Keywords: 3D printing; 3-point bending; implant; PLA; Taguchi; tensile test

ÖZET

Bu çalışmanın amacı, implant yapımında kullanılan, metal, seramik gibi üretim maliyeti yüksek olan materyallere alternatif olarak bilinen polimer bazlı polilaktik asit (PLA) materyalinin, üç boyutlu baskı yöntemi (katmanlı üretim) ile Taguchi metodu kullanılarak, mukavemet testi yapılacak numunelerin üretilmesi ve üretilen numunelerin mekanik testlerinin yapılmasıdır. Üretilen numuneler 3 boyutlu baskı teknolojisinde önemi olan, dolgu oranı, baskı hızı, kabuk sayısı ve katman yüksekliği parametreleri göz önünde bulundurularak, Taguchi yöntemine göre analizleri gerçekleştirilmiştir. Parametrelerin analizi ve optimizasyonu için büyük sinyal gürültü oranı analizi ile birlikte ANOVA varyans analizi kullanıldı. Gerilme testi örnekleri ve 3 nokta eğilme testi deneyleri, 3 boyutlu bilgisayar destekli tasarım programı olan SolidWorks programında tasarlanıp 3D yazıcı teknolojisi ile polilaktik asit malzemeden üretildi. Numune tasarım aşamasında, 4 faktörlü ve 3 seviyeli L9 ortogonal dizi deney tasarımına dayanan yöntem, çekme ve basınç testi üretiminde numune sayısını en aza indirmek için kullanılmıştır. Taguchi'nin ortogonal indeksi, Sinyal / Gürültü (S/N) oranı ve varyans analizi, hangi parametrelerin malzemenin mukavemet değerlerine etki ettiğini ve üretimde optimum seviyelerde en etkili parametre olduğunu belirlemek için kullanıldı daha sonra bu sonuçlara bağlı olarak elde edilen optimum kontrol parametrelerine göre tekrardan numuneler üretilip mekanik testleri yapılmış ve incelenmiştir.

.

Anahtar Kelimeler: 3D yazıcı; Taguchi; Pla; Implant; 3-nokta bükme; Çekme Testi

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

3D: 3 Dimensions
Al: Aluminum
ASTM: American Society for Testing and Materials
CAD: Computer Aided Design
DF: Degree of freedom
DLP: Digital Light Process
DMLS: Direct Metal Laser Sintering
E: Modulus of Elasticity
EBM: Electron Beam Melting
FDM: Fused Filament Deposition
FFF: Fused Filament Fabrication
MJF: Multi Jet Fusion
mm: Milimeter
Pa: Pascal
PEEK: Polyether ether ketone
PGA: Paul Gardner Allen (Liquid rocket engine founder)
PLA: Polylactic Acid
PVC: Polyvinyl chloride
SH: Shell
SLA: Stereolithography
SLS: Selective laser sintering
S/N: Signal-to-noise ratio

CHAPTER 1
INTRODUCTION

Production with fused filament fabrication (FFF) or 3D printing method is a technology that has greatly changed the understanding dimension of production in the past 10 years. This is due to the advantages offered by the technology group in terms of traditional production technologies; that is, these advantages are design and innovation capacities, a stronger link between design and manufacturing, and the ability to produce unique parts with this technology (Travieso and Rodriguez, 2019). The transformation of production techniques focuses on eliminating production costs and cleaner production. It is clear that the ongoing research emphasizes the need for environmentally friendly production and the reduction of emissions and waste during production. The 3D printing technique has a wide vision and coverage to meet the need for environmentally friendly production. This technology can be used easily and at very low cost to produce the required model or sample without any production waste, regardless of its geometry. The aim of this research is to calculate the mechanical properties of 3D printed PLA, such as tensile and bending, to know whether the implant materials used in the field can be replaced with polylactic acid (PLA) instead of existing titanium, ceramic etc. materials commonly used in the field. Tests for solid models were completed using the CAD program and given to the printer suitable for the 3D printer via the interface. Solid models were developed and tested according to ASTM standards. (Raj et al., 2018).

1.1. Background and Review

Skeletal issues brought about by wounds, injury, and sicknesses, for example, tumours or osteoporosis can be treated with impermanent or perpetual inserts. Basic size imperfections, additionally called bone deformities, are hard to fix, even with mechanical help. In this way, to quicken bone recovery and to take care of the issue of non-association of basic size deformities, imperfections can be fixed with biocompatible materials (Kumar and Misra, 2018).

Polylactic acid (PLA) is the most broadly utilized biodegradable polymer in clinical applications. For examples; medicated conveyance frameworks, tissue building, brief and long-haul implantable gadgets. This polymer-based material is continually extending to new areas (Da Silva et al., 2018).

The expanded utilization of additive manufacturing as a learning apparatus and to create practical end-use parts have produced the requirement for a superior comprehension of the mechanical conduct of three-dimensional printed parts and the advancement of expository devices and plan rules for engineers. Materials testing of three-dimensional printed plastics was acted so as to furnish both modern and scholastic networks with new to improve the mechanical and advanced plan with regards to added substance producing. Fused deposition modelling (FDM) which is a nice example of this situation (Farbman and McCoy, 2016).

1.2. Objectives of The Study

The general purpose of this study is to produce PLA (polylactic acid). This material is a polymer-based and biocompatible material and it can be used instead of traditional materials like metal ceramics, etc. according to these we are trying to find out optimum parameters during the production, realize the tensile test and 3-point bending test and analyze the feasibility of implant production.

1.3. Thesis Layout

Chapter one introduces general information and overview of implant and previous research works as well as the problem of statement and motivations, introductory definitions and general objectives. Chapter two discusses more on 3D printing technology and PLA and a detailed literature review including definitions, historical background, current status, application of implant and 3D printing will be discussed. The production method, properties, and standards, merits and drawbacks are also explained in detail. Chapter three will give a brief summary of the methodology followed and experimental setups, as well as formulation, used to carry out this study. Chapter four discusses the result of the experiment; experiment results are interpreted and analyzed in this chapter. In the last, chapter five put the conclusion of the work and points out further work for the future.

CHAPTER 2
LITERATURE REVIEW

2.1. General Overview

Objects that are added to the body temporarily or permanently, internally or externally for treatment and repair are called implant materials. Various factors are taken into consideration when deciding on the material for orthopedic implants. Structural and material properties, manufacture, and regulatory which are basis categories for design consideration of implants. Deciding on the material also depends on the implants intended for use like anatomic location, loading, bearing and articulation. Stainless steel, cobalt-based alloys and titanium alloys are traditionally used materials in implant designing. These materials are continuously improved in order to be effective biomaterials (Jones et al., 2017).

2.2. Brief History of Orthopedic Implants

The first basis of the orthopedic implant, intended by William Arbuthnot Lane, Albin Lambotte Agnes also the first orthopedic nurse Dame Agnes Gwendoline Hunt in the 20th century. This orthopedic implant developed for fixing break bone which was made of stainless steel. In 1935, F. Pauwels and William Lane being together, they combine vanadium-iron, instead of steel, due to its stamina and elasticity. The next generation of bone plate was molybdenum and vitallium. They contained stainless steel, chromium and nickel respectively (Markatos et al., 2016).

2.3. Materials Development of Implants

Before choosing the material, foreign body reaction is a powerful parameter affecting material selection while developing implants. Two common words reveal when developing implants. These are; biocompatibility and biological prerequisite. These factors define the necessity of material selection. Also, physical, chemical and mechanical behaviors are common prerequisites.

High back spring and low fatigue strength in material selection while manufacturing the implant is not desired as implant material (Poh and Wang, 2013). The factors such as foreign body response and biocompatibility therefore make material selection important (Markatos et al., 2016).

2.3.1. Biomaterials and biocompatibility

Because the body tissues are unable to perform their functions, therefore humans have revealed the components of artificially designed materials (Sarı, 2017). Today, the effectiveness of using implants is still being debated but it's very old. However, with advancements such as sterile environments and developments in materials have emerged as a popular implant implementation since the last century (Bandopadhyay et al., 2019). Synthetic, biodegradable surgical thread was first made from polyglycolic acid in the 1970s, and was one of the first studies in biodegradable products. As a result, over 40 plastics, polymers, and ceramics have been used to restore and replace more than 40 separate pieces of the body over the past 40 years (Pekşen and Doğan, 2011). Gold wires were used as a scaffold in the 20th century to connect an artificial tooth to the neighbouring teeth. Bone plaques were widely used until the 20th century to patch bone fractures and to improve their healing. Earlier in the 1950-60s, hip joints and mechanical heart valves were used to bypass the blood vessels (Jones et al., 2017). Popular biomaterials classifying carbon, ceramic polymer and composite in four major classes (Jones et al., 2017; Bandopadhyay et al., 2019). The orthopaedic implants can either be made from plastics, polymers, ceramics, composites, biologically inspired components, hybrid products or a mixture of them (Jones et al., 2017).

2.3.2. Implant materials in orthopedic

Implant materials are generally classified into three categories: plastics, polymers, ceramics and composites (Bandopadhyay et al., 2019). Materials used in ortopedic as it can be seen in the Table 2.1.

Table 2.1: Materials used in implants application
(Bandopadhyay et al., 2019; Prasad et al., 2017)

Metals	Ceramics	Polymers	Composites
Low carbon based austenitic stainless steel :316L	Ultra-High molecules weight polyethylene	Ultra-High Molecules Weight Polyethylene UHMWPE	Fiber based Polymers
Titanium AND its alloys commercial Purity	Zirconia zro2	Acrylic bone Cements PMMA	PMMA Poly (methyl methacrylate)
Cobalt Alloys: Co-Cr-Mo and another Co based Alloys	Calcium phosphate (cap) Based Ceramics	Thermoplastic polyether ether Ketone PEEK	
	Hydroxyapatite Ca10(PO4) (OH)2 Bio glasses	Bioabsorbable Polymers	

1) Metals

Generally, in orthopedic surgeries metallic materials are preferred (Sidambe, 2014). Consequently, several metal materials used in implant's application. Stainless steel, gold, cobalt-chromium alloy and nickel-titanium alloy are the most commonly used metals as biomaterials. In the designing of the metallic implants and medical instrument applications stainless steel is used. Steel is still the most widely used material in engineering applications. 316L stainless steel is an instance of the application of these alloys as biomaterial (Santos, 2017). Titanium and titanium alloys, cobalt-based alloys, tantalum-based alloys (Wilson, 2018), also, nowadays, Al Cr and Ti alloys used instead of Stainless Steel for permanent implants (Bandopadhyay et al., 2019).

Advantages and disadvantages of using metals in orthopedic implants can be listed as follows:

Advantages

- High biocompatibility
- Strong
- Resistant to fatigue degradation

Disadvantages

- Poor resistance to corrosion
- Fatigue strength
- Proven carcinogenicity of chromium
- Need for specific forging method involving compression under high pressure
- The proven carcinogenicity of chromium.
- Production cost (Bandopadhyay et al., 2019)

2) Polymers

Polymer materials as it can be seen in Figure 2.1, cover every centimeter of our lives, which are used by too many products, and a wide range of polymers have also been used as biomaterials in the medical industry. They range from facial prosthesis to tracheal tubes, lungs, liver parts, heart sections, dentures, and hip and knee joints. Polymer biomaterials are added for the preparation of medical adhesives, sealants and coatings for a variety of functions. Physical activity of polymers is similar to soft tissue and is useful for skin regeneration, tendon, cartilage, and vein walls, as well as drug delivery, and so on. Polyethylene is used to replace joint prosthesis, while polycaprolactone is used in resorbable sutures, pins and plates for fracture repair purposes (Balakrishnan et al., 2018).

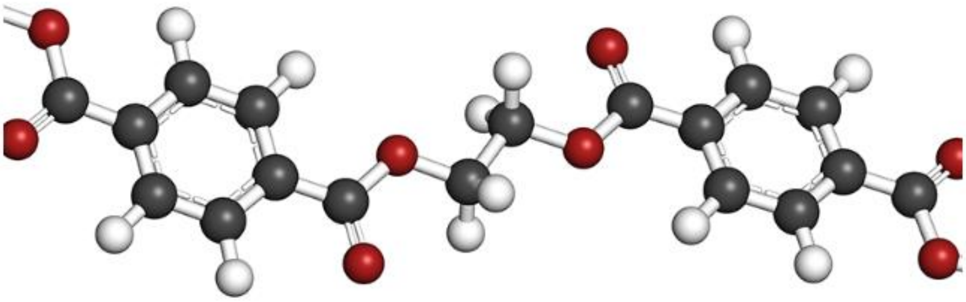


Figure 2.1: Polymers.

Figure 2.2: Polyethylene pellets.

Most of the other polymeric fabrics are nylon, PVC and polyetherketone. It also suffers from creep and gradual wear and deformation due to temperature under load. Creep is suppressed by supporting the polymer with metal (Bandopadhyay et al., 2019). Polymers are too diverse and are better alternatives for biomaterials convenient properties. PEEK, PVC, polyethylene, nylon polymers are similarly useful and have strong properties (Bandopadhyay et al., 2019; Prasad et al., 2017). Polylactic acid, which is a type of biopolymer material that falls into another polymer class, and it’s an eco-friendly and biodegradable biopolymer, therefore biodegradable materials have been preferred for medical implants for many years. Polylactic acid is the most commercially produced polymer which is produced by polymerizing the lactic acid monomer (Pawar et al., 2014; Sarı, 2017). Polyethylene pellets as shown in Figure 2.2.

Cons of polymers materials in orthopedics implants

- Polymers materials are highly corrosion resistant.
- They are appropriate for implantation and very biocompatible with the human body.
- Their properties rely upon the various sorts of material utilized as a biomaterial.
- Good mechanical properties.
- Better biocompatibility of ceramics and metals offers far greater opportunities for potential uses as polymers.

Pros of polymers materials in orthopaedics implants

- Include absence of attachment to living tissues and surfaces, normal mechanical properties.
- Specific unfavorable immunologic responses (Balakrishnan et al., 2018).

3) Ceramics

Ceramics are non-metallic inorganic structures made up of different compounds. This is formed by combining all the particles of the substance together with the organic binder and the atmosphere. Commonly available ceramics include quartz, vitrified, polycrystalline sprayed liquid, sintered solid-state, and ceramic polycrystalline quartz. Mechanical and biological properties depend on the porosity, consistency of the powder used, and the size and distribution of the grain. Ceramics can be categorized as bioactive or inert on the basis of the tissue response (Shanmugam and Sahadevan, 2018). Some ceramic materials are also biodegradable (ShamikaM, 2017).

Advantages of ceramics

- Good wear tolerance and biological properties.
- Ceramic zirconia due to its greater strength and durability.
- Strong and chemically inert.
- High compressive strength.

Disadvantages of ceramics

- The use of ceramics in orthopaedics is difficult in terms of production forms (ShamikaM, 2017).

4) Titanium alloys

Titanium alloys are quickly emerging as the first option for most applications due to the combination of their outstanding characteristics such as high strength, low density, good corrosion tolerance, full-body inertness, improved flexibility, low Young's modulus, and good bone or other tissue bonding ability (Crawford, 2019).

Their lower Young´s modulus, excellent biocompatibility and greater resistance to corrosion compared to traditional stainless steels and cobalt-based alloys make them a perfect alternative for bio use (Crawford, 2019; Poh and Wang, 2013). Titanium and titanium alloys, in artificial arms, teeth, and dental implants are commonly used as hard tissue substitutes (Engel et al., 2009). Concerning the clinical utilizations of these materials, the utilization of monetarily unadulterated Titanium is progressively restricted to the dental inserts on account of its constrained mechanical properties. (Crawford, 2019). Lc-dcp implant made from titanium as it can be seen in Figure 2.3. In addition, titanium implants grow an oxide coating that helps it to integrate with living bone tissue. Furthermore, the body may have adverse reactions such as fibrosis and inflammation that may affect its functional performance in the long term (Poh and Wang, 2013; Crawford, 2019).

Figure 2.3: Lc-dcp implant from titanium

2.4. Implant Manufacturing Methods

Implants are being made using advanced methods of both additive and subtractive technologies, including multi-axis multi-spindle turning and automated coating and cleaning. Metal additive manufacturing for production is on the rise using several methods, including laser and electron beam manufacturing (EBM) and 3D printing modalities (Crawford, 2019). Complex manufacturing methods, such as casting or forging, finishing, polishing and coating, are often used in the production of medical implants. Of course, these methods are more costly than 3D printing technology (Moayedfar et al., 2016).

2.5. Three-Dimensional Printing Technology

2.5.1. A brief history of three-dimensional printing

Enormous excitement surrounds 3D printing, with predictions that it would spark a revival in manufacturing in the world with everyone instantly being able to operate their own cottage production facility. There are many other places where 3D printing really creates major change, particularly in the design and prototyping of modern items, in the arts, and in the representation of abstract ideas. 3D printing, though, is still a very complicated endeavor and the bulk of consumers are only in the early adopter level. 3D printing is very straight forward in concept. An object is formed by starting from nothing and adding a layer of material at a time until you have a finished product. There are several natural examples of the process, and for centuries, other terms used lesser-tech variations; for example, building a brick wall. Nowadays, 3D printing an evolution and convergence of technologies and techniques that have been around for a while.

Nonetheless, this chapter discusses several important technological and business-environment advances that have come together to make 3D printing available to consumers. In 1989 Scott Crump discovered the process for the additive manufacturing of voluminous pieces by layered application of molten polymer (Kuznetsov et al., 2018).

1) The categories of 3D printing

- Binder jetting
- Directed energy deposition
- Materials jetting
- Powder bed fusion
- Sheet lamination
- Vat Photopolymerization (Shahrubudin et al., 2019)

Also, there are many different types of 3D printing technology; These are, (Ahart, 2019)

- Stereolithography (SLA)
- Selective Laser Sintering (SLS)

- Fused Deposition Modeling (FDM)
- Digital Light Process (DLP)
- Multi Jet Fusion (MJF)
- Poly Jet
- Direct Metal Laser Sintering (DMLS)
- Electron Beam Melting (EBM) (Ahart, 2019)

Fused deposition modeling (FDM) is one of the most commonly used additive manufacturing techniques of popular engineering plastics for producing prototypes and usable components (Masood, 2014). Therefore, fused deposition modeling method used in this study.

2) Fused deposition modeling (FDM)

The process creates the digital model by the extrusion of plastic filaments, the heated raw material, to be extruded through a nozzle tip to place the layers on a platform to form a layer by layer directly from the digital model of the part. The FDM processes as it can be seen in Figure 2.4. The efficiency and durability of the FDM process have made industry, universities and customers broadly understand and embrace the additive manufacturing method. Research and production industries have already extensively used the FDM technology to refine the technology, produce new technologies and use the FDM processes in a wide variety of engineering applications (Masood, 2014).

