Stronger fixtures for CNC-Machining

This project is made in collaboration with:

Funding:

INDUSTRIENS FOND

Verner Overgaards Familiefond

Industry partners:

JAI

vola®

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1 Executive Summary

The stronger fixtures project had the goal of finding 2 materials stronger than those used in previous projects, and modelling fixtures faster using 3D scanning technology and FFF printing for low-cost manufacturing. Herein PA6, PA6GF and PC filaments were found to have better mechanical performance than the previous PETGCF and PBT, PVDF had much greater vibration damping properties. This was determined using fluid absorption, tensile, compressive, shear, fatigue, and model tests, which were analysed mechanically and using microscopy to determine changes in rasters and bonds.

For the company cases the 3D scanning equipment worked well in modelling complex geometries seen in castings and faucet shaped objects, wherein a method for a quick fixture design was developed using Blender and 3D printing Slicers. Then using a modern desktop 3D printer, the fixtures were printed at much lower costs than the conventional fixtures and manufactured faster.

A non-confidential machining fixture was made for polymer robotic milling. Wherein the vacuum fixture demonstrated the possibility of using AM to make internal structures for vacuum workholding. In the first company case the old fixture was scanned and repaired in CAD, which resulted in a fixture with the same geometrical accuracy and #machining#.

2 Introduction

Machining fixtures are found in many different geometries and materials and are part of any machining process. Conventional fixtures work well for simple geometries containing cylindrical or square shapes. However advanced machining includes a plethora of complex geometries, wherein fixturing non-symmetrical, curved or thin geometries can be difficult. This required specialised fixturing systems, which increase costs and lead time. Herein the recent advancements in additive manufacturing can help by making complex fixture parts in a short time span.

Companies have shown interest in the advantages of 3D printed fixtures including more geometric flexibility, while also damping vibrations and providing a cheaper/faster specialised fixture than could be achieved with traditional methods. Based on previous projects in UPUV - 3D print fixtures and tools (P654), MADE Advanced fixtures (P600) and Dansk AM Hub 3D Fix (P729), it was found that conventional 3D printed materials, lacked strength and longevity when used in a machining environment. Stronger fixtures for CNC-machining (P1001-4-16) therefore seeks to develop and adapt the 3D printing technology for machining fixtures, using higher strength materials. This includes expanding DAMRC's capabilities to 3D print high-end/engineering grade filaments. And considering methods for implementation in Danish industries, wherein the 3D-scanning technology may play a significant part in reducing lead time and downtime of the machines when designing fixtures. To show the capabilities and limitations of this technology, the materials will be tested in their resistance to chemical and mechanical stresses, and test cases for companies will be engineered and examined to evaluate their practical viability.

The project also seeks to find novel solutions for workholding fixture, which is explored by creating an internal DAMRC showcase. The project end goal is to identify at least 2 filament types, with better performance than in previous experiments regarding strength and longevity of the fixture. While also improving the ease of manufacturing these fixtures, using 3D scanning. The fixture ought also to be economically viable, and therefore has a price cap of 1000 DKK per fixture in material price.

3 Pre-Analysis and Literature Study

3.1 Fused Deposition Modelling / Fused Filament Fabrication

This project uses FDM/FFF technology since it is the most accessible and used technology in machine workshops. The technology uses an XYZ table, to move a heated nozzle and print bed, relative to each other. Then by extruding heated plastic filament thru the nozzle, a line of filament (raster) is laid on the print surface. The raster solidifies, allowing further rasters to be built on top of it, thereby making a 3D object (see figure 3-1).

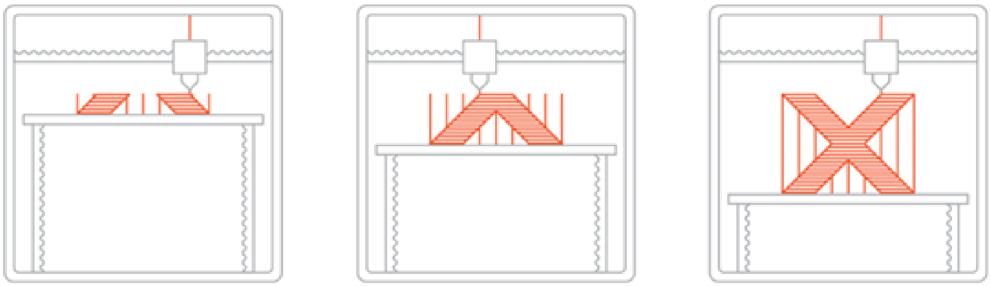


Figure 3.1-1
FFF printing process

The 3D printed object can be printed with different parameters, wherein some key parameters are: Layer height, number of perimeter walls, infill density, infill pattern, nozzle temperature, bed temperature and printing speed/volumetric flow. Which all affect the mechanical properties of the 3D printed object, difficulty of printing and manufacturing time and cost.

3.2 Previous case experience

Previous projects (Dansk AM Hub 3D Fix (P729) and UPUV - 3D print fixtures and tools (P654)) have included machining fixtures. Most companies preferred the PETG-CF fixtures, and many experienced difficulties with the fixture 3D-modelling. Most test cases were jaws / soft jaws, wherein the 3D print would often crack or break either before use, or after few uses of the fixture.

Case	Material	Use	Experience	Ref.
Company 1	PLA	Hydraulic vise Jaws	Failure due to cracking in printing direction after 21 uses. Many vibrations.	[9] [19]
Company 2	PLA	Complex Jaws	Have not been used.	[9] [19]
Company 3	PA (SLS)	Vacuum fixture	Only small prototype made.	[9] [19]
Company 4	PBT, PLA, PETGCF	Jaws	First printed wrong holding geometry, second made a mock-up of PLA to get the right dimensions, third print was too soft, fourth print of PETGCF had good material properties but still some geometric challenges.	[10]
JAI	PBT, PLA, PETGCF	Chip cover	First (PBT) print had holes after 130 uses. PETGCF showed signs of further longevity.	[11]
VOLA	PBT, PETGCF, TPU	Jaws	PBT print cracked when tightened. No further communication.	[12]
Company 5	PBT, PETGCF	Top fixture	PBT print cracked when tightened. PETGCF broke after 20 uses.	[13]
DAMRC	PETG	Vacuum fixture	Vibrations at higher feed and cutting depth.	[18]

Table 3-1
Relevant previous company experience and feedback

Some fixtures did work for a low number of uses. But the documentation on feedback has been either lacking, or the fixture cracking after some use. The first milling test with feedback, was from Company 1, where they reported many vibrations, and breakage after 21 uses/cycles. But this was also made with the most common FFF filament PLA, which is not a mechanically strong filament material. In subsequent projects PLA was used for geometric verification of the fixture. The newer test from Dansk AM Hub 3D Fix (P729) tested PBT, PETG, PETG-CF and TPU as fixtures in different conditions and configurations. The Company 4, JAI and Company 5 cases showed that PETG-CF could withstand the machining environment and the clamping forces for some time. The other materials either did not have feedback or had worse performance. Except in the special demonstration case of the PETG vacuum fixture, which did act as a proof-of-concept vacuum fixture [9] [10] [11] [12] [13] [19]. From the experiments done in UPUV - 3D print fixtures and tools (P654), it was concluded that FFF/PA+ and SLS/PA had the best dimensional stability, with exposed to coolant, and tested in compression. As compared to PLA, Nylon and ABS FFF materials. [2]

3.3 Filament material candidates

The marked available materials found were: PLA, PETG, HIPS, ABS, ASA, OBC, PP, PCTG, TPU, PC/ABS, PC, PA6, PA12, PPE-PS, PVDF, PPS, PSU, PES, PPSU, PEI, PEEK, PEKK, PVA, PBT. With several materials having different reinforcements like carbon or glass fiber to increase stiffness, or additives to increase the toughness. Vendors categorise these materials by grade and give a summary of their characteristics. Grading is given in general purpose for common consumer filaments that can be used by any printer, engineering grade for materials with enhanced properties and usually require higher temperatures, high performance and ultra-high performance for materials that require extremely high temperatures and are equivalent to parts used in high performance industries like aerospace.

Material	Grade	Purpose
PLA	General purpose	Easy to use and cheap filament, high stiffness but also brittle.
PETG	General purpose	Easy to use and cheap filament, tougher than PLA but less stiff.
HIPS	General purpose	Support material, high impact resistance.
ABS	General purpose	Durable and sturdy parts.
ASA	General purpose	A more durable and easier to print version of ABS.
PP	General purpose	Flexible material with low density.
OBC	General purpose	Easier to print version of PP.
PBT	General purpose	Easier to print version of PA12.
PCTG	Engineering	Better ductility then PETG, low moisture absorption compared to ABS, very high layer adhesion.
TPU	Engineering	Flexible very tough material.
PC	Engineering	High temperature resistance, high stiffness, and impact resistance.
PA6	Engineering	High tensile strength, abrasion and wear resistant.
PA12	Engineering	Lower moisture absorption than PA6, more durable and easy to print.
PPE-PS	Engineering	High thermal resistance, flame retardant.
PVDF	Engineering	Chemically inert, high thermal resistance, very high abrasion resistance, very tough
PPS	High performance	High chemical, thermal and moisture resistance, self-extinguishing, but requires annealing.
PSU	High performance	High strength, stiffness and impact strength, flame retarding, low creep, sterilization capable.
PES	High performance	High strength, stiffness and impact strength, flame retarding, low creep, sterilization capable.
PPSU	High performance	High strength, stiffness and impact strength, flame retarding, low creep, sterilization capable.
PEI	High performance	High strength, stiffness and impact strength, flame retarding, low creep, sterilization capable. Improved by annealing.
PEEK	Ultra performance	Self-extinguishing, High stiffness and strength, low creep, high reproducibility, low toxic gas emissions (compared to other high-performance materials).
PEKK	Ultra performance	Easier to print version of PEEK.
TPI	Ultra performance	Stronger than PEI at high temperature, frame retarding, lower cost than PEEK and PEKK.
PVA	Dissolving supports	Dissolvable supports

Table 3-2
Stated properties of filament materials by 3DXTECH

The high-performance materials have very similar descriptions, prices (45-55 USD per 250g), stiffness (2100-2650 MPa) and tensile strength (50-56). PEI has the advantage of improving mechanically after annealing and is therefore mechanically superior as a fixture compared to other high-performance materials. The ultra performance materials have significantly improved mechanical performance, wherein PEEK and PEKK are very similar, but PEKK is easier to print. TPI is stronger than PEI at high temperatures (above 170°C), yet this is not relevant for fixtures in machine environment, and TPI requires an extremely high extrusion temperature of 445°C and can therefore be discarded at a candidate.

The flexible filaments can also be discarded as they have poor stiffness, this including PP, OBC and TPU. Filaments like PPE-PS, PCTG, HIPS and PLA generally have worse mechanical performance than PETG, as PPE-PS is more focused on chemical resistance, PCTG on layer adhesion, HIPS on impact resistance and PLA with ease of print and environmental impact and are therefore discarded as candidates. ASA is a generally superior 3D printing material than ABS, wherein ABS is discarded.

The candidates for a new fixture material therefore include ASA, PEEK, PEKK, PEI, PVDF, PETG, PBT, PC, and different types of PA. These materials often exist with fibre reinforced varieties using carbon fibre (CF) and glass fibre (GF), in different concentrations and lengths. Some key metrics for evaluating these materials are the print settings (what are the maximum temperature requirements for printing), mechanical strength and stiffness (UTS and Youngs-modulus), the chemical resistance, water absorption and price as it can be seen in Table 3-2:

Material	Nozzle temp. [°C]	Bed temp. [°C]	UTS [MPa]	Modulus [MPa]	Water Absorption [w%]	Price [DKK/kg]
ASA	270	100	57	2010	0.3	269
PEEK	440	120	100	3720	0.1	5190
PAHT	300	80	86	3172	0.5-3	700
PVDF	260	90	51	2450	0.05	1752
PETG	250	90	43	1950	0.1	229
PBT	250	115	50	2200	0.2	0
PC	270	100	62	2410	0.2	300
POM	230	130	50	1870	0.5	560
PEI	380	120	84	3440	0.3	2050
PEKK	340	110	90	3000	0.1	5040

Table 3-3
Generalised properties for relevant 3D printed polymers [2]

PETG and PETG-CF were found to be the most successful FFF fixturing materials from Dansk AM Hub 3D Fix (P729). Both because the chemical resistance/dimensional stability, but also mechanical properties (i.e., it was found to be a stronger material compared to PLA, ABS, TPU and PBT). As a baseline, the fixturing material must be compatible or stronger than former PETG fixtures, while still being economical. PEEK has the highest UTS and Youngs modulus, however also the highest price, and printing temperature along with PEI and PEKK. This means that it would need a more expensive 400+ C 3D printer and might fail the project goal of an economically viable 3D-printed fixture. Another strong material is PA, which is a common 3d-printing material, wherein many 3D-printes are built to the PA printing temperature (250 to 300 C). There exists such a plethora of nylon variants, all with different mechanical strengths and print temperatures, that it is difficult to distinguish low grade from high grade (often called "plus" or "milled carbon filled" versions exist, which include additives which diminish mechanical performance). There should be some concern about the water absorption of the PA, since it is higher than most other filaments. However, there exist many different varieties of PA with lower water absorption.

At lower UTS, PC and PVDF could be considered, wherein PVDF has a low absorption level but is comparably expensive, where PC has the higher UTS of the two. ASA has a good price point, decent strength and stiffness, but is known to have a poor printability similar to ABS. POM is often used in milling as fixturing material, but 3D printed, has similar properties to PETG, but is extremely hard to 3D print. PBT was used in previous tests, and found to be non-suitable, but from its mechanical properties, it ought to have potential as a fixture (compared to PETG), it has been used at DAMRC for various 3D printed parts. It is to be noted when using most materials, they should be dried before printing, to optimise mechanical properties and printability.

3.4 3D-printing infrastructure

To use these filaments optimally, DAMRC's infrastructure 3D printing needs improvement. The closest DAMRC has to a PA 3D printer is the Wanhao Duplicator D9. However, it does not have a cabinet, which if often recommended and it frequently warps when printing. The Sindoh 3DWOX have a maximum of 250 °C, and can only use specific spool sizes, limiting the usability of filaments. They both have poor printing speed (mm/s) compared to other printers. Within the projects budget of 28000 DKK, these printers are considered the best candidates' anno 2023:

Brand	Printer	Build vol.	Nozzle temp.	Speed	Price	Stated filaments
Flashforge	Guider 3	300x250x340	320	250	26999	PLA, ABS, PC, PA, HIPS, ASA, PETG, PACF, PLACF, PETGCF, PETGGF
Flashforge	Creator 3 Pro	300x250x200	320	150	22499	PLA, ABS, PA, PC, PVA, HIPS, PETG, Wood, ASA, PACF
Creatbot	F430	400x300x300	420	55-180	29600	PLA, ABS, CF, Wood, Nylon, PC, PETG, HIPS, PP, TPU, Flexible, PVA, PEEK
Creatbot	F160	160x160x200	420	-	14508	PLA, ABS, CF, Wood, Nylon, PC, PETG, HIPS, PP, Flexible, PEEK
Creality3D	Sermoon D3	290x220x300	300	250	19350	PLA, PETG, PET, TPU, PVA, HIPS, PA, ABS, ASA, PC, PCABS, PLACF, PACF, PETCF, Metal
Raise3D	Pro2	305x305x300	300	150	24000	PLA, ABS, HIPS, PC, TPU, NYLON, TPE, FLEX, PETG, Metal PLA, Wood PLA, CF
Bambu Lab	X1-Carbon	256x256x256	300	500	11700	PLA, PETG, TPU, ABS, ASA, PVA, PA, PC, CF, GF
Wanhao	Duplicator D9	300x300x400	300	70	2647	PLA, PVA, PEVA, Nylon
Sindoh	3DWOX 2X	228x200x300	250	40	23820	PLA, ABS, Flexible, PVA
Sindoh	3DWOX1	210x200x195	250	50	8640	PLA, ABS, ASA, PETG

Table 3-4
Capabilities of most relevant 3D printers for the project [2]

The highest temperature printers are the Creatbot F160 and F430, wherein F160 is the smallest & cheapest high temperature 3D printer. However, the 420°C temperature may only be in as of today specialised and expensive PEEK and PEKK. For all other materials ~300°C is adequate.

The build volume for the 3D printers is between 160x160x200 (F160) and 400x300x300 (F430). Bigger build volume makes the printer more versatile when printing and allows for multiple parts printed at the same time. Potentially saving time and cost. The speed in mm/s, is the maximum linear traversal speed capable of the printer. Faster traversal speed results in shorter print time. Though not for all prints, as the material extrusion rate, does impact the mechanical properties. Therefore, it's not a big factor in the evaluation of the printers for this project, as long as it's above 30-40 mm/s.

Many recommended the Bambu Lab X1-Carbon combo. As it has the newest technology, in 3D printing. While also having the highest traversal speed, LIDAR bed levelling, AI monitoring, and multi filament capability. It has the best price point, decent build volume, and a 300 ºC stainless steel or hardened steel nozzle. The savings allow for more versatility for consumables and 3D scanners.

To use the printers, there is often a recommended slicing software, either open source or brand specific. The most common slicer is Cura, but brands like Prusa, Creatbot or Bambulab also have their own slicer. Slicers are used to generate g-code and adjust the print settings (further explanation in section 3.7.2).

3.5 3D-scanning infrastructure

From Dansk AM Hub 3D Fix (P729), it was found that some fixtures (especially those for castings) DAMRC had to model correctly. From this it was found that a 3d-scannner could be a useful tool for decreasing the lead-time. To judge the possible 3d-scanners, it must be within the project budget of 35000 DKK, while also making accurate scans, and being reasonably versatile (therefore generally a handheld scanner would be preferred):

Brand	Scanner	Price	Speed	Accuracy	Part size
Unit	-	DKK	-	mm	M
Shining3D	Einstar	7300	14 FPS	0.1	>0.05
Shining3D	Einscan H	34000	-	0.05	M-L
Shining3D	Einscan Pro 2X	42173	30 FPS	0.045	-
Shining3D	Einscan HX	96000	55 FPS	0.04	-
peel 3d	Peel 3	55242	80s/m2	0.1	0.1-3.0
Artec	Artec Space Spider	203490	7.5 FPS	0.05	S
Handyscan	Handyscan 3D	150000	1300000 mea/s	0.025	0.05-4
Scan Dimension	Sol Pro	14900	15 min	0.05	0.02-0.17
Scan Dimension	Sol	6560	20 min	0.1	0.02-0.17
Revopoint	Revopoint POP3	4600	12-18 FPS	0.1	>0.02
Revopoint	Revopoint RANGE	5390	12-18 FPS	0.3	-

Table 3-5
Metrics for 3D scanners [2]

The Einscan series, generally has the most competitive price for high to medium-end scanners. But products like the Artec Space Spider have a unique selling point of being very accurate with smaller objects but is outside the budget of this project. Handyscan and Peel are also outside the budget but would be used as a one size fits all fast handheld 3D scanner. The Einscan H is within the budget constraint, but is generally made for medium-large scanning, and is generally not advertised as a reverse engineering tool (but was recommended by 3Deksperten). The Einscan Pro 2X is more appropriate for its specifications but does exceed the budget. The Einstar is the cheapest 3D scanner by Shining3D, but also the slowest and more consumer/hobby oriented. The Sol and Sol Pro are stationary 3d- scanners, which are much cheaper, but also less versatile. But considering the build limitations of the 3d-printers, it does not make sense to have a 3d-scan of something bigger than ~300mm. Unless the user is expected to make multiple parts for one fixture, which is outside the scope of this project.

Revopoint is a new 3D scanner vendor, which has an impressive price point. They have been used in projects to 3D print products or make 3D models in games. But the nearest engineering related industry they have worked with is car design. They have 3 “sizes” of products, the MINI for small scans, the POP for medium scans and the RANGE for bigger scans. Their speed is comparable to the Einstar at between 12-18 FPS.

It should also be considered which software/license can be used with the scanner. The Einstar/Einscan series is made by Shining3D, uses the Geomagic Essentials data processor, and recommends using their Solid Edge edition for reverse engineering. Both Sol and Revopoint have free software for their products. Where Revopoint offers Revo Scan 5 (data processor and post processor), and Revo Assistant (for controlling Dial-axis turn table). SOL offers SOL Creator (data processor) and SOL Viewer (viewer and post processor).

At Herningsholm, the Einscan series was demonstrated, using the Shining3D software. Wherein it was clear that it has good quality scans (beyond the draft quality of the cheaper models), that is competitive with the high-end scanners. It also revealed how much processing power is needed to run a 3D scanner, and the hardware costs should also be taken into consideration.

3.6 3D printing and scanning services

An alternative could also be 3d-scanning and printing services. Which also provide some expertise, if DAMRC were to invest in this equipment, which challenges does it present:

Location	Company	Scanning	Printing	Scanner experience	Recommendations
Aarhus	3Dprintaarhus	X	X	Artec	Closed FFF printer, oven/drying chamber
Snedsted	Kvejborg	X		Handyscan	
Nørresundby	3deksperten	X	X	Einscan	Sermoon d3 and Einscan h2
Allerød	Global Scanning	X			
Birkerød	Flashforge	X	X	SOL	Creator 3 Pro, Creator 4, High temp is expensive.
Billund	Davinci print service		X		
Malmø	3Dprima	X	X		
Herning	Herningsholm	X	X	Einscan	Showed the Einscan Combo
Herning	3Dverkstan	X	X	Einscan	Einscan Pro 2X is appropriate for the budget

Table 3-6
Possible expert contacts regarding 3D print and 3D scanning [2]

3Dprintaarhus generally scan for the price of 855 DKK, and can scan produce larger than 50 mm, with an accuracy of 0.1 mm. 3deksperten generally costs 500 DKK and have multiple 3dscanners: Einscan Pro 2X plus, Einscan HX Pro and a dental scanner for small objects. Kvejborg uses the HandySCAN BLACK and HandySCAN BLACK Elite. The other 3d-scanner companies are resellers. Some of these companies have also given general advice on what products they would recommend, or what they use, as can be seen in table 3-5.

3.7 3D-printing parameters

3.7.1 Failure Characterisation

The FFF process involves a molten filament being fused to other rasters in the print. Wherein the new raster can fuse with the lower z layer (inter layer) or the neighbouring XY-rasters (intra layer). The new raster is heated from the nozzle, and at lower layers, the matrix is heated from the bottom layer, thru the heated bed. As the nozzle extrudes the new raster, it travels at some print velocity, parallel to the previous raster. The new raster cools due to heat convection (often helped by a fan), heat conduction through the bonds between the rasters and heat radiation. The heat diffuses through conduction with the neighbouring rasters, making the material expand locally. Depending on the geometry and speed of the print and distance from the heat bed will determine the final/ambient temperature of the raster. The thermal process (see figure 3-6) repeats, as new rasters are laid near the old raster, causing cyclical thermal expansion and contraction throughout the material.

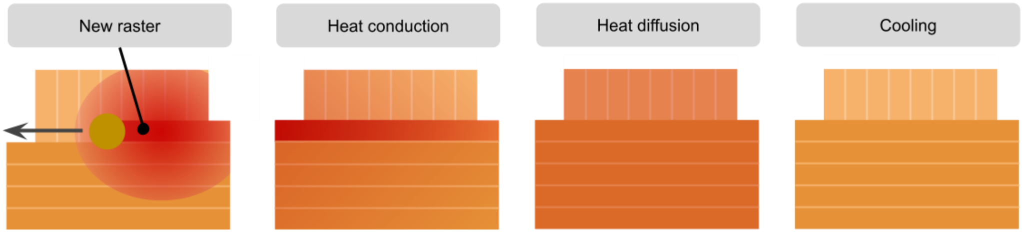


Figure 3.7-1
Heating and cooling cycle in a section of FFF material

When the printing process has high heat conduction and low convection cooling, it results in internal stresses and strong bonding of the rasters and is due to over extrusion of the raster. For a printing process with low heat conduction and high convection, there are few internal stresses and weak bonding, and is due to under extrusion. Wherein the optimal FFF printing process can be found between these states, depending on the required mechanical properties.

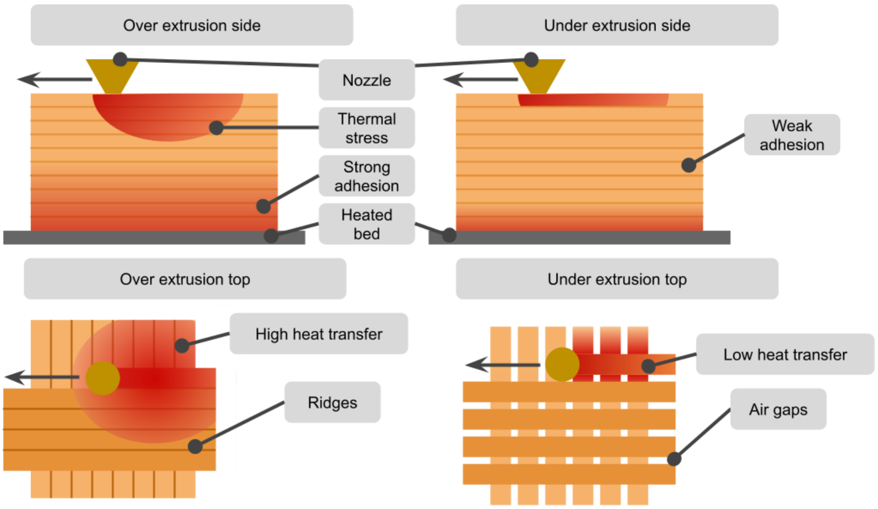


Figure 3.7-2
Diagram of the heat diffusion in over and under extruded FFF

As described by figure 3-7, the defects found in these processes are very different. Over extrusion can be identified by the ridges between rasters, and under extrusion can be identified by air gaps. A microscopy of FFF ABS material can be seen on figure 3-8:

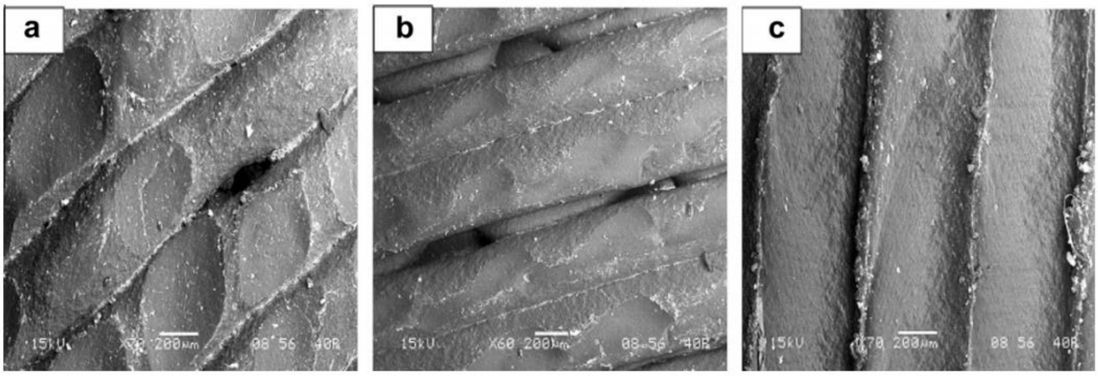


Figure 3.7-3
a. crack between rasters, b. air gaps, c. ridges [4]

Cracks may form either due to the internal stresses in over extrusion, or poor bonding between rasters in under extrusion. On figure 3-8 a, a micro crack can be seen between two lightly under extruded rasters. On figure 3-9 a macro crack in FFF PETG can be seen. It starts at the bottom layer of the print and travels vertically for several layers (A), then taking a 45 degree turn for another ~10 layers, then traveling parallel to the xy-plane.

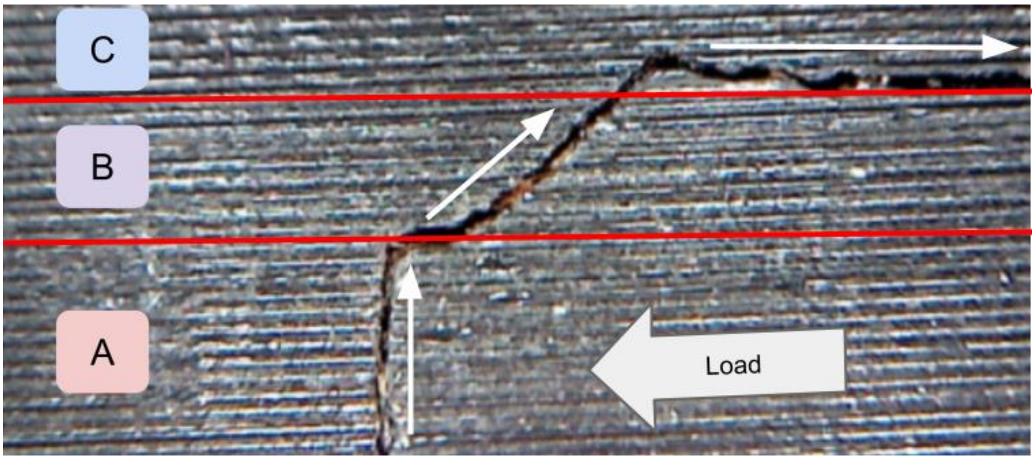


Figure 3.7-4
Crack found in FFF PETG fixture

The fixture was mounted at the bottom using pins (same height as top of A). Which were loaded repeatedly in the x-direction. Resulting in the z-direction surface crack, which the lead to xz-staircase cracking in the B section (the z-direction crack is internally a xy-staircase crack, which is a stronger direction than xz), since the cross-sectional area in an under extruded material is less between the rasters, due to the air gaps (see figure 3-10).

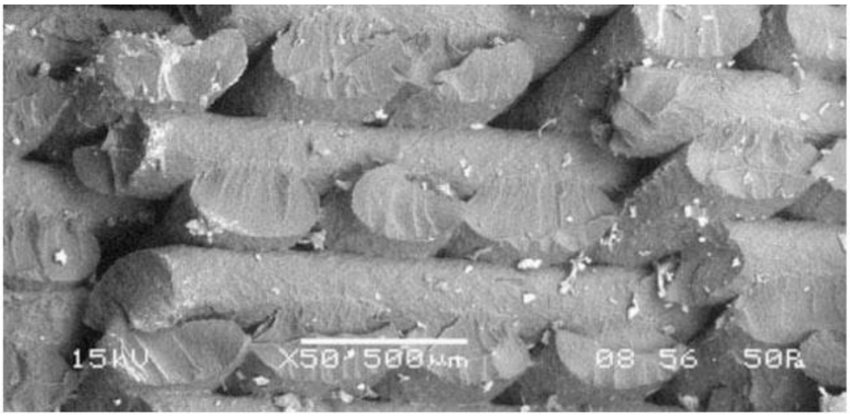


Figure 3.7-5
XY-staircase crack of ABS 3D printed material [6]

As the crack travels up section C, the moment arm from the load increases. Which at section C results in intra layer cracking. The intra layer crack is found at the bonded surfaces of two layers, which is weaker in under extruded materials. Cyclic loading, expands the crack, leading to debonding, which puts further stress on the neighbouring rasters. The sharp corner at the bonding surfaces develops further cracking. Eventually the layers separate (see figure 3-11 and 3-12).

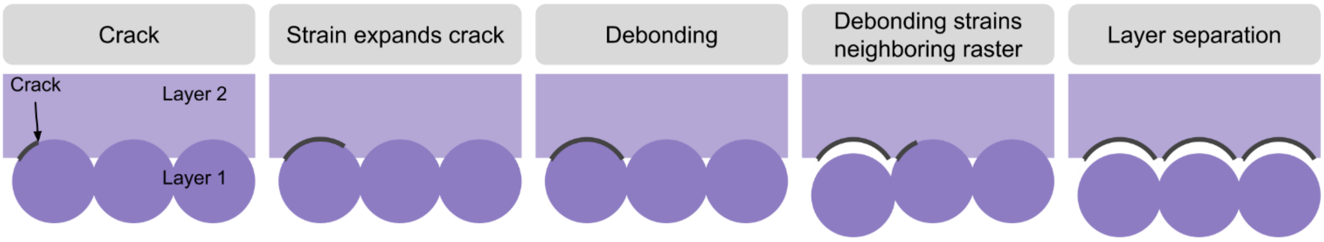


Figure 3.7-6
Failure formation in 3D print. Representing rasters at 90 degrees and stress/strain cycles resulting in layer separation.

The separated layers are weaker and more ductile, due to the lack of support from the surrounding material. In compression, this leads to layers buckling, as seen in figure 3-13:

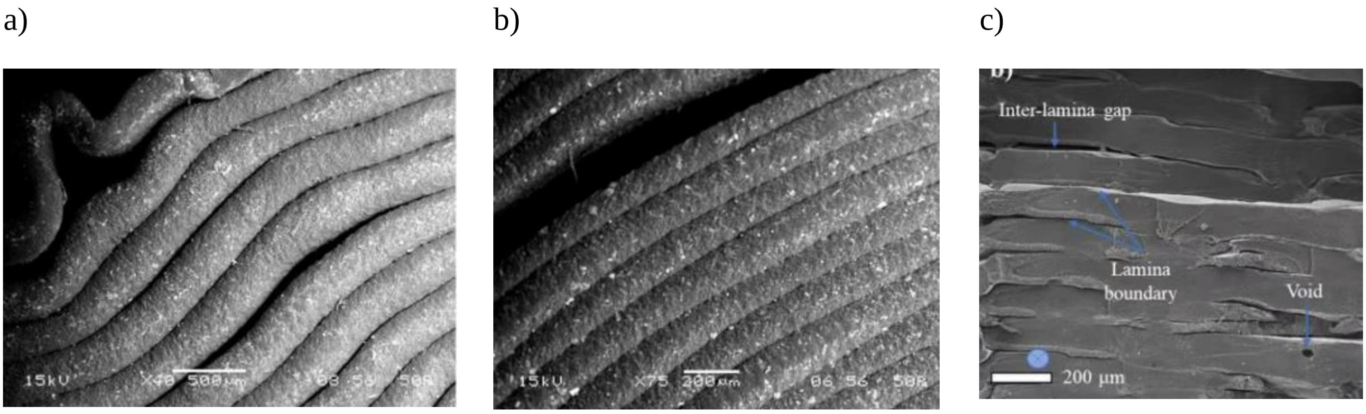


Figure 3.7-7
a. buckling raster, b. debonded surfaces [4], c. void, inter-layer gap [21]

These failure modes are more common from under extruded FFF materials. Since they act more as bonded fibres, wherein the bonds are much weaker than the fibre. Over extruded FFF has a more homogeneous structure and stronger bonds. But suffers from higher heat input creating internal stresses from the repeated thermal expansion and contraction [4] [6] [23]. Resulting in a warped geometry and a porous material, not seen in under extrusion. These stresses also lead to crazing, which forms cracks with repeated loading [20]. The general characteristics are summed up in table 3-6:

Characteristic	Under extrusion	Over extrusion
Heat	Low	High
Convection	High	Low
Conduction	Low	High
Layer thickness	High	Low
Z-Orientation 1	Low	High
Visible defects	Air gaps, intralayer cracks	Warping, pores
Surface	Visible rasters	Ridges, homogenous

Table 3-7
Failure characteristic of FFF material

In a 2021 study of PEEK, they found that gaps and voids were more common in the top and bottom layers of the FFF print. This was attributed to the uneven heating of the part [21]. Analysis of figure 3-14 shows that the distribution of defects in not homogeneous and depends on the printing strategy. Therefore, the mechanical properties relation to the printing settings will be explored further, to find optimal FFF printing settings.

