UNIVERSIDAD DE VALLADOLID

ESCUELA DE INGENIERIAS INDUSTRIALES

Grado en Ingeniería Mecánica

Characteritation of 3D printing parameters

Autor:

Cabezas Arribas, Sergio

RIB: Sánchez Bascones, Isabel

Hochschule Osnabrück

Valladolid, Marzo 2017.

TFG REALIZADO EN PROGRAMA DE INTERCAMBIO

TÍTULO: Characteritation of 3D printing parameters

ALUMNO: Cabezas Arribas, Sergio

FECHA: Julio 2016

CENTRO: Hochschule Osnabrück

TUTOR: Mr. Norbert Bahlmann

Resumen:

El desarrollo de las impresoras 3D en los últimos años ha sufrido un gran desarrollo. Por ello es necesario conocer y estudiar en profundidad las posibilidades que esta tecnología ofrece al mundo de la ingeniería.

En este TFG, se analiza de una manera objetiva las dificultades que surgen de la impresión 3D y se aportan soluciones a las mismas. Para el análisis se ha realizado un riguroso estudio de las condiciones de funcionamiento así como se han utilizado controles dimensionales para determinar la capacidad de la máquina y varios test mecánicos para conocer las propiedades que nos ofrecen los tres tipos de polímeros utilizados: PLA, ABS, CTE.

Palabras Clave: **IMPRESORA 3D, PROPIEDADES MECÁNICAS, PLA, ABS, METROLOGÍA**

Abstract:

The development of 3D printers has taken a big leap in recent years. Therefore it is necessary to know and study in depth the possibilities that this technology offers us.

In this thesis, after describing certain characteristics of 3D printing are analyzed in an objective way the difficulties that we may face when trying to print and how to solve them as far as possible. They were performed a metrological test to determine the capacity of the machine and various mechanical test used to determine the quality and mechanical characteristics of the printed pieces. For this, it has been used 4 different materials: Poly- lactic Acid, Acrylonitrile Butadiene Styrene, Copolyester and Thermoplastic Elastomer Copolymer.

Key words: **3D PRINTER, MECHANICAL PROPERTIES, PLA, ABS, METROLOGY**

Hochschule Osnabrück
University of Applied Sciences

**Fakultät
Ingenieurwissenschaften und Informatik**

Bachelor Thesis

About the theme

Characterization of 3D Printing Parameters.

Author: Sergio Cabezas Arribas
sergio.cabezas.arribas@gmail.com

Professors: Prof. Dr. N.Bahlmann
Prof. Dr. T.Mechlinski

Date: 05.07.2016

Recuerde el alma dormida,
avive el seso y despierte
contemplando
cómo se pasa la vida,
cómo se viene la muerte
tan callando,
cuán presto se va el placer,
cómo, a nuestro parecer,
cualquiera tiempo pasado
fue mejor.

Pues si vemos lo presente
cómo en un punto se es ido
y acabado,
si juzgamos sabiamente,
daremos lo no venido
por pasado.
No se engañe nadie, no,
pensando que ha de durar
lo que espera,
más duró lo que vio
porque todo ha de pasar
por tal manera.

Nuestras vidas son los ríos
que van a dar en la mar,
que es el morir;
allí van los señoríos
derechos a se acabar
y consumir;
allí los ríos caudales
allí los otros medianos
y más chicos,
y llegados, son iguales
los que viven por sus manos
y los ricos.

"Coplas por la muerte de su padre". **Jorge Manrique (1440-1479)**

I Aknowledgments

After four intensive years in my Degree in Mechanical Engineering and just at the end of my thesis I would like to thank all those people who made this thesis possible and an unforgettable experience for me.

First at all, I would like to express my deepest sense of gratitude to my supervisor Dr. Norbert Bahlmann, who offered my the possibility to work with a 3D printer and allowed me to access to all necessary facilities in order to develop my thesis and let me work with independence.

I am thankfull to Hochschule Osnabrück for let my develop my thesis during this six month in an Erasmus+ in Germany.

I would like to express my gratitude to Prof. Bröker from the polymers department and Prof. Tepe from the metrological department of the university for the support for doing the necessary test for this thesis.

Finally, I take this opportunity to express the profound gratitude from my deep heart to my beloved family, for their wise counsel and sympathetic ear during this years.

You are always there for me.

II Abstract

The development of 3D printers has taken a big leap in recent years. Therefore it is necessary to know and study in depth the possibilities that this technology offers us.

In this thesis, after describing certain characteristics of 3D printing are analyzed in an objective way the difficulties that we may face when trying to print and how to solve them as far as possible. They were performed a metrological test to determine the capacity of the machine and various mechanical test used to determine the quality and mechanical characteristics of the printed pieces. For this, it has been used 4 different materials: Polylactic Acid, Acrylonitrile Butadiene Styrene, Copolyester and Thermoplastic Elastomer Copolymer.

In den letzen Jahren hat die Entwicklung von 3D-Druckern einen großen Sprung gemacht. Daher ist es notwendig, die Möglichkeiten, die diese Technoligie uns bietet, zu kennen und zu erforschen.

In dieser Bachelorarbeit werden zunächst die Eigenschaften der 3D-Drucker beschrieben. Dann werden die Schwierigkeiten, die beim Drucken auftreten könnten objektiv anaöysiert und mögliche Ansätze zur Lösung dieser Probleme - soweit möglich - angeführt. Es wurden messtechnische Tests durchgeführt, um die Kapazität der Maschine zu bestimmen. Mit weiteren Tests wurden die Qualität und die technischen Merkmale der gedruckten Objekte bestimmt. Hierzu wurden vier verschiedene Materialen benutzt: Polylactide, Acrylnitril-Butadien-Styrol, Copolyester und thermoplastische Elastomere.

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VI Acronyms and Simbols

a_0	*Specimen thicknes*
A	*Ampere*
ABS	*Acrylonitrile Butadiene Styrene*
b_0	*Specimen width*
CPE	*Chlorinated Polyethylene*
cm	*Centimeter*
dBA	*decibel A-weighting*
DC	*Direct current*
E	*Young's Modulus*
r	*Break Strain*
ε_M	*Resistance Strain*
ε_{tB}	*Nominal Strain on Break Point*
ε_{tM}	*Nominal Strain on Resistance Point*
ε_Y	*Yield strain*
HB	*Brinell Hardness*
Hz	*Hertz*
kg	*Kilogram*
min	*minute*
mm	*Milimeter*
MPa	*MegaPascal*
Nr	*Number*
PLA	*Polylactic Acid*
σ_B	*Break Stress*
σ_M	*Resistance*

σ	*Yield Stress*
s	*second*
.STL	*Stereo Lithography file*
T_g	*Glass transition temperature*
V	*Volt*
W	*Watt*
w/w	*Mass fraction*

1 Introduction

3D printing, also known as AD (Additive Manufacturing) is a process by which a three-dimensional digital model is made into a physical piece.

Rapid prototyping builds three-dimensional parts via layer-by-layer process. In principle, begins with a CAD file representing a three-dimensional object, which is then sliced into many cross-sectional elements or layers. Then, the three-dimensional model is created by depositing each cross-sectional layer, one on top of the other until the object is completed. 3D printers used to perform this task are usually controlled by computers, which create a CNC program that drives the machine in its movements.

1.1 Historical Background

The idea of AM was first conceived in 1980s by Charles Hull. He invented this technology while trying to demonstrate an alternate process for conventional tool-making and molding by fabricating UV-curable polymers for Ultra Violet Products, California. This technique called ”stereolithography” enabled quick production of plastic prototypes. He and 3D Systems Company together created .STL file format which assisted the computer-aided design (CAD) to communicate with the rapid prototyping (RP) machine so as to transmit files for printing 3D objects. The successive arrival of fused deposition modeling (FDM) process developed by Scott Crump heralded the revolution of manufacturing industry. A special machine knowns as 3D printer capable of printing plastic, metal, and ceramic parts was fabricated in 1993 by Michael Cima and Emanuel Sachs of MIT. Companies like DTM Corporation, Z Corporation, Solidscape Geometries, Objet Geometries, Helisys, and Organovo devised 3D printers for commercial applications that are available in the market today.

1.2 Printing Methods

Today, there are three common printing methods:

- Fused Deposition Modeling (FDM).
- Stereolithography (SLA).
- Selective Laser Sintering (SLS).

1.2.1 Fused Deposition Modeling

Fused deposition modeling is a technology developed by Stratasys[1]in 1980 that is used to create rapid prototypes.

The fused deposition modeling is an additive technique, depositing the layered material to form the part. A plastic or metal filament initially stored in coils, is introduced into a nozzle. The nozzle is above the melting temperature of the material and can move in three axes electronically controlled. The nozzle usually is moved by stepper motors or servomotors The piece is built with thin strands of material that solidifies immediately after leaving the nozzle.

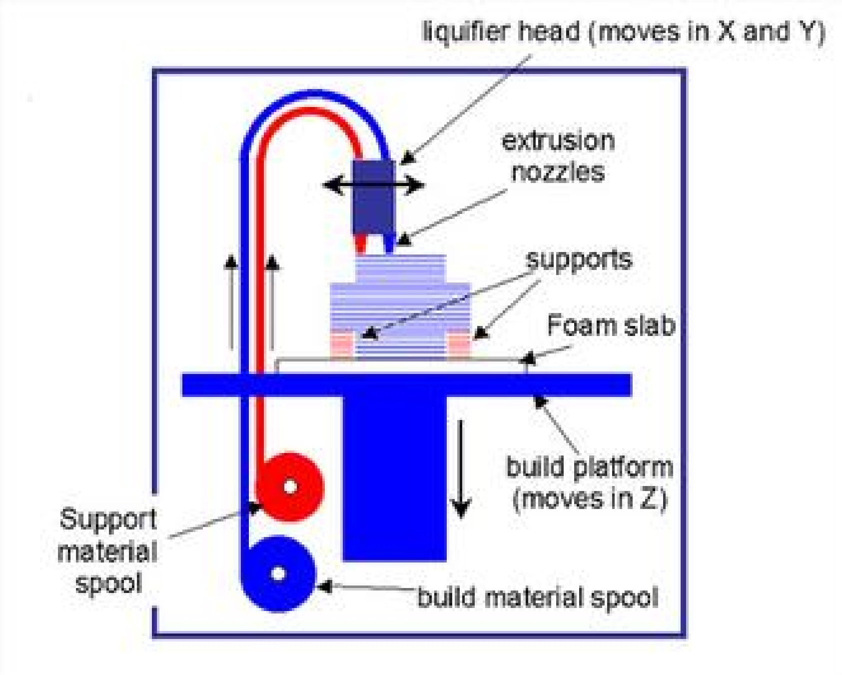


Figure 1: Fused Deposition Modeling

3D printers that use FDM technology create parts layer by layer from the bottom up heating and extruding the thermoplastic filament. The process is simple:

Preprocessing: The preparation software sheet tray and place a 3D CAD file. It then calculates the path to extrude the thermoplastic material and any material required.

Production: The 3D printer heats the thermoplastic material until it reaches a semiliquid state and deposits it in micro-drops along the extrusion path. In cases where a medium or support is needed, the 3D printer deposits a leaving material that serves as scaffolding.

[1]Stratasys: Manufacturer of 3D printers founded in 1989 by S. Scott Crump and Lisa Crump in Minnesota.

Postprocessing: The user removes the carrier material or dissolved in water and detergent and then the piece is ready for use.

The thermoplastic is melted and deposited on the nozzle layers of the required thickness (thinner layers mean better quality final piece) one by one. The layers are deposited from the bottom to up.

Although the fused deposition modeling is a very flexible technology, and is able to perform many different parts, there are some restrictions on the characteristics of what can be produced with this technique, especially with regard to the slope of the cantilevers.

Advantages of FMD technology:

- The technology is clean, easy to use and suitable for office.
- Thermoplastic production is mechanical and environmentally stable.
- Complex geometries and cavities that could be problematic when using other systems become easy thanks to technology FDM.

1.2.2 Stereolithography

Stereolithography (SLA or SL; also known as optical fabrication, photo-solidification) is a manufacturing technology used for the production of models, prototypes, patterns or final parts.

It is the oldest prototyping and rapid manufacturing technique.

The term stereolithography was invented in 1986 by Chuck Hull who patented it as a method and equipment for making solid objects by printing successive thin layers of a material cured by ultraviolet light.

Hull patent describing how an ultraviolet beam was focused on the surface of a container filled of liquid photopolymer. Light rays draw the object on the surface of the liquid, layer by layer, using light curing (or cross-linking) to create the solid. In 1986, Hull founded the first company that commercialized this technique, 3D Systems Inc2 which is still located in Rock Hill, South Carolina.

Stereolithography is a manufacturing process employing addition curing resin with ultraviolet light in a tank, and an ultraviolet laser to build objects. Three-dimensional objects are obtained by the addition of thin layers, printed one above another. Each layer is a cross section of the object that the laser trace on the surface of the resin, which is the consumable material. The liquid resin cured and solidified by exposure to ultraviolet laser light, thus leaving the newly solidified layer bonded to the previous layer that existed under his.

Once the print layer has been created, the lifting platform equipment descends a distance equal to the thickness of a layer of solidified resin (typically between 0.05 and 0.15 mm). A blade sweeps the workpiece leaving a new layer of liquid resin on the surface of the cuvette ready for the next print laser. Thus is being created, layer by layer a three-dimensional piece. Once the three-dimensional part is completed, it is immersed in a chemical bath that removes excess resin and subsequently cured in an oven ultraviolet light. This process can be seen in the Figure 2.

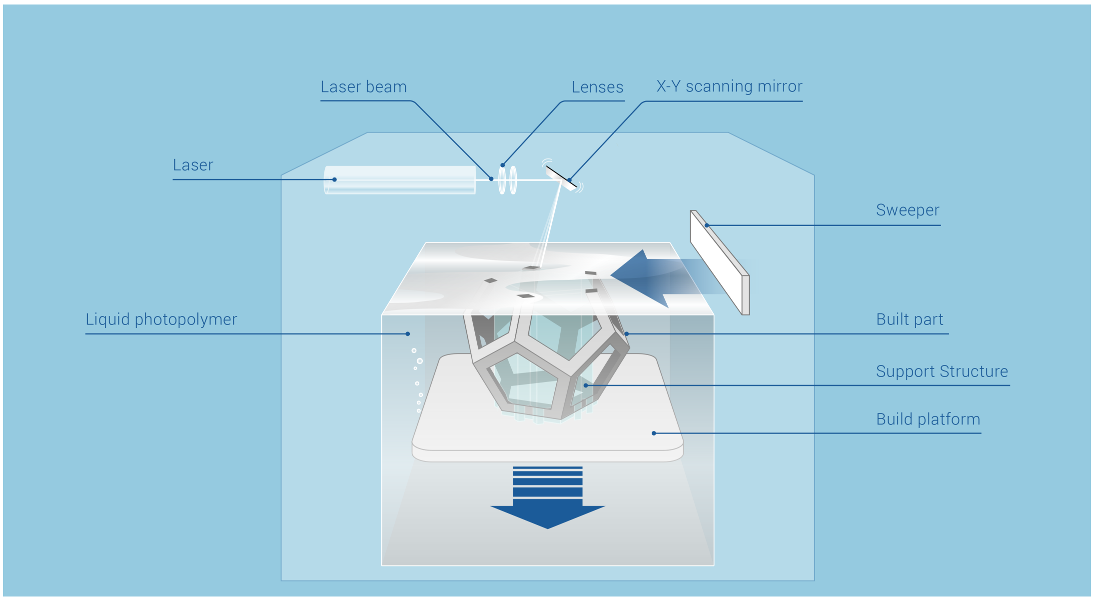


Figure 2: Stereolithography process

Stereolithography needs of structures for supporting the piece to the lifting platform so as to prevent the deflection of the workpiece by gravity. Also subject the cross section in the right place so they do not slide when it passes the sheet re-application of resin. The supports are typically generated automatically during preparation CAD model computer, but may require manual intervention. Supports must be removed from the final model manually.

The resins typically used are:

- Special opaque white resin type ABS (ABS not really).
- White infiltrations Special ABS resin to improve its mechanical properties.
- Translucent resin.

Advantages and disadvantages:

One advantage of stereolithography is its speed. Functional objects can be produced in less than a day. The time depends on their size and complexity, which can vary from simple hours over a day.

The surface finish of the pieces is very good, usually better than that obtained by SLS. Besides the pieces do not come any dust as does happen in the parts produced by SLS. But if not cleaned well after printing, the pieces may contain traces of uncured resin in nooks and crannies (but hardened), which gives a feeling of sticky.

Most stereolithography equipment are able to make objects with a maximum of approximately 50 x 50 x 60 cm, although there are some that reach 70 x 210 x 80 cm.

Parts manufactured by stereolithography are hard enough to be machined, and can also be used in the creation of master molds for injection molding, thermoforming, blow molding, and various forging processes.

A great advantage of this technology over the SLS is that the parts produced are nonporous (as in laser sintering), which makes not require subsequent sealing treatment to make them impermeable to water or air.

The resins used may be more brittle and less flexible than in the laser sintering SLS. A specific disadvantage of this technology comes from the characteristic of photoresists to cure with ultraviolet light. Because of this, the freshly printed parts having a degree of curing concrete that gives hardness and strength to concrete breaking, but those properties change over time (due to continued curing by environmental ultraviolet light) turning the increasingly fragile pieces.

The objects obtained by this technology are sensitive to both humidity and temperature, although there are further processes that mitigate these weaknesses.

Although stereolithography can produce a wide variety of shapes, often expensive. The cost of photo curable resin varies from 60 to 90 euros per liter, and the price of equipment from 75.000 to over 400.000 euros. However, the recent interest in this technology has made consumption patterns with very affordable prices, such as HD Ilios manufacturer and OS-RC Form 1 Formlabs occur

1.2.3 Selective Laser Sintering

The Selective Laser Sintering (SLS) is a technique of addition of rapid prototyping in which a layer of powder is deposited in a tank that has been heated to a temperature slightly below of the melting point of the powder. Next, a CO_2 laser sintered powder at selected points (causing particles to fuse and solidify).

Production of objects by SLS requires the use of a high power laser (for example a

CO_2 laser) to fuse small particles of plastic, metal, ceramic or glass in a desired three-dimensional shape.

The laser selectively fuses of powder material in a tank by sweeping transverse thin layers ranging thus generating the three-dimensional object. Dimensional information of the piece to print comes from a computer file that has been generated or previously scanned. Once the cross-section is formed, the powder tank descends a distance equal to the thickness of the layer formed, and a new layer of base material is added to the surface. The process is repeated so many times as needed to melt layers to create the three-dimensional object.

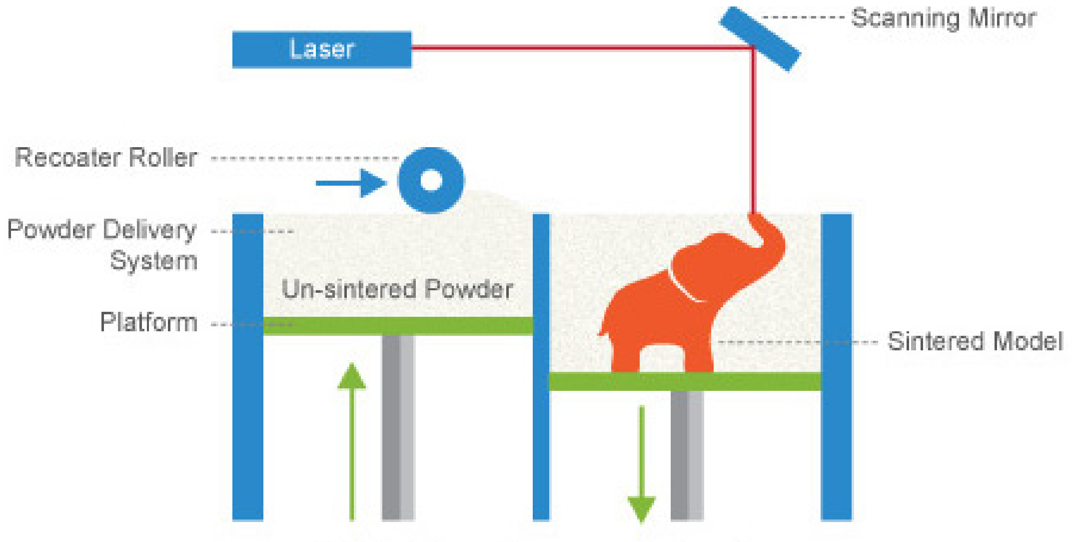


Figure 3: Selective Laser Sintering process diagram

The finished pieces have a density that depends on the peak power of the laser rather than the duration and SLS teams use a laser pulse. The SLS machine preheats the powder in the cuvette base material at a temperature slightly below the melting of the material. Thus it causes the material melting by heating easier.

Unlike other manufacturing processes by addition, such as stereolithography (SLA) and fused deposition thread (FDM), selective laser sintering does not need support structures because the sintered part is all the time surrounded by powder non-sinterized that acts as support.

1.3 State of the art

3D printing has made a great leap in recent years thanks to the multitude of advances in this technology. However, this is still an underdeveloped technology in which there is a wide field for studying.

The following are some of the current applications where 3D technology is involved:

1.3.1 Food

Foodini, the first 3D printer food ready to print all kinds of fresh, nutritious real, savory or sweet, but not solid ingredients. It is suitable for professional or domestic kitchens. It allows customization of forms.

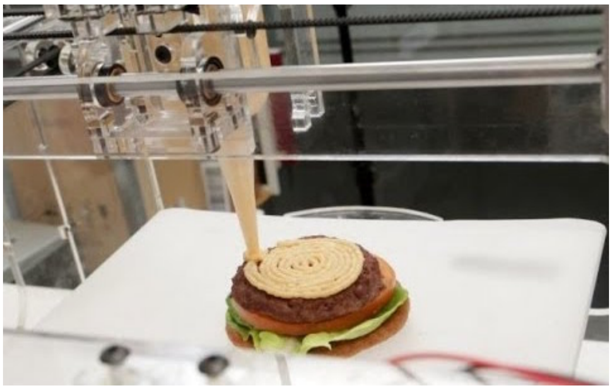


Figure 4: 3D Food printer

1.3.2 Aeronautics

Boeing uses 3D printers to make 200 parts for 10 types of aircraft.

GE will build 20% of the components of its jet engines for commercial aircraft using additive manufacturing with metals.

Figure 5: Some aeronautics 3D printed parts

1.3.3 Automotive

The British company 3TRPD 3D printed a gearbox for racing cars with a sophisticated interior that allows faster gear changes and is lighter than conventional 30%.

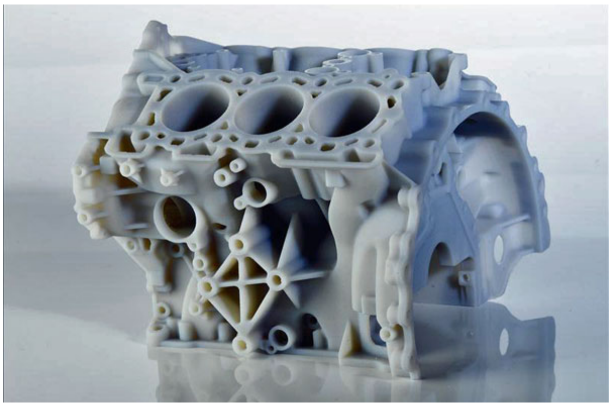


Figure 6: Automotive 3D sample printed part

Most manufacturers and F1 teams and motorcycle GP using additive manufacturing for the production of components or prototypes, production tools and components shipped late in their vehicles.

1.3.4 Sports

In the 2012 Olympics, the Japanese men's fencing team won the silver medal with a weapons-made handles for 3D printing, by researchers at the University of Tsukuba.

Figure 7: Handles for Japan men's fencing team

1.3.5 Medicine and Biology

Materialise, a Belgian medical device company, it makes implants lighter than machined without loss of hardness and designed to fit precisely to the patient.

Not only dental implants or braces need customization for easy 3D printing, but also other types of prostheses, such as hearing or limb. In a laboratory from San Diego they have developed custom legs amputated below the knee or hand with fingers articulated prosthesis.

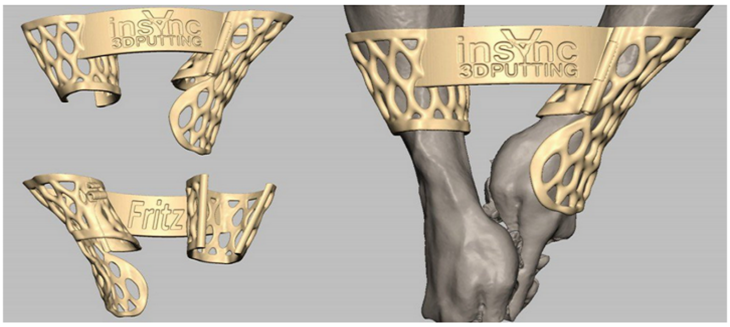


Figure 8: 3D Printed Prosthesis

In several Institutes of bioengineering its use is studied in textile engineering. 3D scaffold for cells to grow inside is made. When the scaffolding is removed, it has the tissue. This technique is used for example, for bone regeneration. 3D technology allows much more accurate than those made with other procedures scaffolding.

2 Equipment & Software Description

2.1 Ultimaker 2 Extended+

Throughout this thesis, it has been used an Ultimaker2 Extended+. In the Table 2 are displayed the general specifications of this machine.

Characteristics	Unit	Amount	Comments
Printer and Printing Properties:			
Print technology			FDM
Print head			Swappable nozzle
Build Volume	mm	223 x 223 x 305	
Filament diameter	mm	2.85	
Layer resolution			
0.25mm nozzle	micron	150 to 60	
0.4mm nozzle	micron	200 to 20	
0.6mm nozzle	micron	400 to 20	
0.8mm nozzle	micron	600 to 20	
X, Y, Z accuracy	micron	12.5, 12.5, 5	
Print head travel speed	mm/s	30 to 300	
Extrusion speed			
0.25mm nozzle	mm^3/s	up to 8	
0.4mm nozzle	mm^3/s	up to 16	
0.6mm nozzle	mm^3/s	up to 23	
0.8mm nozzle	mm^3/s	up to 24	
Build plate	°C	20 to 100	
Supported materials			PLA, ABS, CPE
Nozzle diameter	mm	0.25, 0.4, 0.6, 0.8	
Nozzle temperature	°C	180 to 260	
Nozzle heat up time	min	1	
Build plate heat up time	min	4	
Average operating sound	dBA	50	
File transfer			SD card
Physical dimensions:			
Build Dimensions	mm	357 x 342 x 488	
Nett weight	kg	12.3	
Shipping weight	kg	19.5	

Characteristics	Unit	Amount	Comments
Power Requirements:			
Input	V	100 - 240	
	A	4	
	Hz	50 - 60	
	W	221	
Output	V	24	DC
	A	9.2	
Ambient Conditions:			
Operating ambient temperature	°C	15 - 32	
Non-operating temperature	°C	0- 32	
Software:			
Print preparation			Cura
Supported file types			STL, OBJ, DAE

Table 2: Technical Specifications of Ultimaker 2 Extended+

In the Figure 9 are displayed the all the main parts of the printer.

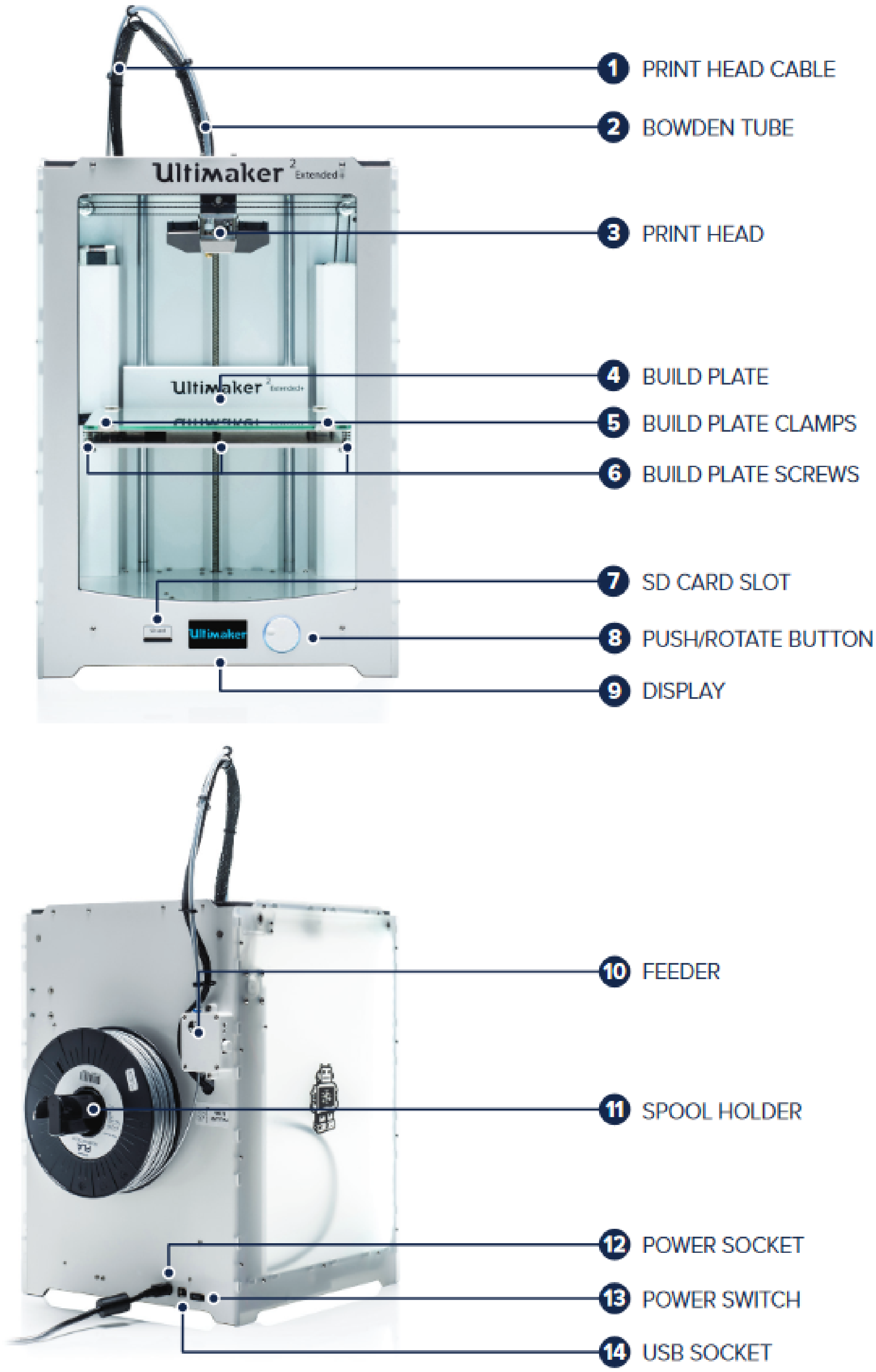


Figure 9: Ultimaker 2 Extender+ main parts

2.2 Cura parameters

Cura is the a free program that allows us to convert our 3D model in a gcode. Every design model for print must be translated by Cura into instructions the printer will understand. It does this by slicing the model into thin layers and exporting the file to the SD card ready for print.