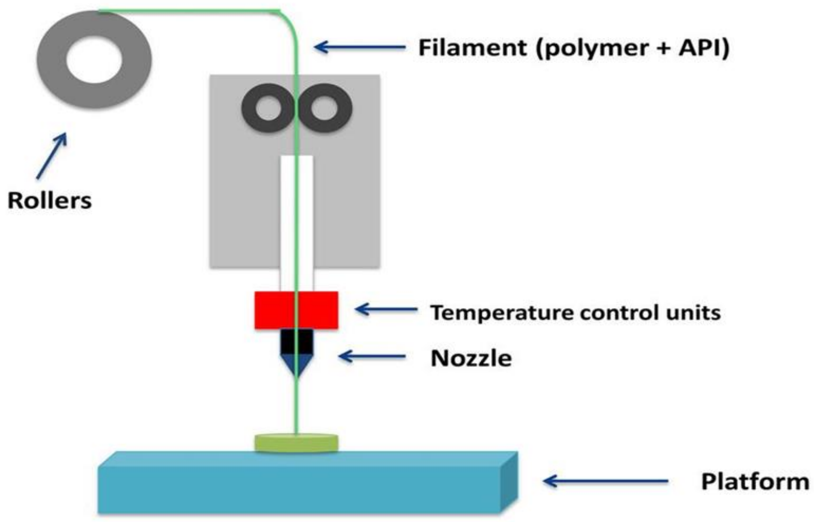


Figure 2.4: Fused deposition modelling (FDM) printing system.

2.5.2. Three-dimensional (3D) printing in orthopedics

3D printing innovation is entering the human services field at an astounding rate. 3D imprinting in orthopedics is no dream. In the Mechanical Engineering Department of MIT, many faculty members find new ways to combine 3D prints in a wide range of research areas. Whether printing metal parts for aircraft, objects on a nanoscale, or printing complex biomaterial scaffolds, they improve drug discovery, and these researchers test the boundaries of 3D printing technologies to have a lasting impact on industries (O'Leary, 2019). Through 3D printing technology, can make physical items from a geometric portrayal using a material (Shahrubudin et al., 2019).

3D printing procedure had many encountered sensational development as of late. First popularized of the additive manufacturing forms in year 1980 by Charles Hull (Hull, 2015; Shahrubudin et al., 2019). Right now, 3D printing basically utilized for creating counterfeit heart siphon, gems assortments, 3D printed cornea, PGA rocket motor and the Stratolaunch propulsion team members have organized the utilization of additive manufacturing for the improvement of its liquid rocket motor. These days, 85 % of assembling has an additive component (Boissonneault, 2018). Steel connect in Amsterdam and different items identified with the aeronautics business just as the food sector.

The additive manufacturing or 3D printing technological innovation has started from the layer by layer creation innovation of three-dimensional (3D) structures straightforwardly from PC supported plan (CAD) drawing. 3D printing innovation is genuinely imaginative and has developed as a flexible innovation stage. It opens new chances and offers would like to numerous opportunities as an organizations hoping to improve fabricating productivity (Shahrubudin et al., 2019).

2.5.3. Three-dimensional (3D) printing in surgical application

The greatest preferred position of this procedure in careful arranging is in altering the models or prostheses according to a patient's one of a kind need. Moreover, it brings down the working time and causes less uneasiness, quicker recuperating, and lessens the hazard factor up to a limited degree. Customary assembling strategies would be less expensive in the large-scale manufacturing of any material. In any case, with a customized material according to a patient's information is required, 3D printing could be a modest and fast assembling strategy. Furthermore, being cost-productive, the procedure could be effectively reproducible and handily controlled to another and comparative strategy without confronting any issues (Rath and Sankar, 2017). To sum up, 3D printing technique has a compelling task to carry out in these three situations:

- Where the number of the products is less.
- When the products are extremely technical and custom-made to fit a specific situation.
- Where the products have to be changed as a result of feedback or need to be changed quickly.

Furthermore, data sharing is easier and by sharing the files, a prosthesis could be a reproducible cross-country boundary. The US National Institutes of Health has already launched an initiative to share meticulously designed prostheses in 3D printable stl files (Rath and Sankar, 2017).

2.6. Orthopedic Plates

Plate and screw fastening of breaks has experienced persistent structure changes and upgrades during the last decades. Friedrich Pauwels just because characterized and implemented the strain band guideline in the fastening of breaks and nonunion. This designing rule applies to the transformation of ductile powers to pressure powers on the raised side 8 of an unconventionally stacked bone. This is practiced by putting a pressure band or bone plate over the break on the strain side of the bone. If the plate is implemented to the pressure side of the bone, it is probably going to twist, exhaustion, and fall flat. In this manner, an essential guideline of strain band plating is that it must be applied to the pressure side of the bone so the bone itself will get the compressive powers as it can be seen in Figure 2.5 (Rouhi and Amani, 2013).

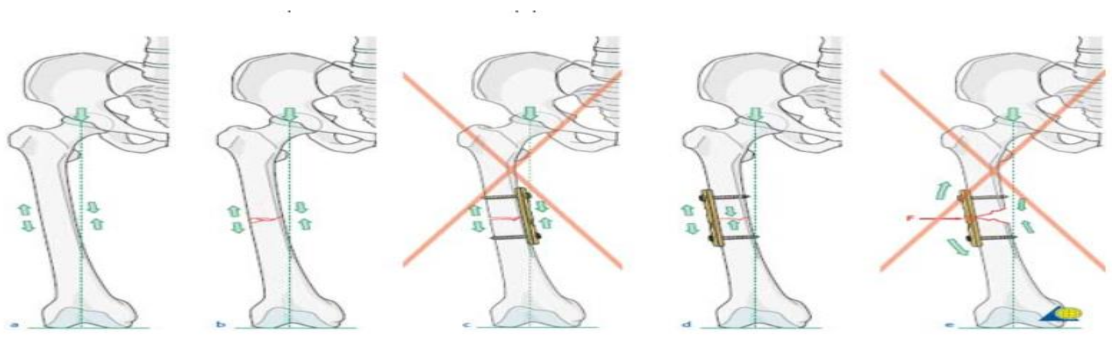


Figure 2.5: Implementing orthopedic implants.

2.6.1. Types of bone implant

Explicit plate structures incorporate rounded plates, T- and L-plates, spoon plates, reproduction plates, dynamic pressure plates (DCP), locking pressure plates (LCP), constrained contact DCP (LC-DCP), and restricted contact LCP (LC-LCP). The types of Plates as it can be seen in the Figure 2.6 and Figure 2.7. A wide range of types and plans of plates can be assembled practically into four classifications: balance plates, pressure plates, support plates, and extension plates. Although there is no specific plate type, the term neutralization plates express how it functions in fracture fixation (Rouhi and Amani, 2013).

Figure 2.6: DCP, LC-DCP, LC-LCP, tubular plate, T-Plate, L-Plate and reconstruction plate (Rouhi and Amani, 2013)

Figure 2.7: Ten fixing holes LC-DCP Plate.

2.7. Polylactic Acid in Biomedical Applications

2.7.1. Polylactic acid (PLA)

Polylactic acid is polyester derived from naturally occurring organic acid and it also biodegradable aliphatic polyester. It is classified as thermoplastic. It melts at a lower temperature in the 180-220 °C range with a glass transition temperature of 60-65 °C.

Since of its outstanding biocompatibility and mechanical properties, PLA and its copolymers have been commonly used in numerous fields such as chemical manufacturing, tissue engineering, drug delivery systems, and various medical applications (Pawar et al., 2014).

Thermoplastics which are petroleum-based, some of the raw materials used for PLA's production contain corn starch, tapioca roots, or sugarcane (Barrett, 2019).

Moreover, polylactic acid and its composites are biodegradable in nature; they quickly degrade under physiological conditions as seen in animal models through basic ester backbone hydrolysis leading to the creation of non-harmful and non-toxic compounds. Their degradation products are easily excreted through kidneys or eliminated in the form of carbon dioxide and water through metabolic processes in animals (Pawar et al., 2014). PLA is biocompatible and makes it perfect choice for medical implants intended to be absorbed by the body. In 2010 PLA was deemed the second most significant bioplastic in the world (Barrett, 2019).

2.7.2. Current and future developments

Thermal depolymerization or hydrolysis can even recycle PLA to its monomer. This can be manufactured by injection molding, extrusion, spinning film and casting, allowing a wide variety of products simple to use. Often, 3D printing equipment processes the PLA (Pawar et al., 2014).

CHAPTER 3
EXPERIMENTAL SET-UP AND METHODOLOGY

3.1. Determination of parameters for samples with Taguchi method

3.1.1. Taguchi approach

The concept experiment is characterized as the standardized process conducted under regulated conditions for discovering an unknown result, testing or hypothesizing, or demonstrating an established result. Experiments are often used when analyzing a process to evaluate which process inputs have a significant impact on the process output, and what the target level of those inputs should be for achieving the desired output. Experiments may be planned to gather knowledge in various different ways (Ellis et al., 2010).

- Factors or system inputs can either be classified as controllable variables or as uncontrollable.
- Levels or settings of each factor. Examples involve the setting of the oven temperature and the exact volume of sugar, flour and eggs picked for assessment.
- Response or experiment output. The texture, quality, and presentation of the cake in the case of cake baking are observable results theoretically determined by the variables and their respective amounts.

1) Properties of an orthogonal array

The orthogonal arrays have the following unique features, which minimize the number of tests to be carried out.

- The vertical column under each independent variable in Table 3.1 has a special combination of level settings. All the level settings appear an equal number of times. For L9 array under variable 4, level 1, level 2 and level 3 appear thrice. This is called the balancing property of orthogonal arrays.

- Both independent variable level values are used to perform the experiments.

The sequence of level values for conducting the experiments shall not be changed. This means one cannot conduct experiment 1 with variable 1, level 2 setup and experiment 4 with variable 1, level 1 setup. The reason for this is that the array of each factor columns orthogonal arrays use following formula;

$L_n(X^Y)$

L_n: No. of rows in the array

X: No. of levels in the columns.

Y: No. columns in the array (Roy, 1990).

As an example, L4 2^3 design consists of up to 3 factors at 2 levels each. There are 4 rows (Hintze, 2007). Also, the following examples follow as in the example above.

L8 2^7

L12 2^{11}

L16 2^{15}

L2 2^{31}

L64 2^{63}

L9 3^4

L27 3^{13}

L27 3^{22}

L16 4^5

L25 5^6

2) S/N Ratio

Signal factors are system control parameters known as an internal array, although outer array consisting of noise factors are variables that are typically difficult to manage or costly to treat. A signal-to-noise ratio is a statistical function that is calculated on a whole outer array. The calculation depends on whether the purpose of the research is to minimize, optimize or exceed a desired assessment of the characteristic level of concern.

S/N ratio is calculated as shown in the following equation (Xiao et al., 2014; Filiz Al-Shanableh et al., 2020).

$$\textbf{S/N}= -10 log\frac{1}{n}\ (\sum_{i=1}^{n}\frac{1}{y_i^2}) \qquad (1)$$

where n is some observations and y is the observed data. In the study the larger-is-better characteristics of S/N ratio were used together with L9 orthogonal array with 4 factors and 3 levels for each factor.

3.1.2 Analysis of variance (ANOVA)

ANOVA is a statistically decision-making tool for detecting average performance differences and helps to test the significance of all major factors (Wahyudin, 2017). Variance analysis (ANOVA) is a mathematical technique for evaluating variance in a response variable (continuous random variable) calculated under conditions specified by discrete factors (classification variables, often with nominal levels). Often, we use ANOVA to check consistency across different measures by comparing variance across groups compared to variance within groups (random error) (Larson, 2008).

Table 3.1: $L_9\,(3^4)$ Orthogonal array

Experiment	Independent Variables				Performance
	Variable 1	Variable 2	Variable 3	Variable 4	Parameter
1	1	1	1	1	p1
2	1	2	2	2	p2
3	1	3	3	3	p3
4	2	1	2	3	p4
5	2	2	3	1	p5
6	2	3	1	2	p6
7	3	1	3	2	p7
8	3	2	1	3	p8
9	3	3	2	1	p9

Table 3.1 displays a number of orthogonal L9 array. There are definitely 9 tests to be performed and each experiment is based on the level values together as seen in the table. The third experiment, for example, conserves the independent design variable 1 at level 1, variable 2 at level 3, variable 3 at level 3 and variable 4 at level 3 (Roy, 1990; Kharisma et al., 2017).

3.2. Experiment Design Guidelines

- The factors which should be checked.
- The levels of factors.
- The structure and layout of test runs, or conditions.

3.3. Methodology

The technique created utilizing Taguchi Method for optimization and analysis of the process parameters to define which parameters are the most effective parameters (layer height, infill, shell and print speed) produced by 3D printing (Erdem et al., 2010; Keskin and Yildirim, 2016; Filiz Al-Shanableh et al., 2020). The road maps of design of experiment shows followings;

1. Selection of control factors
2. Determination of levels of control factors
3. Selection of Taguchi orthogonal array
4. Implementation of experiments
5. Determination of 3-point Bending Test
6. Determination of Tensile Test
7. Calculation of signal-to-noise ratios
8. Analysis of variance (ANOVA)
9. Evaluation of optimum performance
10. Implementation of confirmation test

3.3.1. Design of experiment using with the Taguchi method

An effective method of experimental planning is design of experiments (DoE), which integrate the orthogonal array developed by Taguchi to collect statistically significant data with the minimum possible number of repetitions. Here L9 array was selected and Minitab 2019 software was used to analyze the results. The levels of the parameter used both for tensile and three-point bending tests are shown in Table 3.2 and Taguchi Design summary below.

Taguchi Design summary

Taguchi array	L9 (3^4)
Factors:	4
Runs:	9

Columns of L9 (3^4) array: 1 2 3 4

Table 3.2: Experimental factors and factor levels

Exp. No.	Layer height (mm)	Infill %	Print Speed (mm/s)	Shell
1	0.1	35mm/s	25%	1
2	0.1	60mm/s	50%	3
3	0.1	100mm/s	100%	5
4	0.15	35mm/s	50%	5
5	0.15	60mm/s	100%	1
6	0.15	100mm/s	25%	3
7	0.2	35mm/s	100%	3
8	0.2	60mm/s	25%	5
9	0.2	100mm/s	50%	1

3.3.2. Determination of samples and production test samples

The number of experiments produced during Taguchi optimization and the parts produced according to their parameters were determined according to the ASTM standard and suitable for tensile and bending test, therefore samples are designed in the solidworks program with 3-dimensional CAD software.

3.3.3. Used parameters of produced experiment samples

- **Infill:** The infill the quantity of content that occupies the piece's interior. Infill density is the amount of filament that is printed within the item and this relates directly to the power, weight and length of the print. Different types of 3D print infill or patterns of infilling, may affect the final strength of the object without altering the weight of filament used for the print (Tyson, 2016).

- **Layer height:** Layer height is exactly what it sounds like: the exact height of each layer of plastic extruded, cured or sintered by a 3D printer.

This setting is adjusted through a slicer program and has many more effects on the final print than one might think at first. Used properly, this setting will increase print’s speed, resolution, and smoothness.

Generally, increasing layer height will decrease the resolution and quality of the print (Siber, 2018). The thinner the layer height (or layer thickness) the finer the detail of the print on the Z axis (the vertical dimension of your print), but the more layers it will need. Leading to a longer print time (Tyson, 2016).

- **Shell:** The shell is also known as an outline or outer ring, representing the outer wall of a 3D print. Used in conjunction with a number in plural ("shells") to define the maximum thickness given to the outer wall (Wobith, 2019).

- **Print speed:** 3D printing speed measures the amount of manufactured material over a given time period (amount/time), where the unit of time is measured in hours, and the unit of manufactured material is typically measured in units of either kg, mm or cm^3, depending on the type of additive manufacturing technique (Kuznetsov et al., 2018).

3.3.4. Tensile tests

The Type I specimen is the ideal specimen that can be used if there is appropriate material with a thickness of 7 mm (0.28 in.) or less. The Type II specimen is recommended where a sample fails to break with the desired Type I specimen in the narrow section. The Type V specimen shall be used where there is only limited material available for evaluation with a thickness of 4 mm (0.16 in.) or less, or where a large number of specimens are to be exposed in a limited space (thermal and environmental stability tests, etc.). The Type IV specimen is generally used when direct comparisons between materials are required in different cases of stiffness (i.e., nonrigid and semirigid) (ASTM International, 2015).

1) Standards for tensile test

Tensile tests calculate the force needed to break a specimen, and the degree to which the specimen extends or stretches to the point of breakage. In general, measure elongation at material break is applied at the tensile test methods. Rigid and semirigid plastics test specimen shown in Figure 3.1. Widely used methods are:

- ASTM D638 - Standard test method for tensile properties of plastics
- ISO 527-1:2012 - Determination of tensile characteristics and general basics

Formula of elongation

$$\varepsilon = (\Delta L/L) \times 100 \qquad (2)$$

where:

» ΔL: Final Length

» L: Initial Length

Formula of stress

$$\sigma = \frac{F}{A} \ (N/m^2, Pa) \qquad (3)$$

where:

» F = force (N)

» A_0 = original cross-sectional area (m^2)

Formula of Modulus of Elasticity

$$E = \frac{stress}{strain} = \frac{\sigma}{\varepsilon} = (N/m^2, Pa) \qquad (4)$$

where:

» E: Modulus of Elasticity

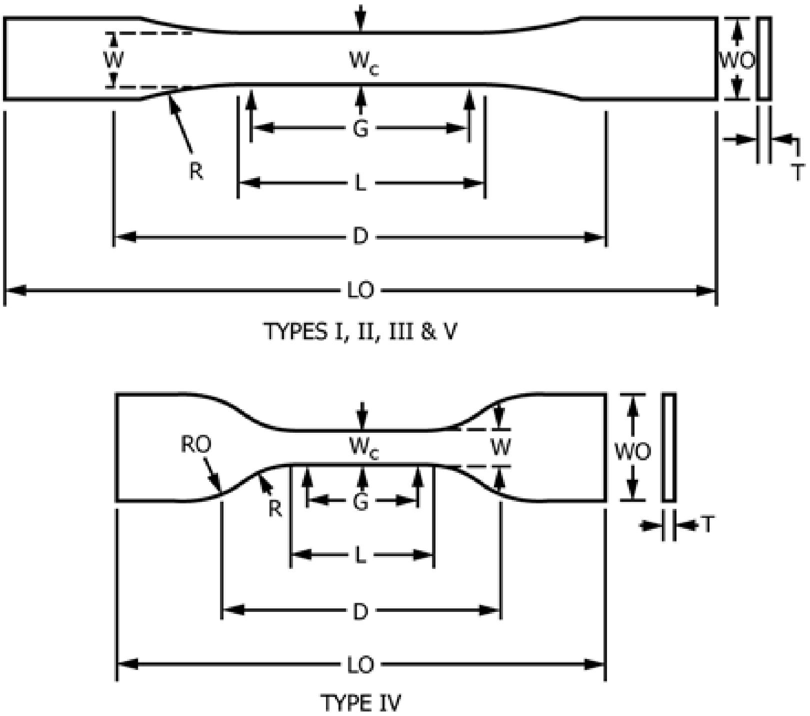


Figure 3.1: Rigid and semirigid plastics test specimen

.

where;

W: Width of narrow section E, F

L: Length of narrow section

WO: Width overall, min G

WO: Width overall, min G

LO: Length overall, min H

G: Gage length I

D: Distance between grips

R: Radius of fillet

RO: Outer radius (Type IV)

Table 3.3: ASTM d638 test specimen (ASTM International, 2015)

VERSION	W	L	WO	WO	LO	G	G	D	R	RO
V4	6	33	19	...	115	...	25	65	14	25
	(0.25)	(1.30)	(0.75)		(4.5)		(1.00)	(2.5)	(0.56)	(1.00)
V5	3.18	9.53	…	9.53	63.5	7.62	…	25.4	12.7	…

In this study Type V specimen used due to limited space.

