DIPLOMARBEIT

Classification of additive manufacturing materials for radiologic phantoms

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Contents

1 Abstract

3D printing offers fascinating possibilities for the production of X-ray phantoms for general (projective) radiography up to CT applications. While in 2D phantoms different attenuations can be realized by different absorption lengths, CT phantoms require materials with different mass density and/or different effective atomic number. In FDM (fused deposition modeling) printing, mass density depends on packing density of solid structures. Common printing parameters, however, result in filling ratios < 100%, and thus lower density negatively affecting reproducibility of phantoms, x-ray attenuation and Hounsfield Units in CT, and thus contrasts. As a consequence, printing parameters need to be optimized and controlled to result in maximum solid density. In SLA (Stereolithography) printing parameters do not influence density, and can only be set manually in one of the printers used (Anycubic Photon).

In this project 41 kinds of materials consisting of filaments and resins were printed with different kinds of printers (Utimaker2+, Anycubic Photon, Formlabs Form 2 and Connex3). The optimal printing parameters for optimal printing quality and optimal filling ratio of 29 kinds of materials for FDM printer were measured respectively. An X-ray phantom was designed and printed out, and it was used for measuring Hounsfield Units (HU) of 41 kinds of materials by CT scanning.

Materials most suitable for mimicking soft tissues and bone in radiographic phantoms could be identified.

2 Introduction

3D printing is also known as additive manufacturing. It is a process of making three dimensional solid objects from a digital file by melting and depositing materials (such as metal, plastics, powders, liquids) in layers [1]. This technology was invented by Charles Hull in a process known as stereolithography (SLA) in the early 1980s [1]. The main 3D printing methods contain Fused deposition modelling (FDM) and Stereolithography (SLA) [2].

Nowadays 3D printing is widely used in daily life, and it plays an important role in many fields, such as jewellery, education, medicine, fashion, advertising, construction, industrial manufacturing, prototyping, cultural relic protection, food product, mold manufacture, space technology, automobile industry and entertainment industry [3] [4].

In the jewellery field, more and more people like 3D printed jewellery (from rings to necklaces to earrings). With the development of 3D printing, jewellery crafters can create new designs that the traditional jewellery-making methods cannot achieve. 3D printing makes it cheaper and more convenient to produce personalized jewellery to satisfy customers' demand [3].

In education field, more and more schools found 3D printing courses for kids. More and more universities have 3D printers for research purpose, and for students to print experimental models, instrument components, and laboratory appliance [3].

In fashion, 3D printing can help people to easily design and manufacture personalized clothes that fit. From 3D printed clothes to 3D printed footwear, 3D printing is offering great possibilities for the fashion industry [5].

In the construction field, 3D printing is envisaged as a way of fabricating buildings or construction components. The printed rough model can be used to evaluate the design at early stage. 3D printing can achieve more complexity and accuracy, faster construction, lower labour costs, greater functional integration, and less waste. Nowadays, in many countries, there are some residential buildings and bridges completely printed by 3D printing technology [6].

In prototyping and manufacturing, it costs thousands of dollars and takes several weeks or months to produce a prototype by traditional injection-molded method. It's very hard to improve designs of the prototype with low costs and in a short time. 3D printing is an ideal choice for small-scale prototyping and manufacturing. The prototype can be produced in several hours, and the cost is very low. This is also the reason why 3D printing is widely used in automobile industry and space technology [7].

In cultural relic protection, usually cultural relics are precious and fragile, and they cannot be moved easily. Through 3D scanning, the cultural relic's data is collected and made accessible. Then the data is input to the 3D printer to make a copy, and the 3D copy is 99% like the original cultural relic, showing the details. These data can be stored in digital form, and can be used in the future restoration work [8].

In the medical field, 3D printing has many applications. It can print custom prostheses for patients with physical defects [9]. The most widely used clinical applications of 3D printing are surgical planning, operative guidance, and implants production [10]. It is a good method for medical manufacturers towards faster production of medical implants and to change the way for doctors and surgeons to make surgery plans [11]. Patient-specific 3D-printed anatomical phantoms are very important tools for personalized treatments. In order to get a 3D printed phantom, there are 5 steps. The 5 steps contain selecting the target anatomical area, generating 3D printing STL files using medical images that come from CT or MRI mostly, optimizing the file for printing, selecting the suitable 3D printer and materials, and the printing quality control [12].

Nowadays, 3D printing is widely used in the medical and healthcare field, and this technology saves and improves lots of lives in every year. In vascular surgery, the 3D printed models of abdominal aortic aneurysm and aortic aneurysm from patients' vascular images were designed and printed for surgery guidance [13]. In urology, functional 3D printed bladder can be sutured to the ureters and the urethra of patients with severe bladder injury [14] [15]. In transplant surgery (such as living donor liver transplantation), the 3D printed liver can help surgeons to identify the vascular and biliary tract anatomy to make a better surgery plan [16]. In radiation oncology, 3D printed phantoms can be used to better determine the internal radiation dose of patients [17]. In pulmonology, the 3D printed patient-specific airway stents are a good choice for the patients who need stenting [18]. In podiatry, the combination of radiological images and the corresponding 3D printed foot models are very useful for podiatry treatment, especially for the patients with transmetatarsal amputation or toe amputation to customize patient-specific shoe fillers [19]. In plastic surgery, doctors can customize templates for facial transplantation surgery and patient-specific craniofacial implants, and produce patient-specific prosthetics by 3D printing technologies [20]. In orthopaedic surgery, 3D printed models can be used in assessing the surgery method of corrective osteotomies to provide more details about anatomy (especially for Minimally Invasive Surgery) [21]. In otolaryngology, 3D printing is capable of producing tissue scaffolds of the nose and auricle and realistic training models [22]. In ophthalmology, due to the complicated anatomic structures of the eye and orbit, 3D printed eye models are accurate and realistic duplications that include the actual anatomic structures of patients' eyes [23]. In neurosurgery, 3D printing technology can be used in producing patient-specific anatomic models for surgical planning and training, designing neurosurgical devices for nerve disease treatment and developing neurosurgical implants [24]. In gastroenterology, 3D bioprinting is capable of printing hepatic structures, and the 3D bioprinting will play an important role for regenerative medicine of the liver [25]. In cardiology, a heart phantom and the model of the complicated cardiovascular system can be printed by 3D printing technology for surgery planning, education and communication with patients [26]. In cardiothoracic surgery, 3D printed pulmonary arteries models can be used in surgery planning and device development [27]. In spine surgery and pelvic surgery, 3D printed models can provide important guidance for preoperative planning, especially for complex surgeries [28] [29] [30].

3D printing can also be used in medical physics such as patient specific dosimetry. A 3D printed thorax phantom with tumour can be designed and printed for radiation dosimetry [31]. Brachytherapy moulds can be printed by 3D printers to achieve a good catheter positioning accuracy and reproducibility [32]. 3D printing materials can be successfully applied in beam modulation and range compensation of proton therapy [33] [34]. 3D printing has also been used in the development of nuclear medicine and imaging phantoms, the assessment of anatomical noise in computed tomography (CT) image reconstruction algorithms, and radiation protection.

3D printed phantoms have also been widely applied in medical education, surgeries, radiology and radiation therapy. The concept and examples of 3D printed radiographic phantoms will be introduced in section 2.3 on Radiologic phantoms.

2.1 3D printing methods

Fused deposition modelling (FDM) was developed by S. Scott Crump in the late 1980s. Now it's the most widely used 3D printing method in the world. The principle of FDM is based on melted material extrusion (Figure 1). A filament of a solid material is extruded by an extruder and melted by a heated print head, then the threadlike melted material flows through a nozzle and deposits on a platform. The nozzle moves in x-y plane to describe the shape and structure of a designed model in one layer by depositing material. After the first layer is printed, the platform moves down (for some kinds of printer, the platform is fixed, and the nozzle moves up) for a small distance (this distance is called layer thickness) to print the second layer. This process repeats and continues until the complete model is printed [35].

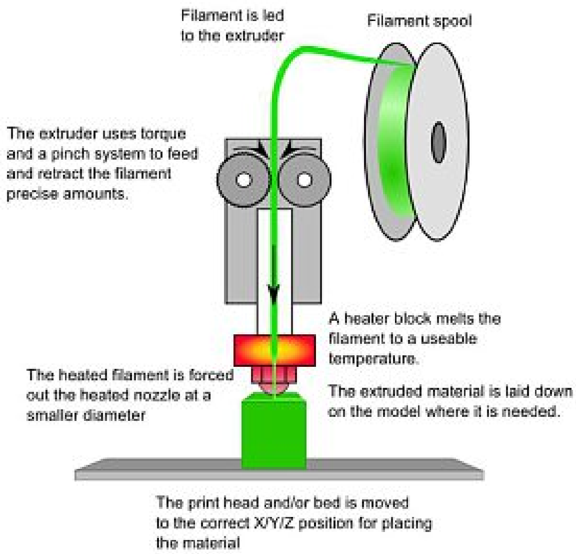

Figure 1. Principle of the **Fused Deposition Modelling**. From [36]

In contrast to the FDM printer, the SLA printer does not process solid filaments by melting them, but uses liquid printing resins which are cured by a light source which could be either a laser or an UV-lamp [37].

Stereolithography (SLA) was named by Chuck Hull in 1984 when he applied for a patent, and the patent was ratified in 1986. SLA is a 3D printing method that uses photopolymer resins and UV light. A vat of photopolymer resin is irradiated by a focused UV laser. The Photopolymer resins are very sensitive to UV light, so the surface layer of the resin is photochemically solidified. The single layer of the computer-designed 3D model is formed by this photochemical solidification. After this, the build platform moves up for a small distance to print the next layer. This process repeats and continues until the complete model is printed [38] (Figure 2).

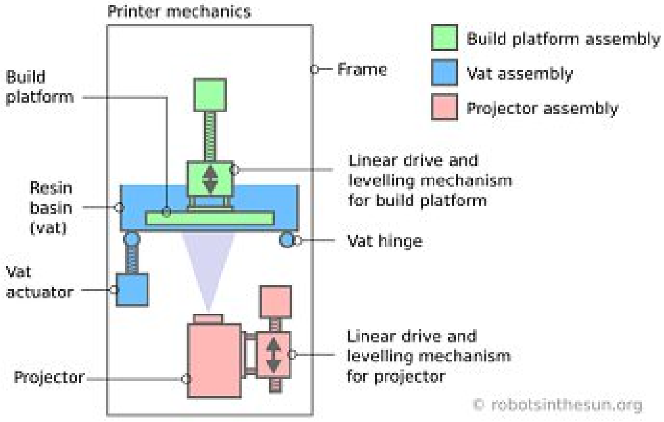

Figure 2. Principle of **Stereolithography**. From [39]

Usually, the resins used in SLA printers are toxic. They are harmful to the eyes, skin, the respiratory system and the digestive system. Therefore, gloves should be worn, and it's necessary to keep ventilation during the printing. After printing, the printer and the model should be cleaned by 99% IPA (Isopropyl Alcohol) to rinse of extra resin left. The printed model should be put into a UV chamber (usually several minutes) or placed under the sunlight (usually half an hour) for curing.

2.2 Common materials used for 3D printing

2.2.1 PLA

PLA (Polylactic acid) is one of the most popular 3D printing materials. It's a biodegradable thermoplastic that is made from renewable resources such as sugar cane, tapioca roots, corn starch and potato starch [40]. PLA is non-toxic, and it doesn't produce any poisonous gas during printing.

PLA is very easy to print with. It requires a low nozzle temperature, and it doesn't warp easily. Therefore, a heated bed is not necessary when print PLA. PLA is the base material for some special materials such as filled filaments like Metalfill, Glowfill, Stonefill, Woodfill (ColorFabb B.V., Belfeld, Niederlande, all used in this work), and others [41].

PLA can degrade in the body and generate lactic acid, thus it can be used in medical suturing and surgical implants. Usually these implants break down in the body in 6 months to 2 years. PLA is non-toxic, so it's widely used in disposable tableware, disposable garments and food packaging [40].

However, compared with others 3D printing filaments, PLA is a little brittle, so it is not usually recommended to be used for mechanical parts. PLA tends to deform when the temperature is over 60°C, thus PLA cannot be used in a high temperature environment [41].

2.2.2 ABS

ABS (Acrylonitrile butadiene styrene) is one of the most popular 3D printing material. It's a non-biodegradable plastic that has high strength and high durability, and it's resistant to high temperature [41].

ABS is not easy to be printed. The required nozzle temperature is much higher than PLA, and warping happens easily. It produces toxic fumes during the printing process, so a ventilation environment is necessary [41].

ABS is an ideal material for moving parts, automobile components and toys, and it's also used in pipes, protective headgear, kitchen appliances, LEGO bricks and so on [40].

2.2.3 ASA

ASA (Acrylonitrile styrene acrylate) is a hardy weather-resistant thermoplastic that is resistant to water, strong UV light, high temperature, chemical exposure and deformation [41].

ASA is much easier to print than ABS, because there is no serious warping. The only thing the user needs to notice is the cooling fan, if the air flow from the cooling fan is too strong, ASA can easily crack [41].

Due to the high chemical stability, ASA is widely used in automobile industry and outdoor applications [40].

2.2.4 PVA

PVA (Polyvinyl alcohol) is a non-toxic and biodegradable plastic that is water-soluble [40]. It's easy to print, and it's a terrific support material in the 3D printing field. After the printing finishes, put the model into the water, the support part (PVA) is dissolved quickly.

PVA is hard to store, because it's susceptible to moisture. Silica, dry boxes or sealed bags are needed [41].

Usually PVA is used in packing and freshwater fishing. PVA bag is filled with bait and thrown into water. After the PVA bag dissolved, the bait released [40].

2.2.5 HIPS

HIPS (High impact polystyrene) is a biodegradable and non-toxic copolymer that combines a rubber's elasticity and polystyrene's hardness. In the 3D printing field, it's a good support material. HIPS is the best choice to be used as support material, when printing ABS with a dual extrusion printer. HIPS can be dissolved in Limonene [41].

HIPS is not easy to print. Warping is a problem, but it's better than ABS. Therefore, a heated bed is needed to print HIPS.

HIPS is commonly used in food packing and CD packing [40].

2.2.6 PET

PET (Polyethylene terephthalate) is a very popular 3D printing material, and it's the most widely used plastic in the world. Almost all plastic bottles are made from PET. PET is recyclable, stable and non-toxic, and it's more flexible than ABS and PLA [40].

In 3D printing field, usually PET is transparent. However, if the room temperature changes, the transparency of this material will also change. If the temperature decreases slowly after printing, crystalline structure will appear [40].

PET is commonly used in food and drink packing, clothing fibers, and mechanical parts that require impact resistance [40].

2.2.7 PETG

PETG is "glycol-modified" PET. The toughness, strength, durability and impact-resistance of PETG are better than PET, and it's not brittle. The flexibility and durability is better than PLA, and it's easier to print than ABS [41].

PETG is widely used in tableware, mechanical components and protective components such as helmets and mobile phone cases [40].

2.2.8 Nylon

Nylon (Polyamide) is a popular synthetic polymer that has high strength, high flexibility, high durability and a high melting point [40].

Due to the strength, flexibility and durability, nylon is an ideal 3D printing material to print mechanical and functional parts. In 3D printing, Nylon requires high nozzle temperature and bed temperature [41].

A serious problem for Nylon is water absorption. Nylon is very susceptible to moisture, and it can absorb about 10% of its weight in 24 hours. Therefore, it's difficult to store Nylon. A dry and sealed packing bag and silica gel are required to store Nylon [40].

Nylon is commonly used in many industrial applications such as machine parts, mechanical components, toys, tools, gears, bearings and so on [40].

2.2.9 TPE, TPU, TPC (Flexible materials)

TPE (Thermoplastic elastomers) are polymer materials exhibiting a "rubber like" quality. It's extremely flexible, durable and super stretchable. TPE is very hard to print, because it's too flexible to be well extruded out of the nozzle [41].

TPU (Thermoplastic polyurethane) is modified TPE, and it's also a popular 3D printing material. TPU is easier to print than TPE, because the rigidity of TPU is higher than TPE. TPU is more durable than TPE, and it can keep the elasticity in a cold environment [41].

TPC (Thermoplastic copolyester) is another modified TPE, and the property is similar to TPE. However, TPC is more resistant to UV light, high temperature and chemical erosion [41].

TPE, TPU and TPC are widely used in clothes, shoes, toys, mobile phone cases and special machine parts for bending, stretching or compressing parts [40].

2.2.10 PC

PC (Polycarbonate) is one of the toughest 3D printing materials, and it has a very high stability and durability. It's extremely resistant to high temperature, physical impact and chemical erosion, and it is very hard to break [41].

In 3D printing, PC requires very high nozzle temperature and bed temperature. PC absorbs water from air, so PC need to be stored in a dry or sealed environment [41].

PC is very tough and transparent, so it's widely used in mechanical components, automobile components, bullet-proof glass, diving masks and display screens [41].

2.2.11 Carbon Fiber PLA

Carbon Fiber PLA is PLA filled with carbon fiber strands. Carbon Fiber 3D printer filament is tough and exhibits a low density. Because of the light weight and toughness, it's an ideal material for specific mechanical components [41].

Carbon Fiber 3D printer filament is easy to print. There is no warping, so the heated bed is not necessary. However, carbon fibers are abrasive, and it increases the wear and tear on the nozzle of printer. Brass nozzle cannot be used to print carbon fiber filaments. A harder nozzle (such as a steel nozzle) is required [40].

2.2.12 Metal PLA 3D printer filament

Metal filled 3D printer filament is PLA filled with metal powders. Usually the percentage of the content of metal powders is from 50% to 85%. Models printed by Metal PLA look and feel like real metal, and weight is also close to the real metal. The common metal filled 3D printer filaments contain steel, copper, bronze, brass or aluminium [41].

The high metal content makes this filament quite abrasive to brass nozzles. Therefore, it's recommended for metal filled filaments to print with abrasive resistant nozzles, for instance steel nozzle [41].

Metal filled 3D printer filament is used for sculpture, jewellery and imitations [40].

2.2.13 Wood PLA 3D printing filament

Wood PLA 3D printing filament is PLA filled with wood fibers, and it looks and smells the same as the real wood. These filaments contain Pine, Birch, Cedar, Ebony, Willow, Bamboo, Cherry, Coconut, Cork, and Olive, e.g. [41].

Wood PLA 3D printing filament can break easily. The wood-like appearance causes the reduction of the strength, flexibility and toughness [40].

It's used for printing wood-like models such as tables, chairs, boxes and artificial wood carving, and it's sometimes hard to detect that the models are made by 3D printing [41].

2.2.14 Glow in the Dark 3D printing filament

Glow in the dark 3d printing filament can glow in the dark. It's PLA or ABS filled with powders of phosphorescent materials. This kind of material can cyclically absorb light and then emit light later [41].

In the 3D printing process, the thicker the wall thickness, and the higher filling ratio, the stronger is the fluorescence intensity [41].

Glow in the dark 3d printing filament is an ideal material to produce children's toys, mobile phone cases, light switches and wearables [40].

2.3 Radiologic phantoms

Phantoms are widely used in medical education, surgeries, radiation therapy and radiology.

Traditional commercially available phantoms are costly and difficult to customize. 3D printing is a rapid prototyping way to print phantoms with lower cost that are easy to customize. The 3D printed phantoms can be functionally equivalent to commercially available phantoms [42]. Therefore, nowadays the 3D printed phantoms can replace traditional commercially available phantoms, and they are widely used in the medical field.

In medical education, anthropomorphic phantoms can help students to deeply and intuitively understand anatomical structures of human bodies and organs, and medical universities often use 3D printed phantoms to supplement cadaveric dissection in anatomy courses [43]. The 3D printed phantoms for imaging purposes can help students to learn and to test imaging devices (such as CT, Ultrasound and MRI), control images quality, and optimize parameters of imaging devices.

In radiation therapy, one important application of the 3D printed phantoms is to confirm the position of the tumour and normal tissues during treatment delivery [44]. 3D printed phantoms can be applied in radiotherapy quality assurance. 3D printing can print more complex models of human structures and inhomogeneities. The dosimetric scalability and validation of inhomogeneities in treatment planning algorithms can be researched with these 3D printed phantoms [45]. 3D printed phantoms can also be used in molecular radiotherapy dosimetry and internal radiation dosimetry measurements to evaluate the absorbed dose of patients [46] [47] [48].

In radiology, 3D printed phantoms are powerful tools for characterizing, evaluating, and optimizing medical imaging systems. It can be used for calibrating and testing of imaging devices (such as CT, Ultrasound and MRI) and imaging systems[49] [50], comparing the properties between different CTs or the others imaging devices [51] [52], researching how imaging parameters (such as noise, contrast, spatial resolution or low contrast detectability) influence the image quality and optimizing imaging parameters [53].

2.4 State of the art: Radiologic Phantoms

2.4.1 Phantom design

The state of the art in Phantom design for radiology and radiation therapy phantoms to be used in optimization and dosimetry including personalized or patient (patient group) specific applications has shifted from stylizes phantoms towards using CT or MRI scans, or in some application radiographic images from real patients. However, this shift is only made possible by advances production methods, like additive manufacturing and 3D printing.

2.4.2 Printing Materials used in State-of-the-Art phantoms

In radiation therapy and radiology applications, usually the 3D printed phantoms are required to be printed with "tissue equivalent materials". However, in most cases materials are used, that are both, readily commercially available, and easy to print. For example, lung tissue can be mimicked by HIPS with 60% infill, ABS with 30% infill or PLA with 30% infill. Muscle tissue can be printed by ABS or PLA with 80%-100% infill. In order to reflect the "real" mechanical properties or appropriate radioopacity in the phantoms, different body tissues are printed with different materials [54]. For mechanical properties, the bone tissues should be replaced by rigid materials, and the soft tissues should be replaced by flexible and elastic materials. However, most of the materials are rigid, it's not easy to find suitable flexible and elastic materials to replace soft tissues [55]. Nowadays, different new materials are available in order to better reproduce the patient anatomy. Therefore, there are some flexible materials can narrow the gap between the real body tissue and the phantom [56].

Some authors use customized materials, e.g. Bismuth-infused ABS [57]. However, Bismuth with an atomic number of 83 is a poor choice to mimic increased x-ray attenuation of calcified tissues. The totally wrong atomic number will result in an inappropriate energy dependence of attenuation. The same holds true for iodine added to printing ink [58] to print bone structures for imaging with diagnostic x-rays.
When designing phantoms for radiologic applications, it is vital to find and select "tissue equivalent" printing materials that have similar x-ray attenuation properties than the tissues they substitute regarding both, absolute (3D phantoms) or relative (2D applications) x-ray attenuation, and photon energy dependence of attenuation. In the development and classification of such materials still a lot of work needs to be done.

2.4.3 Examples of State-of-the-Art radiologic phantoms

In the following, some 3D printed radiographic phantoms are shown and discussed in a little more detail.

A 3D printed anthropomorphic lung phantom containing a complex structure of vessels was designed by Hernandez-Giron et al. and used for assessing the image quality of CT (Figure 3) [59].

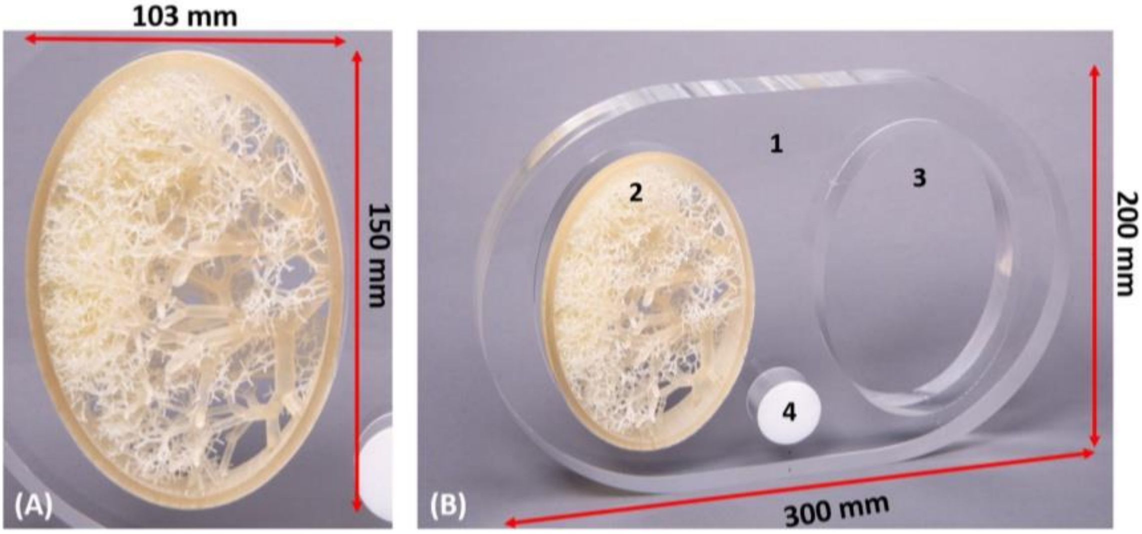

Figure 3. 3D printed lung vessel phantom. From [59]

Photo (A) is the 3D printed lung phantom containing complex vessels with a diameter variation from 10 to 0.25mm. In photo (B), the phantom was set into a PMMA chest phantom container (1). The container has two holes (right lung is 2, left lung is 3) and a Teflon insert (4) replaces the spine, to mimic the human chest [59].

A 3D printed anthropomorphic abdomen phantom for CT closely mimicking and clearly displaying patient anatomy and pathology was used by Jahnke et al. for evaluation and simulation of CT-guided procedures. This phantom can also be used in simulator training, and the training can increase the skills of operators and improve practical abilities (Figure 4) [58].

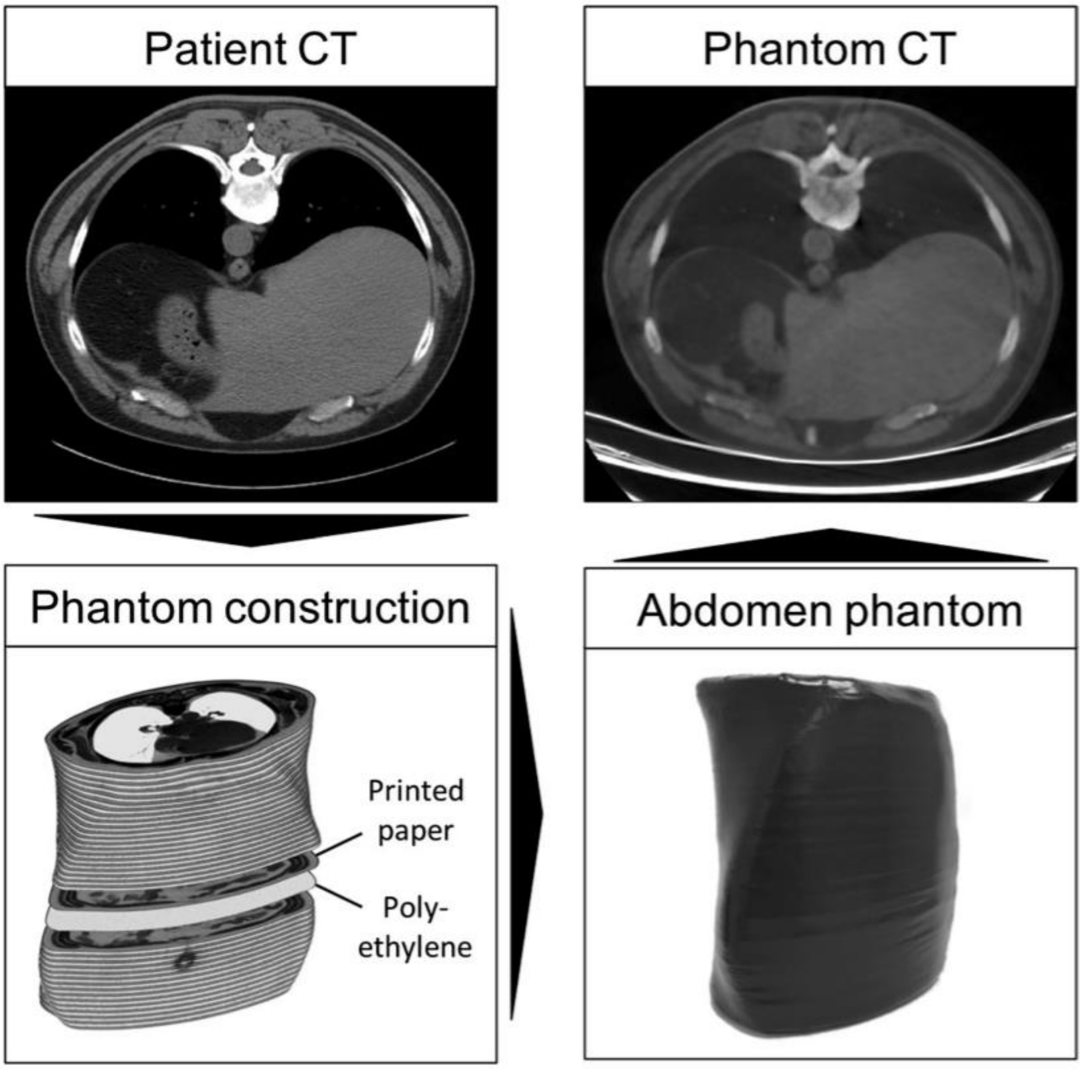

Figure 4. Iodide printed anthropomorphic abdomen phantom for CT-guided procedures. From [58]

Top left: CT images of a patient used to print the phantom. Bottom left: the phantom was printed in actual size and made up of alternating layers of printed paper (printed with potassium iodide water solution) and 1mm polyethylene sheets. Bottom right: the phantom is covered by a black plastic film to protect the phantom materials. Top right: the CT images of the phantom closely mimicking the patient's anatomy [58].

A 3D printed MRI-visible cervical spine phantom built by Mitsouras et al. for simulating MRI guided therapy. The STL file of this cervical spine phantom was taken from CT images, and this phantom was printed by an MR signal-generating material. The 3D printed cervical spine phantom can be used for simulating MRI guided interventions such as cryosurgeries by assessing the accuracy and signal characteristics of the printed phantom by CT and MRI (Figure 5) [60].

Figure 5. 3D printed MRI-visible cervical spine phantom. From [60]

The photo in the left is the STL model of the phantom generated from the CT images. The right 3 photos are the 3D printed MRI-visible cervical spine phantom from different views. The phantom was printed on an Objet 500 (Stratasys) printer using the RGD-525 material [60].

Radiologic phantoms can mimic not only normal human tissues and organs, but also diseased human tissues. Radiologic phantoms can be used for mimicking liver parenchyma and focal liver lesions, e.g., (benign cysts and malignant metastases). In this example water solution filled with iodine was used to mimic focal liver lesions. Different concentrations of iodine can reflect the severity of the disease (Figure 6) [61].

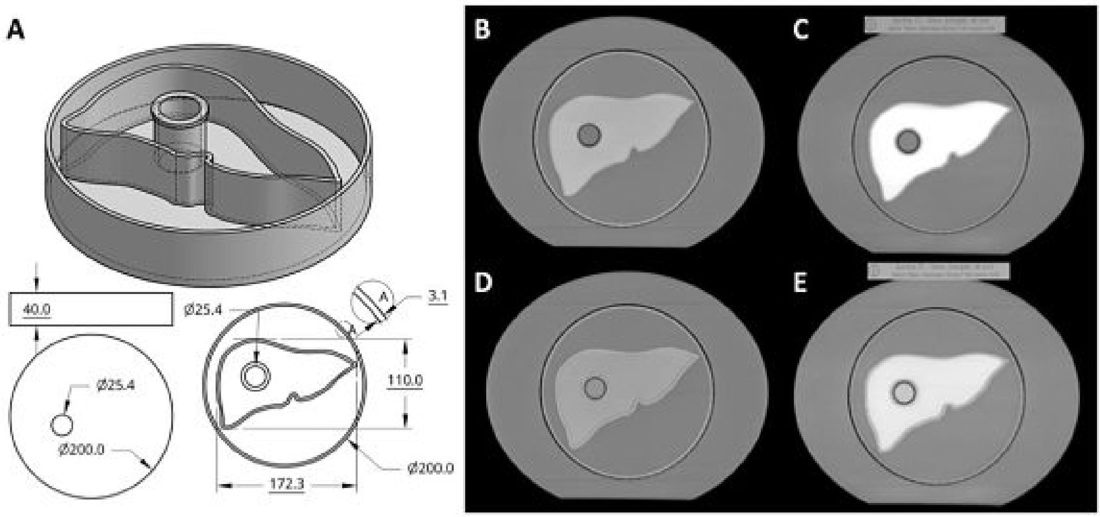

Figure 6. 3D printed and customized Liver Phantom. From [61]

The liver phantom from Große Hokamp et al. contains 3 parts (A), the central part is filled with acrylic tubes that contained distilled water to mimic cysts of the liver. The inner part is filled with water solutions of iodine with different concentrations that mimics metastases of the liver. The outer part is filled with water to mimic the human body. The phantom was scanned by CT with cyst-mimicking insert in highly attenuating liver parenchyma (120HU) in conventional images (B) and 40keV virtual monoenergetic images (C). (D) and (E) show images of a mildly hypodense lesion-mimic (60HU) in poorly attenuating liver parenchyma (80HU) in conventional images (D) and 40keV virtual monoenergetic images (E). So this phantom can be used to identify the clinical value of virtual monochromatic reconstructions in this case [61].

The 3D printed bone phantom described in Ballard et al. can be used in orthopedic surgeries and fracture fixation to improve the surgery planning and test the surgery effect (Figure 7) [10].