The first screen that can be seen at the start of cure is as follows:

Figure 10: Cura printing area

The program is divided into 3 parts, Printing Area, Basic Layer Configuration Settings and Advanced Configuration Settings.

2.2.1 Printing Area

Printing area is a three dimensional representation of the volume of the printer. This is the space in which it can be printed and should not exceed their limits because our par would be outside the physical limits of our machine. The next points are displayed in the Figure 10.

1) **Load** Load 3D model we want to print. Also dragging can load the model file inside the print area.

2) **Save toolpath:** Save the project in a gcode file printable from the SD card of the printer.

3) **View mode:** the view mode icon is a flyout that offers 5 different views of the object we have in the printing area.

We can exchange views to see in detail some elements of the figure.

Normal: Displays the figure as a solid, allowing you to see the final result of the printed piece

Overhang: This view show us the areas that have a higher maximum angle that the set angle. This is very useful to see what areas can be problematic when printing and determine if they need support or not.

Transparent: Makes transparent the figure allowing us to see through it.

X-Ray: This view, besides allowing you to see through the object, shows cavities or internal elements of the parts.

Layers: This is the most useful of all the views because we can see the design in layers. This allows us to see how they actually perform the printer when printing.

4) **Transformation options:** In the lower left part of the print area, we can find several options that allow us to apply simple changes to the 3D model.

To display these options, you must first select the 3D model on which we want to apply the changes.

Rotate: You can rotate the model in any of the 3 axes. It also gives us the option to support the model for its flat side using the button lay flat

Scale: With this function you can resize the 3D model. Pressing this icon, a menu where you can apply a multiplication factor to the scale of the object or indicate the measures we want to have it unfolds.

Mirror: This option creates a mirrored figure of the initial figure. It can be done with respect to any of the 3 axes.

When selecting a piece and right click, will appear a number of options.

2.2.2 Basic Configuration Settings

To configure the way in which the printer will perform the laminate, there is a have a windows on the left side of the screen (Figure 11). In it, we can find the most common options.

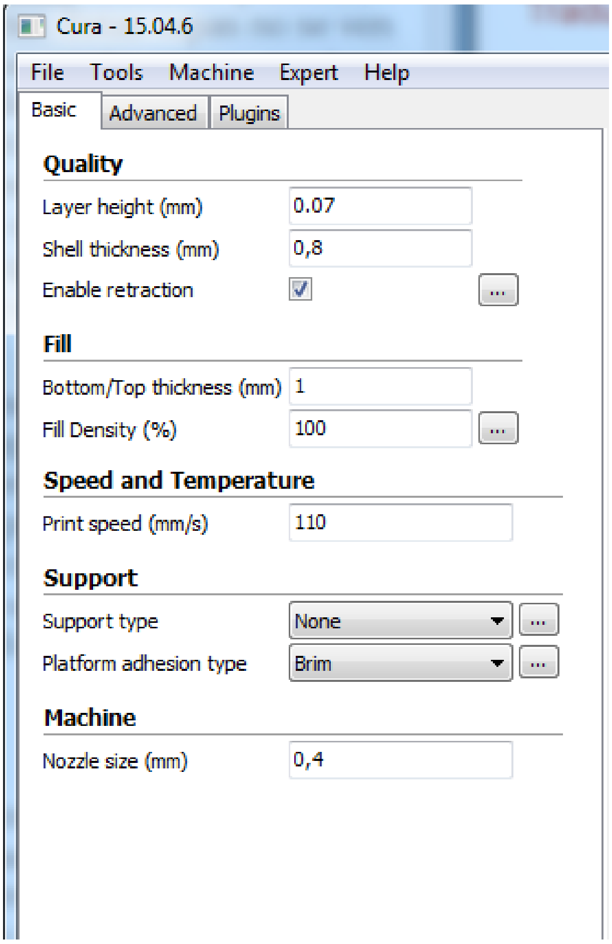


Figure 11: Printing settings menu

Quality

Layer height: This parameter indicates the layer height that the printer will perform. The layer height is directly linked to the quality of the part parameter. A lower layer height higher quality, but also will significantly increase print times. The value of the layer height should not be equal or greater than the diameter of the nozzle.

Shell thickness: This parameter determines the width of the edge of the object. This value must be equal to the diameter of the nozzle multiplied by the number of laps we want to give the object. Typically, making a border with 2 or 3 laps.

Enable retraction: This option causes in the extruder a little retract of plastic during displacements that does not drip, preventing print defects.

Fill

Bottom/top thickness: This parameter will indicate the upper and lower layers thickness. These layers are not affected by the fill settings. Typically use 3 or 4 layers

Fill Density: This value indicates the filling will have the figure. The filling will directly affect the printing time and cost of the part.

Speed and Temperature

Speed and temperature are two parameters which are intimately linked. Generally, with a high temperature we can print faster without diminishing quality.

Print speed: In this parameter will set the speed. A higher speed will get lower quality printing. A value around 40 mm / s is recommended.

Printing temperature: Set the temperature at which extrude our material. It is set according to the type of plastic used.

Bed temperature: Set the temperature of the build-plate. The adhesion of the piece will depend on the temperature of the plate, and it depends on the material used.

Support

For many of the impressions elements should be used to ensure proper printing.

Support type: This option will create supports where necessary. Supports are used when the piece has parts in the air that can not support or when this grows with a higher angle that we have set. In the options we can find two types of support:

> **Touching build-plate:** Create supports relying only on the base.
>
> **Everywhere:** Create supports that support anywhere in the piece.

Platform adhesion type: With this option we can create a platform at the base to improve adhesion of the piece. There are 2 types of bases:

> **Brim:** Create a series of edges around the figure.
>
> **Raft:** Create a complete base on which it will build the part.

Machine

<u>Nozzle size:</u> in this parameter will specify the diameter of the extruder nozzle. We can choose between 0.25mm 0.4mm 0.6mm and 0.8mm.

2.2.3 Advanced Configuration Settings

There are more settings that can be changed with Cura. In the Figure 12 are displayed some of them.

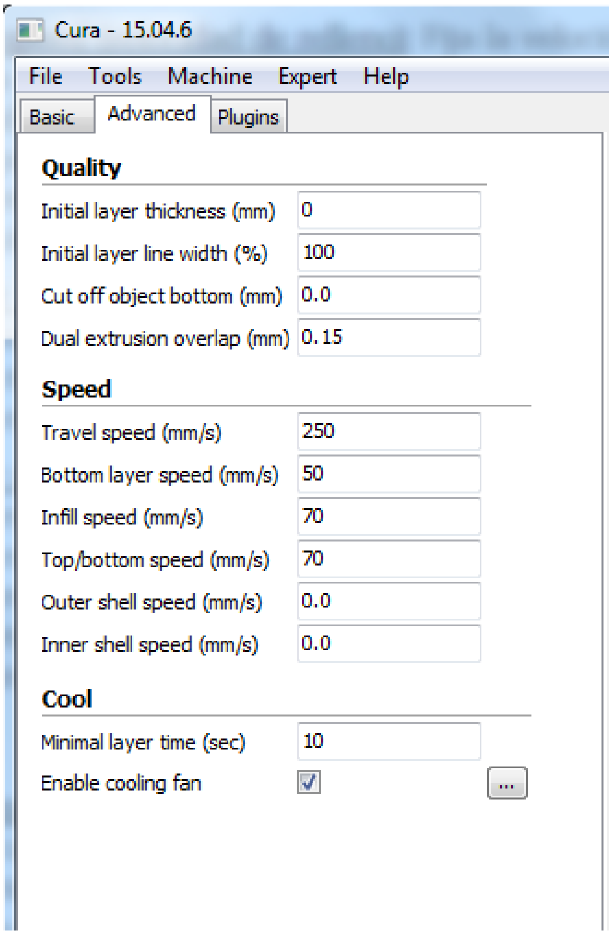


Figure 12: Advanced Printing Settings Menu

Quality

Initial layer thickness: This parameter sets the thickness of the initial layer. If we want the initial layer has the same value as the rest assign it the value 0. It is not recommended that the initial layer is too thick due to adhesion problems.

Initial layer line with: Sets the line width in the first layer.

Cut off bottom object: This parameter can cut the figure to the desired height.

Speed

Travel speed: Sets the speed that will move the extruder to move from one point to another of the machine when not printing. Recommended value of 250mm/s.

Bottom layer speed: This parameter sets the print speed of the first layer. It is very important to the adhesion make the first layer at low speed (20mm/s).

Infill speed: Sets the speed that will make the filling of the figure. Reference value 70 mm/s.

Outer shell speed: This parameter sets the speed of the outer layer of the part. The exterior finish of the piece will depend on this value. It is recommended around 30 mm/s.

Inner shell speed: Sets the speed of the inside edges.

Cool

Minimal layer time: Sets the minimum to complete a layer before starting the next time. It is recommended to set this value to at least 10s

Enable cooling fan: This option enables the fan layer, which greatly improves the quality of parts.

2.3 Maintenance operation. Atomic Method.

The Atomic Method can be used to unclog the nozzle of the printer. It will clear the blockage by pulling dirt or carbonized material out of the nozzle from the top side. Besides using this method to unclog the nozzle, you can use the Atomic Method when switching to a material that requires a lower printing temperature. This way all residue from the previous material will be removed, helping to prevent blockages.

1) **Remove the material from the printer.**

- On an Ultimaker 2+ go to "Material" ⟶ "Change" and select "Cancel" after you have removed the material.

2) **Removing the bowden tube.**

- Remove the clamp clip that is placed around the bowden tube on top of the print head.
- Press down the tube coupling collet and pull the bowden tube out of the print head.

3) **Heating up and preparing.**

Heat the nozzle of the printer to the temperature of the last used material. On an Ultimaker 2+ go to "Maintenance" ⟶ "Advanced" ⟶ "Advanced" and select "Heatup nozzle" up to 260°C.

- Cut off approximately 20 cm of filament with a straight cut and try to straighten it as much as possible.
- Wait until the nozzle has heated up and then insert the piece of material in the print head, all the way down into the nozzle.
- Push the material slightly until it either comes out of the nozzle or cannot be pushed any further.

4) **Removing the material.**

- Lowe the temperature to 90°C for PLA. For ABS it is necessary 110°C.
- Wait until the temperature is reached and then pull the material out with a quick, firm pull.
- Check the color and shape of the tip of the filament. The goal is to have a clean, cone-shaped tip.
- Repeat the steps "Heating up and preparing" and "Removing the material" until the filament comes out without any residue and has a cone-sharped tip.

3) **Re-assembling.**

- Insert the bowden tube in the print head, all the way down into the white coupler.
- Place the clamp clip around the tube coupling collet, so that the bowden tube is secured.

3 Printing materials

Materials used in 3D printing decide the different purpose and characteristics that this technology can offer us. This is why in this point four diverse materials are illustrated.

3.1 ABS

ABS is an engineering plastic that has butadiene part uniformly distributed over the acrylonitrile-styrene matrix. It possesses excellent toughness, good dimensional stability, easy processing ability, chemical resistance, and cheapness. However, it suffers from inherent shortcomings in terms of mechanical strength and vulnerability to environmental conditions. Furthermore, it is non-conducting and easily fretted.

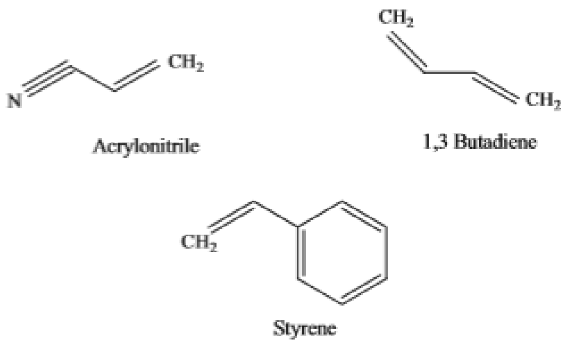


Figure 13: ABS monomer units

Acrylonitrile-styrene copolymers were in use since 1940s and the drawbacks of these copolymers led to the incorporation of third monomer butadiene rubber. Butadiene imparted higher strength and impact resistance character to the plastic. High molecular mass butadiene-acrylonitrile copolymers and styrene-acrylonitrile copolymers were utilized to produce bulletproof polymer sheets during the last years of World War II. The copolymer systems possessed large impact strength because of their low thermoplastic flow properties.

Molded parts such as sheets, profiles, and pipes were the first products to be made out of ABS. The development of injection molding and graft polymerization techniques paved the way for the revolution of applications of ABS plastics. ABS was introduced in 1950 for use in textiles, fashion, toys, and domestic applications. Between late 1950s and early 1960s, the Lego Group R & D lab in Billund switched from process development of cellulose acetate (CA) to ABS. They found that ABS was more stable, tough, and colorfast than CA. By 1970, ABS replaced CA fully in both Europe and North America. The advent of AM techniques especially fused deposition modeling in 1990 and various

3D printers post the year of 1993 led to the increased use of ABS. Open source desktop 3D printers such as RepRap, capable of printing the majority of its own replicate parts, were introduced in the market in 2008.

3.1.1 Manufacturing processes of ABS

ABS can be manufactured by employing AM technologies. AM has emerged to be a mainstream manufacturing technology over few decades since its inception. AM is considered as a feasible technological option by the product manufacturing industry as it addresses the major challenges such as significant reduction of product development time and cost of tooling, human intervention, thereby resulting in rapid product development and manufacturing cycle necessary for the evaluation of form, fit and functionality of a design as well as creation of complicated parts.

3.1.2 Properties

Typically, ABS is a product of systematic polymerization of monomers, namely, acrylonitrile, butadiene, and styrene as shown in Figure 13. There exist two phases of the ABS terpolymer: a continuous phase of styrene-acrylonitrile (SAN) and a dispersed phase of polybutadiene as shown in Figure 14. Commercially available grades of ABS possess medium to high impact, low to high surface gloss, and high heat distortion properties.

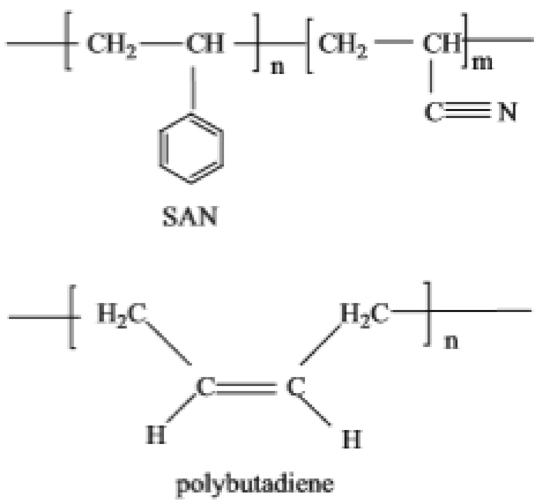


Figure 14: **a** SAN phase of ABS. **b** Butadiene rubber phase

ABS polymers exhibit high toughness (even in cold conditions), adequate rigidity, good thermal stability, and high resistance to chemical attack and environmental stress cracking. Other significant properties of ABS include cheapness, durability, and low coefficient of thermal expansion. No other thermoplastic material displays such a wonderful combination of technically important properties. Molecular and morphological factors are paramount in deciding the properties of ABS. Greater toughness is obtained by increasing the butadiene rubber content and molecular weight of un-grafted SAN phase.

Characteristics	Unit	Amount	Comments
Physical:			
Density	g/cc	1.04	
Melt flow	g/min	1.8 - 2.3	Average = 2.13
Mechanical properties:			
Young's Modulus	MPa	1400 - 3100	Average = 2250 MPa
Hardness, rockwell R		103 - 112	Average = 110
Hardness, Shore D		82 - 85	Average = 83.5
Tensile strength, yield	MPa	42.5 - 44.8	Average = 44
Elongation at break	%	23-25	Average 24.3 %
Flexural modulus	GPa	2.25-2.28	Average = 2.3 GPa
Flexural yield strength	MPa	60.6-73.1	Average = 68.9 MPa
Izod impact, notched	J/cm	2.46 - 2.94	Average = 2.8J/cm
Electrical properties:			
Arc resistance	s	120	
Comparative tracking index	V	600	
Hot wire ignition, HWI	s	15	
High amp arc ignition, HAI	arcs	120	
High Voltage arc-tracking rate HVTR	mm/min	25	
Thermal properties:			
Maximum service temperature, air	°C	88 - 89	Average = 88.7°C
Deflection temperature at 1.8 MPa	°C	88-89	Average = 88.7°C
Vicat softening point	°C	100	
Flammability, UL94	HB	HB	

Table 3: Properties of ABS

3.1.3 Applications

Typical applications of ABS (Acrylonitrile Butadiene Styrene) are:

- **General:** toys, consumer goods, telephones, safety helmets
- **Automotive:** interior door panels, pillars, seat upholstery, grids, dashboards, mirrors housings
- **Appliances:** housings kitchen appliances, vacuum cleaners housings, control panels or white goods
- **Extrude:** Panels, shower trays, tractor roofs, edges of furniture, refrigerators coverings, luggage

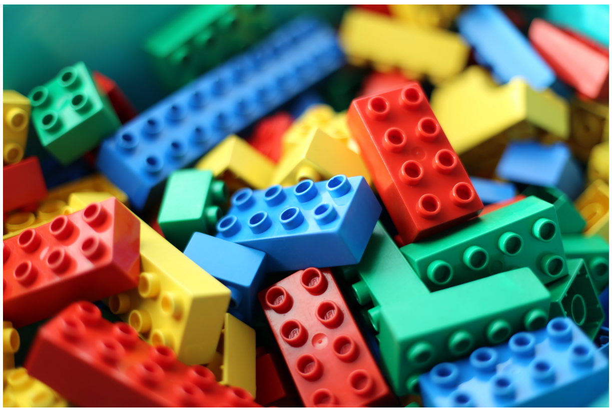


Figure 15: Toy pieces made of ABS

3.2 PLA

PLA or poly-lactide was discovered in 1932 by Carothers. He was only able to produce a low molecular weight PLA by heating lactic acid under vacuum while removing the condensed water. The problem at that time was to increase the molecular weight of the products; and finally, by ring-opening polymerization of the lactide, high molecular weight PLA was synthesized. PLA was first used in combination with polyglycolic acid (PGA) as suture material and sold under the name Vicryl in the U.S.A. in 1974.

In comparison to other biopolymers, the production of PLA has numerous advantages including:

- Production of the lactide monomer from lactic acid, which is produced by fermentation of a renewable agricultural source corn.
- Fixation of significant quantities of carbon dioxide via corn production by the corn plant.
- Significant energy savings.
- The ability to recycle back to lactic acid by hydrolysis or alcoholysis.
- The capability of producing hybrid paper-plastic packaging that is compostable.
- Reduction of landfill volumes.

3.2.1 Production

Lactic acid (2-hydroxy propionic acid), the single monomer of PLA, is produced via fermentation or chemical synthesis. Its 2 opctically active configurations, the L(+) and D(-) stereoisomers are produced by bacterial fermentations of carbohydrates. Industrial lactic acid production utilizes the lactic fermentation process rather than synthesis because the synthetic routes have many major limitations, including limited capacity due to the dependency on a by.product of another process, inability to only make the desirable L-Lactic acid stereoisomer, and high manufacturing costs. The Figure 16 is a schematic showing about PLA production.

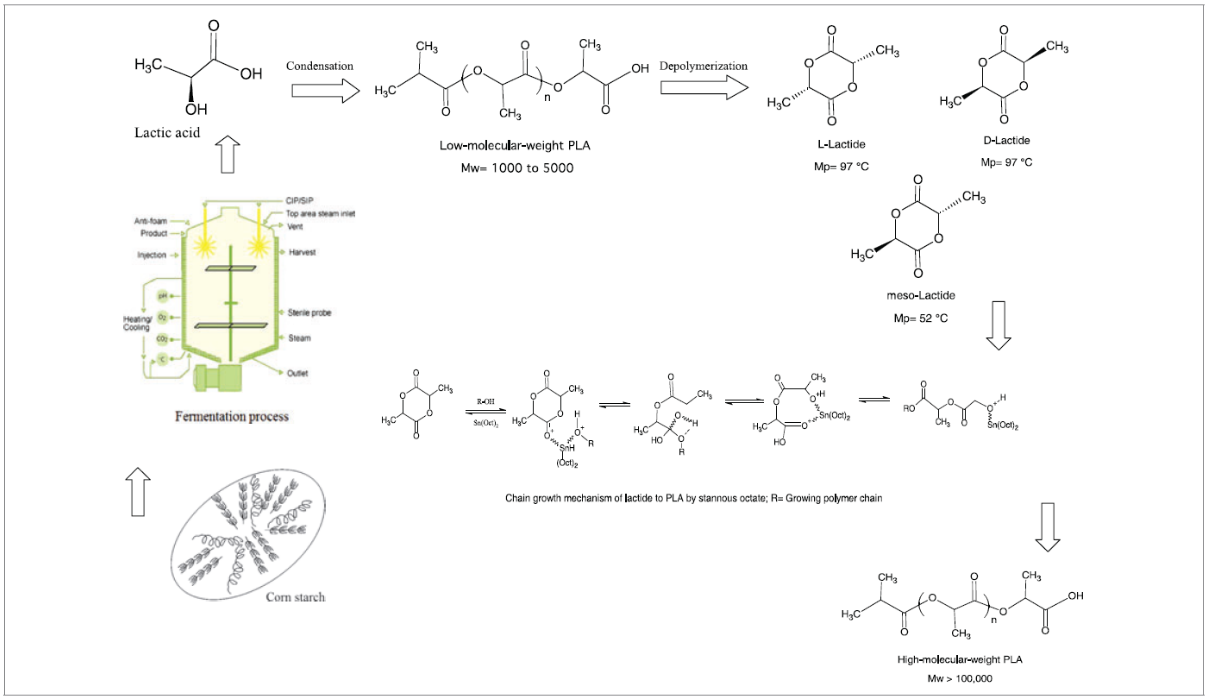


Figure 16: PLA Production

There are companies that exclusively use corn starch as raw material for lactic acid production via lactic fermentation. Many studies have been conducted to fin other sources os carbohydrates for lactic acid production. The use of a specific carbohydrate feedstock depends on its price, availability and purity. Some agricultural by-products, which are potential substrates for lactic acid production include, cassava starch, lignocellulose/hemicellulose hydrolysates, cottonseed hulls, Jerusalem artichokes, corn cobs, corn stalks, beet molasses, wheat bran, rye flour, sweet sorghum, sugarcane press mud, cassava, barley starch, cellulose, carrot processing waste, molasses spent wash, corn fiber hydrolysates, and potato starch.

Other sources of carbohydrate for lactic acid production include kitchen wastes, fish meal wastes and paper sludge.

3.2.2 Drying

As PLA is sensitive to high-relative humidity and temperature conditions, and for minimizing the risk of its molecular degradation, it is necessary to be dried less than 0,01% w/w. This is expressed as 0,025% w/w or below. PLA resins normally are packaged with moisture content below 0,04% w/w in moisture-resistant foil liners to maintain that moisture level, and so the drying process is essential. Drying conditions are dependent on temperature, time, air flow rate, and dew point.

Amorphous pellets must be dried below the T_g (43 to 55°C) to prevent the resin pellets from sticking together, which can bridge and plug the dryer.

For crystalline types, the recommended temperatures and times range between 80 to 100°C and 4 to 2 hours.

3.2.3 Extrusion

The first major step in the conversion of plastic resin into films, sheet, containers and so on, is to change the pellets from solid to liquid or molten phase in an extruder. Extrusion is a common way for melting thermoplastics and it is the first step for extrusion, blown film extrusion, and other polymer processes.

Screw extruders are typically used in the polymer industry. It can be seen in the Figure 17. It consists of an electrically heated metal barrel, a hopper for feeding the resin, a motor for rotating a screw, and a die where the polymer melt exists. So, the combination of thermal energy generated by a heater and frictional heat due to friction between the plastic and the screw and barrel provide sufficient heat to melt the pellets.

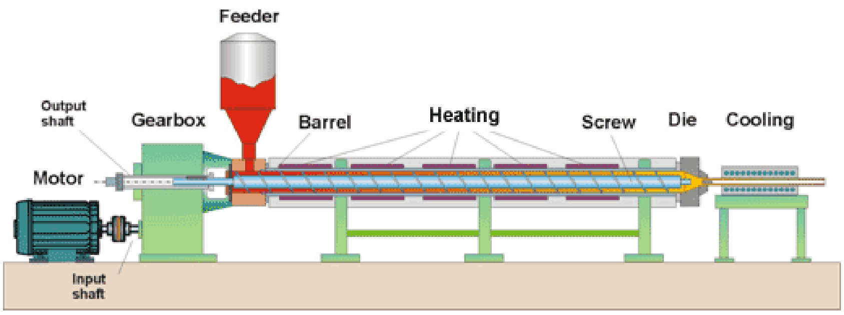


Figure 17: Extruder

The L/D ratio, which is the ratio of flight length of the screw to its outer diameter, determines the shear and residence time of the melt. Screws with a large L/D ratio provide greater shear heating, better mixing, and longer melt residence time in the extruder. Another important screw parameter is the compression ratio, which is the ratio of the flight depth in the feed section to the flight depth in the metering section. The greater the compression ratio a screw possesses, the greater the shear heating it provides.

Recommended extrusion conditions for PLA pellets include general purpose screws with L/D ratios from 21:1 to 30:1 and compression ratio of 2.5:1 to 3:1, melt temperature of 200 to 220°C, and also smooth barrels.

3.2.4 Properties

PLA has unique properties like good appearance, high mechanical strength, and low toxicity; and good barrier properties have broadened it applications. Numerous researchers have studied the different properties of PLA alone and in combination with other polymers as blend or copolymer. Table 4 shows some of them:

Characteristics	Unit	Amount	Reference
Physical:			
Molecular weight	g/mol	66000	Garlotta (2001)
Specific gravity	-	1.27	
Solid density	g/cm^3	1.2515	
Melt density	g/cm^3	1.0727	
Glass transition temperature	°C	55	Mehta and others (2005)
Melting temperature	°C	165	
Specific heat (Cp)	J/Kg°C		
190°C		2060	
100°C		1955	
55°C		1590	
Thermal conductivity	W/m°C		
190°C		0.195	
109°C		0.197	
48°C		0.111	
Optical			
UV light transmission:			Auras and others (2004)
190 to 220 nm		$< 5\%$	
225 to 250 nm		85%	
$> 300nm$		95%	
Mechanical:			
Tensile strength	MPa	59	
Elongation at break	%	7.0	
Elastic modulus	MPa	3500	
Shear modulus	MPa	1287	
Poissons ratio	-	0.3600	
Yield strength	MPa	70	
Flexural strength	MPa	106	
Unnotched izod impact	J/m	195	
Notch izod impact	J/m	195	

Characteristics	Unit	Amount	Reference
Rockwell B hardness	HRB	88	
Brinell hardness	HB	175	
Heat deflection temp.	°C	55	
Ultimate tensile strength	MPa	73	

Table 4: Properties of PLA

3.2.5 Applications

PLA has a potential for use in a wide range of applications. PLA food packaging applications are ideal for fresh products and those whose quality is not damaged by PLA oxygen permeability.

PLA is a growing alternative as a ”green” food packaging polymer. New applications have been claimed in the field of fresh products, where thermoformed PLA containers are used in retail markets for fruits, vegetables, and salads.

The major PLA applications today is in packaging (nearly 70%); the estimation for 2020 shows the increase of other applications especially in fibers and fabrics.

Commercialized PLA products demonstrate this fact that PLA is not being used solely because of its degradability, nor because it is made from renewable resources; it is being used because it functions very well and provides excellent properties at a competitive price. There are many commercialized PLA products in the markets and their variety and consumption are increasing rapidly.

PLA is also used in biomedical applications, with various uses as internal body components mainly in the of restricted load for example, interference screws in ankle, knee, and hand; tack and pins for ligament attachment; rods and pins in bone, plates and screws for craniomaxillofacial bone fixation; and also for surgical sutures, implants, and drug delivery systems.