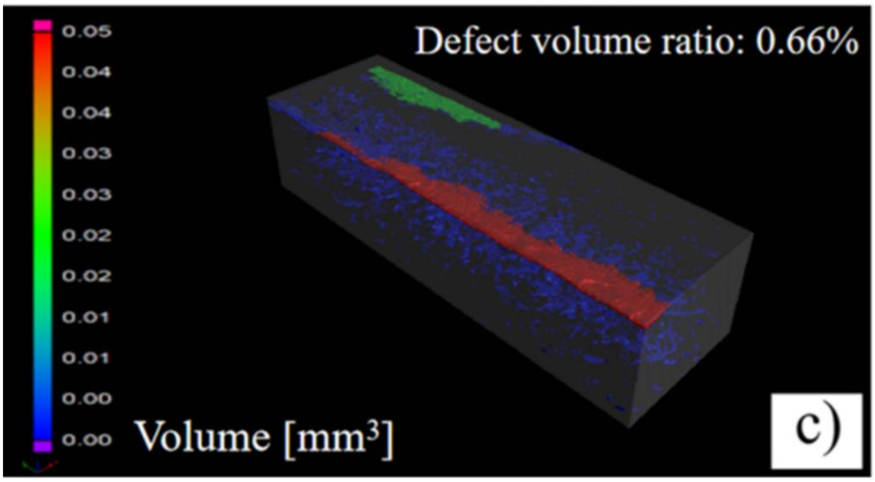


Figure 3.7-8
Defect volume from CT scan (45-45 raster) [21]

3.7.2 Printing Parameters

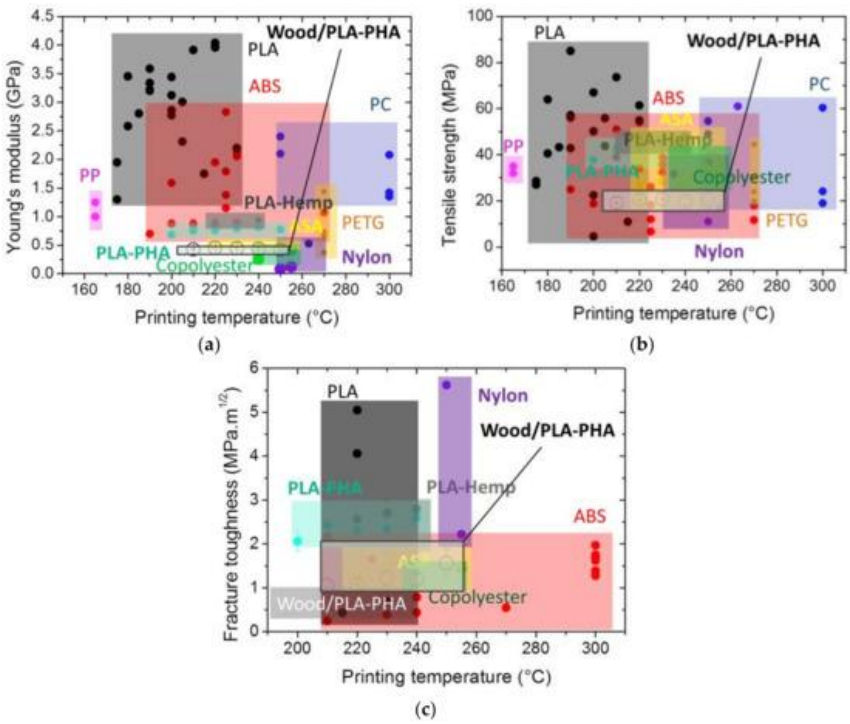


Figure 3.7-9
Relation between nozzle temperature and mechanical properties of 3D printed filaments [15]

3D printed material properties depend on the printing parameters, as seen on figure 3-7, different nozzle temperatures have different effects depending on the material. The key metrics used in most studies is the Youngs modulus and UTS. To have a strong fixture, the print strategy must be considered, to optimize the strength of the material.

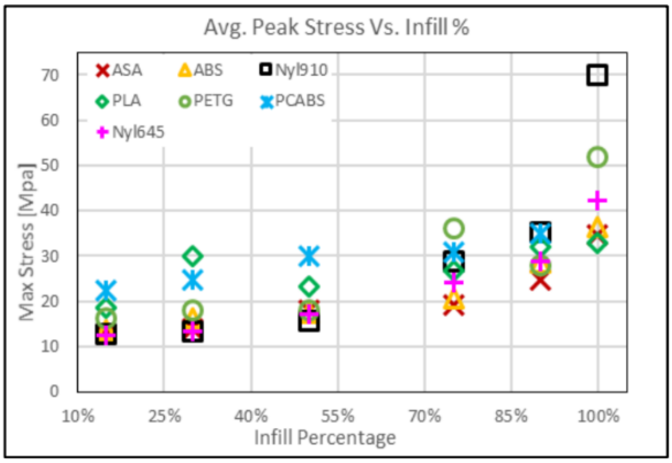


Figure 3.7-10
Average tensile strengths for different materials, as varies infill densities [3]

As seen on figure 3-9, the infill density has a great effect of the strength of the material. Generally, materials get exponentially higher UTS, as the infill density increases. While also increasing the Youngs modulus. [3]

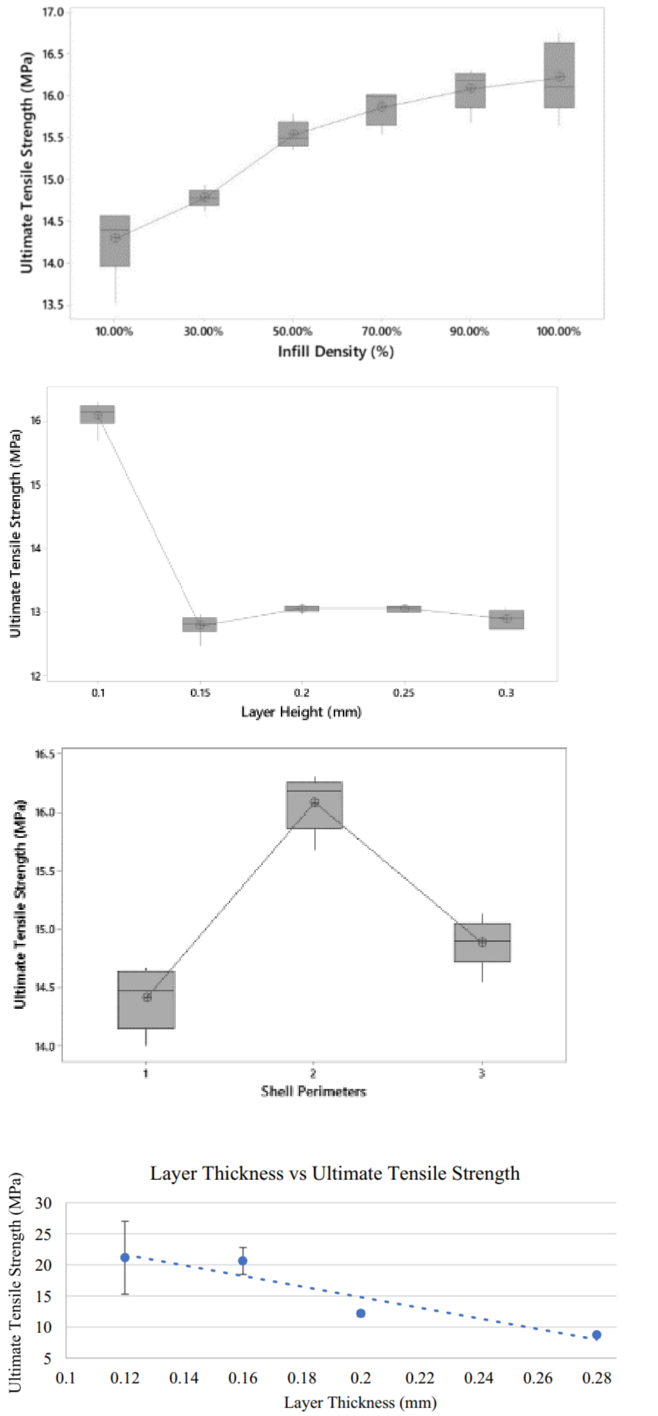


Figure 3.7-11
PCL tensile strength at various Infill density, layer height and shell perimeters [7], PLA tensile strength at different layer heights [35]

A study of PCL also tested layer height and number of perimeters as determinants of strength in the final product. Where they again observed that higher infill density, leads to higher UTS. Whereas layer height of 0.1 mm was found to be best (though they did not test layer heights between 0.1 mm and 0.15 mm). And two perimeters were found to be the strongest configuration. [7]

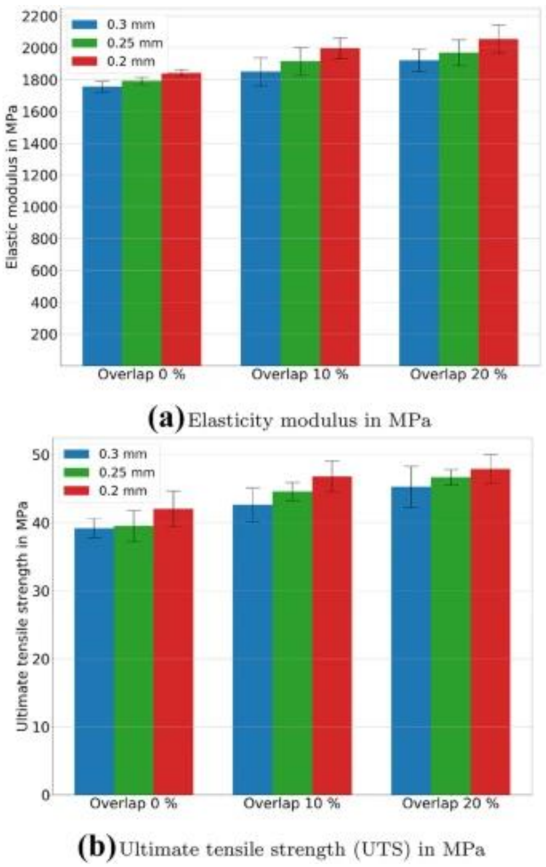


Figure 3.7-13
PETG tensile strength and Youngs modulus at varies layer heights and raster overlap [14]

Similarly, a study using different print layer height for PETG, found that 0.2 mm (the smallest layer height tested) had the highest stiffness and UTS. They only considered the overlap between the rasters, and found a positive influence on mechanical properties, at least till 20% overlap. [14]

For compressive strength, infill pattern was found to be a factor in the products strength. Examining a PACF product, the authors found that the triangular infill pattern was the strongest pattern in compression [5]. In a tensile and bending test, triangular infill also had the highest strength, but honeycomb pattern had the highest weighted strength [16].

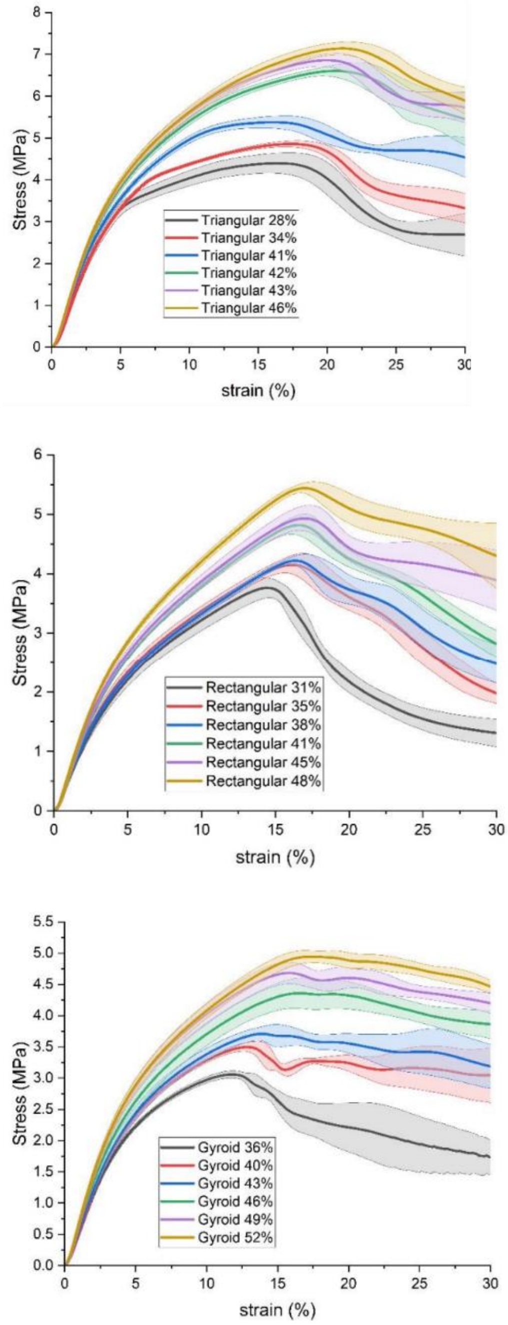


Figure 3.7-12
Stress-strain curves for different infill pattern at varies infill densities [5]

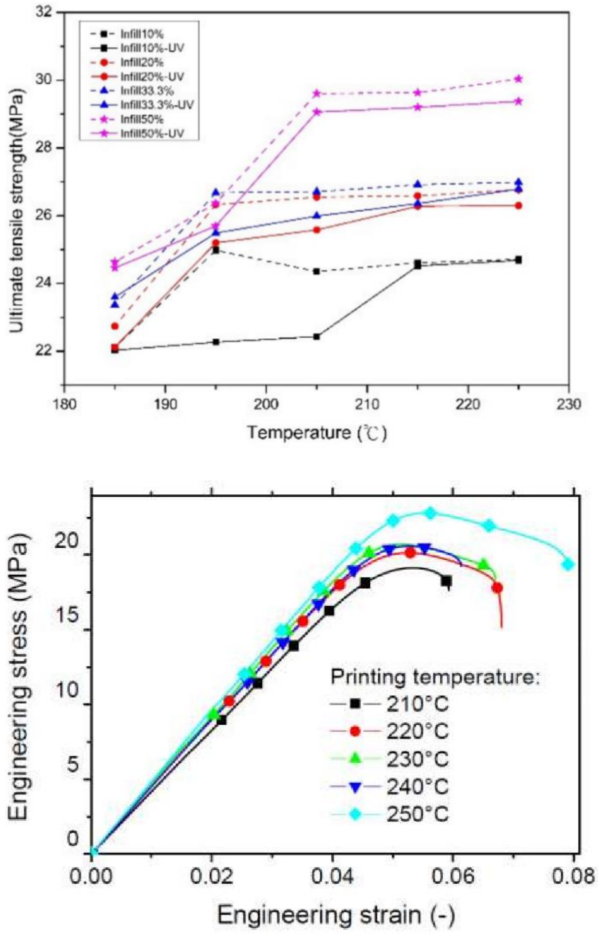


Figure 3.7-14
Nozzle printing temperature, and resulting UTS for PLA 3D printing [8]. Stress-strain curve of wood-PLA with different printing temperatures [15].

For PETG the strength and stiffness are proportional to the nozzle/printing temperature, as can be seen on figure 3-15 [15]. Likewise for PLA, however the figure also shows the strength gain is minor, after a certain temperature [8]. [33] Found that the Yield strength, tensile strength and elastic modulus plateaus after a certain temperature. For PLA that was around 210°C in one study, and 185°C in another.

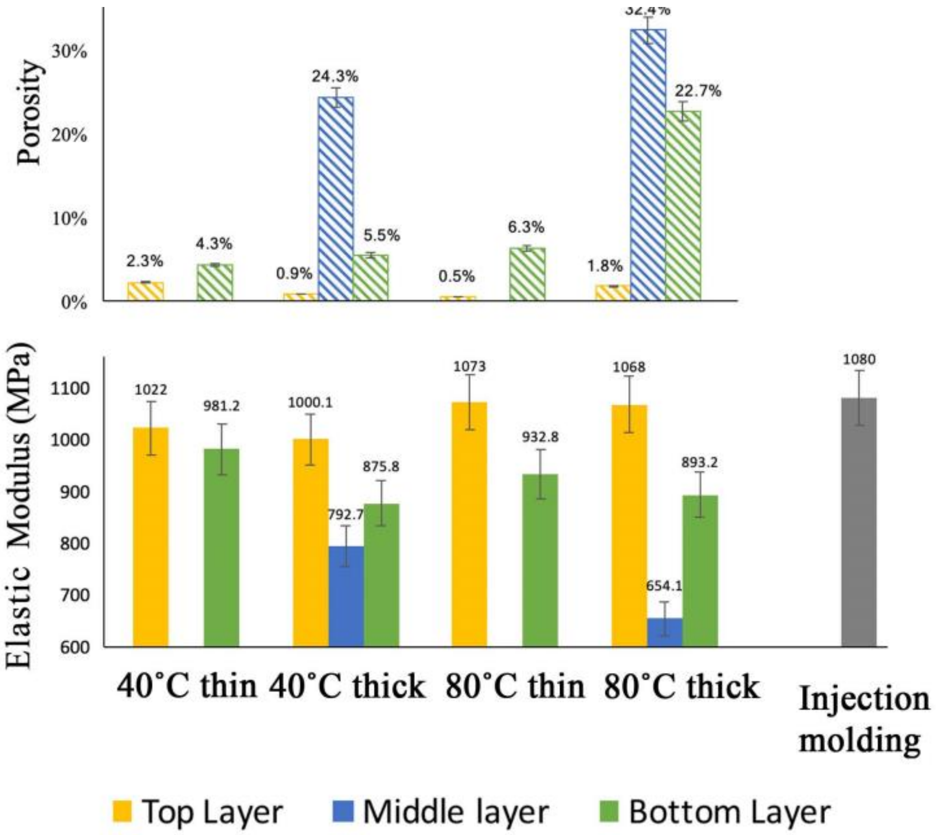


Figure 3.7-15
Porosity and elastic modulus of 40 and 80 C heated PLA, printed in thick (24 layers) and thin (4 layers) samples [22].

The effect on the heat input can also be seen in 3-14, where the porosity is higher at the bottom compared to the top layers when heat treating the specimen at 40C to 80C. Wherein this is exaggerated even further when the temperature is increased. The internal middle layers were shown to have even higher porosity, resulting in a more ductile material [22].

3.7.3 Composite Fibre Filaments

Table 3 – ASTM D 790 flexural test results.

Flexural test parameters	Nylon + Carbon Fiber Specimens			Nylon + Glass Fiber Specimens		
	0° degree	45° degree	90° degree	0° degree	45° degree	90° degree
Flexure stress at Maximum Flexural load (MPa)	50.1	23.7	29.9	145.8	84.39	20.8
Young's Modulus (MPa)	3914	1156	1638	28,379	13,084	915.9
Flexure strain at Maximum Flexural load (mm/mm)	0.047	0.042	0.040	0.011	0.016	0.045
Flexural stress at Break (MPa)	2.2	23.0	28.7	26.7	44.2	20.4

Figure 3.7-16
Fiber direction effect on mechanical properties for 3D printed carbon and glass fibre filled nylon [1].

As can be seen on figure 3-15, the strength and Youngs modulus of fibre reinforced filament, is highly dependent on the orientation of the load. A load parallel to the fibre (0 deg), has the highest strength, whereas at other angles the interaction between matrix and fibre becomes more complicated, and weaker.

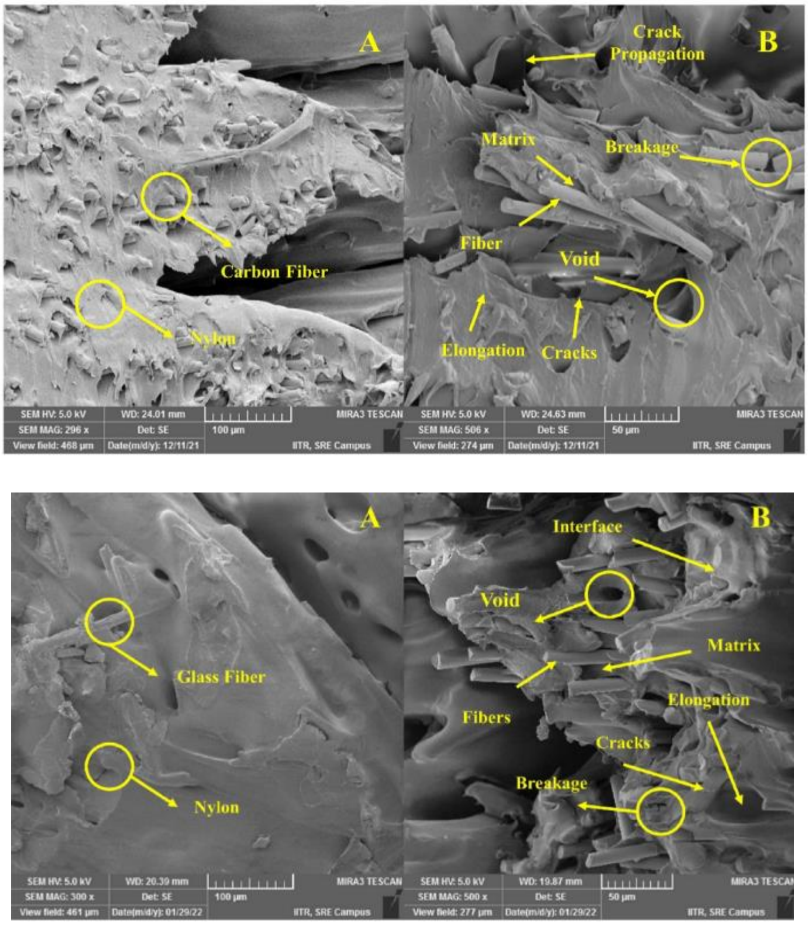


Figure 3.7-17
Microscopy of PA-CF and PA-GF before (A) and after (B) failure [1]

From the microscopy, it is observed that the distribution of fibres is not homogeneous. Since the fibres are generally along the print direction, the composite material is even more anisotropic than normal 3D printed material. The same failure conditions as in 3.5.1 can be applied. However, a fibre with strong adhesion to the matrix, results in a more dimensionally stabile material (less buckling). But a fibre may have bad adhesion, due to porosity and weak bonding (delamination). For PA+CF and PA+GF, it was concluded that fibres had a moderate improvement in mechanical strength. [1]

Material	Nozzle temp.	Bed temp.	UTS	Modulus	Water absorption	Price/kg
PAHT-CF	300	80	125 (+39)	7808 (+4636)	-	340-1500
PAHT-GF	300	80	88 (+2)	4833 (+1661)	0.2	770
PEEK-CF	440	120	80 (-20)	3720 (+0)	0.06	-
PET-CF	320	80	87 (+44)	6025 (+4075)	-	300+

Table 3-8
General material properties of fibre reinforced 3D printed materials, including the relative gain in tensile strength and stiffness.

Table 3-7 shows that fibres generally improve the mechanical properties, though not for PEEK. PET+CF has been tested before in a fixture and can therefore a point of reference if PA composites are to be tested. There is variability in both mechanical properties and price, since the type of PA and amount of fibre is different depending on the product.

3.7.4 Recommended Print Settings

To have parody between the materials, they ought to be printed with the same structural print setting. This may lead to non-optimal printing in some cases. Generally, near 100% infill is ideal for strength. In the Dansk AM Hub 3D Fix (P729) absorption test, the percentage weight gain was related to the infill. Wherein 100%, 95% and 20% infill were tested. For parody with real fixtures, the absorption test ought to also use 95% infill.

Layer height could either be low to maximize adhesion, or high to minimize distortion. Layer heights should be tested further, but the layer height of 0.1 mm from the PCL study was the strongest for that material and is therefore expected to be the same for other materials. By the same study the number of perimeters should be set to 2.

For a non 100% infill part, the triangular infill pattern is strongest for compressive strength. For a 100% filled part, it is important that the raster angle is as high as possible (by default most slicers use a 90-degree raster angle).

Fibres can greatly improve the material strength and stiffness. When printing with fibre composites, use a nozzle with high abrasion resistance. Consider the orientation of the fibres, as they will mostly align with the print direction, and will be strongest in that direction. It is important that the fibre and matrix have good adhesion, therefore the use of an appropriate temperature is required.

The following materials have been chosen for their equivalent or superior mechanical properties to PETG. Wherein, the material vendors with datasheets have been chosen for quality assurance, where they have the temperature settings recommended, to their stated strength properties:

Material	Vendor	Tensile strength/ Flexural strength	Tensile modulus/ Flexural modulus	Nozzle/bed temperature	Price per kg
Unit	-	MPa / MPa	MPa / MPa	C / C	DKK
PETG (comparison)	Material4print	53 / -	- / 2150	225-255 / 60-80	170
ASA	Material4print	50 / -	- / 2300	230-250 / 90-110	220
PA6	Tarfuse	55 / 68	3500 / 3000	270-300 / 30-110	380
PA6GF	3DXTECH	62.8 / 72	4261 / 3600	265 / 70	750
PA12	Handtmann	xy = 40, z = 25 / 53	1293 / 1307	235-255 / 60-110	630
PA12CF	Handtmann	xy = 56, z = 15 / 89	4632 / 3720	245-265 / 60-110	790
PC	Polymaker	xy = 62.7, z = 41.9 / 100.4	xy = 2307, z = 2260 / 2247	255 / 100	240
POM	Tarfuse	50 / -	1870 / -	230 / 130	560
PVDF	add:north	58 / 120	387 / 3155	240-260 / 50-60	1250

Table 3-9
Material vendors stated material properties. [23]

3.8 Selection

Based on previous tests of 3D printed fixtures, it is expected that a better fixture material filament, should possess better material properties than PETG. To judge materials, the general properties of filaments: nozzle temperature, bed temperature, UTS, Youngs modulus, water absorption and price, were used.

The relevant materials found were: ASA, PEEK, PEKK, PA, PVDF, PBT, HIPS, PC, POM, PEI, and fibre composites of these materials may also be considered. From these, PEEK, PEKK and PEI were not economically viable, as they have a high material cost, and a need for very high nozzle temperature. PBT has failed in previous use cases. And HIPS has a lower UTS than PETG and would therefore be expected to also fail when used as a fixture. The selected test materials are therefore: ASA, PA, PVDF, PC, POM. Wherein PA has two main variants: PA6 and PA12. PA12 is more desirable, since it has lower water absorption. Though combined with fiber reinforcement, PA6 is also viable.

The current 3D printers at DAMRC are not designed for printing with these filaments. Since they require high nozzle and bed temperature and are more abrasive than normal consumer filaments. The Creatbot 3D printers do have the best high temperature capabilities. But the F430, does excide the budget, and the F160 has a comparatively small build volume. All the printers offer live print monitoring, automatic bed levelling and cabinets with HEPA filters. BambuLab may have the second smallest build volume, but it offers many advantages, since it is the newest of these products. It is cheaper, faster, integrates automatic filament change (AMS), AI first layer and spaghetti detection. Therefore, it will be used in this project.

3D scanners exist in many price ranges. The high-end scanners including peel 3d, Artec and Handyscan, are not within the budget of these project. Consumer/prosumer scanners including Revopoint, Scan Dimension and the Einstar, have decent capabilities, however lack in precision (especially free hand scanning), size versatility and speed. Therefore, the Einscan series is the primary candidate for a 3D scanner. The Einscan H, is within the budget constraints, but is generally recommended for medium-large objects. Whereas this project concerns small-medium objects. The H series would also have problems scanning holes/cavities in objects. By considering the savings in the 3D printer, the Einscan Pro 2X is viable economically. And is recommended for its versatility and suitability for small-medium objects.

3.9 Post-treatment for enhanced mechanical properties

Thermal treatment of 3d printed polymers have been shown to increase strength. N. Jayanth [29] have compared annealing of PLA at three temperatures with different treatment durations.

Batches of Annealing, their corresponding temperatures and times.

Annealing Temperature (°C)	Time (min)	Part Name
90	60	1A
	120	1B
	240	1C
100	60	2A
	120	2B
	240	2C
120	60	3A
	120	3B
	240	3C
0	–	1

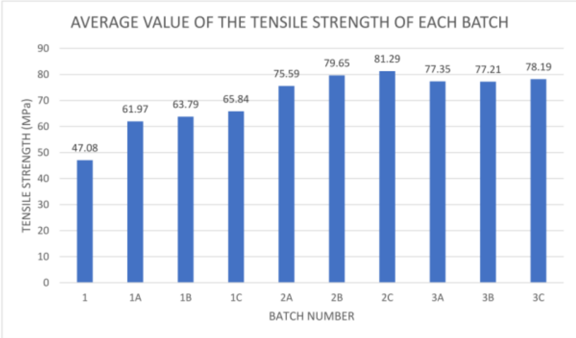


Figure 3.9-1
Thermal treatment parameters and results of PLA, N. Jayanth [29]

All treatments increased the tensile strength, with increased effect of longer treatments durations. The biggest increase of strength was seen at 100degC, which seems to imply there may be a sweet-spot, where both too high and too low temperature is suboptimal.

The PLA test specimens were designed with flat geometries, thereby minimizing the loads during the annealing process. However, concerns arise if specimens are subject to stress during the treatment. It's uncertain if this treatment is fit for parts that can't be positioned without load from its own weight.

Amza et al. [30] have made post thermal treatments of PETG. The samples were packed in glass powder, with allows higher annealing temperatures, without distortion. They treatment temperature was 220degC for 15minutes (Full treatment) and 5minuts (Partial treatment).

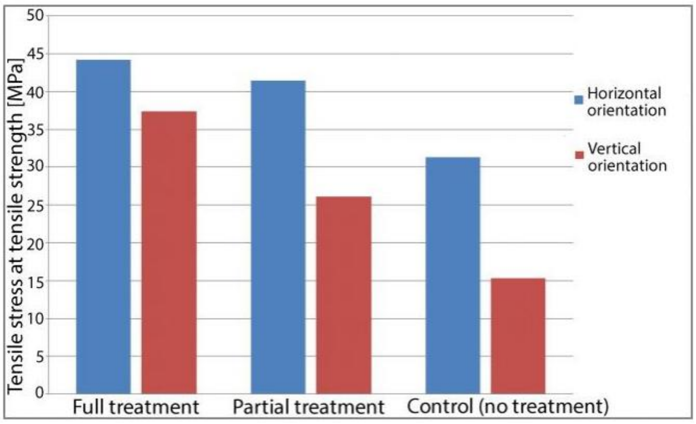


Figure 3.9-2
Thermal treatment results of PETG, Amza [30]

Both treatment durations were seen to influence strength, especially on the vertical oriented specimens, where the pulling was normal to the printing-layers. The material thus came closer to having isotropic strength properties. The test naming of “Full treatment” is up for debate as both this paper [30] and N. Jayanth [29], did not reach a plateau regarding treatment durations.

Wonseok Seok [31] have tested various annealing temperatures of ABS filament reinforced with carbon fibres. In this study, there seems to be a parting with the idea of longer and hotter treatment being always better. The conclusion on this study is the coolest annealing of 105 degC, with 4 hours of annealing makes the tests strongest.

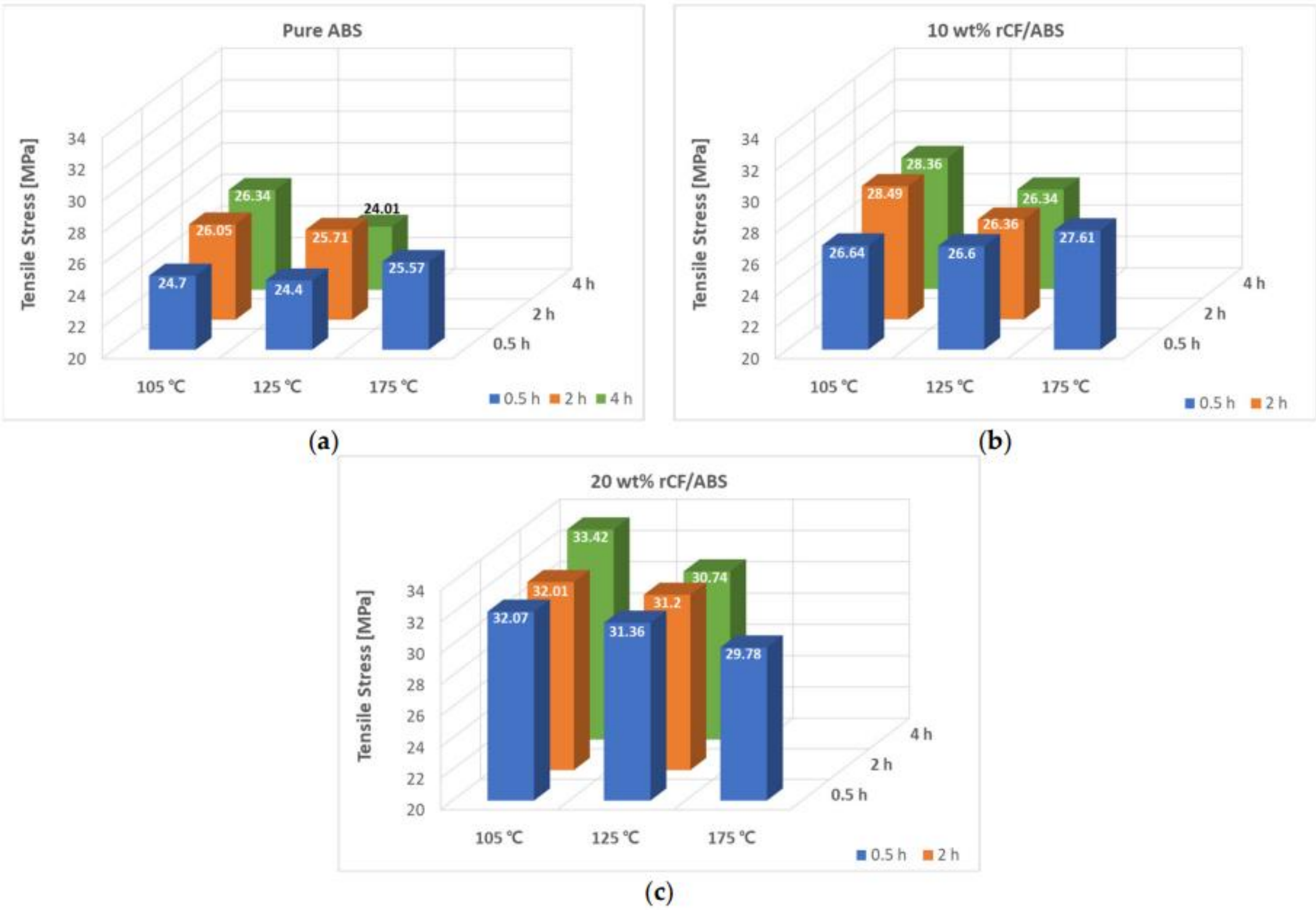


Figure 3.9-3
Thermal treatment of ABS(a) ABS-CF10(b) and ABS-CF20(c), Wonseok Seok [31]

To ensure repeatability there was made three samples for each annealing condition [31]. The deviations of the tests are not stated, nor has the repeatability been commented. It’s therefore unclear how much certainty there can be expected from the studies of specific annealing parameters, compared to how much arbitration is involved.

The annealing treatment has a healing effect on the voids caused by the FFF process [31]. And the voids in the in the filament caused by the reinforced CF is also reduced. It's unclear how much of an impact this have on commercial CFRF, as Wonseok [31] produced their own filament.

The study also tested the dimensional change of the annealing. Higher temperatures had the biggest impact on dimensional change, where it is noticeable that the duration of the low temperature of 105degC had only little change as the duration increased. The heat-deflection resistance was seen to always be better with increasing CF content.