Figure 7. 3D printed bone phantom of a tibial fracture. From [10]

The phantom shown was derived from a 42 years old man undergoing reduction and fixition surgeries of the comminuted tibial fracture. (a) shows a coronal reconstruction of the CT image of the reduced and fixated tibia and healed fibula. (b) CT DICOM data used to generate STL file (3D Slicer version 4.6, www.slicer.org). Anterior and posterior photographs of the 3D-printed bone phantom are shown in (c) and (d), respectively [10].

3D printed phantoms are widely used for testing and optimizing imaging devices without necessitating exposure to human bodies. **A 3D printed anthropopathic thorax phantom** from a patient with lung cancer by Hazelaar et al. is shown in this example. The spatial accuracy of the phantom is very close to a real patient. This phantom is currently being used to assess imaging quality and for positional verification techniques for radiotherapy (Figure 8) [44].

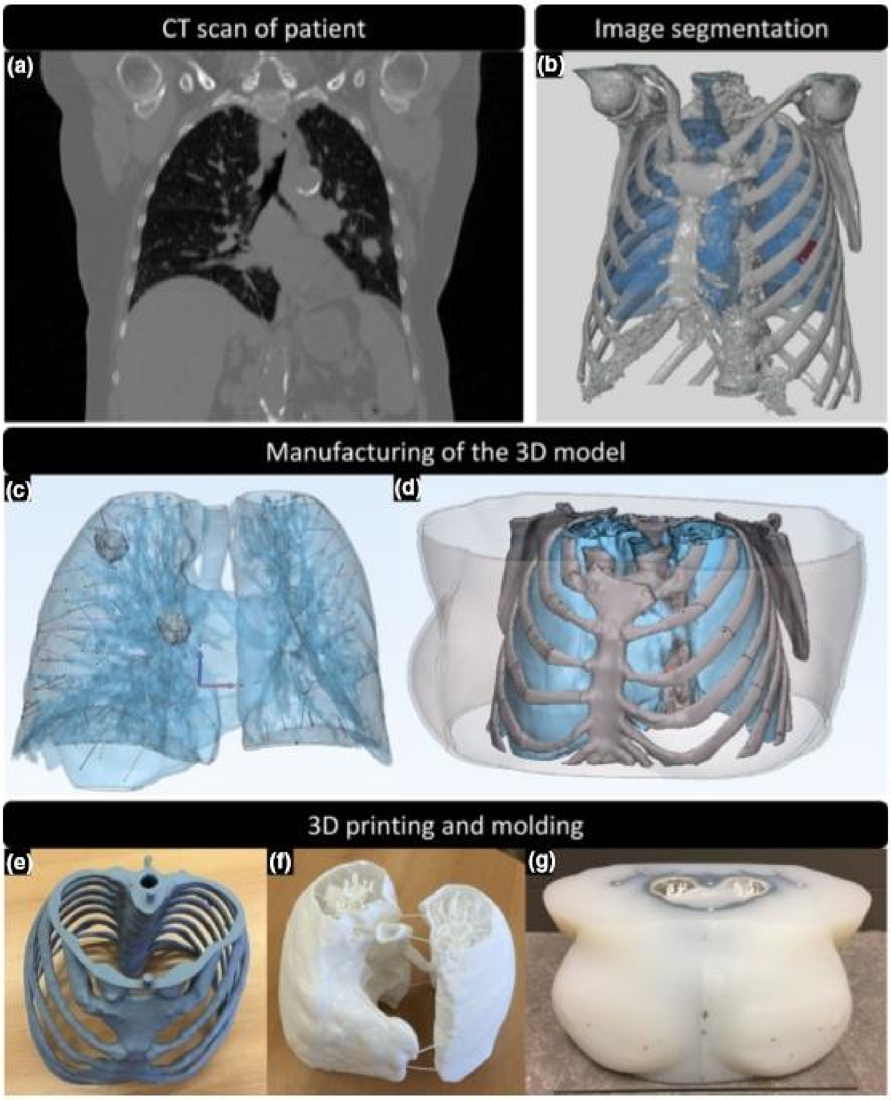

Figure 8. 3D printed thorax phantom. From [44]

Photo (a) is a CT scan image from a patient. Photo (b) shows the segmentation based on HU thresholds to produce a 3D printed phantom of bone structures and lung structures including airways, blood vessels, and tumour. Photo (c) illustrates the manufacturing of the 3D model including copying the tumour to two different locations in the right lung, creating cylindrical extensions between the end of the blood vessels and the outer lung surface. Photo (d) illustrates the extension of the ribs toward the sternum. Photo (e) shows the bony structures printed in gypsum, and Photo (f) the lung structures printed in nylon. Photo (g) depicts the soft tissue outside the lungs replaced by silicone that was cast into a 3D-printed model [44].

A 3D printed anthropomorphic breast phantom (Figure 9) was designed, printed and used by Schopphoven et al. in 2D digital mammography. The breast phantom is based on clinical images of a woman's breast, and it has nearly the same anatomical structures and attenuation characteristics as the real breast [62].

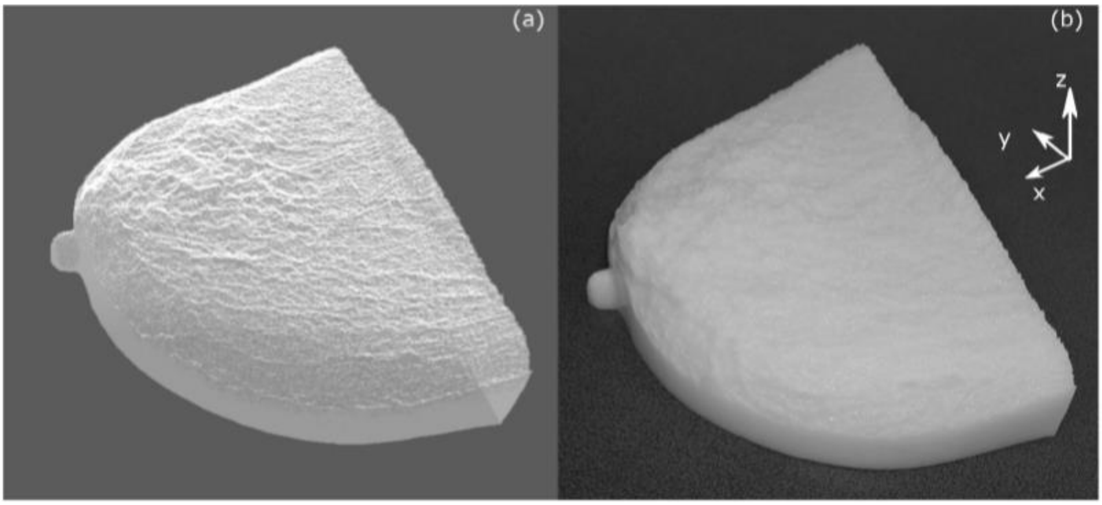

Figure 9. 3D printed breast phantom. From [62]

Photo (a) shows the STL model of the 3D printed breast phantom that is based on the clinical images. Photo (b) is the 3D printed breast phantom. The size in x, y and z directions are 122mm, 208mm and 39 mm [62].

The breast phantom was printed by a PolyJet 3D printer, and the material used was a polypropylene like material (Rigur RGD450™). After the breast phantom was printed, the phantom was imaged by five 2D digital mammography systems of different types to evaluate the imaging parameters and imaging systems. Compared with the clinical images of the real breast, the result demonstrated that the anatomical structures and attenuation characteristics of this 3D printed anthropomorphic breast phantom were nearly the same as in the real breast [62].

A multi-material and multi-colored 3D printed anthropomorphic heart phantom (Figure 10) was designed, printed and used in surgery planning, for education purpose and in communication with patients by Vukicevic et al. [26].

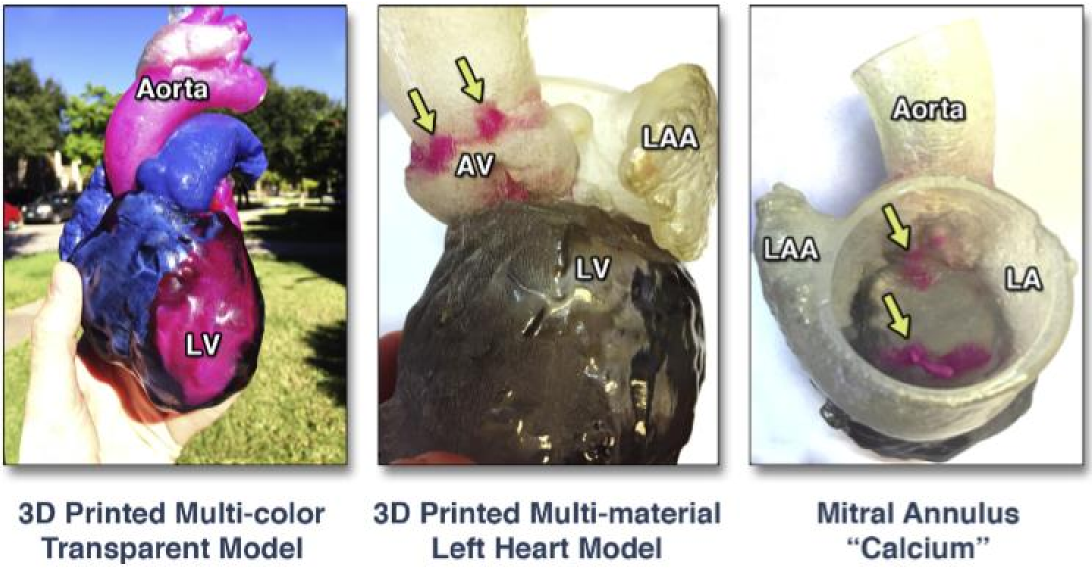

Figure 10. Multi-material and multi-colored 3D printed anthropomorphic heart phantom. From [26]

The left photo is the complete heart phantom. The center photo shows the aortic root complex part and the right photo the mitral valve annulus part. The arrows in the photos identify calcium deposition [26].

A 3D printed anthropomorphic head phantom containing eye inserts was designed and printed by Homolka et al. for eye dosimetry (Figure 11). The head phantom and eye inserts were printed with an Object Eden 350 V (Stratasys, Edina, MN, USA), and the material used was Fullcure 720 (Stratasys, Edina, MN, USA, a photo-cured acrylic resin). The material in the nasal cavities, sinuses, trachea and brain was removed, and the brain cavity filled with deionized water before measurements [63].

Figure 11. 3D printed anthropomorphic head phantom with eye inserts. From [63]

The left photo is the eye insert, and it consists of 3 parts. There are 3 TL dosimeters located in the eye insert (bright white parts) to measure eye lens doses. The right photo is the assembled head phantom with eye inserts. The crosshairs on the forehead indicate dose measurement positions [63].

A 3D printed anthropomorphic phantom representing a prematurely born neonate (Figure 12) was designed and printed by Irnstofer et al. It can be used in neonatal radiography to optimize imaging parameters and image quality, to compare image qualities of different neonatal radiography systems, and to assess how image processing and radiation dose influence the diagnostic imaging performance [64].

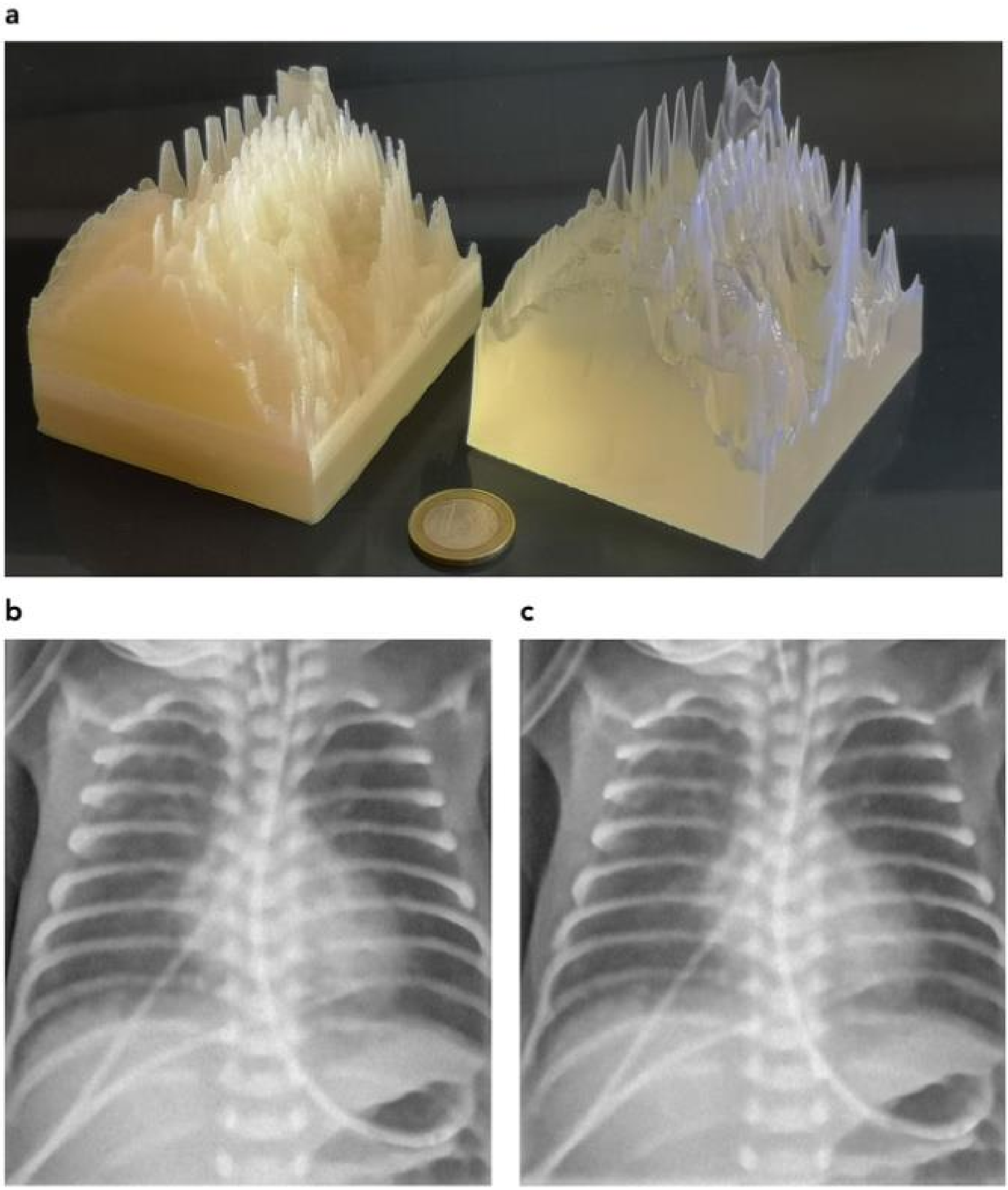

Figure 12. 3D printed anthropomorphic phantoms representing a prematurely born neonate and the corresponding x-ray images. From [64]

In photo (a), the left phantom was printed by an FDM printer, and the right phantom by an SLA printer. Photo (b) shows the x-ray image of the FDM printed phantom, photo (c) the x-ray image of the SLA printed phantom. It's obvious that the fine structures and details are better reproduced by SLA printing [64].

The printers used here were an FDM printer Ultimaker 2+ (Ultimaker B.V., Geldermalsen, the Netherlands) and an SLA printer Formlabs Form 2 (Formlabs Inc., Somerville, MA, USA). The materials used here were PLA (F1906 transparent, Ultimaker B.V.) and photocurable Clear Resin V04 (Formlabs Inc.). The locally different thicknesses in the phantoms stand for the locally different attenuations (the longer the attenuation length, the higher the local attenuation), and correspond to the different grey values on the x-ray image [64].

3 Materials and Methods

3.1 3D printing setups

The **FDM** (fused deposition modelling) printer used in this work was an Ultimaker 2+ (Ultimaker B.V., Netherlands). **SLA** (stereolithography) printers used were an Anycubic Photon open resin printer (Anycubic 3D Printing, Guangdong, China), a Formlabs Form 2 (Formlabs Inc., Somerville, USA) and a Stratasys Connex3 Objet500 (Stratasys Ltd., Eden Prairie, USA).

3.1.1 FDM printer Ultimaker 2+ (Ultimaker B.V., Netherlands)

The Ultimaker 2+ (Ultimaker B.V., Netherlands) is shown in Figure 13.

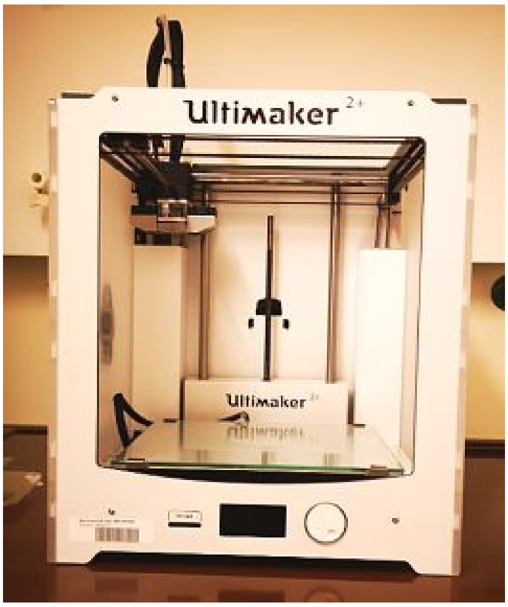

Figure 13. Ultimaker 2+

The Ultimaker 2+ can perform complex 3D printing tasks, and it's good at printing bridging, overhanging, and accurate details. The resolution is 0.02mm, the maximum printing speed is 300mm/s, the nozzle temperature is between 180°C and 260°C, and the temperature of the heated bed is between 20°C and 100°C. The detailed properties and operation parameters of Ultimaker 2+ are shown in the Table 1 [65].

Table 1. Ultimaker 2+ technical specifications

Build volume	223 x 223 x 205mm
Assembled dimension	342 x 493 x 588mm
Print technology	Fused filament fabrication (FFF)
Compatible filament diameter	2.85mm
Weight	11.3kg
Maximum power output	221W
Print head	Swappable nozzle
Nozzle diameters	0.25, 0.4, 0.6, 0.8 mm
Resolution	0.02mm
Extrusion speed	Less than 24mm^3/s
Nozzle temperature	180-260°C
Nozzle heat-up time	Less than 2 minutes
Operation sound	50dBA
Temperature of heated bed	20-100°C
Operation ambient temperature	15-32°C
Safety stored temperature	0-32°C

The adjustable printing parameters of Ultimaker 2+ include nozzle temperature, printing speed, bed temperature, flow rate, fan speed, retraction length, retraction speed, layer thickness and wall thickness. All of the printing parameters can be set accurately in Ultimaker Cura, a professional 3D printing software developed by Ultimaker B.V. Ultimaker Cura supports MacOS, Windows, and Linux systems, and it contains several plugins, such as SolidWorks, Siemens NX, and Autodesk Inventor. It can recognize and generate STL, OBJ, X3D, 3MF, BMP, GIF, JPG, PNG files. The file format used here for the Ultimaker 2+ is STL.

3.1.2 SLA printer Anycubic Photon (Anycubic 3D Printing, Guangdong, China)

The simplest **SLA** printer used here was an Anycubic Photon open resin printer (Anycubic 3D Printing, Guangdong, China) (Figure 14).

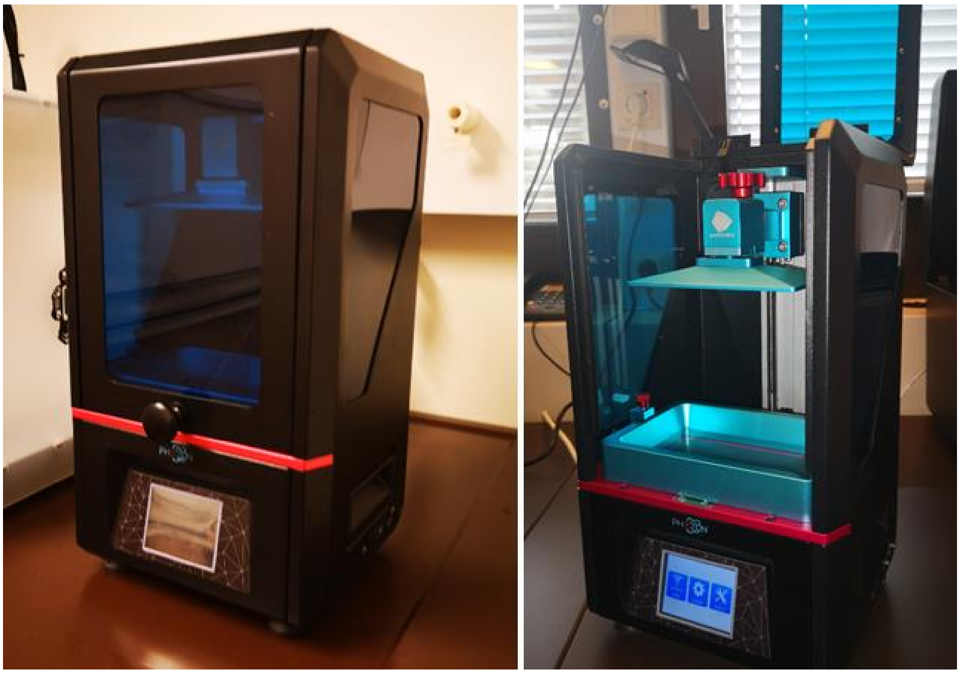

Figure 14. Anycubic Photon

The Anycubic Photon is capable to produce highly detailed prints, and the precision is about 5 times higher than for ordinary FDM printers. The technical specifications of Anycubic Photon are listed in Table 2 [66].

Table 2. Technical specifications of the Anycubic Photon

Printing Technology	LCD-based SLA 3D Printer
Light-source	UV light（wavelength 405nm）
XY DPI	47um (2560 x 1440)
Y axis resolution	1.25um
Layer resolution	25-100um
Printing speed	20mm/h
Rated Power	40W
Printer size	220mm x 200mm x 400mm
Printing volume	115mm x 65mm x 155mm
Printing material	405nm photosensitive resin
Connectivity	USB Port
Weight	6.6kg

The Anycubic Photon can only read and process STL files. The STL files can be designed and generated with Anycubic Photon Slicer, a software developed by Anycubic. In Anycubic Photon Slicer, 5 printing parameters, namely layer thickness, normal exposure time, off time, bottom exposure time and bottom layers can be set and support structures can be generated.

3.1.3 Formlabs Form 2 (Formlabs Inc., Somerville, USA)

Formlabs Form 2 is a high quality and accurate professional stereolithography (SLA) 3D printer that developed by Formlabs (Formlabs GmbH, Berlin) (Figure 15).

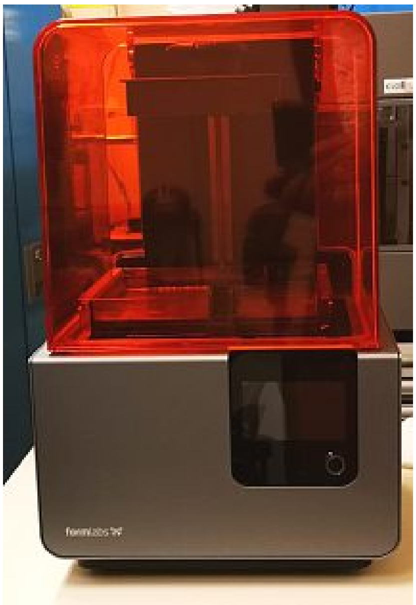

Figure 15. Formlabs Form 2

This printer is widely used in prototyping, and the resolution is high with 140 µm (nominal). It's capable to print parts with different mechanical properties. The Formlabs Form 2 has a powerful optical engine, and the 250mW violet laser is used for curing resins [67]. The technical specification of the Formlabs Form 2 are summarized in Table 3 [68].

Table 3. Technical specifications of Formlabs Form 2

Printing Technology	Stereolithography (SLA)
Laser Power	One 250mW laser
Laser Spot Size	140microns
Build Volume (W x D x H)	14.5 x 14.5 x 17.5cm
Layer Thickness	25-300microns
Resin Fill System	Automated
Biocompatible Materials	Yes

Supports	Auto-Generated and Easily Removable
Printer Dimensions (W x D x H)	34.5 x 33 x 52cm
Weight	13kg
Operating Temperature	Auto-heats to 35°C
Connectivity	Wi-Fi (2.4 GHz), Ethernet (100 Mbit), USB 2.0

The Formlabs Form 2 contains 3 parts: the tank, the cleaner and the build platform. It can print parts with a z-resolution between 25 and 100 microns, and it can print lots of small models with much detail at the same time. The free software used for this printer is ProForm, and it's also developed by Formlabs GmbH. The support can be generated automatically by the software. However, the printing parameters cannot be adjusted manually [69].

3.1.4 Stratasys Objet500 Connex3 (Stratasys Ltd., Eden Prairie, USA).

The Stratasys Objet500 Connex3 (Figure 16) is a professional 3D printer made by Stratasys (Stratasys LTD., Rechovot, Israel), and the Connex3 system was the first 3D printing system in the world capable of printing materials with different colours and properties at the same time. It can provide a very high resolution and precision to print models with quite fine structures [70].

Figure 16. Stratasys Objet500 Connex3

The Stratasys Objet500 Connex3 uses the PolyJet 3D printing technology. The PolyJet 3D printing technology is like ink jet printing, but the PolyJet 3D printers jets the layers of curable resins onto a platform instead of jetting ink onto a paper. The layers of curable resins will be cured by UV light to form solid layers [71]. The technical specification of the Stratasys Objet500 Connex3 are summarized in Table 4 [70].

Table 4. Technical specification of the Stratasys Objet500 Connex3

Printing Technology	PolyJet Stereolithography (SLA)
Maximum Build Size (W x D x H)	49 x 39 x 20cm
Printer Size (W x D x H)	Main Body: 140 x 126 x 110cm Material Cabinet: 33 x 117 x 64cm
Weight	Main Body: 430kg Material Cabinet: 76kg
Resolution	X-axis: 600 dpi; Y-axis: 600 dpi; Z-axis: 1600 dpi
Minimum Layer Thickness	16 microns
Accuracy	Up to 200 microns for full model size
Material Options	Over 1000
Support Material	SUP705 (WaterJet removable); SUP706 (soluble)
Software	GrabCAD
Operating Conditions	Temperature: 18-25°C; Relative Humidity: 30-70%
Network Connectivity	LAN - TCP/IP

Printing parameters of the Stratasys Objet500 Connex3 cannot be adjusted manually.

3.2 Printing materials

In the following, the printing materials used in this work are described. The materials were selected from commercially available printing materials on the basis of potential interest for applications in radiographic phantoms.

3.2.1 Materials printed by FDM with the Ultimaker 2+

There are 29 kinds of materials printed with the FDM printer Ultimaker 2+ in this work. The manufacturer, the product number, the chemical composition, the density and the recommended printing parameters of each material is shown in Table 5.

Table 5. Specifications of 29 kinds of materials for Ultimaker 2+

Material Manufacturer Product number	Complete name	Chemical composition Chemical formula	Density from Vendor [g/cm^3]	Recommended printing parameters from Manufacturer				Reference
				Nozzle temperature [°C]	Printing speed [mm/s]	Bed temperature [°C]	Flow rate [%]	
ABS Verbatim 55019	Acrylonitrile Butadiene Styrene	Acrylonitrile: 15%-35% Butadiene: 5%-30% Styrene: 40%-60% $(C_8H_8 \cdot C_4H_6 \cdot C_3H_3N)_x$	1.08	240-260		90	107	[72] [73]
HIPS ICE Filaments 29548	High impact polystyrene	Polystyrene and a little polybutadiene $(C_8H_8)_n$	1.04	220-260		65-110		[74]
Vinyl 303 Fillamentum VIN303_ 285_nat	PVC: Polyvinyl Chloride	Polymerization of the vinyl chloride monomer $(C_2H_3Cl)_n$	1.35	215-230	40-60	80		[75] [76]
PLA Ultimaker 1612	Polylactic acid	Thermoplastic aliphatic polyester $(C_3H_4O_2)_n$	1.24	195-240		60	100	[77] [78]

StoneFil Formfutura 285STONEFIL-PCLAY-0500	StoneFil™	PLA filled with 50% stone powder	1.70	200-240	High or Medium	0-60	110	[79]
corkFill colorFabb 8719033555327	Fibrolon® HP 7823	PLA and polyesters filled with 10-20% cork fibres	1.18	210-230	45	50-60		[80]
PET Innofil3d natural: Pet-0301b075, black: Pet-0302b075	Polyethylene Terephthalate	Esterification reaction of terephthalic acid and ethylene glycol $(C_{10}H_8O_4)_n$	1.34	200-220	30-60	65-85		[81]
EasyWood Formfutura 285EWOOD-BIRCH-0500	EasyWood™	PLA filled with 40% grinded wood particles	1.20	200-240	High	0-60	104	[82]
HDglass (Heavy duty PETG) Formfutura 285HDGLA-CLEAR-0750	Polyethylene Terephthalate Glycol-modified	Glycol-modified PET > 98% $(C_{10}H_8O_4)_n$	1.27	195-225	High	65-75	110	[83]
colorFabb_XT colorFabb 8719033553019	Eastman Amphora™ 3D Polymer AM1800	Copolyester > 96%, Color additives < 4 %	1.27	240-260	50	70-75	110	[84]
PLA Mineral Fiberlogy PLA-MIN-NATUR-285-085	PLA Mineral	PLA filled with chalk	1.40	190-210		50-70		[85]
nGen colorFabb 8719033554733	Eastman Amphora™ 3D Polymer AM3300	Copolyester > 96%, Color additives < 4 %	1.20	220-240	40-60	75-85		[86]
PC-Plus Polymaker 70409	Makrolon® Polycarbonate	Modified PC	1.19-1.20	250-270 (Fan off)	30-50	90-110		[87]

TPU transparent Extrudr 9010241152001	Thermoplastic polyurethane	Based on Polycaprolacton-Polyester	1.15	230-250	20-30	50-60		[88]
ASA Fillamentum natural 00118, black 00119	Acrylonitrile Styrene Acrylate	Acrylate rubber-modified styrene acrylonitrile copolymer	1.07	240-255		90-105		[89] [90]
ApolloX Formfutura 285APOX-WHITE-0750	ApolloX™	Industrial-grade Modified ASA	1.11	235-255	Medium	80-90	100	[91]
PP Verbatim 55951	Polypropylene	Chain-growth polymerization from monomer propylene. $(C_3H_6)_n$	0.89	230-250	30	80		[92] [93]
Copperfill AprintaPro 195172	AprintaPro Metal copper	PLA filled with 80% copper powder	3.41	195-220	Up to 45	65	102	[94]
Bronzefill AprintaPro 195072	AprintaPro Metal bronze	PLA filled with 80% bronze powder	3.39	195-220	Up to 45	65	102	[94]
steelFill colorFabb 8719033555679	colorFabb SteelFill	PlA filled with about 80% stainless steel powder	3.13	195-220	50-70	50-60		[95]
copperFill colorFabb 8719033555174	colorFabb CopperFill	PLA filled with about 80% copper powder	4.00	195-220	50	50-60		[96]
GreenTEC PRO natural Extrudr 9010241426034	GreenTEC Pro	Biodegradable batch based on PLA, contains copolyester and additives	1.39	190-250	40-120	0-90		[97]
GreenTEC PRO Carbon Extrudr 9010241426973	GreenTEC Pro Carbon	Green TEC Pro filled with 10% carbon fiber	1.15	200-240	60-180	0-90		[98]

CarbonFil Formfutura 175CARBFIL-BLCK -0500	CarbonFil™	Hdglass (PETG) filled with 20% long stringer carbon fibre	1.19	230-265	High	0-60	100	[99]
Nylon Ultimaker 1647	Nylon	Polyamide (grade based on PA6/PA66) PA6:[NH- $(CH_2)_5$-CO]$_N$; PA66:[NH-$(CH_2)_6$- NH-CO-$(CH_2)_4$- CO]$_n$-[NH-$(CH_2)_5$ -CO]$_m$	1.14	230-260		60	100	[100] [101]
glowFill colorFabb 8719033555136	Bio-Flex® V 135001	PLA filled with biodegradable polymer	1.24	195-220	40-100	50-60		[102]
Pegasus PP Ultralight Formfutura 285PEGAPP-NAT-0500	Pegasus PP	PP filled with ultralight nanotechnology enhanced compound	0.75	215-245	High or Medium	0-100	104	[103]
PLA Sparkly Silver Eryone GPLA-SILVER-175-1000	ERYONE Sparkly Galaxy Glitter Silver PLA	Mainly made from corn starch	1.24	195-215	30-60			[104]
Metal Filament Aluminium AptoFun B01ITNXRWD		PLA filled with 10% Aluminum powder		190-230	50			

All the data in Table 5 were taken from official websites of manufacturers, technical data sheets and material safety data sheets.

Note, that the recommended printing parameters in the Table 5 may not be the completely same as the recommended printing parameters in the references, because some of the materials have been improved by the companies. The recommended printing parameters and the technical datasheets are also regularly updated by the respective companies.

Fumes from melted Vinyl 303 (PVC) and ABS are toxic. Therefore, the printing process must be performed in a ventilated environment. In this work, a Laminar Airflow cabinet was used.

3.2.2 Resins used with SLA Printers

12 kinds of resins were printed with the SLA Printers, 4 with the Anycubic Photon open resin printer, 3 with the Formlabs Form 2 and 5 on the Stratasys Objet500 Connex3.