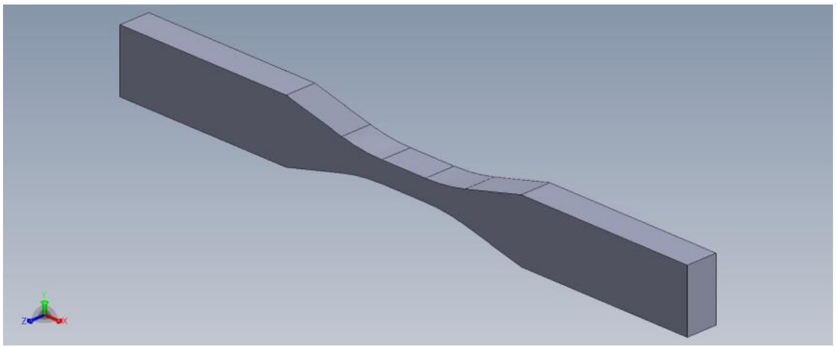


Figure 3.2: ASTM polymer version V solid model in cad program.

2) Specimen characteristics

The tests were performed using polylactic acid (PLA) tensile test, 115*6*4 mm^3 as specified by the D638 ASTM standard. Test specimen about the tensile test shown in Table 3.3 and Figure 3.2. For the experiments this material was chosen as it can be used for medical applications. Also, this has some advantages such as easy manufacturing and low cost (ASTM International, 2015).

3) Printing parameters

Layer Height: 0.1-0.15-0.20, Infill: %25-%50-%100, Print Speed: 35-60-100, Shell 1,3,5. In the Figures 3 to 11, the lines that appear in different colors show the percentage of infill, shell and layer thickness. Yellow and orange colors represent infill and layer thickness, also green colors are represent shell. General purpose setup of tensile test as it can be seen in Figure 3.12.

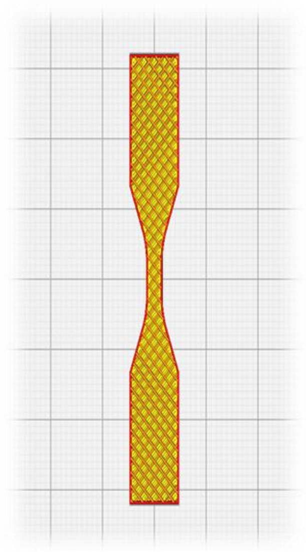


Figure 3.3: Layer height 0.1mm infill %25 Shell 1

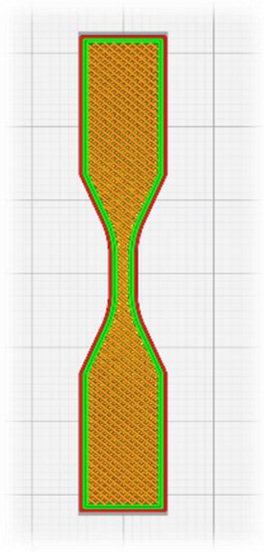


Figure 3.4: Layer height 0.1mm infill %50 Shell 3

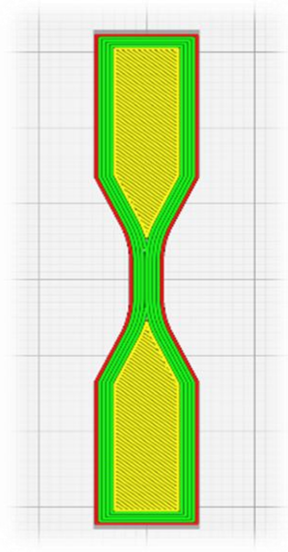


Figure 3.5: Layer height 0.1mm infill %100 Shell 5

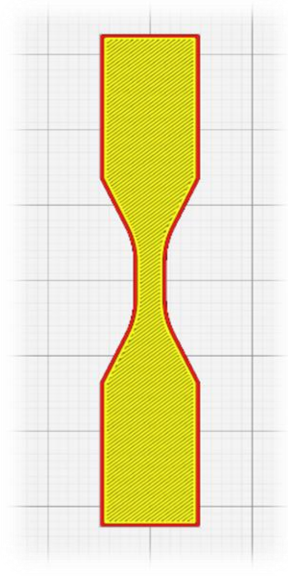


Figure 3.6: Layer height 0.15mm infill %100 Shell 1

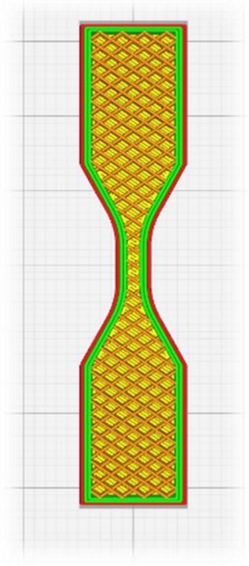


Figure 3.7: Layer height 0.15mm İnfill %25 Shell 3

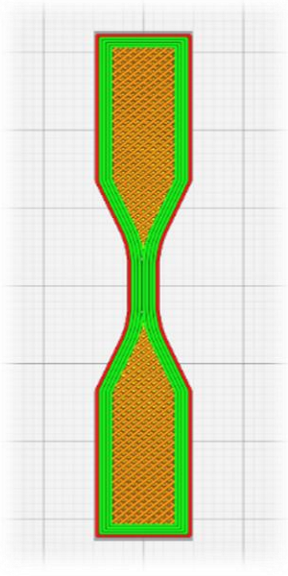


Figure 3.8: Layer height 0.15mm infill %50 Shell 5

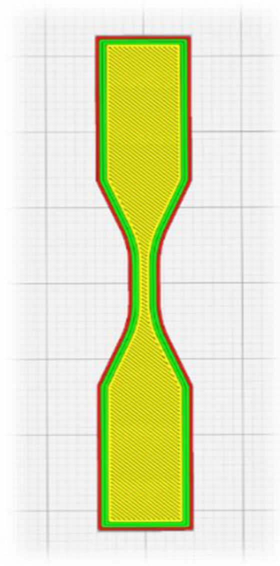


Figure 3.9: Layer height 0.2mm, infill %100, Shell 3

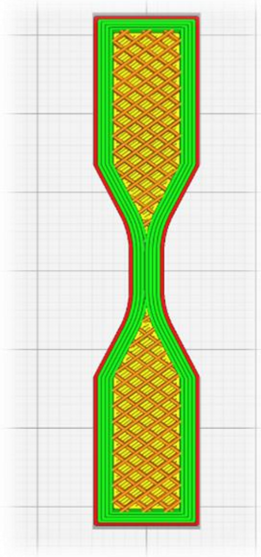


Figure 3.10: Layer height 0.2mm, infill %25 Shell 5

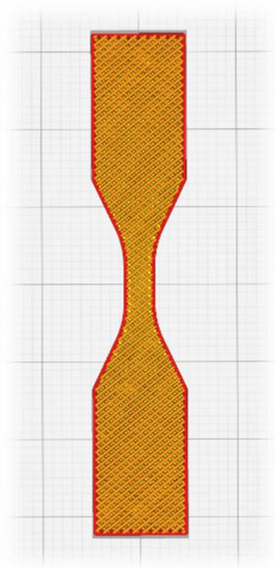
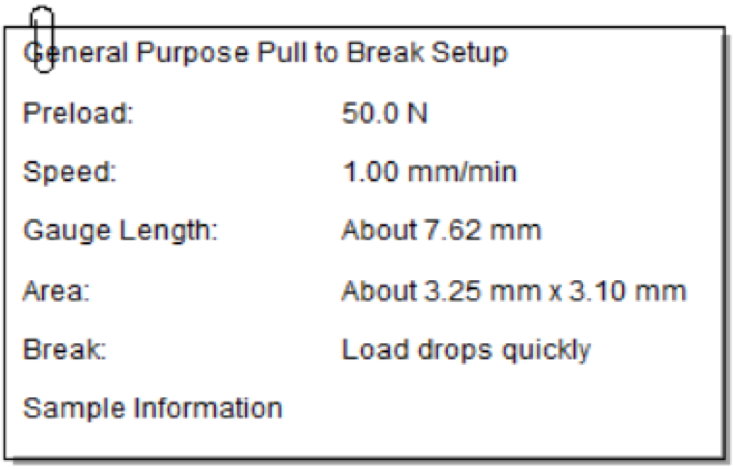


Figure 3.11: Layer height 0.2mm, infill %50 Shell 1



General Purpose Pull to Break Setup

Preload:	50.0 N
Speed:	1.00 mm/min
Gauge Length:	About 7.62 mm
Area:	About 3.25 mm x 3.10 mm
Break:	Load drops quickly
Sample Information	

Figure 3.12: Interface from Universal Tensile Test Machine Test Specimen

According to the results given by Taguchi, the samples are prepared in the program with the interface of 3D printer, the files were converted to the stl format and sent to the machine for production. In Figures below 3.13 and 3.14 as it can be seen 3d printer and their user interface.

Figure 3.13: 3D Printer.

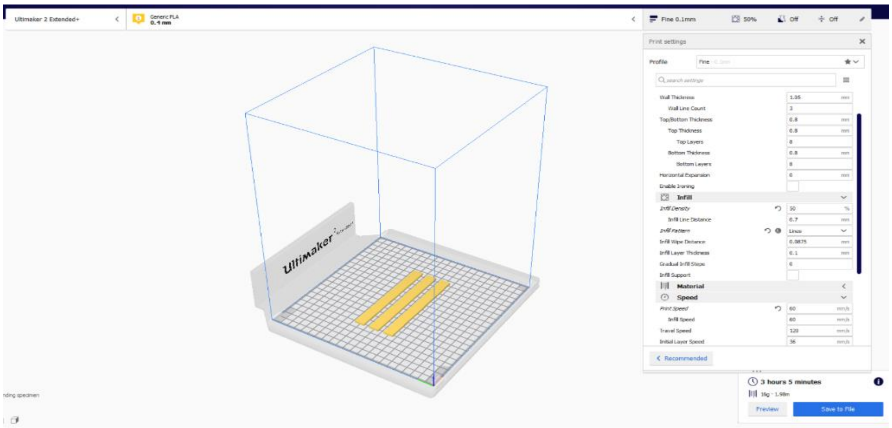


Figure 3. 14: Interface of 3D printer (Cura).

3.3.5. Three-point bending test

1) Test standard ASTM D790

These test methods cover the determination of flexural properties of non-reinforced and reinforced plastics, including high-modulus composites and electrical insulating materials in the form of rectangular bars moulded directly or cut from sheets, plates, or molded forms. These methodologies usually refer to both stiff and semi-rigid materials. However, flexural strength cannot be determined for such materials that do not break or fall within the 5.0 percent strain maximum of these test methods in the outer surface of the test specimen. These test methods use a three-point loading system which is applied to a simply supported beam (ASTM International, 2003). Three-point bending apparatus as it can be seen in Figure 3.15.

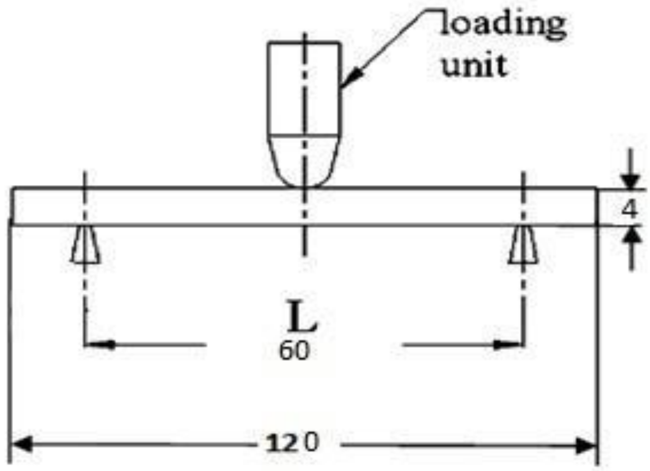


Figure 3.15: Three-point bending apparatus.

For a three-point test, the flexural strength (given the symbol **σ**) can be calculated using:

$\sigma = 3FL / 2wd^2$

where;

F: means the maximum force applied.

L: is the length of the sample.

w: is the width of the sample.

d: is the depth of the sample.

2) Test specimen for three-point bending

The recommended molding material specimen is 127 by 12.7 by 3.2 mm [5 by 1⁄2 by 1⁄8 in.], tested flatly on a support span, resulting in a span-to-depth support ratio of thicker specimens should be avoided when moulded with significant shrink marks or bubbles (ASTM International, 2003).The three point bending test sample is shown in the Figure 3.16 and in Figure 3.17 as it can be seen Nexygen interface from universal tensile test machine test specimen.

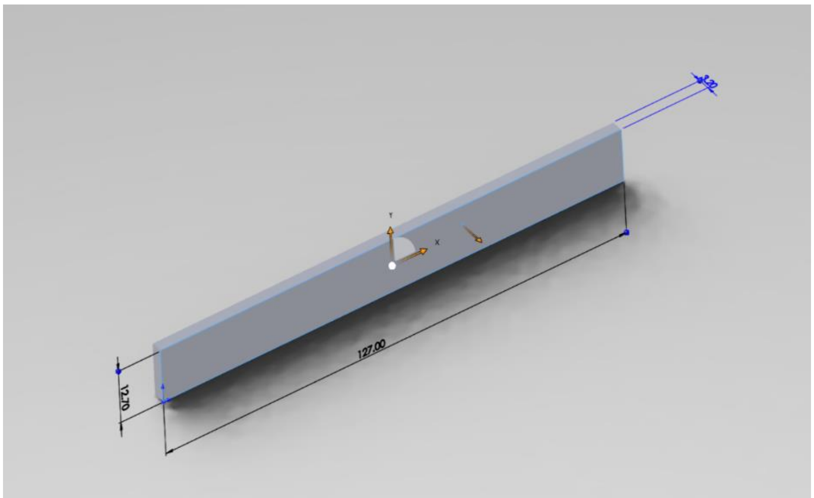
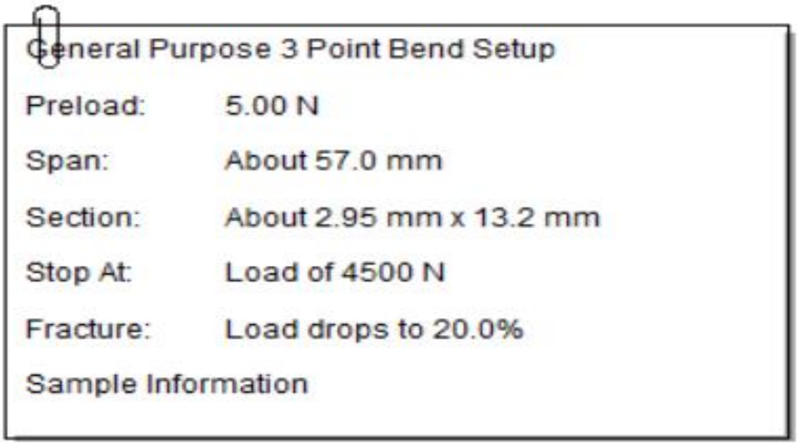


Figure 3.16: Three-point bending test sample in design stage.



General Purpose 3 Point Bend Setup

Preload:	5.00 N
Span:	About 57.0 mm
Section:	About 2.95 mm x 13.2 mm
Stop At:	Load of 4500 N
Fracture:	Load drops to 20.0%

Sample Information

Figure 3.17: Nexygen interface from universal tensile test machine test specimen.

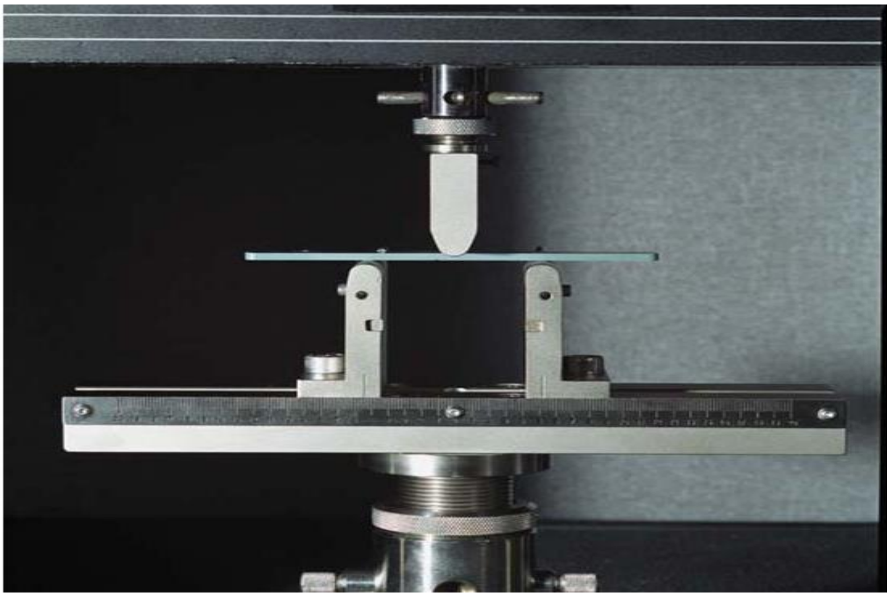


Figure 3.18: Three-point bending techniques

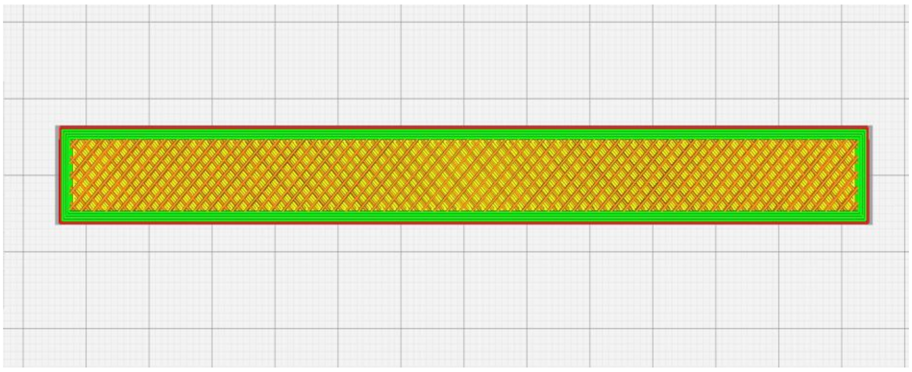


Figure 3.19: Sample of three-point bending test.

In Figures 3.18 and 3.19 shown above shows its preparation in accordance with the parameters in the program interface designed according to the 3-center printing standard and before it was sent to the 3D printer for production.