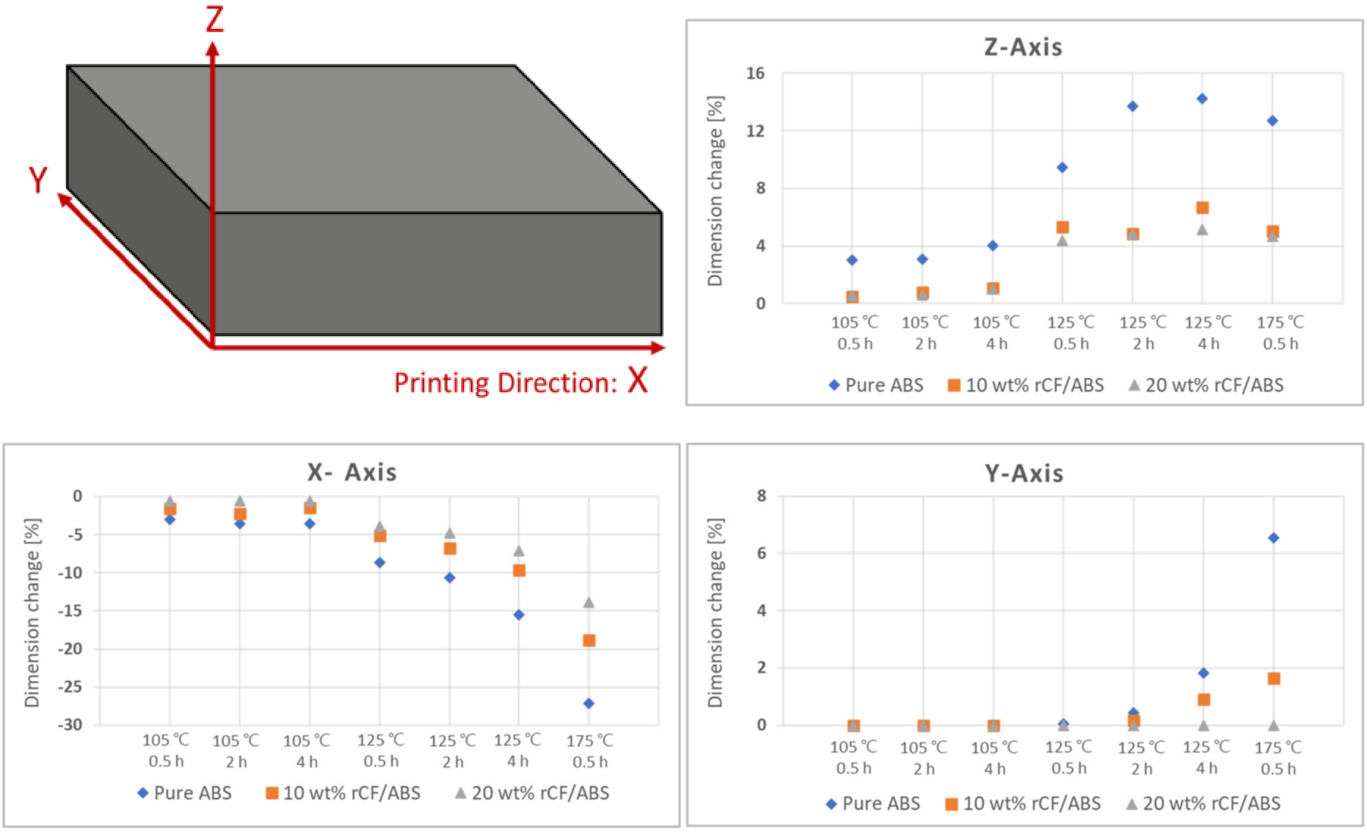


Figure 3.9-4
Dimensional change from annealing, Wonseok Seok [31]

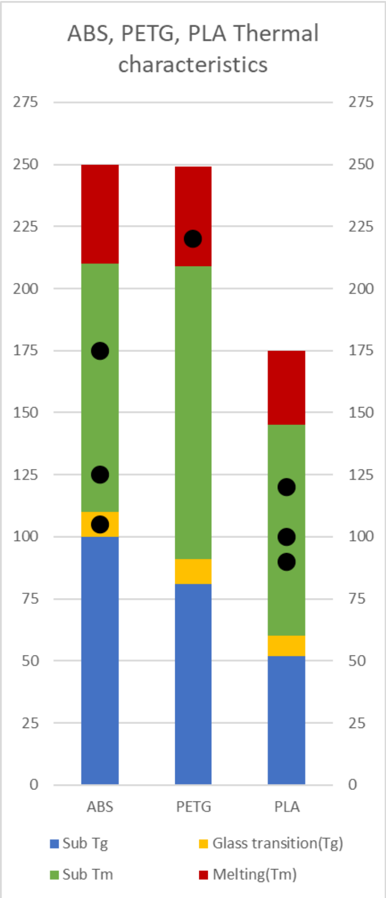


Figure 3.9-5
Annealing temperature in tests

The strength enhancing mechanism of post thermal treatment is likely due to increased fusion between layers and parallel rasters, and a reduction of voids. It may also be partly contributed to relief of residual stresses, so prestressed areas do not cause failure. These mechanisms are expected to be found in most FFF printed materials. The requirement to pack the parts in powder, will likely vary depending on material and geometry, and especially how aggressive the treatment parameters are. This makes the simplest treatment use low temperature for a long duration if it mitigates the need for powder packing.

4 Hypothesis

Using affordable 3D scanning to make 3D printed fixtures, Danish machining industry would be improved in terms of lead time and cost. Using high end / engineering grade filaments, will allow for fixtures to last for longer production runs, than previous materials. Leading to cost savings compared to traditional fixture methods, and methods using commercial grade filament.

5 Success Criteria

At least 2 filaments with better performance as a machining fixture than previously tested materials, wherein the best material was PETG and PETG-CF. Which would be less likely to fracture or deform when tightened as a fixture, and last for longer production runs without failure. Then by using 3D scanning and 3D printing together, the lead time and cost of custom fixtures would be significantly reduced, improving the productivity of machining workshops.

3 cases showing the capabilities of 3D printed fixtures must be carried out. 2 of these cases ought to be at relevant companies with fixturing issues or potential improvements from this process. These ought to show the benefit of 3D scanning too. One case will be made at DAMRC, as a non-confidential demonstration for others.

6 Project Scope

This project seeks to find affordable and easily accessible ways to make fixtures and is therefore only considering FFF/FFF 3D printers, as they are already commonly in use at machining workshops, and generally more affordable than other types of printers. This also includes materials being affordable, therefore a normal fixture must not excide 1000 DKK in material cost.

The project will explore 2 company cases, with previous cases on 3D printed fixtures. To get feedback on the expectation and experience of the process and fixture, a non-confidential fixture will be made as an inspiration case for the wider industry. The company cases will only involve fixturing design and manufacturing, therefore the use and feedback of the fixture will be the responsibility of the user.

7 Risk Analysis

It may occur that none of the materials have better performance than PETG or PETG-CF. This can happen due to economic reasons, wherein fixtures would be more expensive than 1000 DKK. Or the strength and or the fatigue strength of the new materials is poorer than that of PETG and PETG-CF. The filament may not be chemically stable, which may result in fast degradation of the fixture. It may also have poor vibration characteristics, as seen in previous cases. However, using a wide range of low-cost materials, with appropriate documentation ought to show improved material characteristics.

The 3D print settings or machine limits may also impede on the performance of the test fixtures, leading to warped geometries or poor mechanical properties. Especially since high temperature and composite materials are harder to print, and more abrasive. The machine may also break down or have varies flaws. For most filaments it should be possible to fine tune print settings and varies parameters will be tested to find adequate print settings.

It may not be affordable to buy a 3D printer that uses high end filaments, or a 3D scanner with good tolerances for reverse engineering. And the scanner could require high processing power, which may not be within DAMRC's capabilities. A market analysis would show the economic limitations for equipment.

The process of making the fixture, might also not decrease lead time and costs overall, therefore not improving productivity. As the design and manufacturing process can be too complicated, slow or unreliable. Companies may not be interested in 3D printed fixtures, leading to no cases for the project to explore and analyse. They may not see benefits in using the fixture and provide poor feedback. Using company cases this can be analysed, and show the complexities of the design and manufacturing process.

8 Experimental Design

8.1 Measurements

To quantify the capacity of the filament materials to be used as machining fixtures. A number of tests will be performed, to validate their resilience to machining conditions including:

a. Exposure to coolant. Since it is often used in machining, a fixture than weakens or deforms when exposed to coolant is less desirable.
b. Mechanical characteristics and limits. A fixture is used in many strained conditions within the material, which include compression, tension and shear modes of high force applications.
c. Fatigue characteristics. From previous cases fixtures often failed due to fatigue, to improve fixtures, the fatigue limit of the fixtures ought to be better.
d. Microscopy analysis. It was shown in the Pre-Analysis and Literature Study that the structure of the rasters and their bonding had a big influence on the characteristics of the 3D printed part.
e. Vibration characteristics. The advantages of 3D printing include the geometric versatility and anti-vibration properties of the plastic. A well-designed fixture can take advantage of this and make vibration prone process more stable.

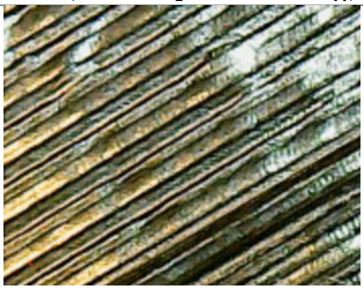
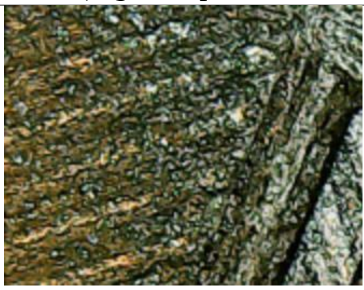
8.1.1 Absorption Testing

As coolant is often used in milling, an absorption test is essential to assess the viability and longevity of the fixture. From UPUV - 3D print fixtures and tools (P654) PA+, ABS, PLA and photopolymer were tested so, likewise in Dansk AM Hub 3D Fix (P729) PLA, ABS and TPU were tested with fluid absorption. Making a similar test to these with the new materials, would prove valuable in term of comparability of the materials. When exposed to coolant. In the UPUV - 3D print fixtures and tools (P654) absorption test the dimensional distortions were very minor. It showed the weight gain as a much more useful metric for determining the absorption. Which would later also be used as the only metric in Dansk AM Hub 3D Fix (P729).

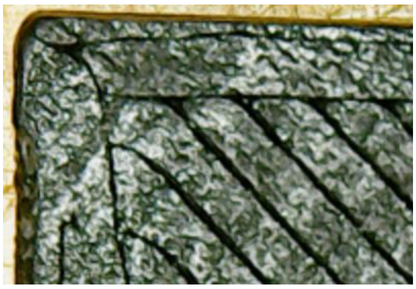
Figure 8.1-1
UPUV - 3D print fixtures and tools (P654) absorption test setup

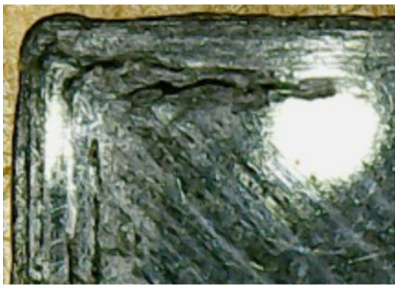
8.1.2 Microscopy

A microscopy of the 3D-printed layers would give feedback on the quality of the print settings. It may also give insight into the failure mode of the fixture, giving valuable feedback on the print strategy. The effect of the heat diffusion distortion would also be observed, wherein some materials made have higher distortion, which may conclude in different materials having different optimal print settings. From preliminary microscopy of current materials at DAMRC, the failure mode can be seen for PLA and PETG-CF, giving insight into the printing challenge:

	PLA (low temperature, stiff)	*PETG-CF (high temperature, ductile)*
Top		

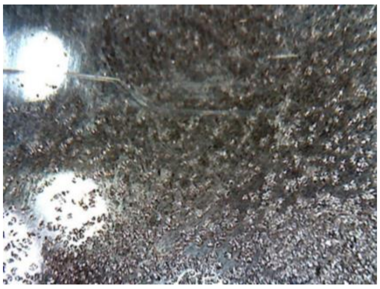
Bottom





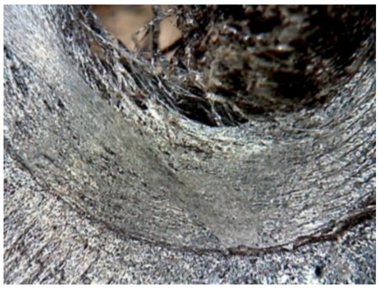
Bottom cracking

Bottom layer adhesion/warping



Side crack growth and debonding

Fiber stringing



As established in section 3.7, there are generally two opposing factors towards failure in 3D printed material: high heat gradient causing strong fusion of rasters and heat gradient causing distortion. In previous 3D prints it is evident that the PLA may have had bad fusion, leading to crack propagation thru the weak bonds. Oppositely, the PETG-CF material fused well, but shows signs of warping, caused by distortion in the material. The stringing is also prominent for the PETG-CF sample, which is often caused by high nozzle temperatures (low viscosity). Using microscopy, the optimal print settings may be found. While also understanding the reason for failures.

8.1.3 Mechanical Testing

In Dansk AM Hub 3D Fix (P729) and UPUV - 3D print fixtures and tools (P654) compressive strength tests were made. In Dansk AM Hub 3D Fix (P729) it was used to select between PBT, PETG and PETG-CF. Using a vise to compress the 3D printed jaw fixture against the workpiece. The vertical movement of the workpiece was then measured using a dial indicator. This wasn't used to test the strength of fatigue limit of the material, but the movement of the workpiece when tightened. However, a setup like this could save time in terms of discarding material that deform too much in this test. In UPUV - 3D print fixtures and tools (P654) samples were put in a vise, for both compressive and twisting stresses, where the moment on the torque wrench at failure was noted.

Figure 8.1-2
UPUV - 3D print fixtures and tools (P654) Compression and twisting test setups

From this a comparison between materials was made:

	PLA	ABS	PETG	Nylon	PA+
Compressive strength (Nm)	200	78	85	200	200
Twisting strength (Nm)	184	108	100	106	130

Table 8-1
UPUV - 3D print fixtures and tools (P654) Strength test results

However, it was limited to a maximum of 200 Nm. Therefore, PLA and PA were not measured at failure for compressive strength. Unexpectedly, the ABS and PETG fared worse than PLA. This may indicate the print conditions were non-ideal for the ABS and PETG, since they normally have greater overall strength when in use (as can also be observed by the cases at companies). Therefore, this test strategy ought to be avoided.

Ideally, to have good parody between test geometry (wrench, vise, 3D-fixture, workpiece) the metric should be in force per unit area (MPa). Since the moment of the wrench, will result in different workholding force, depending on the fixture geometry. The clamping force can be calculated as $F = \frac{M \cdot D}{k}$, where F is the force in Newton, M is the torque in Newton meters, D is the diameter of the screw in meters, and k is the coefficient of friction between the screw and jaws (0.2 for steel) (https://calculator.academy/clamping-force-calculator/). This force will then be distributed on the contact area between the vise grips and jaws. Resulting the stress calculation being $\sigma_{jaw} = \frac{F}{A_{contact}} = \frac{M \cdot D}{k \cdot A_{contact}}$ (8.1). This assumes the stress is linearly distributed in the system.

The material failure in UPUV - 3D print fixtures and tools (P654) was visual breakage, which can conclude in fixtures being plastically deformed being deemed acceptable. Whereas Dansk AM Hub 3D Fix (P729) uses the dial indicator to determine movement of the fixture, at a particular point. The dial indicator may not detect the exact failure point of the material, but movement of a fixture is a good indication of a failed fixture.

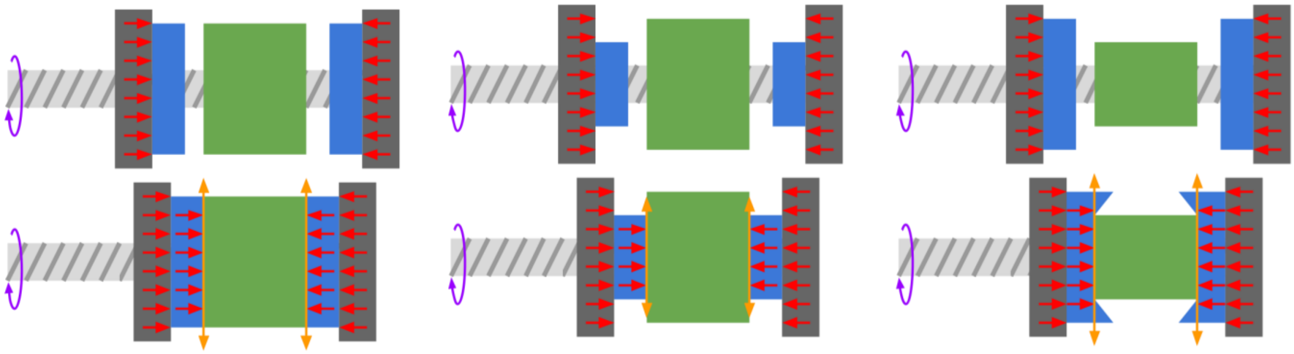


Figure 8.1-3
Diagram of stress distribution in different sizes of jaw fixture

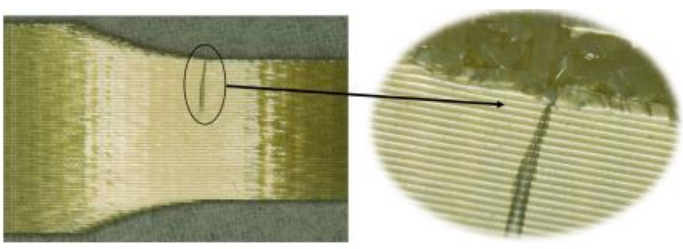
To maintain linearity in the system the 3D printed fixtures (blue), should have a holding surface less than or equal to the workpiece (green). And be less than or equal to the holding surface of the vise (grey). Otherwise, the relatively soft plastic will deform unevenly (see figure 8-3 third diagram). The fixture ought to be thin in the direction of the clamping force, to reduce the chance of buckling.

While compression is the more common stress mode of a fixture, shear and tensile stresses also appear. Therefore, these will also be tested using conventional techniques to compare materials in these modes. The stress and strain can be graphed for analysis of the Ultimate Tensile Strength and Young's modulus, which are key to comparing the strength characteristics of materials.

8.1.4 Fatigue Limit Testing

The successful fixtures from UPUV - 3D print fixtures and tools (P654) and Dansk AM Hub 3D Fix (P729), broke after some uses. As described in 3.7.1, the cyclic stress conditions, lead to debonding in the 3D printed material. Therefore, a fatigue compressive strength test would be valuable in evaluating the theoretical number of uses. It may be performed in a similar manner as the compression test. But below the yield strength, and with repeated tightening and loosening.

There is not much data on the fatigue limit of FFF materials, and the loading type must be considered when using S-N curves [20]. For the best parody with machining fixtures, the fatigue test will be compression-compression fatigue. For the scale of the project, the number of cycles may be very limited. But using Paris law, some knowledge of the crack growth may be used to interpolate the results.



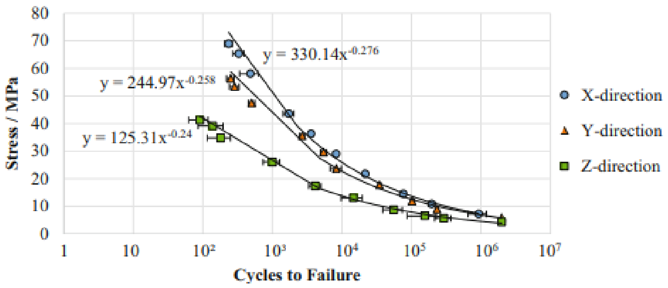


Figure 88.1-4
Tensile fatigue test of ULTEM [24]

It was observed in [24] that cracking would start at shoulder/joint as seen on figure 8-4. The resulting S-N curve for all printing directions would start different at low cycles, the strongest being the x-y direction. However, converge as the loading is lessened.

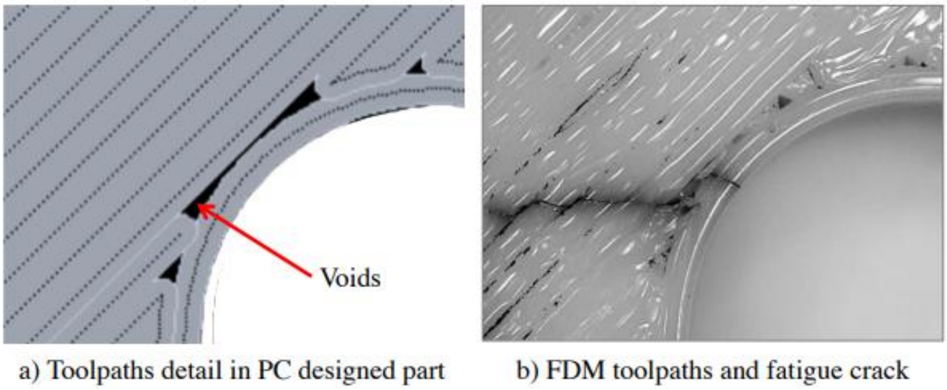


Figure 88.1-5
Tensile fatigue test of ULTEM [25]

Likewise [25] observed that a void from the printing process which then led to the spawn point of a crack, in a fatigue test with a more complex loading configuration.

8.1.5 Vibration Fixture Test

DAMRC has experience with vibration/modal test and analysis. But there is no known direct method to relate fixture modal analysis, to cutting parameters or stability lobe diagrams. However, the real and imaginary parts of the FRF can be used to find the natural frequencies, damping ratios and stiffness of the fixtures. Which would make the materials comparable, in term of vibration characteristics.

8.2 Non-Confidential Machining Demonstration

8.2.1 Holding Setups

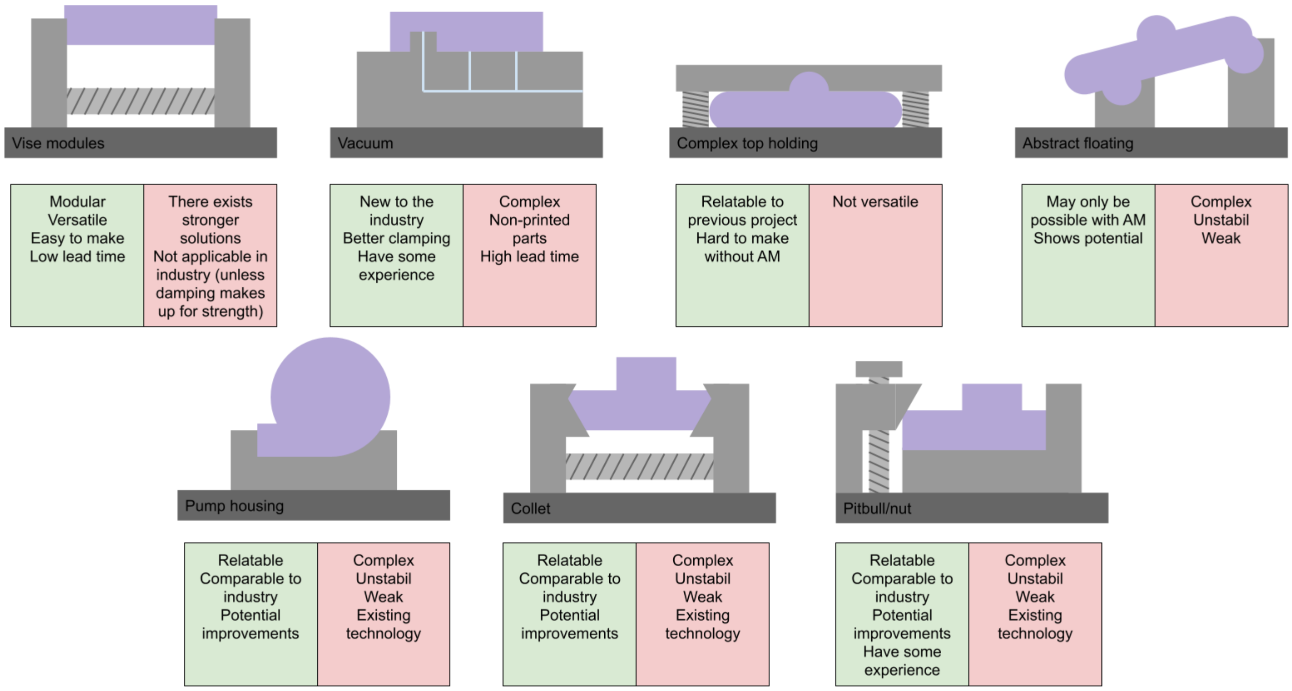


Figure 8.2-1
Possible workholding test setup ideas

To show the use of 3D printed fixtures, the fixture ought to be tested in an industrial machining setting. Wherein there exists many different workholding configurations, as shown on figure 8-5. In Dansk AM Hub 3D Fix (P729) the cases were similar to the vise modules, complex top holding and vacuum fixtures. Whereas MADE Advanced fixtures (P600) had a case more like the custom solution for a pump housing.

Generally, a vise or chuck related solution would demonstrate how companies could replace custom soft jaws with 3D printed jaws. For a 3D printed jaw to work though, it needs to have a good compressive strength and friction with the workpiece.

As for the top holding solution, the stress would be mostly tensile and bending moments. But is useful in many complex geometries that would usually be clamped with nuts and bolts. Which may mark the surface or need a very peculiar geometry. In these cases, the pitbull/nut fixtures are also possibilities. Wherein they have the advantage of covering less of the workpiece and being less bulky and more versatile.

A vacuum fixture has already been tested at DAMRC, with the idea of second side machining in mind. Useability was demonstrated in Dansk AM Hub 3D Fix (P729), although the fixture was not analysed further, considering issues with tolerances or damping. This fixture does require more consideration towards geometry of both the workpiece, vacuum pipes and air insulation, and is therefore only viable for industries that would use it more medium-large series of hard to hold products. Which makes this fixture competing with more common specialised fixtures, used for larger production runs. Therefore, a vacuum fixture must show significant improvement in the workholding. This is most relevant for complex or ornate geometries, that may have thin walls, causing chatter vibrations.

The more complex fixtures are abstract floating and custom fixtures (like a pump housing). Without classic tightening equipment, these fixtures have a much lower clamping force, resulting in a slower milling process. But in some cases, with abstract shapes, these might be the only possible fixture. (See example on figure below).

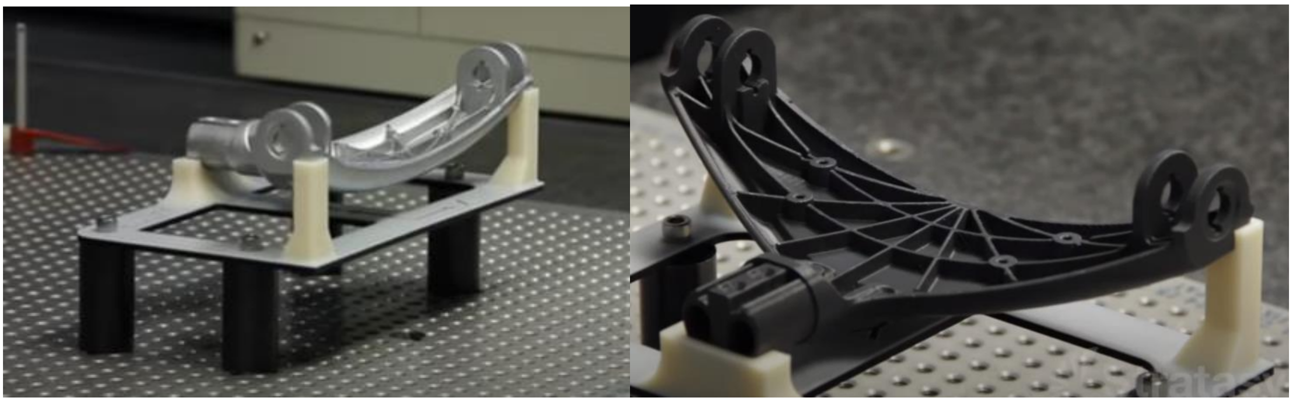


Figure 8.2-2
Stratasys AM fixtures [17]

8.2.2 Previous Demos

In Dansk AM Hub 3D Fix (P729) and UPUV - 3D print fixtures and tools (P654) demonstrative cases were made, as proof of concept cases for 3D printed fixtures. The lobe bowl was used to spark interest in the 3D printed fixture concept and showed the use of 3D scanning and simple CAD modelling to make a jaw fixture.

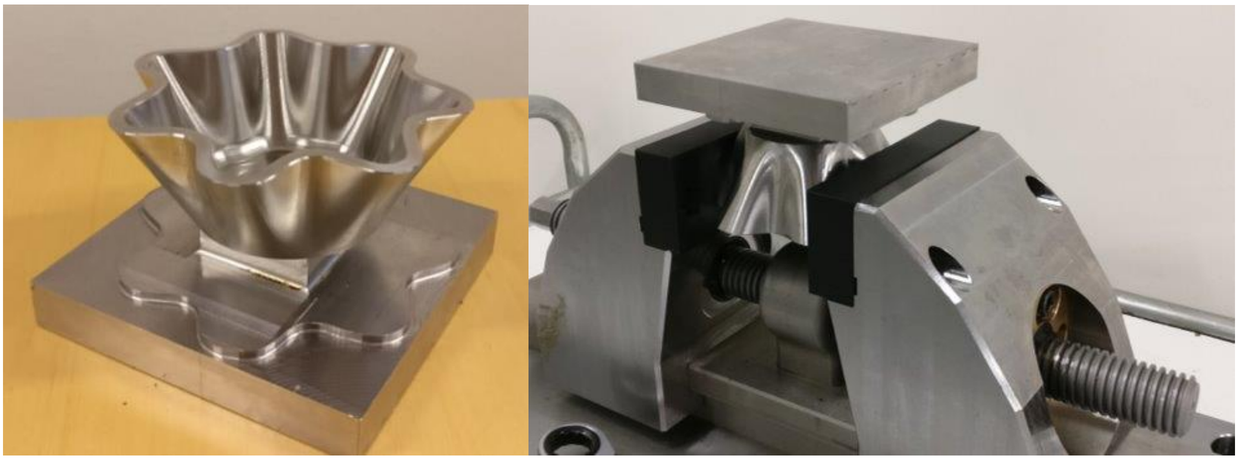


Figure 88.2-3
"Demo 7 lobe bowl" Complex jaw fixture UPUV - 3D print fixtures and tools (P654)

Figure 88.2-4
Vacuum fixture Dansk AM Hub 3D Fix (P729)

In Dansk AM Hub 3D Fix (P729) and UPUV - 3D print fixtures and tools (P654) demonstrative cases were made, as proof of concept cases for 3D printed fixtures. The lobe bowl was used to spark interest in the 3D printed fixture concept and showed the use of 3D scanning and simple CAD modelling to make a jaw fixture. The vacuum fixture demonstrated an alternative to metal fixtures, and disproving the perception a vacuum fixture would be too complex. However, at higher feed and cutting depth, there were problems with vibrations.

9 Experimental Procedure

All tests use the (model), using 95% infill, triangular pattern, 2 perimeter walls, 0.1 mm layer thickness. 3 of each specimen were made with the materials and temperature settings on the Bambu Lab X1-Carbon:

Material	Nozzle [C]	Bed [C]	Volume flow max [mm^3/s]	Dry Temp. - Time [C-hours]	Program:
PETG	255	70	12	none	Jaw draft PETG-1.gcode
ASA	240	110	12	70 – 20	Jaw draft ASA-3v2.gcode
PA6	280	50/110	16	70 – 70	Jaw draft PA6-7.gcode
PA6GF	275	100	16	70 – 6	Jaw draft PA6GF-8.gcode
PA12	250	100	16	70 – 16	Jaw draft PA12-5.gcode
PA12CF	250	100	16	70 – 18	Jaw draft PA12CF-6.gcode
PC	255	90	16	70 – 6	Jaw draft PC-4.gcode
POM	225	110	16	70 – 18	Jaw draft POMmk3.gcode
PVDF	245	45	3.2	none	Jaw draft PVDF-2v2.gcode
PBT+	240	65	16	none	Jaw draft PBT.gcode
PETGCF	245	70	12	none	Jaw draft PETGCF.gcode

Table 9-1
Print heat settings for specimens

Material	1st layer	1st layer infill	Walls	Infill	Top layer	Travel
PETG	50	105	200	350	200	500
ASA	50	105	50	250	200	500
PA6	50	105	60	350	200	500
PA6GF	50	105	200	350	200	500
PA12	50	105	200	350	200	500
PA12CF	25	50	100	175	100	250
PC	50	105	200	350	200	500
POM	25	50	100	175	100	250
PVDF	30	30	30	45	45	500
PBT+	50	105	50	250	200	500
PETGCF	50	105	50	250	200	500

Table 99-2
Printing speed in mm/s for specimens

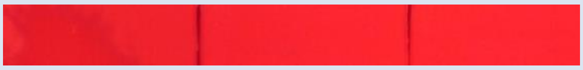
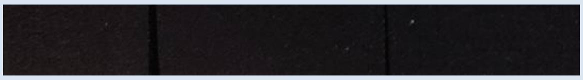
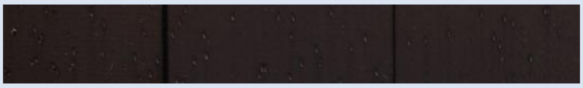
Material	Common defects	Solutions	Surface
PETG	None	N/A	
ASA	Light warping	Drying, using skirt	
PA6	Warping	Drying, using skirt	
PA6GF	None	N/A	
PA12	Blobs	Lower walls printing speed.	
PA12CF	Clogging, Blobs	Drying, lower walls printing speed.	
PC	None	N/A	
POM	Extreme warping	PETG raft, low printing speed.	
PVDF	Clogging, Blobs	Drying, lower walls printing speed.	

Table 99-3
Printing problems and mitigation

The final specimen prints were successfully print, except POM, as the extreme warping resulted in failure. POM was only somewhat successful at very low infill (15%) and using a PETG raft to support. This allowed for a successful print, but the geometry is still warped significantly. Further using a large PA6 raft allowed for the 95% infill, by overfilling a triangular PA6 infill pattern with POM. The print still warped, but it was successful. The timelapse of the successful prints can be found at: https://shorturl.at/CDNZ5. The 3 specimens were labelled A, B and C.

9.1 Filament Absorption Test

The procedure of the filament absorption test will be the next:

1. Weigh all the specimens individually, and note it in 230828 Test-data excel sheet A.
2. Attach weights to the specimens.
3. Lower the specimens into coolant fluid (HOCUT 4260), until they are completely covered.
4. Weigh the specimens after 2 hours of coolant exposure, and note it in 230828 Test-data excel sheet A. (Note: dry off specimen with a towel before weighing)
5. Weigh the specimens after further 20 hours of coolant exposure, and note it in 230828 Test-data excel sheet A.

9.2 Mechanical Stress Tests

9.2.1 Compression Test

This is the procedure followed for the compression test:

1. Insert a specimen with the XY layers normal to the clamping surface, with the long side against the jaws.
2. Place a dial indicator to measure the Z-axis displacement.
3. Tighten in 10 Nm increments and note the torque and displacement.
4. Stop when either the vise cannot be tightened further, or the specimen shows signs of failure.
5. Insert a specimen with the XY layers normal to the clamping surface, with the short side against the jaws.
6. Tighten in 10 Nm increments and note the torque and distance between the jaws.
7. Stop when either the vise cannot be tightened further, or the specimen shows signs of failure.
8. Repeat for all materials.