The specifications of the resins are shown in Table 6, and the printing parameters of the resins used with the Anycubic Photon are shown in Table 7.

Table 6. Specifications of resins for SLA Printers

Resins Manufacturer Product number	Printer	Hardness [Shore]	Optimal wavelength of UV light [nm]	Density specified by Manufacturer [g/cm³]	Curing time in UV chamber [minutes]	Reference
Anycubic Resin green Anycubic 3D Printing AB-POT048	Anycubic Photon	D84	405	1.18 (solid)		[105]
PrimaCreator Resin clear 3D Prima PV-RESIN-B405-0500-CL	Anycubic Photon	D85	395-405	1.05-1.13 (liquid)	2-5	[106]
Wanhao Resin water washable clear Wanhao 23453	Anycubic Photon	D75	395-420	1.00-1.11 (liquid)		[107]
PhotoCentric3D UV Flexible Resin clear Photocentric PHODCL01UVFLEX	Anycubic Photon	A80	385,405	1.18 (liquid)	120	[108]

Formlabs form 2 clear resin Formlabs RS-F2-GPCL-04	Formlabs Form 2			1.09-1.12	30	[109] [110]
Vero PureWhite Stratasys OBJ-03327	Stratasys Connex3	D83-86		1.17-1.18		[111]
VeroBlue Stratasys OBJ-03204	Stratasys Connex3	D83-86		1.18-1.19		[112]
VeroClear Stratasys OBJ-03271	Stratasys Connex3	D83-86		1.18-1.19		[113]
Formlabs form 2 flexible resin Formlabs RS-F2-FLGR-02	Formlabs Form 2	A80-85		1.09-1.12	60	[114] [115]
Formlabs form 2 elastic resin Formlabs RS-F2-ELCL-01	Formlabs Form 2	A50		1.02	20	[116] [117]
RGD 525 Stratasys OBJ-03256	Stratasys Connex3	D87-88		1.17-1.18		[118]
TangoPlus Stratasys OBJ-03224	Stratasys Connex3	A26-28		1.12-1.13		[119]

Table 7. Printing parameters of the resins used for Anycubic Photon

Resins	Printing parameters				
	Exposure Time [s]	Off Time [s]	Layer Thickness [mm]	Bottom Exposure Time [s]	Bottom Layers
Anycubic Resin green AB-POT048	10	1	0.05	50	8
PrimaCreator Resin clear PV-RESIN-B405-0500-CL	10	1	0.05	50	8

Wanhao Resin water washable clear 23453	10	1	0.05	50	8
PhotoCentric3D UV Flexible Resin clear PHODCL01UVFLEX	17	5	0.05	120	8

In SLA printing parameters do not influence density, and can only be set manually in one of the printers used (Anycubic Photon). For Formlabs Form 2 and Stratasys Connex3, printing parameters cannot be changed.

All uncured resins used in SLA printers are toxic. They are harmful to the eyes, skin, the respiratory system and the digestive system. Therefore, gloves should be worn, and it's necessary to use ventilation during printing. After printing, the printer and the model should be cleaned with 99% IPA (Isopropyl Alcohol) to rinse of extra resin left. The printed model should be put into a UV chamber or placed in direct sunlight for curing.

3.3 Optimization of printing parameters for general purpose printing

In the first step the optimal printing conditions were determined for all materials used. Optimal printing parameters are the precondition for density measurement and are used as starting point to obtain an optimal filling ratio in a next step.

29 kinds of FDM printing materials were optimized with regard to optimum printing quality (minimal artefacts like stringing, warping, surface roughness, model accuracy) using the 3DBenchy highres test STL model available from [120] on the Ultimaker 2+. Nozzle temperature, printing speed and bed temperature were optimized using this model.

3DBenchy (Figure 17) is a 3D model that is designed for testing and calibrating 3D printers [121]. The STL file of 3DBenchy can be downloaded freely from their website [120] for public use. 3DBenchy contains lots of challenging geometrical features for 3D printers, and touches on different issues related to 3D printing. All the detailed geometrical features of 3DBenchy can be found in [121]. The model should be printed at 1:1 scale without any support materials, and the print takes about 2 hours and does not use much material [121].

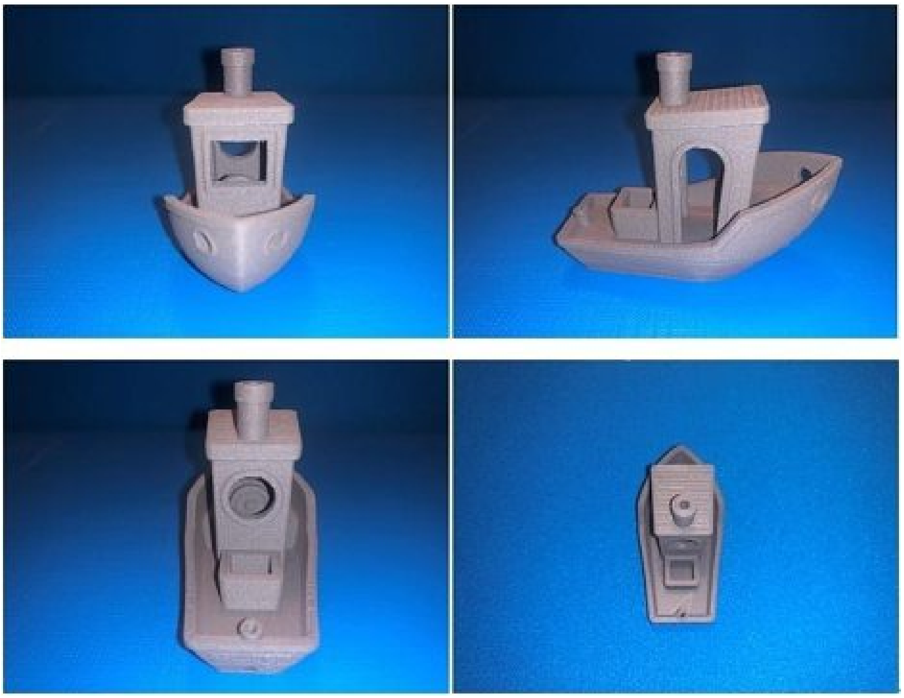

Figure 17. 3DBenchy (printed with steel filled PLA for demonstration)

The hardware and software settings (printing parameters) used determine the accuracy of 3D printers and the printing quality [122]. In order to get the optimal printing quality, the printing parameters were optimized by printing the 3DBenchy and analysing the results. The appearance (such as stringing, warping, surface roughness, dimensional accuracy...) of the 3DBenchy can reflect the printing quality of a certain material, and the printing quality of a certain material can thus be optimized by adjusting the applicable parameters [122].

The optimal printing parameters result in nearly perfect printouts of the 3DBenchy (Figure 18, 20, 22). On the contrary, unsuitable printing parameters may produce a defective 3DBenchy or cause complete failure of the print (Figure 19, 21, 23).

Figure 18. Perfect 3DBenchy (EasyWood material printed with optimal printing parameters)

Figure 19. Missing layer and too much stringing (EasyWood material printed with unsuitable printing parameters)

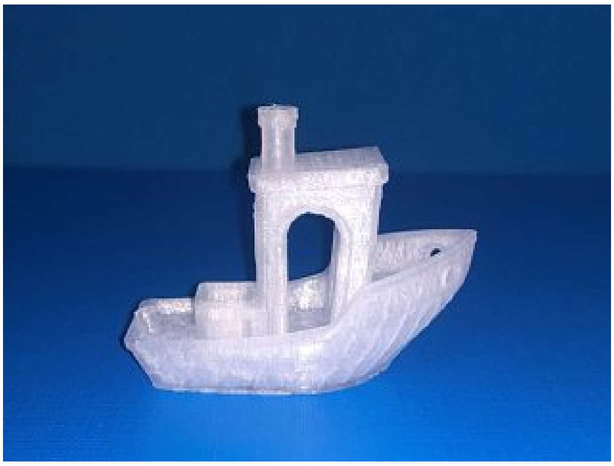

Figure 20. 3DBenchy with good appearance (PP printed with optimal printing parameters)

Figure 21. Top deformation (PP printed with unsuitable printing parameters)

Figure 22. 3DBenchy with good appearance (PVC printed with optimal printing parameters)

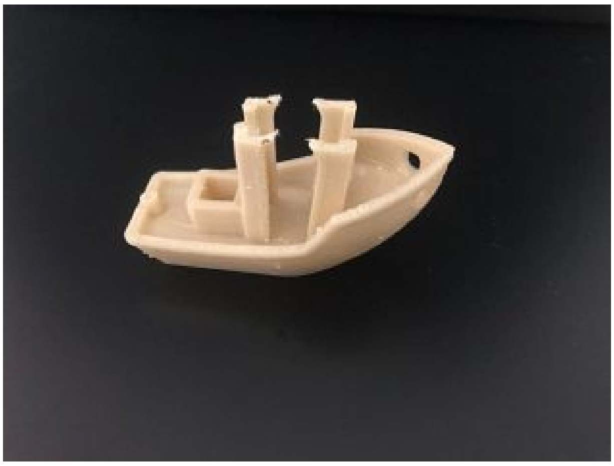

Figure 23. Printing failure (PVC printed with unsuitable printing parameters)

The shape and size of the 3DBenchy model is designed to test 3D printers and printing quality [122]. Comparing the results of 3DBenchy printouts by measuring dimensions is an important method to find the optimal printing parameters. All the detailed standard dimensions (such as length, height, width…) of 3DBenchy are shown on the website [122]. A calliper is appropriate to measure most of the dimensions [122].

In order to find the optimal printing parameters of each material, specific printing parameters were used for most materials. All the printing parameters used in the tests were based on the recommended printing parameters from manufacturers of materials as starting point (Table 5). For very few materials, the recommended printing parameters from manufacturers were inaccurate or the parameters were not suitable for the Ultimaker 2+ printer. Therefore, the actual parameters used in the tests may be outside the range of the recommended printing parameters for some materials.

The main printing parameters that influence the printing quality are

- nozzle temperature and
- printing speed.

These two parameters were adjusted mainly to find the optimal setting. The rest of printing parameters such as bed temperature, fan speed, flow rate, retraction length and retraction speed can also influence the printing quality but to a lesser degree, so these parameters were set to the recommended values or the default of the printer.

In the tests, if not noted differently, the nozzle diameter is 0.4mm, the layer thickness 0.15mm, the flow rate is 100%, the fan speed 100%, the retraction length 6mm and the retraction speed 25mm/s. These parameters correspond to the default and "normal" settings of the Ultimaker 2+.

If the printing was a complete failure or the appearance of the 3DBenchy had some defect, the printing parameters were judged suboptimal and adapted. When the 3DBenchys were printed with high quality and the appearances had no defect, a calliper was be used to measure the length, height and width of the 3DBenchys. Each value of height, width and length of a 3DBenchy was measured 3 times. The averages and the standard deviations were calculated. These values were compared with the nominal value of the 3DBenchy (height 48mm, width: 31mm, length: 60mm). The printing parameters resulting in those values closest to the nominal values correspond to the optimal printing parameters, if no or minimal defects or artefacts are present in the printout.

The printing parameters used for all the materials and the measurement data of each 3DBenchy are shown in Table 8. In the last column a checkbox indicates whether the parameter set shown represents the optimal setting based on the dimensions and the absence of defects in the printout of the 3DBenchy. An "x" in the "appearance" checkbox column indicates failed printouts.

An empty box in the fan speed column corresponds to the default setting of 100%, and if no data is input into the flow rate box, flow rate was set to default of 100%.

Table 8. Summary of important printing parameters of different materials and the optimal printing parameters.

Material	Figure	Nozzle Temp. [°C]	Printing Speed [mm/s]	Bed Temp. [°C]	Fan Speed [%]	Flow Rate [%]	Appear-ance	Height [mm]	ΔH^{*1} [mm]	Width [mm]	ΔW^{*2} [mm]	Length [mm]	ΔL^{*3} [mm]	Optimal Parameter
ABS (Verbatim, 55019)	**54**	**250**	**60**	**80**		**107**	✓	**47.88±0.04**	**-0.12±0.04**	**31.28±0.05**	**+0.28±0.05**	**60.22±0.06**	**+0.22±0.06**	✓
HIPS (ICE Filaments, 29548)	**55**	**240**	**40**	**100**			✓	**47.61±0.04**	**-0.39±0.04**	**30.89±0.06**	**-0.11±0.06**	**59.87±0.04**	**-0.13±0.04**	✓
Vinyl 303 (Fillamentum, VIN303_285_nat)	56	220	60	80			×							
	57	230	60	80			×							
	58	**230**	**40**	**80**			✓	**47.94±0.04**	**-0.06±0.04**	**30.96±0.04**	**-0.04±0.04**	**59.94±0.02**	**-0.06±0.02**	✓
PLA (Ultimaker, 1612)	**59**	**210**	**50**	**60**			✓	**47.57±0.06**	**-0.43±0.06**	**30.93±0.03**	**-0.07±0.03**	**59.84±0.03**	**-0.16±0.03**	✓
StoneFil (Formfutura, 285STONEFIL-PCLAY-0500)	60	240	60	60		110	✓	47.48±0.03	-0.52±0.03	30.98±0.02	-0.02±0.02	59.85±0.05	-0.15±0.05	
	61	**220**	**50**	**60**		**110**	✓	**47.55±0.02**	**-0.45±0.02**	**30.98±0.04**	**-0.02±0.04**	**59.99±0.07**	**-0.01±0.07**	✓
corkFill (colorFabb, 8719033555327)	**62**	**230**	**50**	**60**			✓	**47.62±0.03**	**-0.38±0.03**	**30.95±0.06**	**-0.05±0.06**	**59.93±0.05**	**-0.07±0.05**	✓
	63	220	60	60			✓	47.38±0.03	-0.62±0.03	30.97±0.05	-0.03±0.05	59.89±0.04	-0.11±0.04	
PET natural (Innofil3d, Pet-0301b075）	**64**	**220**	**60**	**75**			✓	**47.47±0.06**	**-0.53±0.06**	**30.93±0.04**	**-0.07±0.04**	**59.94±0.04**	**-0.06±0.04**	✓

PET black (Innofil3d, Pet-0302b075)	**65**	**220**	**60**	**75**			✓	**47.99±0.03**	**-0.01±0.03**	**31.00±0.02**	**+0.00±0.02**	**59.96±0.03**	**-0.04±0.03**	✓
	66	230	50	75			✓	47.41±0.03	-0.59±0.03	30.90±0.04	-0.10±0.04	59.90±0.06	-0.10±0.06	
EasyWood (Formfutura, 285EWOOD-BIRCH-0500)	67	220	60	60		104	×							
	68	240	50	60		104	×							
	69	**200**	**70**	**60**		**104**	✓	**47.93±0.03**	**-0.07±0.03**	**31.02±0.06**	**+0.02±0.06**	**59.89±0.02**	**-0.11±0.02**	✓
HDglass (Formfutura, 285HDGLA-CLEAR-0750)	**70**	**220**	**60**	**75**		**110**	✓	**47.88±0.04**	**-0.12±0.04**	**30.95±0.06**	**-0.05±0.06**	**59.99±0.01**	**-0.01±0.01**	✓
	71	200	50	75		110	✓	47.84±0.02	-0.16±0.02	30.90±0.05	-0.10±0.05	59.88±0.02	-0.12±0.02	
colorFabb_XT (colorFabb, 8719033553019)	72	260	50	70		110	✓	47.81±0.03	-0.19±0.03	31.04±0.06	+0.04±0.06	60.04±0.04	+0.04±0.04	
	73	**260**	**40**	**70**		**110**	✓	**48.04±0.03**	**+0.04±0.03**	**30.94±0.02**	**-0.06±0.02**	**59.96±0.04**	**-0.04±0.04**	✓
PLA Mineral (Fiberlogy, PLA-MIN-NATUR-285-085）	**74**	**210**	**60**	**70**			✓	**47.96±0.04**	**-0.04±0.04**	**31.01±0.02**	**+0.01±0.02**	**59.96±0.05**	**-0.04±0.05**	✓
	75	190	60	70			✓	47.74±0.01	-0.26±0.01	30.95±0.04	-0.05±0.04	59.89±0.03	-0.11±0.03	
nGen (colorFabb, 8719033554733)	**76**	**240**	**60**	**60**			✓	**47.86±0.02**	**-0.14±0.02**	**30.98±0.06**	**+0.02±0.06**	**59.95±0.02**	**-0.05±0.02**	✓
	77	220	40	60			×							
	78	220	40	75			✓	47.73±0.03	-0.27±0.03	30.92±0.02	-0.08±0.02	60.01±0.03	+0.01±0.03	
	79	220	40	60	0		✓	47.72±0.02	-0.28±0.02	30.93±0.03	-0.07±0.03	59.99±0.02	-0.01±0.02	
PC-Plus (Polymaker, 70409)	80	260	60	80	0		✓	47.62±0.04	-0.38±0.04	30.94±0.03	-0.06±0.03	59.91±0.01	-0.09±0.01	
	81	250	40	80	0		×							
	82	250	40	90	100		×							
	83	**250**	**40**	**90**	**0**		✓	**47.76±0.03**	**-0.24±0.03**	**31.06±0.04**	**+0.06±0.04**	**59.98±0.03**	**-0.02±0.03**	✓

TPU green (Extrudr, 9010241152278)	**84**	**230**	**30**	**70**			✓	**47.87±0.04**	**-0.13±0.04**	**30.99±0.04**	**-0.01±0.04**	**59.84±0.04**	**-0.16±0.04**	✓
	85	240	25	70			×							
	86	220	40	70			×							
	87	230	100	70			×							
	88	210	25	70			×							
TPU transparent (Extrudr, 9010241152001)	**89**	**230**	**30**	**70**			✓	**47.84±0.02**	**-0.16±0.02**	**30.93±0.05**	**-0.07±0.05**	**59.88±0.05**	**-0.12±0.05**	✓
	90	220	20	70			×							
ASA black (Fillamentum, black 00119)	91	260	50	80			×							
	92	**260**	**50**	**100**			✓	**47.79±0.03**	**-0.21±0.03**	**31.00±0.01**	**+0.00±0.01**	**59.90±0.04**	**-0.10±0.04**	✓
	93	250	60	100			✓	47.71±0.02	-0.29±0.02	31.02±0.05	+0.02±0.05	59.96±0.06	-0.04±0.06	
ASA natural (Fillamentum, 00118)	**94**	**260**	**50**	**100**			✓	**47.90±0.02**	**-0.10±0.02**	**30.94±0.03**	**-0.06±0.03**	**59.95±0.05**	**-0.05±0.05**	✓
	95	240	40	100			✓	47.78±0.03	-0.22±0.03	30.94±0.06	-0.06±0.06	59.92±0.02	-0.08±0.02	
ApolloX (Formfutura, 285APOX-WHITE -0750)	**96**	**260**	**50**	**100**			✓	**47.87±0.03**	**-0.13±0.03**	**30.99±0.05**	**-0.01±0.05**	**59.94±0.02**	**-0.06±0.02**	✓
	97	240	40	100			✓	47.76±0.01	-0.24±0.01	30.94±0.03	-0.06±0.03	59.97±0.05	-0.03±0.05	
PP (Verbatim, 55951)	98	230	35	100	100		×							
	99	230	35	100	20		×							
	100	**240**	**25**	**100**	**80**		✓	**47.69±0.05**	**-0.31±0.05**	**30.95±0.03**	**-0.05±0.03**	**59.89±0.05**	**-0.11±0.05**	✓
Copperfill (AprintaPro, 195172)	101	220	45	65		102	×							
	102	**200**	**35**	**65**		**102**	✓	**47.89±0.05**	**-0.11±0.05**	**30.99±0.05**	**-0.01±0.05**	**59.91±0.04**	**-0.09±0.04**	✓

Bronzefill (AprintaPro, 195072)	103	210	45	65		102	✓	47.80±0.04	-0.20±0.04	30.99±0.03	-0.01±0.03	59.93±0.04	-0.07±0.04	
	104	**200**	**35**	**65**		**102**	✓	**47.91±0.03**	**-0.09±0.03**	**31.01±0.05**	**+0.01±0.05**	**59.97±0.05**	**-0.03±0.05**	✓
steelFill (colorFabb, 8719033555679)	105	210	60	50		110								
	106	**200**	**50**	**50**		**110**	✓	**48.01±0.04**	**+0.01±0.04**	**31.06±0.03**	**+0.06±0.03**	**60.02±0.01**	**+0.02±0.01**	✓
copperFill (colorFabb, 8719033555174)	**107**	**200**	**35**	**65**			✓	**47.89±0.05**	**-0.11±0.05**	**31.00±0.04**	**+0.00±0.04**	**59.98±0.03**	**-0.02±0.03**	✓
GreenTEC PRO natural (Extrudr, 9010241426034)	108	240	80	80			×							
	109	**220**	**60**	**80**			✓	**47.86±0.04**	**-0.14±0.04**	**31.00±0.04**	**+0.00±0.04**	**59.92±0.04**	**-0.08±0.04**	✓
GreenTEC PRO Carbon (Extrudr, 9010241426973)	**110**	**220**	**60**	**80**			✓	**47.84±0.03**	**-0.16±0.03**	**31.02±0.02**	**+0.02±0.02**	**59.96±0.01**	**-0.04±0.01**	✓
	111	230	100	80			×							
CarbonFil (Formfutura, 175CARBFIL-BLCK-0500)	112	260	80	60			×							
	113	240	60	60			×							
	114	**230**	**50**	**60**			✓	**47.92±0.03**	**-0.08±0.03**	**31.01±0.01**	**+0.01±0.01**	**60.11±0.01**	**+0.11±0.01**	✓

*1, ΔH is the Height differences between the experimental value and the standard value of the 3DBenchy.
*2, ΔW is the Width differences between the experimental value and the standard value of the 3DBenchy.
*3, ΔL is the Length differences between the experimental value and the standard value of the 3DBenchy.

Note the standard values of the 3DBenchy: Height 48mm; Width: 31mm; Length: 60mm. Each value of height, width and length of a 3DBenchy was measured 3 times. The averages and the standard deviations were calculated. Experiment value shown is average ± one standard deviation.

For SLA printers, the printing parameters of Anycubic Photon open resin printer (Anycubic 3D Printing, Guangdong, China) can be adjusted manually. The adjustable printing parameters contain exposure time, off time, layer thickness, bottom exposure time and bottom layers. The printing parameters of SLA printers do not influence the density, thus the printing parameters used in the tests were the recommended parameters from manufacturers. Four kinds of resins were tested with printing 3Dbenchys. Figure 115, 116, 117 and 118 in the Appendix show the 3DBenchys that were printed with Anycubic Resin green, PrimaCreator Resin clear, Wanhao Resin water washable clear and PhotoCentric3D UV Flexible Resin clear.

3.4 Density optimization and measurement

In FDM printing density of the printouts is mostly below filament density. Since it also depends on printing parameters, this poses a severe problem in x-ray phantoms since too low density results in too low x-ray attenuation. Also, density may vary in solid printouts in case of packing ratios below 100% occur with the tendency to be higher in the outer contours than in the core. This is a direct consequence of how a FDM printer prints filled objects, but cannot be tolerated in phantoms. However, this issue is totally neglected since unimportant in the usual applications.

Common "optimized" printing parameters, thus, result in filling ratios < 100%, and lower density negatively affecting reproducibility of phantoms, x-ray attenuation and Hounsfield Units in CT, and thus contrasts. Therefore, printing parameters of all the materials need to be optimized and controlled to result in maximum solid density.

In this part printing parameters are optimized to result in solid prints with 100% packing ratio indicated by a mass density corresponding to 100% of the filament density.

3.4.1 Density optimization

All previously discussed 29 **FDM** printing materials were optimized with regard to maximum packing ratio with minimal overextrusion. In 3.3, the optimal printing parameters of all the materials for optimum print quality have been found by printing and comparing 3DBenchys. In this part, cylinders with 1.5 cm diameter and 2 cm height were printed and flow rate and layer thickness varied to obtain mass densities corresponding to the maximum density achievable.

A printed sample from an FDM printer consists of a lot of layers, and each layer consists of many lines or circles (depending on the infill patterns). Usually there are some gaps between adjacent layers and between adjacent lines or circles in each layer, and the existence of these gaps is the reason why it is difficult or sometimes almost impossible to achieve 100% infill. One effective way to solve this problem is to increase the flow rate to cause overextrusion (excess material is extruded out of the nozzle). The excess extruded material can fill the gaps between adjacent lines or circles in each layer to increase the filling ratio (density) effectively. However, the overextrusion has an upper limit. If the extrusion is too much (Figure 24), a standard cylinder will not be formed and the density cannot be measured.

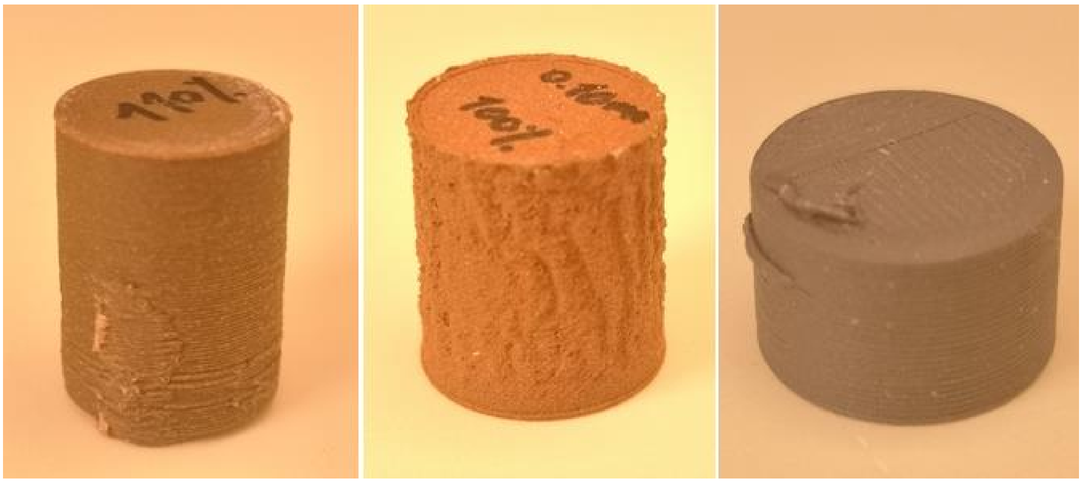

Figure 24. Too much overextrusion. Left photo: corkFill (colorFabb) material. Middle photo: Copperfill (AprintaPro) material. Right photo: steelFill (colorFabb) material

Another effective way is to decrease the layer thickness for minimizing the gaps between adjacent layers. With the Ultimaker 2+, there are 3 recommended options about layer thickness: Normal (0.15mm), Fine (0.10mm) and Extra Fine (0.06mm). For all the tests in 3.3, the layer thickness used was always set to normal corresponding to 0.15mm, but in this part, the layer thickness was selectively decreased to Fine or Extra Fine.

In order to find the optimal filling ratio of each material, many cylinders with 1.5 cm diameter and 2 cm height were printed using different flow rate and/or layer thickness.

In the first step, the infill pattern and wall thickness were determined. With the Ultimaker 2+, there are only two options regarding the infill patterns (Line and Circle) to print a sample with 100% infill. The minimum wall thickness is 0.35mm (wall line count 1), and the maximum wall thickness is 3.5mm (corresponding to wall line count 10). The test prints were carried out with the infill pattern line, the infill pattern circle, minimum wall thickness and maximum wall thickness, respectively. Densities of the cylinders were measured to find out which option results in a higher density.

In the second step, the optimal printing parameters of all the materials for optimal print quality were used to print cylinders. Densities of the cylinders were measured, and the densities were compared with the target densities provided by the manufacturers.

In the third step, if the densities of the printed materials were lower than the target densities indicating < 100% filling ratio, the flow rate was increased gradually, meaning the cylinders were printed with higher flow rates. Note: the flow rate has an upper limit. If the flow rate is too high, the overextrusion will be too much. Then, a cylinder of standard shape cannot be printed; thus, the density cannot be measured. For different materials, usually the upper limits of the flow rates are different but in the range of usually 115-120%.

In the fourth step, when the flow rate reached the upper limit, and if the densities of the printed materials still couldn't achieve the target densities, the layer thickness was decreased from 0.15mm to 0.10mm. If this did not show the desired effect, the layer thickness was further reduced to 0.06mm. Note: because of the specificities of different materials, some materials couldn't be printed with the layer thickness 0.06mm. Although reduction of the layer thickness can increase the filling ratio effectively, it will take much more time to finish printing.

In SLA (Stereolithography) printing parameters do not influence density, and can only be set manually in one of the printers used (Anycubic Photon). Therefore, the densities of all kinds of resins were measured directly by printing cylinders (1.5 cm diameter and 2 cm height) with the standard settings.

3.4.2 Density measurement

A balance and a screw micrometer (Mitotoyu, Japan) were used to measure the densities of all the cylinders. The balance was used to measure the mass of each cylinder, and the screw micrometer was used to measure the diameter and the height of each cylinder. The diameter of each cylinder was measured 9 times (different positions on the cylinder), and the averaged diameter and the standard deviation were calculated. The height of each cylinder was measured 5 times (one time in the center, the rest 4 times at edges). Density was calculated from the measurements dividing the mass of the cylinder by the volume of the cylinder: $M / (\pi \times R^2 \times H)$ where M is the mass of the cylinder, R the averaged radius of the cylinder, H is the averaged height.

The detailed data and the resulting densities of all the materials for FDM printer are shown in Table 9.

Table 9. Method of density optimization and density measurement

Material	Test Number	Flow rate [%]	Layer Thickness [mm]	Height Measurement [mm]		Diameter Measurement [mm]		Mass [g]	Measured Density [g/cm³]	Method	Target Density from Vendor [g/cm³]
				Average	SD	Average	SD				
StoneFil (Formfutura, 285STONEFIL-PC LAY-0500)	1	110	0.15	19.94	0.04	15.03	0.02	5.73	1.62	The printing parameters were the same as the parameters for optimal print quality. The infill pattern was Lines.	**1.70**
	2	110	0.15	19.80	0.00	15.00	0.03	5.59	1.60	The infill pattern was changed to Circles. The density of Circle infill pattern was lower than the density of Line infill pattern. In order to achieve optimal filling ratio, the infill pattern should be Lines.	
	3	110	0.15	19.77	0.02	14.98	0.01	5.60	1.61	The printing parameters were the same as the parameters for optimal print quality. However, the wall thickness was changed to maximum (3.5mm).	
	4	110	0.15	19.87	0.02	15.06	0.02	5.76	1.63	The printing parameters were the same as the parameters for optimal print quality. However, the wall thickness was changed to minimum (0.35mm). The density of minimum wall thickness is higher than the density of maximum layer thickness. Therefore, the layer thickness should be minimum.	
	5	100	0.15	19.80	0.04	14.92	0.02	5.58	1.61	The flow rate was decreased to 100%. The density also decreased. Therefore, it was possible to control the filling ratio by adjusting the flow rate.	
	6	115	0.15							The flow rate was increased to 115%. The printing failed because of too much overextrusion.	

	7	112	0.15							The flow rate was 112%. The printing still failed because of too much overextrusion.	
	8	110	0.10							The layer thickness was decreased to 0.1mm. The printing failed because of too much overextrusion.	
	9	105	0.10	19.82	0.02	14.99	0.02	5.71	1.63	In order to inhibit too much overextursion, the flow rate was decreased to 105%, when the layer thickness was 0.10mm.	
	10	**105**	**0.06**	**19.76**	**0.02**	**14.98**	**0.02**	**5.70**	**1.64**	**The layer thickness was further decreased to 0.06mm.**	
ABS (Verbatim, 55019)	1	107	0.15	19.91	0.05	15.25	0.02	3.87	1.06	The printing parameters were the same as the parameters for optimal print quality.	**1.08**
	2	110	0.15	20.00	0.04	15.33	0.05	3.92	1.06	The flow rate was increased to 110%. With the flow rate increasing, the density has no change. Therefore, it was not necessary to further increase the flow rate.	
	3	110	0.10	20.06	0.07	15.29	0.06	3.92	1.06	The layer thickness was decreased to 0.1mm.	
	4	**110**	**0.06**	**19.87**	**0.01**	**15.15**	**0.02**	**3.84**	**1.07**	**The layer thickness was further decreased to 0.06mm.**	
HIPS (ICE Filaments, 29548)	1	100	0.15	19.78	0.01	14.95	0.03	3.45	0.99	The printing parameters were the same as the parameters for optimal print quality.	**1.04**
	2	110	0.15	19.92	0.01	15.06	0.01	3.57	1.01	The flow rate was increased to 110%. The density increased, but it was not enough.	
	3	115								The flow rate was increased to 115%. The print failed because of too much overextrusion.	
	4	**110**	**0.10**	**19.90**	**0.01**	**14.92**	**0.03**	**3.54**	**1.02**	**The layer thickness was decreased to 0.1mm.**	
	5	**110**	**0.06**	**19.88**	**0.01**	**14.93**	**0.02**	**3.55**	**1.02**	**The layer thickness was further decreased to 0.06mm.**	
Vinyl 303 (Fillamentum, VIN303_285_nat)	**1**	**100**	**0.15**	**19.82**	**0.01**	**14.97**	**0.03**	**4.70**	**1.35**	**The printing parameters were the same as the parameters for optimal print quality. The density had already achieved the target density.**	**1.35**

PLA (Ultimaker, 1612)	1	100	0.15	19.82	0.02	14.93	0.04	4.26	1.23	The printing parameters were the same as the parameters for optimal print quality.	**1.24**
	2	**110**	**0.15**	**19.93**	**0.01**	**14.97**	**0.03**	**4.34**	**1.24**	**The flow rate was increased to 110%**	
	3	**110**	**0.10**	**20.08**	**0.06**	**15.06**	**0.07**	**4.42**	**1.24**	**The layer thickness was decreased to 0.1mm.The density did not change.**	
corkFill (colorFabb, 8719033555327)	**1**	**100**	**0.15**	**19.82**	**0.03**	**15.12**	**0.03**	**4.31**	**1.21**	**The printing parameters were the same as the parameters for optimal print quality.**	**1.18**
	2	**110**	**0.15**	**19.86**	**0.04**	**15.07**	**0.03**	**4.30**	**1.21**	**The flow rate was increased to 110%. With the flow rate increasing, the density has no change. Therefore, it was not necessary to further increase the flow rate.**	
	3	110	0.10							The layer thickness was decreased to 0.1mm. The printing failed because of too much overextrusion.	
PET (Innofil3d natural: Pet-0301b075, black: Pet-0302b075)	1	100	0.15	19.89	0.01	14.92	0.02	4.55	1.31	The printing parameters were the same as the parameters for optimal print quality.	**1.34**
	2	110	0.15	19.91	0.01	15.10	0.03	4.70	1.32	The flow rate was increased to 110%. The density increased.	
	3	115	0.10	20.00	0.02	15.05	0.04	4.71	1.32	The flow rate was increased to 115%, and the layer thickness was decreased to 0.1mm. The density did not change.	
	4	**115**	**0.06**	**20.04**	**0.02**	**15.02**	**0.05**	**4.71**	**1.33**	**The layer thickness was further decreased to 0.06mm.**	
EasyWood (Formfutura, 285EWOOD-BIRCH-0500)	1	104	0.15	19.74	0.03	14.93	0.04	3.82	1.11	The printing parameters were the same as the parameters for optimal print quality.	**1.20**
	2	110	0.15	19.87	0.02	15.08	0.03	4.10	1.16	The flow rate was increased to 110%. The density increased significantly.	