CHAPTER 4
RESULT AND DISCUSSION

The current chapter discusses the results and the consequence of the experiments. A total of 54 samples of three-point bending and tensile test were tested obey Taguchi and variance analysis. The resulting graphs are given in Appendix 1. Instead of making 81 different combination tests with Taguchi method there is only 9 different combinations are tested. Used in both tensile and 3 point bending test specimen. As a result of these tests, it was observed that the changes in factors and levels directly affect the result of the material in strength and elongation and as a result of the optimized combinations, it was able to withstand 572 N (Newtons) in the tensile test and 97 N (Newtons) in the bending test. The most affected parameters in three-point bending test descending order: Shell, Infill also in tensile test the most affected parameters descending order: Infill, Shell. Polylactic acid was printed on a 3D printer by melting at 210 degrees and 60 on the production table. While printing, the room temperature was kept stable at 25 degrees. Sudden cooling and sudden cross-section changes and similar discontinuities cause stress concentration, especially in the stress area. Such as stress concentrations are considered to have a notch effect in the material. While producing the test specimens these problems were encountered therefore metals were placed in the production table while producing the test specimens owing to notch problem on the material caused by sudden cooling has been eliminated with this method.

4.1 Taguchi Analysis for Three-Point Bending Test

Taguchi analysis parameters: Max. load (N) vs layer height (mm), speed (mm/s), infill (%), shell. Response table for signal to noise ratios and response table for means results shown in Table 4.1 and Table 4.2. Also, Taguchi and ANOVA optimization graphs of three-point bending test shown in Figures 4.1 to 4.6.

Table 4.1: Response table for signal to noise ratios

Larger is better.

Level	Layer Height (mm)	Speed (mm/s)	Infill (%)	Shell
1	**40.65**	40.20	**41.18**	38.96
2	40.25	39.96	40.66	39.97
3	40.21	**40.96**	39.28	**42.19**
Delta	0.44	1.01	1.91	3.23
Rank	4	3	2	1

Table 4.2: Response table for means

Level	Layer Height (mm)	Speed (mm/s)	Infill (%)	Shell
1	**108.46**	103.95	**115.43**	89.47
2	105.87	102.34	108.75	100.47
3	104.33	**112.37**	94.48	**128.72**
Delta	4.12	10.03	20.94	39.25
Rank	4	3	2	1

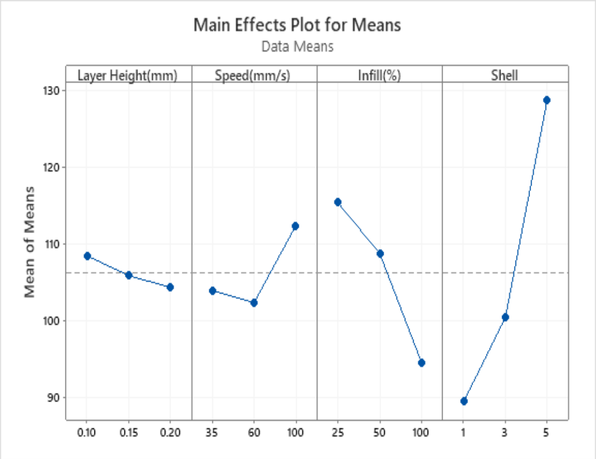


Figure 4.1: Main effects plot for means.

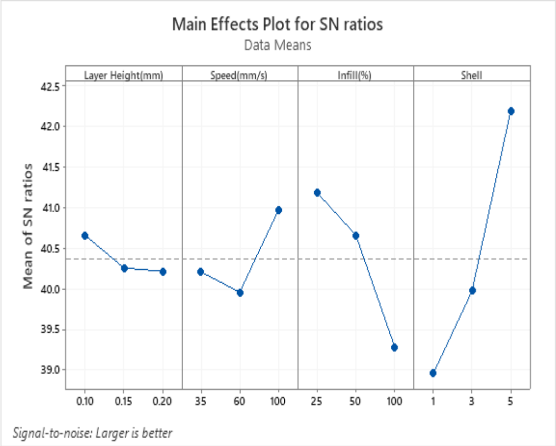


Figure 4.2: Main effects plot for SN ratios.

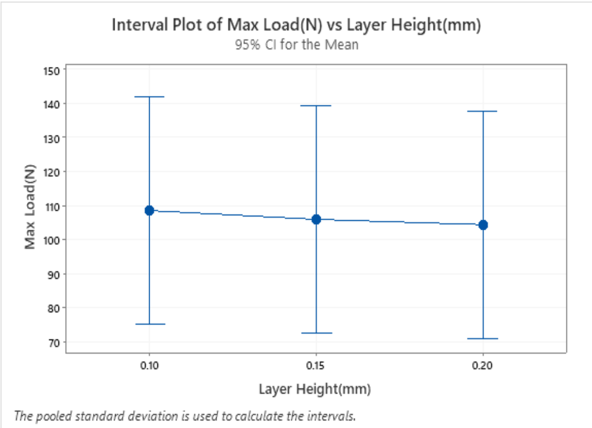


Figure 4.3: Interval plot of max load(N) vs layer height(mm).

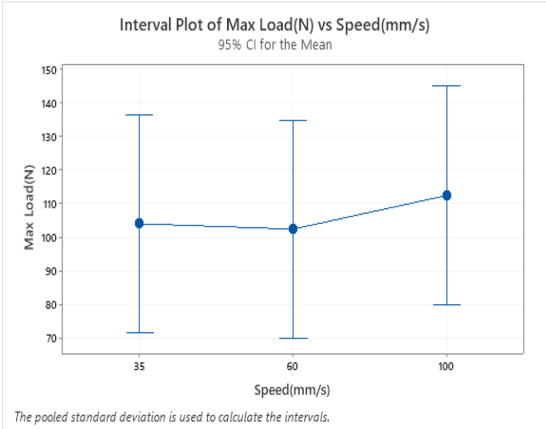


Figure 4.4: Interval plot of max load(N) vs speed(mm/s).

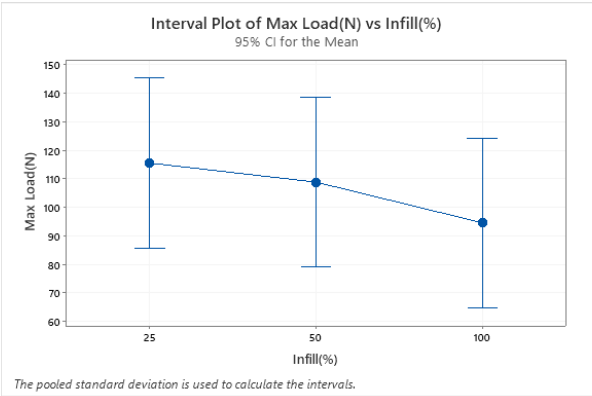


Figure 4.5: Interval plot of max load(n) vs layer infill (%).

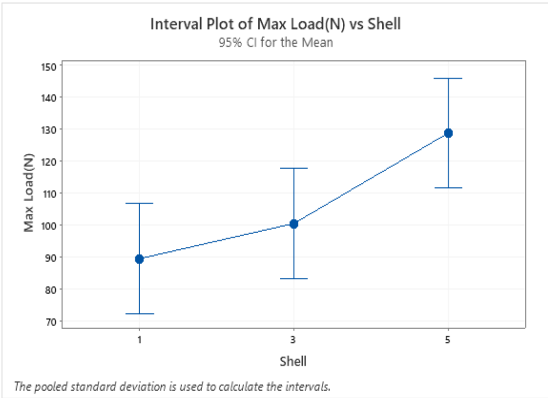


Figure 4.6: Interval plot of max load(N) vs shell.

4.2 Taguchi analysis for tensile test

Taguchi Analysis Parameters: Max load (N) vs Layer height (mm), speed (mm/s), infill (%), shell. Response table for signal to noise ratios and response table for means results shown in Table 4.3 and Table 4.4. Also, Taguchi and ANOVA optimization graphs of tensile test shown in Figures 4.7 to 4.12.

Larger is better.

Table 4.3: Response table for signal to noise ratios

Level	**Layer Height (mm)**	**Speed (mm/s)**	**Infill (%)**	**Shell**
1	50.11	51.37	49.48	50.11
2	**52.45**	**52.71**	**53.24**	51.90
3	52.41	50.89	52.24	**52.95**
Delta	2.34	1.81	3.76	2.83
Rank	3	4	1	2

Table 4.4: Response table for means

Level	**Layer Height (mm)**	**Speed (mm/s)**	**Infill (%)**	**Shell**
1	337.4	403.7	311.8	336.6
2	**432.1**	**431.9**	**465.1**	399.5
3	418.1	351.9	410.6	**451.4**
Delta	94.7	80.0	153.4	114.8
Rank	3	4	1	2

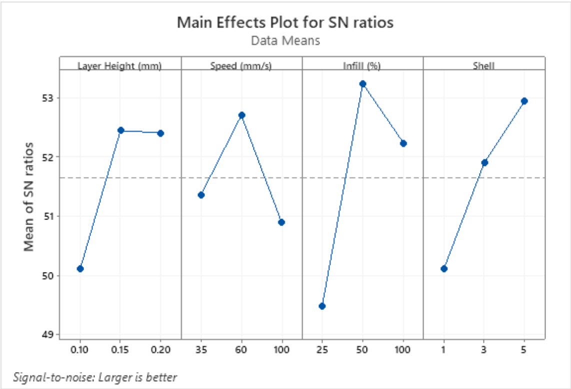


Figure 4.7: Main effects plot for SN ratios

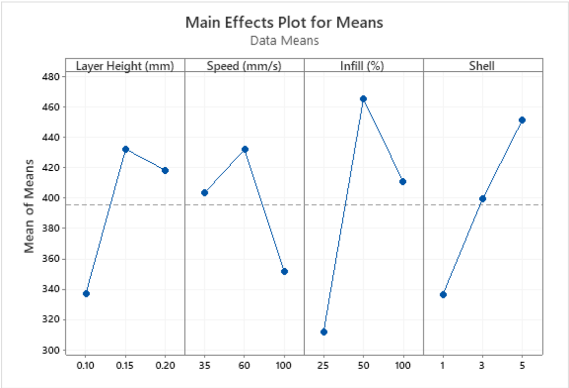


Figure 4.8: Main effects plot for means

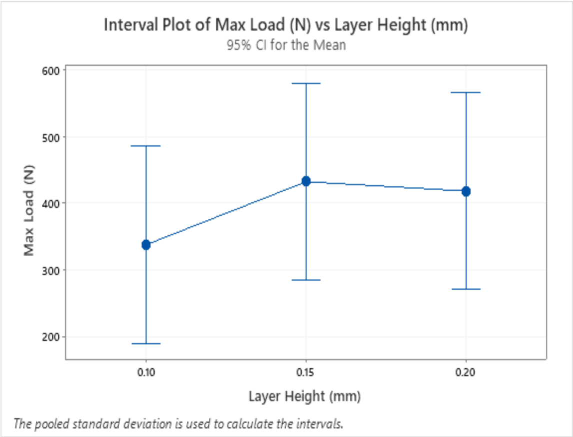


Figure 4.9: Interval plot of max load(N) vs layer height (mm)

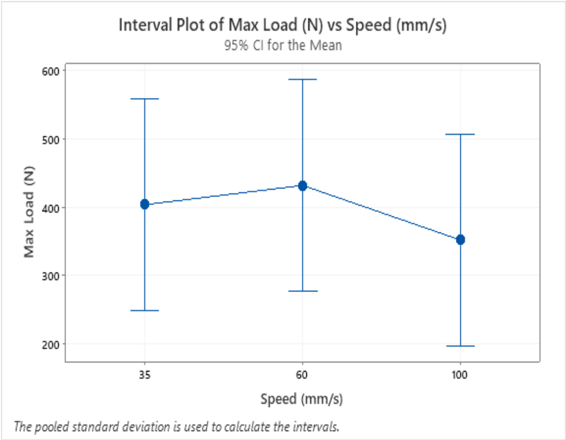


Figure 4.10: Interval plot of max load(N) vs speed(mm/s)

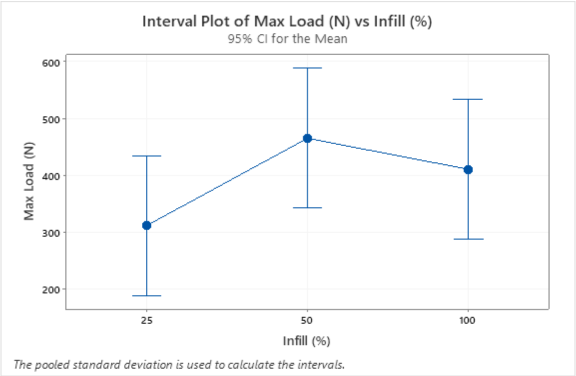


Figure 4.11: Interval plot of max load(N) vs infill (%)

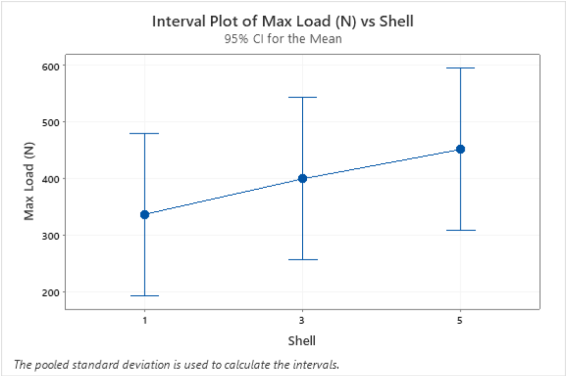


Figure 4.12: Interval plot of max load(N) vs shell

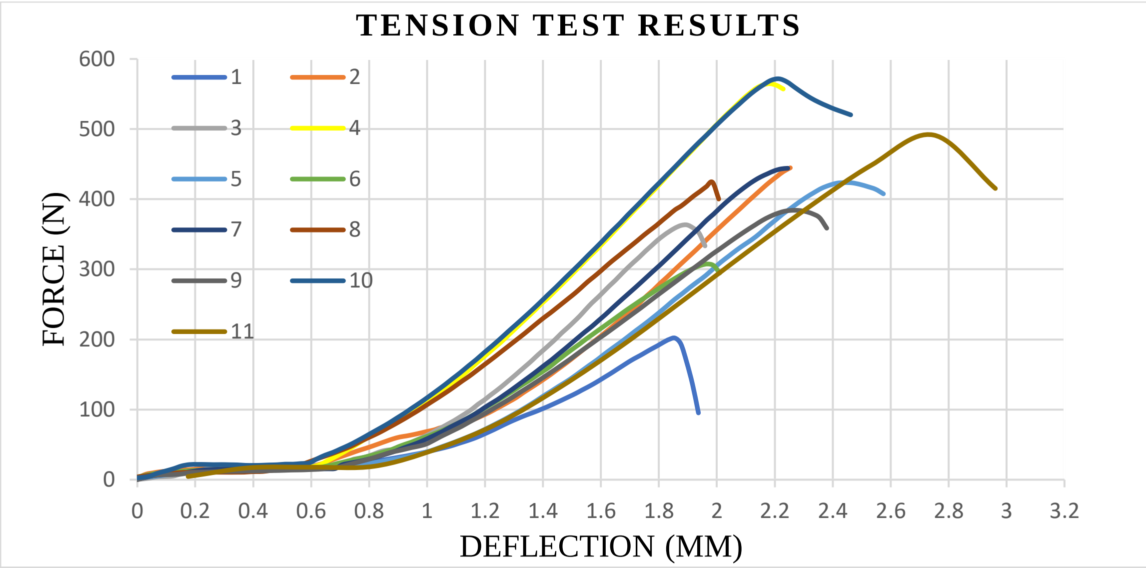


Figure 4.13: Taguchi analysis samples of tension test results force vs deflection graph.

Table 4.5: Taguchi analysis samples of tension test results

Number	Layer Height	Print Speed	Infill	Shell	Max.Load
1).	0.10	35mm/s	25%	1	201.92 N
2).	0.10	60mm/s	50%	3	446.46 N
3).	0.10	100mm/s	100%	5	363.83 N
4).	0.15	35mm/s	50%	5	564.75 N
5).	0.15	60mm/s	100%	1	423.75 N
6).	0.15	100mm/s	25%	3	307.72 N
7).	0.20	35mm/s	100%	3	444.34 N
8).	0.20	60mm/s	25%	5	425.63 N
9).	0.20	100mm/s	50%	1	384.25 N
10).	0.15	60mm/s	50%	5	572 N
11).	0.10	100mm/s	25%	5	496 N

In the Table 4.5 and Figure 4.13 shown above, the results of tensile test are listed as load and deflection graph, and graph of all results according to varying load and deflection. The layer height, shown in mm, and the print speed represents in mm/s, the infill in percent, and the shell of the material in the number without the unit. The results are shown in different colours. The tenth and eleventh samples are the optimum parameters obtained as a result of ANOVA variance analysis.

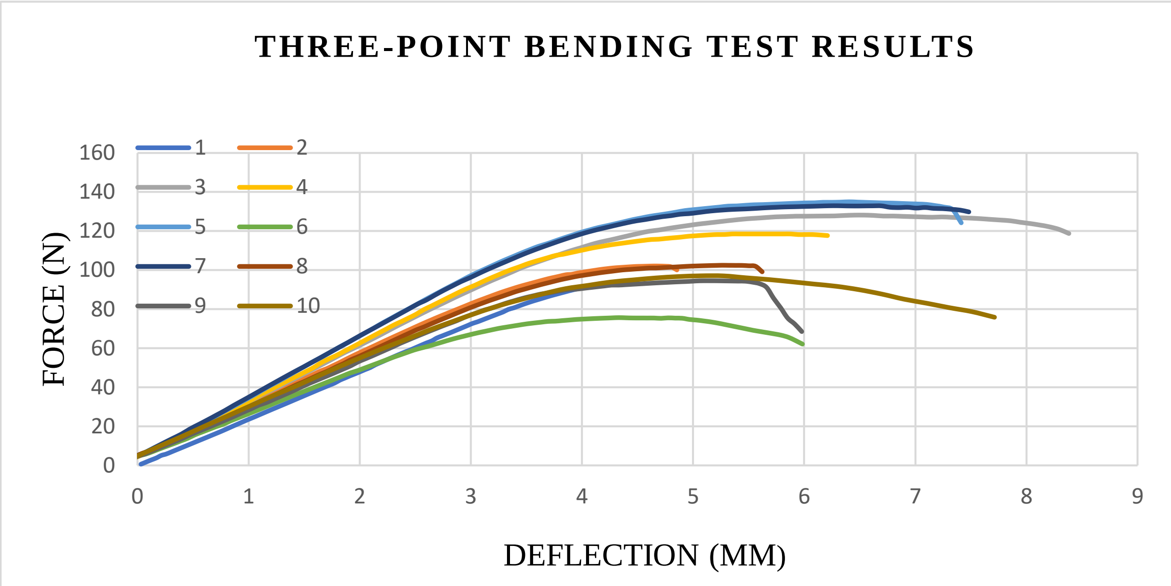


Figure 4.14: Taguchi analysis samples of three-point test results force vs deflection graph.