9.2.2 Shear Test

This is the procedure followed for the shear test:

1. Insert and clamp a specimen in the middle of two aligned vise jaws, wherein one is free to move parallel to the notch section and the other stationary.
2. Place a calliper to measure the displacement of the moveable vise.
3. Tighten the screw of the moveable vise starting at 3 Nm in 1 Nm intervals and note the displacement and torque of the vise and wrench.
4. Stop when either the vise cannot be tightened further, or the specimen shows signs of failure.
5. Repeat for all materials.

9.2.3 Tensile Test

This is the procedure followed for the tensile test (performed by Aarhus University):

1. Insert a specimen in the tensile testing machine.
2. Record the stress and strain of the specimen.
3. Repeat for all materials.

9.3 Vibration Test

Followed procedure for the vibration test:

1. Insert the third (unused) specimen in a vise. Place the shortest side parallel to the clamping surface, and the XY print direction is normal to the clamping surface.
2. Attach accelerometer to the side orthogonal to both the clamping surface and the table.
3. Use a modal hammer to tap test the specimen, by hitting the opposite side of where the accelerometer is attached.
4. Repeat for all materials.

9.4 Fatigue Limit Fixture Test

The steps to do the fatigue limit fixture test:

1. Insert the third specimens into a vise clamp. Place the shortest side parallel to the clamping surface, and the XY print direction is normal to the clamping surface.
2. Tighten the vise to 90% of failure torque.
3. Losen the vise to 0 Nm.
4. Repeat 2 and 3 until:
    a. Cracking.
    b. Excessive deformation.
    c. 30 cycles
5. Note the number of cycles and failure mode in 230828 Test-data excel sheet F.
6. Repeat for all materials.

9.5 Microscopy

The procedure for microscopy:

1. Using the Oitez digital microscope to take pictures at x65 and x255 magnification.
2. Examine top and bottom layers in the corner of the specimens.
3. Examine the side walls of the specimens.
4. Examine defects of the specimens.
5. Note pictures in 230907 Microscopy table Excel.

10 Results

10.1 Filament Absorption Test

The filament absorption test was conducted as planned, using HOCUT 4260 coolant for the 9 specimens. HOCUT 4260 has a density of 999 kg/m^3 and a pH of 9.5.

Project	Material	w% after 2 hours	w% after 20 hours	Expected w% value	Water weight g
MADE Advanced fixtures (P600)	Grøn PLA	0.41 %	0.59 %	Unknown	0.04
	Sort ABS	0.14 %	0.38 %	Yes	0.03
	Sort Flex (TPU)	0.13 %	0.17 %	Unknown	0.01
Dansk AM Hub 3D Fix (P729)	PBT+	0.45 %	0.49 %	Above	0.04
	PETG+CF	0.51 %	0.51 %	Unknown	0.04
UPUV - 3D print fixtures and tools (P654)	FFF / PA+		0.21 %	Below	0.09
	FFF / ABS		2.65 %	Unknown	0.98
	FFF / Nylon		2.10 %	Above	0.89

	FFF / PLA		0.83 %	Unknown	0.36
	SLA /Fotop.		0.52 %	Unknown	0.25
	SLS / PA		2.74 %	Above	1.01
Stronger fixtures for CNC machining (P1001-4-16)	PETG	0.34 %	0.65 %	Above	0.19
	PVDF	0.71 %	0.93 %	Above	0.34
	ASA	0.33 %	0.60 %	Unknown	0.14
	PC	0.43 %	0.96 %	Yes	0.25
	PA12	0.40 %	0.68 %	Yes	0.15
	PA12CF	0.83 %	2.23 %	Above	0.48
	PA6	0.32 %	0.71 %	Above	0.18
	PA6GF	0.32 %	0.59 %	Above	0.17
	POM	26.22%	7.76 %	Above	0.76

Table 10-1
Fluid absorption test data

The %w gain of the specimens is compared to the expected absorption range for 24 hours submerged in water. Wherein only 3 materials were in that range: ABS, PC, PA12. It is more frequent that the material is above the expected value, which is unexpected since the density is lower than water. This could be due to the porosity and gaps in the 3D print, or in the case of POM, the hollow cavities inside. Some residues may also be left on the surface, as post-test microscopy shows them to be more reflective/shiny. However, no concerning defect were observed, meaning that all materials may be considered chemically stable in the machining environment.

10.2 Mechanical Stress Tests

10.2.1 Compression test

The compression test use A specimens did not show any concerning defects, as the 100 Nm were only equivalent to 8.5 MPa. It did however show a disenable difference in displacement.

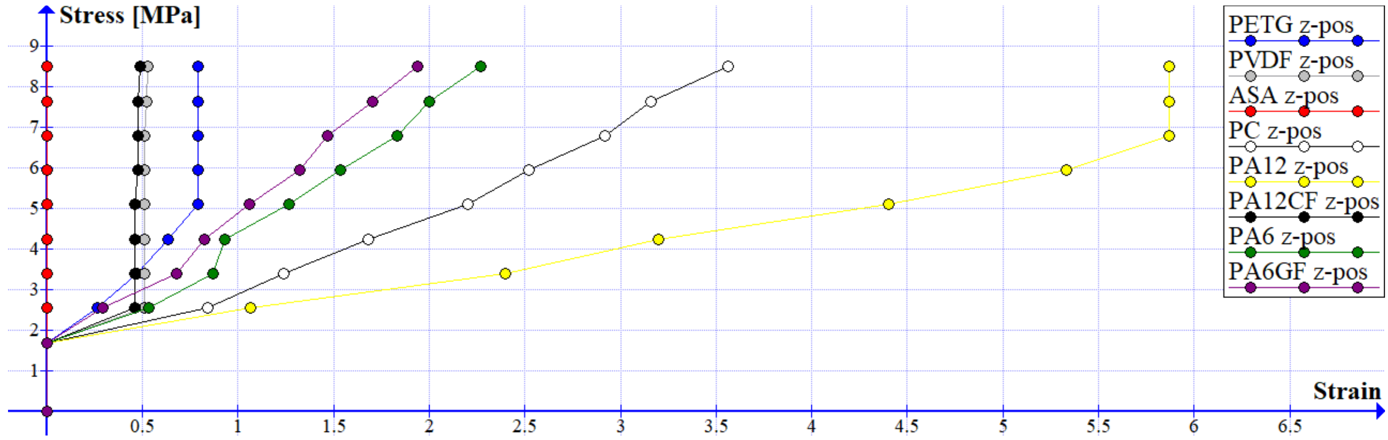


Figure 10.2-1
Displacement at different clamping stress

Since no defects were observed, the displacement would be due to either movement of the specimen, plastic or elastic deformation. Plastic deformation was observed in PA12, PA12CF and PVDF, as the blobs on the surface were flattened. ASA, PA12CF, PETG and PA12 reach a critical strain value, in which the specimen is no longer notably displaced. Whereas PA6GF, PA6, PC continuously become displaced. This may be due to lack of grip/friction, as these materials were stiffer in the following test. The critical strain value may be due to the elastic deformation not traversing the z-axis, as the bonds are more ductile than the rasters.

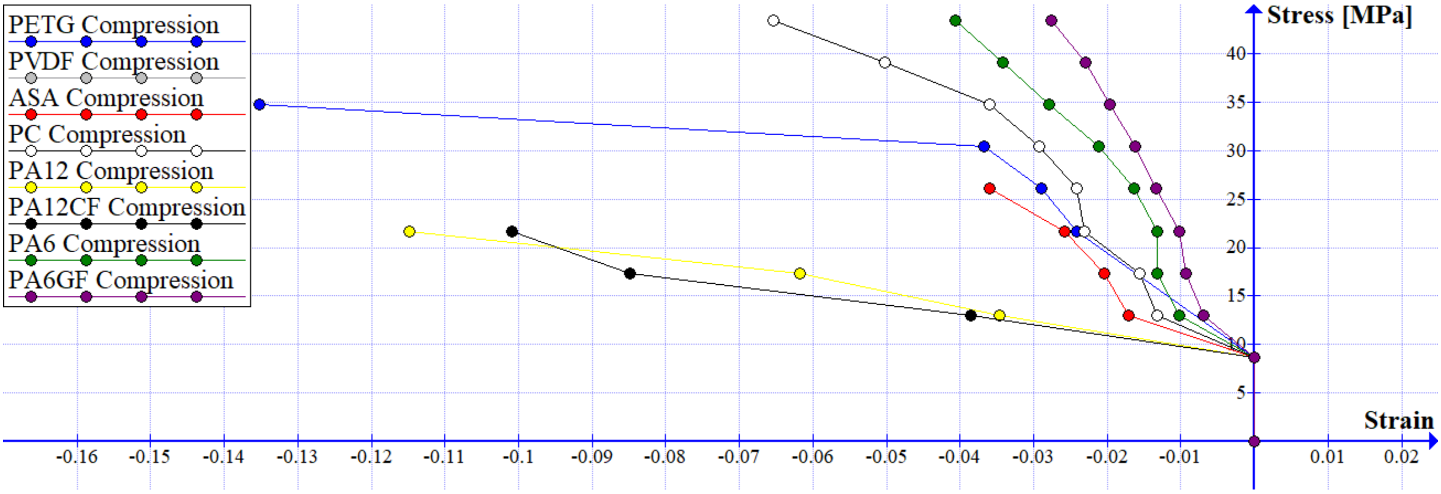


Figure 10.2-2

Compressive xy-stress-strain diagram for specimens B

The compressive tests at max 100 Nm resulted in maximal pressure of 43.4 MPa, wherein 3 materials did not fail at this point: PC, PA6, PA6GF. Whereas PETG, PA12, PA12CF plastically deformed beyond the compressive UTS (UCS), with the maximal deflection at 1/3 of the length, and PVDF plastically deformed below the lowest level of the torque wrench with a maximum deflection at 1/2 of the length. ASA had a brittle failure, with multiple cracks. PC, PA6. PA6GF did have some minor indentations at the clamping surfaces, and PA6 had debonding cracks growing from the edge of the indentations.

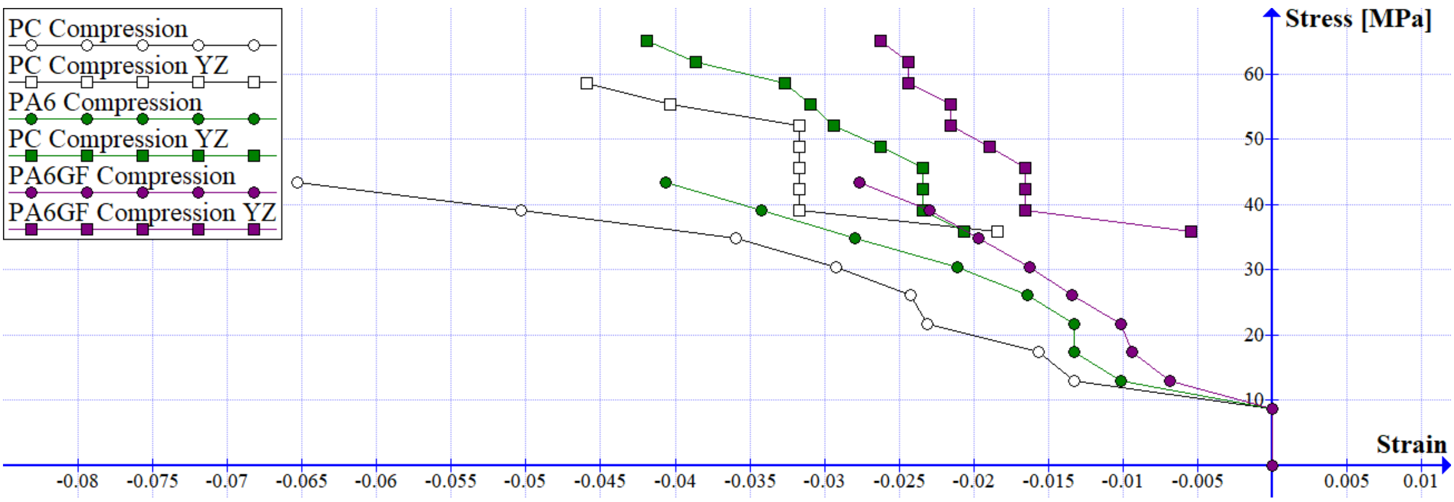


Figure 10.2-3

Compressive xy and yz stress-strain diagram for specimens B and A

Using the A specimens in a different vise, with the capability of using 200 Nm, the 3 unbroken materials were testes at a maximum stress of 65 MPa. However, the use this vise the specimens were now in a yz orientation, which resulted in a stiffer modulus. The PC did fail in a brittle break, however the PA6 and PA6GF did not. The PA6 did elastically deform with a max deflection at 1/2 of the length. The PA6GF had no notable defects or deflection.

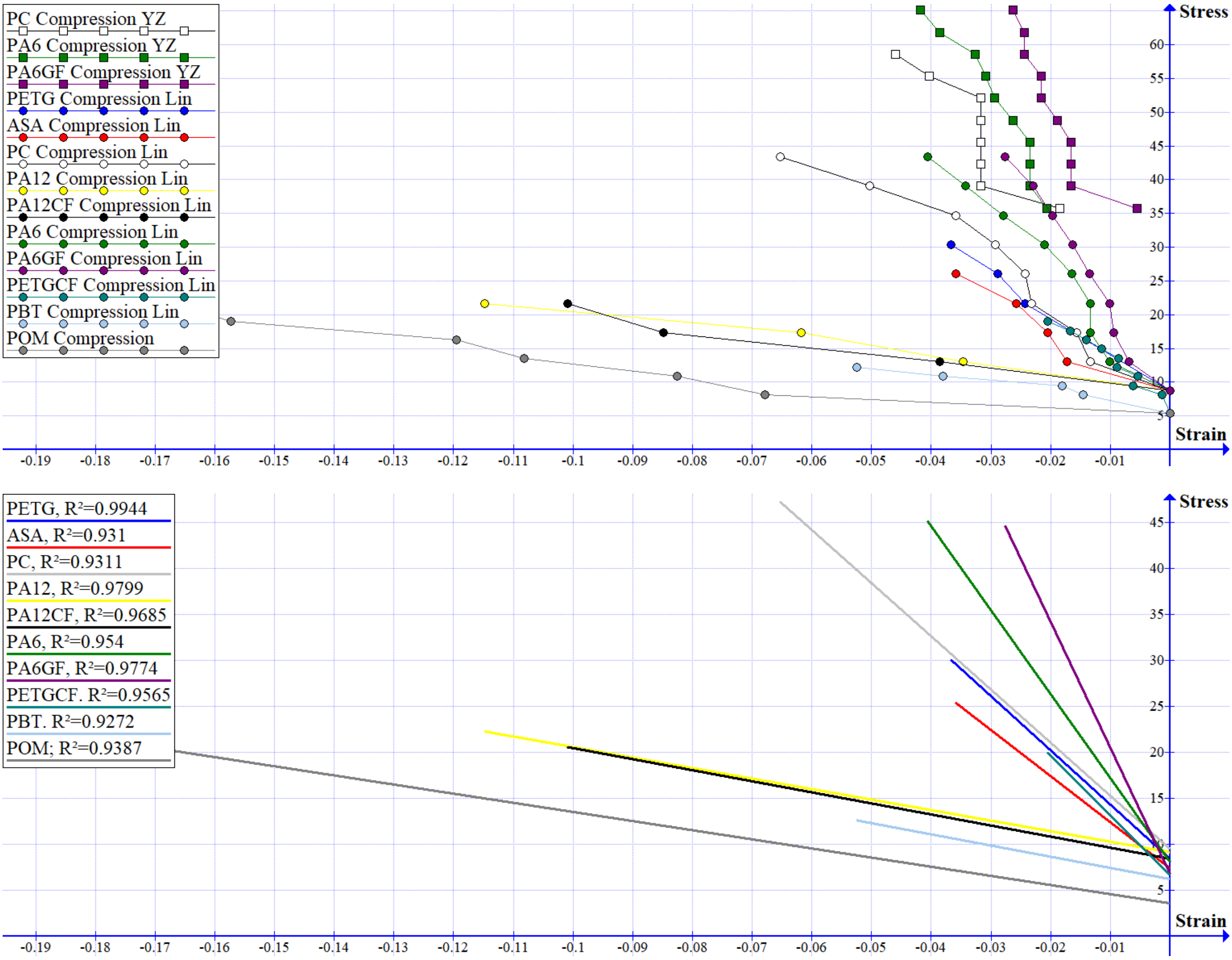


Figure 10.2-4

Compressive modulus regression

Using linear regression, the compressive elastic modulus of the material is the slope of the graph. And the UCS is given by the last stress value before failure. This was not possible to do for PVDF as it failed too soon. PA6 and PA6GF UCS is unknown, but larger than 65 MPa.

Material	UTS	UCS	Modulus	C-Modulus	Failure mode
PETG	53	30	2150	590	Ductile
PVDF	58	0	387	0	Ductile
ASA	50	26	2300	502	Brittle
PC	62.7	59	2307	579	Brittle
PA12	40	22	1293	114	Ductile
PA12CF	56	22	4632	120	Ductile
PA6	55	65+	3500	914	None
PA6GF	62.8	65+	4261	1371	None
PETGCF	-	19	-	652	Ductile
PBT+	-	12	-	121	Ductile
POM	50	22	1870	99	Ductile

Table 10-2
Tensile and compression test data in MPa

The test conclusively showed PA6 and PA6GF as the strongest fixture material. Which shows the benefits of high temperature filaments, though they might also be higher cost. The PVDF, PA12 and PA12CF were too soft to be used as a fixture. Wherein PVDF may be tough, and have good tensile properties, in compression it acts more as a sponge. The PA12CF did not show any improvement over normal PA12 in compression, which may indicate poor fiber adhesion, or a suboptimal fiber ratio or length for this application. PETG, ASA and PC preformed mediocre as fixture material. PETG and PC had a similar compressive modulus, ASA and PETG had a similar UCS, and ASA and PC had a similar failure mode. ASA is similar to ABS, which is also seen in [34] where they found a yield and ultimate compressive strength of 28.14 MPa and 34.57MPa (solid material), and a modules of 410.44 MPa, wherein they observed a 45° angle to be the weakest orientation in compression. To compare futher with the previous cases, the old PBT+ and PETGCF were used in the same test (3DE premium vendor), which conclusively shows the mechanical improvement the more advanced materials have. The UCS was lower than all other materials excluding PVDF. Wherein PBT had a similar stiffness to PA12 and PA12CF (though without the same toughness), and PETGCF had a stiffness between PETG and PC. They both exhibited ductile breaks with wriggles and a large bend.

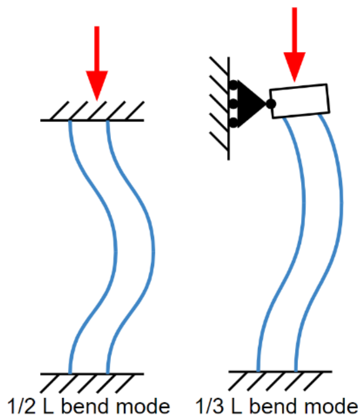


Figure 10.2-5
Pillar bend modes present in compressive tests

It is to be noted that these tests did not show the pure compressive strength of the material, as the length to width ratio of the specimens made some specimens deform as a pillar in the two modes seen in Figure 10.2-5. However, fixtures are using in a multitude complex configurations, which involve both compressive, tensile and shear stresses. But this comparison does show some of the failure modes already encountered, and failure modes that were previously undescribed at DAMRC.

10.2.2 Print parameter test

Since many failures occurred due to the 45-degree cracking, which is related to the raster orientation. Different printing parameters were tested based on the previous Jaw draft model. Since ASA is a cheap material with clear brittle failure modes at low torque, it was chosen as a material. While the orientation of the infill may affect the failure mode, common/theoretical strategies for strength improvement were also tested:

A	B	C	D	E	F	G
Cubic infill	Ironing	0.2 mm layers	5 walls	Control	15deg offset	105deg offset

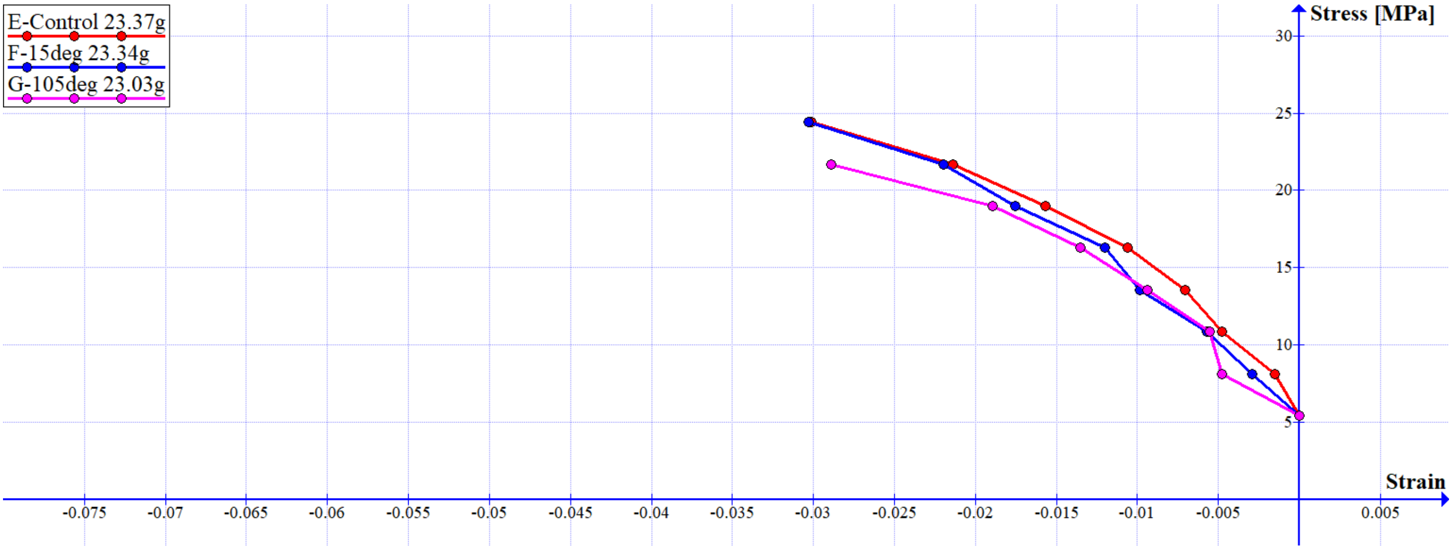


Figure 10.2-6
Compressive strength test with different infill orientations

The control specimen performed better overall in stiffness compared to the offset infill orientations and had similar UCS. But their mode of failure was very different. Whereas E had the predicted 45-degree break, G had a large debonding crack at the center, and a cascade of debonding cracks in the XZ 45-degree direction. F had a much steeper 60-degree z axis crack, which shows the failure mode is very dependent on the internal geometry.

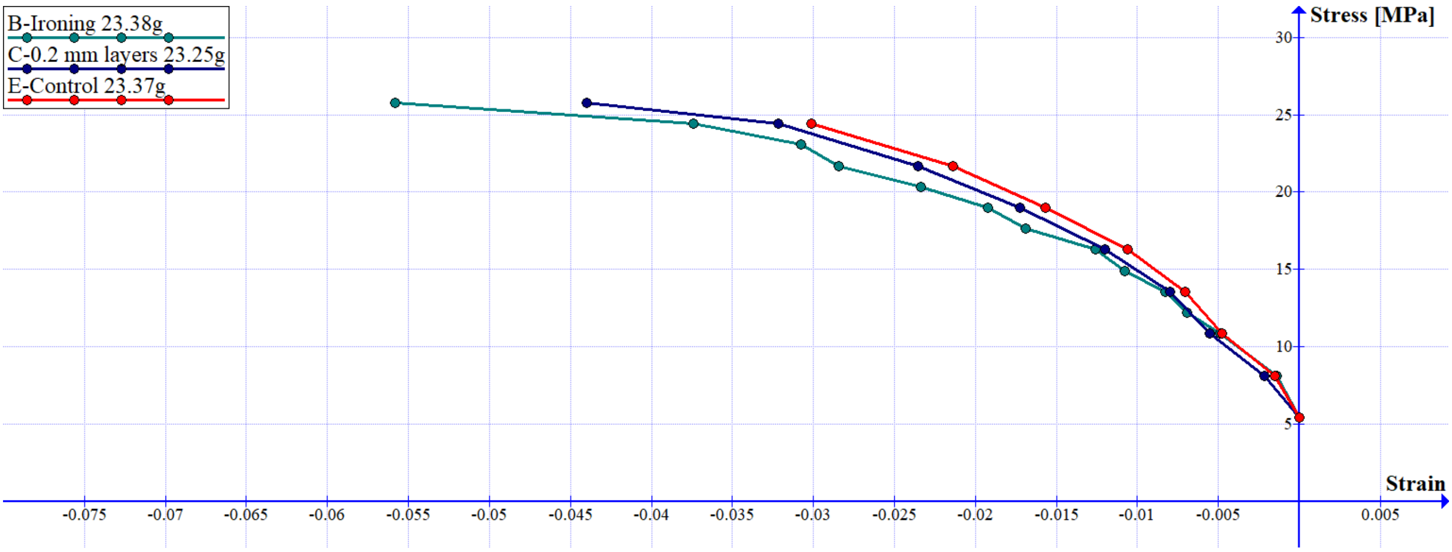


Figure 10.2-7
Compressive strength test with different layer height and ironing

Ironing and increasing layer height changes the termperature dependent adhesive properties of the material. Which has resulted in greater toughness (area under the curve) and less stiffness. They also had a slightly increased UCS,

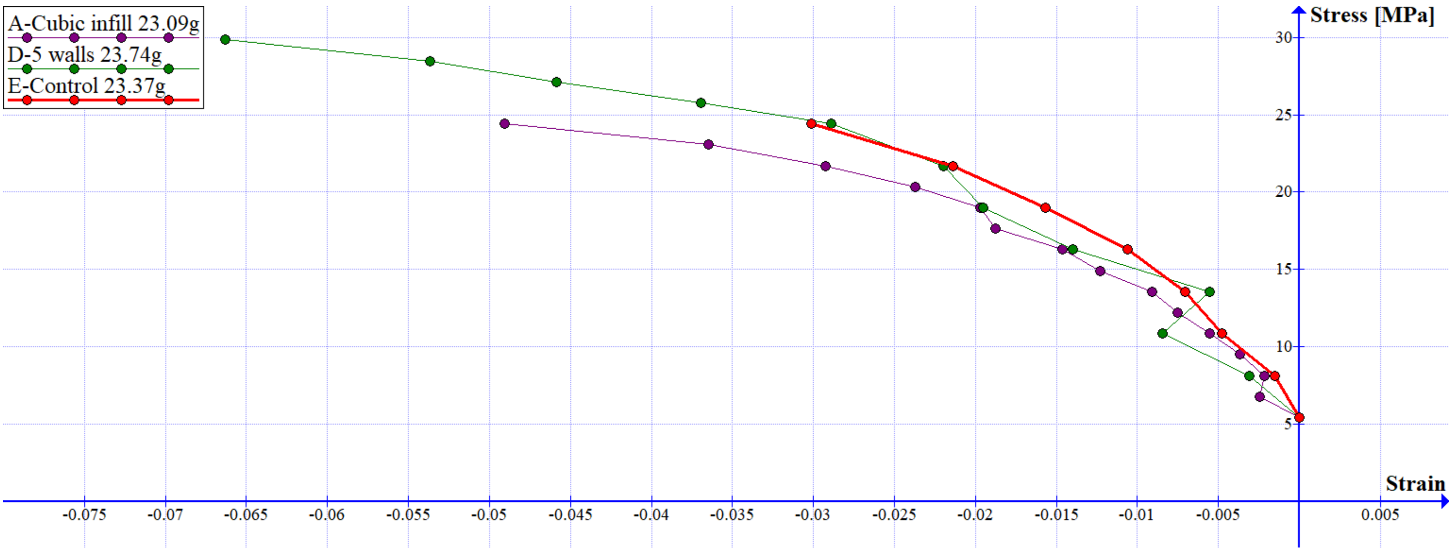
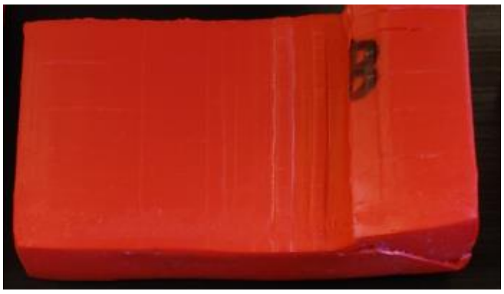
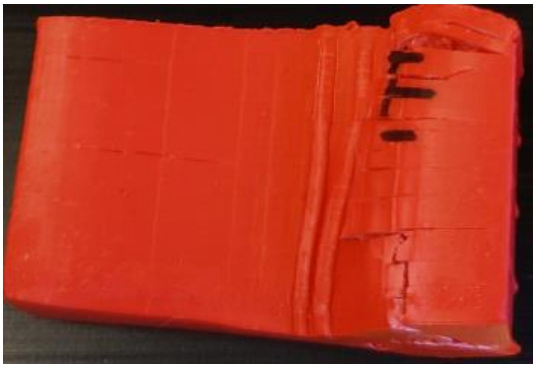


Figure 10.2-8
Compressive strength test with different infill type and wall count

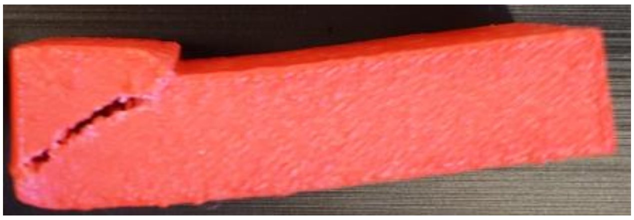
A and D had the most different failure modes. Cubic infill resulted in a tougher and more ductile specimen, but a V-shaped cascade of debonding cracks, in which a large volume of the top is pushed up. The extra walls resulted in a much higher UCS, and showed much wider wriggles, but did fail in the usual 45-degree crack. The defects can be seen in the following table:

	Side view	Top view
A		
B		
C		
D		

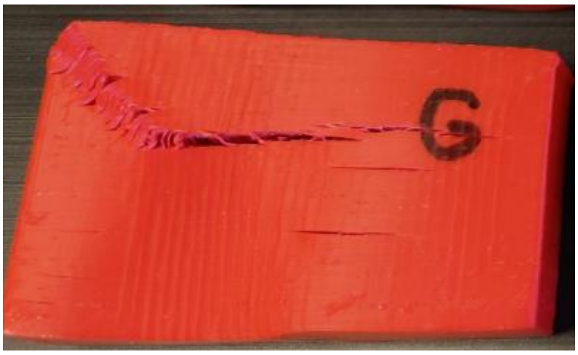
E



F



G



10.2.3 Shear test

Additionally, a notched shear test was performed, using the ASTM 5379 standard. Two specimens in ASA, PC, PA6, PETG and PA6GF materials were printed in different orientations (Z and XY).

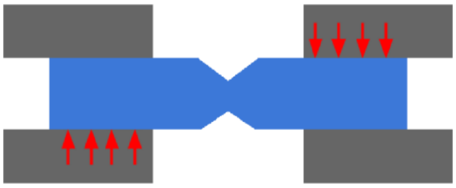


Figure 10.2-9
Shear test loading configuration

As with the other tests a torque wrench was used, and the displacement of the vise was measured. Therefore, the displacement is normalised over the shear length (notch length), and the stress is the screw force on the notched area. Resulting the following graph.

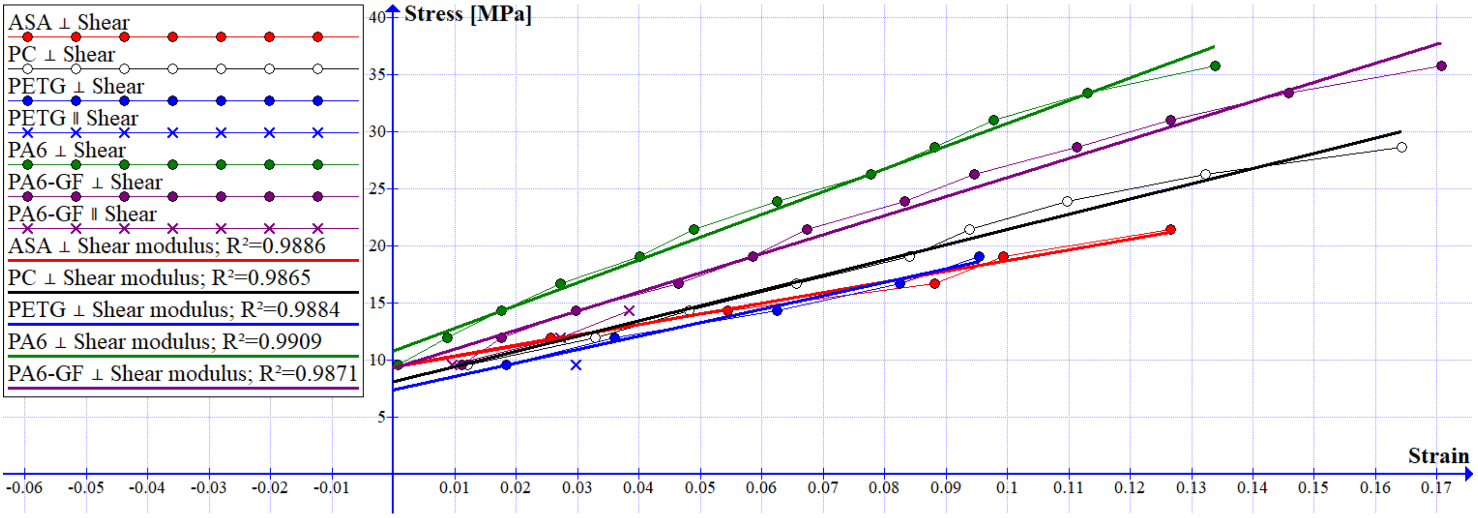
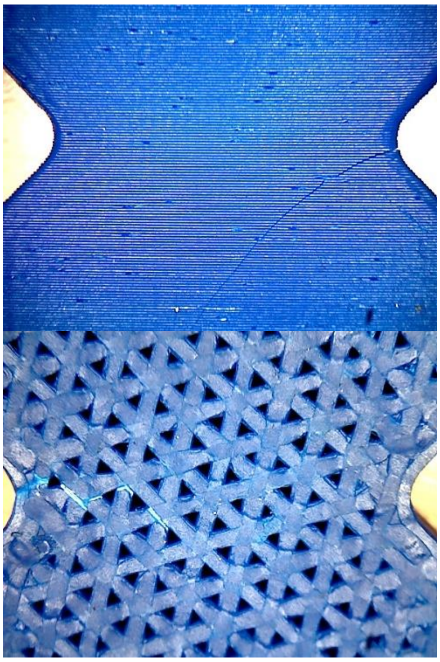


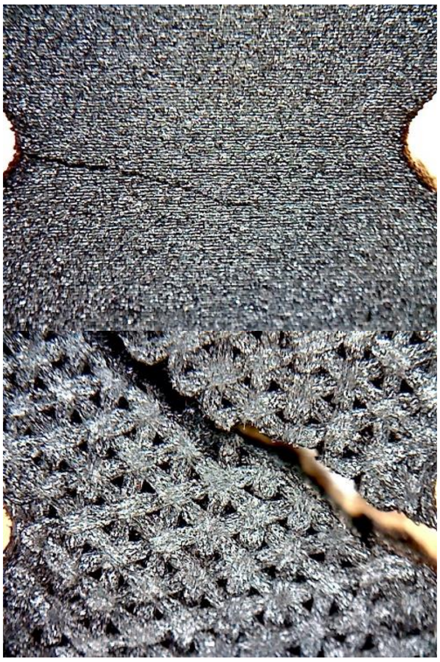
Figure 10.2-10
Shear strength test

The results follow the compression test results with wherein the nylon materials are the strongest, the ASA and PETG being weaker, and PC being in-between. However, the glass fiber reinforcement did not have a great affect in this test, as the PA curves are near parallel. As expected, the samples printed in the Z direction had little to no shear strength and relying merely on bond adhesion result in poor strength. Wherein only the PA6-GF had enough datapoints (from 3 to 6 Nm) to draw a line. Assuming the 15 Nm being near the breaking point if the material, the Z axis has 40% of the strength of the XY orientation.