	3	115	0.10	19.88	0.02	15.07	0.03	4.20	1.18	The flow rate was increased to 115%, and the layer thickness was decreased to 0.1mm. The density increased.	
	4	**115**	**0.06**	**19.92**	**0.01**	**15.02**	**0.02**	**4.27**	**1.21**	**The layer thickness was further decreased to 0.06mm. The density achieved target density.**	
HDglass (Formfutura, 285HDGLA-CLEAR-0750)	1	110	0.15	19.80	0.00	14.87	0.04	4.22	1.23	The printing parameters were the same as the parameters for optimal print quality.	**1.27**
	2	**115**	**0.10**	**19.94**	**0.01**	**14.94**	**0.04**	**4.40**	**1.26**	**The flow rate was increased to 115%, and the layer thickness was decreased to 0.1mm. The density increased significantly.**	
	3	**115**	**0.06**	**19.92**	**0.01**	**14.95**	**0.03**	**4.41**	**1.26**	**The layer thickness was further decreased to 0.06mm.**	
colorFabb_XT (colorFabb, 8719033553019)	**1**	**110**	**0.15**	**19.62**	**0.03**	**15.30**	**0.03**	**4.54**	**1.26**	**The printing parameters were the same as the parameters for optimal print quality.**	**1.27**
	2	115	0.15							The flow rate was increased to 115%. The printing failed because of too much overextrusion.	
	3	110	0.06							The layer thickness was decreased to 0.06mm. The printing failed because of too much overextrusion.	
	4	**105**	**0.06**	**19.84**	**0.02**	**15.10**	**0.02**	**4.49**	**1.26**	**When the layer thickness was 0.06mm, the flow rate was decreased to 105% to inhibit the overextrusion. The density did not change.**	
PLA Mineral (Fiberlogy, PLA-MIN-NATUR-285-085）	1	100	0.15	19.76	0.03	14.92	0.04	4.68	1.35	The printing parameters were the same as the parameters for optimal print quality.	**1.40**
	2	110	0.15	19.98	0.04	14.96	0.03	4.83	1.38	The flow rate was increased to 110%. The density increased significantly.	

	3	115	0.15	19.91	0.01	15.12	0.04	4.93	1.38	The flow rate was increased to 115%. The density did not change.	
	4	120	0.15	19.95	0.03	15.21	0.03	4.99	1.38	The flow rate was increased to 120%. The density did not change.	
	5	120	0.10							The layer thickness was decreased to 0.1mm. The printing failed because of too much overextrusion.	
	6	115	0.10	19.94	0.01	15.10	0.03	4.94	1.38	In order to inhibit too much overextursion, the flow rate was decreased to 115%, when the layer thickness was 0.10mm.	
	7	**115**	**0.06**	**19.90**	**0.03**	**15.06**	**0.02**	**4.91**	**1.39**	**The layer thickness was further decreased to 0.06mm.**	
nGen (colorFabb, 8719033554733)	1	100	0.15	19.43	0.06	15.01	0.04	4.00	1.16	The printing parameters were the same as the parameters for optimal print quality.	**1.20**
	2	110	0.15	19.53	0.01	15.22	0.02	4.20	1.18	The flow rate was increased to 110%. The density increased, but it was not enough.	
	3	**115**	**0.10**	**19.99**	**0.03**	**15.11**	**0.03**	**4.25**	**1.19**	**The flow rate was increased to 115%, and the layer thickness was decreased to 0.1mm. The density increased slightly.**	
	4	**115**	**0.06**	**19.89**	**0.01**	**15.05**	**0.02**	**4.21**	**1.19**	**The layer thickness was further decreased to 0.06mm.**	
PC-Plus (Polymaker, 70409)	1	100	0.15	19.80	0.03	15.11	0.05	4.21	1.19	The printing parameters were the same as the parameters for optimal print quality.	**1.19-1.20**
	2	105	0.15							The flow rate was increased to 105%. The printing failed because of too much overextrusion.	
	3	100	0.10	19.99	0.04	15.04	0.05	4.22	1.19	The layer thickness was decreased to 0.1mm. The density did not change.	
	4	**100**	**0.06**	**19.84**	**0.04**	**14.94**	**0.02**	**4.16**	**1.20**	**The layer thickness was further decreased to 0.06mm.**	

TPU transparent (Extrudr, 9010241152001)	**1**	**100**	**0.15**	**19.74**	**0.01**	**15.08**	**0.16**	**4.09**	**1.16**	**The printing parameters were the same as the parameters for optimal print quality.**	**1.15**
	2	**110**	**0.15**	**19.58**	**0.01**	**15.03**	**0.02**	**4.03**	**1.16**	**The flow rate was increased to 110%. The density had no change, but it had already achieved the target density.**	
ASA (Fillamentum, natural 00118, black 00119)	1	100	0.15	19.94	0.02	14.87	0.03	3.59	1.04	The printing parameters were the same as the parameters for optimal print quality.	**1.07**
	2	110	0.15	20.01	0.02	15.07	0.03	3.73	1.05	The flow rate was increased to 110%. The density increased.	
	3	115	0.10	19.95	0.06	15.09	0.05	3.74	1.05	The flow rate was increased to 115%, and the layer thickness was decreased to 0.1mm. The density did not change.	
	4	**115**	**0.06**	**19.80**	**0.01**	**14.94**	**0.01**	**3.68**	**1.06**	**The layer thickness was further decreased to 0.06mm.**	
ApolloX (Formfutura, 285APOX-WHITE-0750)	**1**	**100**	**0.15**	**19.79**	**0.03**	**15.06**	**0.04**	**3.97**	**1.13**	**The printing parameters were the same as the parameters for optimal print quality.**	**1.11**
	2	**110**	**0.15**	**19.94**	**0.03**	**15.14**	**0.04**	**4.05**	**1.13**	**The flow rate was increased to 110%. The density did not change, but it had already achieved the target density.**	
PP (Verbatim, 55951)	**1**	**100**	**0.15**	**19.77**	**0.01**	**15.02**	**0.04**	**3.08**	**0.88**	**The printing parameters were the same as the parameters for optimal print quality.**	**0.89**
	2	110	0.15							The flow rate was increased to 110%. The printing failed because of too much overextrusion.	
	3	**105**	**0.15**	**19.82**	**0.01**	**15.06**	**0.02**	**3.11**	**0.88**	**The flow rate was adjusted to 105%. The density did not change**	
	4	105	0.10							The layer thickness was decreased to 0.1mm, The printing failed because of too much overextrusion.	

	5	100	0.10							When the layer thickness was 0.1mm, the flow rate was decreased to 100% to inhibit the overextrusion. The printing still failed.	
Copperfill (AprintaPro, 195172)	1	102	0.15	19.87	0.02	14.89	0.04	11.52	3.33	The printing parameters were the same as the parameters for optimal print quality.	**3.41**
	2	**110**	**0.15**	**19.82**	**0.01**	**14.82**	**0.02**	**11.54**	**3.38**	**The flow rate was increased to 110%. The density increased significantly.**	
	3	105	0.10							The layer thickness was decreased to 0.1mm. The printing failed because of too much overextrusion.	
	4	100	0.10							When the layer thickness was 0.1mm, the flow rate was decreased to 100% to inhibit too much overextrusion. The printing still failed.	
Bronzefill (AprintaPro, 195072)	1	102	0.15	19.88	0.02	14.91	0.03	12.38	3.57	The printing parameters were the same as the parameters for optimal print quality.	**3.39**
	2	110	0.15	19.90	0.02	15.07	0.02	13.14	3.70	The flow rate was increased to 110%. The density increased significantly.	
	3	110	0.10	19.93	0.03	15.06	0.04	13.20	3.72	The layer thickness was decreased to 0.1mm. The density increased slightly.	
	4	**110**	**0.06**	**20.00**	**0.01**	**14.93**	**0.03**	**13.06**	**3.73**	**The layer thickness was further decreased to 0.06mm.**	
steelFill (colorFabb, 8719033555679)	1	110	0.15	19.96	0.03	15.29	0.03	11.24	3.07	The printing parameters were the same as the parameters for optimal print quality.	**3.13**
	2	115	0.15							The flow rate was increased to 115%. The printing failed because of too much overextrusion.	
	3	110	0.10							The layer thickness was decreased to 0.1mm. The printing failed because of too much overextrusion.	

	4	100	0.10	19.90	0.01	15.03	0.04	10.88	3.08	When the layer thickness was 0.1mm, the flow rate was decreased to 100% to inhibit too much overextrusion. The density increased slightly.	
	5	**100**	**0.06**	**19.82**	**0.02**	**15.01**	**0.04**	**10.85**	**3.10**	**The layer thickness was further decreased to 0.06mm.**	
copperFill (colorFabb, 8719033555174)	1	100	0.15	19.87	0.00	14.91	0.03	11.76	3.39	The printing parameters were the same as the parameters for optimal print quality.	**4.00**
	2	110	0.15	19.84	0.00	14.89	0.01	12.27	3.55	The flow rate was increased to 110%. The density increased significantly.	
	3	115	0.15							The flow rate was increased to 115%. The printing failed because of too much overextrusion.	
	4	110	0.10	19.93	0.01	14.94	0.04	12.54	3.59	The layer thickness was decreased to 0.1mm. The density increased.	
	5	**110**	**0.06**	**19.95**	**0.02**	**14.88**	**0.01**	**12.65**	**3.65**	**The layer thickness was further decreased to 0.06mm.**	
GreenTEC PRO natural (Extrudr, 9010241426034)	1	100	0.15	19.83	0.01	14.93	0.05	4.58	1.32	The printing parameters were the same as the parameters for optimal print quality.	**1.39**
	2	110	0.15	19.76	0.01	15.06	0.03	4.70	1.34	The flow rate was increased to 110%. The density increased.	
	3	115	0.15	19.77	0.01	15.19	0.02	4.80	1.34	The flow rate was increased to 115%. The density did not change.	
	4	120	0.15	19.78	0.02	15.24	0.04	4.83	1.34	The flow rate was increased to 120%. The density did not change.	
	5	115	0.10	19.92	0.02	15.16	0.07	4.81	1.34	The layer thickness was decreased to 0.1mm. The density did not change.	
	6	**115**	**0.06**	**19.83**	**0.01**	**15.12**	**0.02**	**4.79**	**1.35**	**The layer thickness was further decreased to 0.06mm.**	

GreenTEC PRO Carbon (Extrudr, 9010241426973)	1	100	0.15	19.83	0.02	14.98	0.03	4.61	1.32	The printing parameters were the same as the parameters for optimal print quality.	**1.15**
	2	110	0.15	19.77	0.01	15.10	0.03	4.73	1.34	The flow rate was increased to 110%. The density increased.	
	3	115	0.15	19.78	0.01	15.18	0.02	4.81	1.34	The flow rate was increased to 115%. The density did not change.	
	4	115	0.10	19.92	0.01	15.20	0.05	4.86	1.34	The layer thickness was decreased to 0.1mm. The density did not change.	
	5	**115**	**0.06**	**19.83**	**0.00**	**15.18**	**0.01**	**4.84**	**1.35**	**The layer thickness was further decreased to 0.06mm.**	
CarbonFil (Formfutura, 175CARBFIL-BLCK-0500)	1	100	0.15	19.89	0.01	15.02	0.03	4.02	1.14	The printing parameters were the same as the parameters for optimal print quality.	**1.19**
	2	**110**	**0.15**	**19.80**	**0.00**	**14.97**	**0.02**	**4.14**	**1.19**	**The flow rate was increased to 110%. The density increased significantly and achieved the target density.**	
Nylon (Ultimaker, 1647)	1	100	0.15	19.85	0.01	15.00	0.03	3.89	1.11	The printing parameters were the same as the recommended parameters for optimal print quality.	**1.14**
	2	**110**	**0.15**	**19.86**	**0.02**	**15.04**	**0.03**	**3.94**	**1.12**	**The flow rate was increased to 110%. The density increased.**	
	3	110	0.10							The layer thickness was decreased to 0.1mm. The printing failed because of too much overextrusion.	
	4	105	0.10							When the layer thickness was 0.1mm, the flow rate was decreased to 105% to inhibit too much overextrusion. The printing still failed.	
glowFill (colorFabb, 8719033555136)	1	100	0.15	19.94	0.02	14.93	0.06	4.31	1.23	The printing parameters were the same as the recommended parameters for optimal print quality.	**1.24**
	2	**110**	**0.15**	**19.85**	**0.02**	**15.04**	**0.04**	**4.38**	**1.24**	**The flow rate was increased to 110%. The density increased and achieved the target density.**	

Pegasus PP Ultralight (Formfutura, 285PEGAPP-NAT-0500)	1	105	0.15	19.85	0.00	14.85	0.02	2.34	0.68	The printing parameters were the same as the recommended parameters for optimal print quality.	**0.75**
	2	**115**	**0.15**	**19.81**	**0.00**	**14.88**	**0.02**	**2.51**	**0.73**	**The flow rate was increased to 115%. The density increased significantly.**	
	3	115	0.10							The property of this material was similar to PP. If the layer thickness was lower than 0.15mm, the printing would fail because of too much overextrusion.	
PLA Sparkly Silver (Eryone, GPLA-SILVER-17 5-1000)	**1**	**105**	**0.15**	**20.05**	**0.09**	**14.93**	**0.10**	**4.31**	**1.23**	**The printing parameters were the same as the recommended parameters for optimal print quality.**	**1.24**
	2	110	0.15							The flow rate was increased to 110%. The printing failed because of too much overextrusion.	
	3	105	0.10							The layer thickness was decreased to 0.1mm. The printing failed because of too much overextrusion.	
Metal Filament Aluminium (AptoFun, B01ITNXRWD)	1	105	0.15	19.82	0.04	15.08	0.05	4.47	1.26	The printing parameters were the same as the recommended parameters for optimal print quality.	
	2	110	0.15							The flow rate was increased to 110%. The printing failed because of too much overextrusion.	
	3	105	0.10							The layer thickness was decreased to 0.1mm. The printing failed because of too much overextrusion.	
	4	102	0.10	19.82	0.03	14.98	0.03	4.43	1.26	When the layer thickness was 0.1mm, the flow rate was decreased to 102% to inhibit too much overextrusion. The density did not change.	
	5	**102**	**0.06**	**19.87**	**0.02**	**14.99**	**0.04**	**4.45**	**1.27**	**The layer thickness was further decreased to 0.06mm.**	

The measurement data of densities of all the resins for SLA printers are in Table 10.

Table 10. Density measurement of the resins for SLA printers.

Resin	Height Measurement [mm]		Diameter Measurement [mm]		Mass [g]	Measured Density [g/cm^3]	Target Density from Vendor [g/cm^3]
	Average	SD	Average	SD			
Anycubic Resin green (Anycubic 3D Printing, AB-POT048)	20.33	0.04	15.15	0.01	4.32	1.18	1.18 (solid)
PrimaCreator Resin clear (3D Prima, PV-RESIN-B405-0500-CL)	20.46	0.04	14.93	0.01	4.29	1.20	1.05-1.13 (liquid)
Wanhao Resin water washable clear (Wanhao, 23453)	20.39	0.05	14.85	0.04	4.21	1.19	1.00-1.11 (liquid)
PhotoCentric3D UV Flexible Resin clear (Photocentric, PHODCL01UVFLEX)	20.38	0.04	14.50	0.06	4.14	1.23	1.18 (liquid)
Formlabs form 2 clear resin (Formlabs, RS-F2-GPCL-04)	20.44	0.07	15.08	0.04	4.25	1.16	1.09-1.12
Vero PureWhite (Stratasys, OBJ-03327)	19.95	0.01	14.85	0.03	4.11	1.19	1.17-1.18
VeroBlue (Stratasys, OBJ-03204)	19.98	0.01	14.88	0.06	4.09	1.18	1.18-1.19
VeroClear (Stratasys, OBJ-03271)	20.00	0.02	14.85	0.08	4.07	1.17	1.18-1.19
Formlabs form 2 flexible resin (Formlabs, RS-F2-FLGR-02)	19.37	0.02	14.92	0.15	3.90	1.15	1.09-1.12
Formlabs form 2 elastic resin (Formlabs, RS-F2-ELCL-01)	19.90	0.05	14.61	0.05	3.67	1.10	1.02
RGD 525 (Stratasys, OBJ-03256)	20.26	0.05	14.96	0.03	4.12	1.16	1.17-1.18
TangoPlus (Stratasys, OBJ-03224)	19.78	0.01	14.68	0.08	3.82	1.14	1.12-1.13

3.5 CT measurements

CT measurements of radiographic density (attenuation) were performed to characterize 3D printing materials and to study their suitability for their use in radiographic phantoms. Here, the energy dependence of the attenuation was of particular interest. Therefore, a scanner capable of performing scans at quite low energies also (70 kVp) was used (Somatom Definition AS, Siemens Healthineers, Erlangen, Germany).

3.5.1 Phantom design and production

In order to scan all the printed cylinders in the CT scanner to measure Hounsfield units of all the materials, a phantom was designed and printed to hold all the cylinders (Figure 25) immersed in water. The phantom was designed using Autodesk Fusion 360 (Autodesk Inc., San Rafael, CA, USA). It was printed on the printer Ultimaker 2+ (Ultimaker B.V., Netherlands), and the material used here was colorFabb_XT (colorFabb, 8719033553019). Before CT scanning, the phantom was filled with water.

Figure 25. The appearance of the phantom. Left photo: The frame of the phantom. Right photo: The complete phantom (contains 41 cylinders and outer shell, filled with water)

The phantom contains 3 plates (base plate, middle plate and top plate), some support parts between plates, transparent shell, screws and rubber sealing bands. The 3 plates are connected by friction only. Each plate can hold 24 cylinders maximum, summing up to a total of 72.

The thickness of each plate is 4mm, the diameter 150mm, and the distance between adjacent plates 45mm. The 3 plates were numbered as A, B, C, and in each plate the cylinder positions were number from 1 to 12 (Figure 26). For the cylinder loading positions, the diameter is 16mm, and the depth is1mm.

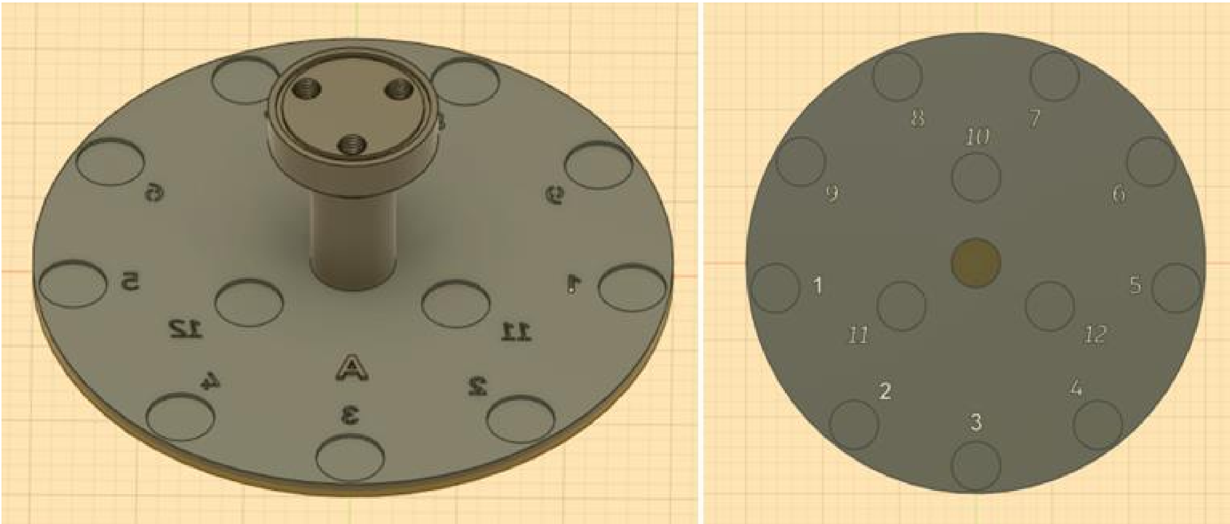

Figure 26. Base plate with numbered cylinder positions (Left photo: the bottom surface of the base plate. Right photo: the top surface of the base plate)

The distribution of the cylinder positions is in Figure 26. Positioning the cylinders in direct lines was omitted, to minimize beam hardening effects during CT scanning.

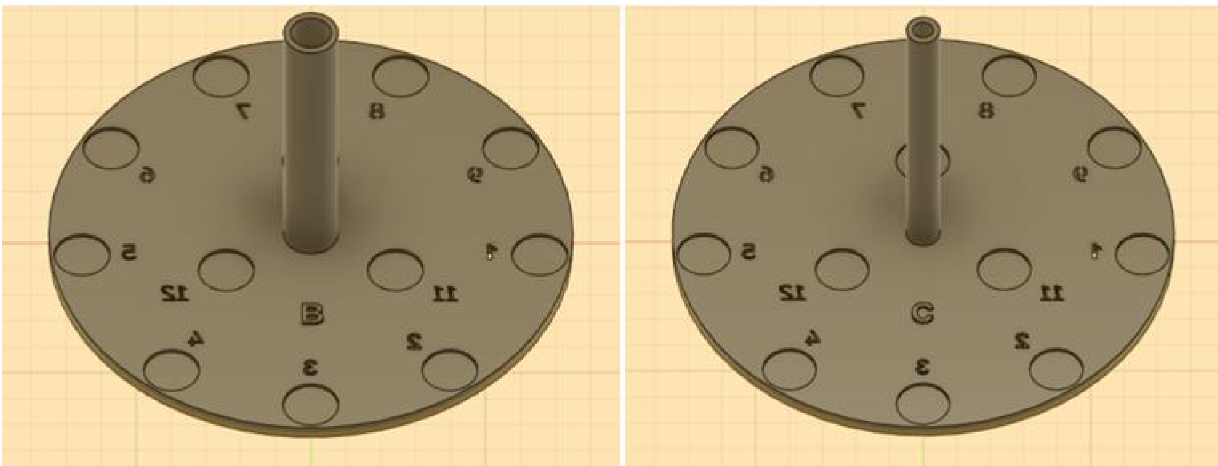

Figure 27. Plates designed by Autodesk Fusion 360 (Left photo: the middle plate. Right photo: the top plate)

The 3D printing material used here was a styrene free co-polymer filament (colorFabb_XT colorFabb, 8719033553019). It has excellent toughness and superior stability and durability, and it's resistant to high temperature, physical impact and chemical erosion. Therefore, it is an ideal material to be used for printing the phantom components. The screws of the phantom were also printed by this material.

The first print of the phantom failed, because of serious warping (refer to 5.1.1). In order to avoid the warping effectively, an adhesive primer spray (3Dlac, Laboratorios 3D Print, S.L., San Cristobal de Entreviñas, Zamora) was used, a Brim was created and the cooling fan was switched off at the beginning of printing.

After the phantom was printed and assembled, all 41 test cylinders were glued on the three plates of the phantom (Figure 28).

Figure 28. 41cylinders were stuck on 3 Plates

Different kinds of glue were tested. Uhu Poly Max crystal express (Bolton Adhesives, Rotterdam, the Netherlands) and Ultimate Gel Epoxy (Mud Hole Custom Tackle Inc., Oviedo, FL USA) didn't work. Adheseal (Innotec International N.V., Dessel, Belgium) and the Presto Plastic primer (Motip Dupli GmbH, Haßmersheim, Germany) were the best choice. To test the durability of the glues, 20 cylinders with different materials were stuck on a plate of the phantom with the glue and immersed into water for about one week, none of them fell off when using Adheseal.

The positions of 41 cylinders on the 3 plates are described in Table11.

Table 11. Positions of 41 cylinders on the 3 plates

Plates		Positions of cylinders on each plate (1-12)
Plate A (base plate with screws)	Top side	1. RGD 525 Stratasys (OBJ-03256)
	Bottom side	1. Bronzefill (AprintaPro, 195072), 3. SteelFill (colorFabb, 8719033555679), 5. CopperFill (colorFabb, 8719033555174), 7. Copperfill (AprintaPro, 195172)
Plate B (middle plate)	Top side	1. PLA mineral (Fiberlogy, PLA-MIN-NATUR-285-085), 2. HIPS (ICE Filaments, 29548), 4. Anycubic Resin green (AB-POT048), 5. PrimaCreator Resin clear (PV-RESIN-B405-0500-CL), 7. PhotoCentric3D UV Flexible Resin clear (PHODCL01UVFLEX), 8. ABS (Verbatim, 55019), 10. GreenTEC Pro Carbon (Extrudr, 9010241426973), 11. Metal filament Aluninium (AptoFun, B01ITNXRWD), 12. Wanhao Resin water washable clear (23453)
	Bottom side	1. GreenTEC Pro natural (Extrudr, 9010241426034), 2. ASA (Fillamentum, natural 00118), 4. VeroBlue Stratasys (OBJ-03204), 5. Vero PureWhite Stratasys (OBJ-03327), 7. Formlabs form 2 elastic resin Formlabs (RS-F2-ELCL-01), 8. Formlabs form 2 flexible resin Formlabs (RS-F2-FLGR-02), 10. TangoPlus Stratasys (OBJ-03224), 11. Formlabs form 2 clear resin (RS-F2-GPCL-04), 12. VeroClear Stratasys (OBJ-03271)
Plate C (top plate)	Top side	1. StoneFil (Formfutura, 285STONEFIL-PCLAY-0500), 2. Pegasus PP Ultralight (Formfutura, 285PEGAPP-NAT-0500), 4. PLA (Ultimaker, 1612), 5. ApolloX (Formfutura, 285APOX-WHITE-0750), 7. Nylon (Ultimaker, 1647), 8.PC-Plus (Polymaker, 70409), 10. HDglass (Formfutura, 285HDGLA-CLEAR-0750), 11. TPU transparent (Extrudr, 9010241152001), 12. PLA Sparkly Silver (Eryone, GPLA-SILVER-175-1000)
	Bottom side	1. Vinyl 303 (Fillamentum, VIN303_285_nat), 2. PP (Verbatim, 55951), 4. CarbonFil (Formfutura, 175CARBFIL-BLCK-0500), 5. ColorFabb_XT (colorFabb, 8719033553019),

		7. EasyWood (Formfutura, 285EWOOD-BIRCH-0500), 8. GlowFill (colorFabb, 8719033555136), 10. nGen (colorFabb, 8719033554733), 11. CorkFill (colorFabb, 8719033555327), 12. PET (Innofil3d natural, Pet-0301b075)

3.5.2 CT scanning parameters

The CT device used here was a Siemens Somatom Definition AS (Siemens Healthineers, Erlangen, Germany) (Figure 29, 30).

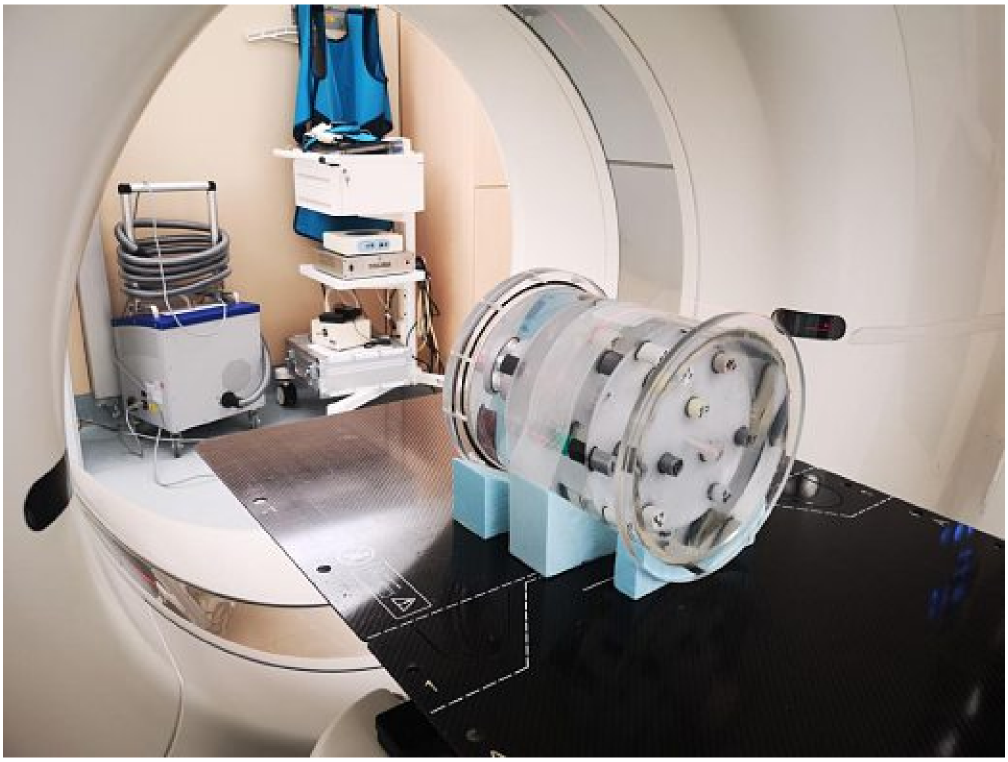

Figure 29. The phantom was fixed on the bed of the CT

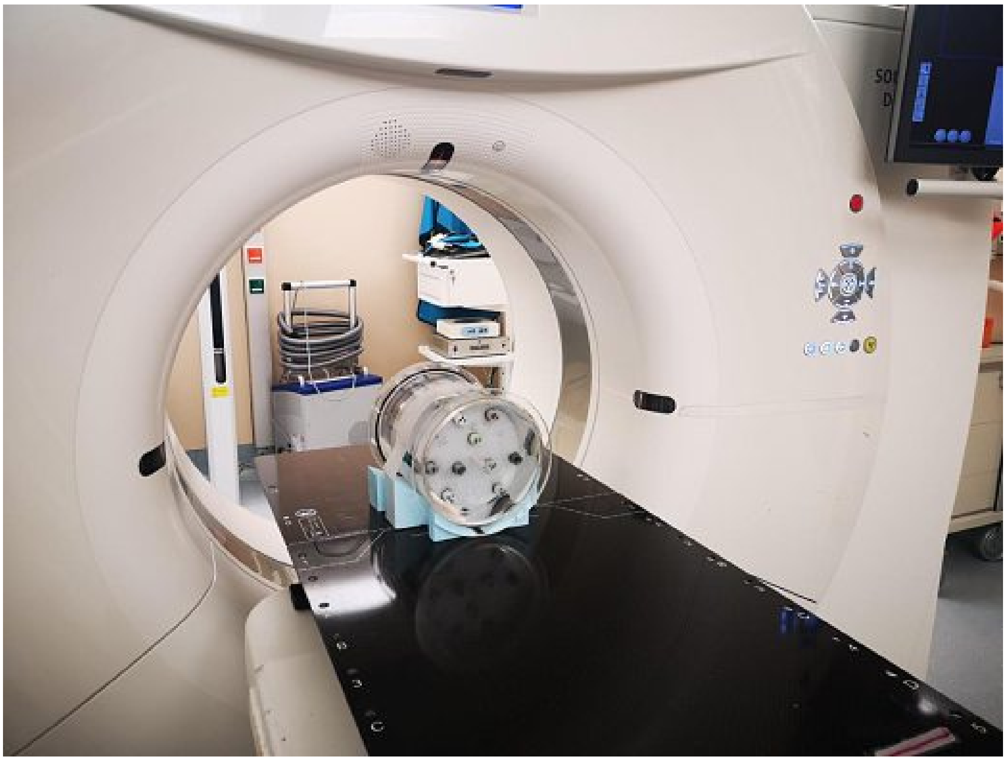

Figure 30. Phantom in the CT gantry

CT scanning parameters were: collimation: 32 x 0.6mm, a medium sharp soft tissue kernel (H40s), rotation time 1s, pitch: 0.55, reconstructed slice thickness 1mm, and slice increment also 1mm.

mAs values were adjusted to result in a $CTDI_{vol}$ of as close to 100 mGy independent of kV setting. For 80 and 70 kV maximum mAs values were selected. mAs and $CTDI_{vol}$ used are summerized in Table 12.