Table 4.6: Taguchi analysis samples of three-point bending test results

Number	Layer Height	Print Speed	Infill	Shell	Max.Load
1).	0.10	35mm/s	25%	1	98.65 N
2).	0.10	60mm/s	50%	3	101.35 N
3).	0.10	100mm/s	100%	5	125.37 N
4).	0.15	35mm/s	50%	5	128.63 N
5).	0.15	60mm/s	100%	1	73.50 N
6).	0.15	100mm/s	25%	3	115.47 N
7).	0.20	35mm/s	100%	3	84.87 N
8).	0.20	60mm/s	25%	5	132.16 N
9).	0.20	100mm/s	50%	1	96.25 N
10).	0.10	100mm/s	25%	5	97 N

In the Table 4.6 and Figure 4.14 shown above, the results of bending test are listed as load and deflection graph, and graph of all results according to varying load and deflection. The layer height, shown in mm, and the print speed represents in mm/s, the infill in percent, and the shell of the material in the number without the unit. The results are shown in different colours. The tenth sample is the optimum parameters obtained as a result of anova variance analysis.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1. Conclusion

3D printing method is a technology that increased the capacity of innovation and changed the understanding dimension production by improving the link between design and manufacturing and by this improvement the ability to produce unique parts increased. Fused Filament Fabrication (FFF) technique focused reduction in production cost and cleaner production. This technology provides more environmentally friendly production parameters according to absences of emissions and waste products during the production. This manufacturing technique can be used easily and at very low cost to produces required parts, models and samples without any production waste and regardless of its geometry. The aim of this investigation is to search for new materials while producing implants. Due to the rapid and low cost of the production of polylactic acid with this technology, thanks to such studies, the search for new materials that will increase day by day will be answered. These materials will replace the usual materials that are difficult and costly to manufacture. Only 9 different combinations are tested using with taguchi method instead of 81 tests for both tensile and three-point bending tests. As seen in the results of the tests, it was observed that the material was enduring a load of 572 N (newtons) in the tensile test and 97 N (newtons) in the bending tests. 3 tests were done from each sample.

5.2. Recommendation and Future Works

This study and similar studies will enable the use of easy production techniques such as 3D printing method in the medical and other industrial fields and will help engineering science. In products to be produced using 3D printer technology, it was observed that preventing sudden cooling affects the durability of the product produced, therefore it is recommended to prevent sudden cooling during production due to the result of this study. Due to the rapid and low cost of the production of polylactic acid with this technology, thanks to such studies, the search for new materials that will increase day by day will be answered. These materials will replace the usual materials that are difficult and costly to manufacture so, the next steps of this work are to test samples, in collaboration with the veterinary faculty, by producing samples for rat, rabbit and sheep testing. Afterwards, to make tests to produce special implants from the CT model according to the needs of the patient. This 3d printed implant has already given as a PhD thesis in veterinary faculty and their work will investigate decomposition of the PLA in living tissue. The implants that PhD thesis in veterinary faculty will be printed by the best performing parameters. The end goal of this research is to create implants which will have all required mechanical properties till a broken bone re-join and decompose without having any medical consequences which will also stop the need of the second surgery operation to remove the implant.

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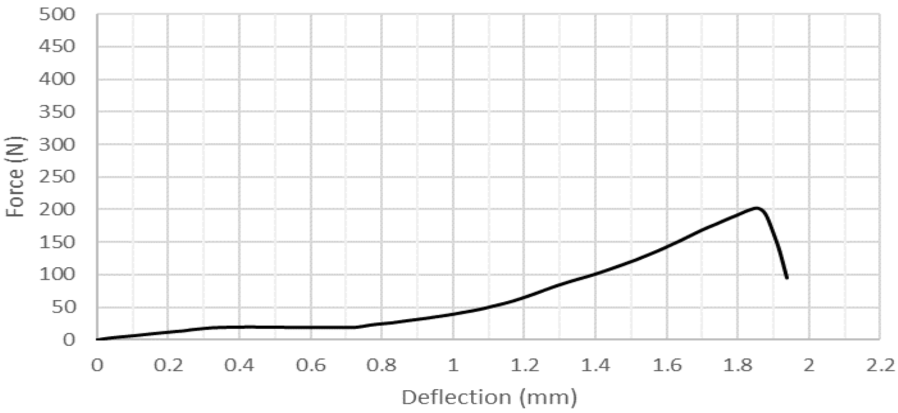
APPENDICES

APPENDIX 1

FORCE VS DEFLECTION AND STRESS VS STRAIN GRAPHS FOR TENSILE AND BENDING TESTS

Tensile Test Results

Specimen 1: 0.1 L.H, P.S. 35mm/s   Infill 25% Shell 1



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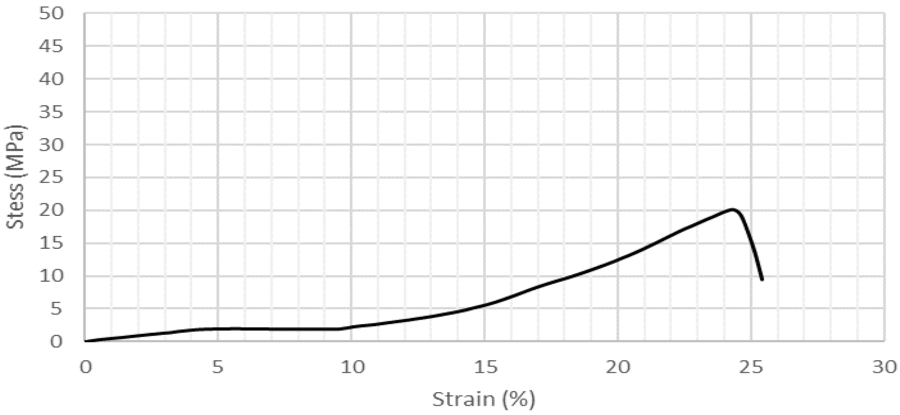
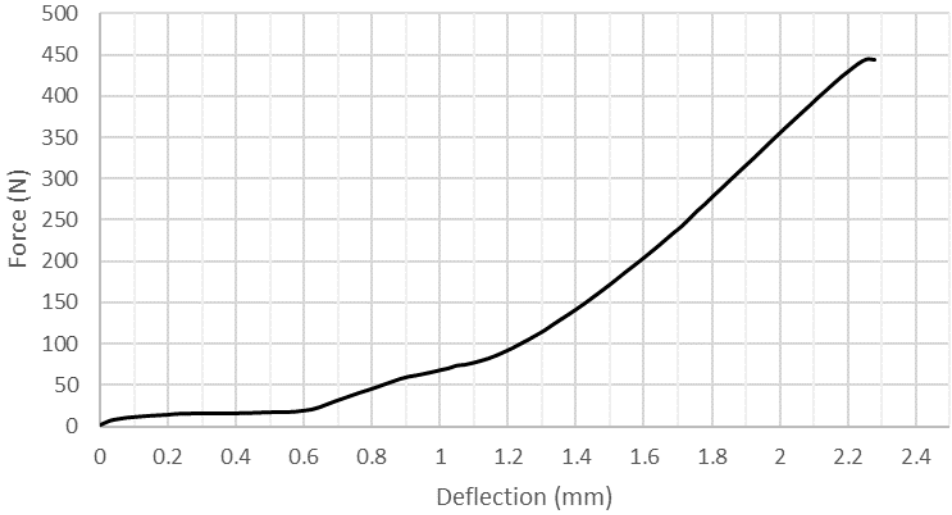


(b)

Specimen 2: 0.1 L.H, P.S. 60mm/s, Infill 50%, Shell 3



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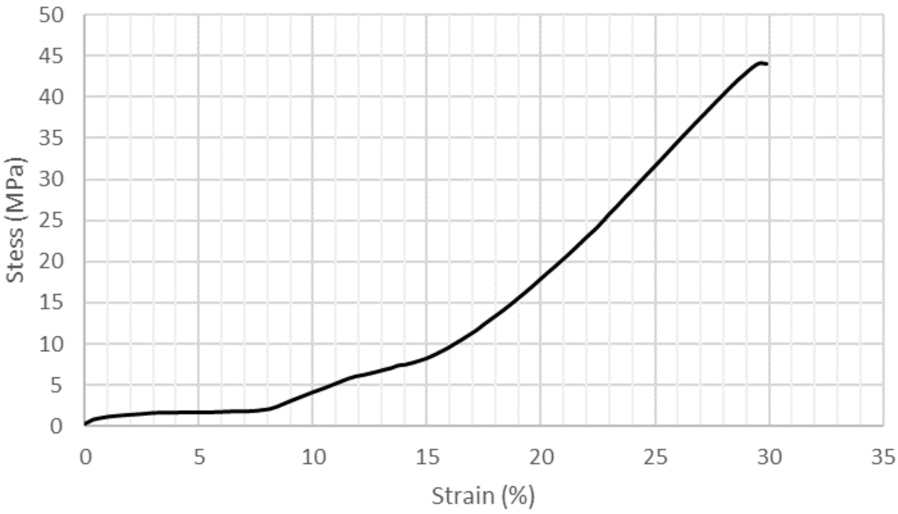

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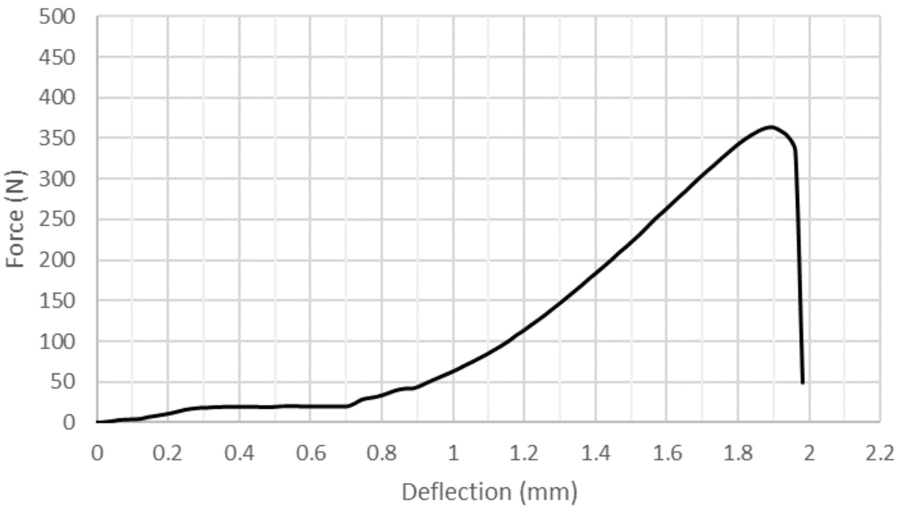
Specimen 3: 0.1 L.H, P.S. 100mm/s, Infill 100%, Shell 5



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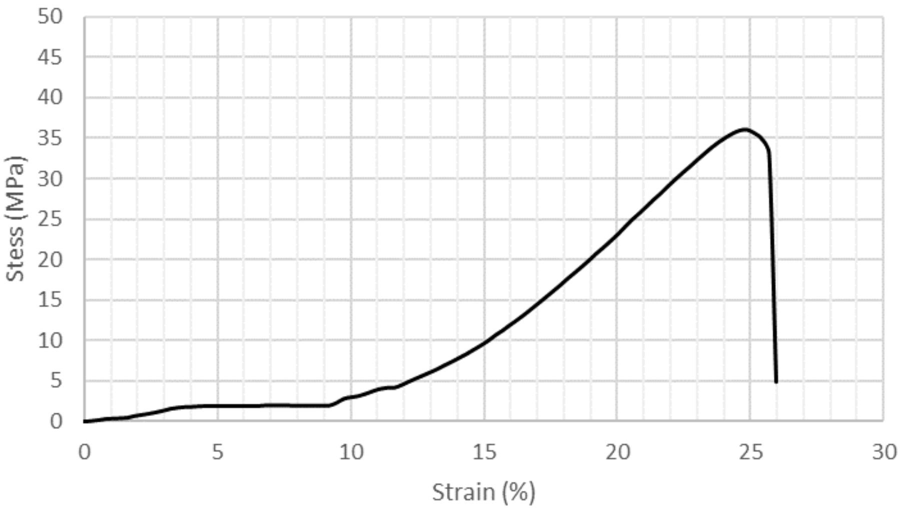
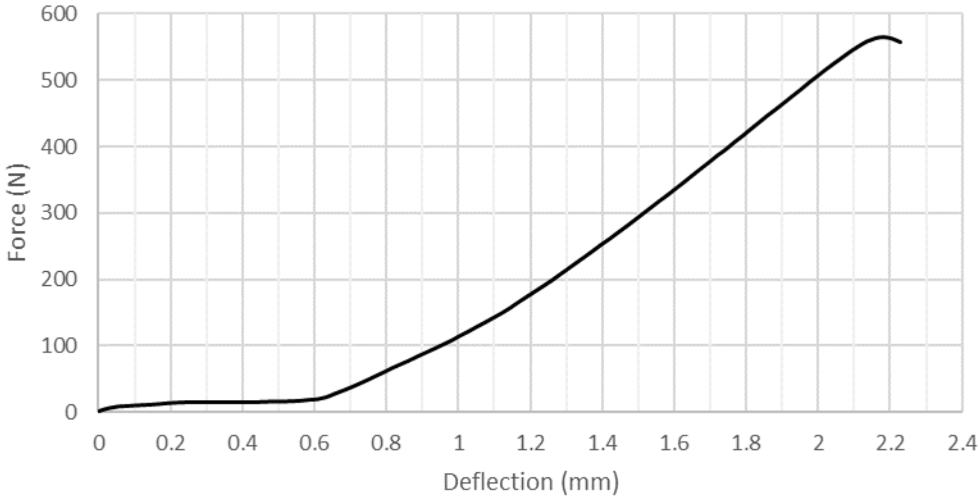


(b)

Specimen 4: 0.15 L.H, P.S. 35 mm/s, Infill 50%, Shell 5



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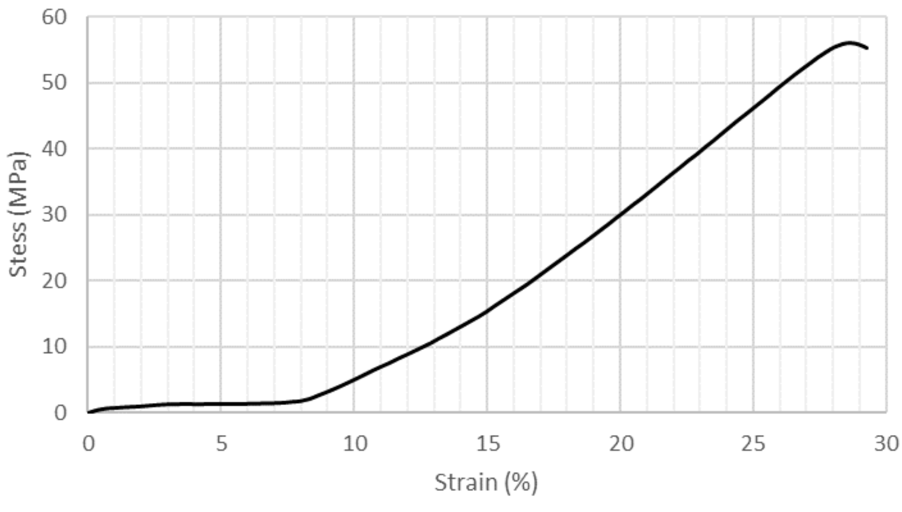
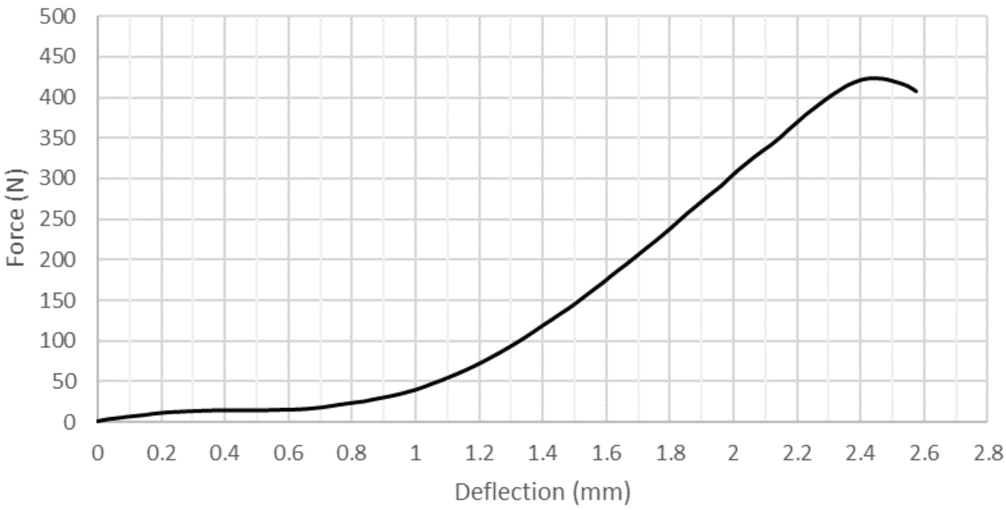


(b)

Specimen 5: 0.15 L.H, P.S. 60mm/s, Infill 100%, Shell 1



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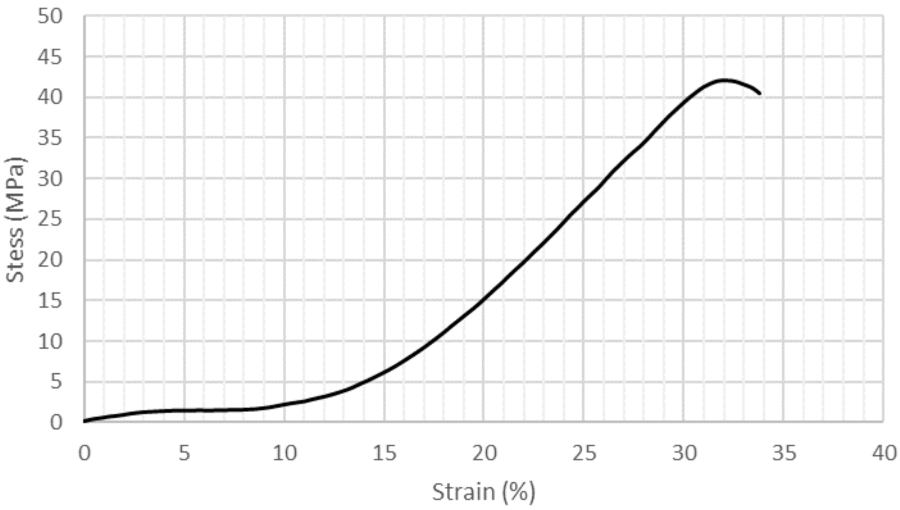
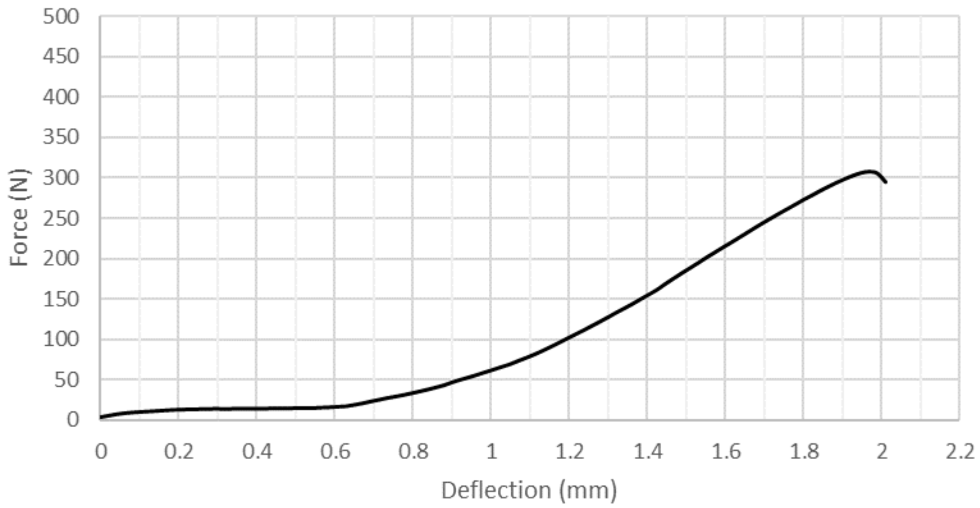