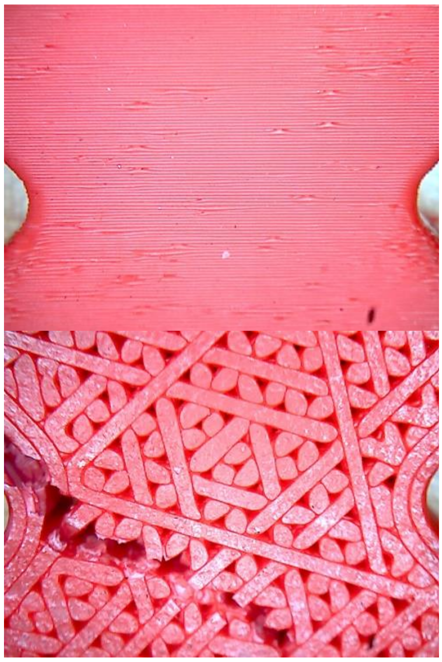
PETG



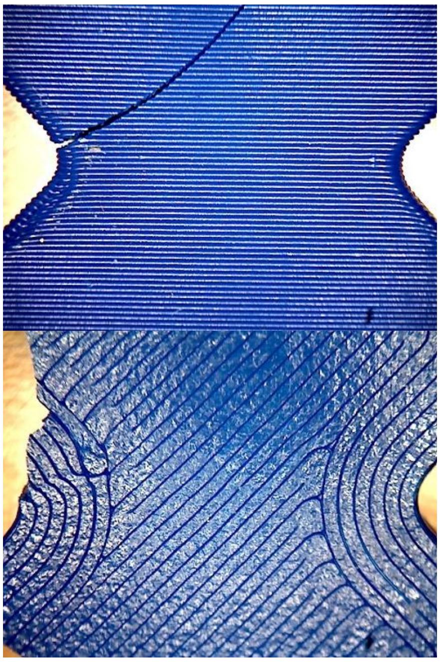
PA6-GF



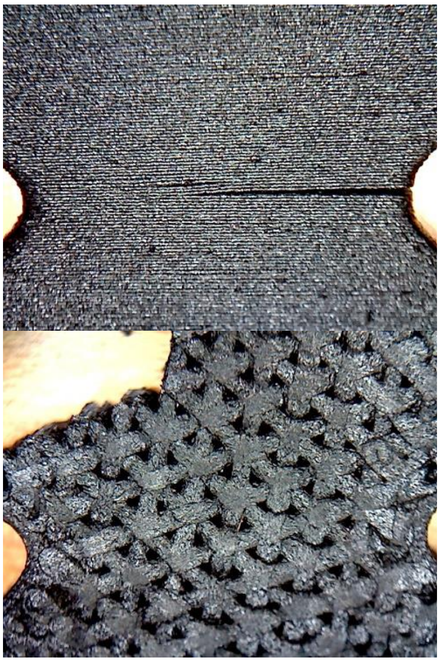
ASA



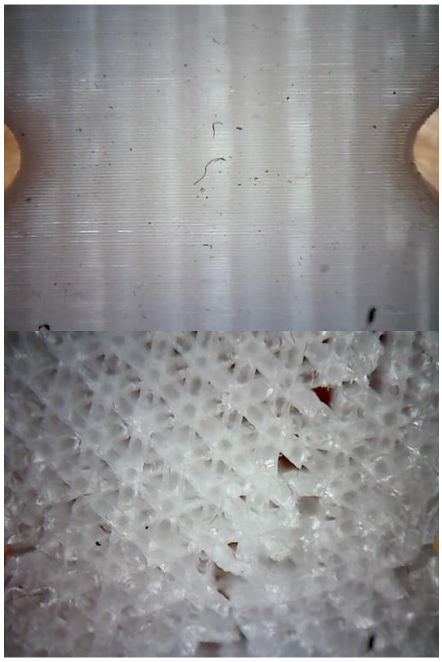
PETG solid



PA6



PC



10.2.4 Tensile test

Together with student from Aarhus University tensile strength tests were performed using the ISO 527-2:2012(E) type 1BA standard.

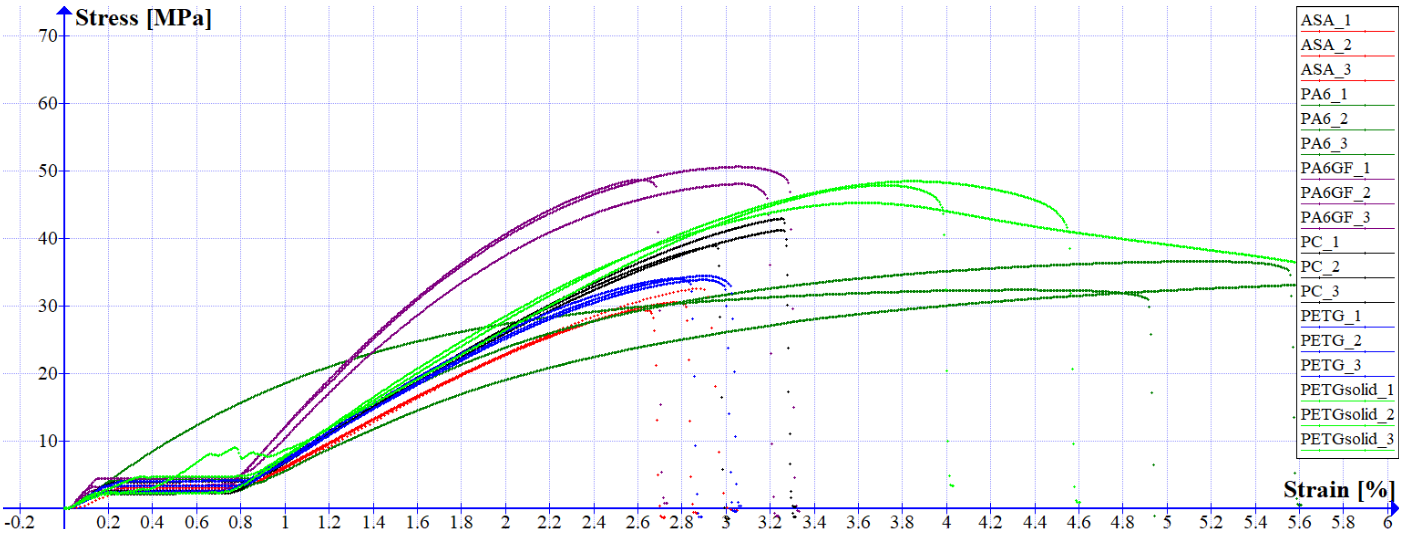


Figure 10.2-11
Tensile strength test [32]

Some error occurred between 0.2% and 0.8% strain, wherein the graph plateaus. This may be due to angular deformation of the infill lattice due to air gaps, debonding of weak layers, straightening of the slightly warped specimen, slipping of the specimen, or a fault in the measurement machine. This didn't occur in the first PA6 specimen, and some anomaly is seen in solid PETG specimen 3. The Young's modulus is therefore based on the slope between 1% and 2% strain.

Material	Test UTS	Stated UTS	UTS fraction	Test Modulus	Stated Modulus	Modulus fraction
PETG	34.1	53	64%	1900	2150	88%
ASA	30.81	50	62%	1700	2300	74%
PC	41.03	62.7	65%	1900	2307	82%
PA6	34.22	55	62%	1600	3500	46%
PA6-GF	49.11	62.8	78%	2900	4261	68%
PETG solid	47.19	53	89%	1900	2150	88%

Table 10-3
UTS and modulus comparison

The stated value from the manufacturer is based on 100% infill, the ideal UTS fraction would therefore be 95% using the 95% infill. However, for the homogeneous materials it is between 62%-65%, and 78% for the glass fiber reinforced specimens. Suggesting that in practical use, the material is weaker, as many factors impact the print quality (noting that not all print conditions are stated by the manufacturers test specimens). But there may be a 22%-53% strength increase to be found by changing printing conditions. As seen by having solid infill though only using 5% more material, gives a 38% strength increase (but no increase in stiffness), but may not be practical in many applications (longer print time and material use, which can be wasteful for larger prints, and can be more difficult because of warping). The result are better for PETG than shown in [36] as they used solid 45° degree raster orientation, as they had a UTS of 30 MPa, and 32 MPa for ABS (comparable to ASA). They observed a stiffness of 1700 MPa for PETG, and 2200 for ABS. Making the tested PETG stiffer, but the ASA less stiff than their study. One ought to believe that the highly praised Composite Filament Fabrication using carbon fibres often with a nylon matrix should perform significantly better. However, compared with the tensile results found in [37, table 3-8] on CFF PA-CF found maximal UTS of 50.12 MPa and modulus of 2597 MPa, which is less than the PA6-GF used in this test. PEEK is also praised as the strongest FFF material, but [38]'s tensile test show PEEK to have a maximal UTS of 40.0 MPa and modulus of 522.9 MPa. The authors materials may have different applications, but that shows an important distinction between the manufacturers stated properties, as compared to the practical properties when in use.

In the tests all the specimens were observed to have a brittle break, except for solid PETG specimen 1. Suggesting that like the compression tests, these materials are brittle, except for PETG which is more ductile. Comparatively, the test shows that PA6-GF is the strongest filament, but the second strongest compressive test material PA6 did poor in this test, as it is significantly weaker and less stiff than seen in compression, but the most ductile material. This could be due to the change in heat bed temperature, as it could not be printed with 50°C because of warping but with 110°C. ASA, PETG and PC correlate well with the results from the compression tests. They have similar Young's modulus and follow the same ranking (PC being the strongest, and ASA being the weakest).

10.3 Vibration Test

Using the tap test equipment to measure the modal characteristics of the specimens showed clear results for most materials. MetalMax txf was used to calculate modal parameters: natural frequency, modal stiffness, damping ratio, modal mass and peak magnitude. Of these the most relevant are the natural frequency, modal stiffness and damping ratio. The natural frequency is the square root of the modal stiffness to mass ratio, therefore more dense and less stiff materials are expected to have a lower natural frequency. All specimens were measured at least twice. Resulting the following FRF data (separate graphs in appendix):

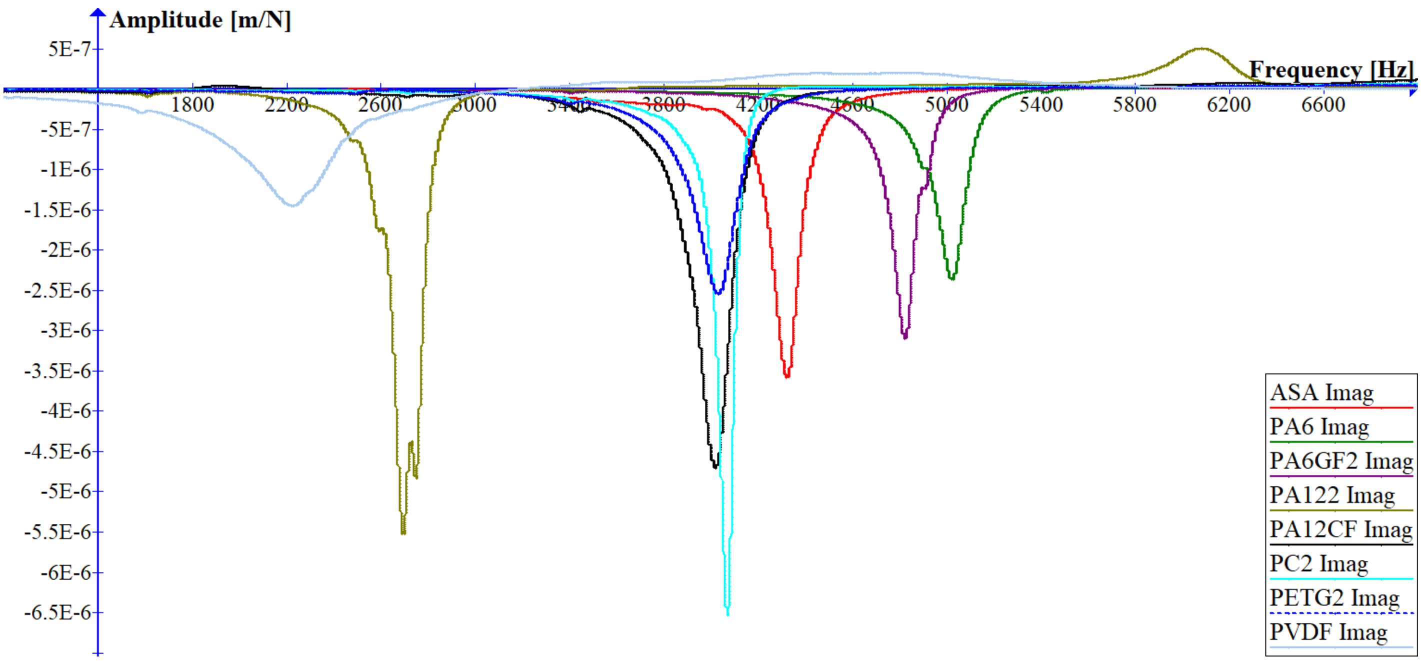
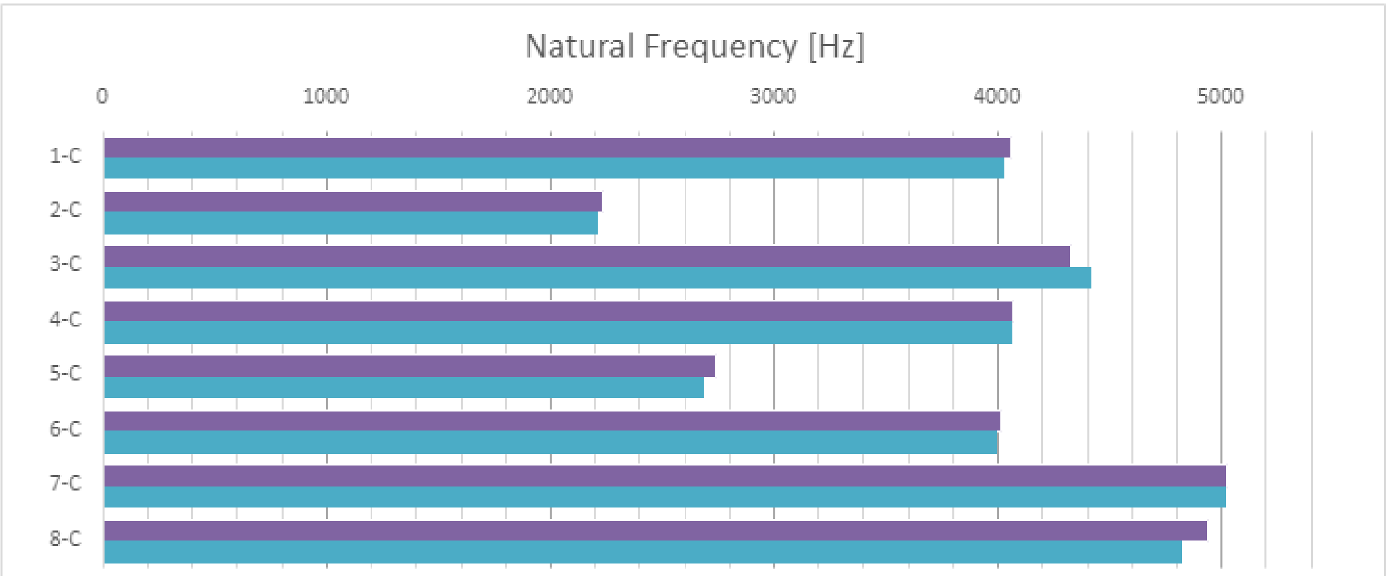


Figure 10.3-1
Imaginary FRF data of different filament materials

From the FRF data the modal parameters can be determined using the peak picking method.



	8-C	7-C	6-C	5-C	4-C	3-C	2-C	1-C
wn	4942	5022	4016	2745	4069	4323	2230	4059
wn2	4823	5022	4000	2694	4069	4421	2217	4034

Figure 10.3-2
Natural frequency of primary mode of specimens

PVDF expectedly has a low natural frequency, as it is the heaviest material, and is very flexible. Likewise, PA12 is also very flexible which results in a low natural frequency. PETG, PC and PA12-CF have similar natural frequencies. PETG is the heaviest, and PA12-CF the lightest specimen, meaning that to end at the same natural frequency, PETG ought to be the stiffest, and PA12-CF the most flexible. Which does correlate with the compressive modulus previously calculated. ASA, PA6 and PA6GF had the highest natural frequencies. ASA is the lightest and PA6-GF the heaviest of the specimens. Meaning that ASA is relatively flexible compared to the others, as the lower mass would result in a higher frequency.

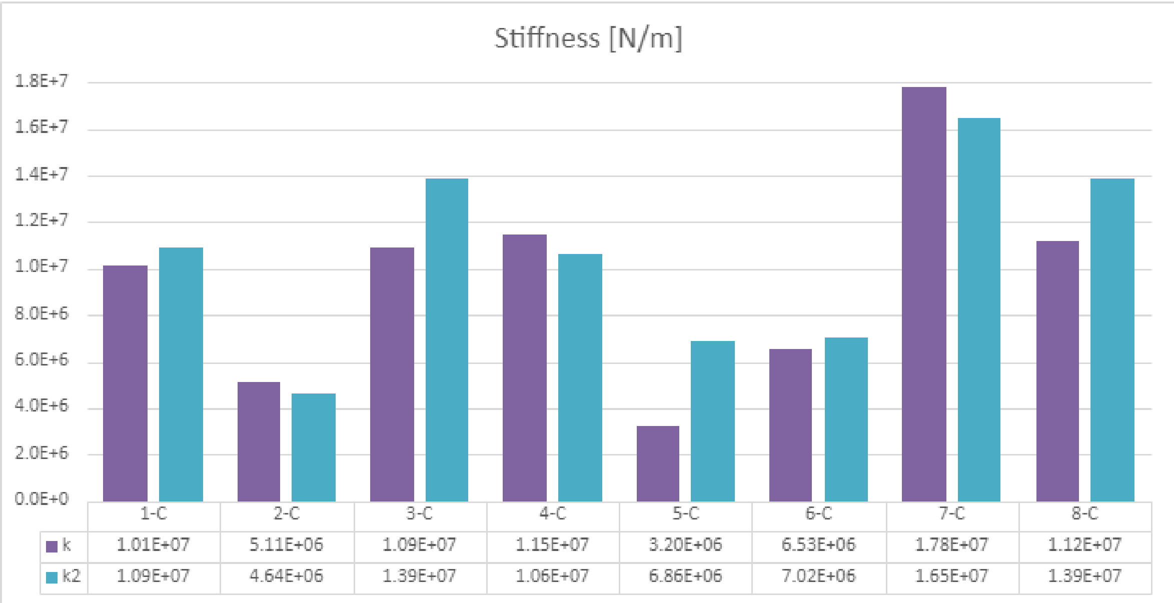


Figure 10.3-3
Modal stiffness of specimens

As compared to the compressive modulus ASA has a higher or similar stiffness to PETG and PC, whereas the compressive modulus showed ASA to be lower or similar to these materials. The other of the PA6 and PA6-GF is also reversed. The modal stiffness of the softer materials (PA12, PA12-CF and PVDF) are the lowest as expected.

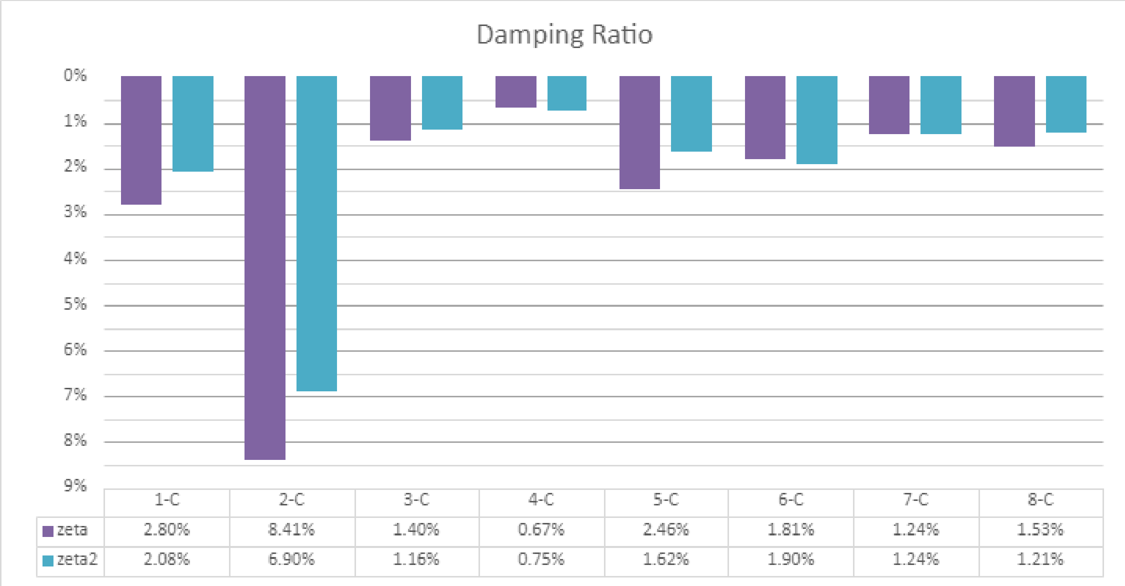


Figure 10.3-4
Damping ratio of specimens

The damping ratio gives insight into the material damping of the specimens. Wherein, it is roughly inversely proportional to stiffness. Damping ratio is the ratio between actual versus critical damping, were high values result in less overshoot and lower magnitude vibrations. This means a fixture made from PC would be prone to vibrations, whereas PVDF may dampen vibrations.

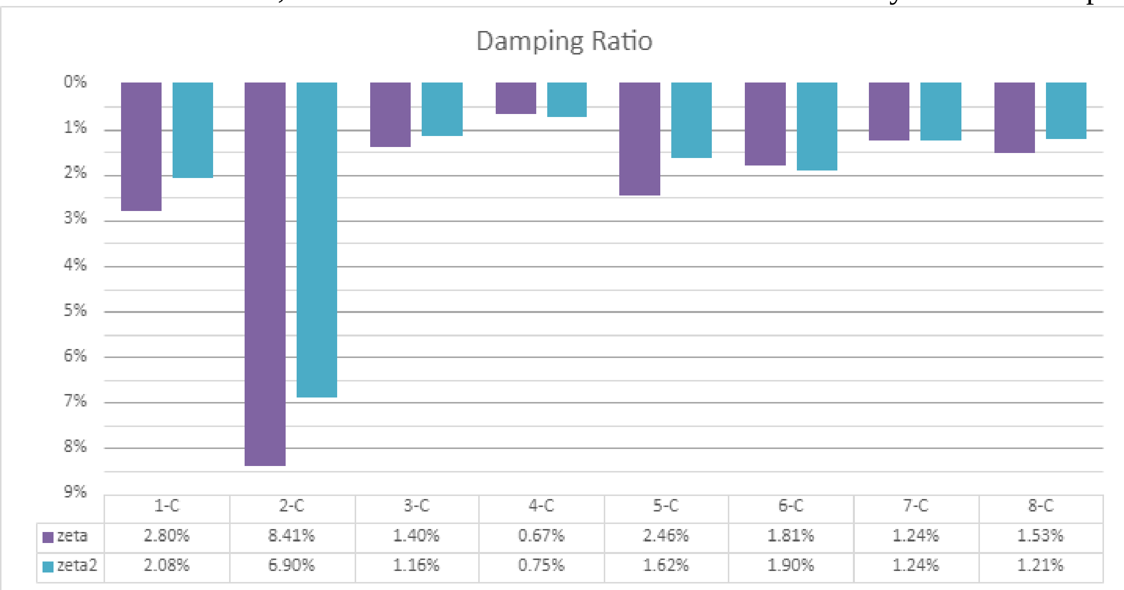


Figure 10.3-4 should only be used comparatively, as the values are not independent of geometry and joints. Metals usually have a damping ratio of >1%, and rubber is ~5% [26]. Wherein the results are comparable to this.

PVDF therefore has superior damping characteristics compared to other materials at 7-8%. At 2-3% PETG and PA12 give a decent material damping compared to the usual metal fixtures. At 1-2% ASA, PA12-CF, PA6 and PA6-GF have a small advantage in damping. PC had the lowest damping ratio and is therefore expected to have a vibration characteristic similar to conventional metal fixtures.

10.4 Fatigue Limit Fixture Test

The fatigue limit test resulted in defects in the PETG, ASA, PA12 and PC specimens. The PC was initially tested at 100 Nm, but the different vice resulted in a stress level very close to the UTS. It therefore failed early at only 4 cycles. Therefore, another PC sample was tested at 50 Nm. The failure mode of the PC was more ductile (less explosive) than in the compressive strength test.

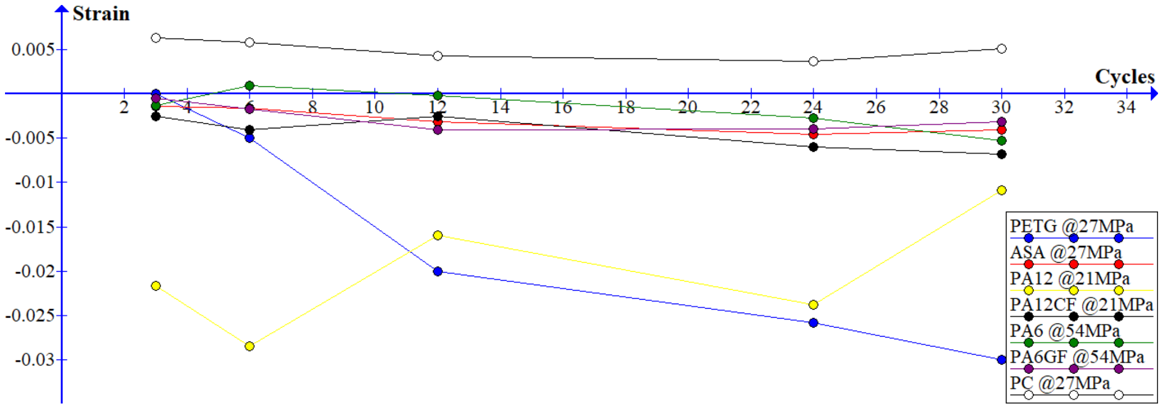


Figure 10.4-1
Compressive fatigue test results

A difference between the defected and non-defected specimens were wriggles. Which is explained in detail in the microscopy section. The PA12 and PA6 follows an odd curve, since the strain decreases over time. This may be due to some stiffening factor, therefore the PA12 specimen was compression tested, to compare the compressive modulus. The modulus was increased from 282 MPa to 345 MPa. Nylon is a semi-crystalline plastic, therefore it may be the material is recrystalising.

PC may have had an odd initial measurement, as the strain is positive, but is slowly decreasing (meaning compressively the expected direction), expect for the last measurement. The fibre reinforced materials are expected not to fatigue at low cycles, as a critical number of fibres must break before significant deformation [27]. That is also observed in the test, as PA12-CF and PA6-GF show less variation in strain compared with the homogeneous PA12 and PA6.

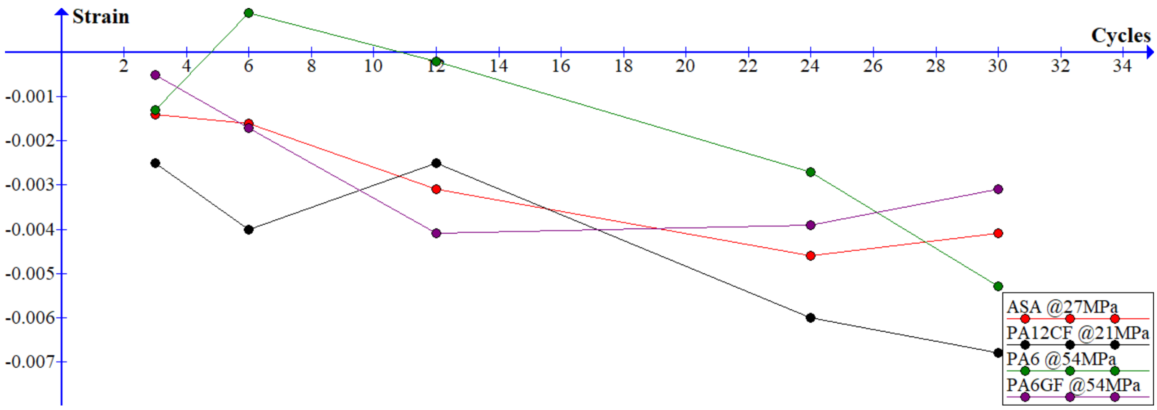


Figure 10.4-2

Compressive fatigue test results for stiff materials

For low number of cycles, the strain is expected to follow logistic growth as described in [27]. ASA and PETG fit this model well, however for PC and PA12-CF the increasing strain values were removed, resulting in a good fit.

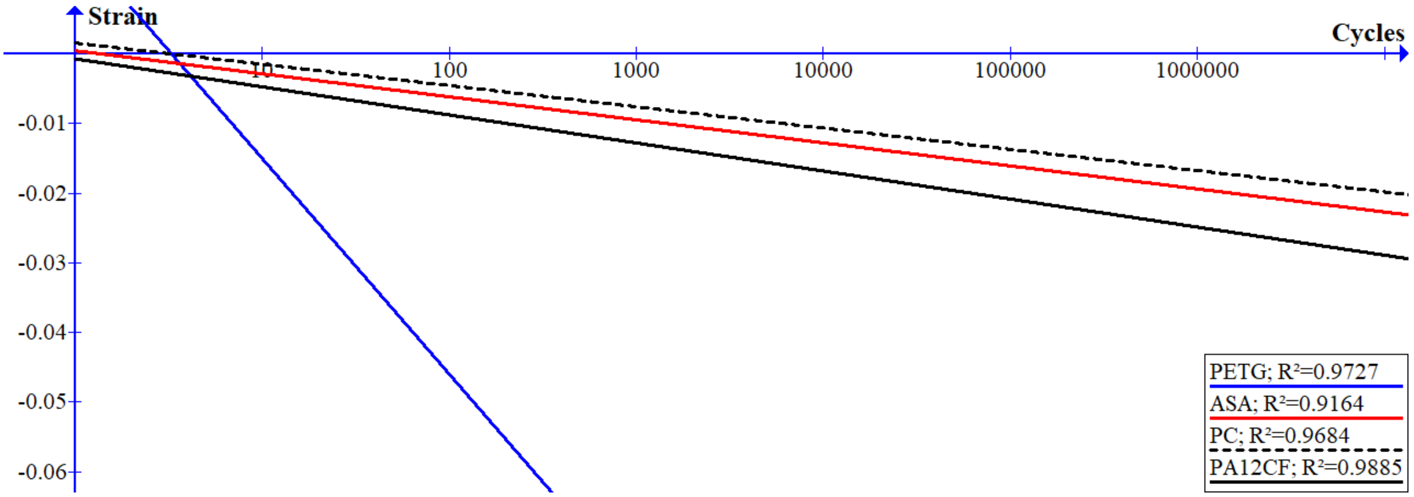


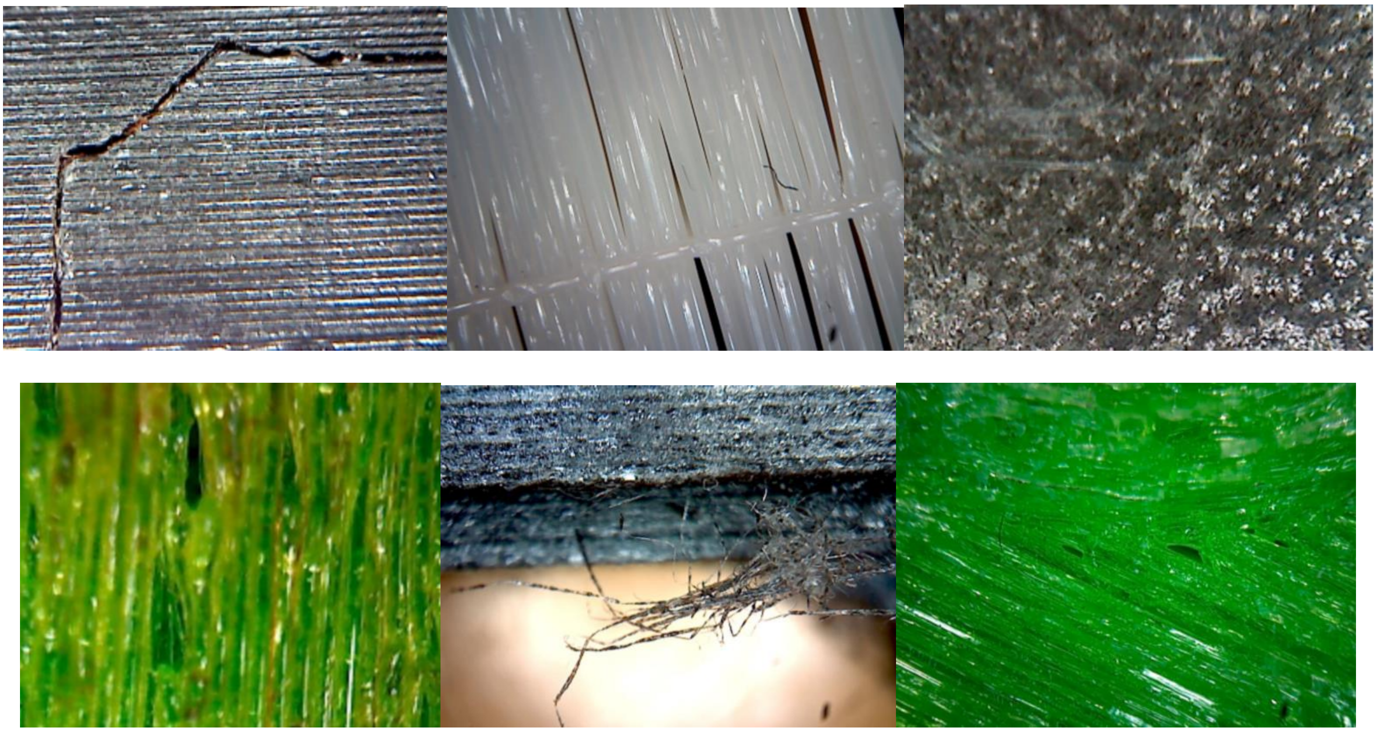
Figure 10.4-3

Compressive fatigue logarithmic regression

The other materials did not fit this model with an R^2 above 0.9. In the context of fixture selection, PETG can be seen to have a poor response to fatigue/creep. Many more cycles and different stress levels ought to be done to get a clear picture of the fatigue characteristics, however for the project ASA, PC, PA12-CF, PA6 and PA6-GF will be considered having the good fatigue characteristics for a fixture.