Table 12. CT scanning parameters

kV	mAs	$CTDI_{vol}$ (mGy)
70	900	31
80	1100	60
100	990	101
120	600	102
140	420	102

3.5.3 CT image analysis and HU measurement

The phantom was scanned with 70kV, 80kV, 100kV, 120kV and 140kV, respectively. In the reconstructed images each cylinder is seen on 17 slices (CT images); the first and last slice showing the respective cylinder was omitted to avoid partial volume artefacts resulting in wrong HU numbers. The software used here to analyse the CT images was Analyze 12.0, Biomedical Image Resource (Mayo Clinic, Rochester, MN USA). The averaged HU values and the standard deviation of each slice were determined individually resulting in 17 values per cylinder. The averaged HU and the standard deviations of the mean values from these 17 slices were calculated to represent the HU of the respective cylinder, i.e., representing the resulting values for the respective material.

In order to get accurate HU values of all the cylinders, the resulting HU numbers need to be calibrated by subtracting the HU value of water. In general, the HU of water should be 0. However, due to the artefacts or slight miscalibration, actual HU differ slightly from 0. This would influence the accuracy of the HU measurement of the cylinders. Therefore, subtracting the HU of water from the averaged HU of the printed cylinders will improve accuracy. This is especially the case for the determination of the energy dependence if the background (water) signal differs for scans taken at different kVp.

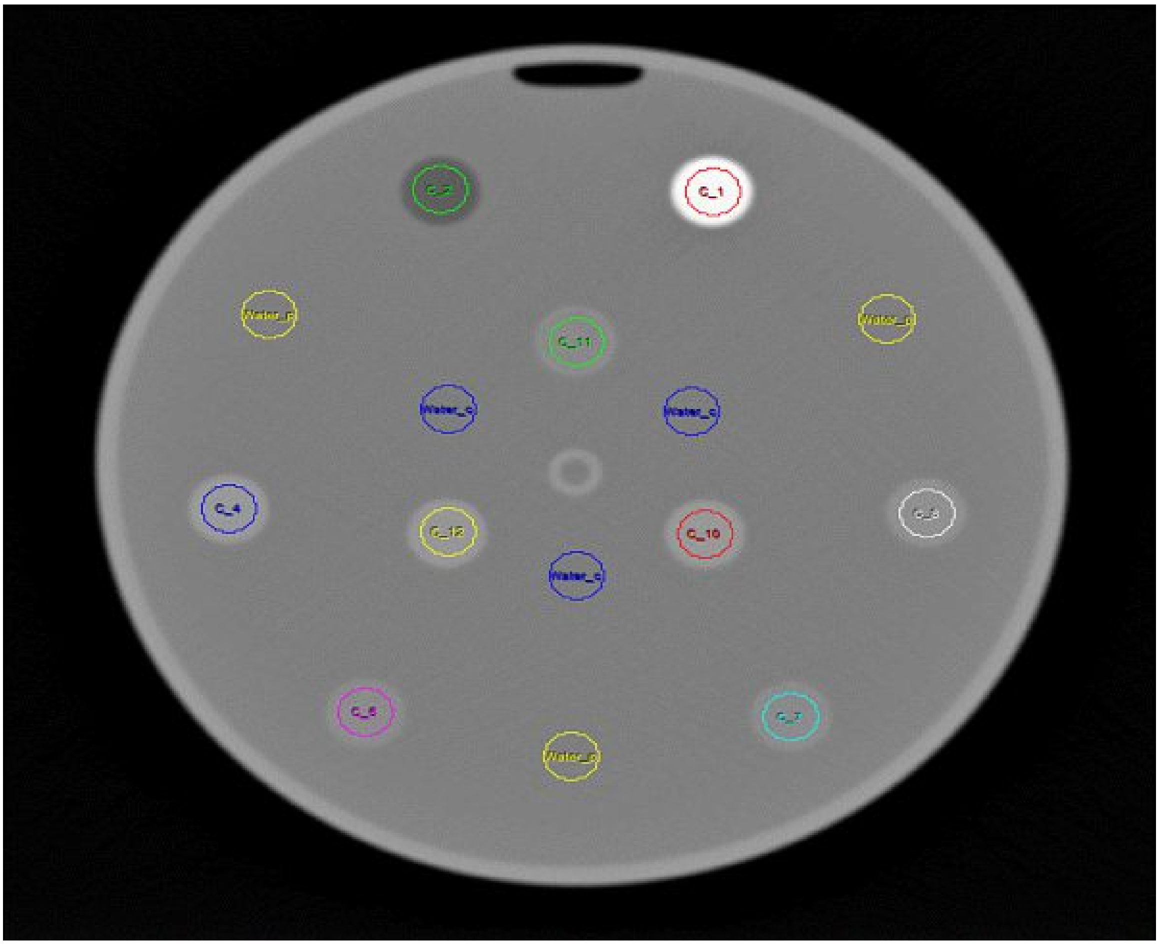

Figure 31. CT image illustrating the HU determination by subtracting the HU of water. ROIs used for determination of the water value are shown in blue (inner circle, central positions) and dark yellow (outer circle, peripheral positions)

In Figure 31, the ROIs used for HU measurements are shown. The positions C1 to C8 in the image represent the different cylinders on the periphery of the plate. The ROI marked Water_p in the image represents the ROIs used to determine the HU number value used to subtract from the samples C1 to C8 in the periphery of the plate. The positions of C10, C11 and C12 represent the different cylinders on the central positions of the plate. The ROIs marked Water_c were used to determine the background/water value to be subtracted from the inner cylinders' HU values.

4 Results

4.1 Optimum printing parameters for general purpose prints

4.1.1 FDM Printer

The optimum printing parameters of the 27 materials used with the FDM printer are summarized in Table 13. The nozzle diameter was 0.4mm, and the layer thickness 0.15mm.

Table 13. Optimum printing parameters of FDM Printer for general purpose prints.

Material	Nozzle Temperature [°C]	Printing Speed [mm/s]	Bed Temperature [°C]	Fan Speed [%]	Flow Rate [%]	Retraction Length [mm]	Retraction speed [mm/s]
StoneFil (Formfutura, 285STONEFIL-PCLAY-0500)	220	50	60	100	110	6	25
ABS (Verbatim, 55019)	250	60	80	100	107	6	25
HIPS (ICE Filaments, 29548)	240	40	100	100	100	6	25
Vinyl 303 (Fillamentum, VIN303_285_nat)	230	40	80	100	100	6	25
PLA (Ultimaker, 1612)	210	50	60	100	100	6	25
corkFill (colorFabb, 8719033555327)	230	50	60	100	100	6	25
PET natural (Innofil3d, Pet-0301b075）	220	60	75	100	100	6	25
PET black (Innofil3d, Pet-0302b075)	220	60	75	100	100	6	25
EasyWood (Formfutura, 285EWOOD-BIRCH-0500)	200	70	60	100	104	5	25

HDglass (Formfutura, 285HDGLA-CLEAR-0750)	220	60	75	100	110	6	25
colorFabb_XT (colorFabb, 8719033553019)	260	40	70	100	110	4.5	40
PLA Mineral (Fiberlogy, PLA-MIN-NATUR-285-085）	210	60	70	100	100	6	25
nGen (colorFabb, 8719033554733)	240	60	75	100	100	6	25
PC-Plus (Polymaker, 70409)	250	40	90	0	100	6	25
TPU green (Extrudr, 9010241152278)	230	30	70	100	100	6	25
TPU transparent (Extrudr, 9010241152001)	230	30	70	100	100	6	25
ASA black (Fillamentum, black 00119)	260	50	100	100	100	6	25
ASA natural (Fillamentum, 00118)	260	50	100	100	100	6	25
ApolloX (Formfutura, 285APOX-WHITE -0750)	260	50	100	100	100	6	25
PP (Verbatim, 55951)	240	25	100	80	100	6	25

Copperfill (AprintaPro, 195172)	200	35	65	100	102	4.4	25
Bronzefill (AprintaPro, 195072)	200	35	65	100	102	4.4	25
steelFill (colorFabb, 8719033555679)	200	50	50	100	110	4.5	25
copperFill (colorFabb, 8719033555174)	200	35	65	100	100	4.5	25
GreenTEC PRO natural (Extrudr, 9010241426034)	220	60	80	100	100	6	25
GreenTEC PRO Carbon (Extrudr, 9010241426973)	220	60	80	100	100	6	25
CarbonFil (Formfutura, 175CARBFIL-BLCK-0500)	230	50	60	100	100	5	25

Based on the optimal printing parameters of all the materials, models with different materials could be printed perfectly. All the materials used in the tests are ordinary, popular or interesting materials in daily life and in the 3D printing field. All the optimal printing parameters are provided for the Ultimaker 2+. With different FDM printers, the optimal printing parameters may be a little bit different. However, the differences will not be big, especially for printers of the Ultimaker series.

For the printing parameters, almost all optimal printing parameters are in the range of the parameters recommended by the manufacturers. The nozzle temperature varies from 200°C to 260°C. The printing speed varies from 25mm/s to 70mm/s depending on the material. Usually, flexible materials or materials with a higher high temperature (extrusion) viscosity require lower printing speed, such as PP with 25mm/s, and TPU with 30mm/s, respectively. The bed temperature varies from 50°C to 100°C, and this is a very important parameter to avoid warping. However, sometimes the heated bed is not enough to avoid warping, so some kinds of glues, sprays or anti-warping sheets must be used on the build plate before printing. The default fan speed is 100%, and usually there is no requirement to adjust the fan speed. However, for special materials like PC-Plus, the fan must be switched off, otherwise warping will happen immediately. The flow rate varied from 100% to 110%. It's not an important parameter for general purpose prints, but it's very important for printing 100% infill models. The retraction is not an important parameter for FDM printers when achieving optimum infill density is the goal, and it only influences stringing. Therefore only several manufacturers give recommended values for the retraction settings. In the Ultimaker 2+, the default of retraction length is 6mm, and the default of retraction speed is 25mm/s.

4.1.2 SLA printers

The printing parameters of the four resins printed on the Anycubic Photon printer (Anycubic 3D Printing, Guangdong, China) are shown in Table 14.

Table 14. Printing parameters of resins for Anycubic Photon open resin printer

Resins	**Printing parameters**				
	Exposure Time [s]	Off Time [s]	Layer Thickness [mm]	Bottom Exposure Time [s]	Bottom Layers
Anycubic Resin green (AB-POT048)	10	1	0.05	50	8
PrimaCreator Resin clear (PV-RESIN-B405-0500-CL)	10	1	0.05	50	8
Wanhao Resin water washable clear (23453)	10	1	0.05	50	8
PhotoCentric3D UV Flexible Resin clear (PHODCL01UVFLEX)	17	5	0.05	120	8

The printing parameters used are those recommended by the resin manufacturers.

For the other two printers, Formlabs Form 2 (Formlabs Inc., Somerville, USA) and Stratasys Objet500 Connex3 (Stratasys Ltd., Eden Prairie, USA), the printing parameters cannot be adjusted manually.

4.2 Optimum printing parameters for radiographic phantoms

4.2.1 FDM printer

Optimum printing parameters of the FDM printer for optimal filling ratio are shown in Table 15.

Table 15. Optimal printing parameters of FDM materials for radiographic phantoms and densities achieved.

Material	Nozzle Temp. [°C]	Printing Speed [mm/s]	Bed Temp. [°C]	Flow Rate [%], layer thickness [mm] for optimum print quality	Flow Rate [%], layer thickness [mm] for optimum filling ratio	Density optimum print quality [g/cm3]	Density optimum filling ratio [g/cm3]	Target Density (Vendor, [g/cm^3])	Differences in Density to Spec. (optimum print quality/optimum filling ratio)
StoneFil (Formfutura, 285STONEFIL-PCLAY-0500)	220	50	60	110/0.15	105/0.06	1.62	**1.64**	1.70	-4.71%/-3.53%
ABS (Verbatim, 55019)	250	60	80	107/0.15	110/0.06	1.06	**1.07**	1.08	-1.85%/-0.93%
HIPS (ICE Filaments, 29548)	240	40	100	100/0.15	110/0.06 or 110/0/10	0.99	**1.02**	1.04	-4.81%/-1.92%
Vinyl 303 (Fillamentum, VIN303_285_nat)	230	40	80	100/0.15	100/0.15	1.35	**1.35**	1.35	0.00%/0.00%
PLA (Ultimaker, 1612)	210	50	60	100/0.15	110/0.15	1.23	**1.24**	1.24	-0.81%/0.00%
corkFill (colorFabb, 8719033555327)	230	50	60	100/0.15	110/0.15 or 100/0.15	1.21	**1.21**	1.18	2.54%/2.54%

PET (Innofil3d natural: Pet-0301b075, black: Pet-0302b075)	220	60	75	100/0.15	115/0.06	1.31	**1.33**	1.34	-2.24%/-0.75%
EasyWood (Formfutura, 285EWOOD-BIRCH-0500)	200	70	60	104/0.15	115/0.06	1.11	**1.21**	1.20	-7.50%/0.83%
HDglass (Formfutura, 285HDGLA-CLEAR-0750)	220	60	75	110/0.15	115/0.06 or 115/0.10	1.23	**1.26**	1.27	-3.15%/-0.79%
colorFabb_XT (colorFabb, 8719033553019)	260	40	70	110/0.15	105/0.06 or 110/0.15	1.26	**1.26**	1.27	-0.79%/-0.79%
PLA Mineral (Fiberlogy, PLA-MIN-NATUR-285-085)	210	60	70	100/0.15	115/0.06	1.35	**1.39**	1.40	-3.57%/-0.71%
nGen (colorFabb, 8719033554733)	240	60	60	100/0.15	115/0.06 or 115/0.10	1.16	**1.19**	1.20	-3.33%/-0.83%
PC-Plus (Polymaker, 70409)	250（Fan off)	40	90	100/0.15	100/0.06	1.19	**1.20**	1.19-1.20	0.00%/0.00%
TPU transparent (Extrudr, 9010241152001)	230	30	70	100/0.15	110/0.15 or 100/0.15	1.16	**1.16**	1.15	0.87%/0.87%

ASA (Fillamentum, natural 00118, black 00119)	260	50	100	100/0.15	115/0.06	1.04	**1.06**	1.07	-2.80%/-0.93%
ApolloX (Formfutura, 285APOX-WHITE-0750)	260	50	100	100/0.15	110/0.15 or 100/0.15	1.13	**1.13**	1.11	1.80%/1.80%
PP (Verbatim, 55951)	240	25	100	100/0.15	110/0.15 or 100/0.15	0.88	**0.88**	0.89	-1.12%/-1.12%
Copperfill (AprintaPro, 195172)	200	35	65	102/0.15	110/0.15	3.33	**3.38**	3.41	-2.35%/-0.88%
Bronzefill (AprintaPro, 195072**)**	200	35	65	102/0.15	110/0.06	3.57	**3.73**	3.39	5.31%/10.03%
steelFill (colorFabb, 8719033555679)	200	50	50	110/0.15	110/0.06	3.07	**3.10**	3.13	-1.92%/-0.96%
copperFill (colorFabb, 8719033555174)	200	35	65	100/0.15	110/0.06	3.39	**3.65**	4.00	-15.25%/-8.75%
GreenTEC PRO natural (Extrudr, 9010241426034)	220	60	80	100/0.15	115/0.06	1.32	**1.35**	1.39	-5.04%/-2.88%
GreenTEC PRO Carbon (Extrudr, 9010241426973)	220	60	80	100/0.15	115/0.06	1.32	**1.35**	1.15	14.78%/17.39%

CarbonFil (Formfutura, 175CARBFIL-BLCK-0500)	230	50	60	100/0.15	110/0.15	1.14	**1.19**	1.19	-4.20%/0.00%
Nylon (Ultimaker, 1647)	250	45	60	100/0.15	110/0.15	1.11	**1.12**	1.14	-2.63%/-1.75%
glowFill (colorFabb, 8719033555136)	210	50	60	100/0.15	110/0.15	1.23	**1.24**	1.24	-0.81%/-0.00%
Pegasus PP Ultralight (Formfutura, 285PEGAPP-NAT-0500)	240	25	100	105/0.15	115/0.15	0.68	**0.73**	0.75	-9.33/-2.67
PLA Sparkly Silver (Eryone, GPLA-SILVER-175-1000)	210	50	60	105/0.15	105/0.15	1.23	**1.23**	1.24	-0.81/-0.81
Metal Filament Aluminium (AptoFun, B01ITNXRWD)	210	50	60	105/0.15	102/0.06	1.26	**1.27**		

In order to achieve optimal filling ratio, the infill pattern should be set to lines, and the wall thickness should be minimum (0.35mm, wall line count one). The filling ratio can be adjusted by changing the flow rate and layer thickness. Increase of the flow rate and decrease of the layer thickness are effective methods to increase the filling ratio. The flow rate has an upper limit, and the layer thickness has a lower limit. The upper limit of flow rate and the lower limit of layer thickness depend on the properties of respective material. Usually the upper limit of the flow rate is about 110% - 115%, and the layer thickness for the printing of PP, Nylon, Copperfill (Aprintapro) and Pegasus PP Ultralight cannot be less than 0.15mm.

For FDM materials recommended printing parameters and printing parameters found to result in best print quality in the 3DBenchy resulted in densities lower than filament densities specified by the manufacturer in most cases (see table). By adjusting flow rate upwards and/or layer thickness downwards densities close to solid material density could be achieved. Some materials exhibited higher densities than specified.

Polymers with a density ρ close to water and soft tissue were:

- **HIPS** (high impact PS, ICE Filaments, Ham, Belgium; ρ=1.02),
- **ASA** (Fillamentum s.r.o., Hulin, CZ; ρ=1.06) and
- **ABS** (Verbatim, Mitsubishi Chemical, Tokyo, Japan; ρ=1.07).

Promising materials for printing bone equivalent structures were:

- **PVC** (Vinyl, Fillamentum; ρ=1.35),
- **GreenTEC pro** (Extrudr, FG3D GmbH, Lauterach, Austria; ρ=1.35),

materials filled with calcium compounds or stone powder:

- **PLA mineral** (Fiberlogy, Fiberlab S.A., Brzezie, Poland; containing chalk; ρ=1.39),
- **StoneFil** (Formfutura B.V., Nijmegen, The Netherlands; containing 50% gravimetric powdered stone filling; ρ= 1.64),

and materials filled with phosphorescent dyes, most likely containing doped sulphides of metals from 2nd group or zinc, or strontium aluminate:

- **glowFill** (colorFabb B.V., Belfeld, The Netherlands; ρ=1.24)

Metal filled polymers achieved densities from 3.10 to 3.73 g/cm^3, except the aluminum filled PLA (AptoFun; PLA mixed with 10% aluminum powder; ρ=1.27).

4.2.2 SLA printers

The printing parameters of resins and the data of the density measurements are shown in Table 16.

Table 16. Printing parameters and densities of resins.

Resins	Exposure Time [s]	Off Time [s]	Layer Thickness [mm]	Bottom Exposure Time [s]	Bottom Layers	Density [g/cm³]	Density specified by Manufacturer [g/cm³]
Anycubic Resin green (AB-POT048)	10	1	0.05	50	8	1.18	1.18g/cm³ (solid)
PrimaCreator Resin clear (PV-RESIN-B405-0500-CL)	10	1	0.05	50	8	1.20	1.05-1.13g/cm³ (liquid)
Wanhao Resin water washable clear (23453)	10	1	0.05	50	8	1.19	1.00-1.11 g/cm³ (liquid)
PhotoCentric3D UV Flexible Resin clear (PHODCL01UVFLEX)	17	5	0.05	120	8	1.23	1.18 g/cm³ (liquid)
Formlabs form 2 clear resin (RS-F2-GPCL-04)						1.16	1.09-1.12 g/cm³
Vero PureWhite Stratasys (OBJ-03327)						1.19	1.17-1.18 g/cm³
VeroBlue Stratasys (OBJ-03204)						1.18	1.18-1.19g/cm³

VeroClear Stratasys (OBJ-03271)						1.17	1.18-1.19g/cm^3
Formlabs form 2 flexible resin Formlabs, (RS-F2-FLGR-02)						1.15	1.09-1.12
Formlabs form 2 elastic resin Formlabs, (RS-F2-ELCL-01)						1.10	1.02
RGD 525 Stratasys, (OBJ-03256)						1.16	1.17-1.18
TangoPlus Stratasys, (OBJ-03224)						1.14	1.12-1.13

SLA Resins exhibited cured densities from 1.10 to 1.23 g/cm^3.

4.3 CT scanning and Hounsfield units measurements

All the cylinders with different materials were scanned by CT, and their Hounsfield units were measured (Table 17). Figures 32 to 39 illustrate the results graphically. Standard deviation shown in table 17 corresponds to standard deviation of HU measurements on individual CT slices rather than STDs of voxel values, because the latter are dominated by quantum noise that cannot be attributed to material properties and does not represent a measurement uncertainty but a inherent feature of the CT imaging process.

Table 17. CT scanning and Hounsfield units measurement

Material	X-ray tube voltage (kV)	Hounsfield units	Standard Deviation
StoneFil (Formfutura, 285STONEFIL-PCLAY-0500)	70	1592	11.49
	80	1410	8.69
	100	1187	7.98
	120	1063	5.71
	140	986	5.70
ABS (Verbatim, 55019)	70	-12	0.60
	80	3	0.66
	100	21	0.57
	120	30	0.70
	140	37	0.83
HIPS (ICE Filaments, 29548)	70	-91	2.56
	80	-74	2.14
	100	-54	1.50
	120	-42	2.05
	140	-35	2.11
Vinyl 303 (Fillamentum, VIN303_285_nat)	70	1804	26.45
	80	1521	23.43
	100	1188	18.90
	120	996	17.73
	140	878	15.77
PLA (Ultimaker, 1612)	70	193	2.24
	80	197	1.72
	100	202	1.41
	120	205	1.81

	140	207	1.61
corkFill (colorFabb, 8719033555327)	70	153	4.36
	80	161	4.22
	100	172	4.97
	120	178	3.39
	140	182	2.99
PET (Innofil3d natural: Pet-0301b075, black: Pet-0302b075)	70	253	4.11
	80	261	3.40
	100	271	4.44
	120	274	3.43
	140	278	3.43
EasyWood (Formfutura, 285EWOOD-BIRCH-0500)	70	191	9.15
	80	195	10.57
	100	199	13.35
	120	203	10.86
	140	206	11.64
HDglass (Formfutura, 285HDGLA-CLEAR-0750)	70	173	2.47
	80	185	1.73
	100	199	1.89
	120	208	2.04
	140	212	1.85
colorFabb_XT (colorFabb, 8719033553019)	70	176	7.19
	80	190	3.90
	100	204	7.35
	120	211	3.59
	140	216	2.87
PLA Mineral (Fiberlogy, PLA-MIN-NATUR-285-085)	70	739	2.44
	80	670	3.07
	100	584	2.58
	120	537	2.43
	140	507	2.38
nGen (colorFabb, 8719033554733)	70	101	3.26
	80	113	1.74
	100	129	3.36
	120	138	2.26
	140	143	1.98
PC-Plus (Polymaker, 70409)	70	107	1.38
	80	119	1.16
	100	132	0.95
	120	140	1.11
	140	145	1.02

TPU transparent (Extrudr, 9010241152001)	70	64	11.65
	80	76	12.00
	100	92	12.89
	120	100	12.30
	140	106	12.41
ASA (Fillamentum, natural 00118, black 00119)	70	-41	3.01
	80	-27	1.96
	100	-8	1.07
	120	2	0.89
	140	8	0.97
ApolloX (Formfutura, 285APOX-WHITE-0750)	70	78	2.15
	80	85	1.10
	100	93	1.10
	120	97	0.92
	140	100	1.26
PP (Verbatim, 55951)	70	-190	6.10
	80	-173	4.40
	100	-152	6.92
	120	-140	3.96
	140	-133	4.13
GreenTEC PRO natural (Extrudr, 9010241426034)	70	372	8.72
	80	363	10.74
	100	351	10.13
	120	344	10.71
	140	340	10.53
GreenTEC PRO Carbon (Extrudr, 9010241426973)	70	372	4.90
	80	365	4.64
	100	355	4.58
	120	349	3.83
	140	346	4.57
CarbonFil (Formfutura, 175CARBFIL-BLCK-0500)	70	99	19.71
	80	113	16.96
	100	128	19.86
	120	135	16.86
	140	140	17.71
Nylon (Ultimaker, 1647)	70	52	2.57
	80	67	1.37
	100	84	0.90
	120	94	0.76
	140	100	1.02
glowFill (colorFabb,	70	481	9.36

8719033555136)	80	440	8.95
	100	386	9.28
	120	353	7.47
	140	332	6.58
Pegasus PP Ultralight (Formfutura, 285PEGAPP-NAT-0500)	70	-197	20.47
	80	-218	20.23
	100	-243	19.54
	120	-258	19.16
	140	-266	18.76
PLA Sparkly Silver (Eryone, GPLA-SILVER-175-1000)	70	177	2.89
	80	185	1.84
	100	193	1.65
	120	197	1.71
	140	200	1.87
Metal Filament Aluminium (AptoFun, B01ITNXRWD)	70	256	7.22
	80	253	6.39
	100	251	6.70
	120	250	5.65
	140	248	6.00
Anycubic Resin green (AB-POT048)	70	117	1.40
	80	130	1.28
	100	143	0.98
	120	151	1.06
	140	155	1.20
PrimaCreator Resin clear (PV-RESIN-B405-0500-CL)	70	139	1.27
	80	150	1.53
	100	163	1.28
	120	170	1.13
	140	174	1.52
Wanhao Resin water washable clear (23453)	70	134	20.14
	80	145	22.15
	100	157	24.03
	120	165	26.14
	140	169	26.49
PhotoCentric3D UV Flexible Resin clear (PHODCL01UVFLEX)	70	119	1.40
	80	130	1.09
	100	143	0.67
	120	150	0.68
	140	154	0.68
Formlabs form2 clear resin (RS-F2-GPCL-04)	70	109	0.96
	80	121	0.60

	100	135	0.57
	120	143	0.42
	140	149	0.50
Vero PureWhite Stratasys (OBJ-03327)	70	156	3.61
	80	164	3.83
	100	171	3.73
	120	176	3.83
	140	178	3.74
VeroBlue Stratasys (OBJ-03204)	70	116	2.12
	80	128	2.23
	100	141	1.98
	120	149	2.06
	140	154	2.28
VeroClear Stratasys (OBJ-03271)	70	104	1.06
	80	117	1.47
	100	133	1.06
	120	142	1.02
	140	147	1.23
Formlabs form 2 flexible resin Formlabs, (RS-F2-FLGR-02)	70	66	5.87
	80	77	7.76
	100	91	8.67
	120	98	9.83
	140	103	10.23
Formlabs form 2 elastic resin Formlabs, (RS-F2-ELCL-01)	70	16	1.50
	80	28	0.74
	100	43	0.88
	120	52	1.21
	140	57	1.32
RGD 525 Stratasys, (OBJ-03256)	70	105	1.73
	80	116	2.05
	100	129	1.78
	120	141	2.00
	140	140	2.36
TangoPlus Stratasys, (OBJ-03224)	70	56	0.83
	80	68	0.92
	100	81	1.18
	120	89	0.95
	140	94	0.89

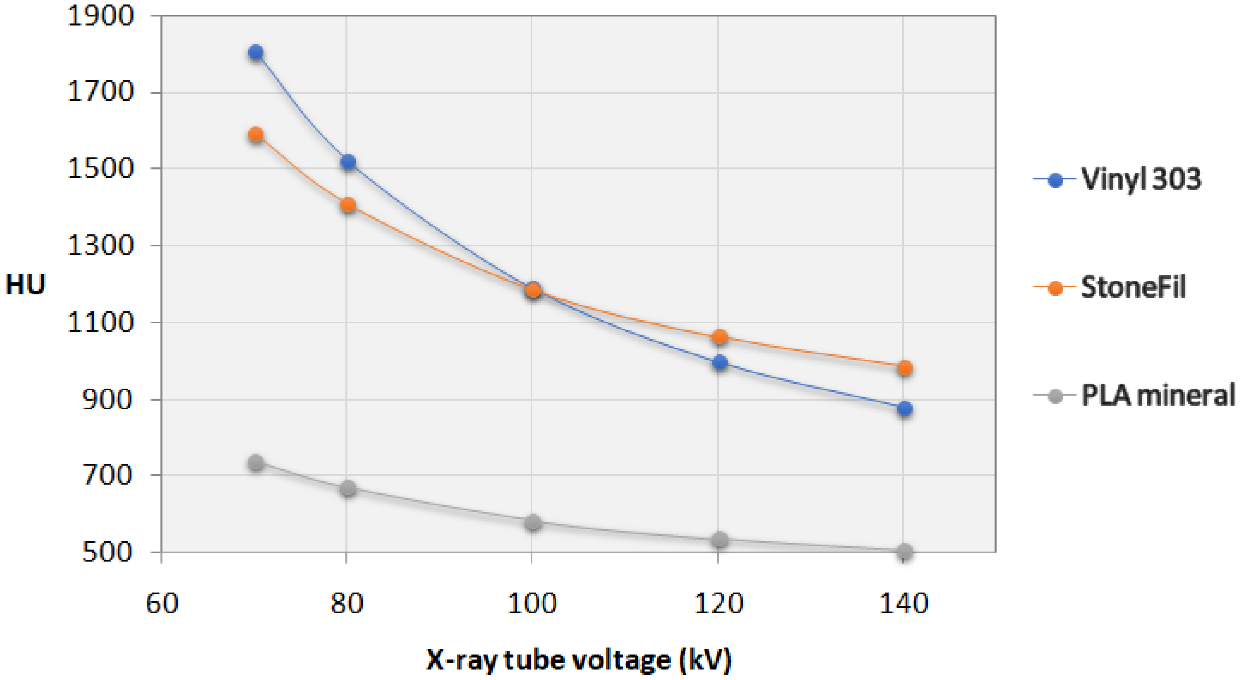

Figure 32. The energy dependence of high attenuation filaments

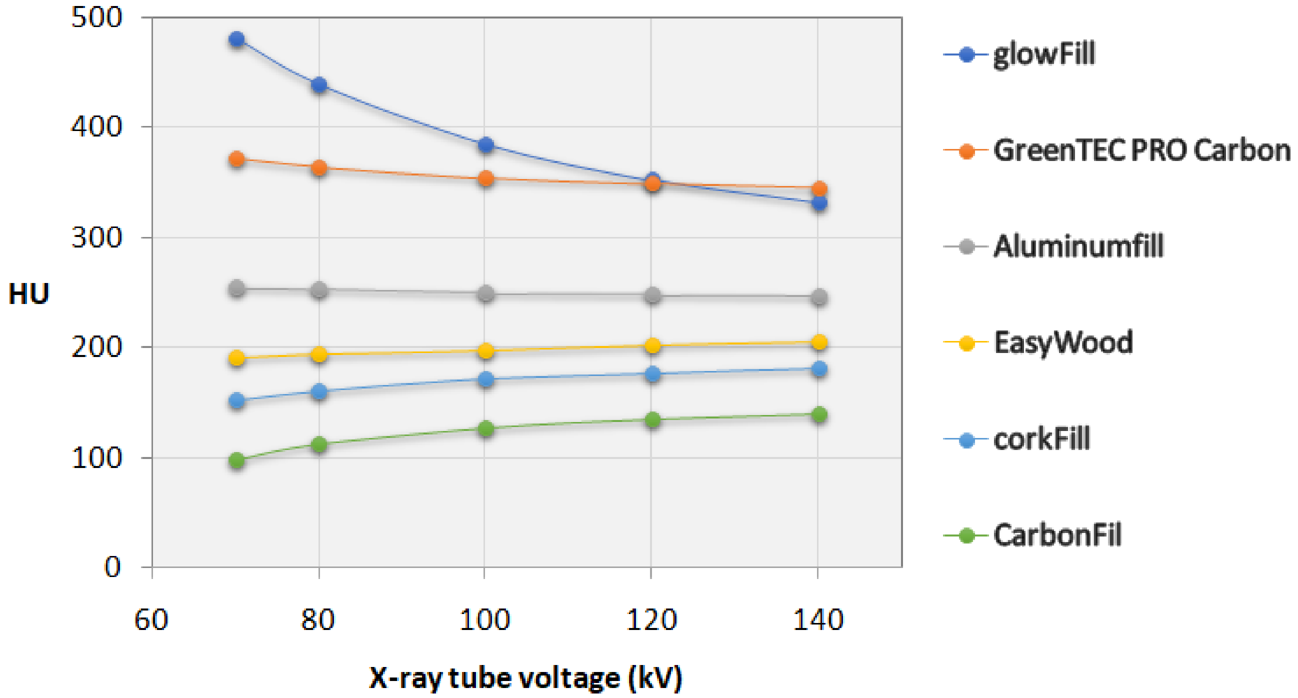

Figure 33. The energy dependence of the filled PLA, PLA/PHA and PETG low attenuation filaments