(b)

Specimen 6: 0.15 L.H, P.S. 100mm/s, Infill 25%, Shell 3



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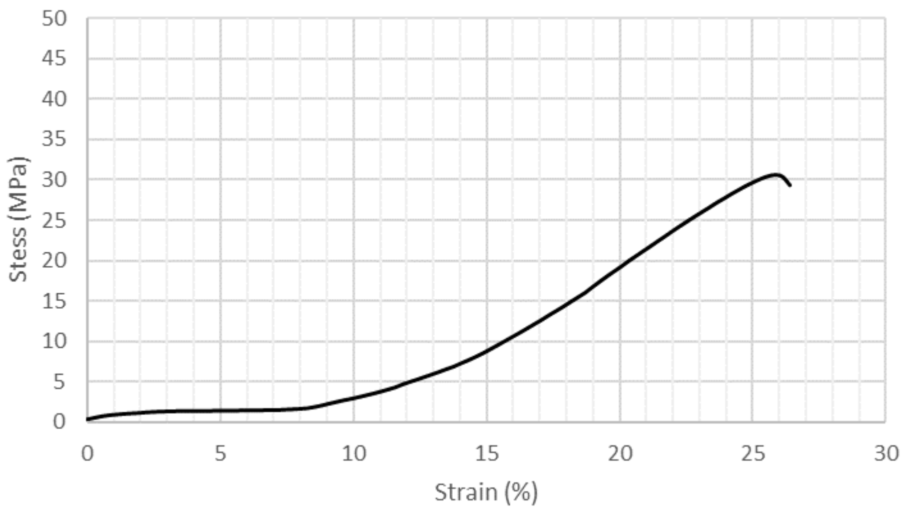

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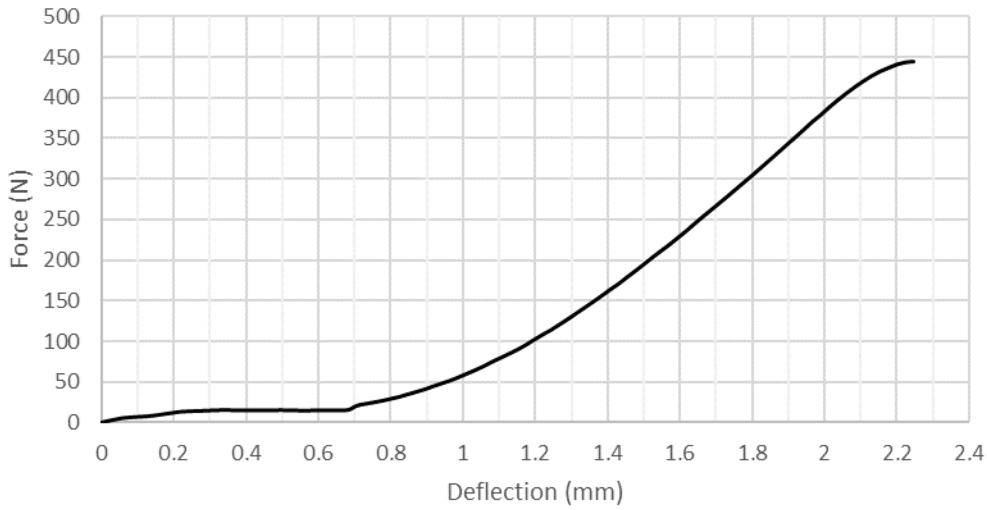
Specimen 7: 0.2 L.H, P.S. 35mm/s, Infill 100%, Shell 3



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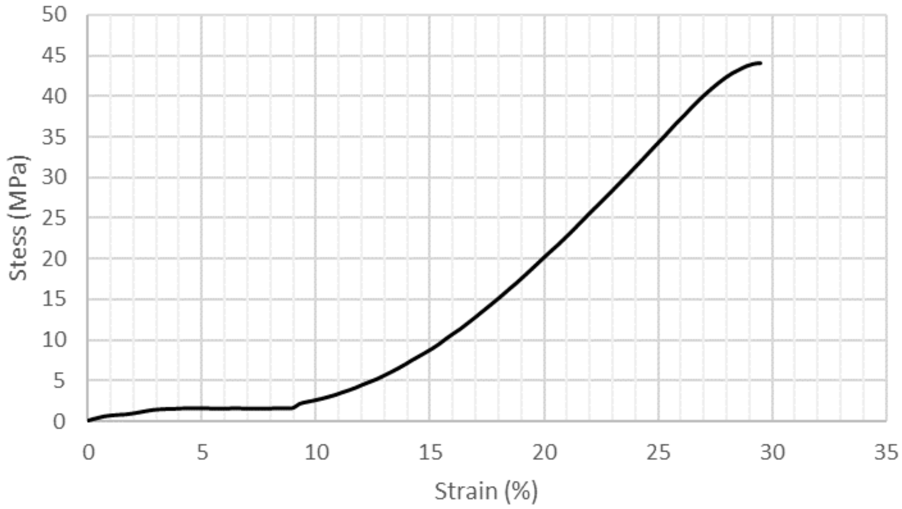
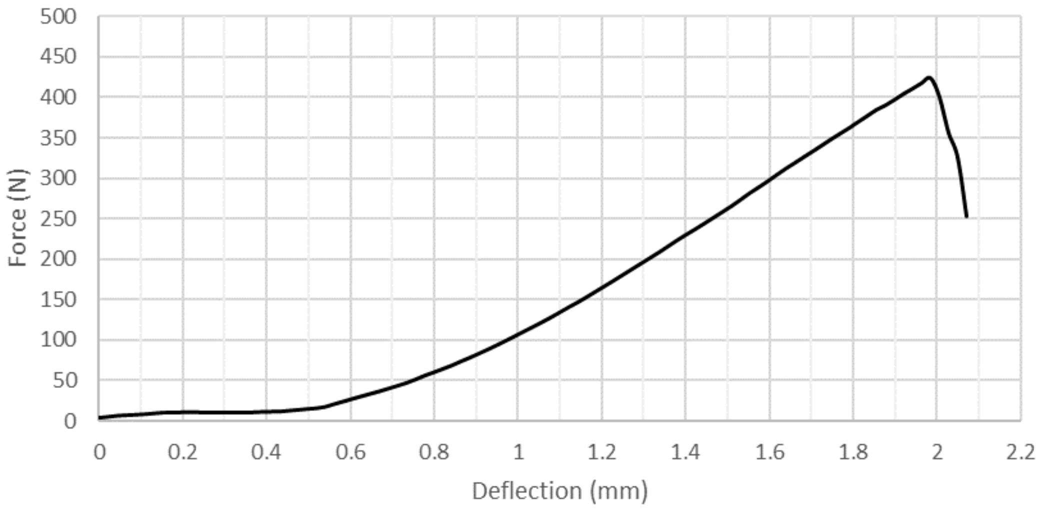


(b)

Specimen 8: 0.2 L.H, P.S. 60mm/s, Infill 25%, Shell 5



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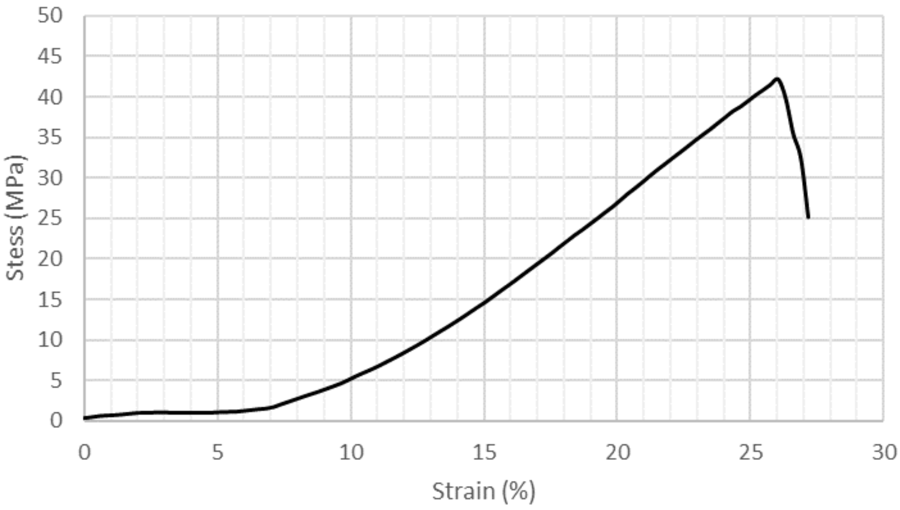
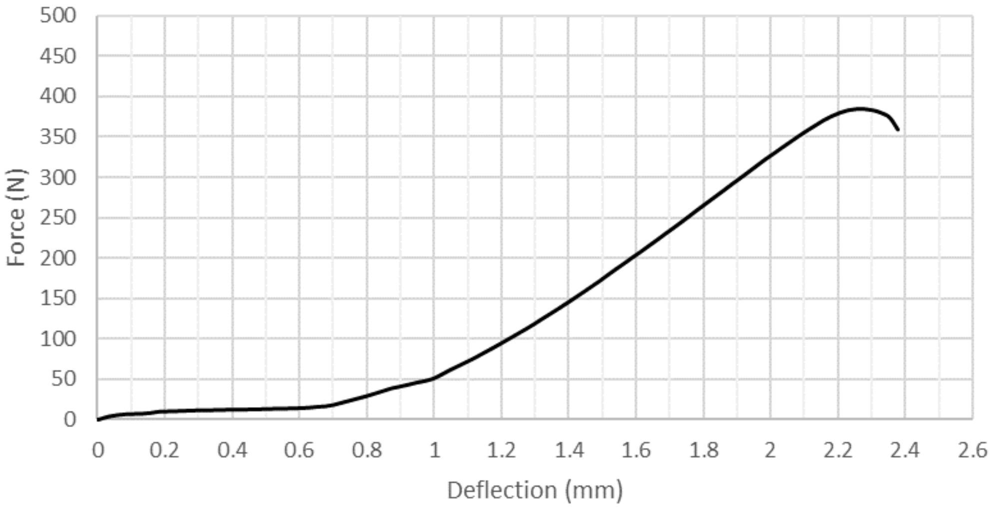


(b)

Specimen 9: 0.2 L.H, P.S. 100mm/s, Infill 50%, Shell 1



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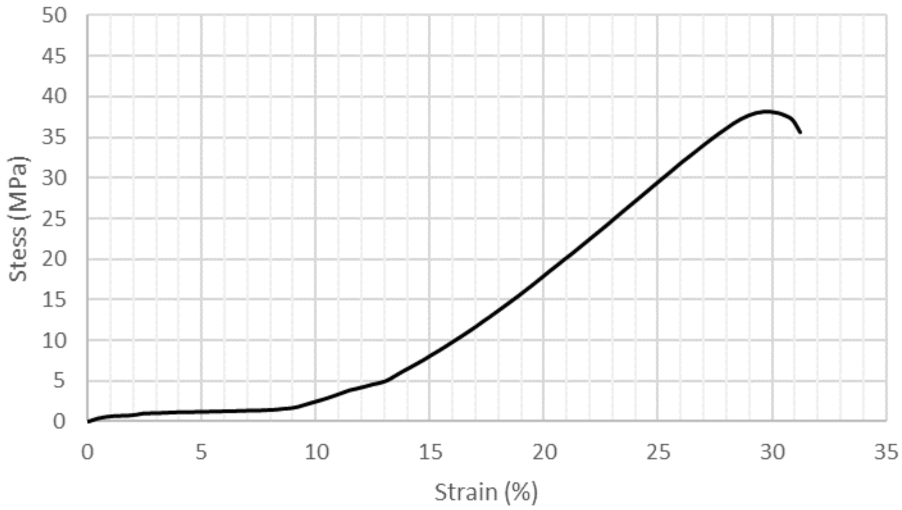

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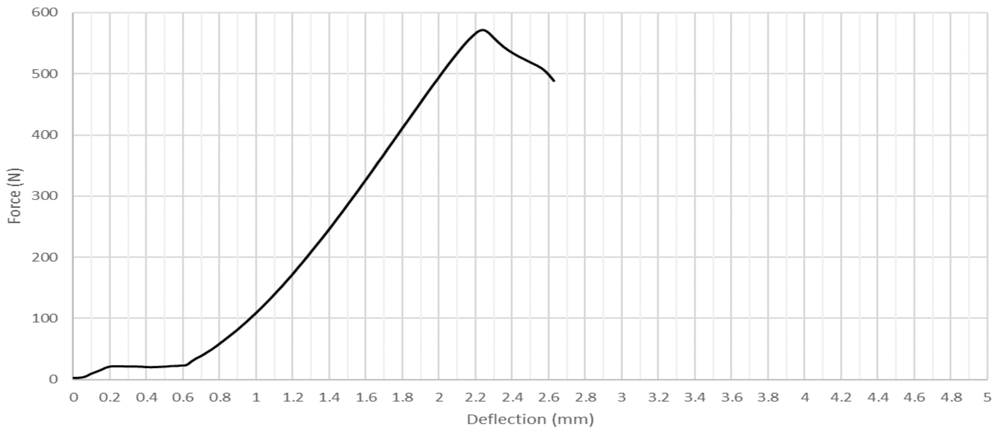
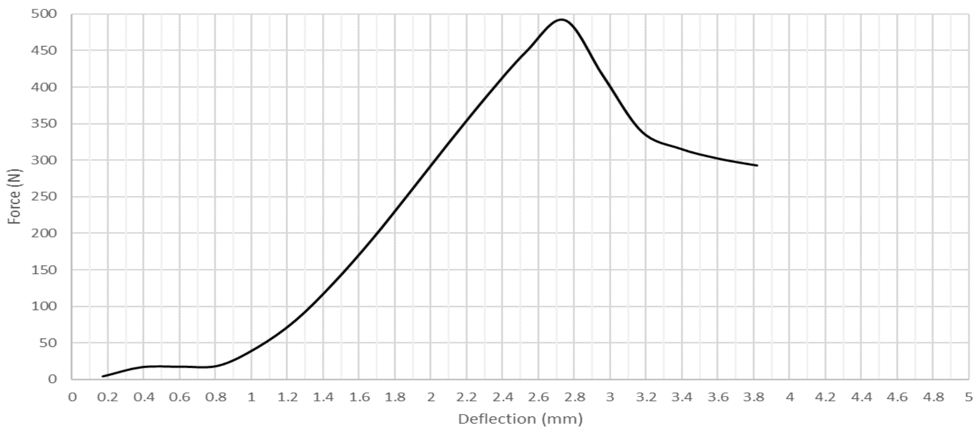
Specimen 10: 0.15 L.H, P.S. 60mm/s, Infill 50%, Shell 5



(a)

Specimen 11: 0.1 L.H, P.S. 100mm/s, Infill 25%, Shell 5



(b)

Bending Test Results

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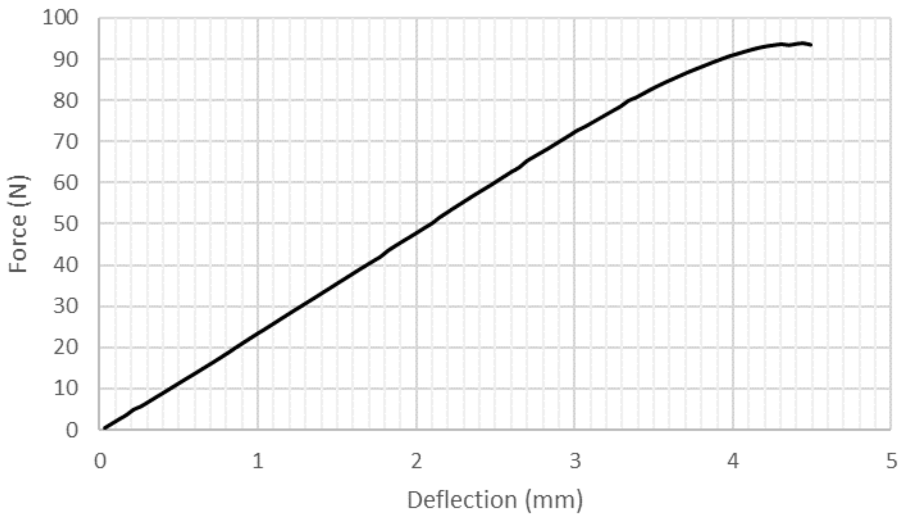

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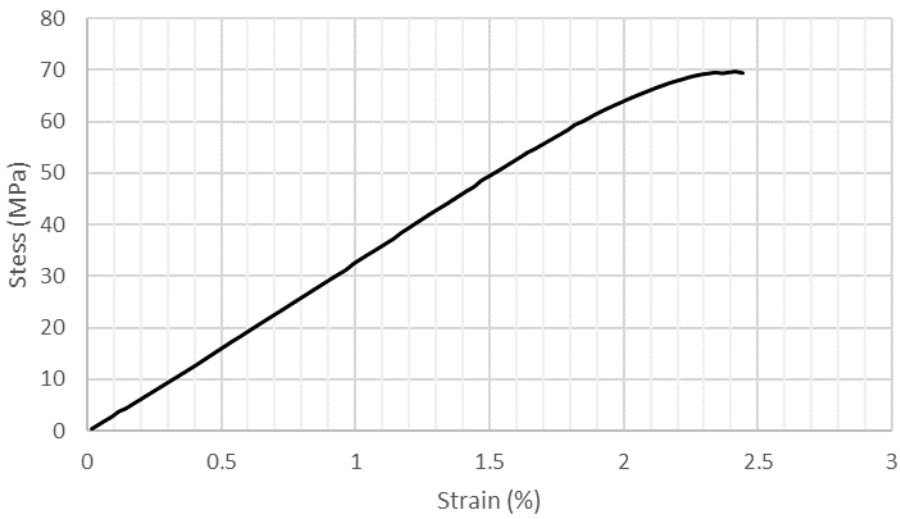

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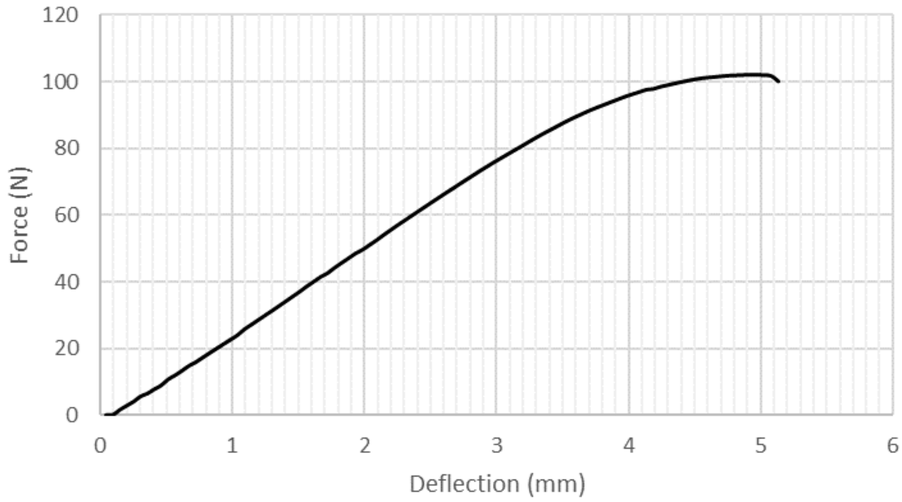