10.5 Microscopy

DAMRC had some discarded 3D prints, which give a comparison between previous projects, and this microscopy. While also explaining some of the reasons why the parts failed. Defects in previous 3D prints:



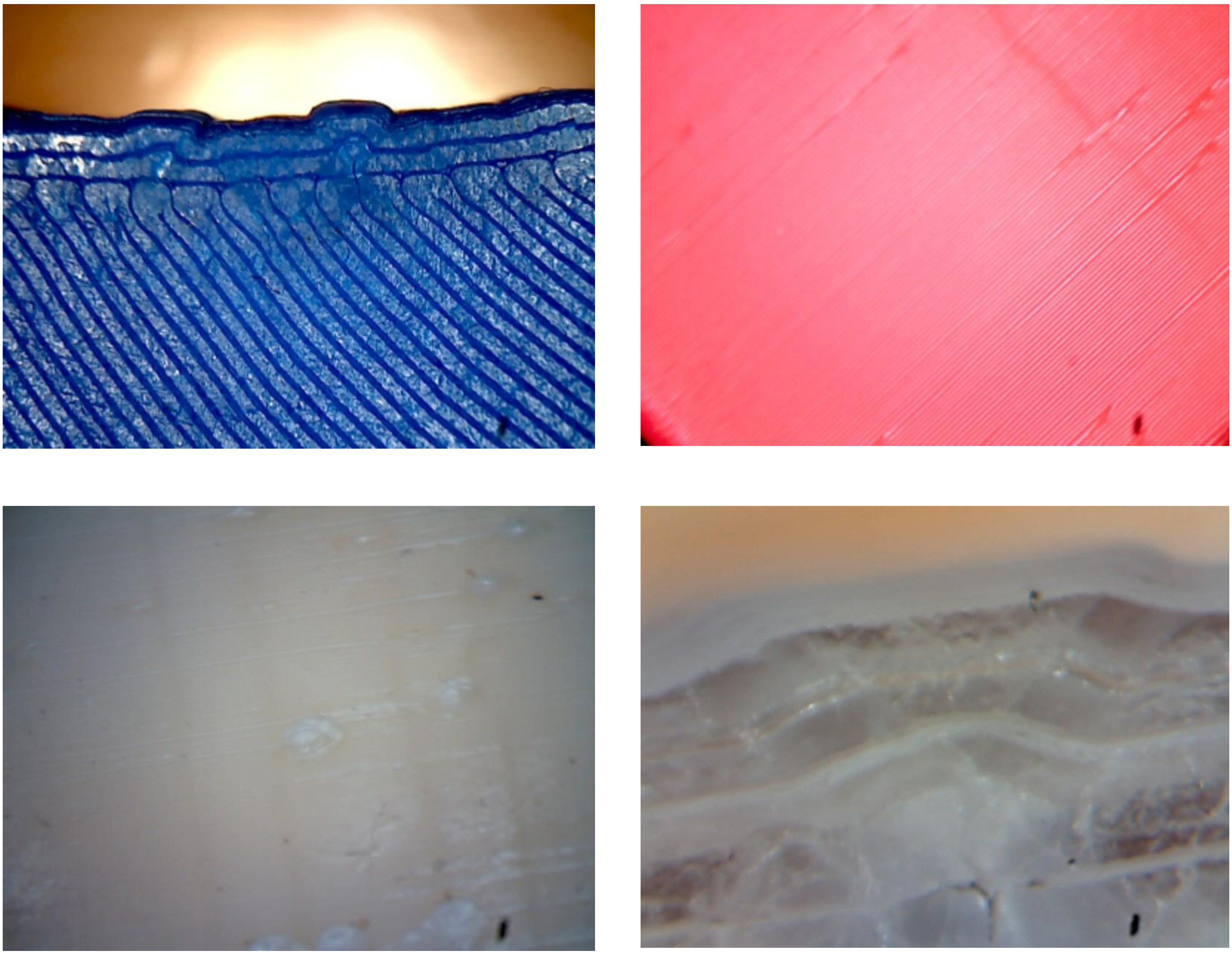
(Cracking, Air gaps, bed adhesion, debonded layers/pores, stringing/heat input, air gap in seams)

The print quality can be judged by the surface microscopy of the specimens. At explained in the preliminary analysis, at under extrusion air gaps are visible, and at over extrusion ridges and pores are visible. The observations made on the test materials were as follows:

Material	Specimen	Top µm	Bottom µm	Pre-test defects	Post-test defects/comments
PETG	A	0	133	-	None
	B	0	133	-	Large 45° z axis crack, 1/3 L bend, Debonding crack at at 32 mm, z axis wriggles
	C	0	133	-	Wriggles
PVDF	A	-	-	-	None
	B	-	-	-	½ L bend, wriggles
	C	-	-	-	½ L bend, wriggles (tested at higher strain than B)
ASA	A		89	-	None
	B	-444	89	-	Large 45° z axis crack, Debonding crack at pressure edges, z axis wriggles, cracks
	C	-267	89	-	Minor wriggles
PC	A	-	-	-	Large 45° z axis crack
	B	-	-	-	Minor indents
	C	-	-	-	Large 45° z axis crack, wriggles
PA12	A	0	178	-	None
	B	0	178	-	1/3 L bend, wriggles
	C	44	178	-	1/3 bend, wriggles
PA12CF	A	89	222	-	None
	B	44	222	-	Large 45° z axis crack, Cascading debonding cracks, wriggles
	C	89	222	-	None
PA6	A	0	44	Crack at 5mm, pores	Crack at 5mm, pores
	B	0	0	Crack at 4mm and 12mm, pores	Cracks at pressure edges, Crack at 4mm and 12mm, pores
	C	0	0	Crack at 12mm, pores	Crack at 12mm, pores
PA6GF	A	0	0	Pores	None
	B	0	0	Pores	Minor indents
	C	0	0	Pores	None
POM	A	-	-	Pores	Bottom fell off

Wriggles

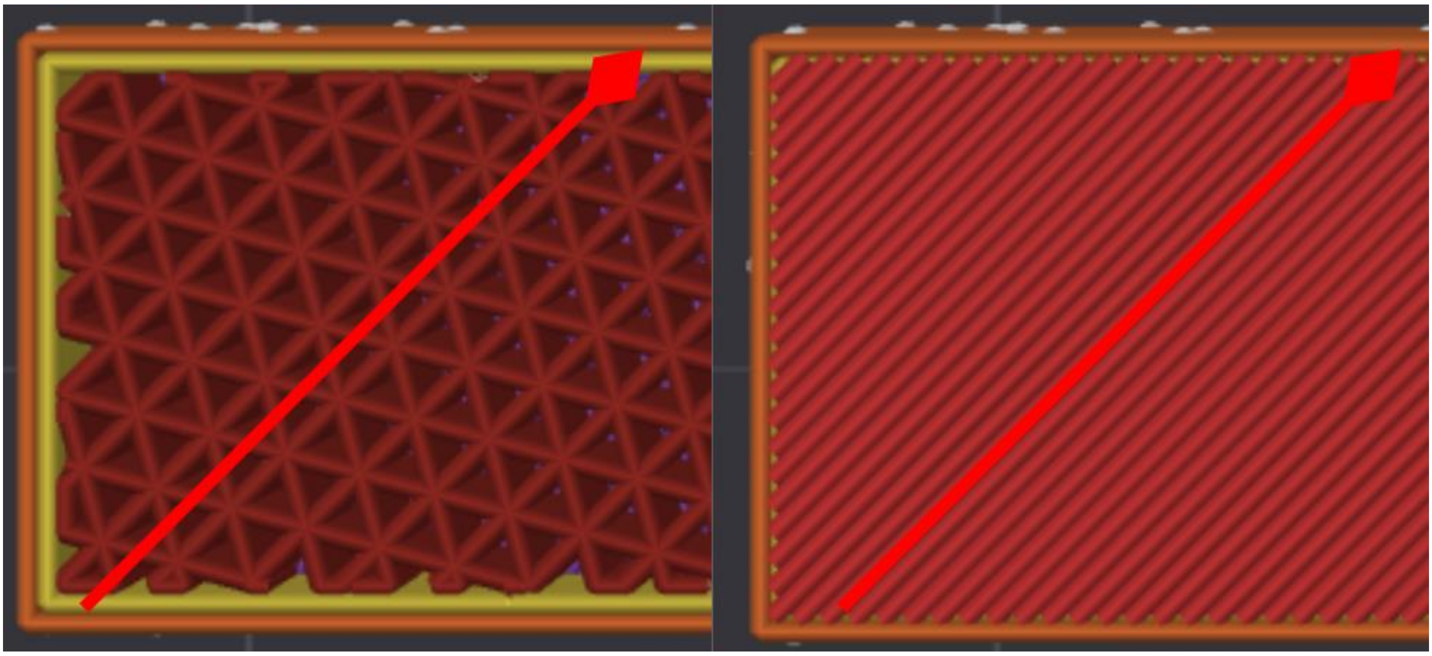
Wriggles are small buckling areas on the surface. They occur near air gaps at the wall-infill boundary. If was the most common failure and was present in all specimens that failed in compression and fatigue test, expect PC in compression test. This type of failure occurs because of fibre deformation and is aligned with the z print axis:



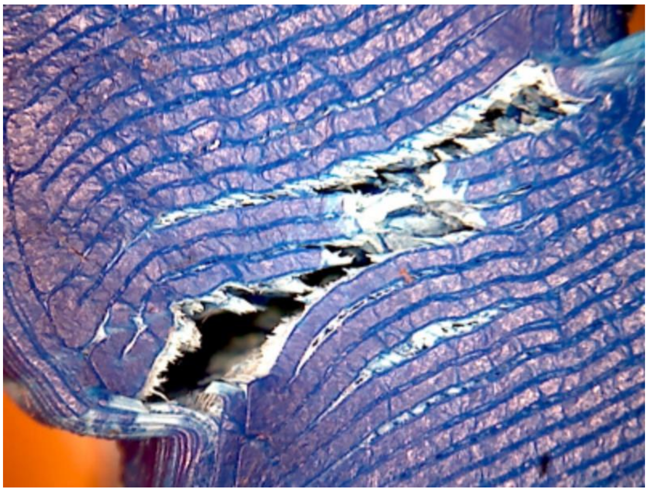
This defect is only found in compression, whereas the tensile deformations stay straight. Its presence may be an early indicator of failure but is also dependent on the internal structure of the print. The exceptional case of PC was a brittle break, whereas in the fatigue test it was present, which had a ductile break. This indicates wriggles might not appear in brittle high UTS materials. As there are no signs of wriggles in the other high UTS materials (PA6, PA6GF).

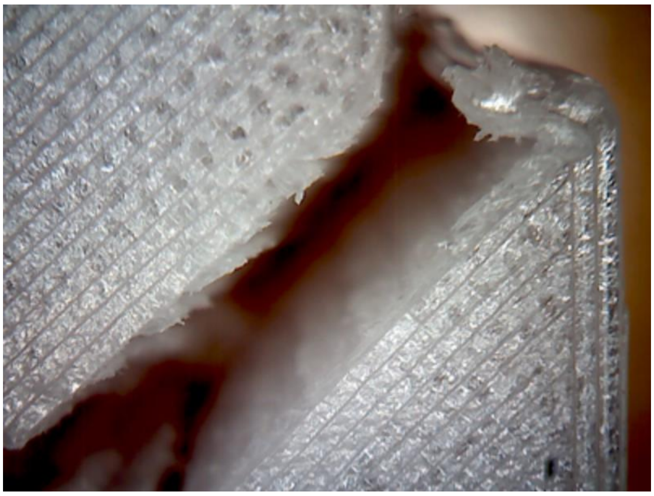
45-degree crack

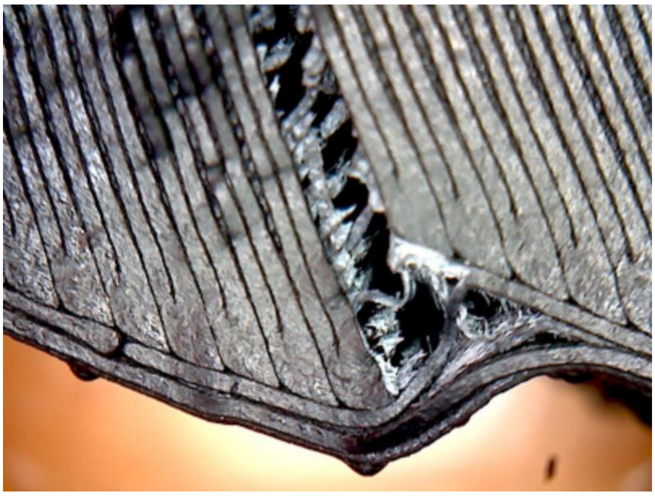
The 45° z axis crack was present in 4 materials, PETG, ASA, PC and PA12-CF. This is due to suboptimal orientation of the infill, as it aligns with half of the top and bottom rasters, while also loading unevenly as the raster -60° with the highest load, leading to that failing and shearing in the 45° plane.



There were some differences in the crack though. The PETG had some bottom rasters torn in the middle. ASA debonded at the holding edges. PC had almost fully intact top and bottom rasters. PA12-CF debonded at the top layers and sheared much further from the pressure area.



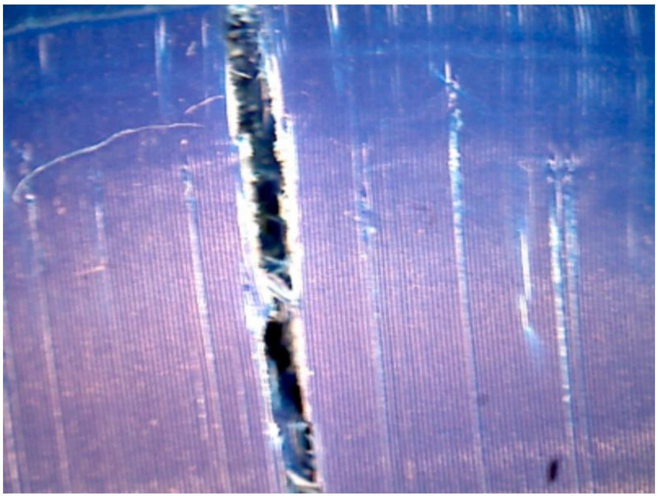


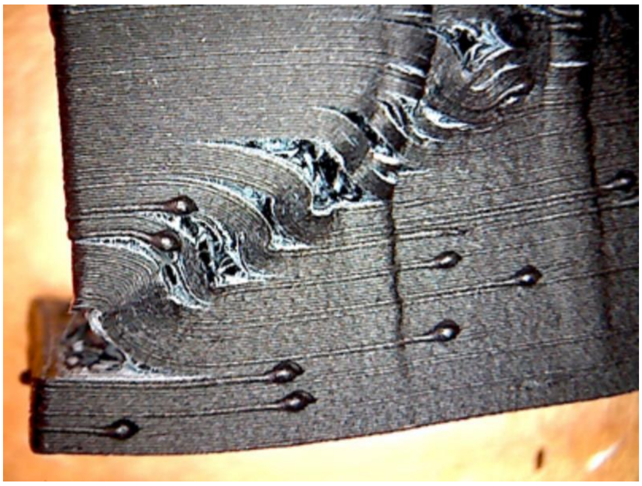


In PETG and PA12-CF a colour change (whitening) can also be observed, which can be because of recrystallization, as PET and PA are semi-crystalline polymers.

Debonding

Debonding occurred in PETG, ASA and PA12-CF in the compression test, and PA6 already had cracks from the manufacturing process. The PETG crack appears at the middle layers, and appears to have been in tension, as the surrounding area is bulging out. The ASA cracks are at the edges of the holding pressure and may have initially occurred to the shear forces as the 45° section separated. PA12-CF has a cascade of debonding cracks on both sides of a 45° crack, and they appear along a 45° XZ angle.





PA6 had crack formation from the 3D printing process. The compression test specimen cracks may have widened, but the dark colour makes it hard to distinguish features.

Defects Correlations

For these 3D printed specimens, the following defects were identified:

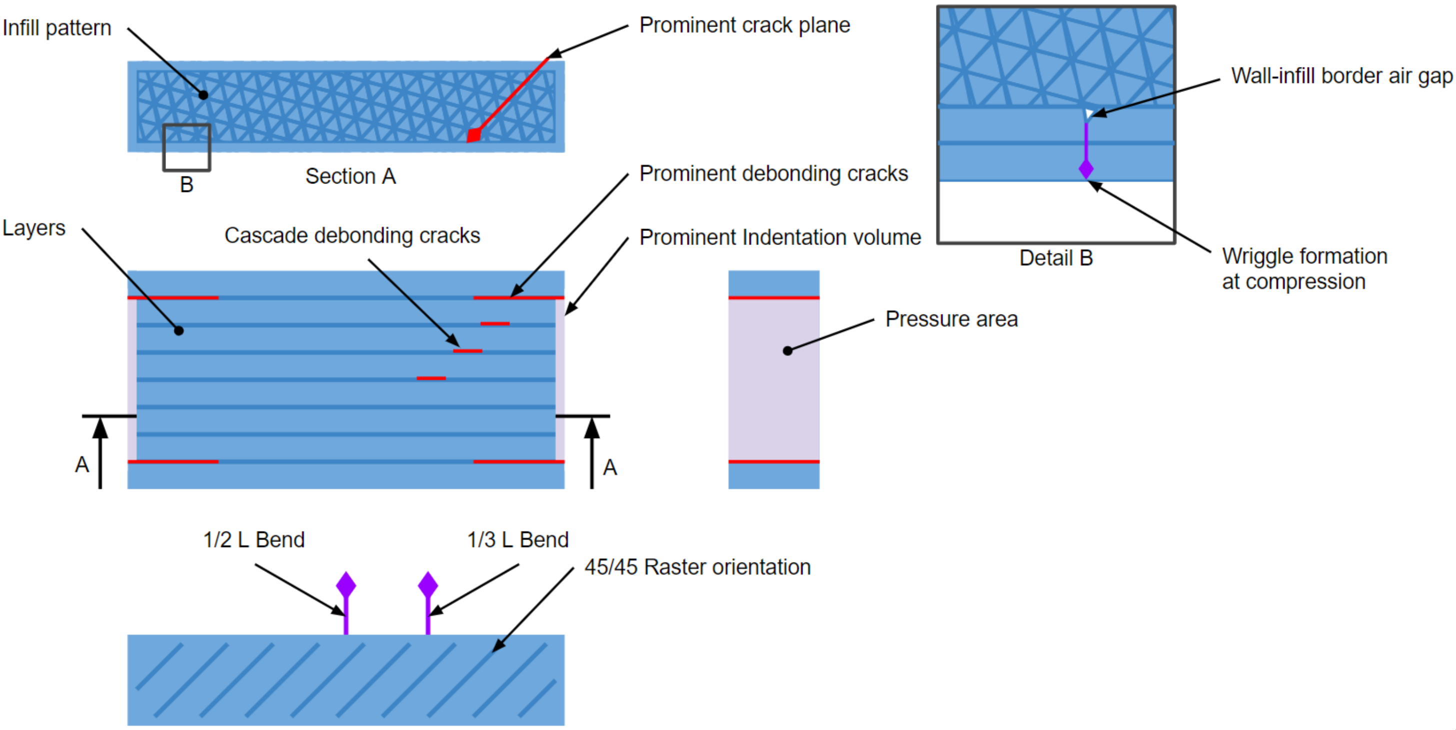


Figure 10.5-1
Identified failure modes in 3D printed specimens

The 45° crack, wriggles and bending are defects found in the Z printing direction and are therefore related to failures in the XY fibres. Debonding cracks relate to the adhesion between the fibres, which relates to the bonding strength. A 3D printed specimen can therefore have advantages or disadvantages in either or both, which will be judged based on the observed defects in the compression test:

	45° crack	Debonding	Wriggles	Bend	Mode	Fiber	Bonds
PETG	X	X	X	X	Ductile	-3	-1
PVDF			X	X	Ductile	-2	0
ASA	X	X	X		Brittle	-2	-1
PC	X				Brittle	-1	0
PA12			X	X	Ductile	-2	0
PA12-CF	X	X	X		Ductile	-2	-1
PA6		X			None	0	-1
PA6-GF					None	0	0

Likewise, the fatigue test indicates the fatigue resistance by observing the defects:

	45° crack	Debonding	Wriggles	Bend	>30 cycles	Resistance
PETG			X		X	-2
ASA			X			-1
PC	X		X		X	-3
PA12			X	X	X	-3
PA12-CF						0
PA6		X				-1
PA6-GF						0

As a general overview the PA6-GF is the clearly the strongest in both tests, as it shows no signs of defects. PA6 has an initial defect from manufacturing, but changes in print settings may avoid it. PETG, which has been used in previous fixturing project, has a poor to mediocre performance compared with the other materials. But unlike the better candidates ASA and PC, it has a less explosive break. Therefore, caution is advised when using high strength brittle materials in these high force applications. ASA and PC are the cheaper materials compared with PA6 and PA6-GF and should therefore be considered low-cost alternatives. Wherein ASA may have better fatigue properties, and PC high strength applications.

10.6 Additional 3D printing tests

Throughout the project additional tests of the capabilities of 3D printing were tested. Modern FFF technologies include many filament types, which are most often used only using one type at per part. However, with the AMS system, up to 16 different filaments can be used in one print. It is meant for multi-colour prints in the same material such as PLA, but many materials have similar nozzle temperatures making it possible to merge them. Initially a Benchy was printed using PETG, ASA and PC on different layers, using the same print settings as in the test specimens. The PETG bonded well, but the ASA and PC had weak adhesion, resulting in debonding. Following this a car model was printed using PETG, PETG-CF, ASA and PC, using 255°C nozzle temperature and 85°C bed temperature, which performed much better.

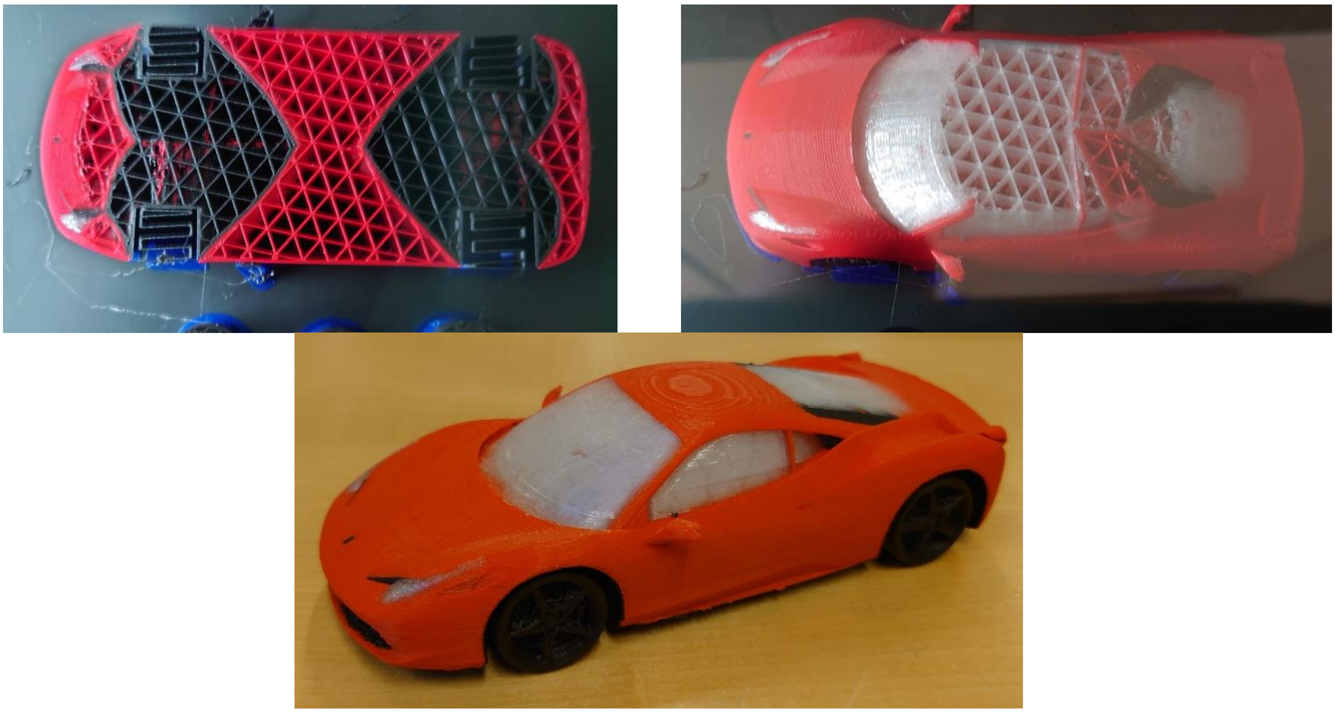


Figure 10.6-1
3D printed part using red ASA, transparent PC, black PETG-CF, and remaining blue PETG for supports

This may have applications in having diverse mechanical and thermal properties throughout the part, and cost savings in using cheaper material in some layers. The most common application seen in social media is PLA-TPU, as the PLA part is very stiff, and the TPU part is flexible.

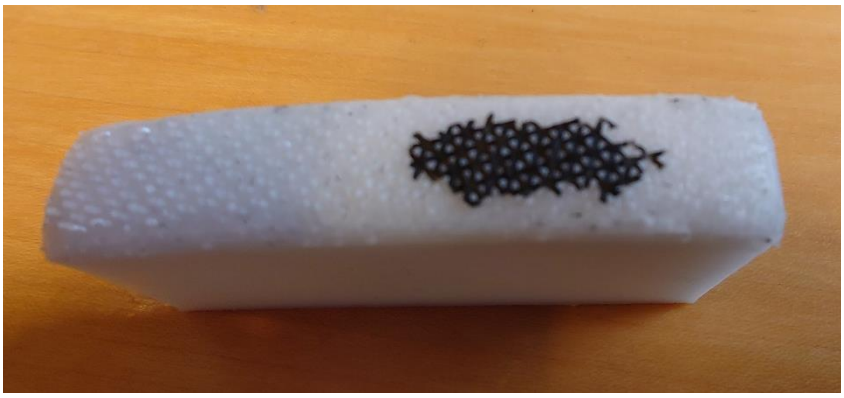


Figure 10.6-2
3D printed POM using PETG and PA6 raft

For this project POM was used in the various test. POM has very low bed adhesion, wherein it is recommended to use a cellulose bed, which is not available for most 3D printers. A solution was found by using a raft of PETG or PA6, which had great adhesion, and then over extruding POM into a triangular pattern to fix the first layers. Resulting the more consistent prints and allowing for more geometric design freedom. The POM did still warp, and the PETG-POM contact surface has a large bend. This was mitigated using PA6 with its higher thermal and mechanical resistance, wherein the POM did warp from the PA6, but the final shape was closer to the desired one.

The major problems with multi material print are interlayer adhesion, but also the AMS and printer. The filament spools tend to tangle, overloading the AMS motors and stopping the print. It is a simple fix when the knot is visible to untangle it. Filament spools using very light materials such as cardboard tend to wobble a lot when retracted, increasing the chance for failure when low on material. The printer wastes a lot of material when changing filaments, as it must purge old filament and clean the nozzle each time. The old filament is extruded into a chute, which can get clogged if the filament gets stuck inside. This requires the operator to empty it or remove the stuck piece manually occasionally.

10.7 Case fixtures

10.7.1 Modelling fixtures

3D scans were used to model the fixture, wherein many methods can be used. The common reverse engineering strategies involve either creating planes from surfaces, then cutting them to size for every pane. The other option is to create a part using the scanned file as a guide for sketches. Both these methods are very time consuming. Therefore, Blender was found to be a good alternative, as it has many tools that work well with meshes. It was also better at setting a datum for more complex shaped parts. Compared to normal CAD software tools like Boolean difference operations, manifolds and sculpting were useful for creating the fixture.

The profile can be smoothed with sculpting, holes can be filled using manifolds, and shapes can be added then made in the desired fixture shape, and then have the part profile removed.

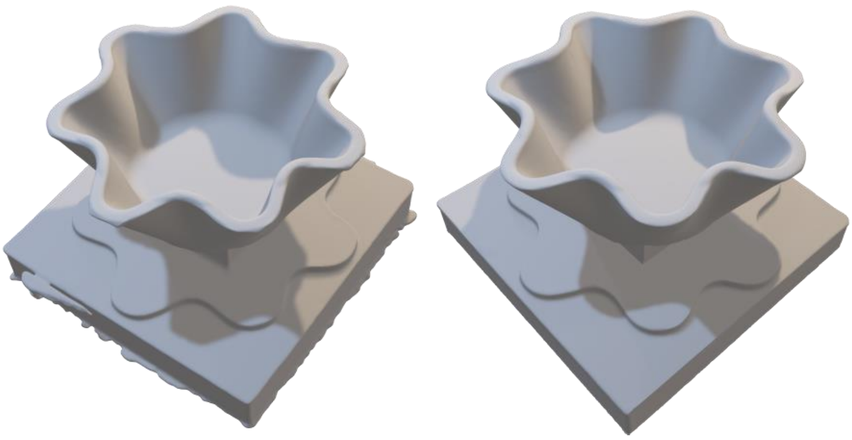


Figure 10.7-1
Raw 3D scanned object (left) compared to cleaned object (right)

The slicer itself also has tools that help with fixture design. With a simple part and fixture the model can be imported as a negative part, which can be placed in the fixture part. More complex configurations can also be made using strategic cuts in the mould part. Additional guides like pins can also be added using cylinder as a part and negative part.

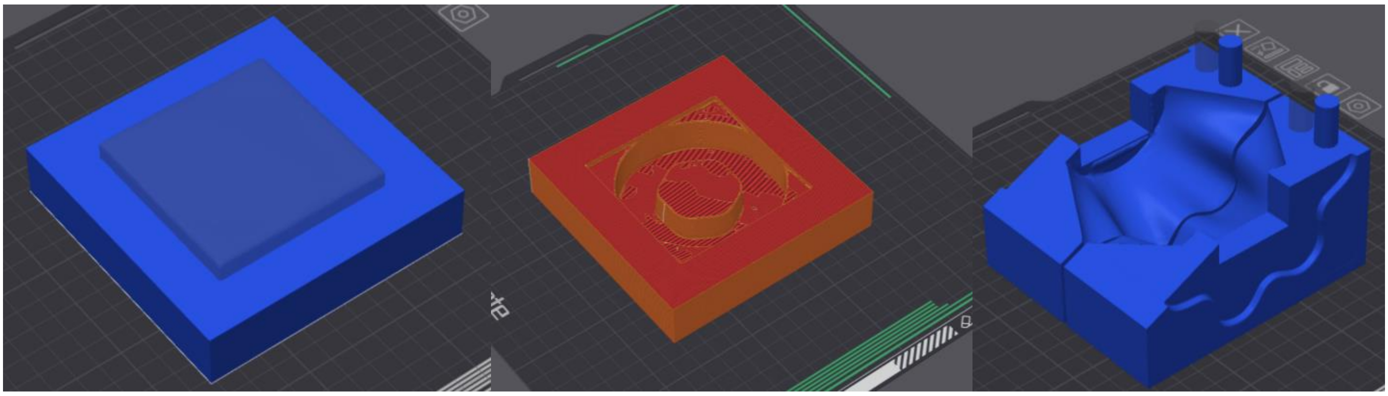


Figure 10.7-2
Simple mould for hexagonal part and fixture made for cup using cuts and pins

10.7.2 Jydsk Aluminium Industri

At the first company visit on 9/1-2024, Jydsk Aluminium Industri (JAI) presented a case wherein a hand moulded fixture was used to machine areas a part with a delicate surface treatment. The current fixture was damaged (some more than others) from chips and wear. They did already use FFF for varies applications, including fixtures. Wherein they primarily used PETG and ABS. The second visit on 16/1 the fixture was 3D scanned and reconstructed into a 3D model:

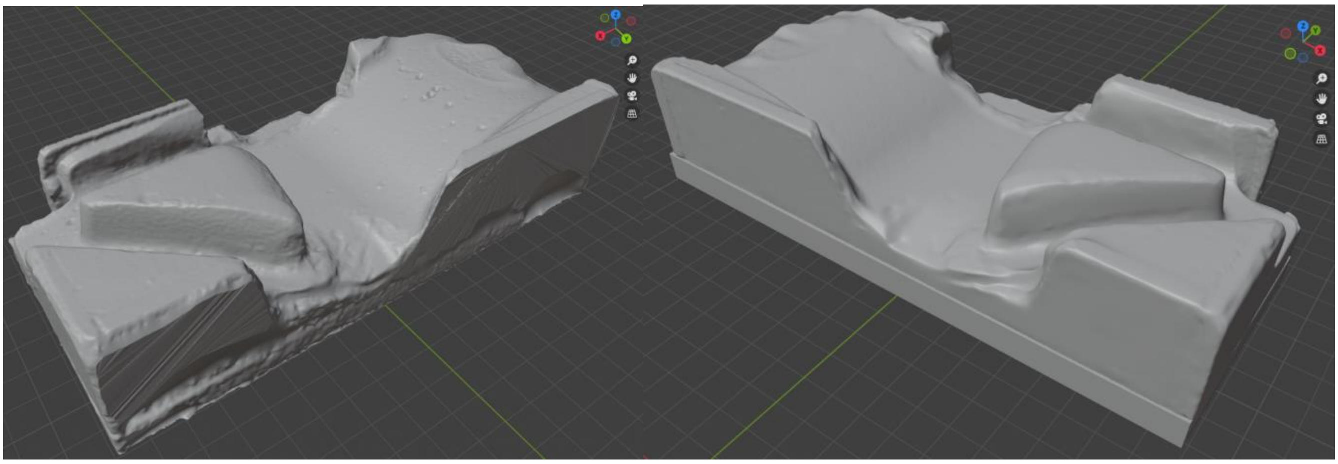


Figure 10.7-3
Raw scanned model (left) Repaired model (right)

Part of the fixture was printed to test the fit on the workpiece (Figure 10.7-5), wherein some volume was removed to grind less against the part. On the 26/1 a draft model (printed in PLA) including the holes on the bottom to fit the worktable was tested at JAI, but some distances were measured wrong by the technician. Other dimensions were good, and it was agreed to remeasure the final hole geometry and make the final part in a combination of PA6-GF for a rigid bottom, and PA6 for a strong non-abrasive surface (Figure 10.7-4).

Figure 10.7-5

Figure 10.7-4

The PA had some warping on the bottom, which may be mitigated by lowering temperatures on bed and nozzle or using a brim. It used the PA6-GF print setting used for test specimens, with a varying infill density ranging from 50% to 15% in different sections, to cut down printing time and cost. 15-20% was used in non-load bearing areas. The final print took 18 hours and 402g for a set of 2, 128g of PA6-GF and 274g of PA6 for a total cost of 208 DKK per set. The final fixtures were tested on the 1/2, which should've included machining test, however the product until March was finished before the visit. However, the fit was tested, wherein the warping made it a bit difficult to assemble the first side of the fixture, but the second side was alike the old fixture. There were problems with the threads, as the plastic threading is weaker than the usual steel, therefore one of the was tightened too much damaging the thread. The fixture fit the workpiece as well as the old one and tolerated the pressure from the clamping blocks above. They were generally impressed by the strength of the fixture, as no dents could be observed when hammering it into the fixture.