3.3 CPE

Copolyester (CPE) is a copolymer of Polyethylene terephtalate (PET). PET is a polymer obtained by a polycondensation reaction between terephthalic acid and ethylene glycol. It belongs to the group of polyesters called synthetic materials. PET is the most common thermoplastic polymer resin of the polyester family and is used in fibers for clothing, containers for liquids and foods, thermoforming for manufacturing, and in combination with glass fiber for engineering resins.

It is a linear thermoplastic polymer with a high degree of crystallinity. As all thermoplastics can be processed by extrusion, injection, injection blow preform blowing and thermoforming.

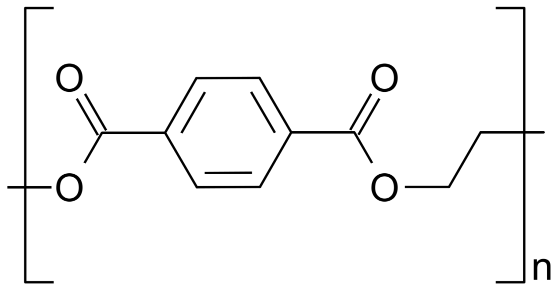


Figure 18: Polyethylene Terephtalate molecular structure

3.3.1 Properties

The physical properties of PET and its ability to meet various specifications were the reasons why the material has reached a significant development in the production of textile fibers and production of a wide variety of containers, especially in the production of bottles , trays, strips and sheets.

It presents most relevant features:

- High resistance to wear and corrosion.
- Very good coefficient of sliding.
- Good chemical and thermal resistance.
- Very good barrier to CO2, O2 and acceptable moisture barrier.
- Compatible with other barrier materials that improve the quality as a whole barrier containers and thus allow use in specific markets.
- Recyclable, although it tends to decrease its viscosity with the thermal history.
- Approved for use in products that should be in contact with food products.

In the Table 5 are displayed some properties of this polymer:

Characteristics	Unit	Amount	Test method
Mechanical properties:			
Tensile modulus	MPa	1900	ASTM D638
Tensile stress at yield	MPa	50	ASTM D638
Tensile stress at break	MPa	28	ASTM D638
Elongation at yield	%	5	ASTM D638
Elongation at break	%	11	ASTM D638
Flexural modulus	MPa	2100	ASTM D790
Izod impact strength, notched	J/m	ASTM 256	
Hardness	N/mm^2	170	
Hardness Shore D	-	85-87	ASTM D2240
Hardness (R scale)	-	108	ASTM D785
Thermal properties:			
Heat deflection (HDT) at 0.455 MPa	°C	70	ASTM D648
Heat deflection (HDT) at 1.82 MPa	°C	62	ASTM D648
Glass transition	°C	82	DSC
Specific heat			
60°C	kJ/kg°K	1.30	
100°C	kJ/kg°K	1.76	
150°C	kJ/kg°K	1.88	
200°C	kJ/kg°K	1.97	
250°C	kJ/kg°K	2.05	
Coefficient of thermal expansion (flow)	mm/mm°C	$7E^{-}5$	ASTM E693
Physical properties:			
Specific gravity		1.27	ASTM D792
Density	g/cm^3	1.27	ISO 1183
Typical printing conditions:			
Bed temperature	°C	70-75	+ glue
Printing temperature (0.4 mm nozzle)	°C	235-250	
Printing speed guideline (0.4 mm nozzle)	mm/s	30-50	

Table 5: Properties of CPE

3.3.2 Applications

Throughout the 25 years at the market, PET has diversified into many sectors replacing traditionally implanted materials or raising new packaging alternatives unthinkable so far.

Packaging:

- Carbonated drinks
- Purified water
- Oil
- Preserves
- Cosmetics.
- Detergents and Chemicals
- Pharmaceutical products

Engineering Applications:

This segment covers several kind of films and applications from ultra-thin films for capacitors of one micron or less to 0.5 millimeters, used for insulation of engines. Capacitors have dielectric PET film used for telecommunications, electronics and others. It is also used for photographic film and transparencies. The polyester fibers are used industrially in strings and construction filters. Its chemical resistance allows to apply it in bristles of brushes for industrial paints and brushes.

Fibers:

In the textile industry, the polyester fiber is used to make a variety of fabrics and clothing. Because it is stronger than cotton and cellulose, if mixed well with the cotton is also used in the production of fibers. Garments made of these fibers are resistant to wrinkles. Business familiar names such as Dacron and Fortrel are known, and are widely used in products such as clothing and home.

The polyesters also have medical applications to be able to use their strength fibers on surgeries to repair damaged tissues or even sutures.

3.4 Flexifil - TPC

FlexiFil filament is a rubber-like 3D printer filament which allows us to print flexible objects, such as rubber machine parts, soft toys, flip-flops, and other rubbery items.

It is a revolutionary new rubber-like high-performance Thermoplastic Co-Polyester (TPC) filament. It has flexural strength properties, as 3D printed objects with FlexiFil will have a flexural memory, allowing objects to return back to their original position after being bent, dent, or folded.

FlexiFil is a high-performance TPC that offers a unique combination of flexibility, high temperature resistance, strength, and an excellent UV resistance and good resistance to chemicals.

This filament is a BIO-performance TPC with a substantially reduced carbon footprint compared to typical Co-Polyester 3D printer filaments, as FlexiFill is partially made out of renewable carbon content, such as bio-based oils.

3.4.1 Properties

- Very flexible / Flexural memory
- Good resistance to chemicals
- Excellent UV resistance
- Long term heat resistant
- Strength

In the Table 6 are displayed some properties of this polymer:

Characteristics	Unit	Amount	Test method
Physical:			
Specific gravity	g/cc	1.14	ISO 1183
Melt flow rate	cm^3/min	39	ISO 1133
Water absorption	%	0.69	-
Moisture absorption	%	0.30	-
Mechanical:			
Impact strength		No Break	ISO 180/1A
Tensile strength	MPa	24	ISO 527 1/2
Tensile modulus	MPa	95	ISO 527 1/2
Elongation at break	%	530	ISO 527 1/2
Shore D Hardness		54	ISO 868
Thermal:			

Characteristics	Unit	Amount	Test method
Print temperature	°C	220 - 260	
Melting temperature	°C	180	ISO 11357 1/3
Viscat softening temperature	°C	90	

Table 6: Properties of Flexifil

3.4.2 Printing settings

It is recommended to significantly lower the printing speed (compared to printing with PLA, or ABS) when printing with FlexiFil. The guideline for an optimal printing temperature is to print at approximately 210°C. The recommended heated bed temperature varies between 60°C and 100°C. Various other options (also without heated bed) are possible depending on the type and size of the object to be printed.

In order to get a good first layer adhesion it is important that the print bed is really level and clean. Depending on the printer it can also help to use a glue stick to improve the first layer adhesion. A combination of Blue Tape, and glue stick can also do wonders.

The flexibility/rubbery characteristics of FlexiFil can cause some friction in the printer's bowden tube, resulting in unstable feeding process of the filament into the extruder. As a remedy one can use a tiny bit of lubricant in one's bowden tube in order make sure there will not be any friction.

4 Mechanical properties testing

Nowadays it is very easy to know the mechanical characteristics about extruded polymers. However, it is not easy to find characteristics about printed materials. This are supposed to be different than extruded because of the way in which they are make. Therefore, this section shows the diverse aspects tested in order to know more about the influence of the process in the final characteristics of the material.

4.1 Specimen design

Firstly, it is necessary to define and create a specimen. It has to fulfill the size specified in the standard ISO 527-2:2012 for the Tensile Test. It has two shoulders and a gage in between. The shoulders are large so they can be readily gripped, whereas the gauge section has a smaller cross-section so that the deformation and failure should occur in this area.

It has been created on Solidworks (Figure 19), a powerful 3D design software trough which it is possible to design the part and save it in .STL format. This is the mandatory format to print with Ultimaker 2 Extended+ .

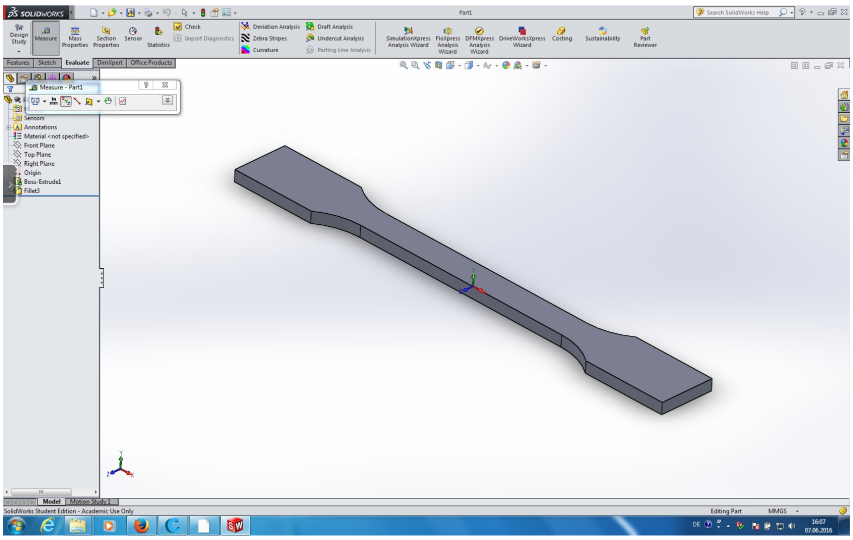


Figure 19: Specimen designed in Solidworks

4.2 Young's Modulus

Young's Modulus or Modulus of Elasticity is a parameter characterizing the behavior of an elastic material, according to the direction in which a force is applied.

For a linear isotropic elastic material, Young's modulus has the same value for traction as for compression, being an independent constant effort that does not exceed a maximum value called elastic limit and is always greater than zero. In this case, its value is defined as the ratio between the stress and the strain appearing (Equation 1) in a straight stretched or compressed bar made of the material which is necessary to estimate the modulus of elasticity. Both the Young's modulus and yield strength are different for different materials. The modulus of elasticity is a elastic constant which like the elastic limit can be found empirically by tensile test.

$$E = \frac{\sigma}{\varepsilon} = \frac{F/S}{\Delta L/L} \quad (1)$$

Where:

E is the Young's Modulus.
σ is the pressure on the cross sectional area of the object.
ε is the strain at any point of the bar.

4.2.1 ABS

To perform the test according to the standard ISO 527-1:2012 it is necessary to test at least 5 different specimens. The measure results of ABS material are shown in the Table 7. In this table it can be seen the diverse values for the Young's Modulus, width and the thickness.

Nr	E (MPa)	$b_0(mm)$	$a_0(mm)$
1	2178,19	10,35	4,02
2	2180,83	10,25	3,96
3	1961,87	10,15	4,01
4	2182,35	10,05	4
5	2168,68	10,05	4
6	2113,42	10,1	4,09

Table 7: ABS general results of Young's Modulus Test

After obtaining this results, it is necessary to calculate some statistics in order to get a general view about the value of the Young's Modulus. This values are represented in the Table 8. The most representative value is the average of the Young's Modulus. It is obtained a value of 2130.39MPa whereas a standardized value for ABS is 2250MPa (a difference of 7%).

This little decrease of the Young's Modulus is due to the way in which the part are done (layer-by-layer). The obtained part is not a solid mass, but a succession of joined solid slices of material.

Serie n=6	E (MPa)	$b_0(mm)$	$a_0(mm)$
$\overline{x}$	2130,89	10,16	4,013
s	86,81	0,1201	0,04274
ν	4,07	1,18	1,06

Table 8: ABS statistics results of Young's Modulus Test

4.2.2 PLA

The results of the Young's Modulus Test are shown in the Table 9 .In this case, five specimens were used to define the Young's Modulus, and how can be seen, all are inside the specifications of the standard ISO 527-1:2012. Apparently, this is higher than ABS. To be sure it's necessary to calculate some statistics values.

Nr	E (MPa)	$b_0(mm)$	$a_0(mm)$
1	2878,86	9,9	3,98
2	2664,97	9,98	4,12
3	2768,73	10	4,03
4	2884,02	10,04	4,04
5	2983,93	10,08	4,04

Table 9: PLA general results of Young's Modulus Test

In the Table 10 are shown the statistics of this material. PLA has an average of 2836,10MPa less than the standardized value of 3500MPa. Again the value obtained in the test is less than the standardized value (around 19%), like it happened with ABS.

Serie n=5	E (MPa)	$b_0(mm)$	$a_0(mm)$
$\overline{x}$	2836,10	10	4,042
s	122,27	0,06782	0,0502
ν	4,31	0,68	1,24

Table 10: PLA statistics results of Young's Modulus Test

4.2.3 CPE

The third tested material is CPE. Five specimens of CPE have been tested. General results are displayed in the Table 11. Like in the two others, it is necessary to calculate the statistics values of this sample to get a significant value.

In the Table 12 it can be read the value of CPE's average. It has been obtained a value for the Young's Modulus of 1915.61MPa. This is more or less the same value than the standardized of 1900 Mpa for this material

Nr	E (MPa)	$b_0(mm)$	$a_0(mm)$
1	1903,59	10	4,08
2	1928,29	10,01	4,06
3	1952,43	10,03	4,08
4	1868,98	10,07	4,05
5	1924,80	10,04	4,05

Table 11: CPE general results of Young's Modulus Test

Serie n=5	E (MPa)	$b_0(mm)$	$a_0(mm)$
$\overline{x}$	1915,61	10,03	4,064
s	31,30	0,02739	0,01517
ν	1,63	0,27	0,37

Table 12: CPE statistics results of Young's Modulus Test

4.2.4 Flexifil

In the Table 13 are displayed the results for the Young's modulus test. In this case, only two specimens have been tested because the difficulty of print this material.

Nr	E (MPa)	$b_0(mm)$	$a_0(mm)$
1	90,17	10	3,81
2	96,24	10,1	3,83

Table 13: Flexifil general results of Young's Modulus Test

As can be seen in the table 14 the average for the Young's Modulus is 93.20MPa very close to the standard value of 95MPa for this material, with only a difference of 2%.

Serie n=2	E (MPa)	$b_0(mm)$	$a_0(mm)$
$\overline{x}$	93,20	10,05	3,82
s	4,29	0,07071	0,01414
ν	4,61	0,7	0,37

Table 14: Flexifil statistics results of Young's Modulus Test

4.3 Tensile test

The tensile test of a material consist in submitting a standardized specimen to an axial force, increasing tensile until fracture occurs. This test measures the resistance of a material to a static or slowly applied force. The strain rates in a tensile test are usually very small.

It is performed for several reasons. The results of tensile test are used in selecting materials for engineering applications. The strength os a material often is the primary concern. The strength of interest may be measured in terms of either the stress necessary to cause appreciable plastic deformation or the maximum stress that the material can withstand.These measures of strength are used, with appropriate caution, in engineering design.Finally, tensile properties often are used to predict the behavior of a material under forms of loading other than uniaxial tension.

In the Figure 20 it can be seen the different kind of diagrams that are obtained through doing a tensile test and the meaning of the used symbols.

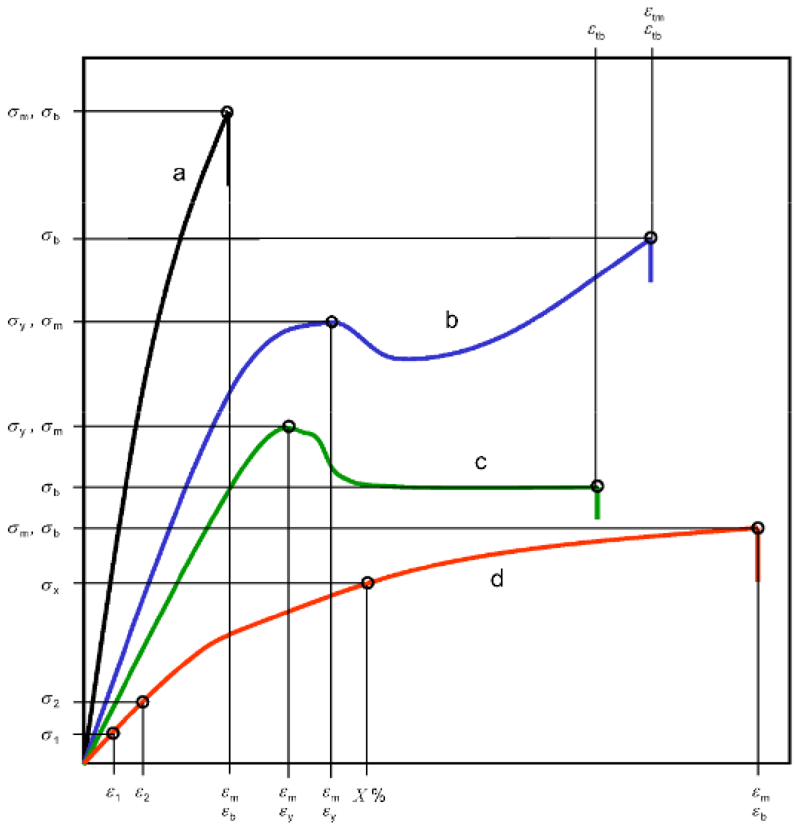


Figure 20: Tensile diagrams

4.3.1 Description of the method

To prepare the test is necessary to follow the next steps:

1) The specimen has to be clear and straight. If not the results could be wrong.

2) Trough a specific machine (Figure 21), stamping two marks on the specimen.This marks will be read by the tensile machine to calculate the specimen linear strain (Figure 22).

3) Inserts the specimen between the machine jaws (Figure 23).

4) Runs the program and wait until the specimen break (Figure 24).

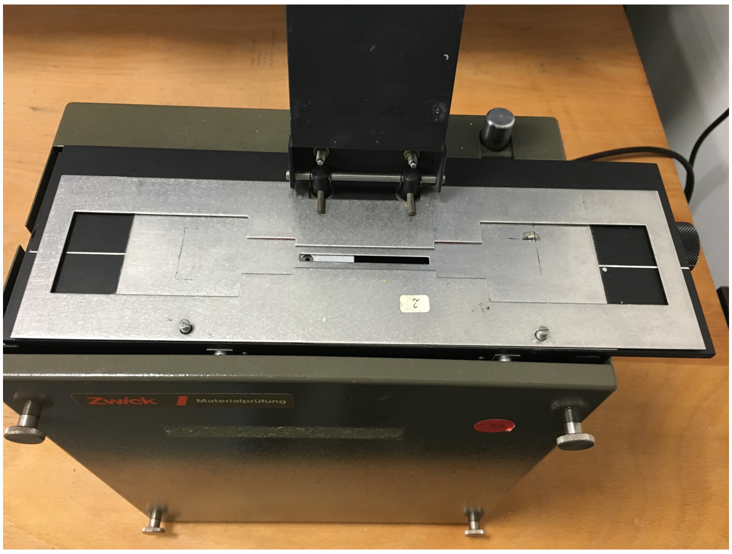


Figure 21: Stamping machine

Figure 22: Specimen point marks

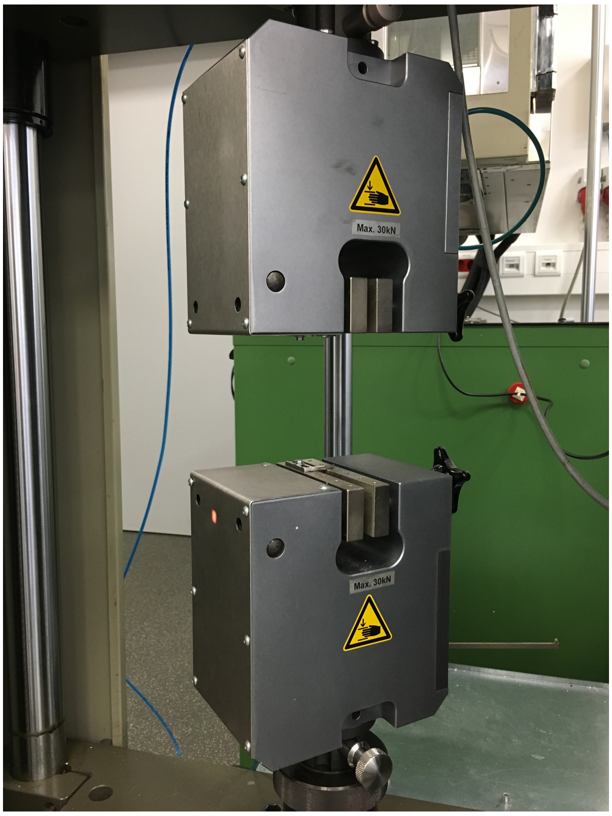


Figure 23: Jaws

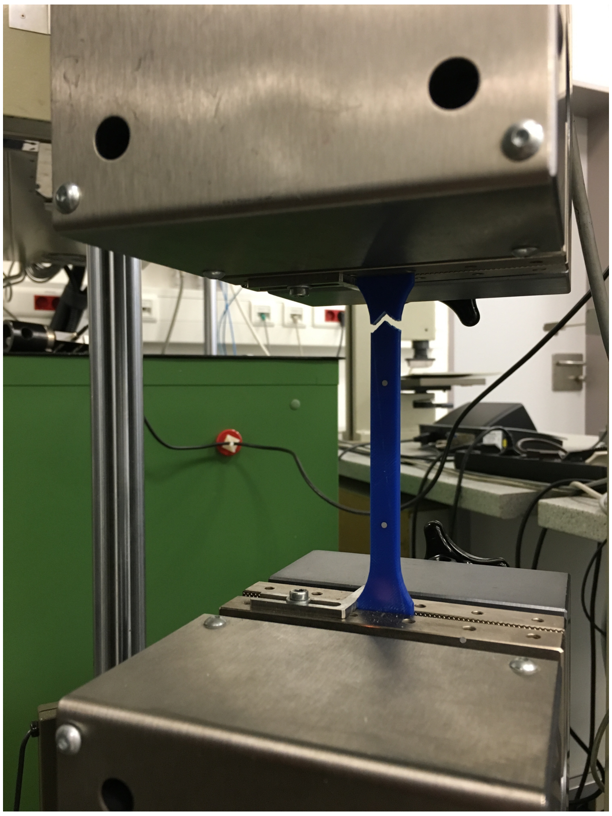


Figure 24: Specimen break

4.3.2 ABS

To perform the test according to the standard ISO 527-1:2012 it is necessary to test at least 5 different specimens. In this case have been tested six specimens. The measure results of ABS material are shown in the Table 15. In this table it can be seen diverse values: width, thickness, initial length, proportionality limit, yield strength, yield point, ultimate stress.

Nr	$b_0(mm)$	a_0(mm)	$L_0(mm)$	$\sigma_B(MPa)$	$\sigma_Y(MPa)$	$\sigma_M(MPa)$	$\varepsilon_Y(\%)$	$\varepsilon_M(\%)$	$\varepsilon_{tM}(\%)$	$\varepsilon_B(\%)$	$\varepsilon_{tB}(\%)$
1	10.10	3.99	49.94	33.78	36.70	36.70	2.5	2.5	2.5	3.0	2.9
2	10.12	4.10	49.59	39.49	41.64	41.64	2.6	2.6	2.7	3.0	3.0
3	10.35	4.02	49.94	38.49	44.61	44.61	2.9	2.9	3.1	4.3	4.5
4	10.05	4.01	50.40	38.00	40.42	40.42	2.5	2.5	2.7	2.9	3.0
5	10.05	4.00	50.09	41.30	41.79	41.79	2.5	2.5	2.7	2.7	2.9
6	10.3	3.96	51.27	41.07	44.71	44.71	2.7	2.7	2.9	3.4	3.5

Table 15: ABS general results of Tensile Test

After obtaining this results, it is necessary to calculate some statistics in order to get a general view about the different values obtained. This values are represented in the Table 16. It has been obtained a value of the yield stress of 41.64MPa. This is only around a 8% less than the standardized value of 44MPa.

For the break strain it has been obtained a value of 3.2%. This is a 87% less than the standardized value for a extruded specimen.

	$b_0(mm)$	a_0(mm)	$L_0(mm)$	$\sigma_B(MPa)$	$\sigma_Y(MPa)$	$\sigma_M(MPa)$	$\varepsilon_Y(\%)$	$\varepsilon_M(\%)$	$\varepsilon_{tM}(\%)$	$\varepsilon_B(\%)$	$\varepsilon_{tB}(\%)$
$\overline{x}$	10.16	4.01	50.20	38.69	41.64	41.64	2.6	2.6	2.8	3.2	3.3
s	0.1304	0.04719	0.59	2.75	2.97	2.97	0.1	0.1	0.2	0.6	0.6
ν	1.28	1.18	1.17	7.10	7.14	7.14	5.64	5.64	8.04	17.96	19.51

Table 16: ABS statistics results of Tensile Test

4.3.3 PLA

In the Table 17 it can be seen the results of the tensile test for this material. It has been used a set of 5 different specimens to define the characteristics of this material.

Nr	$b_0(mm)$	a_0(mm)	$L_0(mm)$	$\sigma_B(MPa)$	$\sigma_Y(MPa)$	$\sigma_M(MPa)$	$\varepsilon_Y(\%)$	$\varepsilon_M(\%)$	$\varepsilon_{tM}(\%)$	$\varepsilon_B(\%)$	$\varepsilon_{tB}(\%)$
1	9.95	4.00	50.11	45.99	49.89	49.89	2.2	2.2	2.5	2.9	3.3
2	10	4.1	49.82	37.21	45.59	45.59	2.4	2.4	2.4	4.9	4.9
3	10	4.04	49.91	38.49	42.23	51.08	2.4	2.4	2.7	5.3	5.5
4	10.05	4.05	49.80	41.40	53.29	53.29	2.4	2.4	2.6	4.6	4.8
5	10.03	4.05	49.72	41.91	56.26	56.26	2.5	2.5	2.9	5.2	5.5

Table 17: PLA general results of Tensile Test

The statistics results are calculated in the Table 18. The yield stress average obtained is 36,70MPa, around 48% less than the standardized value of 70MPa for a extruded specimen. The elongation at break obtained is 3%, that is a 58% less than the standardized value of 7%.

	$b_0(mm)$	a_0(mm)	$L_0(mm)$	$\sigma_B(MPa)$	$\sigma_Y(MPa)$	$\sigma_M(MPa)$	$\varepsilon_Y(\%)$	$\varepsilon_M(\%)$	$\varepsilon_{tM}(\%)$	$\varepsilon_B(\%)$	$\varepsilon_{tB}(\%)$
$\overline{x}$	10.1	3.99	49.94	33.78	36.70	36.70	2.5	2.5	2.5	3.0	2.9
s	10.12	4.1	49.59	39.49	41.64	41.64	2.6	2.6	2.7	3.0	3.0
ν	10.35	4.02	49.94	38.49	44.61	44.61	2.9	2.9	3.1	4.3	4.5

Table 18: PLA statistics results of Tensile Test

4.3.4 CPE

The tensile results for the CPE are displayed in the Table 19. A set of 5 specimens have been tested in order to obtain the characteristics values for this material.

Nr	$b_0(mm)$	a_0(mm)	$L_0(mm)$	$\sigma_B(MPa)$	$\sigma_Y(MPa)$	$\sigma_M(MPa)$	$\varepsilon_Y(\%)$	$\varepsilon_M(\%)$	$\varepsilon_{tM}(\%)$	$\varepsilon_B(\%)$	$\varepsilon_{tB}(\%)$
1	10.01	4.08	49.93	39.44	46.00	46.00	3.6	3.6	3.7	4.7	4.7
2	10.02	4.05	49.56	42.09	43.06	43.06	3.1	3.1	3.2	3.4	3.4
3	10.05	4.06	49.69	43.41	46.66	46.66	3.5	3.5	3.5	4.0	4.0
4	10.05	4.03	50.13	36.69	39.13	39.13	2.8	2.8	2.8	3.2	3.1
5	10.05	4.03	49.83	42.20	44.17	44.17	3.1	3.1	3.3	3.5	3.6

Table 19: CPE general results of Tensile Test

In the Table 20 it can be seen that the yield stress for CPE is 43,80MPa. It is a 14% less than the value for a extruded specimen of CPE (50MPa). About the elongation at yield, the value obtained in this test is 3.2%, which is a 30% less than the value for a extruded standardized specimen of CPE (5%).

	$b_0(mm)$	a_0(mm)	$L_0(mm)$	$\sigma_B(MPa)$	$\sigma_Y(MPa)$	$\sigma_M(MPa)$	$\varepsilon_Y(\%)$	$\varepsilon_M(\%)$	$\varepsilon_{tM}(\%)$	$\varepsilon_B(\%)$	$\varepsilon_{tB}(\%)$
$\overline{x}$	10.04	4.05	49.83	40.77	43.80	43.80	3.2	3.2	3.3	3.8	3.7
s	0.01949	0.02121	0.22	2.70	2.98	2.98	0.3	0.3	0.3	0.6	30.6
ν	0.19	0.52	0.44	6.63	6.80	6.80	9.74	9.74	9.88	16.10	16.48

Table 20: CPE statistics results of Tensile Test

4.3.5 Flexifil

The results of the tensile test are displayed in the Table 21. Only two specimens has been tested because the great difficulty that this material suppose for the 3D printer.