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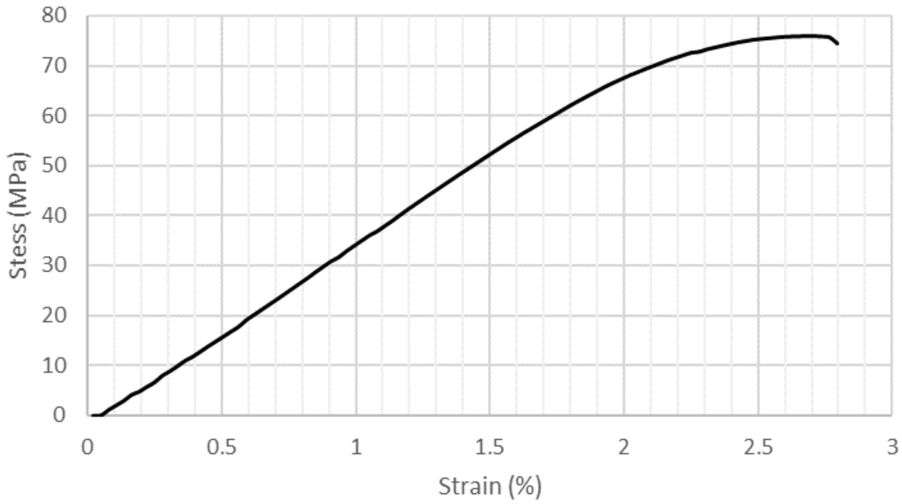
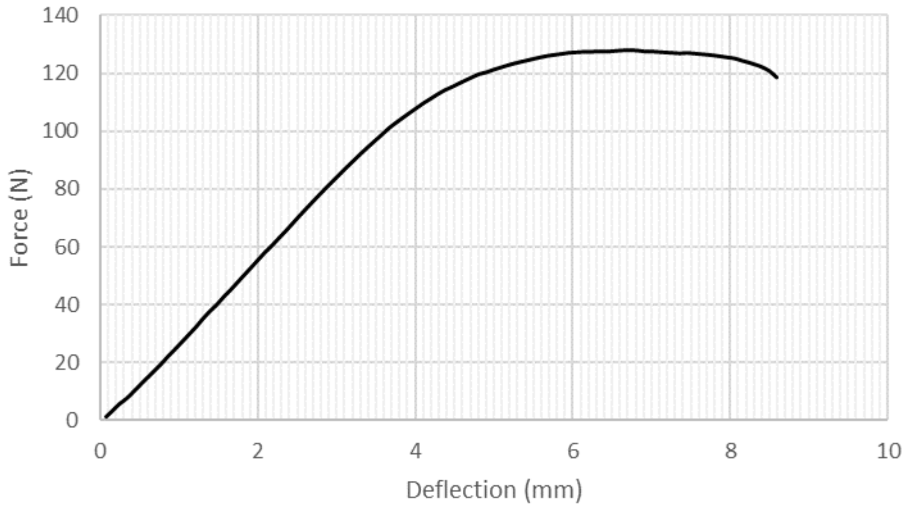


(b)

Specimen 3: 0.1 L.H, P.S. 100mm/s, Infill 100%, Shell 5



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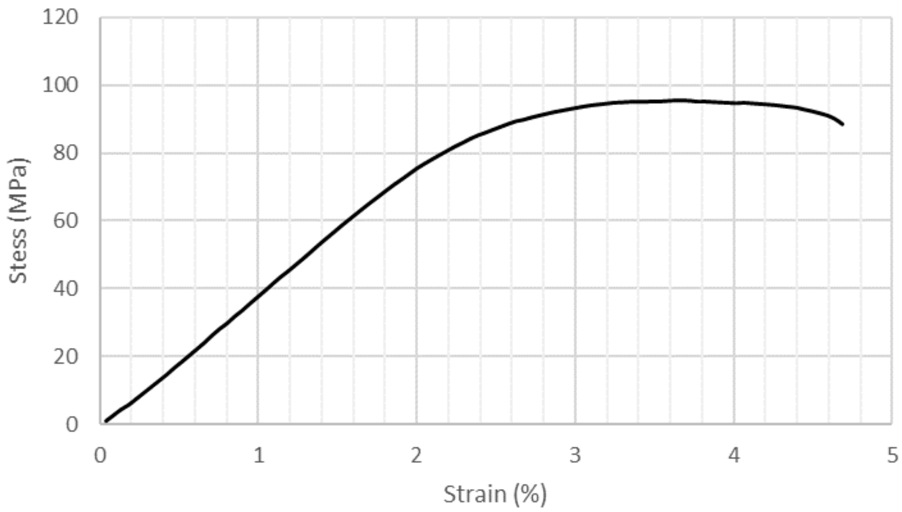
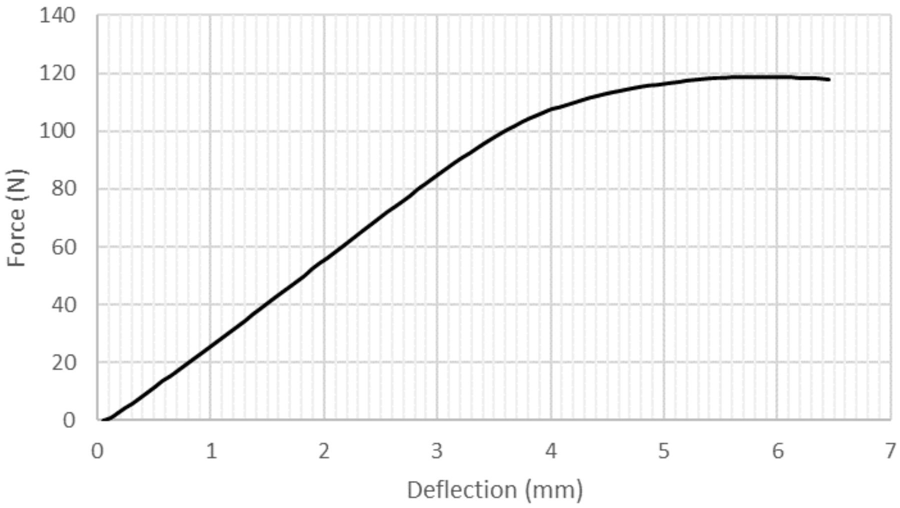


(b)

Specimen 4: 0.15 L.H, P.S. 35 mm/s, Infill 50%, Shell 5



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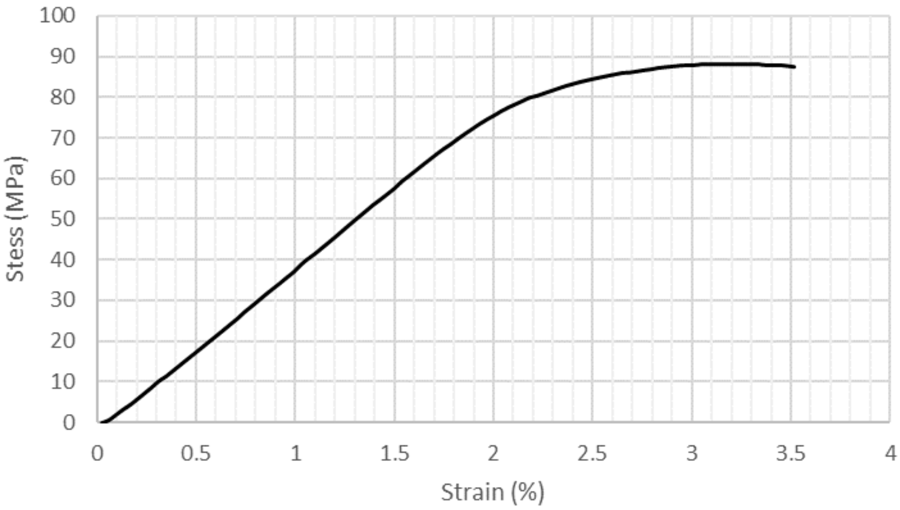
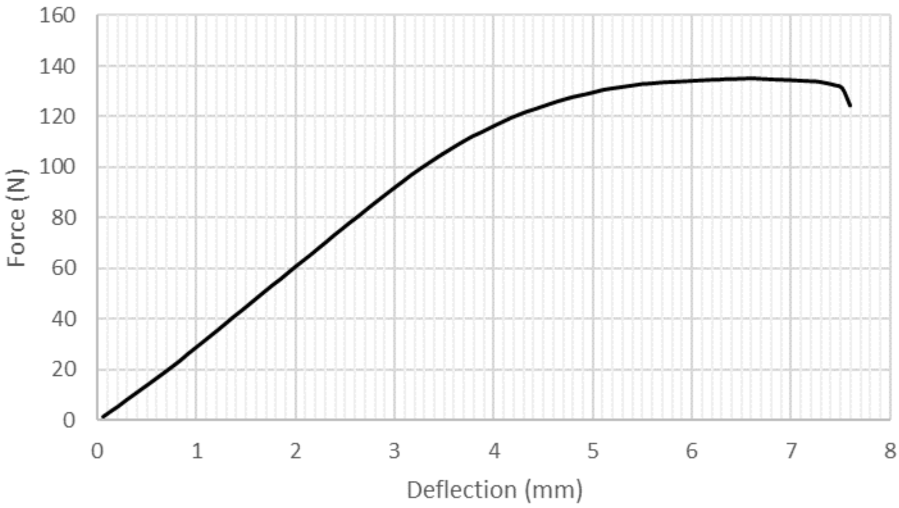


(b)

Specimen 5: 0.15 L.H, P.S. 60mm/s, Infill 100%, Shell 1



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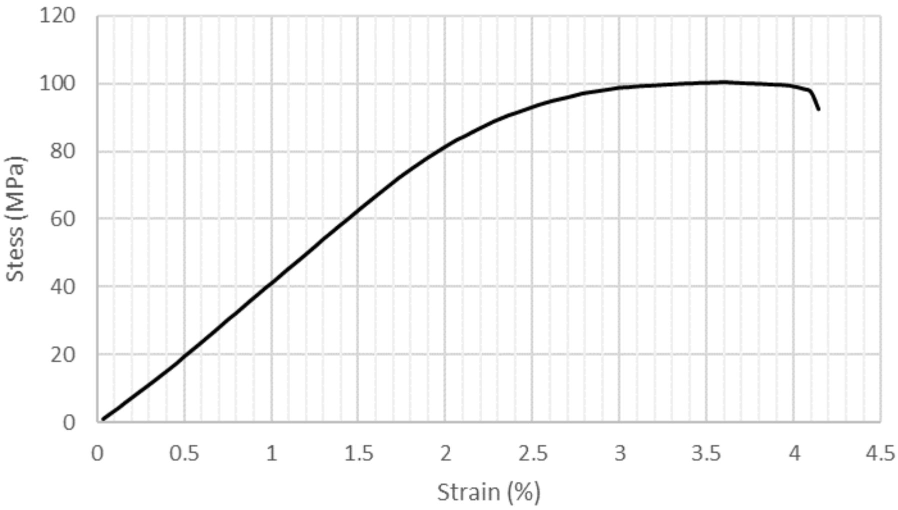

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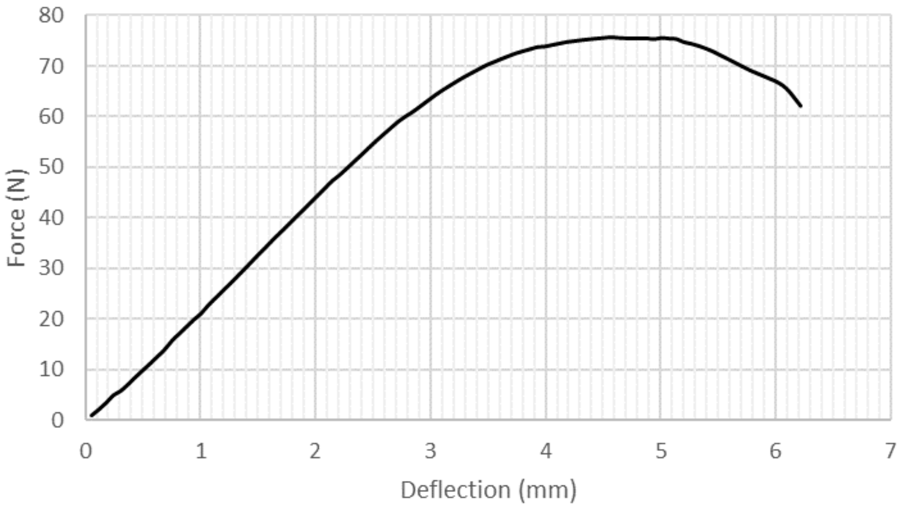
Specimen 6: 0.15 L.H, P.S. 100mm/s, Infill 25%, Shell 3



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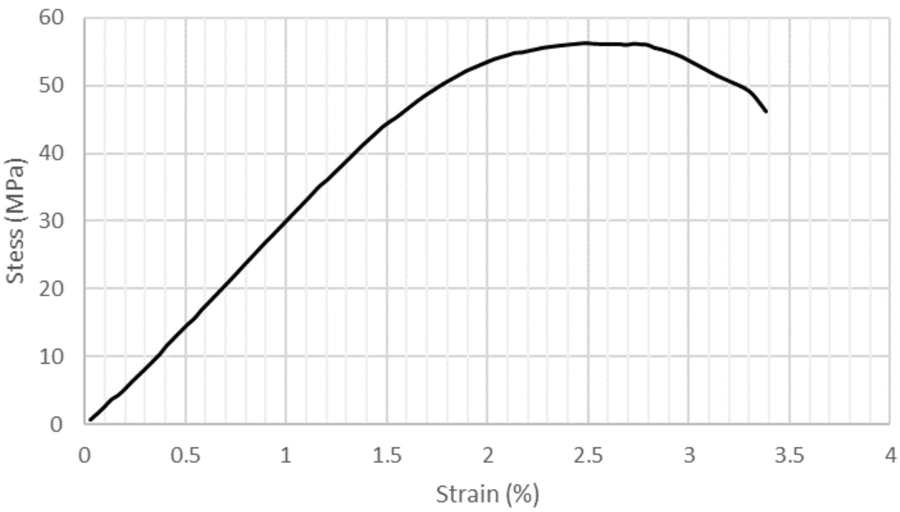
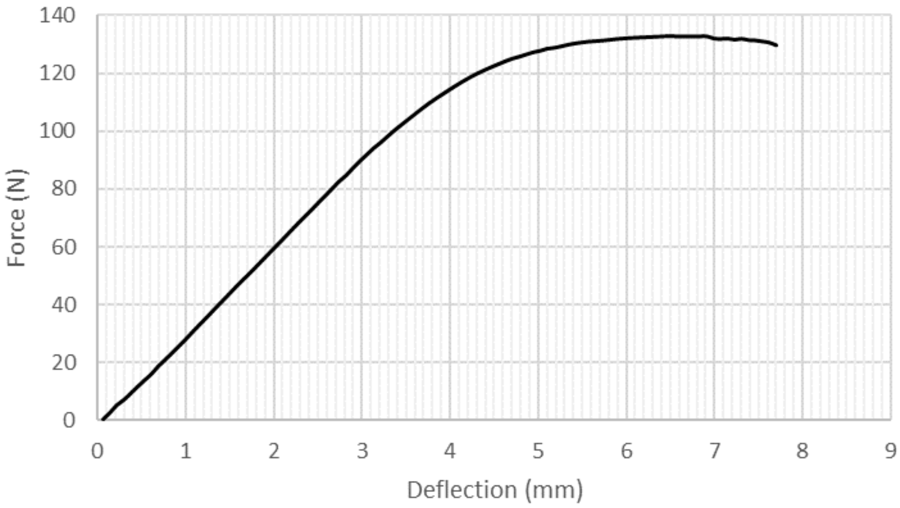
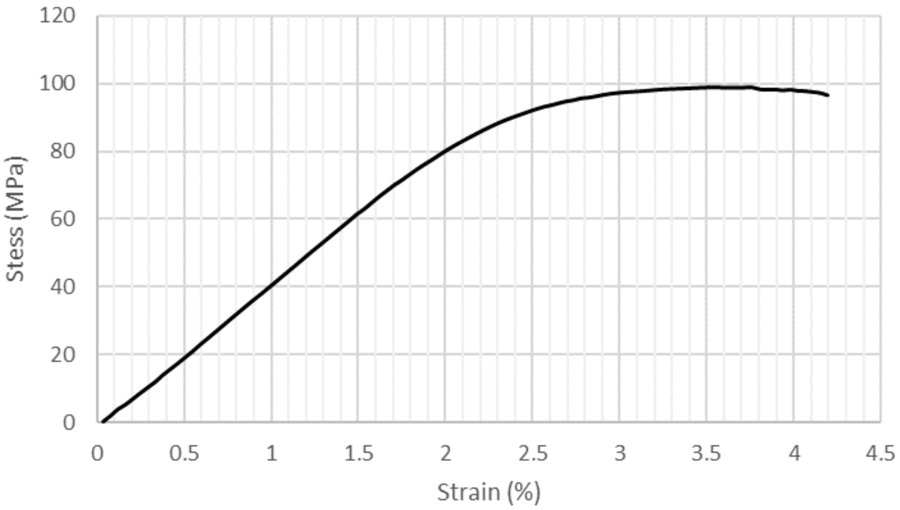


(b)

Specimen 7: 0.2 L.H, P.S. 35mm/s, Infill 100%, Shell 3

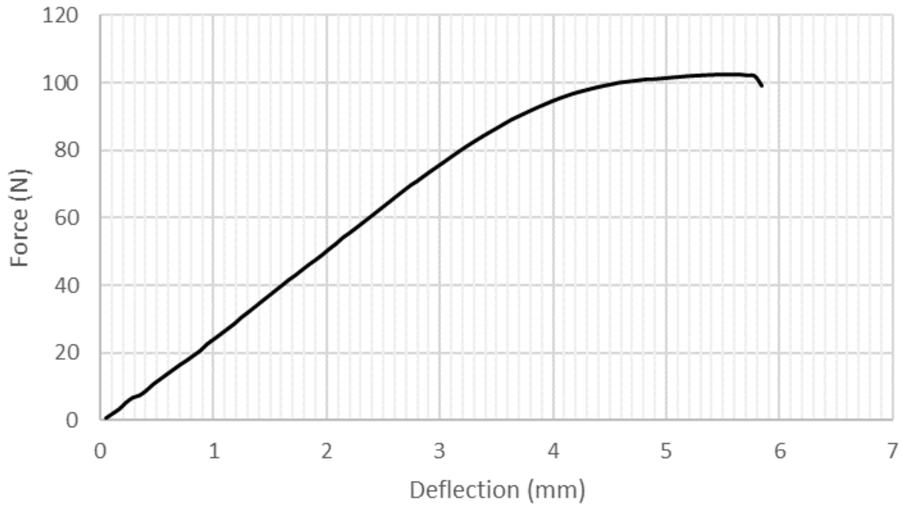


(a)