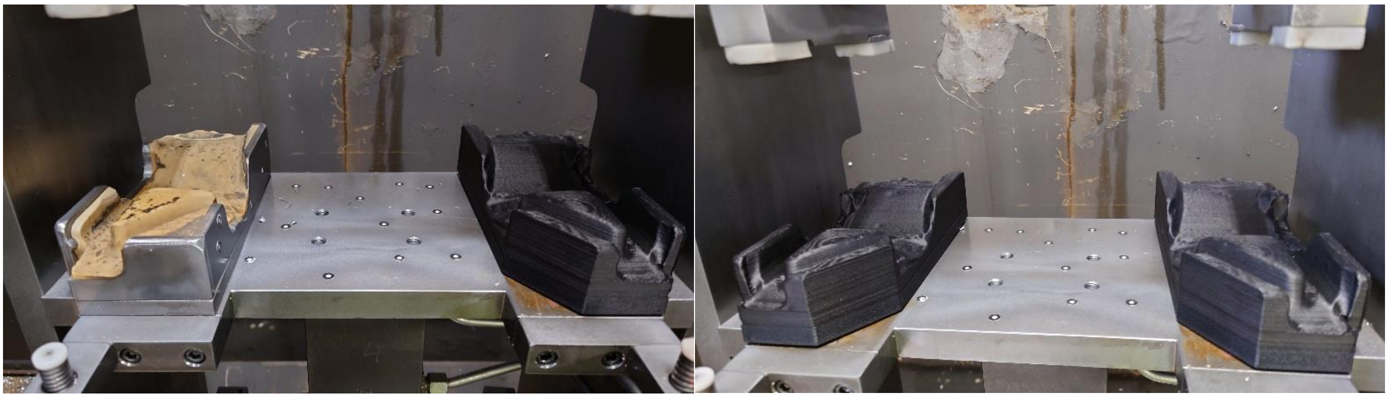


Figure 10.7-6
Final JAI fixture setup using PA6GF+PA6 FFF fixture

The fixture was used for one day (however the company contact was not informed), wherein the operators didn't adjust datums on the machine, and therefore switched back to the old fixture. The operators experienced no vibrations, resonance, or any other defects when machining. They wish to continue testing the fixture in future production.

10.7.3 VOLA

VOLA's case was introduced at a meeting on the 11/1-2024. They needed a fixture for sawing off the end of bend pipe pieces, which they had difficulty modelling due to the non-circular curve of the bend pipe. They already had many 3D printed parts in their workshop (including the design from MADE Advanced fixtures (P600)) mostly from PETG. On the 14/3-2024 they delivered 6 pipe pieces with the bend, one was 3D scanned to make the fixture:

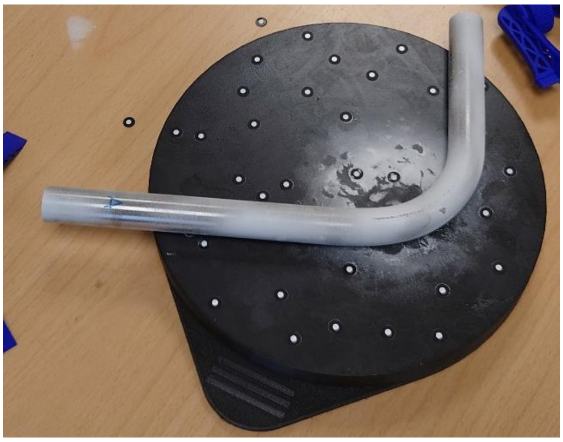
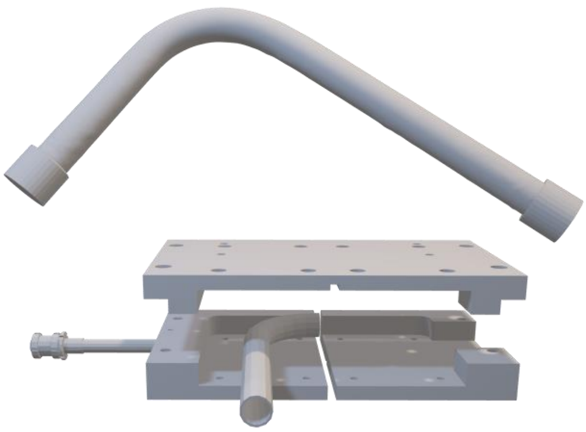


Figure 10.7-7
VOLA 3D scan using spray and markers

There were difficulties when scanning as the object is very symmetrical and shiny, spray and markers are required to get a quality 3D scan. The 3D model was then smoothed/repaired in Blender, and VOLA provided the saw matrix which the fixture would sit in. By the careful use of negative, positive and modifier parts in Bambuslicer, a fixture was quickly created without the need for external software.



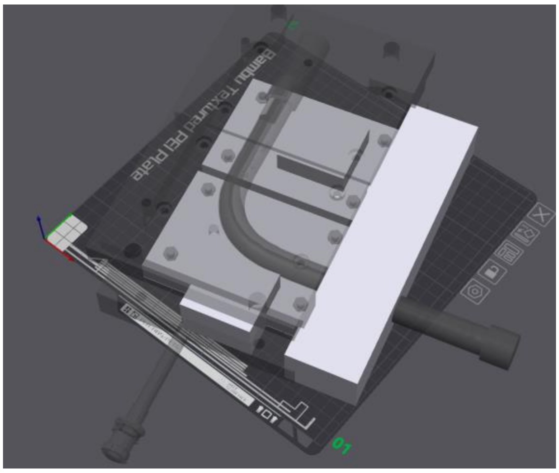
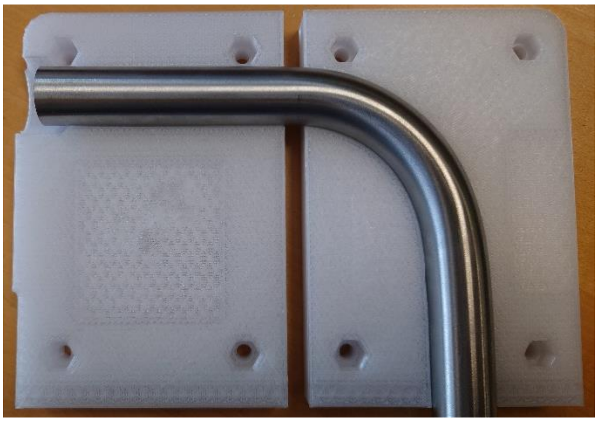


Figure 10.7-8
VOLA fixture design for 3D printing

It was decided to make the fixture in PC, as it has good dimensional stability compared to the PA6, decent superior compressive strength compared to common filaments, and non-abrasive unlike PA6-GF.

It was possible to fit all 6 pipes in the fixture using just the raw scan. However, it requires some force (~80kg), therefore a set was made with a ±0.4% tolerance in all axis, which resulted in a good fit.



At the company they reported no flaws in the fixture or sawing process. It had adequate holding force and made no marks on the part.

10.7.4 DAMRC

As an internal case a fixture was needed for the robotic milling in Polymers [39]at DAMRC, wherein it was decided to make a vacuum fixture system, to in future showcase a low cost automated production. The vacuum generator from previous projects was used, and provided at max -0.8 bar and it practice on the fixture -0.67 bar. Theoretically this provides 109 N of holding force (10.9 kg), which has not been measured, but in practice it is near impossible to remove the workpiece by hand when the vacuum is active.

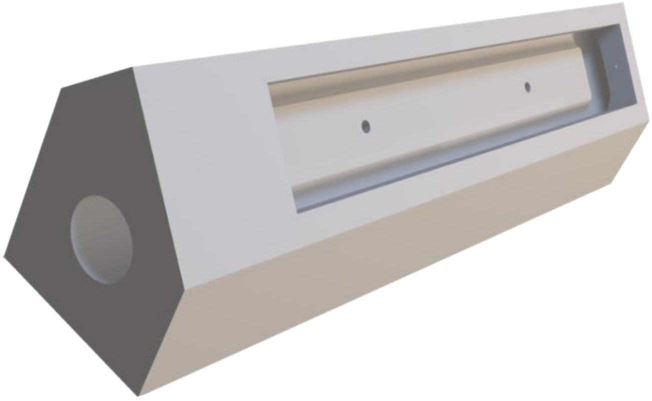


Figure 10.7-9
Robotic milling vacuum fixture

Using 3D printing the internal air channels were manufactured directly, and the tubing was connected using thread directly cut/deformed in the plastic, using the thread adaptor piece. The fixture was made in PETG, and rubber lining was installed in the corners of the bottom surface of the workpiece. When tested the vacuum was airtight and held the workpiece firmly.

11 Discussion

Ranking the materials depending on their performance (without considering to which degree) results in the following table:

	Printing Experience	Absorb-tion	Compression		Vibration		Fatigue	Total Rank
			UCS	Stiffness		Damping		
PA6-GF	Easy	1	1	1	2	5	1	1
PA6	Easy	5	1	2	1	8	2	2
PETG	Easy	3	3	3	5	2	3	2
ASA	Mediocre	2	4	5	3	7	2	3
PC	Easy	7	2	4	4	8	4	4
PA12	Mediocre	4	5	7	7	3	4	5
PA12-CF	Mediocre	8	5	6	6	4	1	5
PVDF	Hard	6	6	8	8	1		6
POM	Extremely Hard	9						7

Table 11-1
Ranking of filament materials based on tests

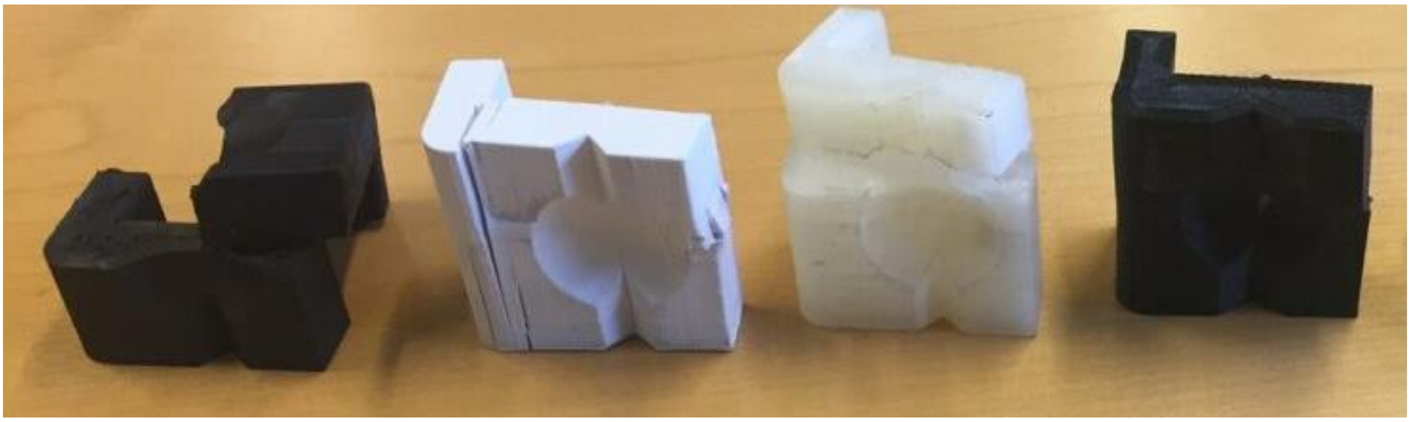
By nearly all metrics except damping, PA6-GF is the best fixturing materials from these tests. Although PETG has a mediocre performance, the consistency makes it a decent fixturing material, although it doesn't have any key advantages in any one field. PA6 on the contrary has weaknesses in damping and absorption, but high scores in others. As mentioned before, PC and ASA may have low-cost applications within fixturing, as they are significantly cheaper at 237 and 216 DKK/kg respectively, compared to PA6 and PA6-GF at 378 and 750

DKK/kg respectively. They are still more economical than high end filament like PEEK at ~5000-6000 DKK/kg. While also considering these filaments are easier to print hardware and technique wise.

Though there are many unknowns about the previous test, like the clamping forces, coolant and cutting forces, these tests have decent parody with the application, and show at least two materials with equal or better capabilities than the previously used PETG. Though the PETG may also deviate from the previous cases.

It has also been shown that print parameters both in theory and practice, have a great impact on the capabilities of a 3D printed part. Not much is known about the failure mode in previous project, but some pictures and gcode was available to analyse. At Company 5 a crack appeared after 20 parts, in a PETG-CF fixture, at 0.2 mm layer height, 12 walls, 40 top and bottom layers and 90% cubic infill. It appeared more similar to the 45-degree Z-axis crack, indicating a brittle staircase break in the top layers. From the G-code, there were only 59/129 layers with infill, wherein the resulting crack is at a 45-degree angle to both raster directions. Stronger fibres could have prevented this defect, which could be done using PA6 or PA6-GF, or a stronger infill pattern.

The UPUV - 3D print fixtures and tools (P654) tests had no documented printing parameters, and no failure (although deformation was note qualitatively). They did fail in shear tests and judging from the following picture of the tested specimens, they all seem to have debonded (even ABS though it was printed in a different orientation). The test results were not normalised for geometry, and therefore do not show an equivalent UCS or compressive modulus.



PA+, ABS, PA, PLA

The MADE Advanced fixtures (P600) fixture made fixtures at 95-100% infill, 0.25 mm layer height, 6 walls, 6 top and bottom layers, using PBT, PETG, ABS, PLA, PETG-CF at different orientations. PETG and PBT showed debonding cracks.

Compared to the previous print strategies, the specimens in this project seem to have good bonding, since all specimens that debonded in the tests, did so because of the 45-degree crack. In the print parameter test, it was also the stiffest geometry tested, though not the toughest.

12 Conclusion

The previous cases primarily used PLA, PBT and PETGCF for fixturing materials. Wherein PEGTCF showed the best results. Thise filaments are generally categorized as general purpose materials, wherein the materials tested in this project were engineered grade. Which required higher print temperatures and hardened mechanical parts to print, for which the Bambulab X1-carbon was used. The filaments were selected based on a balance of cost and mechanical capabilities, which were ASA, PETG, PC, PA6, PA6GF, PA12, PA12CF, PVDF and POM. High performance materials were outside the scope of a viable AM-fixture process, as they require specialised >400°C 3D printers and are extremely hydroscopic, and sometimes require post treatment using high temperatures.

The Einscan Pro 2X was selected as a 3D scanner, as it provides adequate model resolution for 3D printing. While also being significantly more affordable than high end scanners, and more versatile and useable than consumer grader scanners. Multiple test scans were performed to use the equipment and software properly, and gain experience in using it for reverse engineering.

For optimizing the strength of 3D prints, it was found that the temperature and speed of the process was important. As higher heat input can increase layer adhesion, but also reduce strength in the xy plane, while also creating defects and internal stresses. The print geometry also influences the strength of the part, wherein layer height, wall count, infill density and pattern can be optimized to increase strength. Adding fibres can also increase strength in the xy plane, depending on the material, length and adhesion to the matrix, but may also decrease layer adhesion. The crystallinity of the polymer increases the strength as well, especially the weaker z direction is improved by annealing the part. Based on this different temperatures and printing speeds were used to print the materials, and a triangular infill pattern at 95% density with 2 walls and a 0.1 mm layer height was used with 0.4 mm nozzle.

Previous projects conducted absorption tests, and some mechanical tests, but had mixed results. For this project 7 tests were made to determine the capacities of the materials. The absorption test showed little to no correspondence with the material water absorption. Which may be due to the porosity of the material when printed. However no damage was observed on any material when exposed to coolant fluid. The compression test simulated the conventional used of a fixture, which is most often in compression. It showed PA6, PA6GF and PC as the strongest, wherein the PA6 and PA6GF didn’t fail, and only had minor indents at 200 Nm (65MPa), and PC failed at 180 Nm (59 MPa). Where conventional PETG failed at 70 Nm (30 MPa). They also had significantly higher stiffness in comparison. The previously used PETGCF and PBT performed worse than the generic PETG.

The strongest 5 materials from the compression test were selected for shear and tensile testing. These 3 materials consistently performed better than PETG and ASA, with PA6 and PA6GF failing after 15 Nm and PC at 12 Nm in the shear test, compared to 8 Nm for PETG. The UTS was also higher than PETG, however lower than expected based on the stated UTS and modulus in the material data sheets provided by the manufacturer. The PA6 was more ductile in the tensile test, as it was not possible to have good bed adhesion at lower temperatures, the higher bed temperature may have influenced the stiffness of the part.

In the modal test, using an accelerometer and modal hammer, the material damping was determined. This showed great damping properties of the more flexible filaments. Wherein PVDF had a damping ratio of up to 8%, which is near equivalent to rubber. The damping ratio influences the vibrational properties of the system, wherein a high damping ratio would help reduce vibrations. PA12, PA12CF and PETG also showed decent material damping at around 2-3%. The compressive fatigue limit test showed inconclusive results, as it was only possible to test few cycles. It was found that PETG had generally poorer fatigue strength that all other materials.

The compression test was also performed on ASA using different printing parameters, wherein most failed at the same of lower stress, and had a lower stiffness. However, using more walls showed a great increase in strength, while not significantly changing the stiffness. All the specimens were evaluated under the microscope, to detect defects. 4 main defects were identified as: 45° crack, debonding, wriggles and bending. No defects were found in PA6GF, and some debonding occurred in the printing process of PA6. The PC had a brittle brake when under high stress.

From the test results materials were selected for company cases, wherein JAI and VOLA participated. JAI needed a faster, easier, and more robust way to make a currently hand moulded fixture. VOLA needed a sawing fixture for holding the non-circularly bend pipes. 3D geometry was scanned, and modelled into a fixture with satisfactory dimensions, and participants were pleasantly surprised by the strength of the materials used, and were able to machine and cut metal without the 3D print fixture breaking. Additionally, and internal case at DAMRC was made for the robotic mill. Wherein a specialised vacuum fixture was designed, and 3D printed.

Appendix

12.1 Material documentation

Material Data Sheet

MATERIAL 4PRINT
your filament experts

ASA

Description:

Acrylester-Styrol-Acrylnitril (ASA) is a thermoplastic material, with similar properties as ABS. ASA is extremely weather-resistant and has very good mechanical properties.
It is not so easy to print like PLA and we recommend a heated enclosure.

Storage:

Store at room temperature, out of direct heat and sunlight and in a dry place.

Identification:	
Name	ASA
Chemical Name	Acrylester-Styrol-Acrylnitril
Usage	FDM 3D Printing
Manufacturer	Material 4 Print GmbH & Co. KG, Germany

Properties:		
Test	**Value**	**Method**
Specific Gravity	1,06 g/cm³	DIN EN ISO 1183
Elongation at Break	20%	DIN EN ISO 527
Tensile Strength	50 MPa	DIN EN ISO 527
Flexural Modulus	2300 MPa	DIN EN ISO 178
Melting Point	240 - 260°C	
Heat Distortion Temperature	84°C	DIN EN ISO 75/1
Flammability	HB	UL94

Print Settings:	
Nozzle Temperature	230-250°C
Bed Temperature	90-110°C

Colors (ca. RAL) :	
● Tiefschwarz (9005)	○ Natur
○ Signalweiß (9003)	● Eisengrau (7011)
● Staubgrau (7037)	

Certificate:

REACH COMPLIANCE
RoHS

These data were are taken from the raw material manufacturer.

Contact: info@material4print.de 12.04.2021

Grupa Azoty

Tarfuse®

TECHNICAL DATA SHEET

Tarfuse® PA ESD
3D Filament

Version No.: 4.0
Date: March 2022

RECOMEMDED PRINT PROCESSING PARAMETERS

Nozzle temperature: 270 - 300°C
Build chamber temperature: 20 - 70°C
Bed temperature: 30 - 110°C
Bed material: polycarbonate (PC) mat, polyamide (PA) mat + PVA glue type
Nozzle diameter: ≥ 0.4 mm
Print speed: 30 - 60 mm/s

Physical Properties	Unit	Value	ISO standard	Test conditions
Melting temperature; DSC	°C	220	11357-1-3	10°C/min.
Glass transition temperature; DSC	°C	55-57	11357-1-3	10°C/min.
Crystalization temperature; DSC	°C	160-180	11357-1-3	10°C/min.
Density	g/cm3	1,18	1183	-
Moisture absorption	%	2	62	23°C/50%RH
Water absorption	%	9	62	23°C/sat.
Melt volume-flow rate MVR	cm^3/10min	25	1133	275°C/5 kg

Mechanical Properties	JM	XY	XZ	ZX	ISO standard	Test conditions
Print direction		Flat	On its edge	Upright		
Tensile strength	MPa	55	63	20	527-1,-2	5mm/min
Elongation at break	%	5,7	3,2	1	527-1,-2	5mm/min
Tensile E-modulus	MPa	3500	4800	2600	527-1,-2	1mm/min
Flexural strength	MPa	68	120	-	178	2mm/min
Flexural modulus	MPa	3000	4700	-	178	2mm/min
Charpy impact strength	kJ/m^2	35	-	-	179-1	1eU
Charpy notched impact strength	kJ/m^2	4.2	-	-	179-1	1eA
Vicat softening point	°C	98			306	50N
Heat deflection temperature	°C	189			75-1,-2	1.8 MPa
Surface resistivity	Ω	10xE9	-	-	IEC 60093	-
Volume resistivity	Ωxcm	10xE9	-	-	IEC 60093	-

Dry condition - moisture content max. 0.2%
Tests were performed at 23°C, unless otherwise specified.

Print processing parameters:

Nozzle temperature	*280°C*
Build chamber temperature	*70°C*
Bed temperature	*50 °C*
Nozzle diameter	*0.4 mm*
Layer	*0.2 mm*
Filling	*100%; 45°/45°*

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www.grupaazoty.com

3DXTECH Advanced Materials

TDS Rev 1.0

Technical Data Sheet: AmideX™ PA6-GF30 Glass Fiber Nylon 3D Printing Filament

Physical Properties	Standard	Unit	Typical Value
Density	ISO 1183	g/cc	1.35

Mechanical Properties	Standard	Unit	Typical Value
Tensile Strength, Break	ISO 527	MPa	62.8
Tensile Modulus	ISO 527	MPa	4261
Tensile Elongation, Break	ISO 527	%	6
Flexural Strength	ISO 178	MPa	72
Flexural Modulus	ISO 178	MPa	3600

Thermal Properties	Standard	Unit	Typical Value
Glass Transition Temperature (Tg)	DSC	°C	70
Deflection Temperature at 0.45 MPa (66psi)	ISO 75	°C	186

Electrical Property	Standard	Unit	Typical Value
Surface Resistance	ASTM D257	Ohm/sq	$>10^9$

Printed Specimen Conditions
Printer: Gearbox™ HT2
Nozzle: 0.4mm
Layer Height: 0.25mm
Infill: 100%, +/- 45°
Extrusion Temp: 265°C
Bed Temp: 70°C
Specimen Orientation: XY Flat

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Handtmann Elteka
Kunststofftechnik

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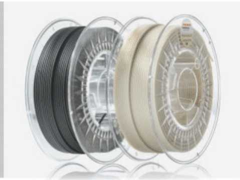
Ideen mit Zukunft.

LAURAMID® Engineered Solutions PA12

LAURAMID® 3D

PA12 FILAMENT



Das Polyamid 12 Druckfilament Lauramid® 3D zeichnet sich durch seine hohe Chemikalienbeständigkeit und Dimensionsstäbilität aus.
Aufgrund der sehr guten thermischen sowie mechanischen Eigenschaften eignet es sich hervorragend zur Herstellung von technischen Produkten.

Verfügbar in [N]atur und [C]arbonkurzfaserverstärkt in den Dimensionen Ø1,75 ±0,05 mm sowie Ø2,85 ±0,05 mm. Spulengrößen: 0,75 kg sowie 2,5 kg

Anwendungen und Eigenschaften: Funktionsbauteile, Prototypen, Vorrichtungen, Hilfsvorrichtungen

- Hohe Temperaturbeständigkeit
- Dimensionsstabil
- Sehr gute Witterungsbeständigkeit
- Gute Chemikalienbeständigkeit
- Hervorragende tribologische Eigenschaften
- Ausgezeichnete Kombination aus Festigkeit und Zähigkeit
- Ansprechende Optik

Parameterempfehlungen:	■ Lauramid® 3D N01 (Natur)	■ Lauramid® 3D C01 (Carbonfaser)
Drucktemperatur:	235-255 °C (Druckerabhängig)	245-265 °C (Druckerabhängig)
Druckbetttemperatur:	60 - 110 °C (Bettmaterialabhängig)	60 - 110 °C (Bettmaterialabhängig)
Druckunterlage[1]:	PEI, Glas; Alu, Lauramid®	PEI, Glas; Alu, Lauramid®
Druckgeschwindigkeit:	<40 mm/s (Düse Ø0,6 ~4,8 mm³/s)	<40 mm/s (Düse Ø0,6 ~4,8 mm³/s)
Lagerung:	trocken (Verarbeitung aus Trockenbox)	trocken (Verarbeitung aus Trockenbox)
Bauteilkühlung[2]:	keine	keine
Düse:	≥ Ø 0,2 mm	≥ Ø 0,4[3]

EIGENSCHAFT	PRÜFVORSCHRIFT	■ N01	□ C01	EINHEIT
Dichte	DIN EN ISO 1183	1,03	1,10	kg/m³
Streckspannung (x-y/z)	DIN EN ISO 527	40/25	56/15	Mpa
Bruchdehnung	DIN EN ISO 527	17	7	%
Zug-E-Modul	DIN EN ISO 527	1293	4632	Mpa
Biegespannung	DIN EN ISO 178	42	77	Mpa
Biegemodul	DIN EN ISO 178	1307	3720	Mpa
Biegefestigkeit	DIN EN ISO 178	53	89	Mpa
Kerbschlagzähigkeit +23°C (Charpy)	DIN EN ISO 179	100	19	kJ/m²
Vicat B50	DIN EN ISO 306	125	125	°C
HDT A	DIN EN ISO 75	70	108	°C

Werte können abhängig der Druckparameter abweichen. Prüfkörper mittels 3D-Druck erstellt.
100% Solide (Perimeter/Walls)
Messungen in x-y soweit nicht anders angegeben.

[1] Haftvermittler wie z.B. Magigoo PA verwenden
[2] Bei kurzen Layerzeiten (<10 s) bzw. kleinen Teilen/Elementen kann eine Bauteilkühlung verwendet werden.
[3] Bei großen und länger dauernden Druckaufträgen ≥ Ø 0,6 mm empfohlen. Düsenwerkstoff für abrasives Material verwenden.

MECHANICAL PROPERTIES

Property	Testing Method	Typical Value
Young's modulus (X-Y)	ISO 527, GB/T 1040	2307 ± 60 MPa
Young's modulus (Z)		2260 ± 137 MPa
Tensile strength (X-Y)	ISO 527, GB/T 1040	62.7 ± 1.3 MPa
Tensile strength (Z)		41.9 ± 2.1 MPa
Elongation at break (X-Y)	ISO 527, GB/T 1040	3.15 ± 0.35 %
Elongation at break (Z)		2.2 ± 0.2 %
Bending modulus (X-Y)	ISO 178, GB/T 9341	2247 ± 159 MPa
Bending modulus (Z)		N/A
Bending strength (X-Y)	ISO 178, GB/T 9341	100.4 ± 2.1 MPa
Bending strength (Z)		N/A
Charpy impact strength (X-Y)	ISO 179, GB/T 9343	3.41 ± 0.03 kj/m^2
Charpy impact strength (Z)		N/A
Low temperature impact strength (X-Y)	ISO 179-1/1eA:2010, -30°C	9.8 ± 0.5 kj/m^2

HOW TO MAKE SPECIMENS

Printing temperature	255 °C
Bed temperature	100 °C
Shell	2
Top & bottom layer	4
Infill	100%
Environmental temperature	70 – 80 (recommended) (°C)
Cooling fan	OFF

Note:

- When printing with PolyLite™ PC it is recommended to use an enclosure. For large part it is recommended to use a heated chamber.
- It is recommended to anneal the printed part right after the printing process to release the residual internal stress. Annealing settings: 100°C for 2h

Material Data Sheet

MATERIAL 4PRINT
your filament experts

PETG

Description:

Polyethylenterephthalat (PET) is a thermoplastic Material, which the most people know in form of PET-bottles. PETG is a glycol-modified PET, which is knowen for transparency and it is nearly undestroyable. It is easy to print like PLA and in terms of mechanical characters even a bit better than ABS.

Storage:

Store at room temperature, out of direct heat and sunlight and in a dry place.

Identification:	
Name	PETG
Chemical Name	Polyethylenterephthalat + Glykol
Usage	FDM 3D Printing
Manufacturer	Material 4 Print GmbH & Co. KG, Germany

Properties:

Test	**Value**	**Method**
Specific Gravity	1,27 g/cm³	ASTM D792
Elongation at Break	70%	ASTM D638
Tensile Strength	53 MPa	ASTM D638
Flexural Modulus	2150 MPa	ASTM D790
Melting Point	200 - 230 °C	ASTM D3418
Heat Distortion Temperature	70 °C	ASTM D648
Flammability	HB	UL-94

Print Settings:	
Nozzle Temperature	225-255 °C
Bed Temperature	60-80 °C

Certificate:

REACH COMPLIANCE

RoHS

Colors (ca. RAL) :	
Eisengrau (7011)	Leuchtrot (3024)
Leuchtgrün (6038)	Transp. Gelb
Tiefschwarz (9005)	Transp. Grün
Signalweiß (9003)	Transp. Rot
Transparent	Transp. Blau
Signalblau (5005)	Transp. Schwarz
Verkehrsgelb (1023)	Himmelblau (5015)
Leuchthellorange(2007)	Reinrot (3028)
Graualuminium (9007)	Staubgrau (7037)

These data were are taken from the raw material manufacturer.

Contact: info@material4print.de

12.04.2021

Grupa Azoty

Tarfuse®

PRELIMINARY TECHNICAL DATA SHEET

Tarfuse® POM

3D Filament

Version No.: 1.1
Date: April 2021

RECOMMENDED PRINT PROCESSING PARAMETERS

Nozzle temperature: 210 - 240˚C
Build chamber temperature: 70 - 140˚C
Bed temperature: 100 - 130˚C
Bed material: cellulose (paper, wood, cork) mat + PVA glue type
Nozzle diameter: ≥ 0.4 mm
Print speed: 10-30 mm/s (slowly)

Physical Properties	Unit	Value	ISO standard	Test conditions
Melting temperature; DSC	°C	165-170˚C	11357-1-3	10°C/min.
Glass transition temperature; DSC	°C	-50˚C	11357-1-3	10°C/min.
Crystalization temperature; DSC	°C	140	11357-1-3	10°C/min.
Density	g/cm³	1,42	1183	-
Humidity absorption	%	0,2	62	23°C/50%RH
Water absorption	%	0,8	62	23°C/sat.
Melt volume-flow rate MVR	cm³/10min	2,5	1133	275˚C/5 kg

Mechanical Properties	Unit	XY	XZ	ZX	ISO standard	Test conditions
Print direction		Flat	On its edge	Upright		
Tensile strength	MPa	50	To be tested	To be tested	527-1,-2	50mm/min
Elongation at break	%	11	-	-	527-1,-2	50mm/min
Tensile E-modulus	MPa	1870	-	-	527-1,-2	1mm/min
Flexural strength	MPa	-	-		178	2mm/min
Flexural modulus	MPa	-	-	-	178	2mm/min
Charpy impact strength	kJ/m²	-	-	-	179-1	1eU
Charpy notched impact strength	kJ/m²	-	-	-	179-1	1eA
Vicat softening point	°C	-			306	50N
Heat deflection temperature	°C	-			75-1,-2	1,8 MPa

Tests were performed at 23˚C, unless otherwise specified.

Print processing parameters:

Nozzle temperature	*230˚C*
Build chamber temperature	*70˚C*
Bed temperature	*130˚C*
Nozzle diameter	*0.4 mm*
Layer	*0.2 mm*
Filling	*100%; 45°/45°*

Grupa Azoty S.A.
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Poland

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Faks: +48 14 637 21 51

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add:north
3D-FILAMENT

TECHNICAL DATA SHEET

Ulricehamnsvägen 11
514 62, Ölsremma

+46 73 400 38 78
info@addnorth.com

Adamant S1 is made of 100% PVDF [Polyvinylidene fluoride], which makes it the ideal industrial-grade printing material. The Adamant S1 offers good thermal and excellent chemical and solvent resistance.