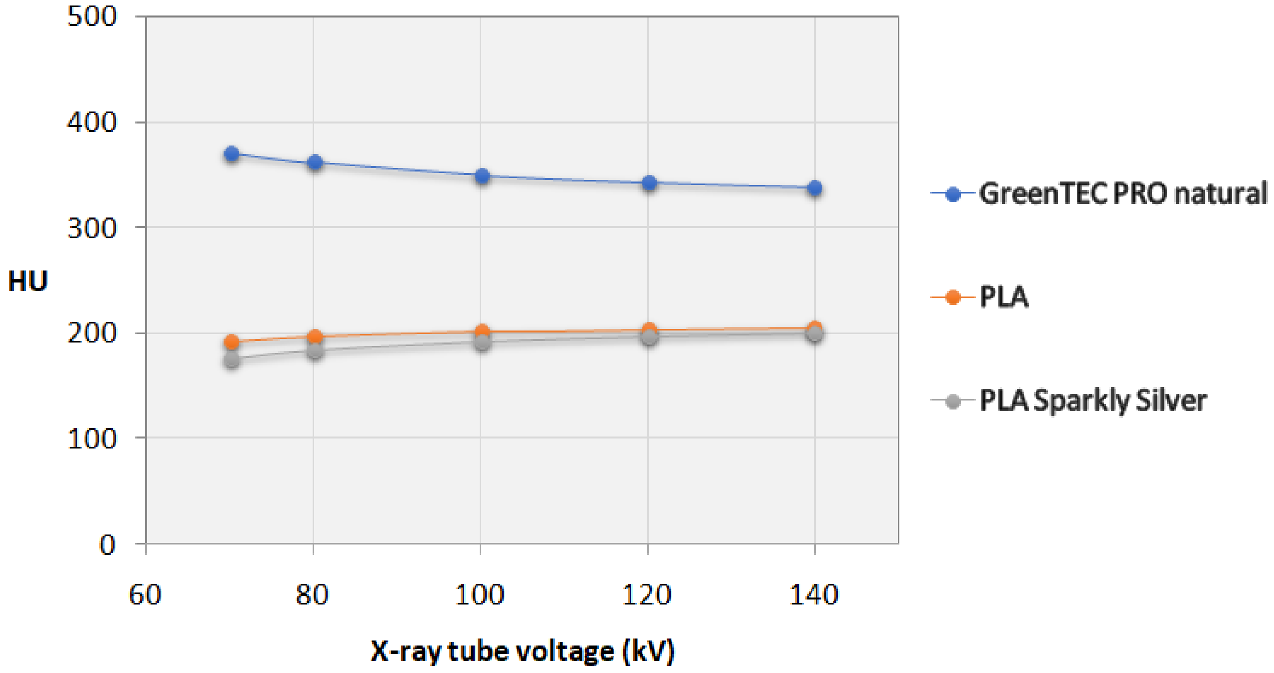

Figure 34. The energy dependence of PLA and PLA based unfilled filaments

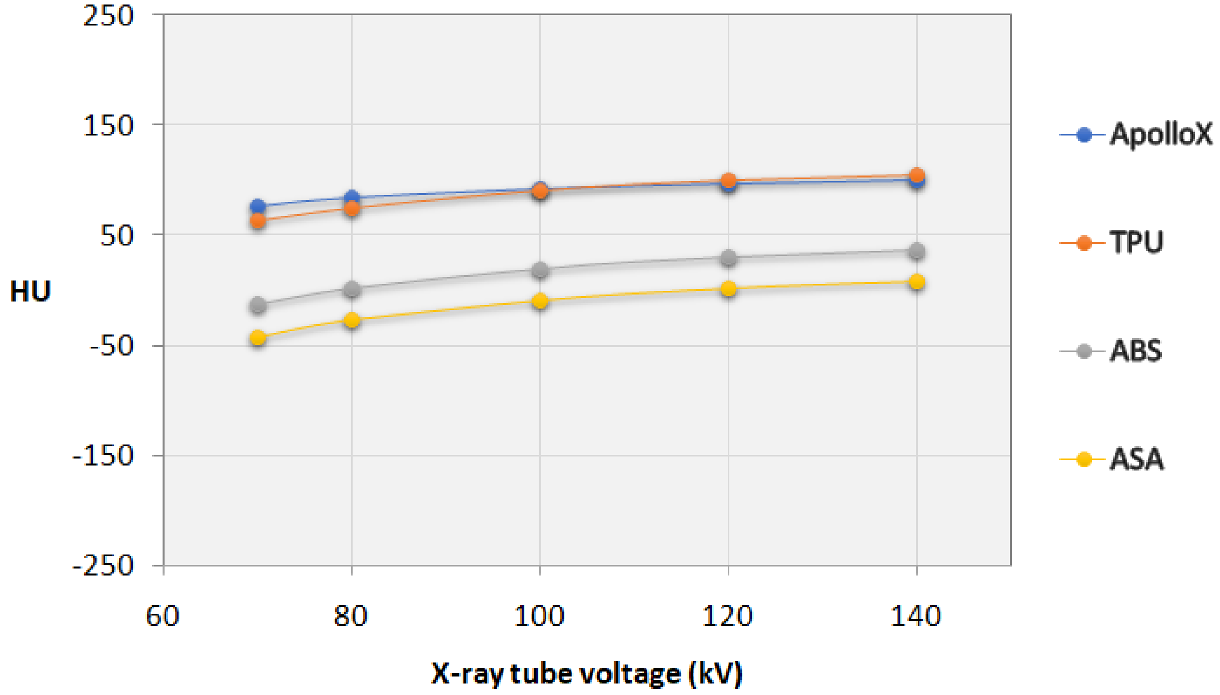

Figure 35. The energy dependence of ASA, ABS and TPU

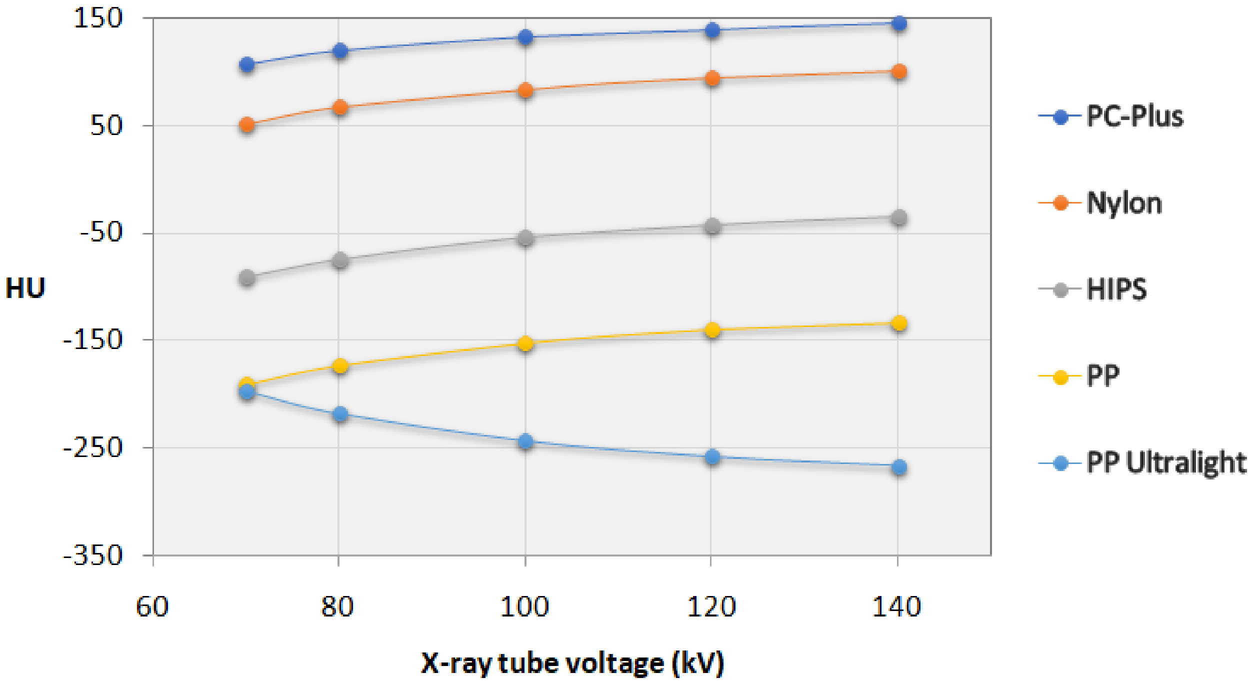

Figure 36. The energy dependence of PP, PS, PC and Polyamide

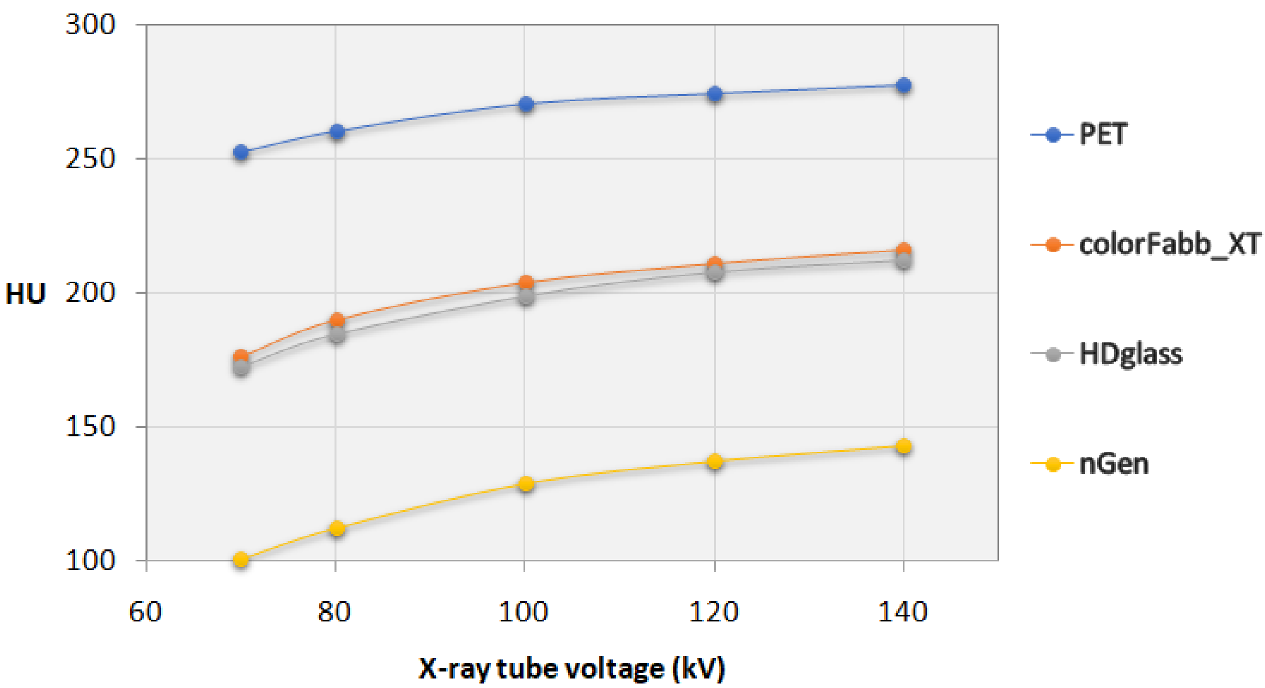

Figure 37. The energy dependence of PET/PETG unfilled filaments

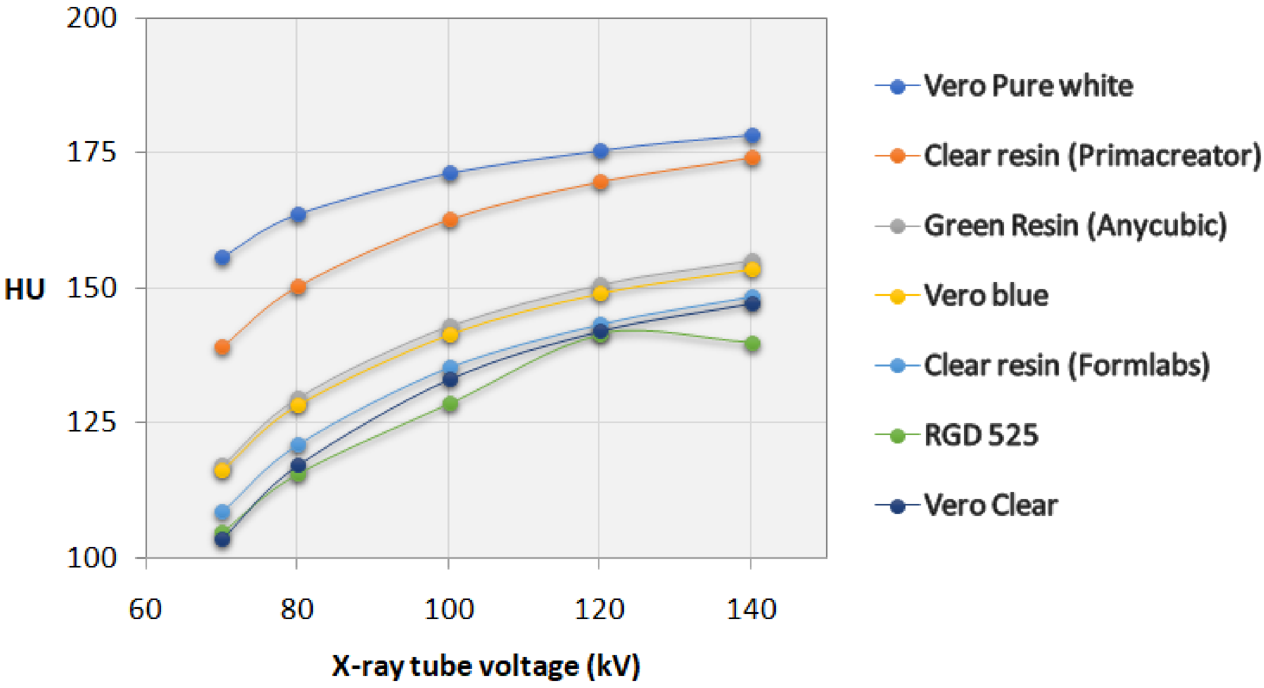

Figure 38. The energy dependence of rigid resins

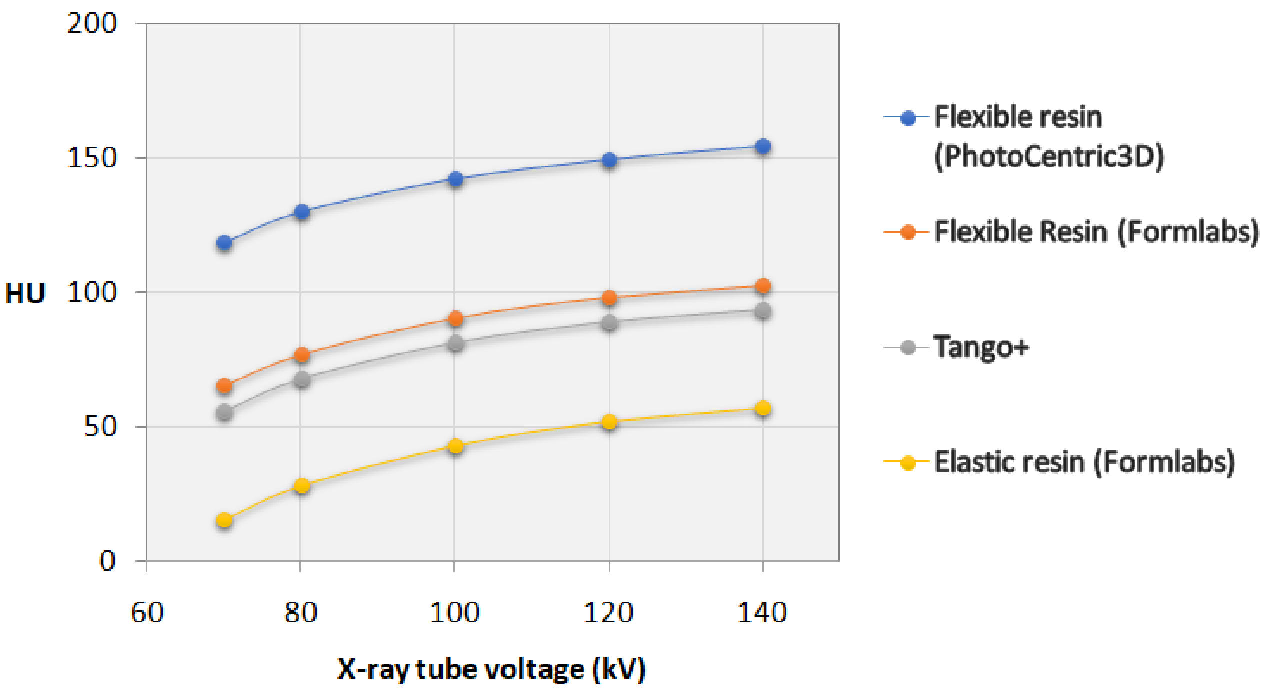

Figure 39. The energy dependence of flexible resins

The Hounsfield units of **Copperfill** (AprintaPro, 195172), **Bronzefill** (AprintaPro, 195072), **steelFill** (colorFabb, 8719033555679) and **copperFill** (colorFabb, 8719033555174) materials could not meaningfully be measured, due to severe artefacts resulting from the high metal filling ratios.

TPU transparent (Extrudr, 9010241152001), **CarbonFil** (Formfutura, 175CARBFIL-BLCK-0500) and **Pegasus PP Ultralight** (Formfutura, 285PEGAPP-NAT-0500) exhibited large standard deviations in HU values, because the densities inside the cylinders were not homogenous. This problem indicates an issue during the 3D printing process of these materials despite all optimization attempts. Therefore, these materials are not recommended for use in phantoms.

Wanhao Resin water washable clear (23453) could not be measured since the printed cylinder disintegrated in the water filled phantom.

With the X-ray tube voltage (kV) increasing, the HU values of some materials increased and the HU values of some materials decreased. This energy dependence can be seen in Figures 32-39. Results are summarized in Tables 18 and 19, where Table 18 lists all materials with HU numbers increasing with increasing beam hardness, whereas Table 19 lists materials, where HU numbers decreased with increasing kV.

Table 18. All materials with HU numbers increasing with increasing beam hardness

HU numbers increasing with increasing kV	**EasyWood** (Formfutura, 285EWOOD-BIRCH-0500)
	corkFill (colorFabb, 8719033555327)
	CarbonFil (Formfutura, 175CARBFIL-BLCK-0500)
	PLA (Ultimaker, 1612)
	PLA Sparkly Silver (Eryone, GPLA-SILVER-175-1000)
	ApolloX (Formfutura, 285APOX-WHITE-0750)
	TPU transparent (Extrudr, 9010241152001)
	ABS (Verbatim, 55019)
	ASA (Fillamentum, natural 00118)
	PC-Plus (Polymaker, 70409)
	Nylon (Ultimaker, 1647)
	HIPS (ICE Filaments, 29548)
	PP (Verbatim, 55951)
	PET (Innofil3d natural, Pet-0301b075)
	colorFabb_XT (colorFabb, 8719033553019)
	HDglass (Formfutura, 285HDGLA-CLEAR-0750)
	nGen (colorFabb, 8719033554733)

	Vero PureWhite Stratasys (OBJ-03327)
	PrimaCreator Resin clear (PV-RESIN-B405-0500-CL)
	Anycubic Resin green (AB-POT048)
	VeroBlue Stratasys (OBJ-03204)
	Formlabs form 2 clear resin (RS-F2-GPCL-04)
	RGD 525 Stratasys (OBJ-03256)
	VeroClear Stratasys (OBJ-03271)
	PhotoCentric3D UV Flexible Resin clear (PHODCL01UVFLEX)
	Formlabs form 2 flexible resin Formlabs (RS-F2-FLGR-02)
	TangoPlus Stratasys (OBJ-03224)
	Formlabs form 2 elastic resin Formlabs (RS-F2-ELCL-01)

Table 19. All materials with HU numbers decreasing with increasing beam hardness

HU numbers decreasing with increasing kV	**Vinyl 303** (Fillamentum, VIN303_285_nat)
	StoneFil (Formfutura, 285STONEFIL-PCLAY-0500)
	PLA Mineral (Fiberlogy, PLA-MIN-NATUR-285-085)
	glowFill (colorFabb, 8719033555136)
	GreenTEC PRO Carbon (Extrudr, 9010241426973)
	Metal Filament Aluminium (AptoFun, B01ITNXRWD)
	GreenTEC PRO natural (Extrudr, 9010241426034)
	Pegasus PP Ultralight (Formfutura, 285PEGAPP-NAT-0500)

5 Discussion

5.1 Printing issues with FDM printers

5.1.1 Warping

Warping is a very common and serious problem for FDM printers, and it may cause model deformation and even complete failure of printing (Figure 40). Warping may occur any time during printing, so it is the reason why we need to check the model many times (usually every 15 minutes) in the printing process. The 3D printing materials that have an obvious property of thermal expansion and contraction (such as ABS, ASA, PC, PP, nGen and so on) easily exhibit warping.

Figure 40. Warping (Left photo: slight warping, local deformation; Right photo: complete failure, the models broke away from the heated bed)

It's very important to avoid warping effectively for FDM printers, and usually there are 3 main methods. A heated bed is effective to avoid warping, but usually this is not enough. The heated bed needs to be covered with additional primers or adhesive sheets. Primers like 3Dlac or PrintaFix, and Kapton, BuildTak or similar products, and the anti-warping sheets in Figure 41 can prevent warping effectively. All of them were tested in the course of this work.

Figure 41. Method to avoid warping (upper left: 3Dlac. Upper middle: PrintaFix. Upper right: Kapton. Lower left: BuildTak. Lower right: anti-warping sheets from Ultimaker)

However, 3Dlac and PrintaFix are sprays that have very strong adhesive forces, so they are not suitable to be used in with fragile and loose materials such as corkFill and EasyWood filaments. They may damage printed models (Figure 42) preventing safe removal from the print plate.

Figure 42. 3Dlac destroyed the bottom of 3DBenchy printed with corkFill material.

The second effective method to avoid warping is to decrease the fan speed or switch off the cooling fan at the beginning of printing. Switching off the cooling system can relieve the thermal expansion and contraction stress on the materials and lead to a better adhesion between the printed model and heated bed.

The third effective method to avoid warping is to create a brim or raft for the designed model that can be created by the software (Ultimaker Cura, Figure 43). The principle is to obtain a better adhesion between the printed model and heated bed by increasing the contact area.

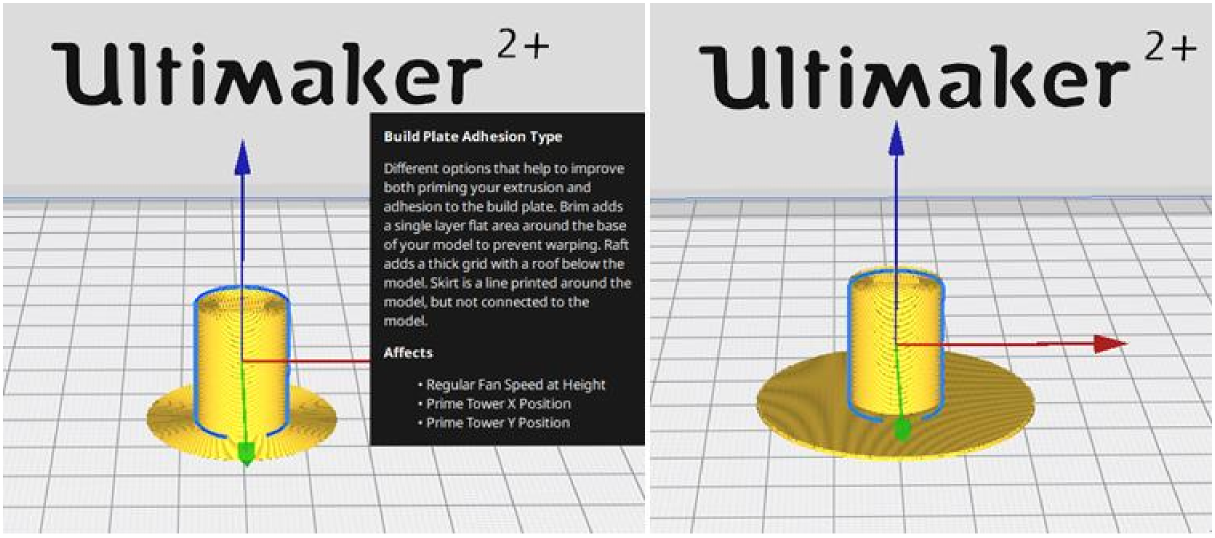

Figure 43. Print previews from Ultimaker Cura (Left photo: Brim for a cylinder. Right photo: Raft for a cylinder)

5.1.2 Tangled filament

Tangled filament is a common problem in 3D printing. Filaments in different layers twisted together will result in a blocking of the spool. As a result, the filament cannot be transported by the feeder correctly (Figure 44). This problem occurs during the printing process: the knot is getting pulled tighter and tighter, slips, causing the extruder to sag, and then keeps pulling tighter until the extruder can no longer pull past it at last.

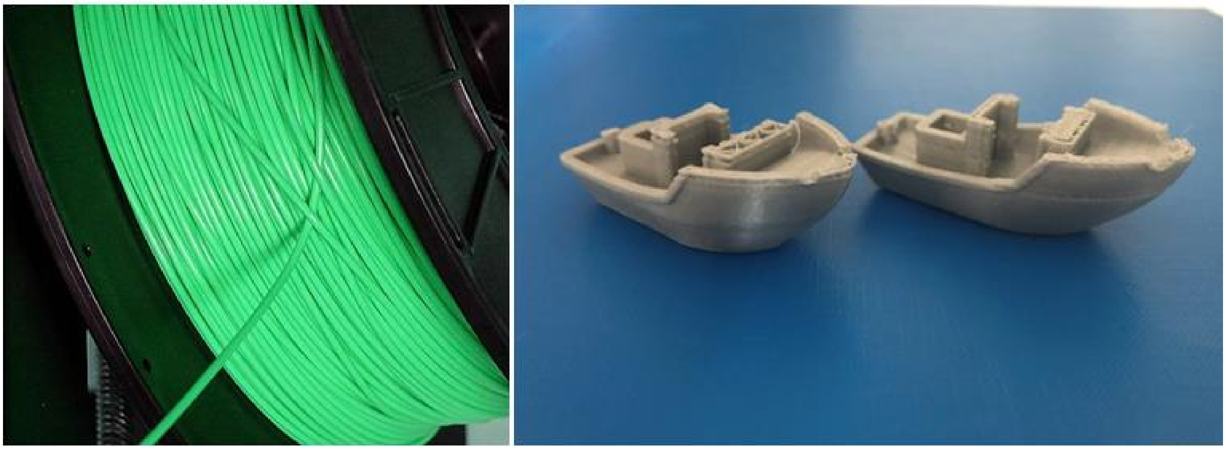

Figure 44. Tangled filament (Left photo: filaments twisted together. Right photo: printing interrupted because of tangled filament)

In order to avoid tangled filament, it’s necessary to check the spool and to make sure that there is no knot in the filament before starting the print. When tangling occurs in the printing process, usually it’s too late for any remedial action. However, if we notice the tangle when the print is running normally, it’s possible to open the knot without stopping the print and removing the filament. It’ll take a little time to be careful to not snap the filament [123].

5.1.3 Printing of flexible materials

With the Ultimaker 2+ (Ultimaker B.V., Netherlands), it’s not possible to pint highly flexible materials without any additional mechanical components. If the filament is too soft, the thrust of the feeder will deform the filament. Therefore, the filament cannot be transported and extruded out of the nozzle.

The Ultimaker 2+ (Ultimaker B.V., Netherlands) is capable of printing PP and TPU (shore 98A), but the thrust of the feeder should be reduced. If the normal thrust of the feeder is used to print soft materials, the filament will be likely to twist on the gear of the feeder. Moreover, the motor of the feeder will stop turning, and there will be no extrusion (Figure 45).

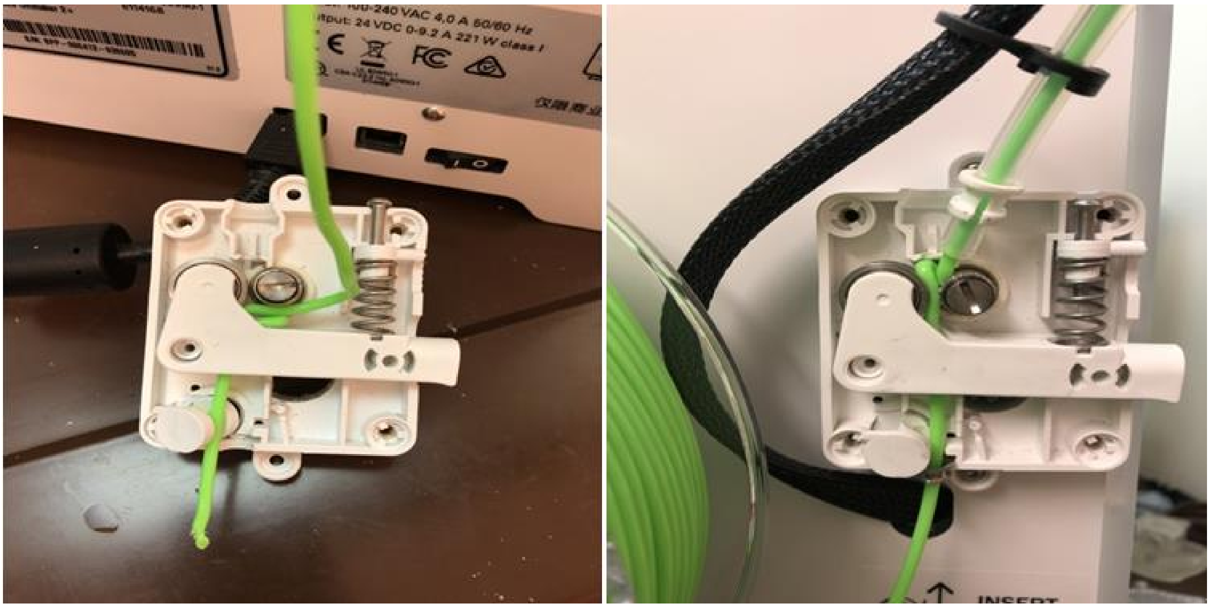

Figure 45. The filament wound around the gear of the feeder twice during the printing of TPU

The thrust of the feeder should be decreased by adjusting the screw on the top of the feeder (Figure 46). After adjusted the screw, this problem didn't occur again in the following tests with TPU.

Figure 46. The optimal thrust of the feeder for TPU printing

5.1.4 Levelling

Levelling is a very important and indispensable step for FDM printers. It determines the printing quality of the first layer, and the printing quality of the first layer influences the adhesion between the model and the bed. When we use an FDM printer for first time, change nozzles or put a piece of anti-warping sheet on the bed, the levelling should be repeated before starting a print.

5.1.5 Selection of nozzles

Brass nozzles and stainless steel nozzles are the most common nozzles for FDM printers, and both of them were used in the tests. Usually brass and stainless steel nozzles are capable of printing most 3D printing materials, but some special materials are exceptions. The melted Vinyl 303 (PVC, Fillamentum, VIN303_285_nat) can produce toxic fumes, and it can corrode stainless steel. Therefore, the stainless steel nozzle cannot be used for printing this kind of material. CarbonFil (Formfutura, 175CARBFIL- BLCK-0500) is filled with carbon fibers. Carbon fibers are quite abrasive, and it will accelerate the nozzle-wear of brass nozzle. Therefore, a wear resistant nozzle is necessary, such as a stainless steel nozzle.

5.1.6 Under extrusion

Under extrusion means that the FDM printer does not extrude enough material to print properly (Figure 47). Many reasons can cause this problem, for example the malfunction of the feeder motor and a clogged nozzle. However, usually increasing the nozzle temperature, decreasing the printing speed and increasing the flow rate can solve this problem effectively. If the extrusion is higher than optimal, it's called overextrusion. If the flow rate is too high, the extrusion will be too much (refer to 3.4.1).

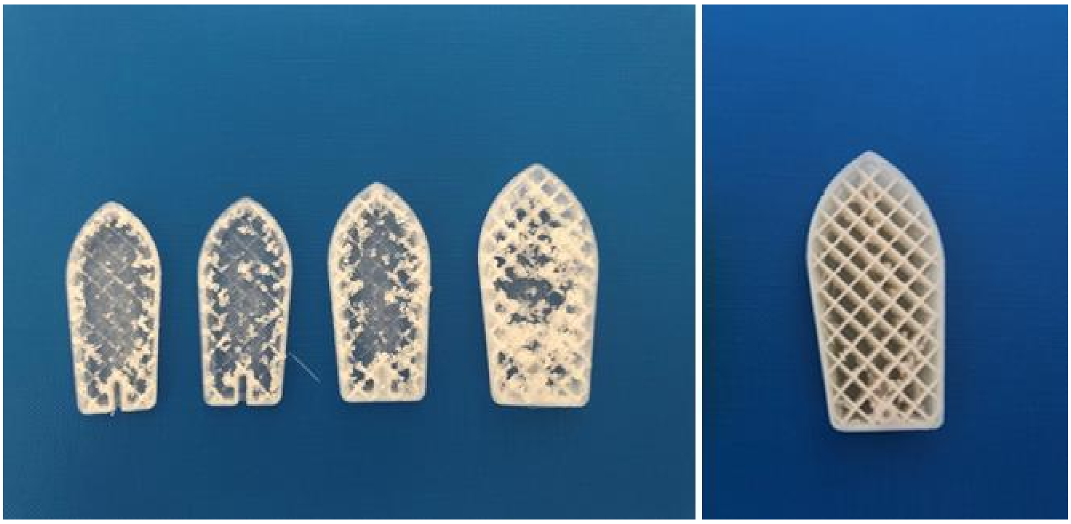

Figure 47. Under extrusion (left) and normal extrusion (right)

5.1.7 Toxic materials

Usually solid 3D printing filaments are non-toxic, but for some special materials the melted filaments can produce toxic fumes under high temperature. Vinyl 303 (PVC, Fillamentum,

VIN303_285_nat) and ABS (Verbatim, 55019) that were used in the tests belong to this kind of materials.
Therefore, it's necessary to ventilate the room during printing in order to avoid inhaling the toxic fumes. Usage of a printer with air filtration, or printing in a laminar flow box is appropriate.