Nr	$b_0(mm)$	a_0(mm)	$L_0(mm)$	$\sigma_B(MPa)$	$\sigma_Y(MPa)$	$\sigma_M(MPa)$	$\varepsilon_Y(\%)$	$\varepsilon_M(\%)$	$\varepsilon_{tM}(\%)$	$\varepsilon_B(\%)$	$\varepsilon_{tB}(\%)$
1	10.01	3.86	49.72	11.85	9.65	12.50	26.70	194.2	190.0	200.0	195.8
2	10.03	3.86	49.63	13.12	9.90	13.46	26.5	238.9	235.4	241.5	238.0

Table 21: Flexifil general results of Tensile Test

After obtaining the values for the two specimens, in the Table 22 are displayed the values for elongation and yield stress. It is very important the elongation of this material. A value of 26.6% has been obtained at the yield point and 220.7% at the break point. this is around a 59% less than the standardized value of 530% for the elongation at the break point.

The value of the yield stress is 9.77 MPa. This is a 70% less than the standard value of 24 MPa for this material.

	$b_0(mm)$	a_0(mm)	$L_0(mm)$	$\sigma_B(MPa)$	$\sigma_Y(MPa)$	$\sigma_M(MPa)$	$\varepsilon_Y(\%)$	$\varepsilon_M(\%)$	$\varepsilon_{tM}(\%)$	$\varepsilon_B(\%)$	$\varepsilon_{tB}(\%)$
$\overline{x}$	10.02	3.86	49.67	12.49	9.77	12.98	26.6	216.6	212.7	220.7	216.9
s	0.01414	0.000	0.07	0.90	0.18	0.68	0.1	31.6	32.1	29.4	29.9
ν	0.14	0.000	0.14	7.19	1.81	5.22	0.51	14.57	15.07	13.31	13.78

Table 22: Flexifil statistics results of Tensile Test

4.4 Hardness test

4.4.1 Brinell hardness

Brinell hardness is a hardness measuring scale of a material by the indentation method, measuring the penetration of an object in the material to study. It was proposed by the Swedish engineer Johan Brinell in 1900, being the oldest method of hardness.

This test is used in soft materials (low hardness) and thin samples. The indenter or used penetrator is a ball of hardened steel of different diameters. For harder materials tungsten carbide balls are used. In the typical test is used a steel ball from 10 to 12 millimeters of diameter, with a force of 3000 kilograms. The measured value is the diameter of the mark on the material surface. Brinell hardness measurements are very sensitive to the state of preparation of the surface.

The load to be used in the test can be obtained with the following expression:

$$P = K * D^2 \tag{2}$$

Where:

P: Load to be used in Kg.
K: Material constant.
D: Ball diameter (indenter) in mm.

The equation 3 determine the Brinell hardness value :

$$HB = \frac{2P}{\pi D^2}\left(\frac{1}{1-\sqrt{1-\frac{d^2}{D^2}}}\right) \tag{3}$$

Where:

P: Load to be used in Kg.
D: Ball diameter (indenter) in mm.
d: Ball mark diameter in mm

This test is only valid for values lower than 600HB in the case of using the steel ball. In this case it is then used the Vickers hardness test.

4.4.1.1 ABS

To perform the test according to the standard ISO 2039-1:2001 it is necessary to test at least 5 different specimens. In this case have been tested four specimens. The measure results of ABS material are shown in the Table 23. In this table it can be seen diverse values: hardness, applied force, time and depth mark.

Nr	H (N/mm^2)	Fm (N)	$t_2(s)$	h(μm)
1	84.1	357.92	46.8	267.54
2	88.1	357.92	46.4	257.22
3	87.2	357.92	44.0	259.66
4	84.9	357.92	44.4	265.38

Table 23: ABS general results of Hardness Test

In the Table 24 are displayed the statistics results of this test. For ABS the average of the hardness obtained is $86.1 N/mm^2$.

Nr	H (N/mm^2)	Fm (N)	$t_2(s)$	h(μm)
$\overline{x}$	86.1	357.92	45.4	262.43
s	1.9	0.02	1.4	4.84
ν	2.18	0.00	3.02	1.84

Table 24: ABS statistics results of Hardness Test

4.4.1.2 PLA

To perform the test for this material six specimens has been tested. The measure results of PLA material are shown in the Table 25.

In the Table 26 are displayed the statistics results of this test. For PLA the average of the hardness obtained is $130.8 N/mm^2$. The standardized value for a solid extruded specimen is 175HB so that it has been obtained around a 26% less than the standardized value.

Nr	H (N/mm^2)	Fm (N)	$t_2(s)$	h(μm)
1	137.0	357.90	47.9	179.66
2	128.8	357.92	44.1	188.64
3	127.7	357.94	50.1	189.92
4	132.3	357.94	44.5	184.64
5	124.1	357.93	45.6	194.26
6	135.1	357.93	49.0	181.72

Table 25: PLA general results of Hardness Test

Nr	H (N/mm^2)	Fm (N)	$t_2(s)$	h(μm)
$\overline{x}$	130.8	357.93	46.9	186.48
s	4.9	0.01	2.5	5.47
ν	3.72	0.00	5.33	2.93

Table 26: PLA statistics results of Hardness Test

4.4.1.3 CPE

To perform the test for this material eight specimens has been tested. The measure results of CPE material are shown in the Table 25.

Nr	H (N/mm^2)	Fm (N)	$t_2(s)$	h(μm)
1	85.3	357.93	44.6	264.50
2	63.8	357.92	44.7	340.16
3	84.2	357.94	44.8	267.42
4	69.6	357.93	44.9	314.82
5	89.5	357.89	44.2	253.76
6	80.3	357.89	44.5	278.32
7	71.9	357.89	45.7	306.24
8	77.9	357.93	45.0	285.66

Table 27: CPE general results of Hardness Test

In the Table 28 are displayed the statistics results of this test. For CPE the average of the hardness obtained is $77.8 N/mm^2$.

Nr	H (N/mm^2)	Fm (N)	$t_2(s)$	h(μm)
$\overline{x}$	77.8	357.92	44.8	288.86
s	8.8	0.02	0.4	29.31
ν	11.27	0.01	0.99	10.15

Table 28: CPE statistics results of Hardness Test

4.4.2 Shore hardness

The Shore hardness is determined by measuring the penetration of the durometer tip, acting under the force of a spring, within the sample. The contact force should be enough so that the durometer bottom surface contacts its entire surface with the part to be measured, therefore, must exceed the maximum spring force so that it does not win out the contact force.

During the measure, reading can decrease over time due to the resilient nature of the rubber and plastics. For this reason reading must always be taken after a fixed time of application. Likewise also it affects the temperature measurement and should be recorded in the test report.

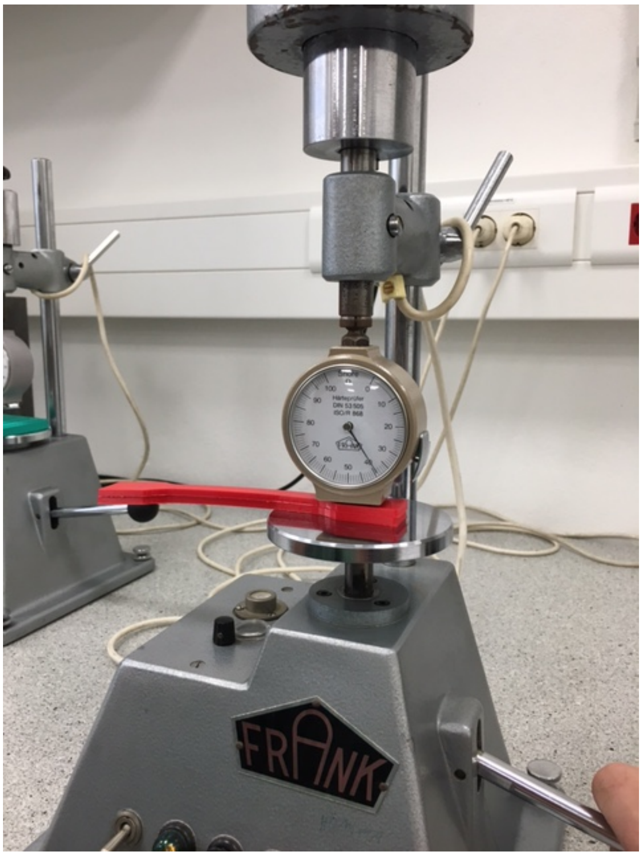


Figure 25: Shore D Hardness Equipment

4.4.2.1 ABS

To perform the test for this material according to the standard ISO 868:2003 ten specimens has been tested. The measure results of ABS material are shown in the Table 29.

Nr	Shore D
1	68.0
2	71.0
3	72.0
4	71.5
5	70.5
6	69.0
7	67.0
8	70.0
9	67.0
10	68.5

Table 29: ABS general results of Shore Hardness Test

As can be seen in the Table 29 the ABS hardness is 69.4 Shore D. This is around 17% less than the standardized value of 83.5 Shore D for this material.

Nr	Shore D
$\overline{x}$	69.4
s	2.15

Table 30: ABS statistics results of Shore Hardness Test

4.4.2.2 PLA

In the Table 31 are displayed the results obtained for the ten parts tested.

Nr	Shore D
1	79.5
2	78.0
3	79.0
4	79.0
5	80.5
6	80.0
7	79.5
8	79.0
9	79.0
10	78.5

Table 31: PLA general results of Shore Hardness Test

The statistics results for PLA shore hardness are displayed in the Table 32. The value for the PLA is 79.2 Shore D.

Nr	Shore D
$\overline{x}$	79.2
s	0.71

Table 32: PLA statistics results of Shore Hardness Test

4.4.2.3 CPE

To perform the test for this material ten specimens has been tested. The measure results of CPE material are shown in the Table 33.

Nr	Shore D
1	73.0
2	72.0
3	72.0
4	70.0
5	73.5
6	73.0
7	72.5
8	73.0
9	72.0
10	71.5

Table 33: CPE general results of Shore Hardness Test

In the Table 34 it can be seen that the hardness value for this material is 72.3 Shore D. This is a 17% less than the reference value for an extruded specimen of this material (86 Shore D)

Nr	Shore D
$\overline{x}$	72.3
s	1.01

Table 34: CPE statistics results of Shore Hardness Test

4.4.2.4 Flexifil

The measure results of Flexifil material are shown in the Table 35. Ten different specimens have been tested in order to know the hardness value.

Nr	Shore D
1	39.0
2	39.0
3	39.0
4	38.5
5	42.0
6	41.0
7	38.0
8	39.5
9	42.0
10	38.0

Table 35: Flexifil general results of Shore Hardness Test

In the Table 36 are displayed the statistics values for the Shore Hardness. It has been obtained a value of 39.6 Shore D. This is around a 26% less than the standard value of 54 Shore D for an extruded specimen.

Nr	Shore D
$\overline{x}$	39.6
s	1.52

Table 36: Flexifil statistics results of Shore Hardness Test

4.5 Crash-test

A crash test is a destructive testing usually performed to ensure safe design standards in crashworthiness and crash compatibility for various modes of transportation or related systems and components.

Consist on crashing several models and determine which one has been able to absorb the most amount of energy. For his we have used a lane in which are coupled the models and a high-speed camera that allows us to watch and analyze the results.

In collaboration with the students of Prof. Bahlmann, it has been tested some 3D printed parts. This parts before testing are displayed in the Figures 26, 27, 28, 29, 30 and 31:

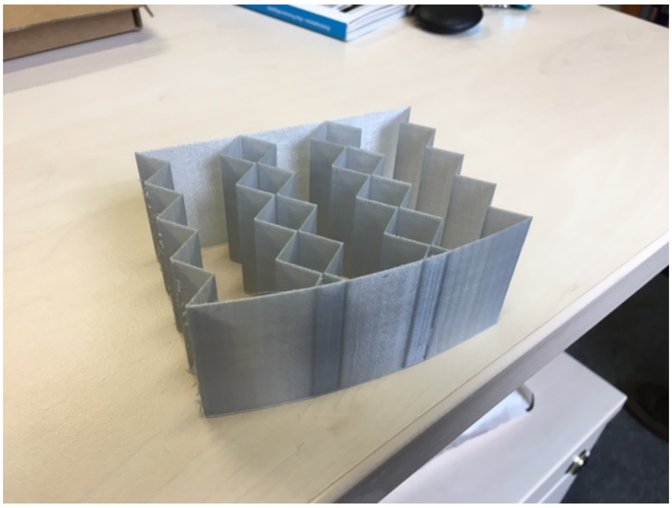


Figure 26: Model 1 for the Crash Test

Figure 27: Model 2 for the Crash Test

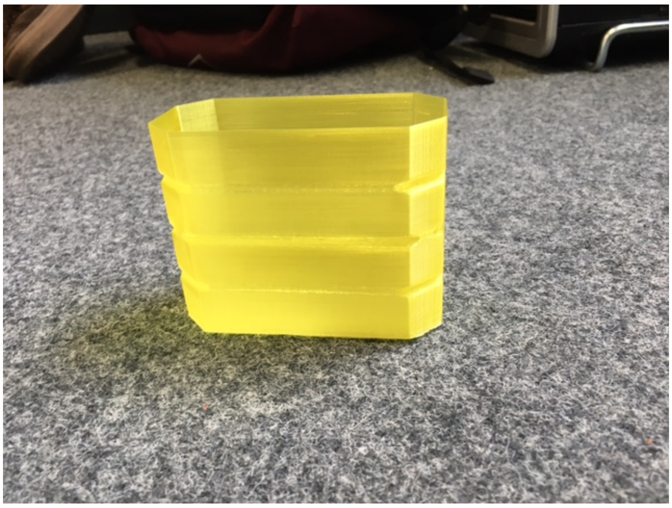


Figure 28: Model 3 for the Crash Test

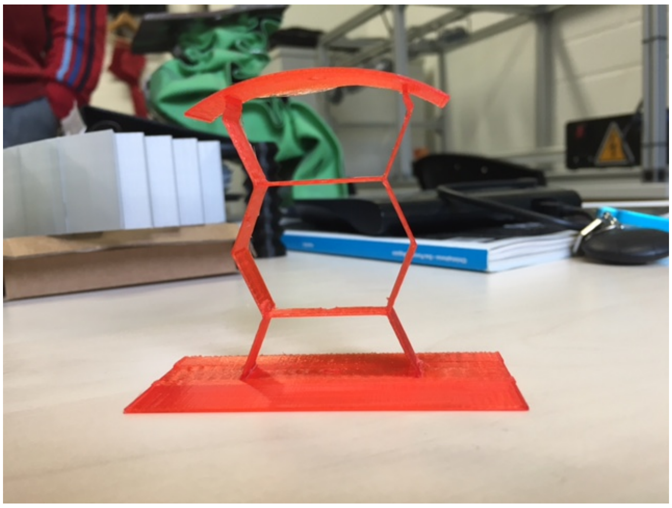


Figure 29: Model 4 for the Crash Test

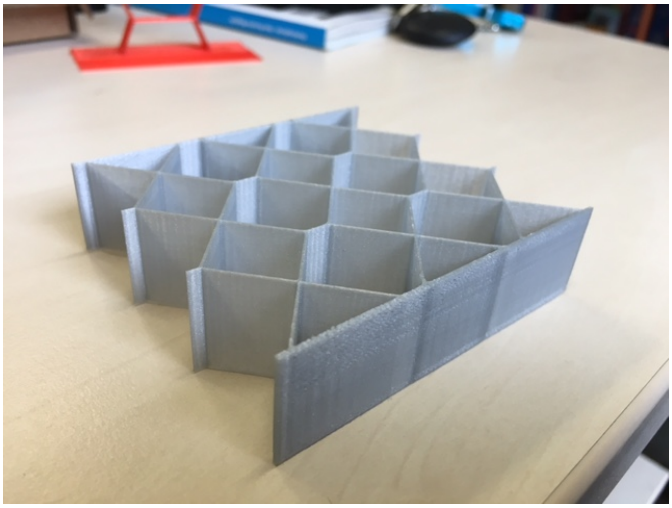


Figure 30: Model 5 for the Crash Test

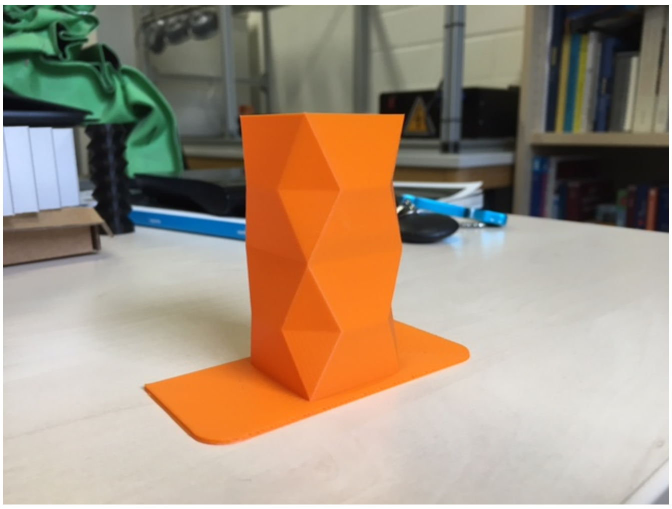


Figure 31: Model 6 for the Crash Test

In the Figures 32, 33 and 34 it can be seen the way in which the test was done. After analyze the slow-motion videos obtained, the goal is determinate what is the model which is able to absorb more energy.

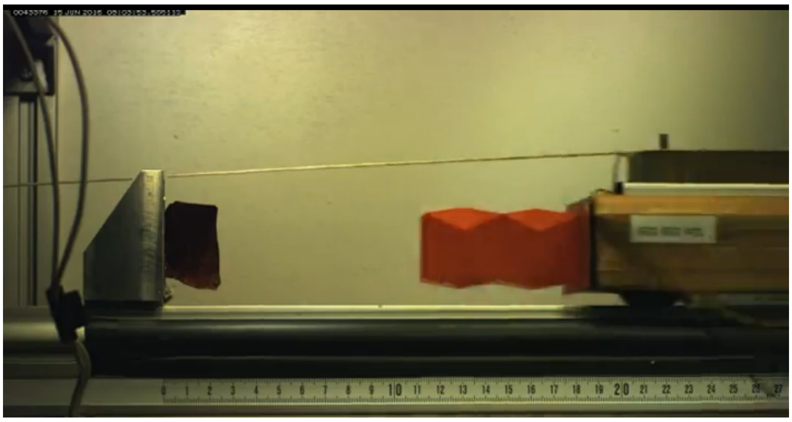


Figure 32: Instant just before the crash of the model 6

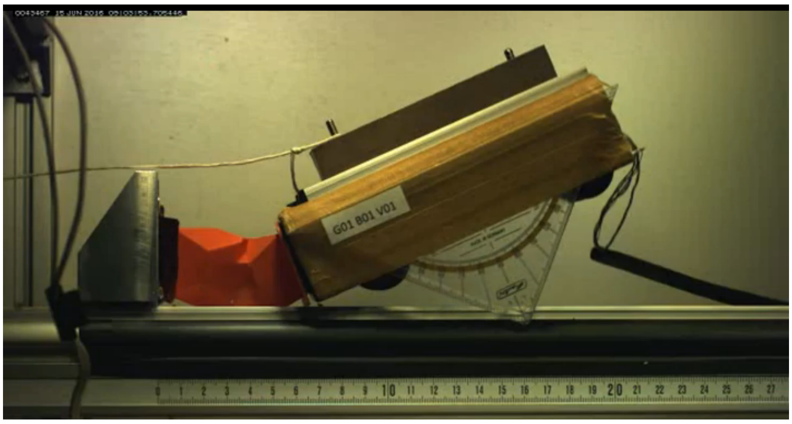


Figure 33: Instant in which the model 6 is crashing

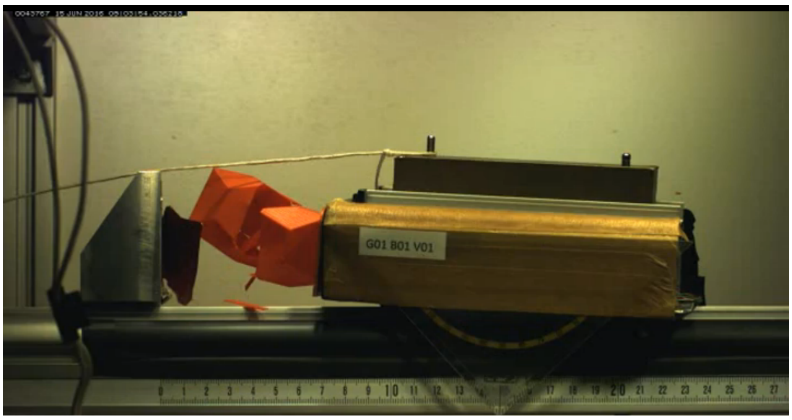


Figure 34: Instant just after the crash of the model 6

5 Defectology

In this chapter are described many defects that arise with 3D printing and several methods to avoid them.

5.1 Warping

Warping is due to the cooling and contraction of the plastic. During the printing of the part, the extruded plastic cools and shrinks. Over time, the internal forces becomes so large that the corners of the part begins to separate from the base of the printer. It can be seen in the Figure 35.

The best way to correct this problem is using a heated build platform (common called hot bed). While the printer is working, the platform keeps warm the base of the piece just to avoid the solidification of the plastic. It seeks to maintain the temperature of the part above the glass transition[2]and in this way the base surface remains flat and stuck to the plate surface. In many cases, it is necessary to add a thin film of glue in order to improve the adherence between the part and the build plate surface.

The glass transition of the used polymers are:

- 60-65°C for PLA.
- 105°C for ABS.

It is also important to level the platform as well as possible. Besides getting a non-deformed printing, an uniform lower layer is obtained. The lines have to be uniform and they have to touch each other. If the lines show signs of overflow, it means that the platform is too attached to the head and it is necessary to recalibrate it. On the other hand, if the lines do not stick and are unordered means that the platform is too low.

Figure 35: Warping

[2]Glass transition: Is the reversible transition in amorphous materials from a hard an brittle ”glassy” state into a molten state, as the temperature is increased. It is always lower than the melting temperature of the crystaline state of the material.

Another alternative is to use "Brim" or "Raft" option in Cura to prevent the deformation of the part. Brim option prints multiple filament wraps around the part until touching it creating a surface (like the brim of a hat) in the first layer of the part to relax the forces of traction. Since this edge consists on a single thick layer, it is very easy to remove once the printing is complete. Raft instead create a little dense surface below the workpiece so if any part of the printing surface will be up, it will not be the surface of our piece.

ABS and Nylon are materials that shrink much, therefore, they are much more likely to deformation that the PLA or other material so it is necessary to take extra care. In addition to needing a higher temperature in the hot bed it is advisable not to activate the extra cooling. To achieve extraordinary qualities it would be convenient for printer to be covered and thermostatically uniform throughout the whole printing.

5.2 Pillowing

Sometimes when the printer closes and creates the final part of a piece, bumps or holes appear as it can be appreciated in Figure 36. This effect is more common using PLA. The most important thing to solve the problem is to modify the cooling and the thickness of the final ceiling. Without proper cooling, the strands of plastic tend to curl and ascend from the printing surface, making more difficult the correct deposition of subsequent layers. With high cooling the strands grow gradually building a consistent mesh for proper deposition of subsequent layers and achieving a complete closure of the surface.

Another important aspect further cooling is the thickness of the top layer. As a general rule it is advisable to print six solid layers on the roof.

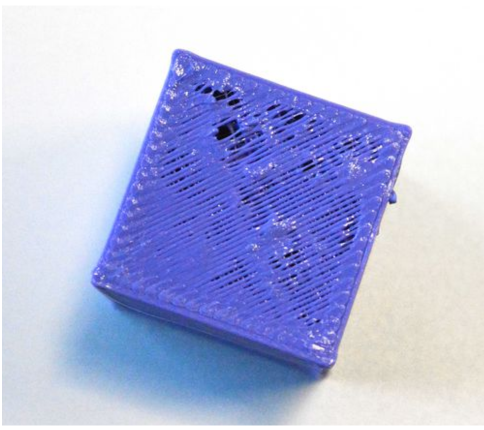


Figure 36: Pillowing

In the pieces with little filler it may happen that the strand are not deposited correctly due to lack of supports on the inside of the workpiece, thereby generating potential problems of holes in the roof. The software Cura has an automatic system to try to solve the problem. This software is stipulated that 25% is the limit of optimal filling. If it is used more than 25% filler it will generate layers in one direction and diagonally but if it is used a lower percentage it make each layer in a different sense. Therefore it is achieved that the strands of the new layer are deposited smoothly and avoid possible pillowings.

5.3 Stringing

Stringing consists of horizontal wires that are generated when two pieces are printed at the same time moving from one part to another layer by layer or when the object to be printed has layers in distanced and independent parts. Figure 37 is an example of this defect.

The main solution to solve the appearance of stringing is the "retraction" option. When retraction option is activated, we allow the printer to absorb some filament before moving the print head through an open space where it do not have to print. Retracting the filament helps to prevent the drip of plastic through the nozzle during vacuum displacement of the head.

Another option to reduce the effect of stringing is to increase the unprinted travel speed (Travel speed). By default in the Cura software, the scroll speed is set to 150 mm/s but it is advisable a value of 200 mm/s. By increasing the speed of travel the nozzle has less time for plastic ooze.

The temperature can also play an important role. With too high temperatures stringing appears. With a lower temperature material is not as liquid and prevents fall easily. As always when the temperature is lowered also should verify that it is printing slowly enough to avoid under-extrusion.

It should be clear that some filaments are simply likely to generate stringing and that the indications given above do not solve the problem. It may be that in some cases are impossible to remove completely. Even different colors of the same manufacturer may differ in terms of stringing results.

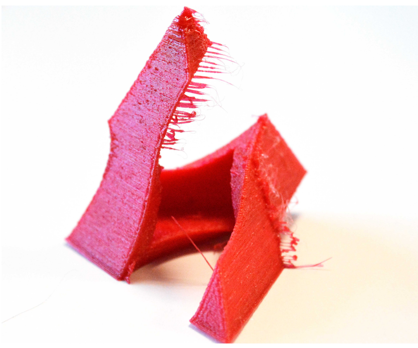


Figure 37: Stringing

5.4 Overhang

3D printers can not deposit material in the air. This limitation creates pieces with unwanted aspects and tangles of wires. Fortunately this problem can be solved either through changes in the design or several options that are provided by the printing software.

Each layer is printed on the previous, serving this support to the next layer. There are times that due to the shape of the object to be printed do not have material below and hanging material is forming a U instead of being a straight line. It are printed partially in the air and tend to sink slightly downward. Sometimes these problems making each layer worse than the last. Dealing with overhangs is complicated, there are many variables that affect this process:

- Temperature
- Print speed
- Angle and length of the overhang
- Material
- Cooling

The cooling of the material is very important. It is necessary to be sure that the cooling fan is working at 100%.

Print speed also affects to the print quality. If is necessary to print a cantilever (place a layer from one column to another) is recommended to increase the printing speed. However if it is wanted to print an inclined wall best results are achieved if the printing speed is decreased. This always results in a marked improvement of quality.

It is important to reduce the printing temperature as much as possible without causing under-extrusion. If the printing speed is reduced, it is necessary to reduce the temperature of extrusion. Besides reducing printing temperature can be worth reducing the temperature of the bed.

If possible, it is advisable to reorient the object to minimize the number of cantilevers. Sometimes just by changing the position of the object using the Rotate option of the software to a position without overhangs the problem is solved. The limit for the inclined wall is between 90°- 45°.

When there are no possibilities to reorient the part, it can be used the support option. It generates a structure below the overhang, so when it has to create the overhang will have a surface to lean. There are different types of supports and options that can be controlled.

5.5 Under-extrusion

Under extrusion occurs when the extruder of the printer can not supply the amount of plastic it should. Symptoms of this problem may be three:

- Missing layers.
- Very thin layer.
- Random holes.

The direct cause of this problem is probably the most difficult to find since there are many variables.

The printer will do everything possible to try to achieve the set printing speed but if they go beyond what the printer is able to perform may be problems. If the limits are exceeded the printer continues printing but the printed object will probably have walls that do not fuse properly and gaps between layers like in the Figure 38 . Below are several actions that can be done to prevent under-extrusion and improve the quality of the pieces.

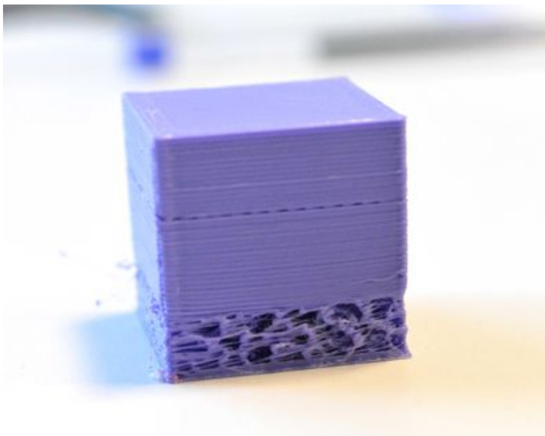


Figure 38: Under-Extrusion

5.5.1 Not increase the flow rate to compensate

Although it seems obvious the only thing that is achieved is hurt even more the printing. If the nozzle is blocked and the plastic flow is increased further clog the exit.

5.5.2 Know and respect the limits of the printer

The most common and probable cause that the printer does not extrude material enough is simply because it are printing at a higher speed than it is able to print. It measures how fast a printer can print plastic in volume per second (mm^3/s). Ideally an Ultimaker 2 Extended+ is able to print about $5mm^3/s$. With these speeds, the print quality is not as good.

The equation (4) show us how fast is printing the printer:

$$\text{Nozzle Diameter (mm)} * \text{Layer Height (mm)} * \text{Print Speed}(mm/s) \leq 5mm^3/s \quad (4)$$

5.5.3 Temperature

The faster a piece is printed, plastic has less time to warm up to the correct temperature before forced out through the nozzle. PLA is the plastic which needs less temperature but it is also more viscous and requires higher pressures to push through the nozzle. It may be that the pressures become too high and have extrusion problems.