Revision 1.0

Product ADAMANT

		STANDARD	UNIT	TYPICAL VALUE
PHYSICAL PROPERTIES	Density	ISO 527	g/cc	**1.8**
MECHANICAL PROPERTIES	Tensile Strength, Break	ISO 527	MPa	**58**
	Tensile Modulus	ISO 527	MPa	**387**
	Tensile Elongation, Break	ISO 527	%	**>50**
	Flexural Strength	ISO 178	MPa	**120**
	Flexural Modulus	ISO178	MPa	**3155**
THERMAL PROPERTIES	Glass Transition Temperature (Tg)	DSC	°C	**-34**
	Continuous Operating Temperature		°C	**120**
THERMAL PROPERTIES	Flammability Classification (1.5 mm)	IEC 60695-11		**V-0**

DATE ISSUED

MONTH
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18 19 20 21 22 23 24 25 26 27 28 29 30 31
YEAR
2017 2018 **2019**

DISCLAIMER

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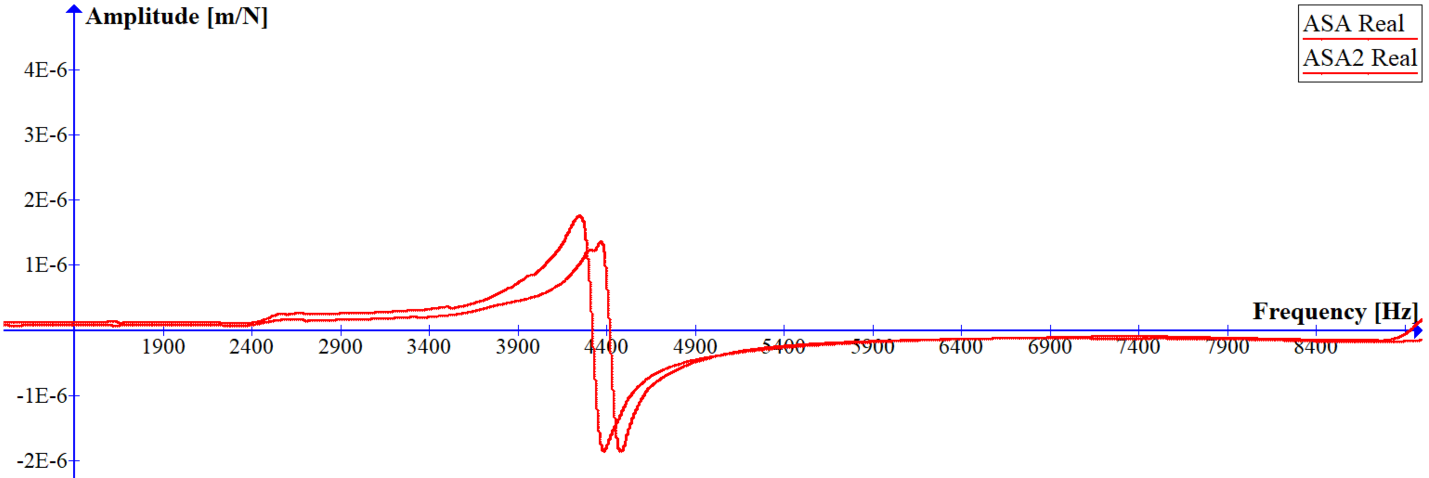
12.2 FRF data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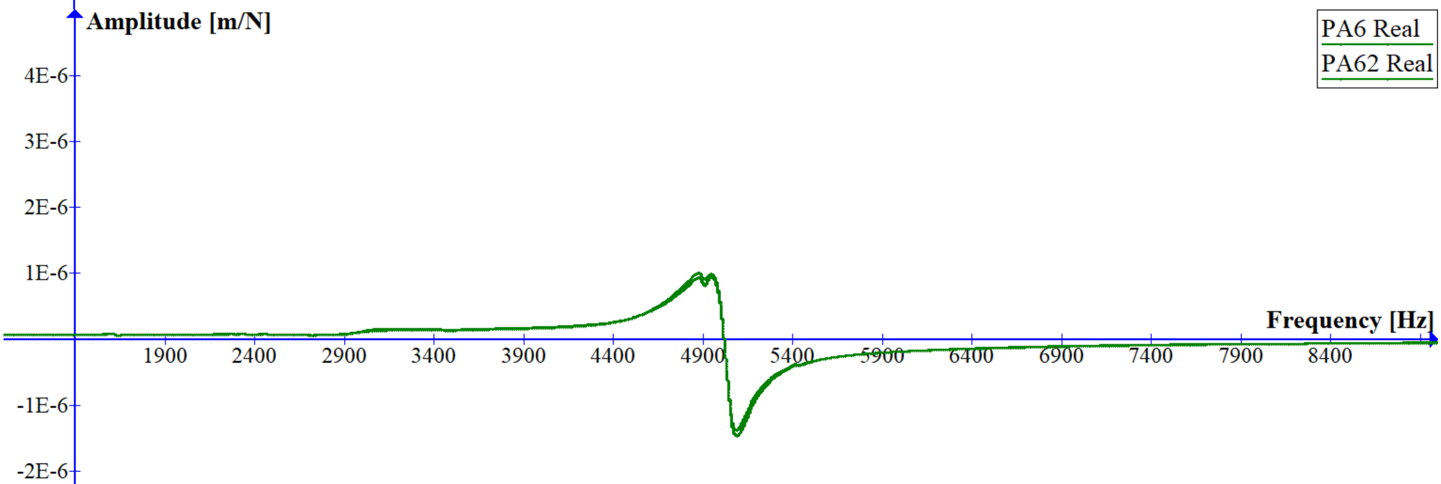
ASA2 Real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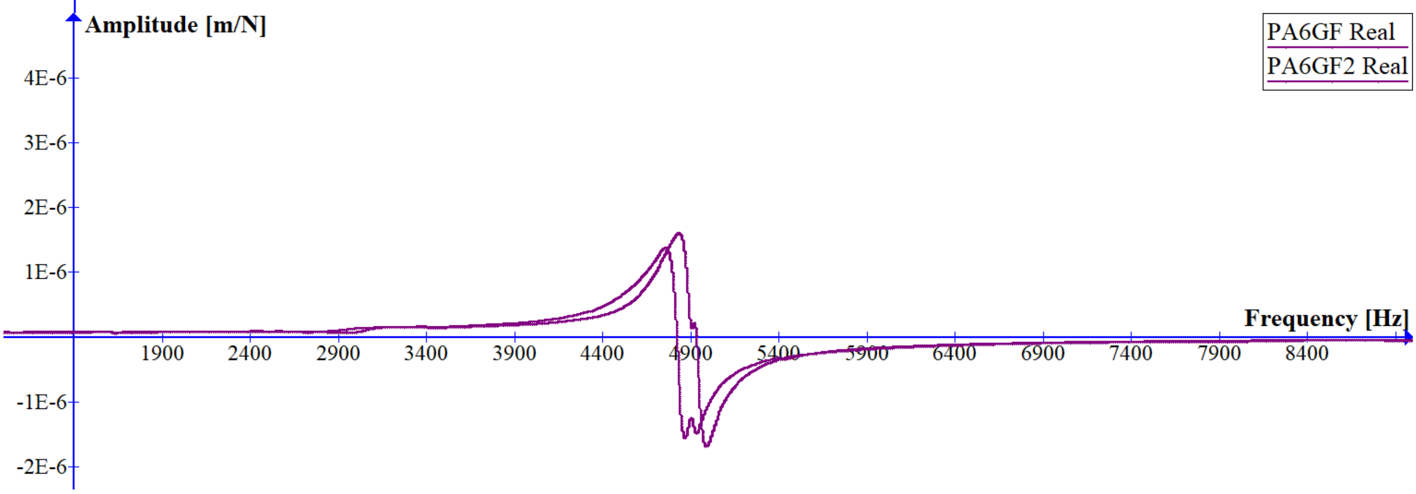
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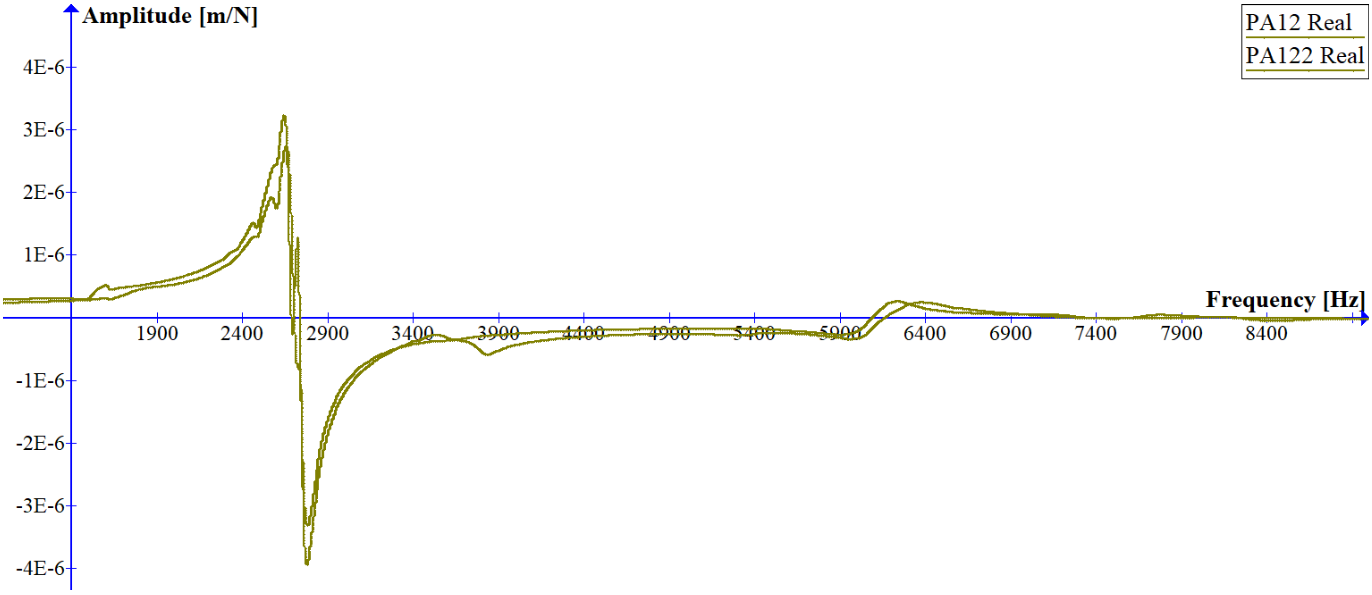
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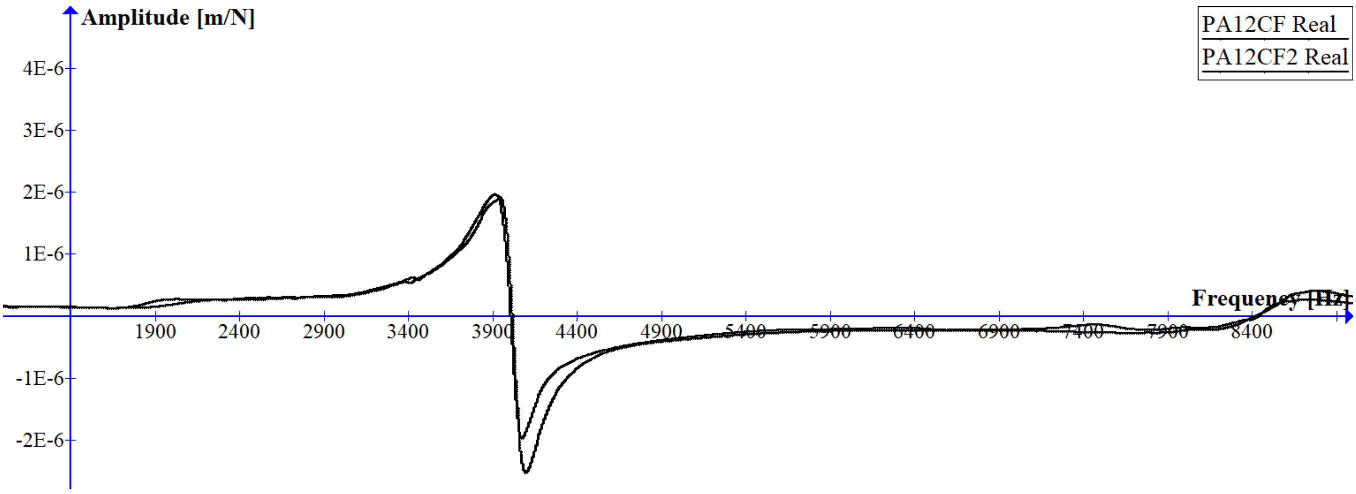
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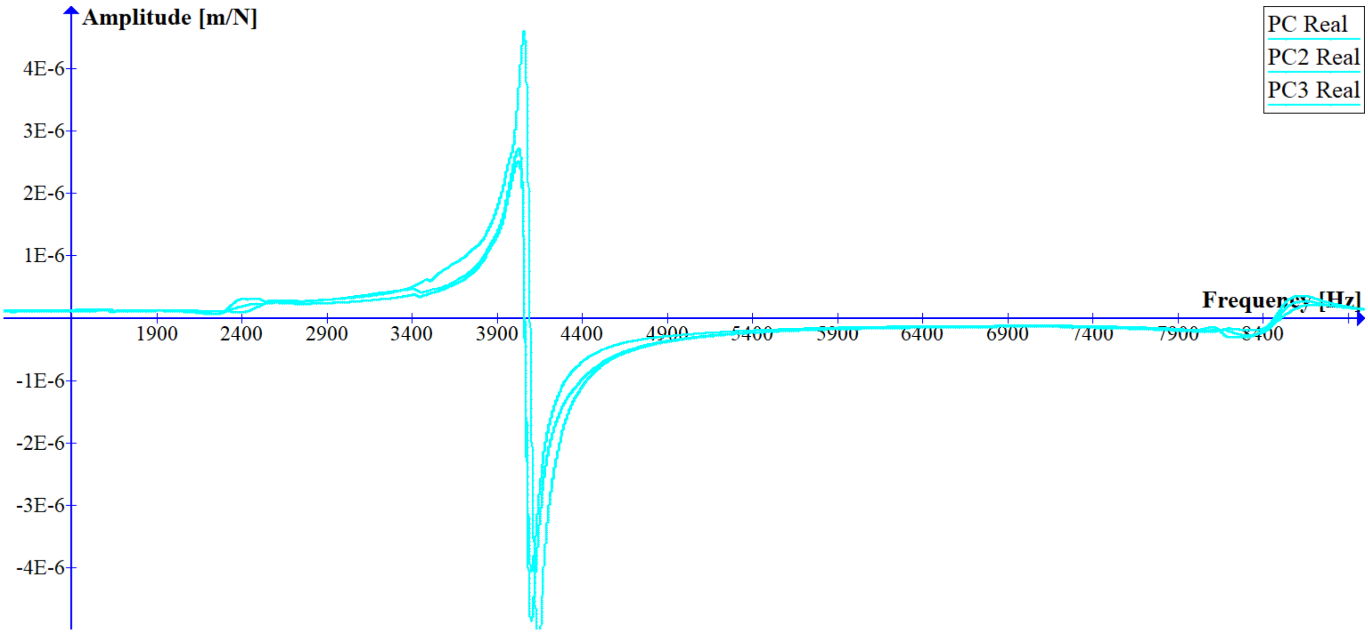
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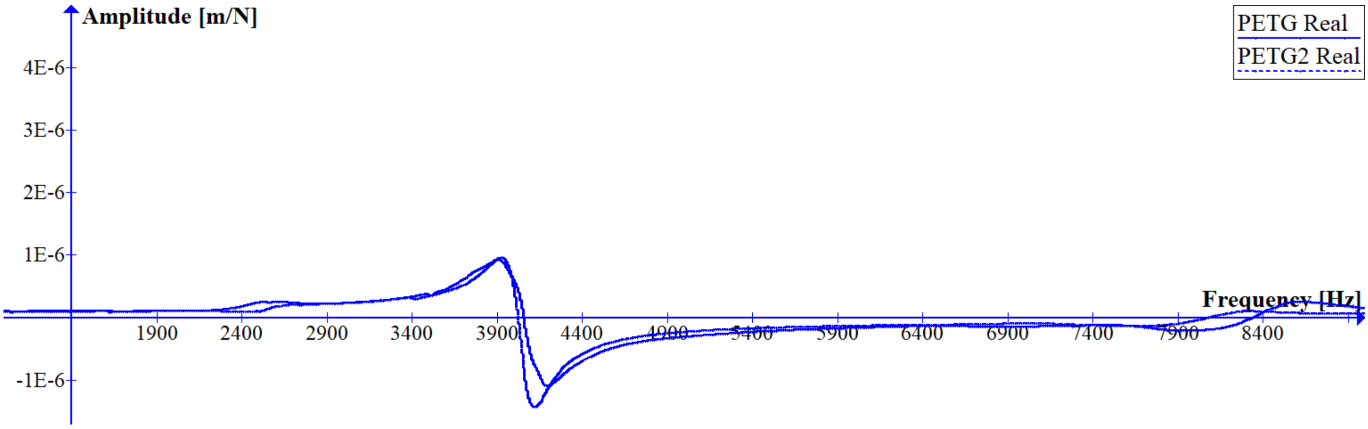
PC2 Real
PC3 Real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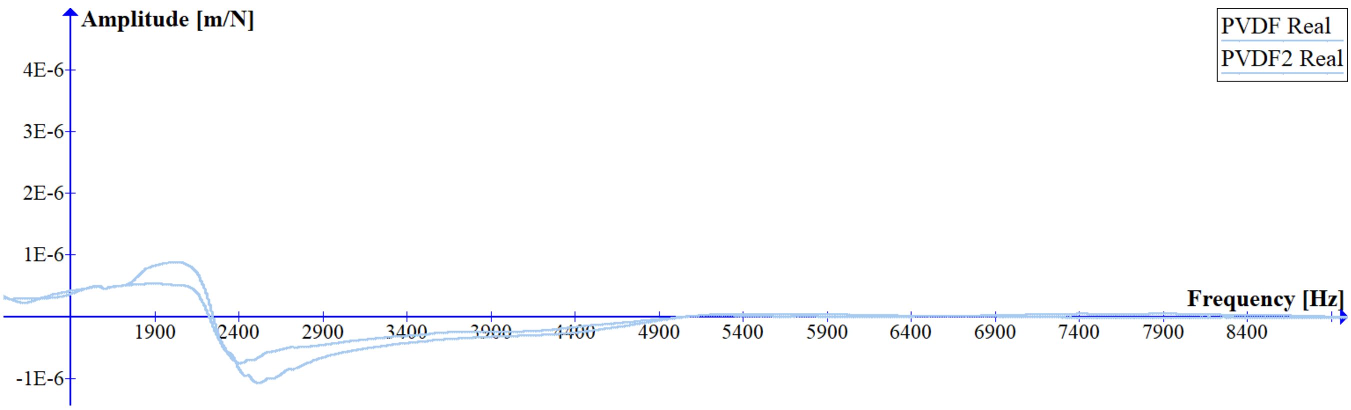
PETG2 Real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Frequency [Hz]
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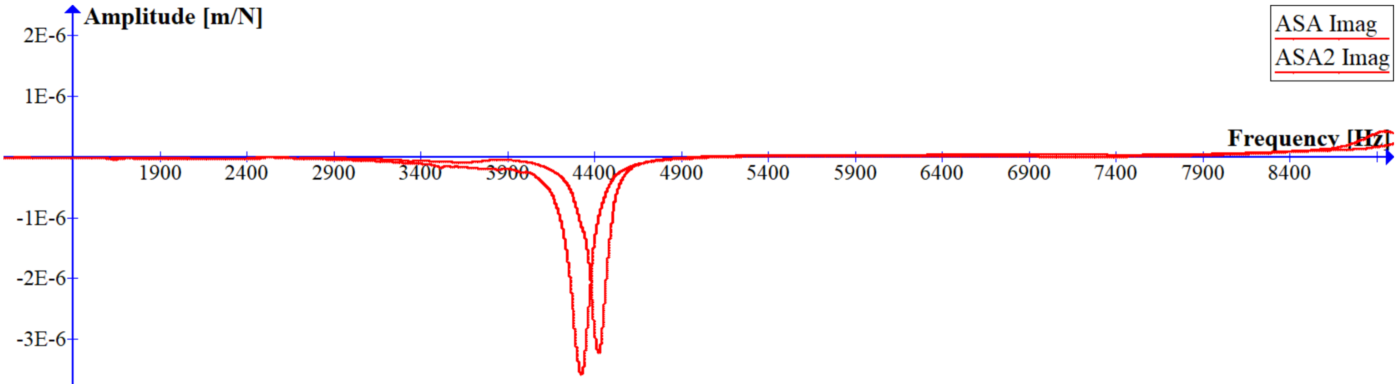
PVDF2 Real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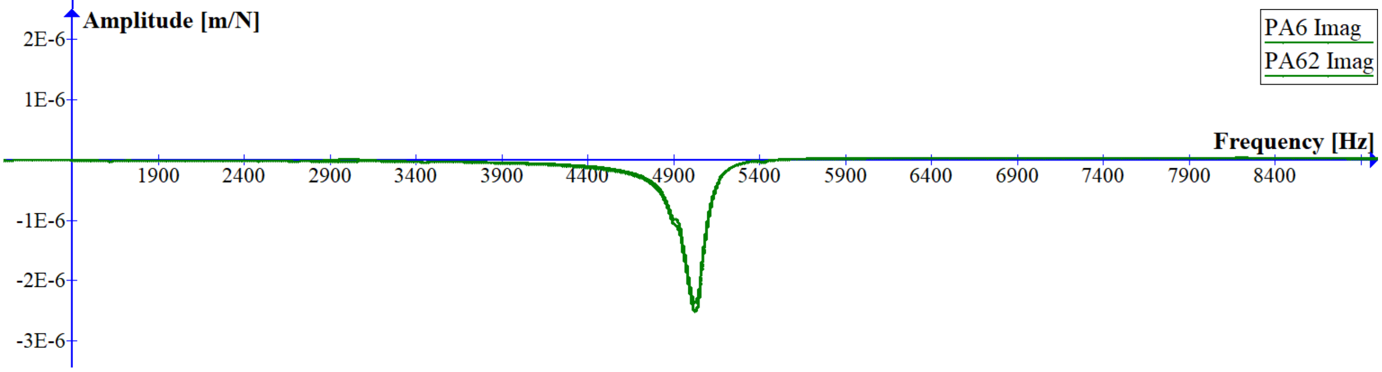
ASA2 Imag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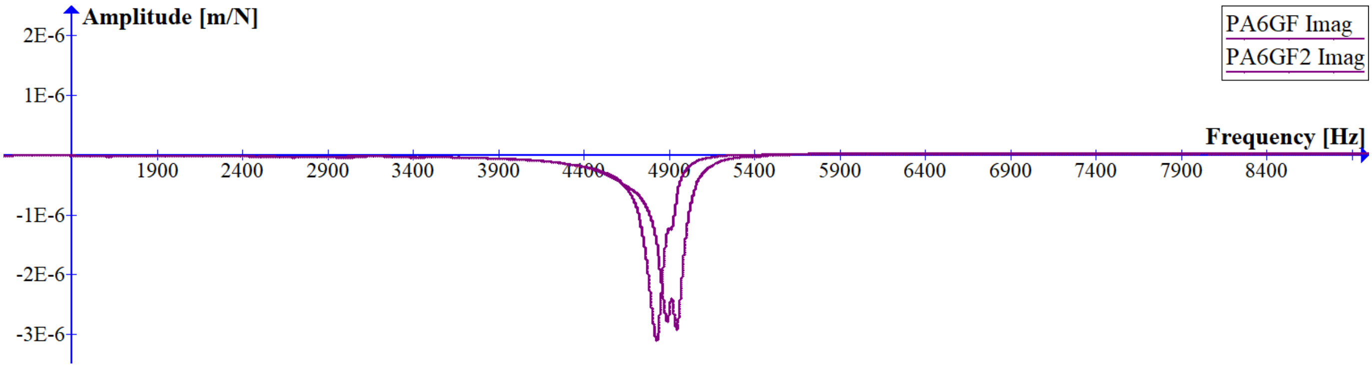
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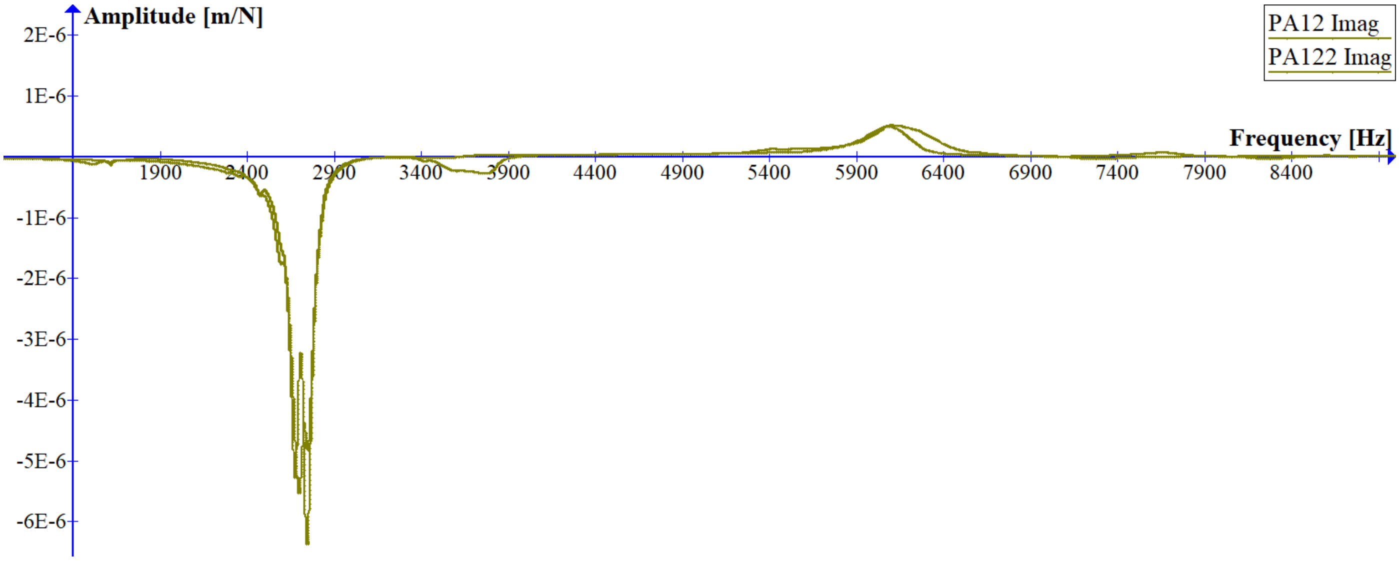
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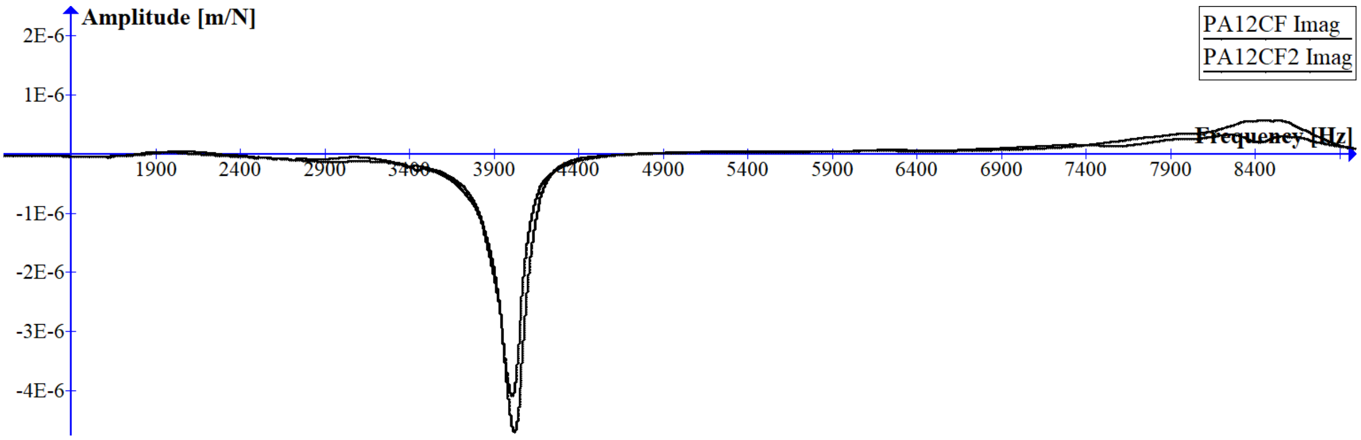
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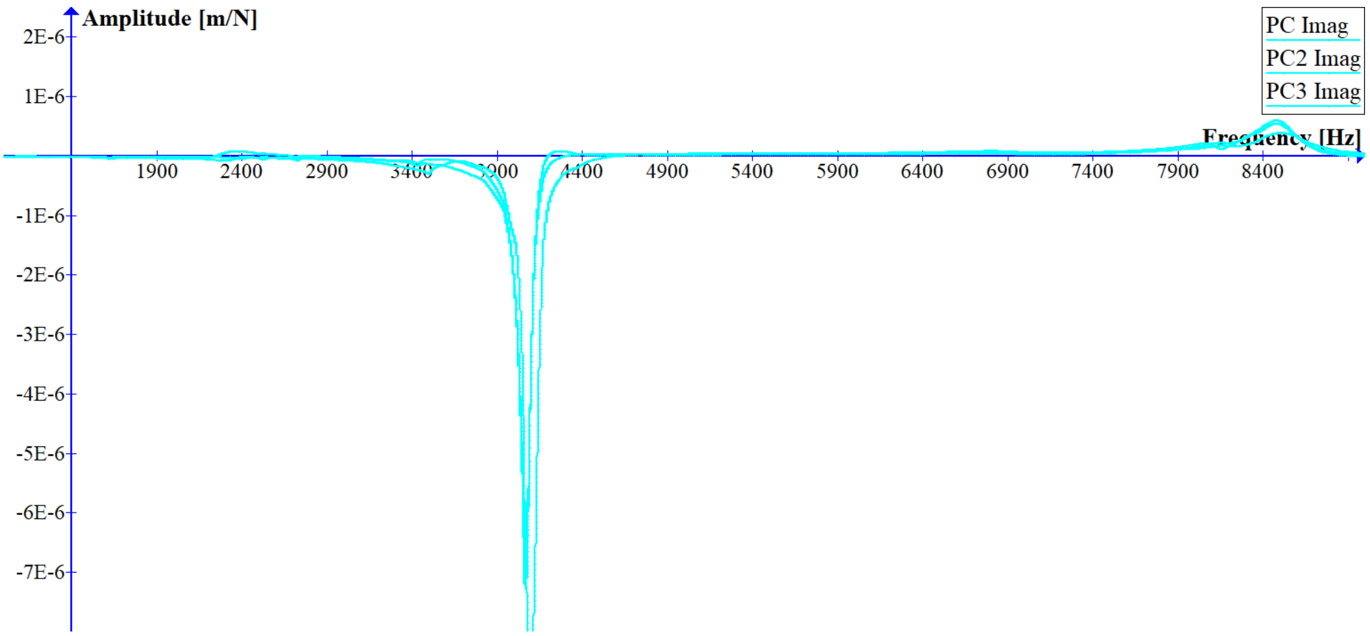
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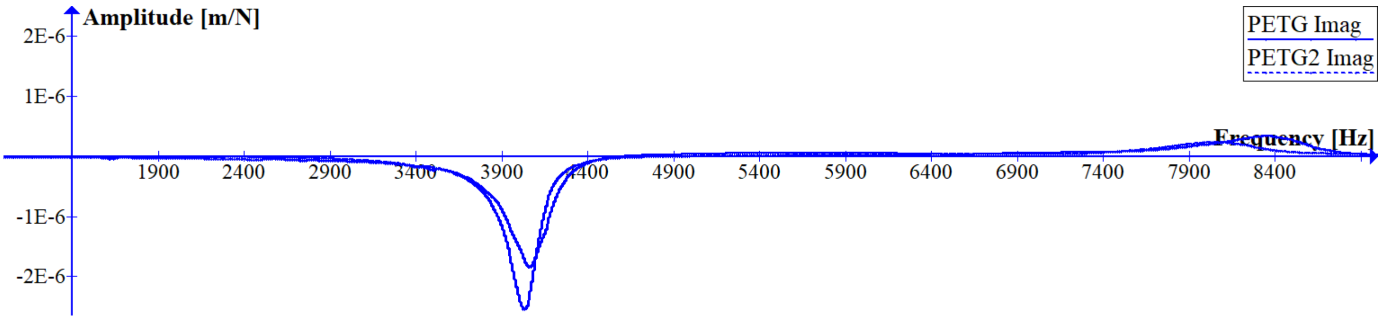
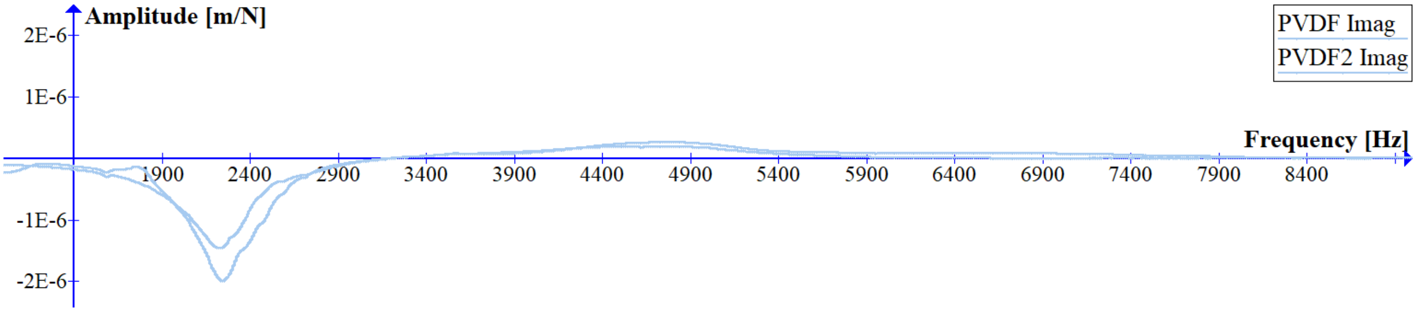
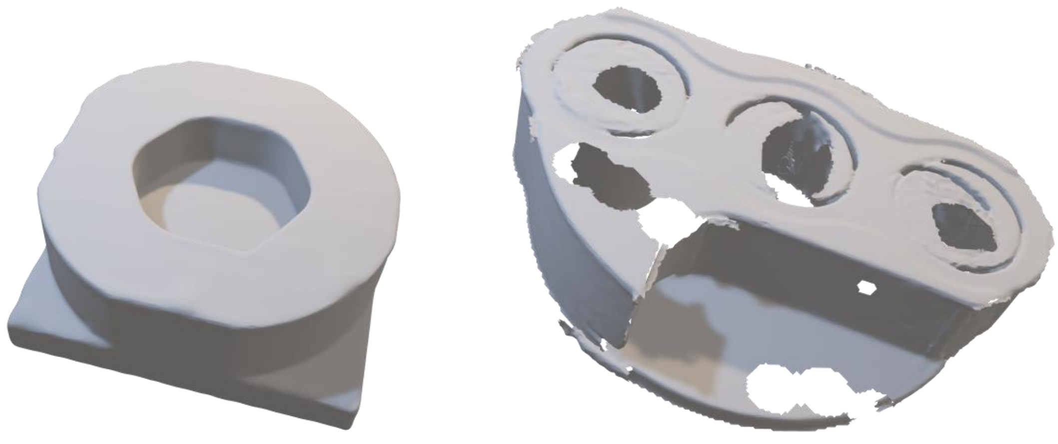
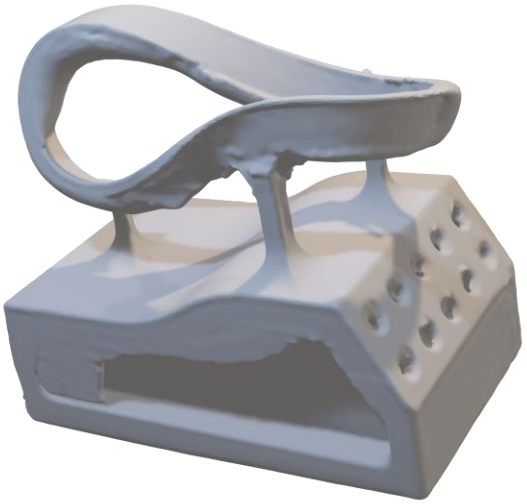
PC3 Imag

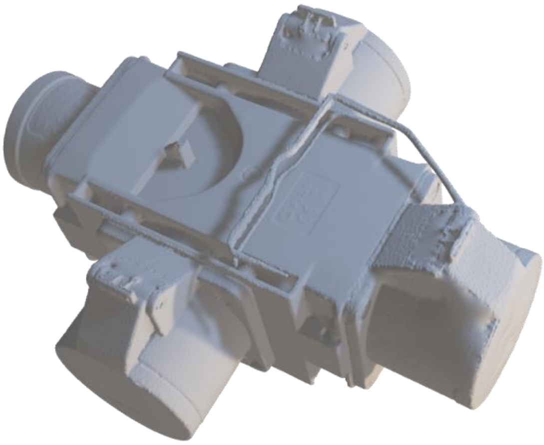
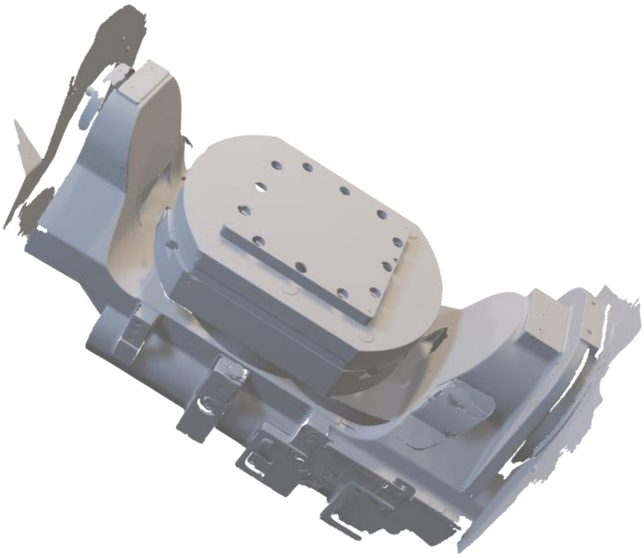




12.3 3D scan tests





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