5.1.8 Water absorption of materials

Almost all 3D printing filaments can absorb water from air moisture, so using a dry and sealed packing bag and silica gel as desiccant is the best method to store the 3D printing filaments. Unlike the 3D printing filaments, usually printed models are not susceptible to moisture, so the printed models can be stored in ordinary environment. However, ABS (Verbatim, 55019) used in the tests turned out to be a very special material in the way that the printed models of ABS are still susceptible to water if immersed in water. The printed model of ABS absorbed water and developed many cracks on the surface of the models. As time passed, the cracks became larger and larger. Therefore, ABS is definitely not recommended for printing phantom details to be used in a water filled phantom.

In order to verify whether ABS printed cylinders can still be used in a CT phantom filled with water, and to find out if the water absorption influence the densities of ABS printed cylinders, a simple test was designed. Four ABS printed cylinders with 100% infill were used in the test, and the density of each cylinder measured 3 times. The first density measurement was performed directly after printing. The second density measurement was taken after the four cylinders were stored in the ordinary environment for several months. The third density measurement after the four cylinders were immerged into water for 3 days and dried. The data of density measurement is shown in Table 20.

A balance and a screw micrometer were used to determine the density. The balance was used to measure the mass of each cylinder, and the screw micrometer was used to measure the diameter and the height of each cylinder. The diameter of each cylinder was measured 9 times (different positions on the cylinder), and the averaged diameter and the standard deviation were calculated. The height of each cylinder was measured 5 times (one time in the center, the rest 4 times at edges), and the averaged height and the standard deviation were calculated. However, no effect on the density or physical size of the material was detected.

Table 20. Density measurement of four ABS printed cylinders

ABS printed Cylinders	When the cylinders printed out						After the cylinders stored in ordinary environment for several months						After the cylinders immerged into water for 3 days and dried					
	Height [mm]		Diameter [mm]		Mass [g]	Density [g/cm^3]	Height [mm]		Diameter [mm]		Mass [g]	Density [g/cm^3]	Height [mm]		Diameter [mm]		Mass [g]	Density [g/cm^3]
	Average	SD	Average	SD			Average	SD	Average	SD			Average	SD	Average	SD		
Cylinder 1	20.00	0.04	15.33	0.05	3.92	1.06	20.02	0.04	15.33	0.05	3.92	1.06	20.02	0.03	15.33	0.05	3.92	1.06
Cylinder 2	19.87	0.01	15.15	0.02	3.84	1.07	19.87	0.01	15.17	0.03	3.85	1.07	19.87	0.02	15.17	0.02	3.85	1.07
Cylinder 3	19.91	0.05	15.25	0.02	3.87	1.06	19.91	0.07	15.25	0.02	3.87	1.06	19.92	0.05	15.26	0.03	3.88	1.06
Cylinder 4	20.06	0.07	15.29	0.06	3.92	1.06	20.07	0.06	15.29	0.05	3.92	1.06	20.07	0.05	15.29	0.04	3.92	1.06

5.2 Printing issues with the Anycubic Photon SLA printer

5.2.1 Issues with Wanhao Resin water washable clear (23453)

Most kinds of uncured liquid 3D printing resins are not soluble in water and should be cleaned with 99% IPA (Isopropyl Alcohol). Wanhao Resin water washable clear (23453) is a very special 3D printing resin that contains hydrophilic groups, so it is soluble in water and can be cleaned simply using water. Solid printed models should not absorb water, but in the tests the printed cylinders made of of Wanhao Resin absorbed water when immersed in a water bath and deformed and even disintegrated finally (Figure 48, 49).

Figure 48. Wanhao Resin printed cylinder after having been immersed into water

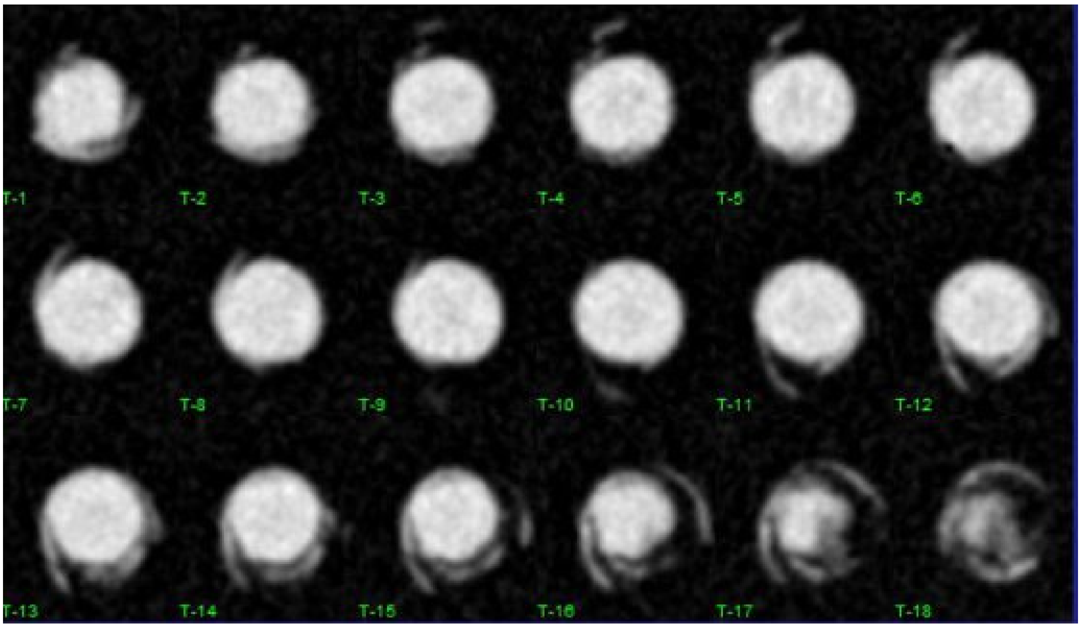

Figure 49. CT images of the deformed cylinder (Wanhao water washable Resin)

One possible reason of this phenomenon might be that the curing time of the printed models was not long enough, so the models had not cured completely, or that the light intensity of the Anycubic Photon printer is too low for this material. Therefore, it's most likely necessary to increase the curing time for models printed with Wanhao Resin water washable clear (23453).

5.2.2 Accurate printing of models' height

For the Anycubic Photon open resin printer (Anycubic 3D Printing, Guangdong, China), there are two ways to print a model. One way is to print the model on the platform directly, and another way is to print the model with a support. Although nearly the same, the heights of the models are slightly different depending on which of the two possibilities was used. In order to find out which reflects the intended height of the models, a small test was designed (Figure 50). In the first print, a cylinder with 20mm height was designed and printed directly on the platform. In the second print, a cylinder with 20mm height was designed and printed with a support.

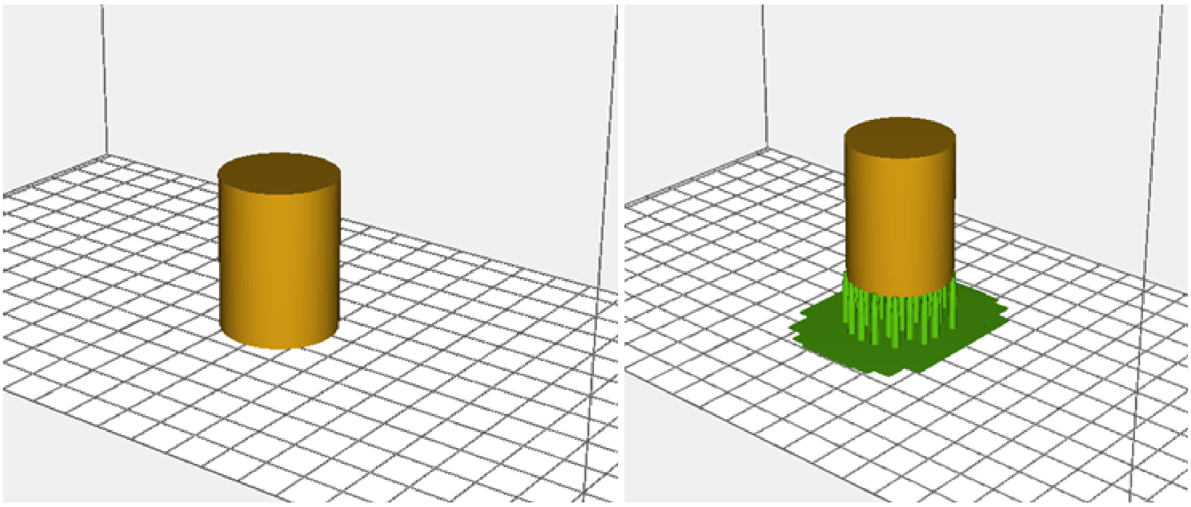

Figure 50. Print previews from Anycubic Photon Slicer (Left photon: 20mm height cylinder was printed directly on the platform. Right photon: 20mm height cylinder was printed with a support)

The heights of the printed models in the first and second print were measured. The height of the model in the first print was 19.5mm, and the height of the model in the second print was 20mm. Therefore, the model should not be printed directly on the platform, and it is necessary to create a support in order to print the model with an accurate height. However, the result may also indicate a height adjustment issue of the print platform. To be on the safe side, using support below the model is advisable.

5.3 CT scanning and Hounsfield units measurements

5.3.1 Metal filled materials

Metal filled materials like Copperfill (AprintaPro, 195172), Bronzefill (AprintaPro, 195072), SteelFill (colorFabb, 8719033555679) and CopperFill (colorFabb, 8719033555174) turned out to be too dense to be useful for large volume samples in CT phantoms (Figure 51). However, because of their extremely high contrast, they could be useful for markings or fiducials in multi material prints. This does not apply for materials filled with various amounts of aluminium powder.

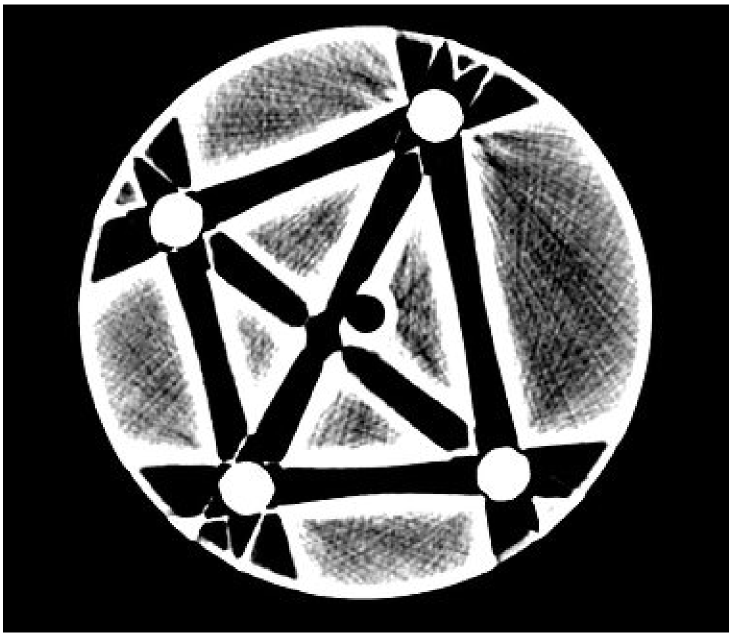

Figure 51. CT image of Copper, Bronze and Steel filled cylinders (Metal artefacts)

The atomic numbers of these metals are high, so the densities of the cylinders of these metals are too causing severe artefacts during CT scanning. However, the metal filament aluminuium (AptoFun, B01ITNXRWD) can be used for CT phantoms without creating severe artifacts because of the low atomic number of aluminium.

5.3.2 Inhomogeneities in density

Some of the printed cylinders had inhomogeneities in density that could only be seen in the CT images. In Table 17, the measured Hounsfield units of these cylinders (made from TPU transparent (Extrudr), CarbonFil (Formfutura) and Pegasus PP Ultralight (Formfutura) exhibit large standard deviations caused by inhomogeneities in the densities of the cylinders.

The detailed data of the Hounsfield units measurements of these 3 materials are shown in Table 21, Table 22 and Table 23 for all slices in the respective materials.

Table 21. HU measurements of TPU transparent (Extrudr, 9010241152001)

Slice	HU in 70 kV		HU in 80 kV		HU in 100 kV		HU in 120 kV		HU in 140 kV	
	Mean	Std.Dev.	Mean	Std.Dev	Mean	Std.Dev	Mean	Std.Dev	Mean	Std.Dev
1	66	23.4	80	16.6	93	11.3	103	10.5	107	10.8
2	60	25.0	76	16.9	90	11.3	100	11.4	106	11.5
3	57	24.3	70	17.8	85	12.7	93	13.7	99	12.2
4	51	24.4	62	18.3	77	14.2	85	14.4	91	11.5
5	47	24.3	59	16.9	74	13.4	83	13.3	87	12.9
6	46	24.0	56	18.3	71	13.4	81	12.2	87	13.2
7	49	24.2	60	15.9	74	12.2	84	11.8	90	11.4
8	57	22.9	67	18.0	84	13.2	94	11.5	97	11.9
9	61	26.1	72	17.9	88	13.0	98	12.4	103	12.3
10	66	31.0	76	20.4	93	14.5	102	12.7	109	13.5
11	66	28.4	79	20.0	96	13.4	104	13.5	111	13.3
12	72	25.2	79	19.9	97	13.8	106	15.0	112	13.5
13	76	28.4	87	20.1	104	13.2	113	13.5	117	13.6
14	79	29.2	93	20.6	111	13.3	119	14.0	123	13.3
15	77	27.3	91	19.8	108	13.6	115	12.8	122	12.1
16	77	23.0	86	17.9	105	12.1	113	11.1	119	10.9
17	80	27.1	92	19.6	107	14.0	116	12.4	121	12.7

Table 22. HU measurements of CarbonFil (Formfutura, 175CARBFIL-BLCK-0500)

Slice	HU in 70 kV		HU in 80 kV		HU in 100 kV		HU in 120 kV		HU in 140 kV	
	Mean	Std.Dev.	Mean	Std.Dev	Mean	Std.Dev	Mean	Std.Dev	Mean	Std.Dev
1	94	19.9	108	16.0	121	13.1	130	11.4	137	11.4
2	96	21.5	109	16.1	121	12.2	131	11.9	137	11.9
3	93	23.6	109	17.1	118	11.9	130	12.7	134	12.3
4	100	20.9	112	16.5	126	11.2	134	12.3	139	12.0
5	94	19.6	112	16.6	126	12.8	134	12.6	141	13.7
6	95	23.5	111	17.6	122	12.7	135	13.1	137	12.1
7	97	23.7	109	18.0	126	12.3	132	14.6	136	13.9
8	110	24.9	114	20.4	127	13.6	137	14.1	145	14.8
9	92	25.7	112	22.9	124	16.2	136	15.9	141	16.3

10	83	31.6	104	21.1	122	17.0	126	16.3	132	15.5
11	75	33.9	87	21.1	108	22.9	110	15.2	114	15.0
12	72	28.4	90	19.9	104	14.0	113	13.1	115	14.2
13	77	26.5	98	17.4	108	15.6	121	12.6	123	13.2
14	108	23.2	113	19.7	122	17.1	135	17.6	138	17.5
15	129	17.6	137	14.5	157	16.1	161	13.1	167	12.8
16	144	16.5	155	12.2	183	11.9	178	10.4	183	9.6
17	129	17.3	139	13.6	155	14.0	159	13.6	165	13.0

Table 23. HU measurements of Pegasus PP Ultralight (Formfutura, 285PEGAPP-NAT-0500)

Slice	HU in 70 kV		HU in 80 kV		HU in 100 kV		HU in 120 kV		HU in 140 kV	
	Mean	Std.Dev.	Mean	Std.Dev	Mean	Std.Dev	Mean	Std.Dev	Mean	Std.Dev
1	-143	20.0	-163	13.4	-190	9.6	-206	9.4	-214	9.3
2	-163	21.2	-186	14.5	-212	9.0	-228	9.9	-238	9.0
3	-182	19.3	-206	14.9	-230	11.3	-244	10.8	-254	10.3
4	-189	22.6	-208	15.3	-234	11.6	-247	11.3	-256	10.1
5	-191	20.6	-211	14.4	-236	11.3	-252	9.9	-260	11.4
6	-193	22.7	-214	14.4	-238	12.1	-254	10.5	-262	11.5
7	-190	22.2	-214	15.4	-239	11.0	-253	10.1	-262	10.9
8	-196	20.9	-219	14.5	-244	10.7	-258	10.2	-267	10.8
9	-199	21.0	-219	15.1	-246	9.7	-261	10.5	-268	10.5
10	-203	21.1	-222	14.0	-248	9.7	-264	9.6	-272	9.6
11	-206	20.6	-228	15.2	-252	9.6	-267	9.5	-275	10.0
12	-211	22.0	-232	15.5	-256	9.8	-270	10.2	-278	10.4
13	-216	23.4	-236	15.1	-260	10.2	-275	9.5	-282	10.8
14	-213	21.1	-234	15.4	-259	10.3	-272	9.6	-280	10.9
15	-220	22.4	-239	16.2	-265	12.1	-280	11.0	-288	10.5
16	-215	22.2	-237	14.8	-261	11.6	-275	10.1	-282	10.3
17	-217	21.6	-240	15.2	-263	11.1	-277	10.0	-285	10.0

For these three materials, in different slices the Hounsfield units exhibit differences of several to several 10 HU as well as STD values higher than those of properly printing materials.

TPU transparent (Extrudr), CarbonFil (Formfutura) and Pegasus PP Ultralight (Formfutura) are spongy materials. At least in the last, there should be some micro-bubbles in the filament to lower the density. The temperature during the printing process becomes a significant factor that influences the density. The variation or fluctuation of the temperature during the 3D printing process may cause the difference of density in different layers. It's necessary to keep a nearly constant temperature, in order to get homogenous cylinders. The temperature of the heated bed, the speed of cooling fan and the environment temperature are the temperatures that can be controlled and adjusted during the 3D printing process. Decreasing the temperature of the heated bed, switching off the cooling fan and placing the 3D printer into an isolating box may solve this problem effectively. However, printing of these materials without inhomogeneities would require more stable and more exactly controlled parameters. This does not apply for every day printing, since these issues were only detectable in the CT scans.

CT scanning also detected issues with SLA printouts. It turned out being a good way to check and find defects on 3D printed models.

Figure 52. Left: CT image of Anycubic Resin green on Plate B top side position 4 (window settings level: 150, width: 100). Right : CT image of PrimaCreator Resin clear on Plate B top side position 5 (level: 180, width: 100)

Figure 52 shows the CT images of the cylinders that printed with Anycubic Resin green (left) and PrimaCreator Resin clear (right). In order to better demonstrate this issue, the reconstructed slice thickness in the slices shown in the figure is set to 6mm (120 kVp). It's very obvious that there is a hole in the center of each cylinder. This problem appeared in the 3D printing process. The printer used to pint these two cylinders was the Anycubic Photon open resin printer (Anycubic 3D Printing, Guangdong, China). During the 3D printing process, the platform of this printer moves up and down, so it might produce some bubbles in the resin. Therefore, the hole was formed by air bubbles in the resin. The cylinders were printed several times, but this problem was not solved.

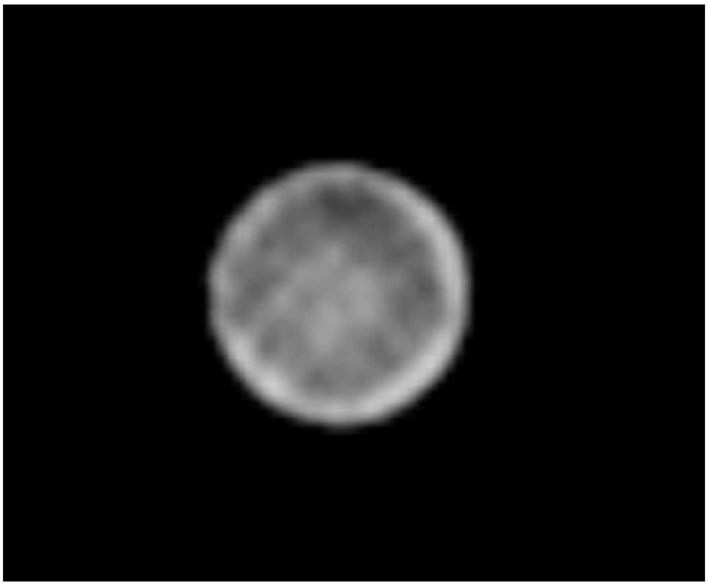

Figure 53. CT image of TPU transparent on Plate C top side position 11 (level: 90, width: 100)

Figure 53 shows the CT image of the cylinder printed with TPU transparent (120kV, reconstructed slice thickness is 6mm). It’s obvious that the density of the wall part is higher than the center part in the cylinder. This problem arises from the 3D printing process. TPU is printed by FMD, and it’s a difficult material that is hard to print due to its flexible nature.

6 Conclusion and outlook

3D printing is an effective way to manufacture phantoms for medical applications. For FDM printers, 100% filling ratio can be achieved by adjusting printing parameters, such as increasing flow rate and decreasing layer thickness.

41 kinds of materials were explored. In this work, optimized printing parameters could be found for most materials, and others could be identified to be not suitable for printing of phantoms with standard consumer grade 3D printers because of density issues.

Still, mimicking soft tissues with regards to x-ray attenuation properties is difficult. In most materials, the effective atomic number is too low. This is seen in the energy dependence of the HU numbers, with HU numbers increasing with beam hardness. These materials do not only have suboptimal energy dependence, but also most of them exhibit too high attenuation to realistically mimick soft tissues. However, if contrast rather than absolute values are important in phantoms, the situation is much better; using the results of this work, material pairs resulting in desired contrast can be selected.

For adipose tissues, and bone, the situation is different. The HU value of HIPS ranges from -35 to -91, so it is quite suitable to mimic fatty tissues. StoneFil, Vinyl 303 and PLA Mineral are suitable to mimic bone tissues.

A possible solution is to combine water or other liquid phantom materials mimicking soft tissue with printed immersed contrast structures/details made from suitable materials. For this approach, the HU measurements in this work can help in the selection of the latter. This will, e.g., allow design and production of three material phantoms, mimicking soft tissue by water, e.g., and adipose tissue and bone by appropriate polymer-based printing materials.

Printing technologies allowing customized mixtures of polymer powders and additives will change the situation, however. Compositions based on printable base polymers with additives like $CaCO_3$, MgO, and TiO_2 mainly, radiologically mimicking water, soft tissues, and bone tissues are available from the literature. Another possibility using standard FDM printers would be the production of custom filaments from these recipes allowing printing of phantoms with materials radiologically tissue equivalent (with regard to absolute attenuation values and energy dependence) with standard low-cost hardware.

7 Appendix

Appendices are available in the online version.

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7 Appendix A1

7.1 3DBenchys printed with different materials

The photos of printed 3DBenchys with different materials are shown below corresponding to the Table 8.

In order to show the detailed structures and the printing qualities, usually one 3DBenchy will be shown by four pictures from different views. Upper left is the frontal view; Upper right is the side view; Lower left is the back view; Lower right is the top view.

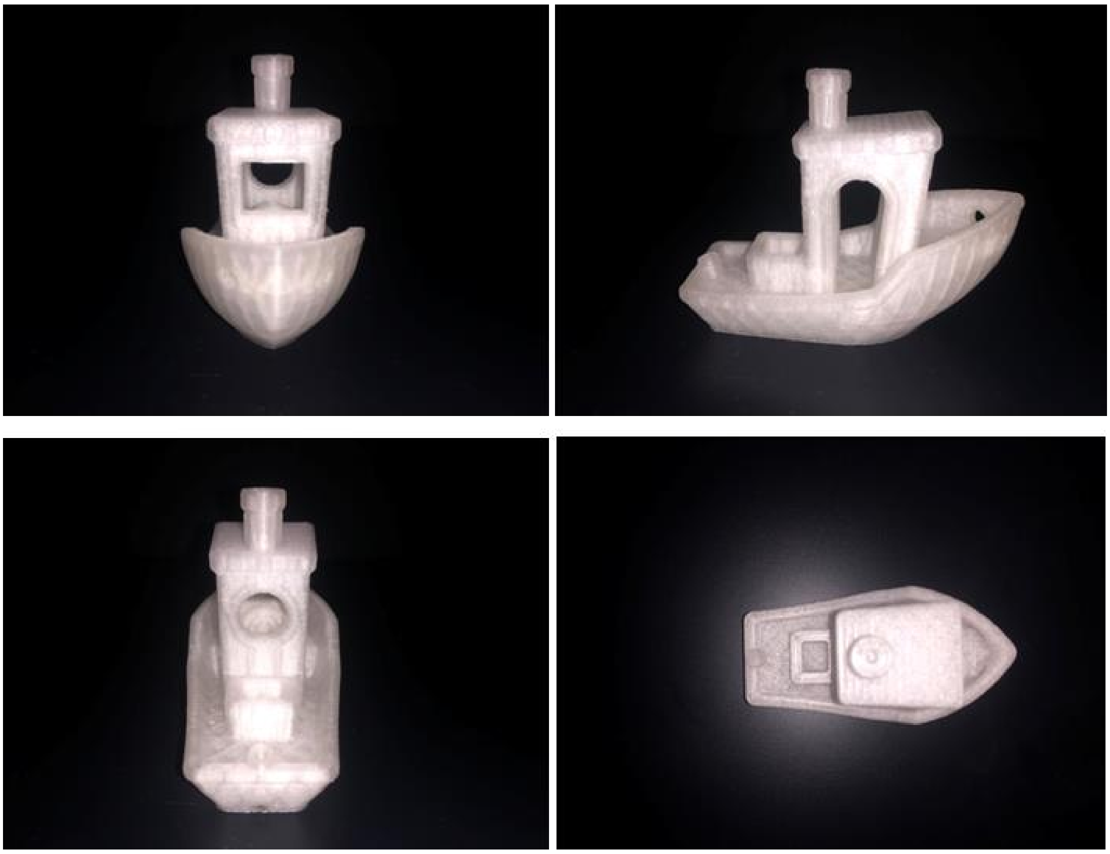

Figure 54. 3DBenchy printed with ABS.

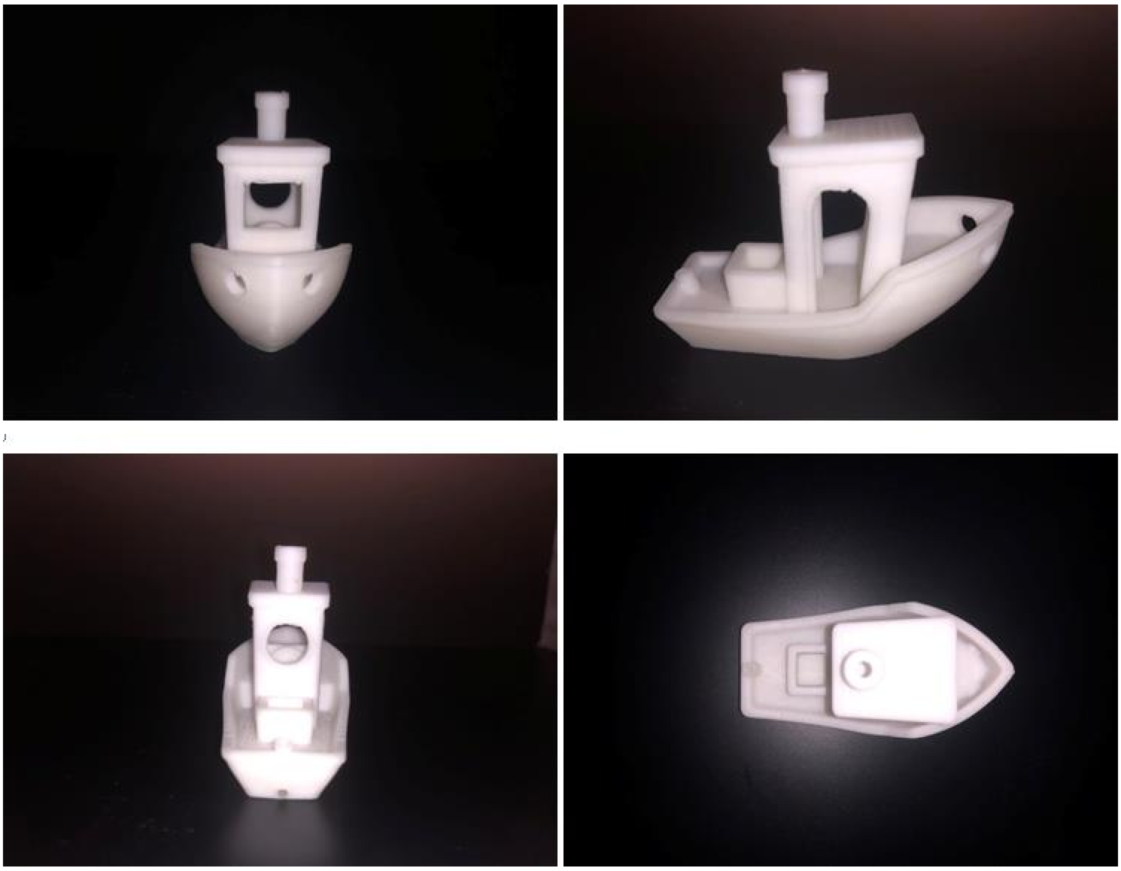

Figure 55. 3DBenchy printed with HIPS

Figure 56. The first print of Vinyl 303 (PVC)

Figure 57. The second print of Vinyl 303 (PVC)

Figure 58. The third print of Vinyl 303 (PVC)