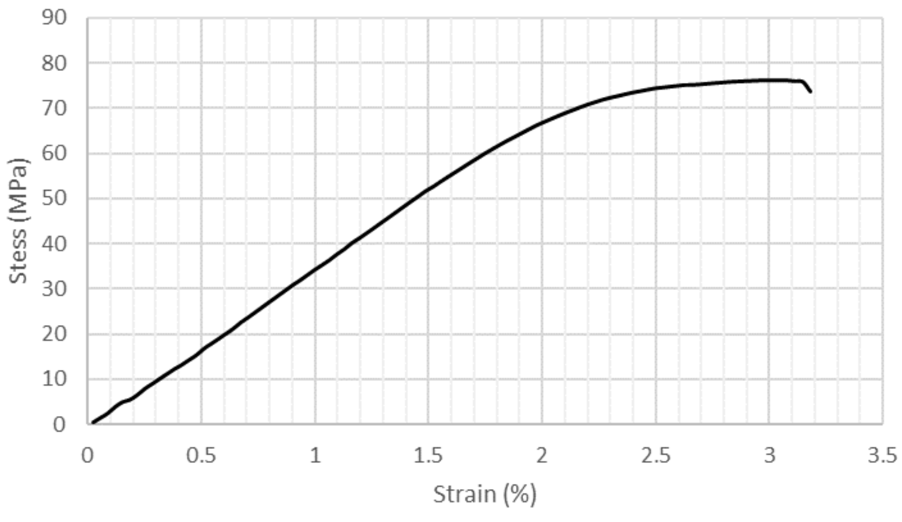


(b)

Specimen 8: 0.2 L.H, P.S. 60mm/s, Infill 25%, Shell 5

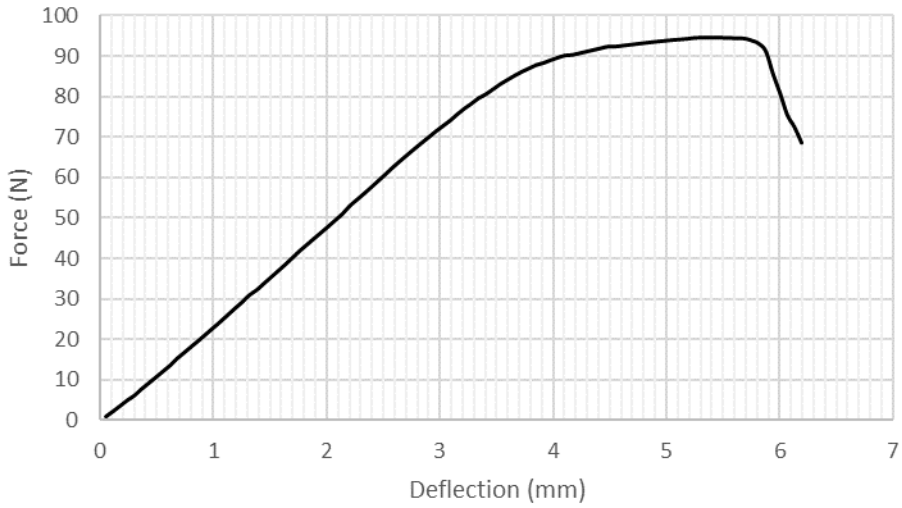


(a)

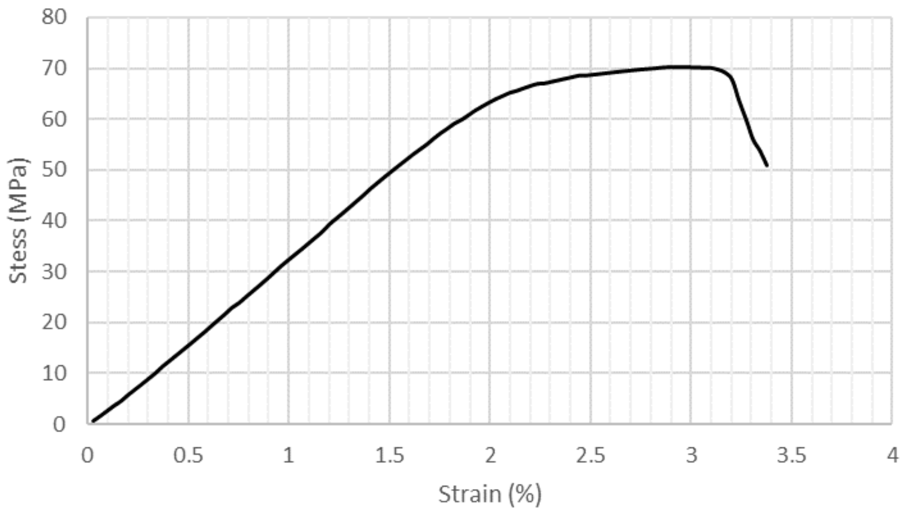


(b)

Specimen 9: 0.2 L.H, P.S. 100mm/s, Infill 50%, Shell 1

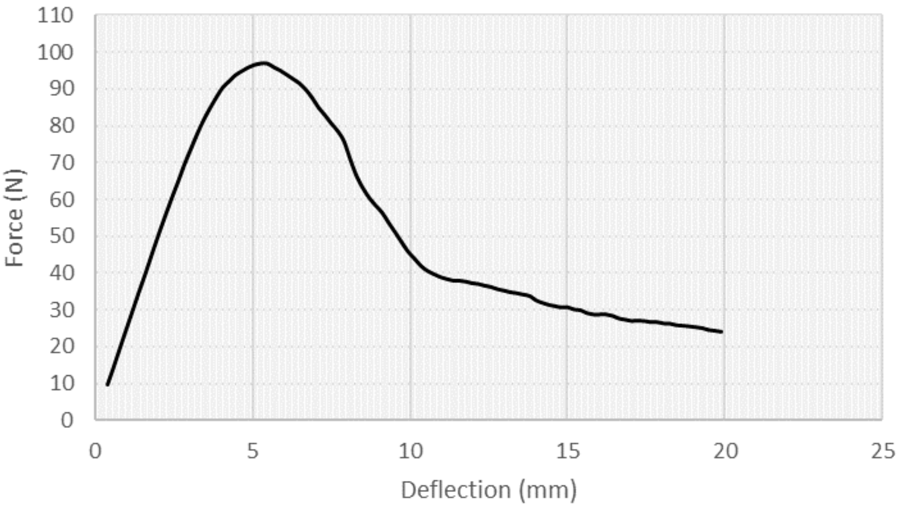


(a)



(b)

Specimen 10: 0.1 L.H, P.S. 100mm/s, Infill 25%, Shell 5



(a)

APPENDIX 2

TAGUCHI AND ANOVA ANALYSIS RESULTS FOR TENSILE AND BENDING TESTS

Taguchi analysis for three-point bending test

Taguchi Analysis: Max load(N) versus layer height(mm), speed(mm/s), infill (%), shell.

Response Table for Signal to Noise Ratios

Larger is better.

Level	Layer Height(mm)	Speed(mm/s)	Infill (%)	Shell
1	**40.65**	40.20	**41.18**	38.96
2	40.25	39.96	40.66	39.97
3	40.21	**40.96**	39.28	**42.19**
Delta	0.44	1.01	1.91	3.23
Rank	4	3	2	1

Response Table for Means

Level	Layer Height(mm)	Speed(mm/s)	Infill (%)	Shell
1	**108.46**	103.95	**115.43**	89.47
2	105.87	102.34	108.75	100.47
3	104.33	**112.37**	94.48	**128.72**
Delta	4.12	10.03	20.94	39.25
Rank	4	3	2	1

One-way ANOVA: Max load(N) versus layer height(mm)

Method

Null hypothesis: All means are equal

Alternative hypothesis: Not all means are equal

Significance level $\alpha = 0.05$

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Layer Height(mm)	3	0.10, 0.15, 0.20

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Layer Height(mm)	2	26.06	13.03	0.02	0.977
Error	6	3320.91	553.49		
Total	8	3346.98			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
23.5263	0.78%	0.00%	0.00%

Means

Layer Height(mm)	N	Mean	StDev	95% CI
0.10	3	108.46	14.71	(75.22, 141.69)
0.15	3	105.9	28.8	(72.6, 139.1)
0.20	3	104.3	24.8	(71.1, 137.6)

Pooled StDev = 23.5263

One-way ANOVA: Max load(N) versus speed (mm/s).

Method

Null hypothesis: All means are equal

Alternative hypothesis: Not all means are equal

Significance level: $\alpha = 0.05$

Equal variances were assumed for the analysis.

Table Factor Information

Factor	Levels	Values
Speed(mm/s)	3	35, 60, 100

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Speed(mm/s)	2	174.0	86.99	0.16	0.852
Error	6	3173.0	528.83		
Total	8	3347.0			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
22.9964	5.20%	0.00%	0.00%

Means

Speed(mm/s)	N	Mean	StDev	95% CI
35	3	104.0	22.5	(71.5, 136.4)
60	3	102.3	29.3	(69.9, 134.8)
100	3	112.37	14.80	(79.88, 144.86)

Pooled StDev = 22.9964

One-way ANOVA: Max load(N) versus infill (%)

Method

Null hypothesis: All means are equal

Alternative hypothesis: Not all means are equal

Significance level: $\alpha = 0.05$

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Infill (%)	3	25, 50, 100

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Infill (%)	2	686.8	343.4	0.77	0.502
Error	6	2660.2	443.4		
Total	8	3347.0			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
21.0564	20.52%	0.00%	0.00%

Means

Infill (%)	N	Mean	StDev	95% CI
25	3	115.43	16.76	(85.68, 145.18)
50	3	108.7	17.4	(79.0, 138.5)
100	3	94.5	27.3	(64.7, 124.2)

Pooled StDev = 21.0564

One-way ANOVA: Max load(N) versus shell

Method

Null hypothesis: All means are equal

Alternative hypothesis: Not all means are equal

Significance level: $\alpha = 0.05$

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Shell	3	1, 3, 5

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Shell	2	2460.2	1230.1	8.32	0.019
Error	6	886.8	147.8		
Total	8	3347.0			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
12.1572	73.50%	64.67%	40.39%

Means

Shell	N	Mean	StDev	95% CI
1	3	89.47	13.88	(72.29, 106.64)
3	3	100.47	15.47	(83.29, 117.64)
5	3	128.72	3.40	(111.55, 145.90)

Pooled StDev = 12.1572

Taguchi Analysis for Tension Test

Taguchi Analysis: Max Load (N) versus Layer Height (mm), Speed (mm/s), Infill (%), Shell

Larger is better

Response Table for Signal to Noise Ratios

Level	Layer Height(mm)	Speed (mm/s)	Infill (%)	Shell
1	50.11	51.37	49.48	50.11
2	**52.45**	**52.71**	**53.24**	51.90
3	52.41	50.89	52.24	**52.95**
Delta	2.34	1.81	3.76	2.83
Rank	3	4	1	2

Response Table for Means

Level	Layer Height (mm)	Speed (mm/s)	Infill (%)	Shell
1	337.4	403.7	311.8	336.6
2	432.1	431.9	465.1	399.5
3	418.1	351.9	410.6	451.4
Delta	94.7	80.0	153.4	114.8
Rank	3	4	1	2

One-way ANOVA: Max load (N) versus layer height (mm)

Method

Null hypothesis: All means are equal

Alternative hypothesis: Not all means are equal

Significance level: $\alpha = 0.05$

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Layer Height (mm)	3	0.10, 0.15, 0.20

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Layer Height (mm)	2	15676	7838	0.71	0.527
Error	6	65954	10992		
Total	8	81630			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
104.844	19.20%	0.00%	0.00%

Means

Layer Height(mm)	N	Mean	StDev	95% CI
0.10	3	337.4	124.3	(189.3, 485.5)
0.15	3	432.1	128.7	(284.0, 580.2)
0.20	3	418.1	30.7	(270.0, 566.2)

Pooled StDev = 104.844

One-way ANOVA: Max load (N) versus speed (mm/s)

Method

Null hypothesis: All means are equal

Alternative hypothesis: Not all means are equal

Significance level: $\alpha = 0.05$

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Speed(mm/s)	3	35, 60, 100

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Speed (mm/s)	2	9869	4935	0.41	0.679
Error	6	71761	11960		
Total	8	81630			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
109.362	12.09%	0.00%	0.00%

Means

Speed (mm/s)	N	Mean	StDev	95% CI
35	3	404	185	(249, 558)
60	3	431.91	12.55	(277.41, 586.41)
100	3	351.9	39.6	(197.4, 506.4)

Pooled StDev = 109.362

One-way ANOVA: Max load (N) versus infill (%)

Method

Null hypothesis: All means are equal

Alternative hypothesis: Not all means are equal

Significance level: $\alpha = 0.05$

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Infill (%)	3	25, 50, 100

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Infill (%)	2	36266	18133	2.40	0.172
Error	6	45364	7561		
Total	8	81630			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
86.9519	44.43%	25.90%	0.00%

Means

Infill (%)	N	Mean	StDev	95% CI
25	3	311.8	111.9	(188.9, 434.6)
50	3	465.1	91.7	(342.3, 588.0)
100	3	410.6	41.8	(287.8, 533.5)

Pooled StDev = 86.9519

One-way ANOVA: Max load (N) versus shell

Method

Null hypothesis: All means are equal

Alternative hypothesis: Not all means are equal

Significance level: $\alpha = 0.05$

Equal variances were assumed for the analysis.

Factor Information

Factor	Levels	Values
Shell	3	1, 3, 5

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Shell	2	19818	9909	0.96	0.434
Error	6	61812	10302		
Total	8	81630			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
101.499	24.28%	0.00%	0.00%

Means

Shell	N	Mean	StDev	95% CI
1	3	336.6	118.3	(193.2, 480.0)
3	3	399.5	79.5	(256.1, 542.9)
5	3	451.4	102.9	(308.0, 594.8)

Pooled StDev = 101.499

APPENDIX 3

ETHICAL APROVAL DOCUMENT

Date: 22/07/2020

To the **Graduate School of Applied Sciences**

The research project titled ‘’ OPTIMIZATION AND ANALYSIS OF PLA IMPLANT PRODUCED BY 3D PRINTER’’ has been evaluated. Since the researcher(s) will not collect primary data from humans, animals, plants or earth, this project does not need through the ethics committee.

Title: Assoc. Prof. Dr

Name Surname: Ali Evcil

Signature:

Role in the Research Project: Supervisor

Title: Prof. Dr

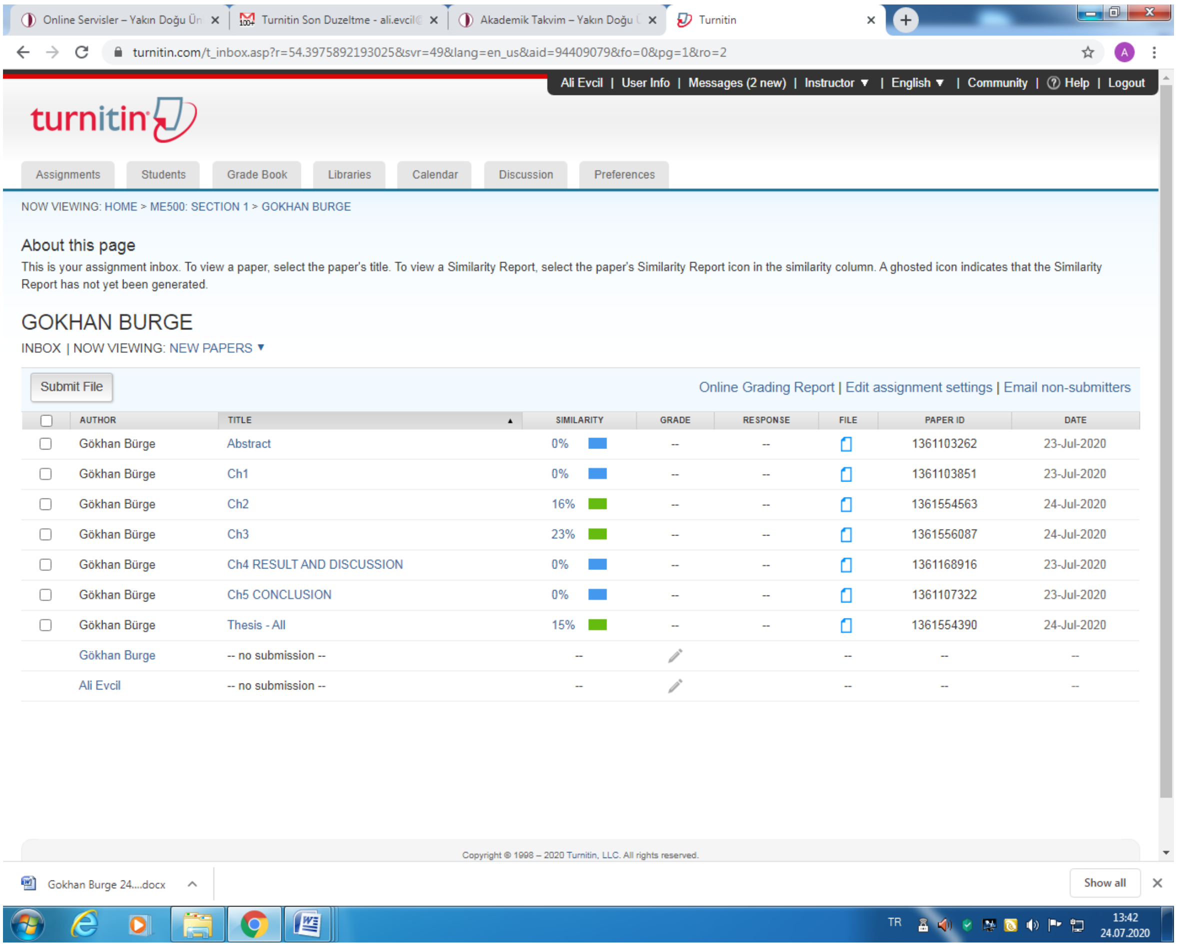
Name Surname: Mahmut A. Savaş

Signature:

Role in the Research Project: Co-Supervisor

APPENDIX 4

SIMILARITY REPORT



GOKHAN BURGE

INBOX | NOW VIEWING: NEW PAPERS

AUTHOR	TITLE	SIMILARITY	GRADE	RESPONSE	FILE	PAPER ID	DATE
Gökhan Bürge	Abstract	0%	--	--		1361103262	23-Jul-2020
Gökhan Bürge	Ch1	0%	--	--		1361103851	23-Jul-2020
Gökhan Bürge	Ch2	16%	--	--		1361554563	24-Jul-2020
Gökhan Bürge	Ch3	23%	--	--		1361556087	24-Jul-2020
Gökhan Bürge	Ch4 RESULT AND DISCUSSION	0%	--	--		1361168916	23-Jul-2020
Gökhan Bürge	Ch5 CONCLUSION	0%	--	--		1361107322	23-Jul-2020
Gökhan Bürge	Thesis - All	15%	--	--		1361554390	24-Jul-2020
Gökhan Burge	-- no submission --	--			--	--	--
Ali Evcil	-- no submission --	--			--	--	--