To solve this problem it can increase the extrusion temperature but within a limit. Set the temperature above 240°C for PLA can cause problems. From these temperatures plastic properties begin to change if left for too long into the nozzle and the plastic can be burned and cause blockages. It is also probable that the print quality is less at high temperatures, such as increasing the stringing.

5.6 Curved base

This defect appears because of the high temperature of the platform. Hot filament layers are deposited on the other filament layers and contact with these layers keep the new lines in place until they cool and harden.

With a hot bed, the plastic is kept at a temperature in which it is still malleable. As a new layers are being put on the top of this semisolid plastic mass the contraction forces of the new layers make the object shrink on the bottom as it can be seen in the Figure 39. This continues until printing reaches a height where the heat of the bead no longer keeps the object warm and each layer becomes solid before the next is deposited on it, thereby keeping the top of the piece in position.

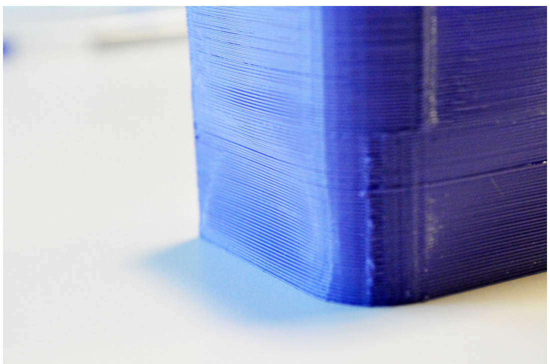


Figure 39: Curved Base

To avoid this problem it is recommended to lower the temperature of the platform. The second option to solve the problem is to activate the fan. The fan cools the extruded thread deposited on the piece.

5.7 Grinding

Like in the Figure 40 the filament are bitten when the motor tries to push it through the nozzle, but instead of pushing begins to slip on the filament creating a groove in the thread. The more grind the filament less grip is able to achieve. It can happen for four reasons:

- By having a blockage in the nozzle.
- By not having the nozzle at the right temperature.
- By having the nozzle too close to the platform.
- By not having the spring adjusted to the needs of the material.

In the first three cases the plastic may not go smoothly through the nozzle while the extruder pushes the material, thus the filament can not advance and the extruder begins to eat him. To avoid these error it is necessary to make sure that the head is clean and at the correct temperature.

The last case may occur because of a high tension on the extruder spring.

Figure 40: Grinding

5.8 Scratches

As the print head completes a top layer, travel movements (which do not deposit material) can make unsightly lines on the surface as it is shown in Figure 41 . This may be caused by two reasons:

The first reason is that more material than needed is extruding. Therefore it performs higher layers than indicated by the program. In this case the layers exceed the head height so each time the nozzle it is moved on the printed surface it left marked lines. To solve this problem it is necessary to lower the temperature slightly (one or two degrees) or lower the flow in order to reduce the deposited amount of filament.

The second problem might be that there is a slight plastic extrusion during travel movements. As in the cases of the stringing it may occurs when the head moves without extruding filament spill some own gravity. This is specially true with viscous materials such as PLA.

Figure 41: Scratch

It is possible to activate the z-hop[3]option to solve this problem. With faster movement the amount of time the nozzle ooze plastic can be reduced. A side effect of the z-hop function is that it can leave a tiny drop every time the movement is made. However, the drops are less visible and easier to remove than scratches.

5.9 Non-adherence

The most common cause in these cases is that the printing platform is not correctly calibrated. It is very important to be sure that the print head is perfectly calibrated regarding the platform and the distance between the nozzle and the bed has to be as perfect as possible. If the head is printing the first layer too far from the platform, the plastic will not crash against printing platform properly. Therefore, our piece will be released as it is shown in the Figure 42.

[3]Z-hop: A function of Cura Software. This feature will make the printer down the bed the distance indicated just before making a movement and then travel back up once the destination point is reached.

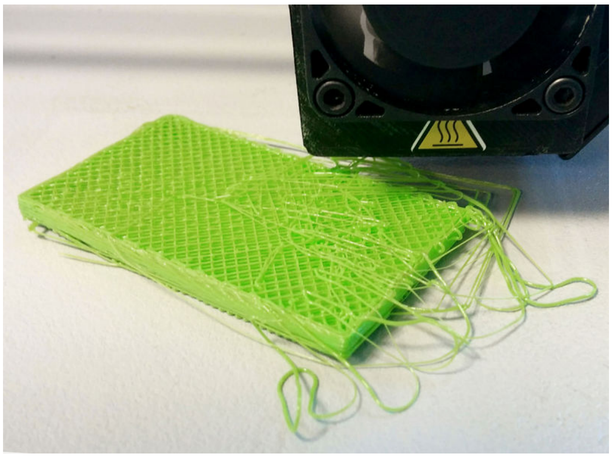


Figure 42: Non-adherence

5.10 Hairy print

First of all it is important to clarify that hairy print is a different problem than stringing. The threads that appear in the hairy print are very thin and seem to be able to appear even without performing travel movements as it is shown in the Figure 43

Although the causes of this problem are not entirely clear yet, this appear with viscous materials. You also have to make sure our nozzle is clean so that small amounts of plastic are not randomly deposited during printing.

Fortunately, small hairs are fairly easy to remove by rubbing them with your fingers or passing a fine sandpaper.

Figure 43: Hairy print

5.11 Bubbles

When a piece has on its surface bubbles or small gaps probably is because the printing temperature is too high as it is shown in the Figure 44. When a filament is extruded at a higher temperature than necessary, bubbles are created in the thread which is extruded an these irregularities are on the walls of the parts. Also when printing at high temperatures the material is more viscous and unstable position and is harder to set the thread in an appropriate coordinates thus creating grooves on the workpiece.

Figure 44: Bubbles

5.12 Cracks

As in the Figure 45 Cracks in the pieces appear specially when the piece is large. The hot bed provides heat to the workpiece but in the case of large pieces, temperatures goes not reach the upper layers. This is when the cracks appear.

This problem has little practical solutions. It is advisable, in case of having to print large pieces, to use other materials such as PLA. If it is impossible to change the material, it is necessary to raise the hot bed temperature as much as possible.

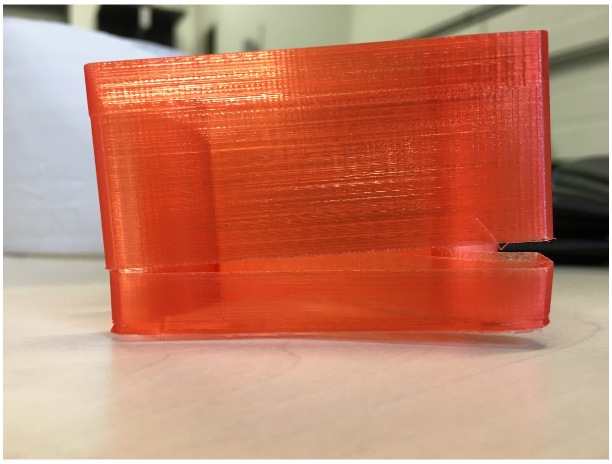


Figure 45: Cracks

6 Metrological control

In this section are displayed the results of the different metrological test. When a part is designed, it has a standard dimensions and values. If this part is used in an assembly, it is necessary to be between a tolerance.

In order to know the accuracy of the printed piece, four test have been done: Distance between planes, diameter, curvature and slope. The 3 axis measure machine used is a DEA from the metrology company Hexagon. Whit a little stick the piece was scanned though touching it in a several points, and the result were displayed in an auxiliary equipment. This machine can be seen in the Figures 46 and 47.

Figure 46: Hexagon Measure Machine

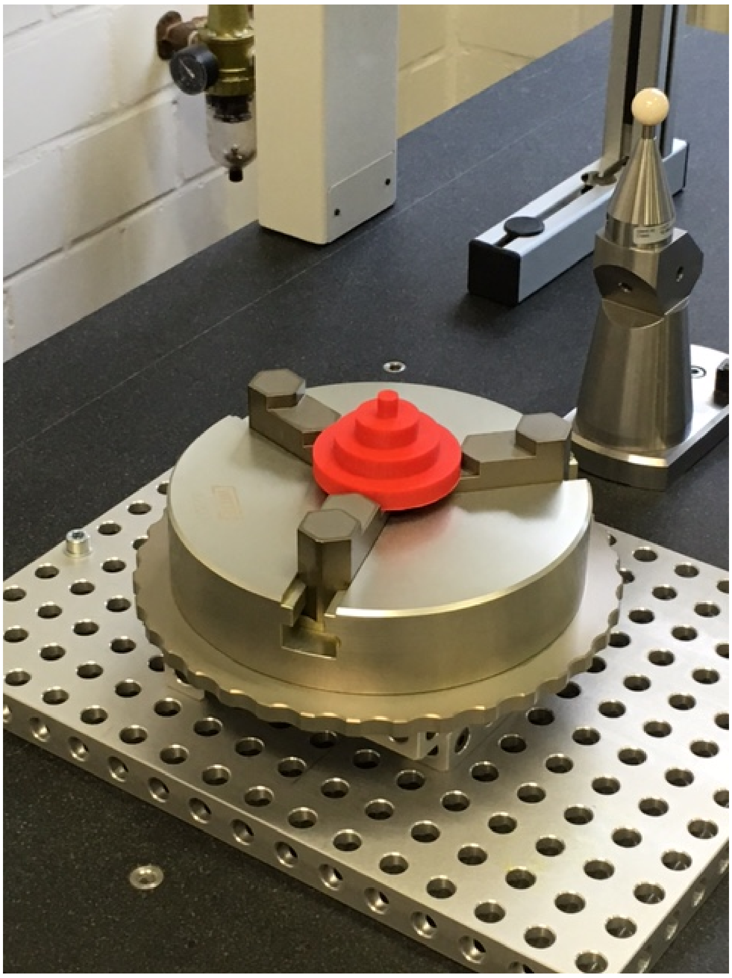


Figure 47: Metrological Specimen Location

6.1 Distance between planes

The Figure 48 is the used specimen to develop the test. The top plane is the Plane 1 and the bottom plane is Plane 4.

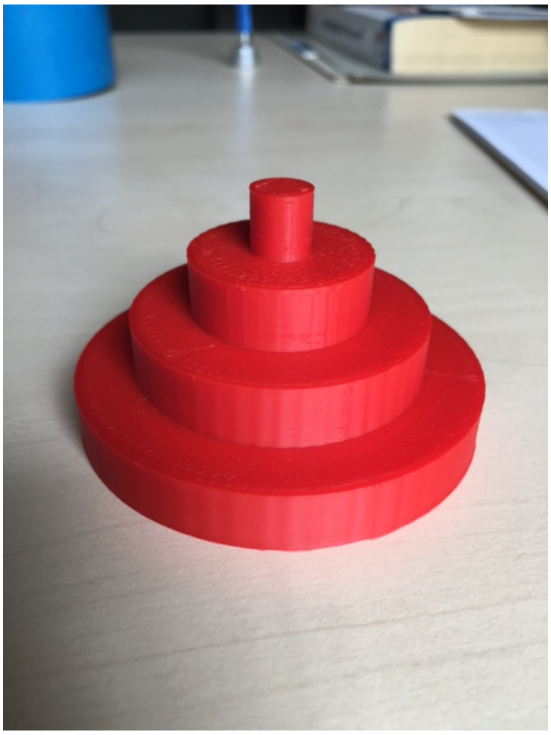


Figure 48: Metrological Specimen: Distance Between Planes

In the Table 37 are displayed the results for this test. The reference axis point is the top of the Plane 1 and Z direction is negative in the direction of the other planes. The planes should be at a distance of 10mm between them. Therefore, there is approximately a tolerance of ± 0.1000 mm for vertical length between planes.

Element	Value	Normal value	Deviation
Plane 1:			
	0.0279 mm	0.0000 mm	+0.0279 mm
Plane 2:			
	-9.9394 mm	-10.0000 mm	+0.0606 mm
Plane 3:			
	-20.0320 mm	-20.0000 mm	-0.0320 mm
Plane 4:			
	-30.0070 mm	-30.0000 mm	-0.0070 mm

Table 37: Metrological Control: Distance Between Planes

6.2 Diameter

The Figure 48 is the used specimen to develop the test. Because of the printer only have 3 axis, the accuracy of the diameters are not good. If the printed surface is touched, it can be felt that the curvature of the diameter is composed by little planes.

In the Table 38 are displayed the results for this test. There is approximately a tolerance of ± 0.4000 mm for vertical length between planes.

Element	Value	Normal value	Deviation
Diameter 1:			
	9.8184 mm	10.0000 mm	-0.1816 mm
Diameter 2:			
	29.7830 mm	30.0000 mm	-0.2170 mm
Diameter 3:			
	49.7228 mm	50.0000 mm	-0.2772 mm
Diameter 4:			
	69.6372 mm	70.0000 mm	-0.3628 mm

Table 38: Metrological Control: Diameter

Figures 49, 50, 51 and 52 are the plots obtained in the test. In these are displayed the graphics of the analyzed points.

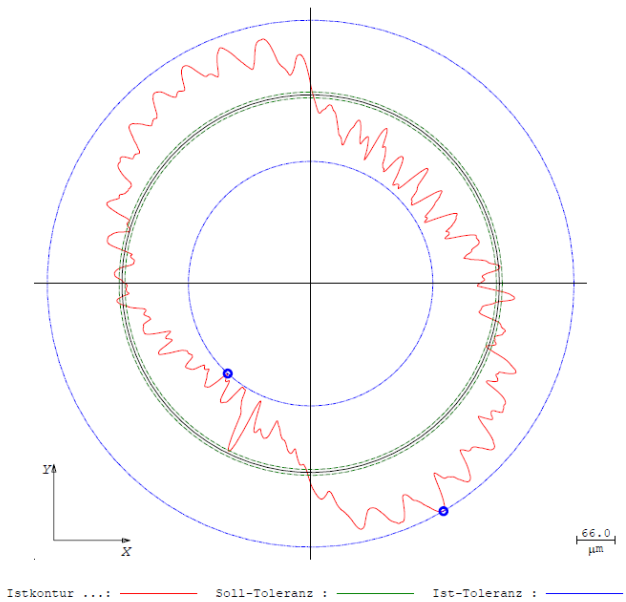


Figure 49: Diameter 1 Metrological Plot

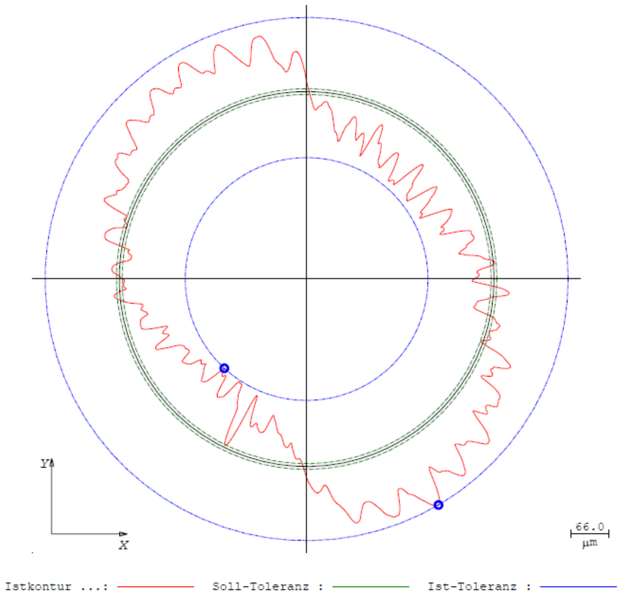


Figure 50: Diameter 2 Metrological Plot

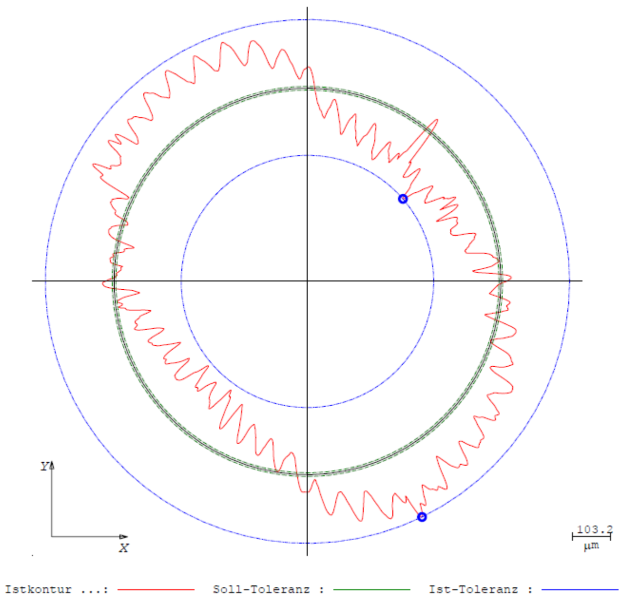


Figure 51: Diameter 3 Metrological Plot

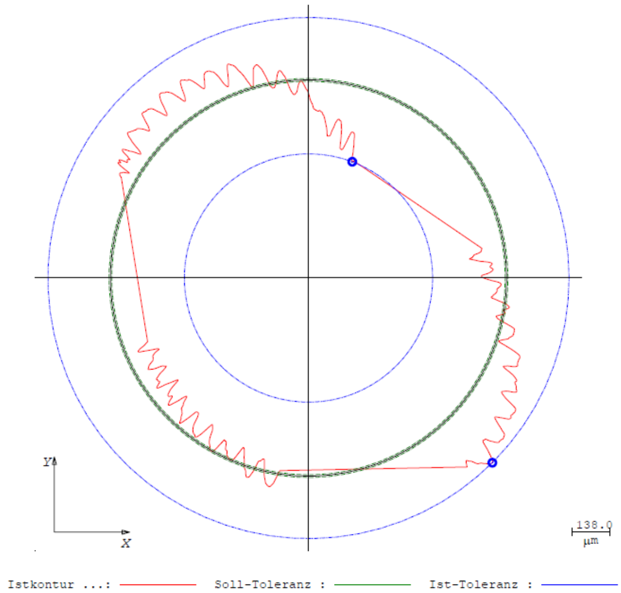


Figure 52: Diameter 4 Metrological Plot

6.3 Curvature

The Figure 53 is the specimen used to develop the test. The vertical curvature is checked in this test.

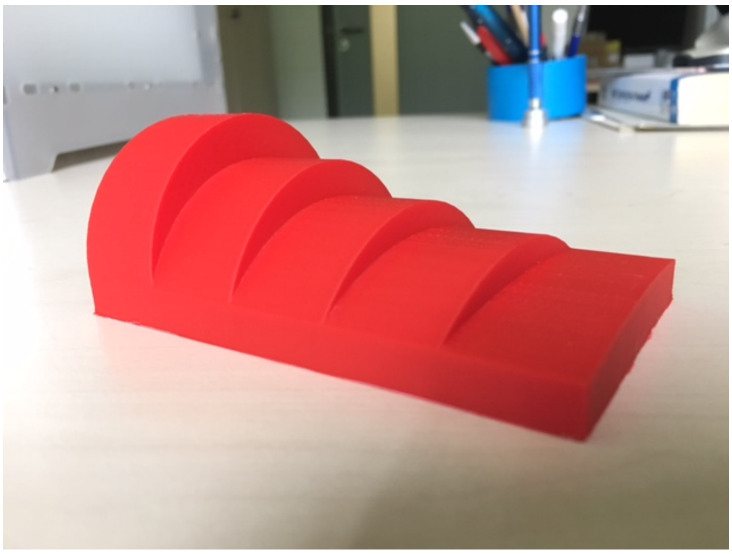


Figure 53: Metrological Specimen: Curvature

In the Table 39 are displayed the results for this test. In this case it has not sense to define a tolerance interval. As can be seen, the more increases the diameter, the tolerance is worse.

Also the finish surface has less quality when the diameter increases.

Element	Value	Normal value	Deviation
Diameter 1:			
	59.6530 mm	60.0000 mm	-0.347 mm
Diameter 2:			
	63.8137 mm	64.0000 mm	-0.1863 mm
Diameter 3:			
	80.3561 mm	80.0000 mm	0.3561 mm
Diameter 4:			
	120.9517 mm	120.0000 mm	0.9517 mm
Diameter 5:			
	404.4453 mm	140.0000 mm	4.4453 mm

Table 39: Metrological Control: Curvature

6.4 Slope

The Figure 54 is the used specimen to develop the test.

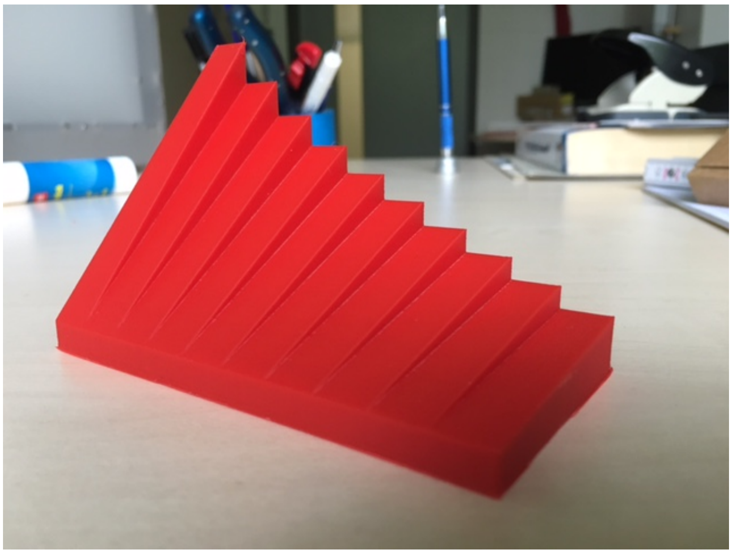


Figure 54: Metrological Specimen: Slope

In the Table 40 are displayed the results for this test. There is approximately a tolerance of ± 0.6000°for the angle with a reference on the horizontal plane.

Element	Value	Normal value	Deviation
Angle 1:			
	49.9197 mm	50.0000 mm	-0.0803 mm
Angle 2:			
	44.4037 mm	45.0000 mm	-0.5963 mm
Angle 3:			
	39.4242 mm	40.0000 mm	-0.5758 mm
Angle 4:			
	34.4033 mm	35.0000 mm	-0.5967 mm
Angle 5:			
	29.4018 mm	30.0000 mm	-0.5882 mm
Angle 6:			
	24.4334 mm	25.0000 mm	-0.3628 mm
Angle 7:			
	19.4875 mm	20.0000 mm	-0.5666 mm
Angle 7:			
	14.6084 mm	15.0000 mm	-0.3916 mm
Angle 8:			
	9.6180 mm	10.0000 mm	-0.3820 mm
Diameter 4:			
	4.7159 mm	5.0000 mm	-0.2841 mm

Table 40: Metrological Control: Slope

7 References

[1] Hesketh, Peter J., *BioNanoFluidic MEMS*, 1°edition, Springer, Massachusetts Institute of Technology.

[2] ISO 527-1:2012, *Plastics. Determination of tensile properties. Part 1: General principles.*

[3] ISO 527-2:2012, *Plastics. Determination of tensile properties. Part 2: Test conditions for moulding and extrusion plastics.*

[4] ISO 868:2003, *Plastic and ebonite. Determination of indentation hardness by means of a durometer (Shore hardness).*

[5] ISO 2039-1:2001, *Plastics. Determination of hardness. Part 1:Ball indentation method.*

[6] ISO 2602:1980, *Statistical interpretation of test results. Estimation of the mean. Confidence interval.*

[7] Jamshidian,M. ; Tehrany, E. ; Imran, M. ; Jacquot, M. ; Desobry, S. (2010) . *Poly-Lactic Acid: Production, Applications, Nanocomposites, and Release Studies. Comprehensive Reviews in Food Science and Food Safety. Vol 9.*

[8] Olivera.S ; Muralidhara.B ; Venkatesh.K ; Gopalakrishna.K ; Vivek. C. (2016). *Plating on acrylonitrile-butadiene-styrene (ABS) plastic: a review. Springer Science+Business Media New York 2016.*

[9] Ultimaker. *https://ultimaker.com*

A Young's Modulus Test Results

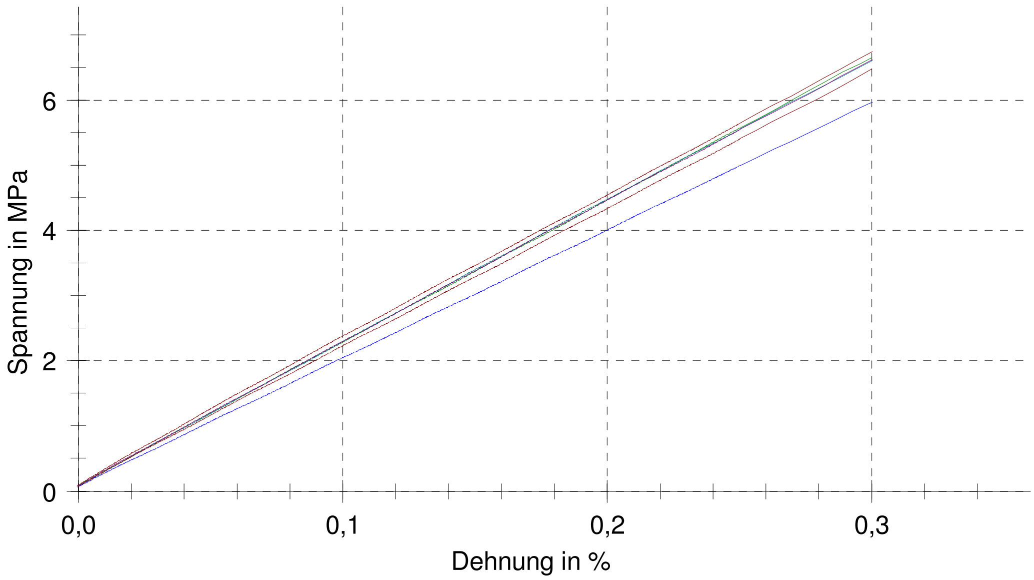
Parametertabelle:

Kunde	:
Prüfer	: Sergio Cabezas
Prüfnorm	: DIN ISO 527 - E-Modul
Material	: Flexifil
Kraftaufnehmer	: 2 kN
Wegaufnehmer	: Clipon Ansetzdehnungsaufnehmer
Probenhalter	: Schraubspannkopf
Maschinendaten	: 2.5N1S WN:141058 Traversenwegaufnehmer WN:141058 Kraftsensor ID:0 WN:141098 2 kN Zwick inkrementeller Clip-On ID:33 WN:802030
LE	: 115 mm
Fv	: 0,05 MPa
v-Fv	: 0,5 mm/min
v-EMOD	: 1 mm/min
v-Prüf	: 1 mm/min

Ergebnisse:

Legende	Nr	E t MPa	Breite b0 mm	Dicke a0 mm	Bemerkung
	1	2178,19	10,35	4,02	
	2	2180,83	10,25	3,96	
	3	1961,87	10,15	4,01	
	4	2182,35	10,05	4	
	5	2168,68	10,05	4	
	6	2113,42	10,1	4,09	

Seriengrafik:



Statistik:

Serie n = 6	E t MPa	Breite b0 mm	Dicke a0 mm
$\bar{x}$	2130,89	10,16	4,013
s	86,81	0,1201	0,04274
ν	4,07	1,18	1,06

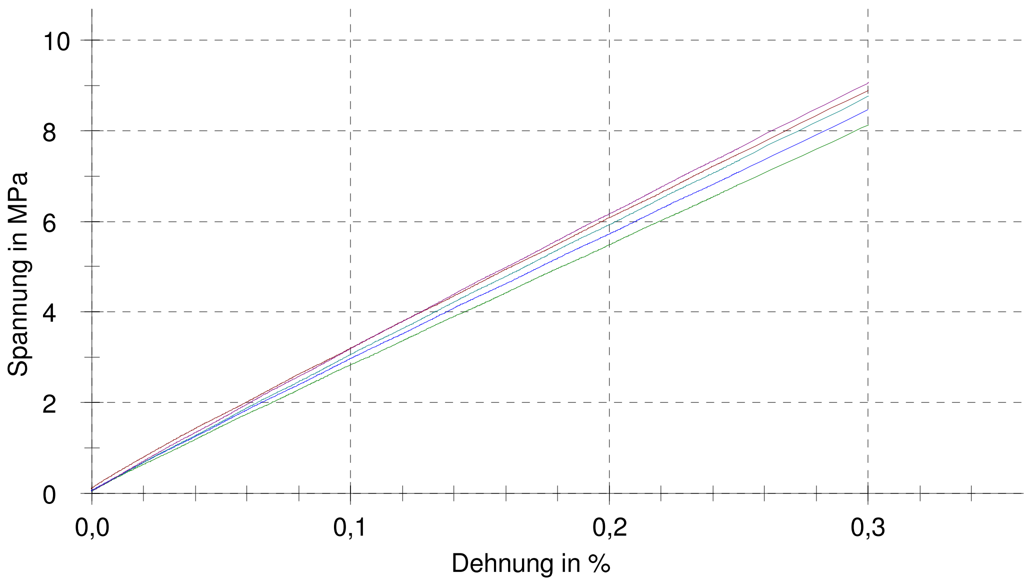
Parametertabelle:

Kunde :
Prüfer : Sergio Cabezas
Prüfnorm : DIN ISO 527 - E-Modul
Material : Flexifil
Kraftaufnehmer : 2 kN
Wegaufnehmer : Clipon Ansetzdehnungsaufnehmer
Probenhalter : Schraubspannkopf
Maschinendaten : 2.5N1S WN:141058
Traversenwegaufnehmer WN:141058
Kraftsensor ID:0 WN:141098 2 kN
Zwick inkrementeller Clip-On ID:33 WN:802030
LE : 115 mm
Fv : 0,05 MPa
v-Fv : 0,5 mm/min
v-EMOD : 1 mm/min
v-Prüf : 1 mm/min

Ergebnisse:

Legende	Nr	E t MPa	Breite b0 mm	Dicke a0 mm	Bemerkung
	1	2878,86	9,9	3,98	
	2	2664,97	9,98	4,12	
	3	2768,73	10	4,03	
	4	2884,02	10,04	4,04	
	5	2983,93	10,08	4,04	

Seriengrafik:



Statistik:

Serie n = 5	E t MPa	Breite b0 mm	Dicke a0 mm
$\overline{x}$	2836,10	10	4,042
s	122,27	0,06782	0,0502
ν	4,31	0,68	1,24

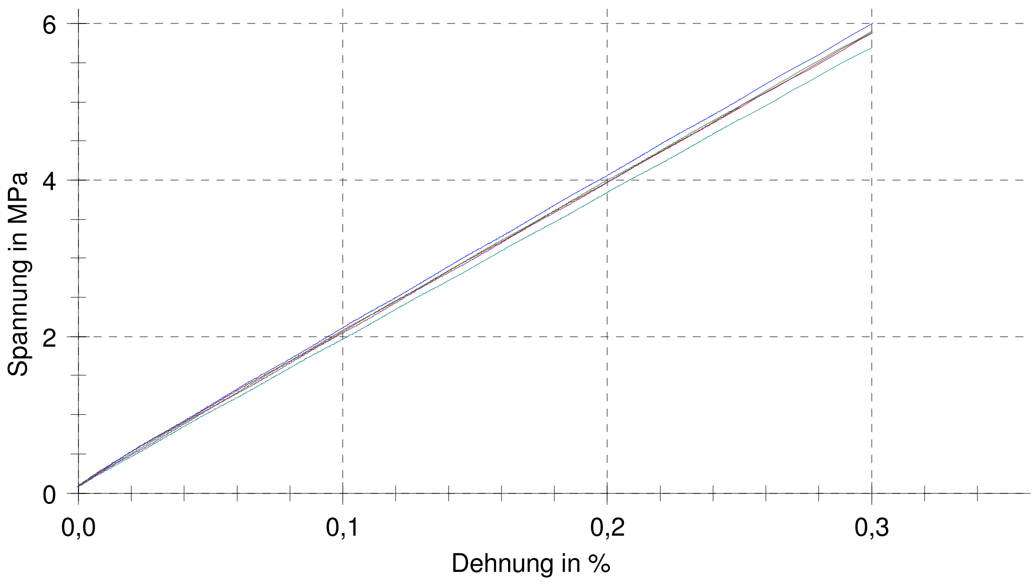
Parametertabelle:

Kunde	:
Prüfer	: Sergio Cabezas
Prüfnorm	: DIN ISO 527 - E-Modul
Material	: Flexifil
Kraftaufnehmer	: 2 kN
Wegaufnehmer	: Clipon Ansetzdehnungsaufnehmer
Probenhalter	: Schraubspannkopf
Maschinendaten	: 2.5N1S WN:141058 Traversenwegaufnehmer WN:141058 Kraftsensor ID:0 WN:141098 2 kN Zwick inkrementeller Clip-On ID:33 WN:802030
LE	: 115 mm
Fv	: 0,05 MPa
v-Fv	: 0,5 mm/min
v-EMOD	: 1 mm/min
v-Prüf	: 1 mm/min

Ergebnisse:

Legende	Nr	E t MPa	Breite b0 mm	Dicke a0 mm	Bemerkung
	1	1903,59	10	4,08	
	2	1928,29	10,01	4,06	
	3	1952,43	10,03	4,08	
	4	1868,98	10,07	4,05	
	5	1924,80	10,04	4,05	

Seriengrafik:



Statistik:

Serie n = 5	E t MPa	Breite b0 mm	Dicke a0 mm
$\bar{x}$	1915,61	10,03	4,064
s	31,30	0,02739	0,01517
ν	1,63	0,27	0,37

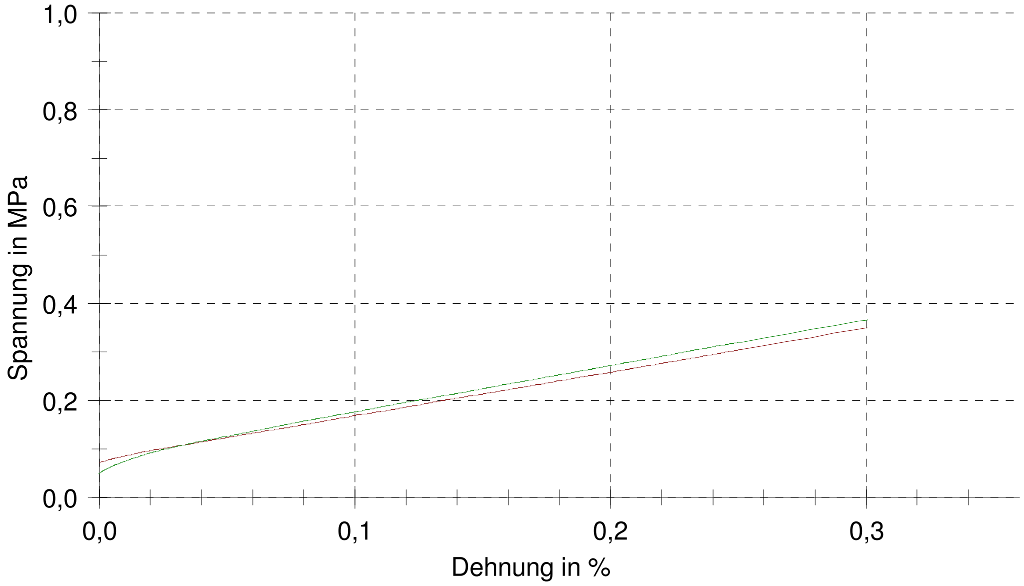
Parametertabelle:

Kunde	:
Prüfer	: Sergio Cabezas
Prüfnorm	: DIN ISO 527 - E-Modul
Material	: Flexifil
Kraftaufnehmer	: 2 kN
Wegaufnehmer	: Clipon Ansetzdehnungsaufnehmer
Probenhalter	: Schraubspannkopf
Maschinendaten	: 2.5N1S WN:141058 Traversenwegaufnehmer WN:141058 Kraftsensor ID:0 WN:141098 2 kN Zwick inkrementeller Clip-On ID:33 WN:802030
LE	: 115 mm
Fv	: 0,05 MPa
v-Fv	: 0,5 mm/min
v-EMOD	: 1 mm/min
v-Prüf	: 1 mm/min

Ergebnisse:

Legende	Nr	E t MPa	Breite b0 mm	Dicke a0 mm	Bemerkung
(rot)	1	90,17	10	3,81	
(grün)	2	96,24	10,1	3,83	

Seriengrafik:



Statistik:

Serie n = 2	E t MPa	Breite b0 mm	Dicke a0 mm
$\bar{x}$	93,20	10,05	3,82
s	4,29	0,07071	0,01414
ν	4,61	0,70	0,37

B Hardness Test Results

Parametertabelle:

Prüfnorm	: DIN EN ISO 2039
Prüfer	: Sergio Cabezas
Material	: ABS
Prüftemperatur	: 23℃
Maschinendaten	: Steuerung WN: 181790 Traverse WN: 181790 Kraft WN: 181791 2.5 kN Härtemeßkopf WN: 181792
Belastungspunkt Kugeleindruckhärte	: 358 N

Prüfverfahren:

Härteprüfverfahren	: Kugeleindruckhärte
Wartezeit am Belastungspunkt	: 30 s
Geschwindigkeit Vorkraft	: 1 mm/min
Geschwindigkeit Belastung	: 20 mm/min
Geschwindigkeit Entlastung	: 20 mm/min

Ergebnisse:

Legende	Nr	H N/mm²	Fm N	t2 s	h µm	t1 s	h_{max} µm	t0 s	t4 s	Eindruck	Bez Unters
	max				350,00						
	min				150,00						
	1	84,1	357,92	46,8	267,54	16,8	267,6	14,27	47,6	1	1
	2	88,1	357,90	46,4	257,22	16,4	257,3	13,87	47,2	2	
	3	87,2	357,94	44,0	259,56	14,0	259,6	11,50	44,9	3	
	4	84,9	357,90	44,4	265,38	14,4	265,4	11,91	45,3	4	

Statistik:

1 n = 4	H N/mm²	Fm N	t2 s	h µm	t1 s	h_{max} µm	t0 s	t4 s	Eindruck
$\bar{x}$	86,1	357,92	45,4	262,43	15,4	262,5	12,89	46,2	3
s	1,9	0,02	1,4	4,84	1,4	4,8	1,39	1,4	1
ν	2,18	0,00	3,02	1,84	8,92	1,84	10,75	2,93	51,64

Parametertabelle:

Prüfnorm	: DIN EN ISO 2039
Prüfer	: Sergio Cabezas
Material	: PLA
Prüftemperatur	: 23℃
Maschinendaten	: Steuerung WN: 181790 Traverse WN: 181790 Kraft WN: 181791 2.5 kN Härtemeßkopf WN: 181792
Belastungspunkt Kugeleindruckhärte	: 358 N

Prüfverfahren:

Härteprüfverfahren	: Kugeleindruckhärte
Wartezeit am Belastungspunkt	: 30 s
Geschwindigkeit Vorkraft	: 1 mm/min
Geschwindigkeit Belastung	: 20 mm/min
Geschwindigkeit Entlastung	: 20 mm/min

Ergebnisse:

Legende	Nr	H N/mm²	Fm N	t2 s	h µm	t1 s	h_{max} µm	t0 s	t4 s	Bez Unters
	1	137,0	357,90	47,9	179,66	17,8	179,7	15,64	48,6	
	2	128,8	357,92	44,1	188,64	14,1	188,7	11,74	44,8	
	4	127,7	357,94	50,1	189,92	20,1	190,0	17,78	51,0	
	5	132,3	357,94	44,5	184,64	14,5	184,7	12,22	45,3	
	6	124,1	357,93	45,6	194,26	15,6	194,3	12,69	46,8	
	7	135,1	357,93	49,0	181,72	19,0	181,8	16,69	49,9	

Statistik:

Serie n = 6	H N/mm²	Fm N	t2 s	h µm	t1 s	h_{max} µm	t0 s	t4 s
$\bar{x}$	130,8	357,93	46,9	186,48	16,9	186,5	14,46	47,7
s	4,9	0,01	2,5	5,47	2,5	5,5	2,57	2,5
ν	3,72	0,00	5,33	2,93	14,82	2,93	17,75	5,21

Parametertabelle:

Prüfnorm	: DIN EN ISO 2039
Prüfer	: Sergio Cabezas
Material	: CPE
Prüftemperatur	: 23°C
Maschinendaten	: Steuerung WN: 181790 Traverse WN: 181790 Kraft WN: 181791 2.5 kN Härtemeßkopf WN: 181792
Belastungspunkt Kugeleindruckhärte	: 358 N

Prüfverfahren:

Härteprüfverfahren	: Kugeleindruckhärte
Wartezeit am Belastungspunkt	: 30 s
Geschwindigkeit Vorkraft	: 1 mm/min
Geschwindigkeit Belastung	: 20 mm/min
Geschwindigkeit Entlastung	: 20 mm/min

Ergebnisse:

Legende	Nr	H N/mm²	Fm N	t2 s	h µm	t1 s	h_{max} µm	t0 s	t4 s	Bez Unters
	1	85,3	357,93	44,6	264,50	14,6	264,5	12,14	45,5	
	2	63,8	357,92	44,7	340,16	14,6	340,2	11,97	45,5	
	3	84,2	357,94	44,8	267,42	14,8	267,5	12,29	45,6	
	4	69,6	357,93	44,9	314,82	14,9	314,9	12,19	45,7	
	5	89,5	357,89	44,2	253,76	14,2	253,8	11,74	45,1	
	6	80,3	357,92	44,5	278,32	14,5	278,4	11,96	45,3	
	7	71,9	357,89	45,7	306,24	15,7	306,3	12,87	46,6	
	8	77,9	357,93	45,0	285,66	15,0	285,7	12,41	45,8	

Statistik:

Serie n = 8	H N/mm²	Fm N	t2 s	h µm	t1 s	h_{max} µm	t0 s	t4 s
$\bar{x}$	77,8	357,92	44,8	288,86	14,8	288,9	12,20	45,6
s	8,8	0,02	0,4	29,31	0,4	29,3	0,34	0,5
ν	11,27	0,01	0,99	10,15	3,00	10,15	2,82	0,99

C Tensile Test Results

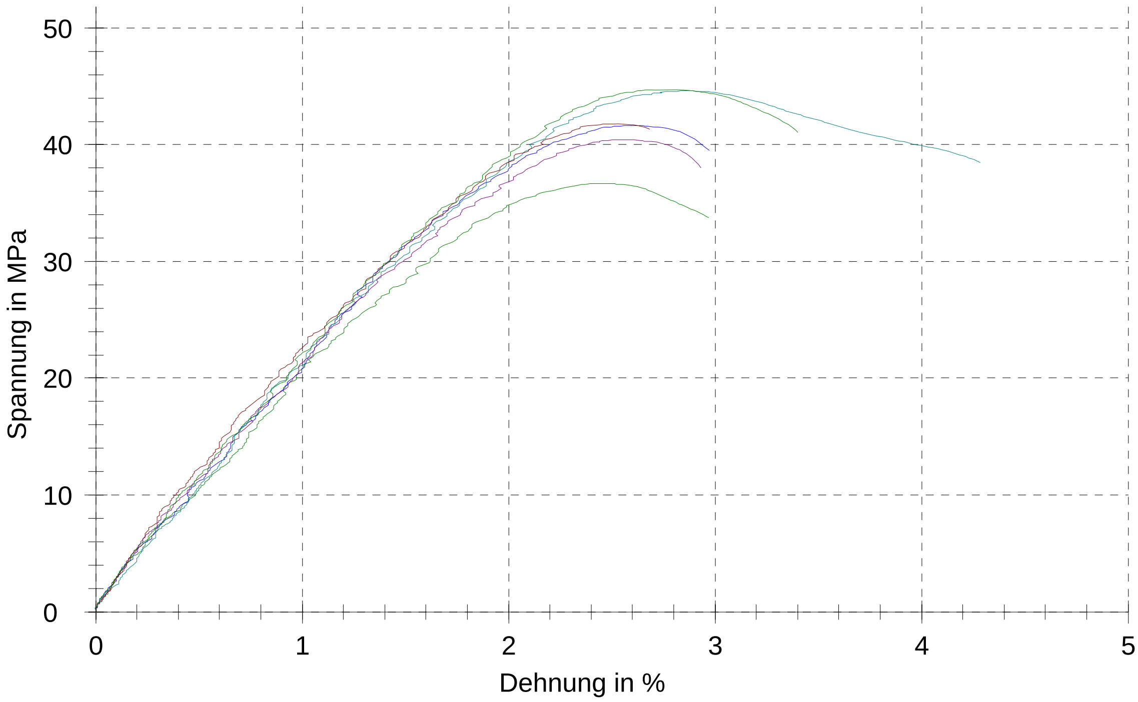
Parametertabelle:

Prüfnorm	: ISO 527
Material	: ABS
Maschinendaten	: 1465 WN:112226 Traversenwegaufnehmer WN:112226 Kraftsensor ID:0 WN:112227 50 kN optischer Aufnehmer ID:3 WN:119789

Ergebnisse:

Legende	Nr	b mm	h mm	L0 mm	σ_B MPa	σ_Y MPa	σ_M MPa	ε_y %	ε_M %	ε_{tM} %	ε_B %	ε_{tB} %
	✝1	9,9	3,97	50,00	-	-	-	-	-	-	-	-
(grün)	2	10,1	3,99	49,94	33,78	36,70	36,70	2,5	2,5	2,5	3,0	2,9
(blau)	3	10,12	4,1	49,59	39,49	41,64	41,64	2,6	2,6	2,7	3,0	3,0
(türkis)	4	10,35	4,02	49,94	38,49	44,61	44,61	2,9	2,9	3,1	4,3	4,5
(violett)	5	10,05	4,01	50,40	38,00	40,42	40,42	2,5	2,5	2,7	2,9	3,0
(dunkelrot)	6	10,05	4	50,09	41,30	41,79	41,79	2,5	2,5	2,7	2,7	2,9
(grün)	7	10,3	3,96	51,27	41,07	44,71	44,71	2,7	2,7	2,9	3,4	3,5

Seriengrafik:



Statistik:

Serie n = 6	b mm	h mm	L0 mm	σ_B MPa	σ_Y MPa	σ_M MPa	ε_y %	ε_M %	ε_{tM} %	ε_B %	ε_{tB} %
$\bar{x}$	10,16	4,013	50,20	38,69	41,64	41,64	2,6	2,6	2,8	3,2	3,3
s	0,1304	0,04719	0,59	2,75	2,97	2,97	0,1	0,1	0,2	0,6	0,6
ν	1,28	1,18	1,17	7,10	7,14	7,14	5,64	5,64	8,04	17,96	19,51

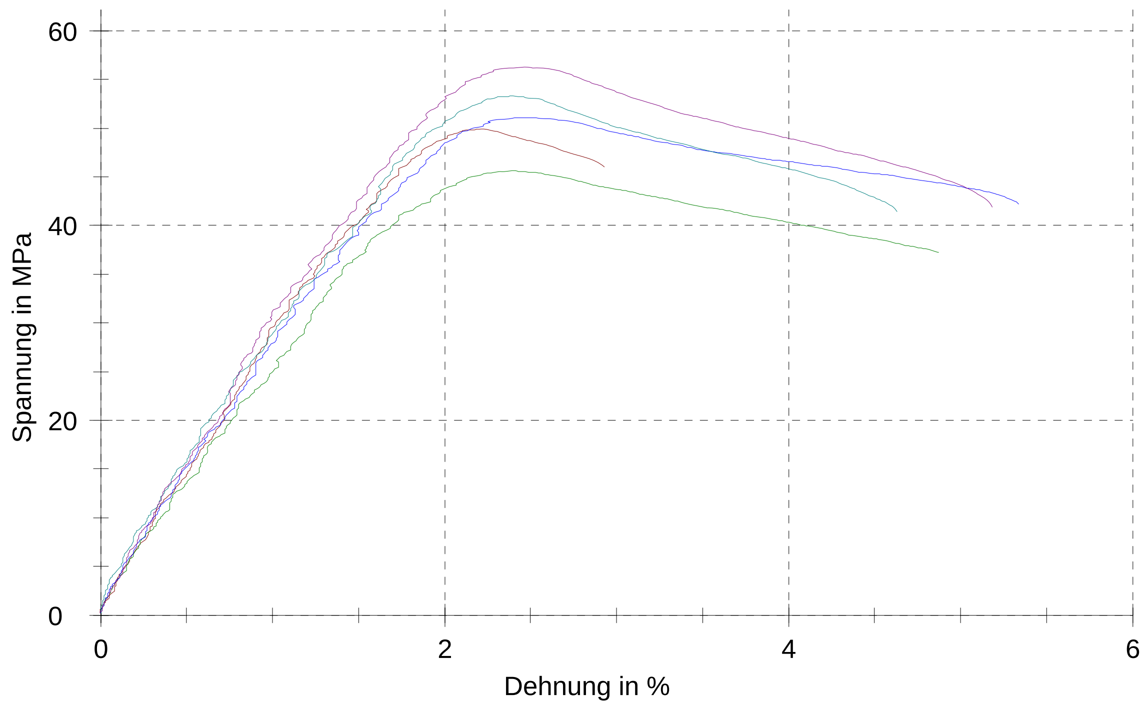
Parametertabelle:

Prüfnorm : ISO 527
Material : PLA
Maschinendaten: 1465 WN:112226
Traversenwegaufnehmer WN:112226
Kraftsensor ID:0 WN:112227 50 kN
optischer Aufnehmer ID:3 WN:119789

Ergebnisse:

Legende	Nr	b mm	h mm	L0 mm	σ_B MPa	σ_Y MPa	σ_M MPa	ε_y %	ε_M %	ε_{tM} %	ε_B %	ε_{tB} %
	1	9,95	4	50,11	45,99	49,89	49,89	2,2	2,2	2,5	2,9	3,3
	3	10	4,1	49,82	37,21	45,59	45,59	2,4	2,4	2,4	4,9	4,9
	4	10	4,04	49,91	42,23	51,08	51,08	2,4	2,4	2,7	5,3	5,5
	5	10,05	4,05	49,80	41,40	53,29	53,29	2,4	2,4	2,6	4,6	4,8
	6	10,03	4,05	49,72	41,91	56,26	56,26	2,5	2,5	2,9	5,2	5,5

Seriengrafik:



Statistik:

Serie n = 5	b mm	h mm	L0 mm	σ_B MPa	σ_Y MPa	σ_M MPa	ε_y %	ε_M %	ε_{tM} %	ε_B %	ε_{tB} %
$\bar{x}$	10,01	4,048	49,87	41,75	51,22	51,22	2,4	2,4	2,6	4,6	4,8
s	0,03782	0,03564	0,15	3,12	3,97	3,97	0,1	0,1	0,2	1,0	0,9
ν	0,38	0,88	0,30	7,48	7,75	7,75	4,60	4,60	6,49	21,11	19,27

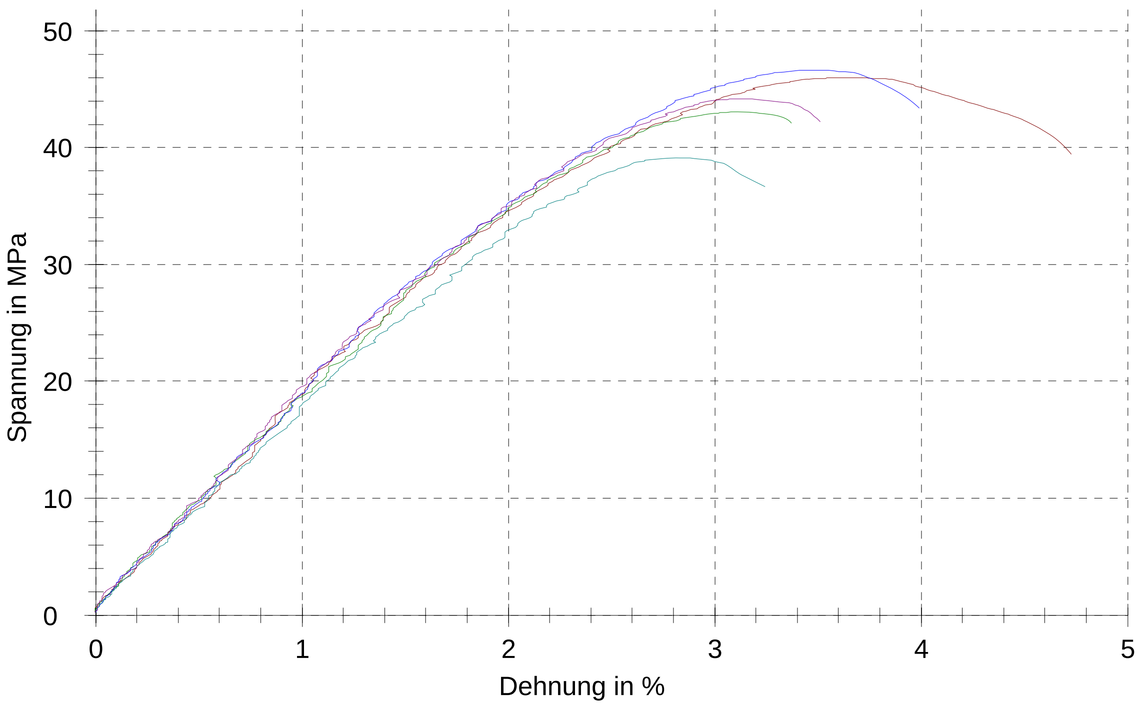
Parametertabelle:

Prüfnorm : ISO 527
Material : CPE
Maschinendaten : 1465 WN:112226
Traversenwegaufnehmer WN:112226
Kraftsensor ID:0 WN:112227 50 kN
optischer Aufnehmer ID:3 WN:119789

Ergebnisse:

Legende	Nr	b mm	h mm	L0 mm	σ_B MPa	σ_Y MPa	σ_M MPa	ε_y %	ε_M %	ε_{tM} %	ε_B %	ε_{tB} %
	1	10,01	4,08	49,93	39,44	46,00	46,00	3,6	3,6	3,7	4,7	4,7
	2	10,02	4,05	49,56	42,09	43,06	43,06	3,1	3,1	3,2	3,4	3,4
	3	10,05	4,06	49,69	43,41	46,66	46,66	3,5	3,5	3,5	4,0	4,0
	4	10,05	4,03	50,13	36,69	39,13	39,13	2,8	2,8	2,8	3,2	3,1
	5	10,05	4,03	49,83	42,20	44,17	44,17	3,1	3,1	3,3	3,5	3,6

Seriengrafik:



Statistik:

Serie n = 5	b mm	h mm	L0 mm	σ_B MPa	σ_Y MPa	σ_M MPa	ε_y %	ε_M %	ε_{tM} %	ε_B %	ε_{tB} %
$\bar{x}$	10,04	4,05	49,83	40,77	43,80	43,80	3,2	3,2	3,3	3,8	3,7
s	0,01949	0,02121	0,22	2,70	2,98	2,98	0,3	0,3	0,3	0,6	0,6
ν	0,19	0,52	0,44	6,63	6,80	6,80	9,74	9,74	9,88	16,10	16,48

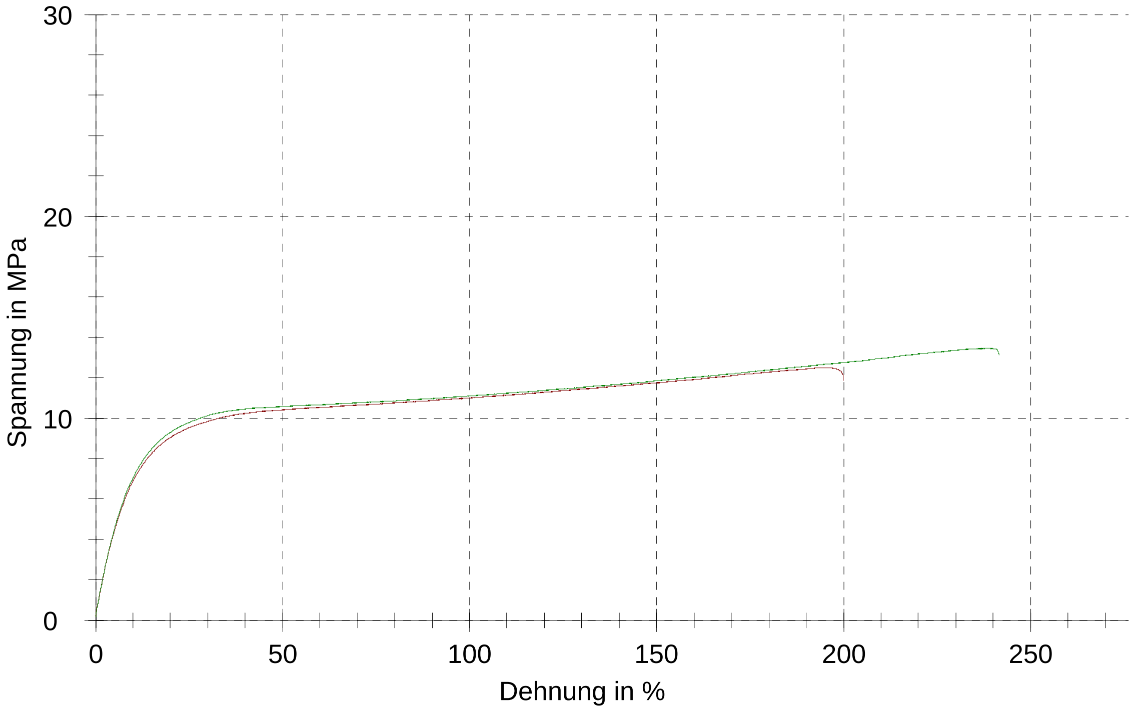
Parametertabelle:

Prüfnorm : ISO 527
Material : Flexifil
Maschinendaten: 1465 WN:112226
Traversenwegaufnehmer WN:112226
Kraftsensor ID:0 WN:112227 50 kN
optischer Aufnehmer ID:3 WN:119789

Ergebnisse:

Legende	Nr	b mm	h mm	L0 mm	σ_B MPa	σ_Y MPa	σ_M MPa	ε_y %	ε_M %	ε_{tM} %	ε_B %	ε_{tB} %
(rot)	1	10,01	3,86	49,72	11,85	9,65	12,50	26,7	194,2	190,0	200,0	195,8
(grün)	2	10,03	3,86	49,63	13,12	9,90	13,46	26,5	238,9	235,4	241,5	238,0

Seriengrafik:



Statistik:

Serie n = 2	b mm	h mm	L0 mm	σ_B MPa	σ_Y MPa	σ_M MPa	ε_y %	ε_M %	ε_{tM} %	ε_B %	ε_{tB} %
$\bar{x}$	10,02	3,86	49,67	12,49	9,77	12,98	26,6	216,6	212,7	220,7	216,9
s	0,01414	0,000	0,07	0,90	0,18	0,68	0,1	31,6	32,1	29,4	29,9
ν	0,14	0,00	0,14	7,19	1,81	5,22	0,51	14,57	15,07	13,31	13,78

D Metrological Control Results

Messprotokoll

3D-Anwendungstechnik

Bezeichnung		Hersteller	
Zeichnungs-Nr.		Seriennummer	
Bemerkung		Sachnummer	
Lieferant		Lieferdatum	
Lieferschein		Lieferumfang	
Losnummer		Losgröße	
Prüfplan		Stichprobenumfang	
Fertigungsmaschine		Werkzeug	
Fertigungsdatum		Uhrzeit	
Auftrag		Abteilung	
Prüfer	GLOBAL	Prüfdatum	24-JUN-2016, 10:59:41
Messgerät	DTX 5 7 5 # 222	QDS-Version	Quindos7 - V 7.10.14363-R-2
Benutzername	GLOBAL	Werkstückname	Kreispyramide

Text	Ausw.	Istmaß	Nennmaß	O.Tol.	U.Tol.	Ist-Soll	Grafik
CIR(1)			CIR				
	DM	9.8184	10.0000	0.0500	-0.0500	-0.1816	
	FORM	0.1866	0.0000	0.0500	0.0000	0.1866	
CIR(2)			CIR				
	DM	29.7830	30.0000	0.5000	-0.5000	-0.2170	
	FORM	0.2403	0.0000	0.5000	0.0000	0.2403	
CIR(3)			CIR				
	DM	49.7228	50.0000	0.5000	-0.5000	-0.2772	
	FORM	0.3630	0.0000	0.5000	0.0000	0.3630	
Kreis70			CIR				
	X	-0.5310	0.0000	0.0500	-0.0500	0.5310	
	Y	0.7775	0.0000	0.0500	-0.0500	0.7775	
	Z	-34.9962	0.0000	0.0500	-0.0500	34.9962	
	DM	69.6372	70.0000	0.0500	-0.0500	-0.3628	
Plane(1)			PLA				
	FORM	0.2410	0.0000	0.0500	0.0000	0.2410	
	Z	0.0279	0.0000	0.0500	-0.0500	0.0279	
Plane(2)			PLA				
	FORM	0.1243	0.0000	0.0500	0.0000	0.1243	
	Z	-9.9394	0.0000	0.0500	-0.0500	9.9394	
Plane(3)			PLA				
	FORM	0.0658	0.0000	0.0500	0.0000	0.0658	
	Z	-20.0320	0.0000	0.0500	-0.0500	20.0320	
Plane(4)			PLA				
	FORM	0.0778	0.0000	0.0500	0.0000	0.0778	
	Z	-30.0070	0.0000	0.0500	-0.0500	30.0070	

Messprotokoll

3D-Anwendungstechnik

Bezeichnung	Winkel	Hersteller	
Zeichnungs-Nr.		Seriennummer	
Bemerkung		Sachnummer	
Lieferant		Lieferdatum	
Lieferschein		Lieferumfang	
Losnummer		Losgröße	
Prüfplan		Stichprobenumfang	
Fertigungsmaschine		Werkzeug	
Fertigungsdatum		Uhrzeit	
Auftrag		Abteilung	
Prüfer	GLOBAL	Prüfdatum	24-JUN-2016, 13:19:34
Messgerät	DTX 5 7 5 # 222	QDS-Version	Quindos7 - V 7.10.14363-R-2
Benutzername	GLOBAL	Werkstückname	Winkel

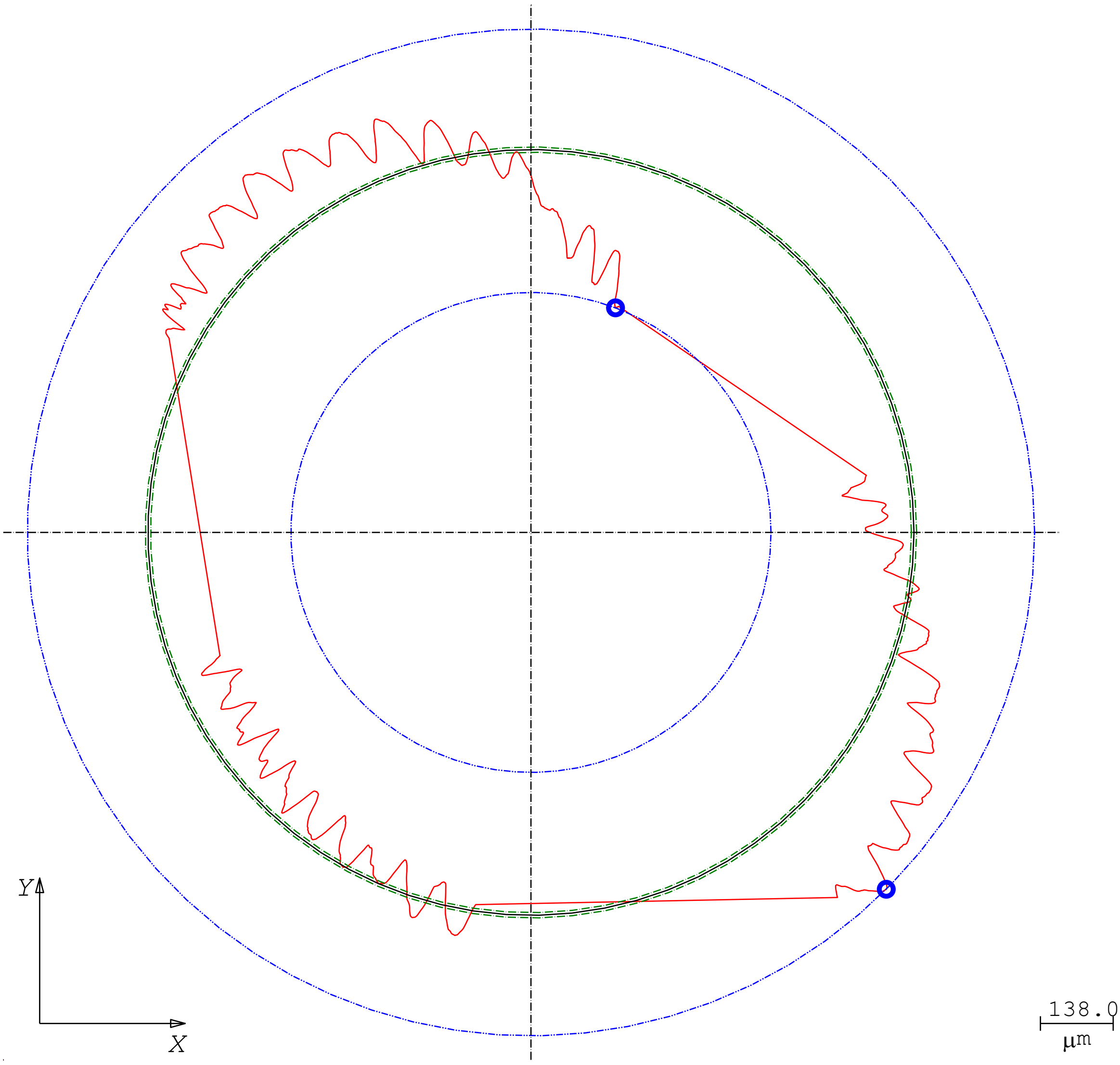
Text	Ausw.	Istmaß	Nennmaß	O.Tol.	U.Tol.	Ist-Soll	Grafik
Winkel(1)			ANG				
	C_ANG90	49.9197	0.0000	0.0500	-0.0500	49.9197	
Winkel(2)			ANG				
	C_ANG90	44.4037	0.0000	0.0500	-0.0500	44.4037	
Winkel(3)			ANG				
	C_ANG90	39.4242	0.0000	0.0500	-0.0500	39.4242	
Winkel(4)			ANG				
	C_ANG90	34.4033	0.0000	0.0500	-0.0500	34.4033	
Winkel(5)			ANG				
	C_ANG90	29.4018	0.0000	0.0500	-0.0500	29.4018	
Winkel(6)			ANG				
	C_ANG90	24.4334	0.0000	0.0500	-0.0500	24.4334	
Winkel(7)			ANG				
	C_ANG90	19.4875	0.0000	0.0500	-0.0500	19.4875	
Winkel(8)			ANG				
	C_ANG90	14.6084	0.0000	0.0500	-0.0500	14.6084	
Winkel(9)			ANG				
	C_ANG90	9.6180	0.0000	0.0500	-0.0500	9.6180	
Winkel(10)			ANG				
	C_ANG90	4.7159	0.0000	0.0500	-0.0500	4.7159	

Messprotokoll

3D-Anwendungstechnik

Bezeichnung	Durchmesser	Hersteller	
Zeichnungs-Nr.		Seriennummer	
Bemerkung		Sachnummer	
Lieferant		Lieferdatum	
Lieferschein		Lieferumfang	
Losnummer		Losgröße	
Prüfplan		Stichprobenumfang	
Fertigungsmaschine		Werkzeug	
Fertigungsdatum		Uhrzeit	
Auftrag		Abteilung	
Prüfer	GLOBAL	Prüfdatum	24-JUN-2016, 12:32:25
Messgerät	DTX 5 7 5 # 222	QDS-Version	Quindos7 - V 7.10.14363-R-2
Benutzername	GLOBAL	Werkstückname	Durchmesser

Text	Ausw.	Istmaß	Nennmaß	O.Tol.	U.Tol.	Ist-Soll	Grafik
CIR(1)			CIR				
	FORM	0.0707	0.0000	0.0500	0.0000	0.0707	
	DM	59.6530	0.0000	0.0500	-0.0500	59.6530	
CIR(2)			CIR				
	FORM	0.1046	0.0000	0.0500	0.0000	0.1046	
	DM	63.8137	0.0000	0.0500	-0.0500	63.8137	
CIR(3)			CIR				
	FORM	0.0975	0.0000	0.0500	0.0000	0.0975	
	DM	80.3561	0.0000	0.0500	-0.0500	80.3561	
CIR(4)			CIR				
	FORM	0.0867	0.0000	0.0500	0.0000	0.0867	
	DM	120.9517	0.0000	0.0500	-0.0500	120.9517	
CIR(5)			CIR				
	FORM	0.0979	0.0000	0.0500	0.0000	0.0979	
	DM	404.4453	0.0000	0.0500	-0.0500	404.4453	



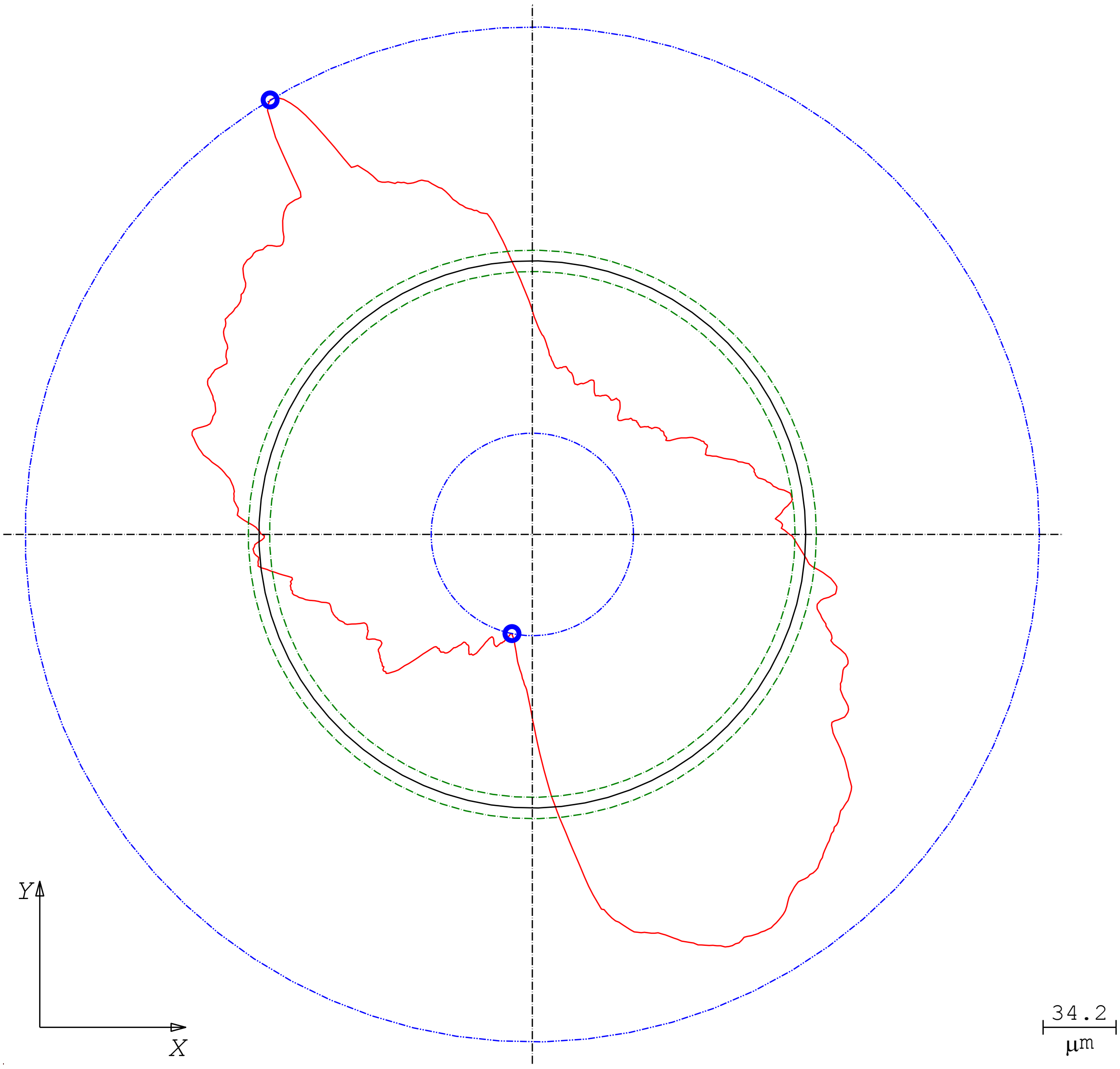
Istkontur ...: Soll-Toleranz : Ist-Toleranz :

Bez. ....:		Herst. ..:		Zeich.-Nr.:	
Ser.-Nr. :		Sachnr. .:		Abteilung :	
Berechn. :	Gauss	Filter ..:	Kein Wel./Umf.	Tast. Dur.:	3 mm
Element .:	Kreis70				
Durchm. :	69.6372	Form ....:	0.4901		
X-Koord. :	-0.5310	Toleranz :	0.0100		
Y-Koord. :	0.7775	Ueberh. .:	50		
Z-Koord. :	-34.9962	Punkte ..:	2193		

HEXAGON METROLOGY

RUNDHEIT

Pruefer ..:GLOBAL
Datum ....:24-JUN-2016
Uhrzeit ..:10:59:41



Istkontur ...:   Soll-Toleranz :   Ist-Toleranz :

Bez. ....: Herst. ..: Zeich.-Nr.:

Ser.-Nr. : Sachnr. .: Abteilung :

Berechn. : Gauss Filter ..: Kein Wel./Umf. Tast. Dur.: 3.000 mm

Element .: CIR(1)

Durchm. : 9.8184 Form ....: 0.1866

X-Koord. : -0.0373 Toleranz : 0.0100

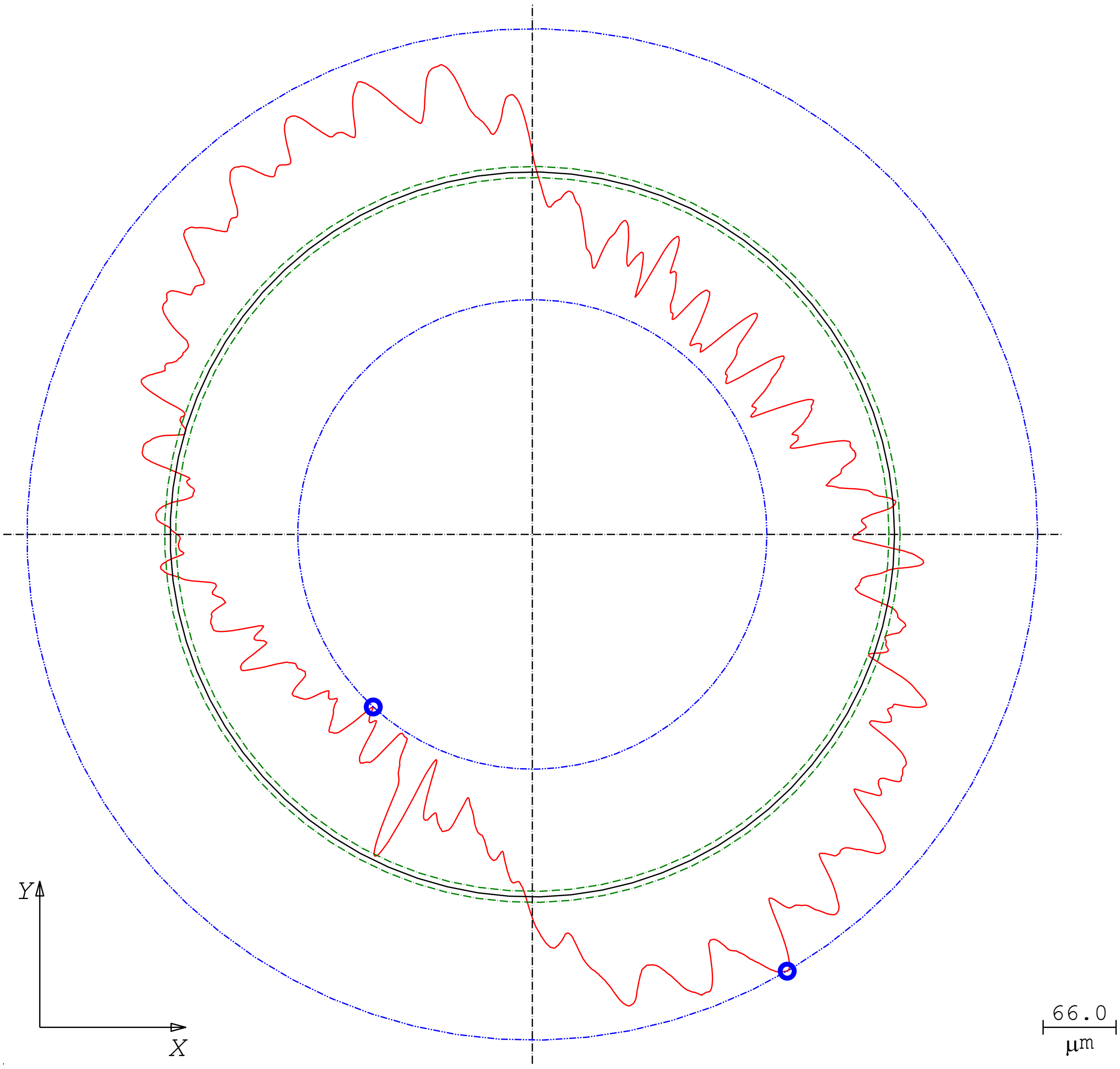
Y-Koord. : 0.0793 Ueberh. .: 50

Z-Koord. : -5.0006 Punkte ..: 792

HEXAGON METROLOGY

RUNDHEIT

Pruefer ..:GLOBAL
Datum ....:24-JUN-2016
Uhrzeit ..:10:59:41



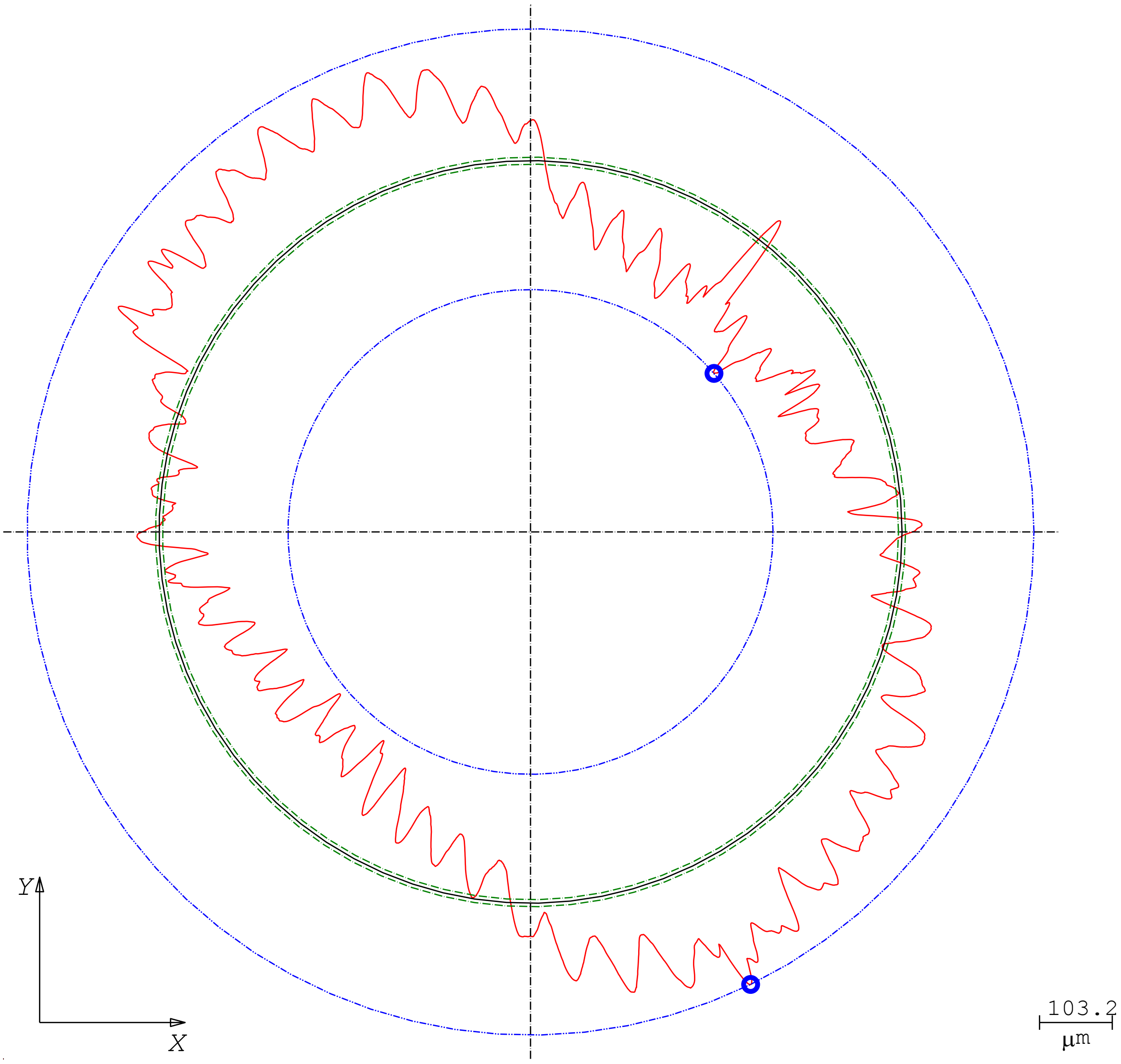
Istkontur ...: Soll-Toleranz : Ist-Toleranz :

Bez. ....:		Herst. ..:		Zeich.-Nr.:	
Ser.-Nr. :		Sachnr. .:		Abteilung :	
Berechn. :	Gauss	Filter ..:	Kein Wel./Umf.	Tast. Dur.:	3.000 mm
Element .:	CIR(2)				
Durchm. :	29.7830	Form ....:	0.2403		
X-Koord. :	-0.2070	Toleranz :	0.0100		
Y-Koord. :	0.2816	Ueberh. .:	50		
Z-Koord. :	-15.0001	Punkte ..:	2038		

HEXAGON METROLOGY

RUNDHEIT

Pruefer ..:GLOBAL
Datum ....:24-JUN-2016
Uhrzeit ..:10:59:41



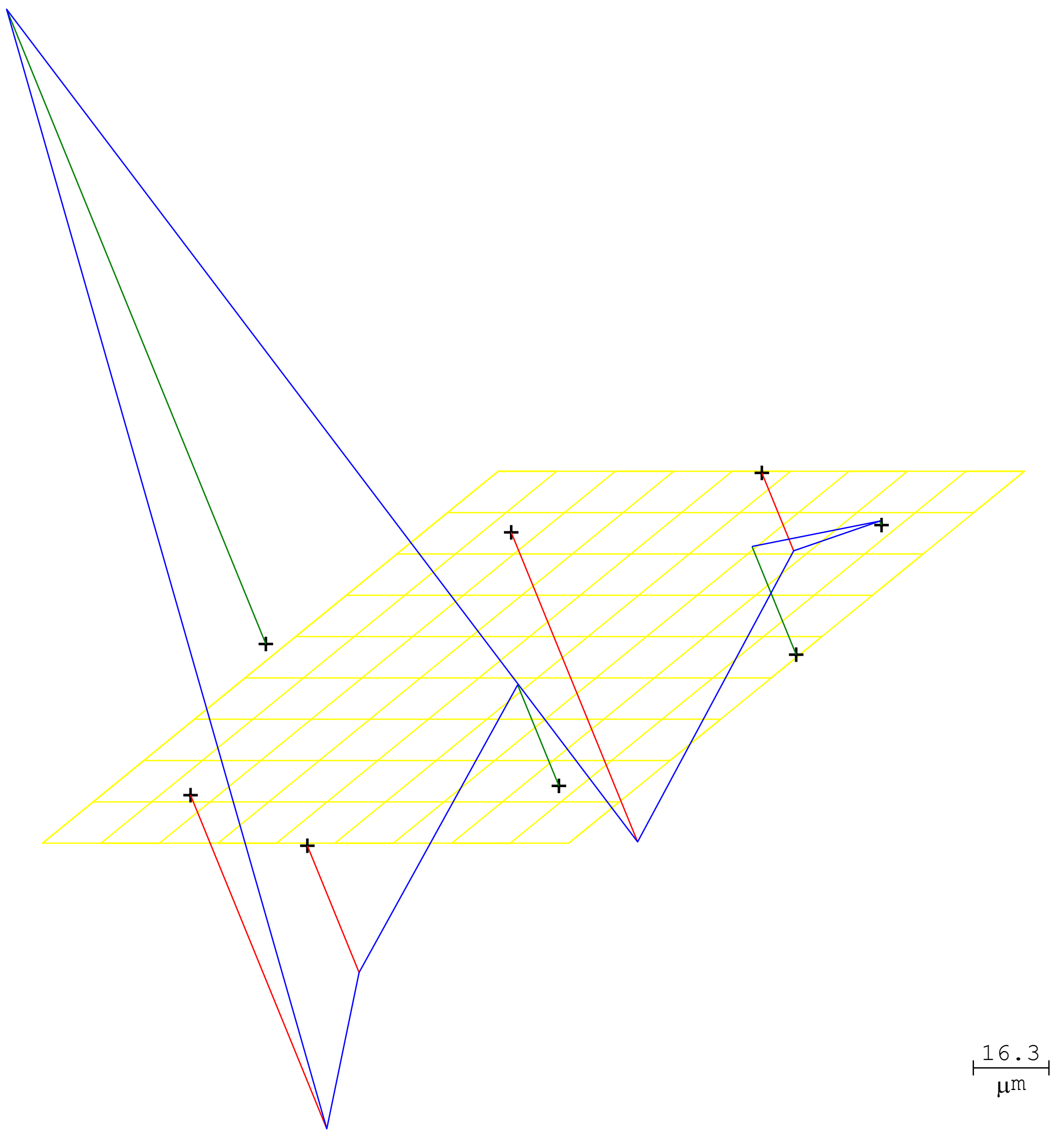
Istkontur ...: ——— Soll-Toleranz : - - - - - Ist-Toleranz : -·-·-·-

Bez. ....:		Herst. ..:		Zeich.-Nr.:	
Ser.-Nr. :		Sachnr. .:		Abteilung :	
Berechn. :	Gauss	Filter ..:	Kein Wel./Umf.	Tast. Dur.:	3.000 mm
Element .:	CIR(3)				
Durchm. :	49.7228	Form ....:	0.3630		
X-Koord. :	-0.4012	Toleranz :	0.0100		
Y-Koord. :	0.4898	Ueberh. .:	50		
Z-Koord. :	-24.9998	Punkte ..:	3260		

HEXAGON METROLOGY

RUNDHEIT

Pruefer ..:GLOBAL
Datum ....:24-JUN-2016
Uhrzeit ..:10:59:41



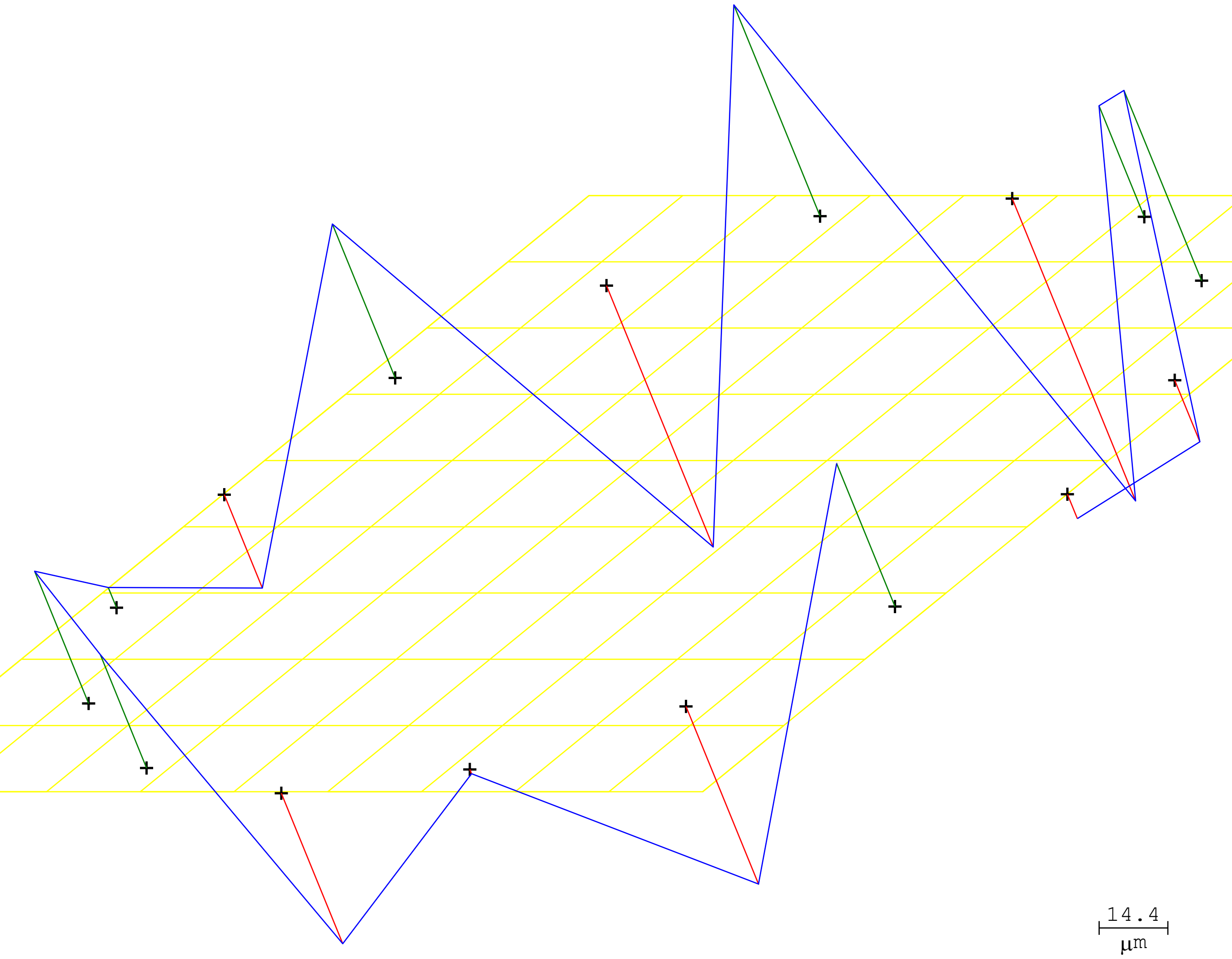
Istpunkte ....: * * * Neg. Abweichung : Pos. Abweichung :

Bez. ....:		Herst. ..:		Zeich.-Nr.:		
Ser.-Nr. :		Sachnr. .:		Abteilung :		
Berechn. : Gauss		Filter ..: Kein		Tast. Dur.: 3 mm		
Element .: Plane(1)			X	Y	Z	Nr.
Form ....:	0.2410	Neg. Abwchg.: -0.0830	-2.8698	-2.8016	-0.0281	6
Ueberhoehung.:	50	Pos. Abwchg.: 0.1579	-4.0512	0.0317	0.3095	5
Punktanzahl .:	8					

HEXAGON METROLOGY

EBENHEIT

Pruefer ..:GLOBAL
Datum ....:24-JUN-2016
Uhrzeit ..:10:59:41



Istpunkte ....: * * *   Neg. Abweichung :   Pos. Abweichung :

Bez. ....:   Herst. ..:   Zeich.-Nr.:

Ser.-Nr. :   Sachnr. .:   Abteilung :

Berechn. : Gauss   Filter ..: Kein   Tast. Dur.: 3 mm

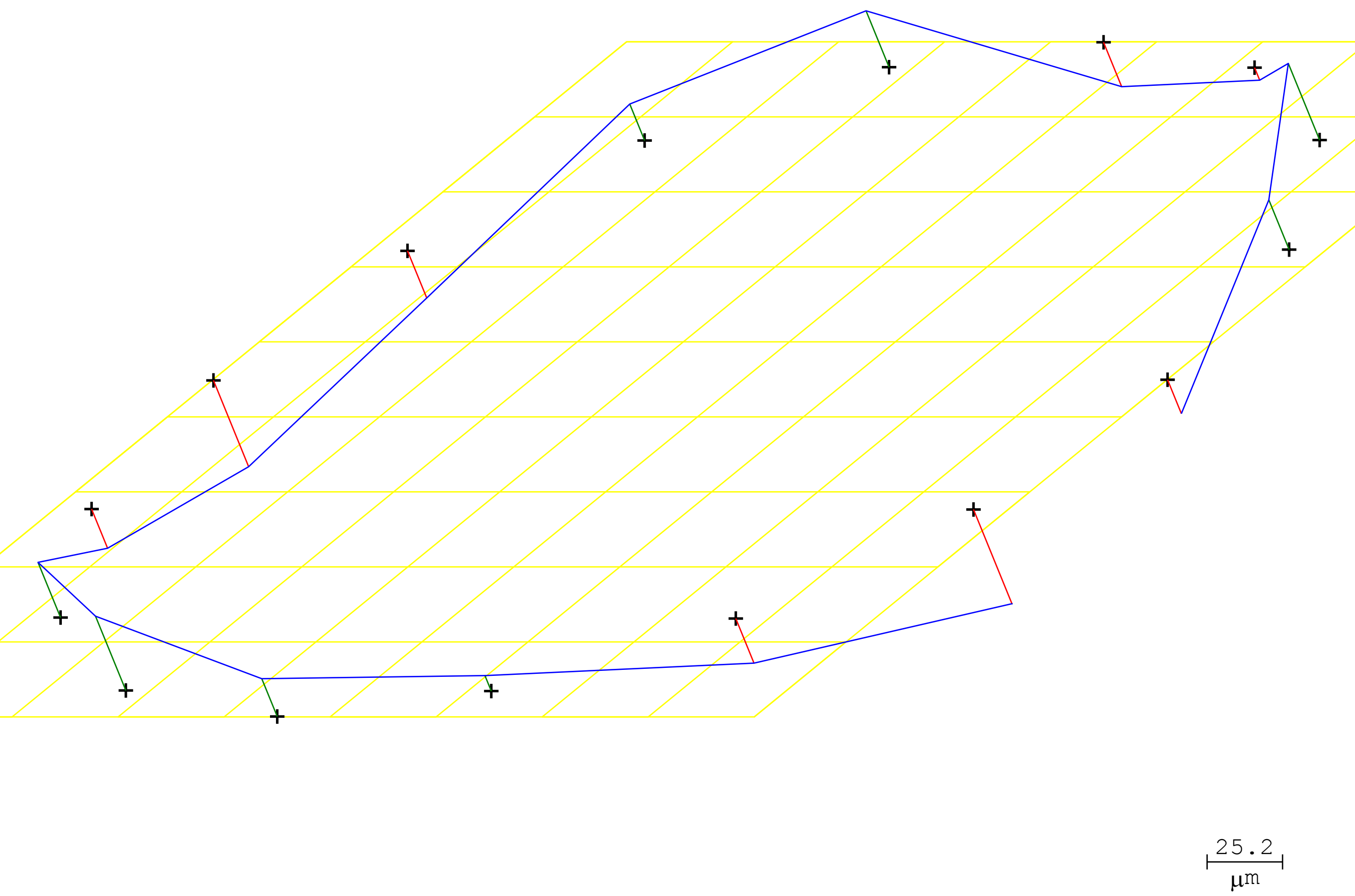
Element .: Plane(2)

			X	Y	Z	Nr.
Form ....: 0.1243	Neg. Abwchg.:	-0.0732	-0.0096	12.5255	-9.7397	5
Ueberhoehung.: 100	Pos. Abwchg.:	0.0511	-4.8154	11.5698	-9.5499	6
Punktanzahl .: 16						

HEXAGON METROLOGY

EBENHEIT

Pruefer ..:GLOBAL
Datum ....:24-JUN-2016
Uhrzeit ..:10:59:41



Istpunkte ....: * * *   Neg. Abweichung :   Pos. Abweichung :

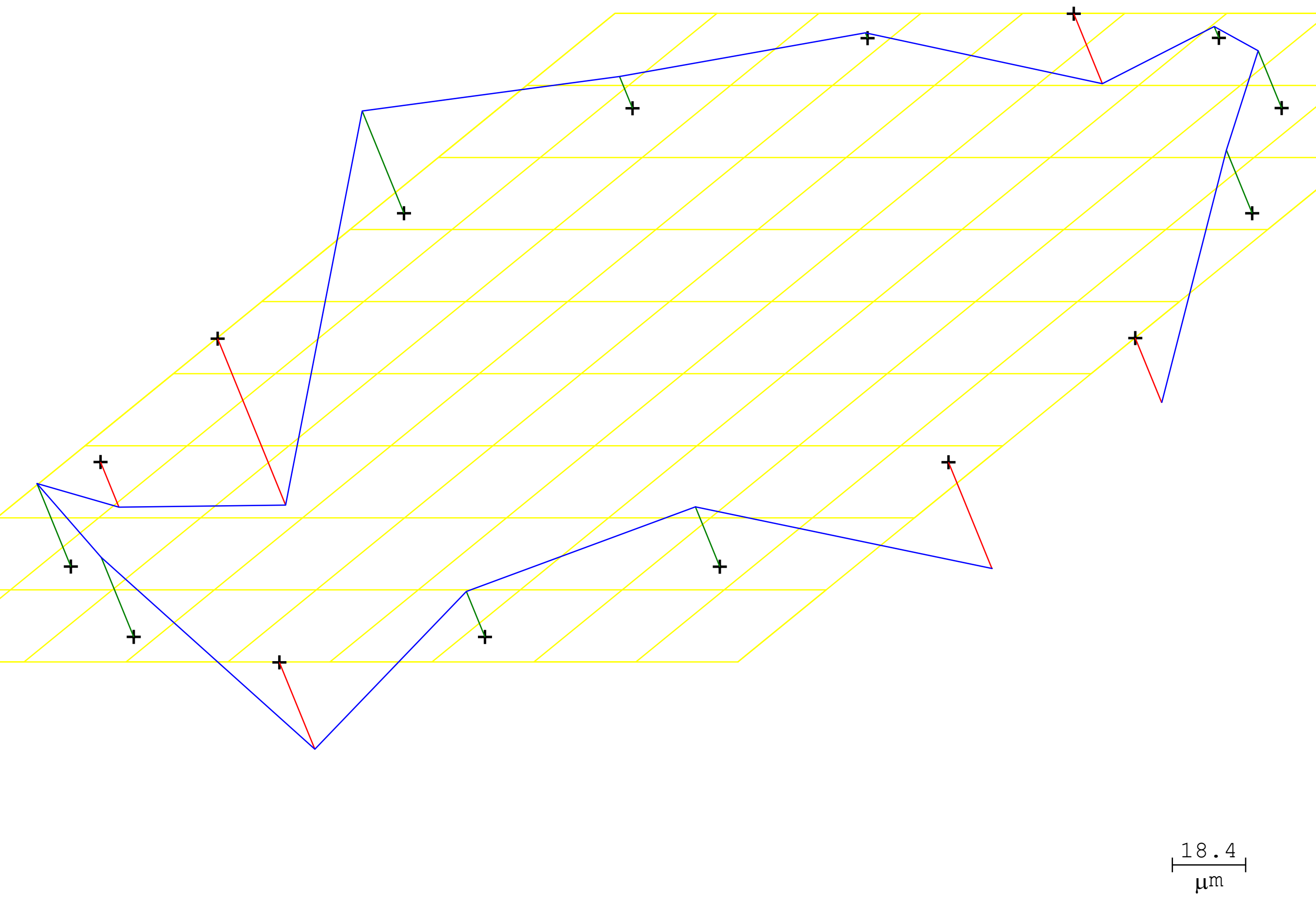
Bez. ....:		Herst. ..:		Zeich.-Nr.:	
Ser.-Nr. :		Sachnr. .:		Abteilung :	
Berechn. : Gauss		Filter ..: Kein		Tast. Dur.: 3 mm	

Element .: Plane(3)			X	Y	Z	Nr.
Form ....: 0.0658	Neg. Abwchg.:	-0.0363	20.7634	-8.5759	-20.6262	16
Ueberhoehung.: 100	Pos. Abwchg.:	0.0295	15.8958	15.9374	-19.9308	3
Punktanzahl .: 16						

HEXAGON METROLOGY

EBENHEIT

Pruefer ..:GLOBAL
Datum ....:24-JUN-2016
Uhrzeit ..:10:59:41



Istpunkte ....: * * *   Neg. Abweichung :   Pos. Abweichung :

Bez. ....:		Herst. ..:		Zeich.-Nr.:	
Ser.-Nr. :		Sachnr. .:		Abteilung :	
Berechn. : Gauss		Filter ..: Kein		Tast. Dur.: 3 mm	

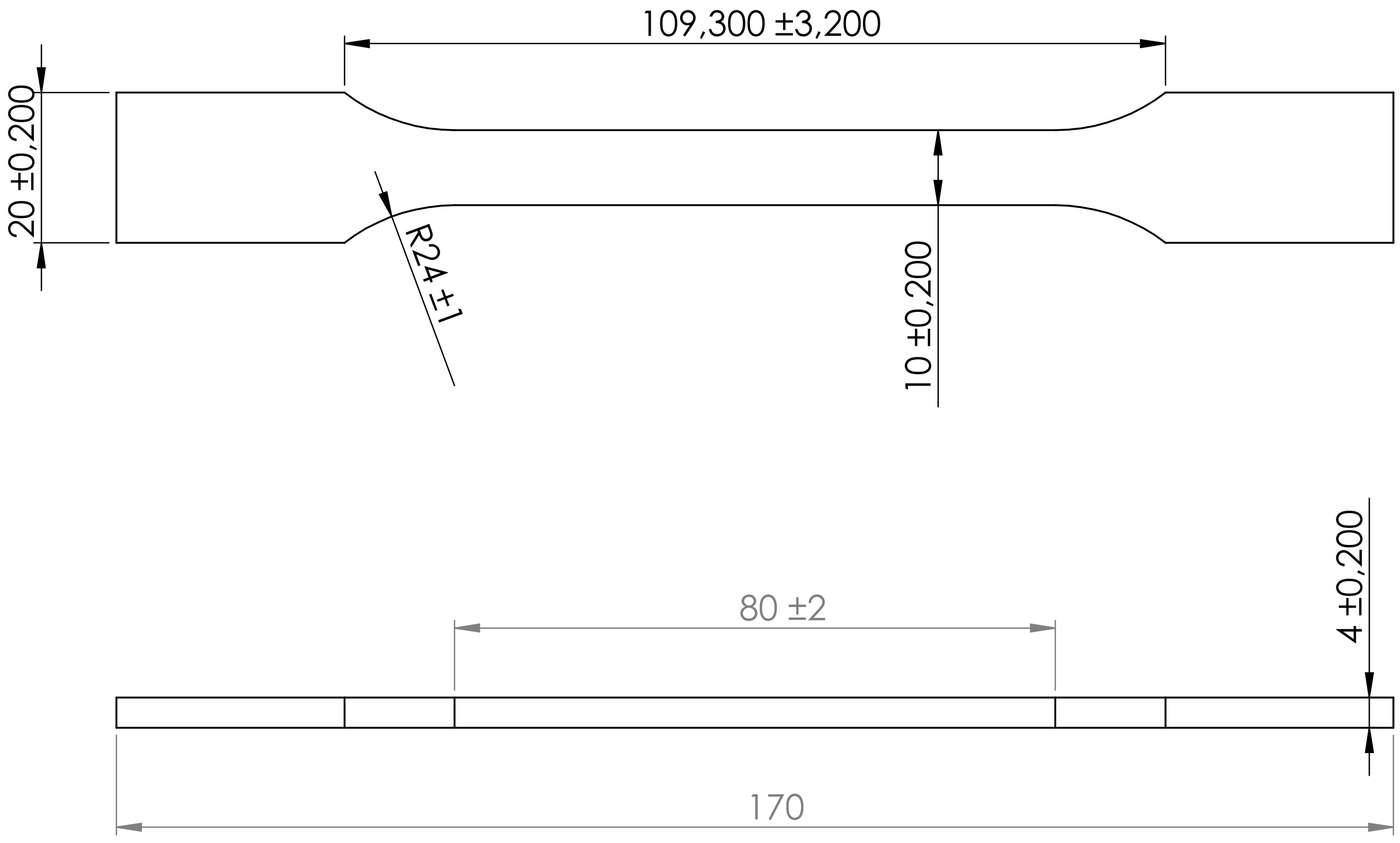
				X	Y	Z	Nr.
Element .:	Plane(4)						
Form ....:	0.0777	Neg. Abwchg.:	-0.0482	-32.5259	0.0124	-29.4996	9
Ueberhoehung.:	200	Pos. Abwchg.:	0.0296	-30.0558	12.4513	-29.1995	8
Punktanzahl .:	16						

HEXAGON METROLOGY

EBENHEIT

Pruefer ..:GLOBAL
Datum ....:24-JUN-2016
Uhrzeit ..:10:59:41

E Designed Plans



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	**Sergio Cabezas**		02/05/2016
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:
PLA
ABS
CPE
Flexifil

WEIGHT:

TITLE:

SPECIMEN FOR 3D PRINTER
ISO 527-2:2012

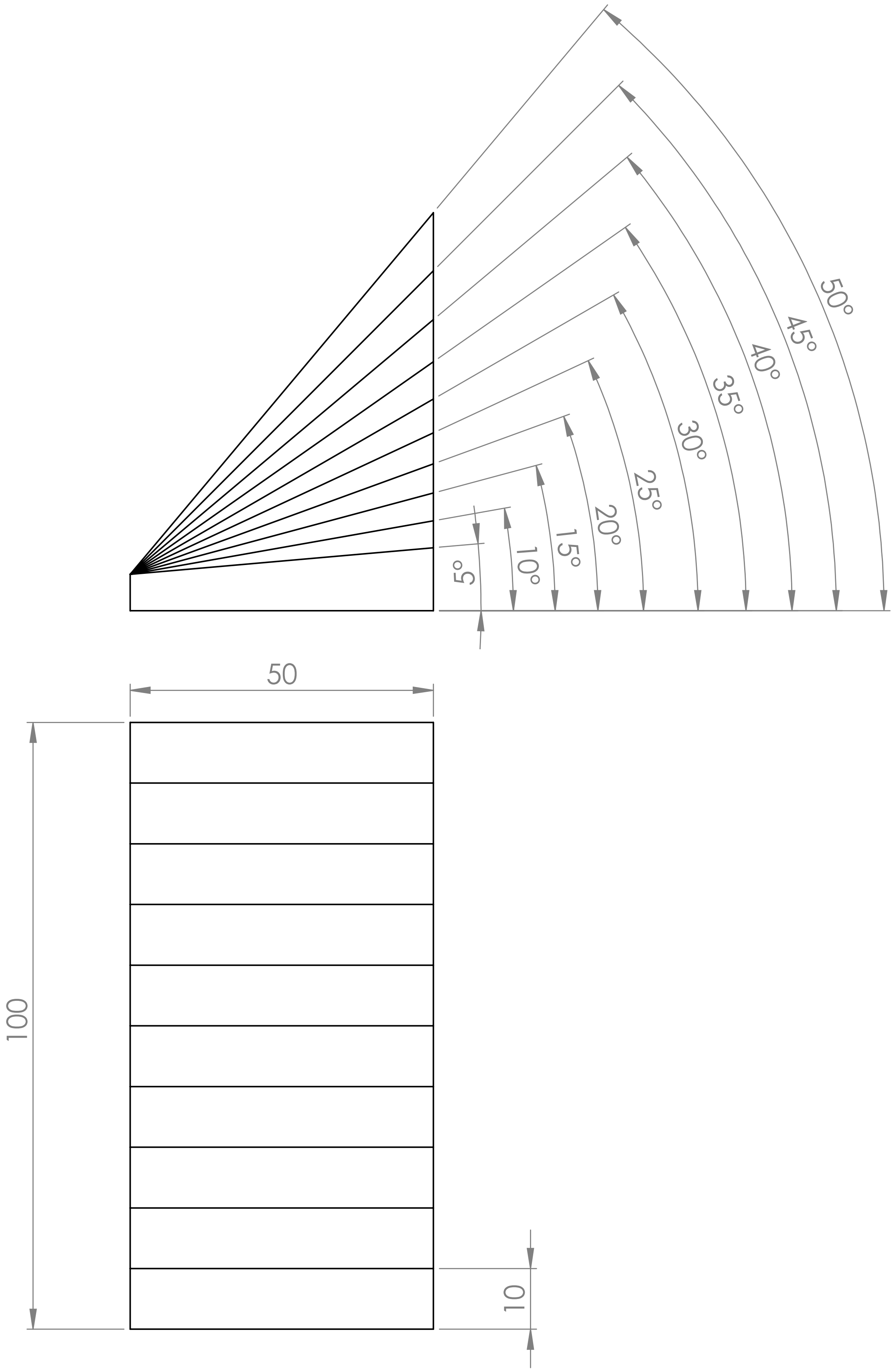
DWG NO.

Part1

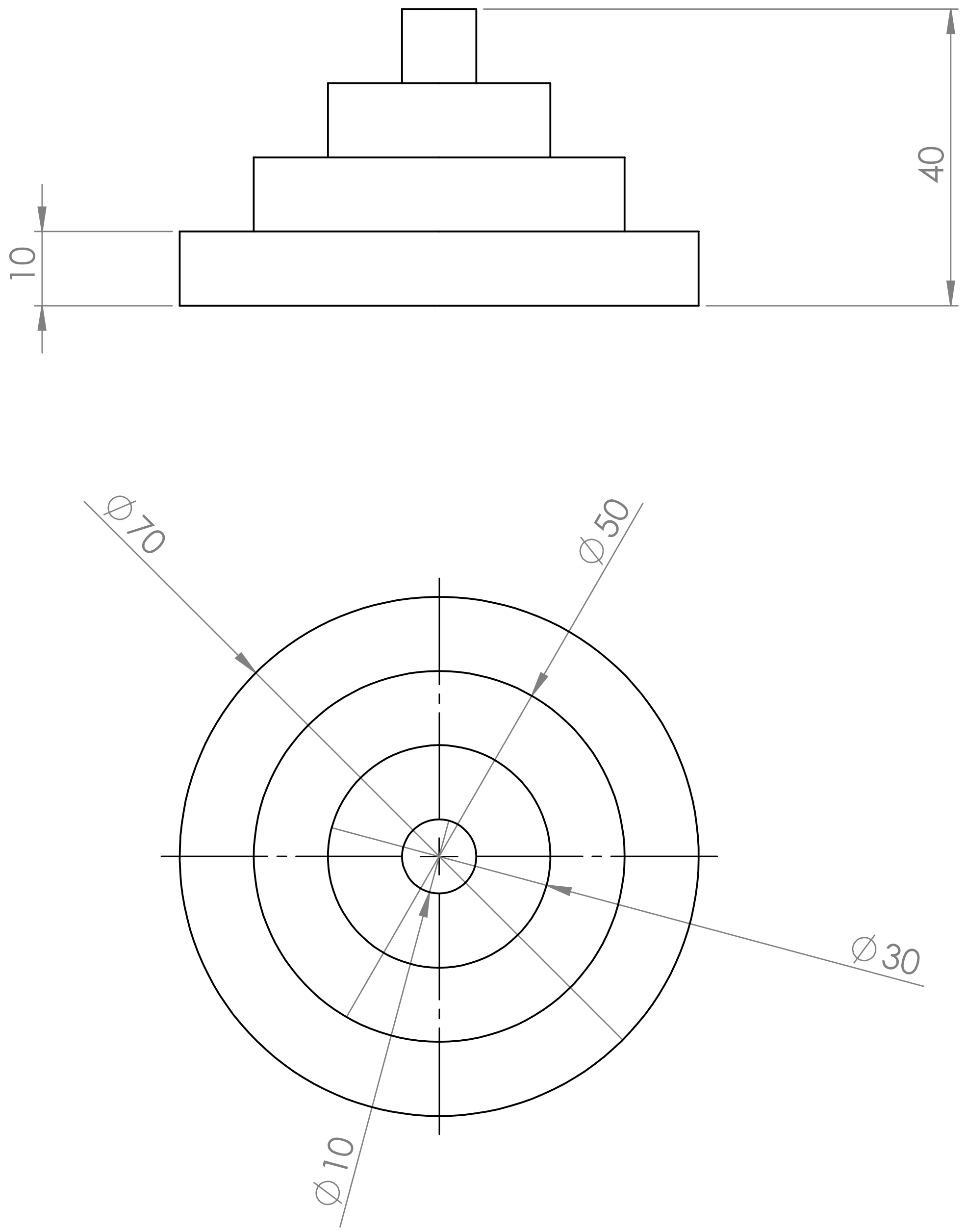
A4

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR:	FINISH:		DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION
	NAME	SIGNATURE	DATE	TITLE:	
DRAWN	Sergio Cabezas		02/06/2016	SPECIMEN FOR METROLOGICAL CONTROL	
CHK'D					
APPV'D					
MFG					
Q.A			MATERIAL: ABS	DWG NO. Slope	A4
			WEIGHT:	SCALE:1:1	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

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REVISION

	NAME	SIGNATURE	DATE
DRAWN	Sergio Cabezas		02/06/2016
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: ABS

WEIGHT:

TITLE:

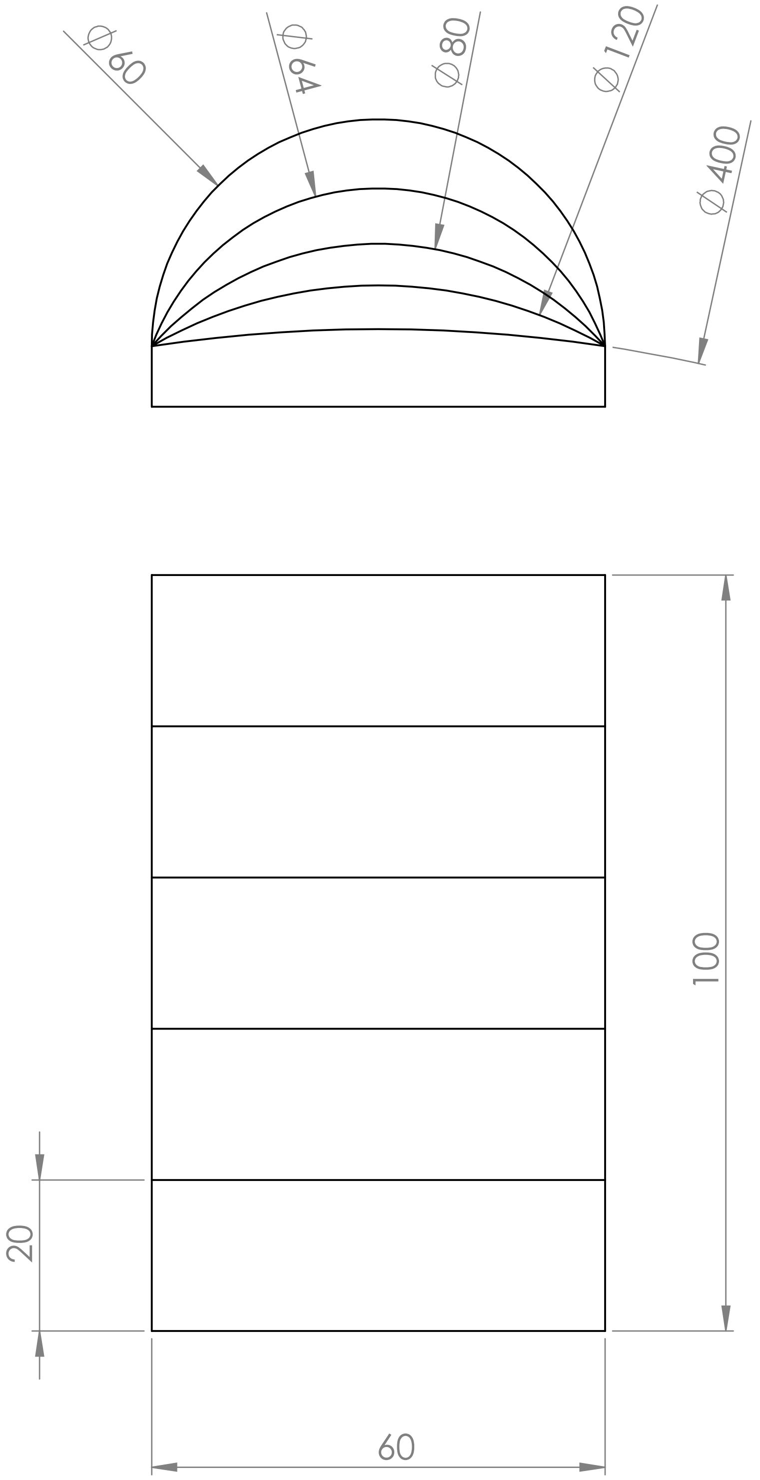
SPECIMEN FOR METROLOGICAL CONTROL

DWG NO. Concentricity

A4

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN	Sergio Cabezas		02/06/2016
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: ABS

WEIGHT:

TITLE:

SPECIMEN FOR METROLOGICAL CONTROL

DWG NO. Curvature

A4

SCALE:1:1

SHEET 1 OF 1

Statement

I hereby certify that I have used my thesis written itself constantly and no other than the specified sources and aids.

Date: ....

(Sign)