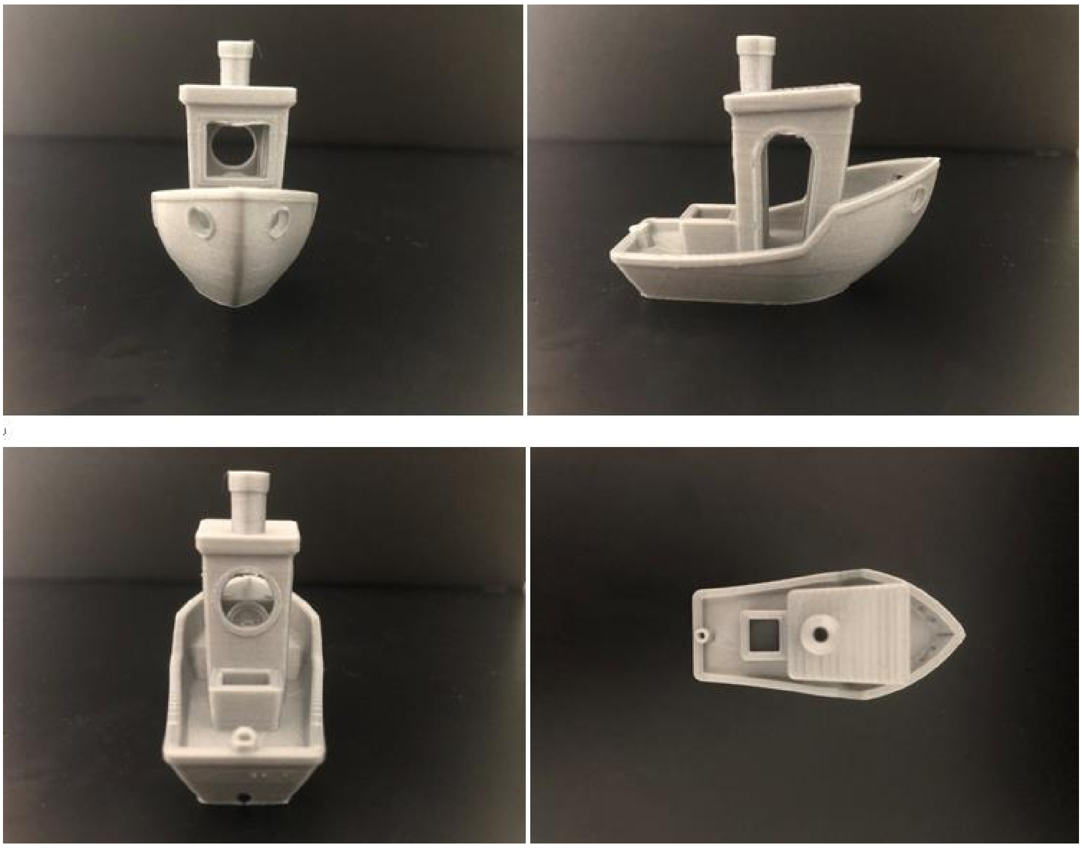

Figure 59. 3DBenchy printed with PLA

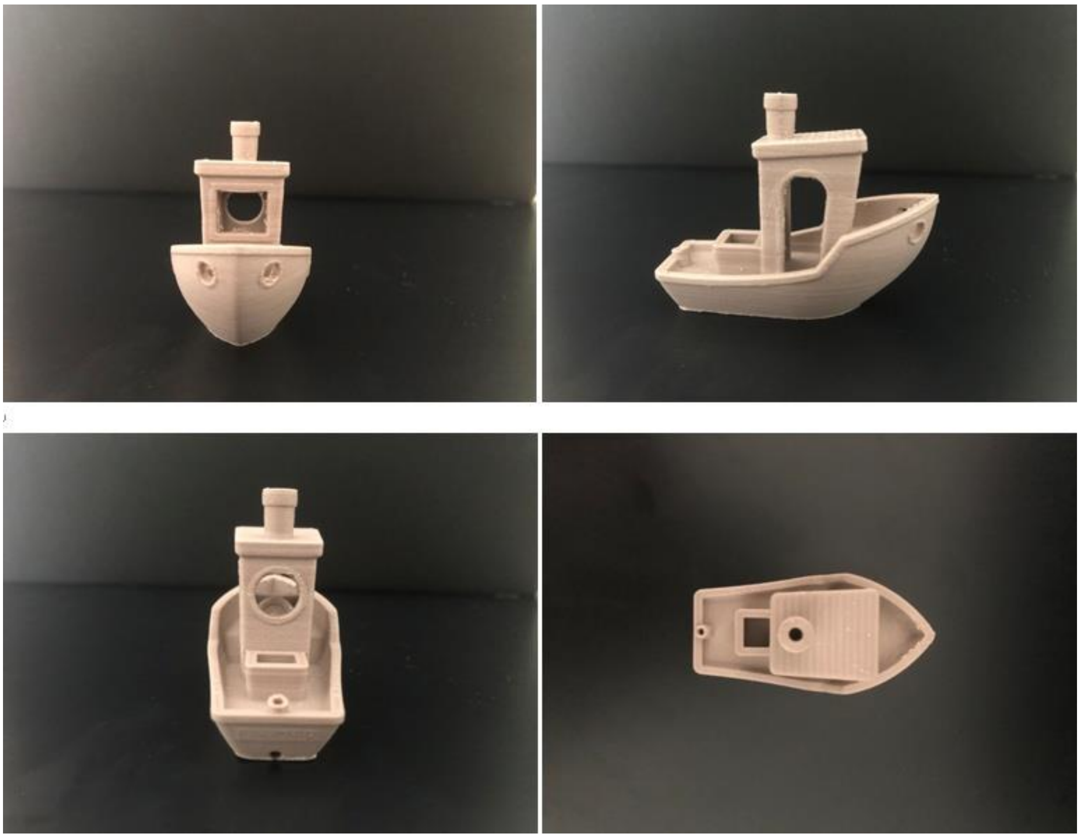

Figure 60. The first print of StoneFil material

Figure 61. The second print of StoneFil material

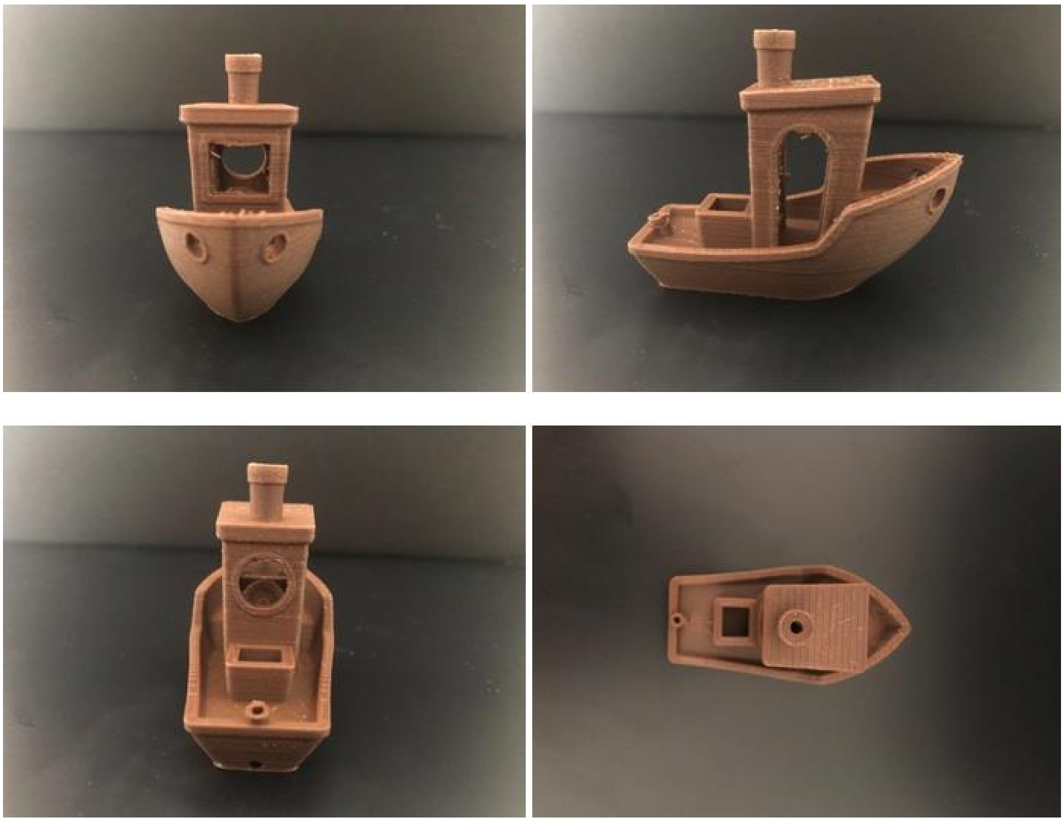

Figure 62. The first print of corkFill material

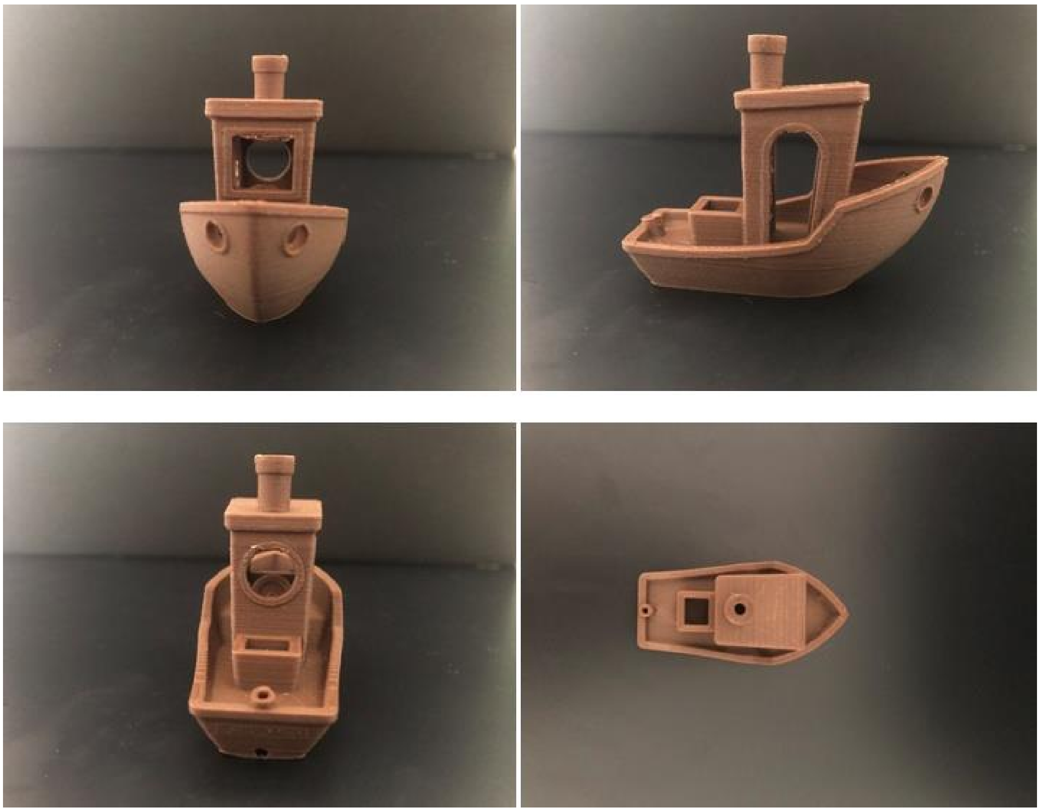

Figure 63. The second print of corkFill material

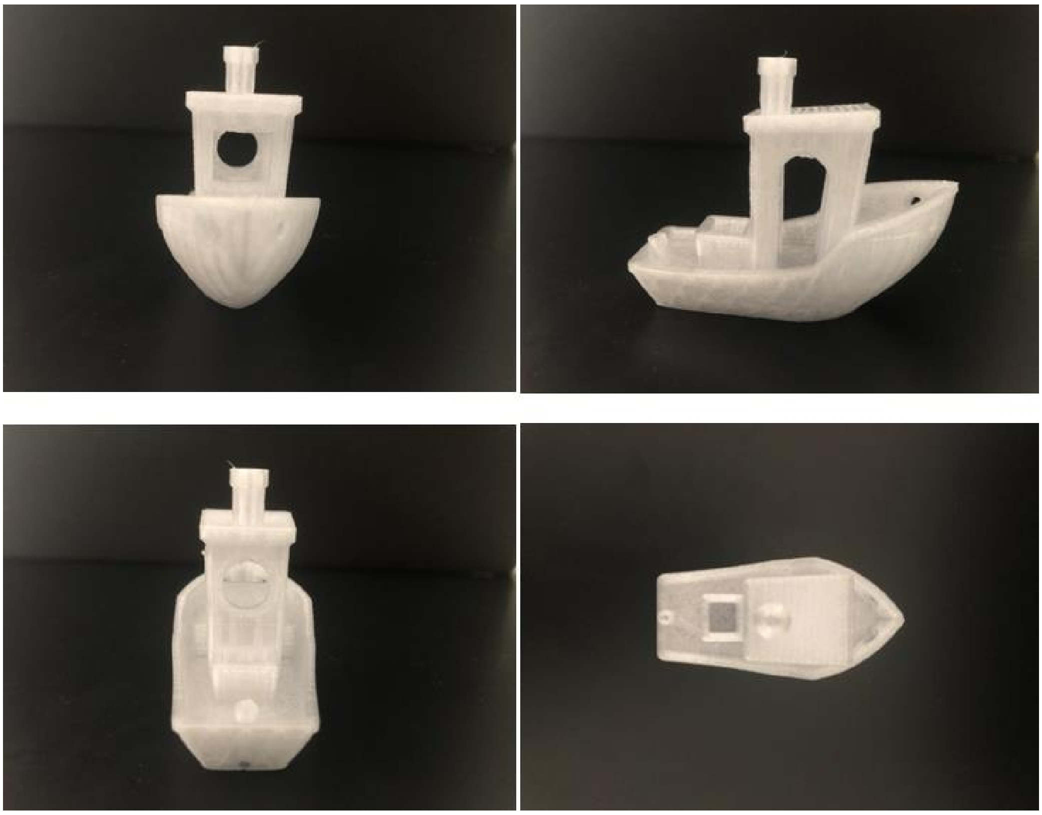

Figure 64. 3DBenchy printed with PET natural

Figure 65. The first print of PET black

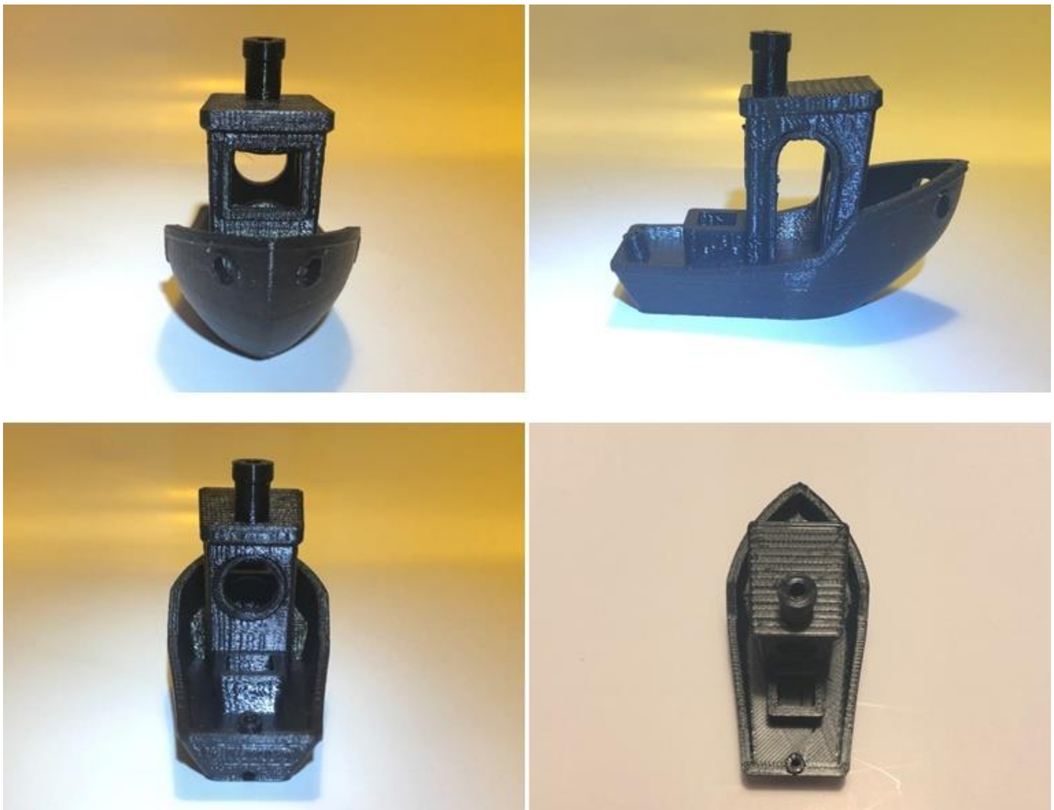

Figure 66. The second print of PET black

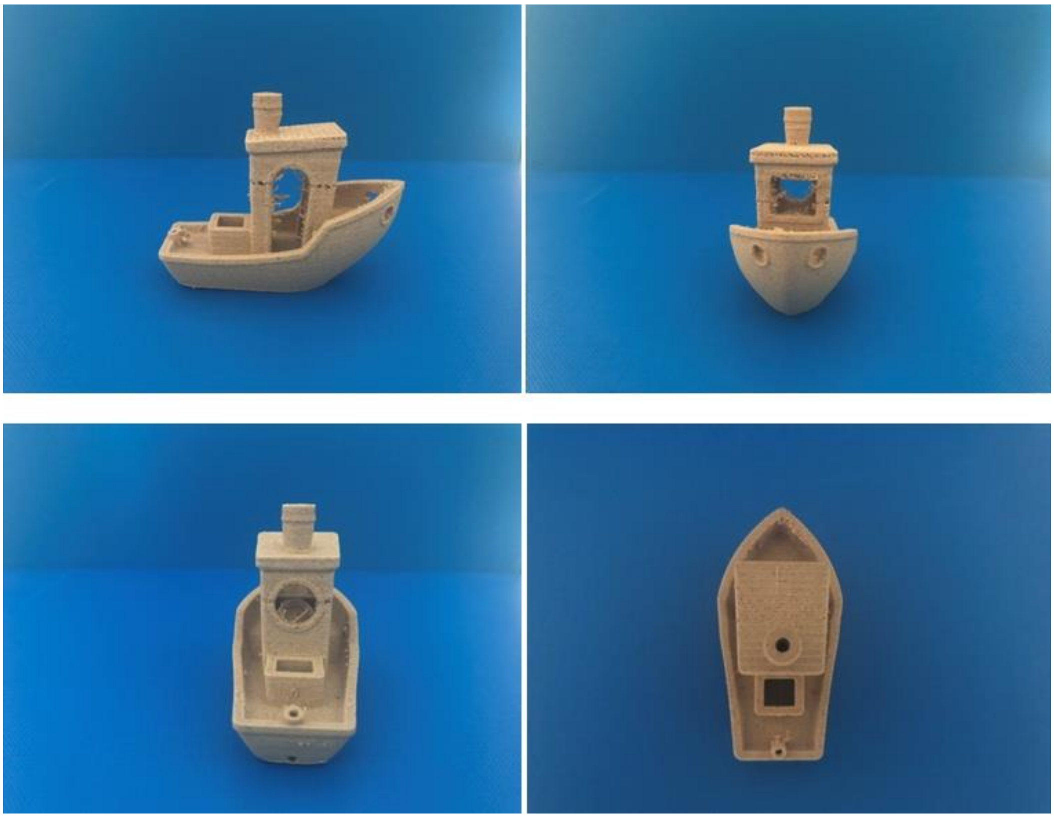

Figure 67. The first print of EasyWood material

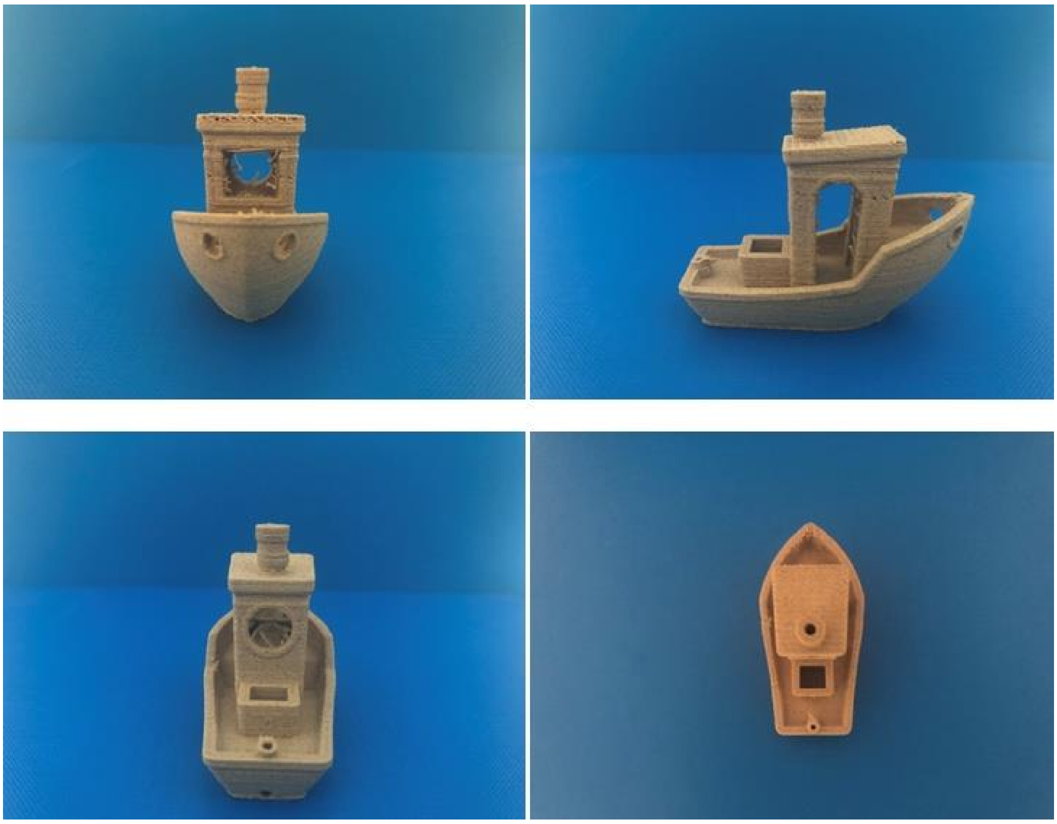

Figure 68. The second print of EasyWood material

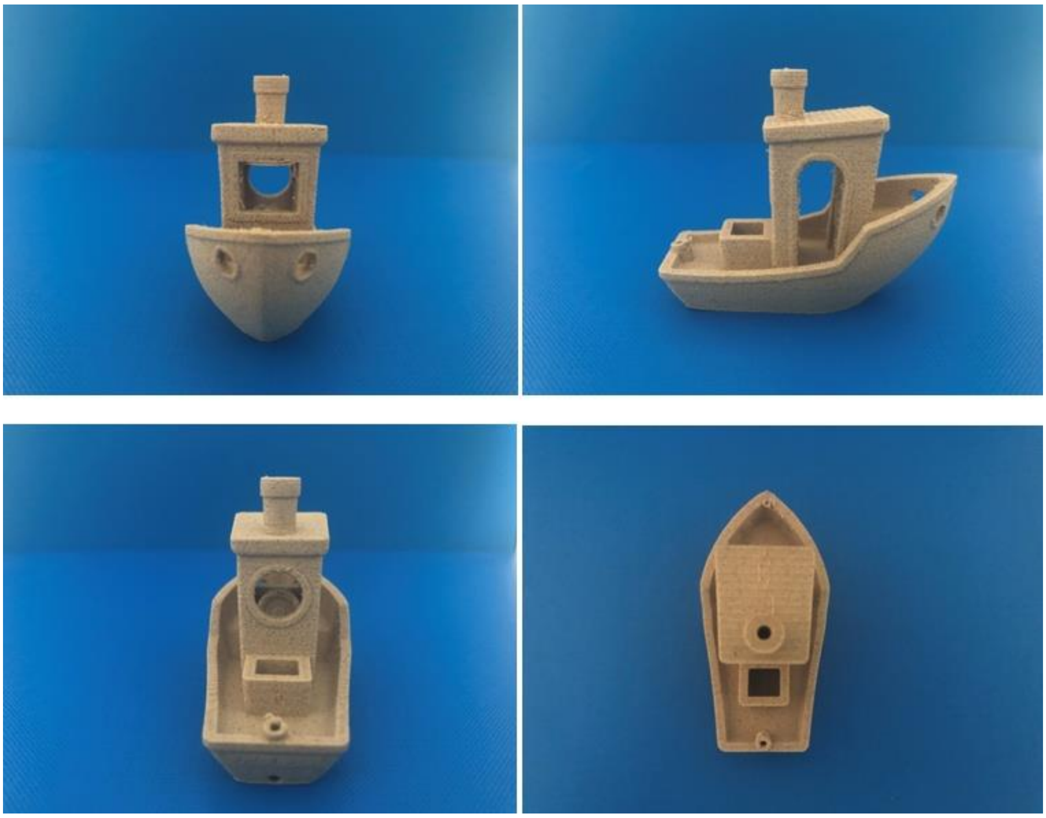

Figure 69. The third print of EasyWood material

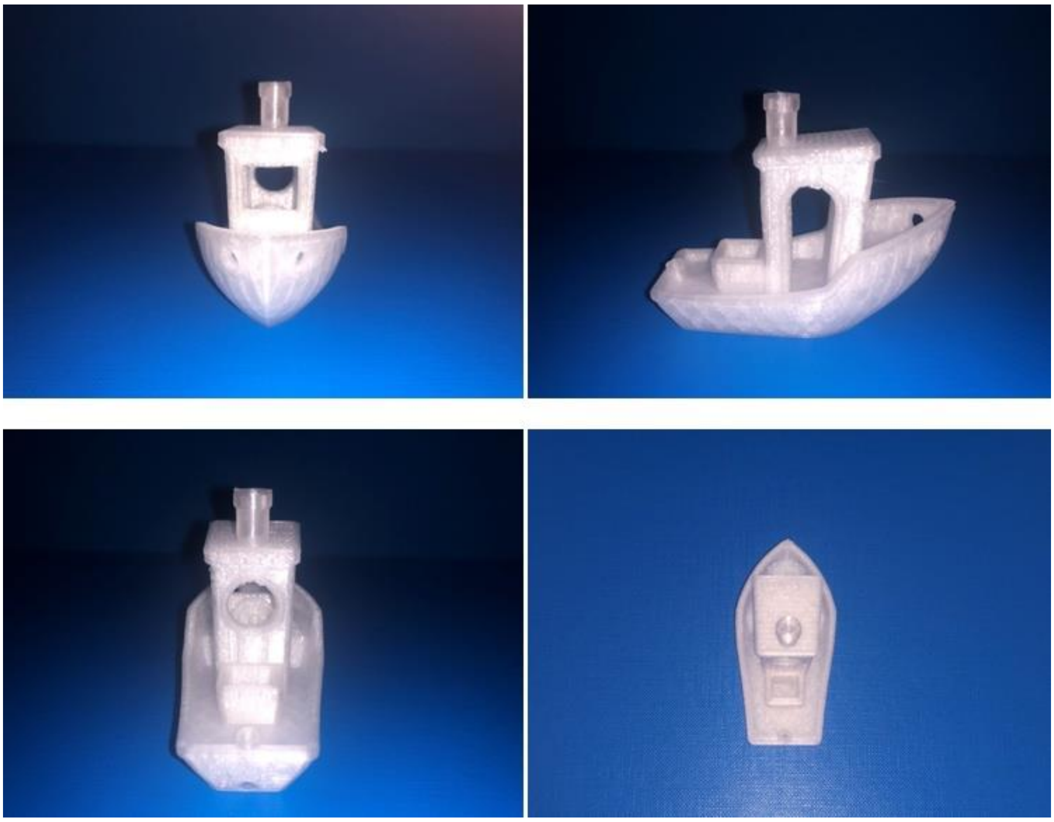

Figure 70. The first print of HDglass

Figure 71. The second print of HDglass

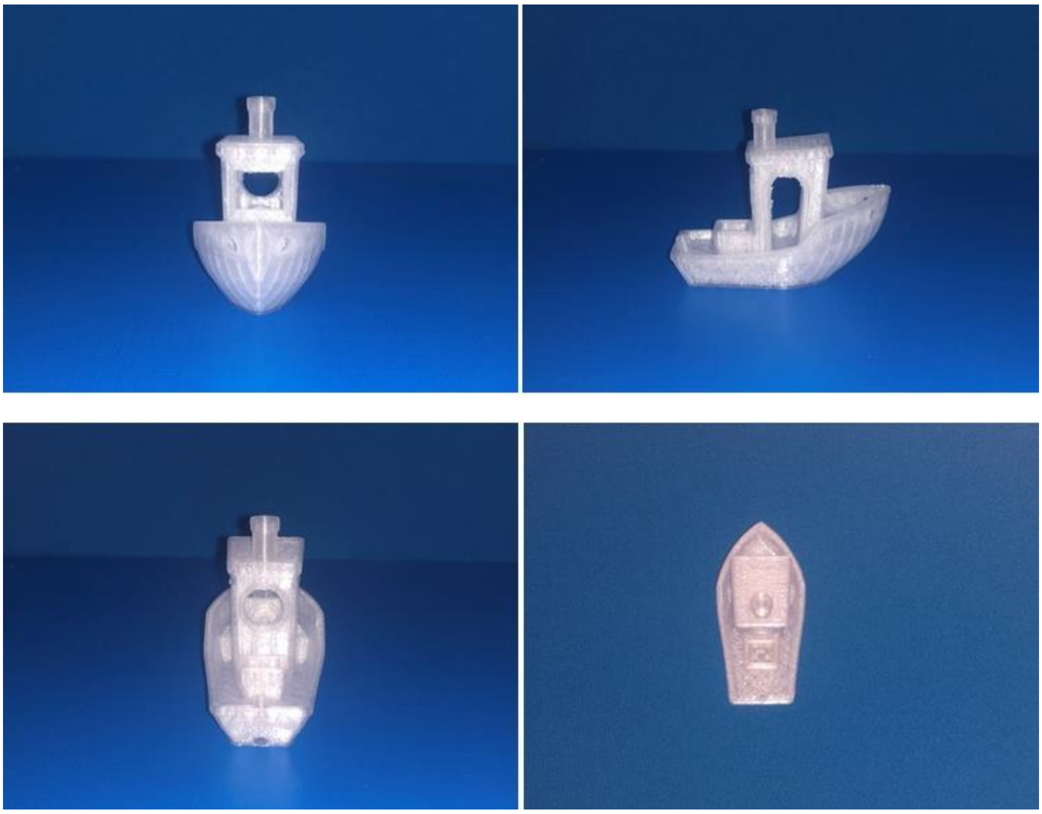

Figure 72. The first print of colorFabb_XT

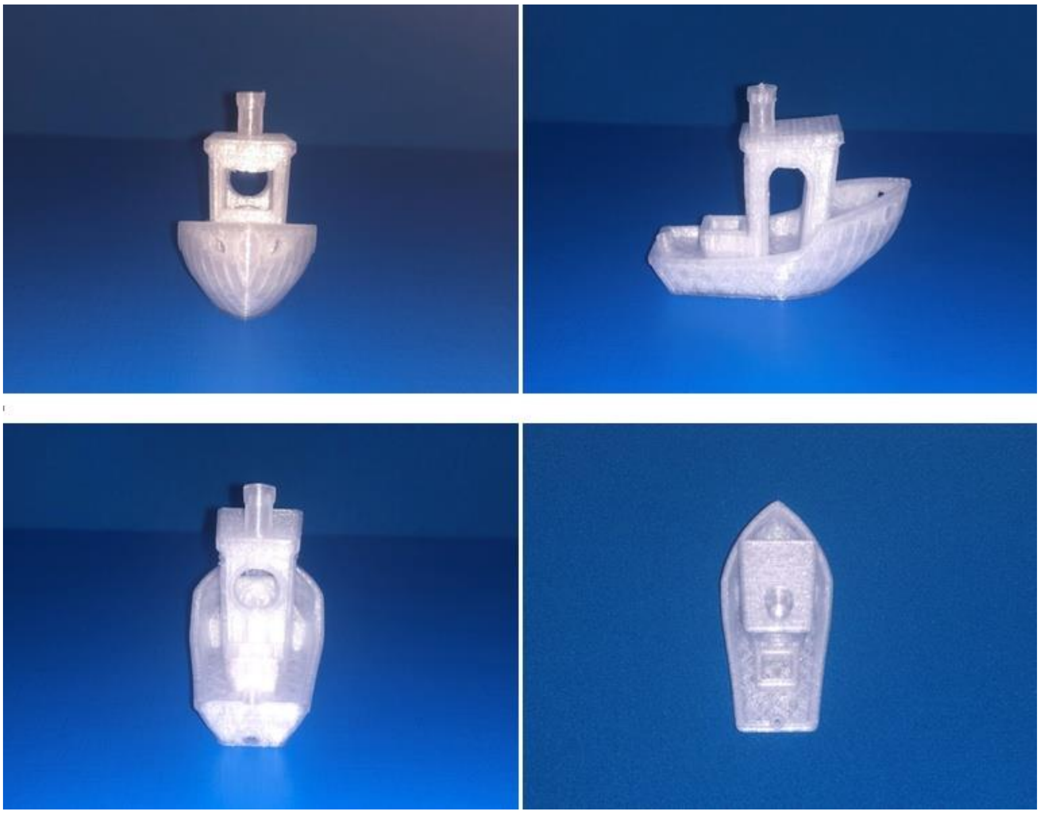

Figure 73. The second print of colorFabb_XT

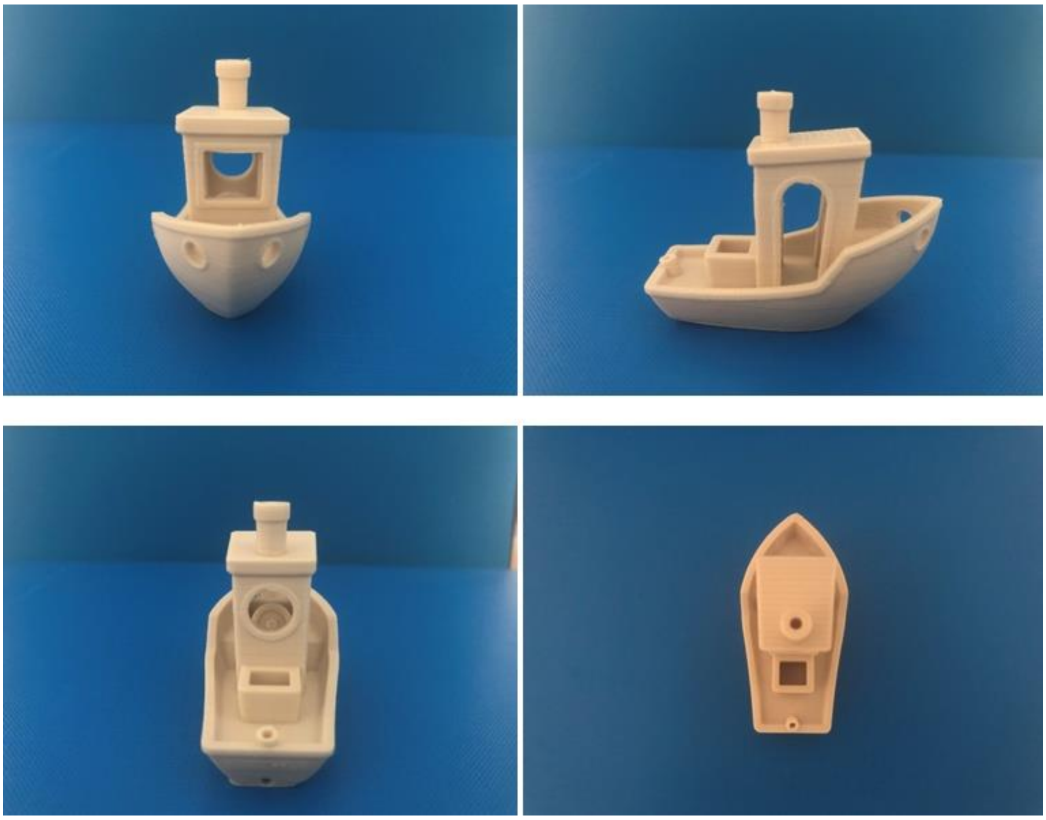

Figure 74. The first print of PLA mineral

Figure 75. The second print of PLA mineral

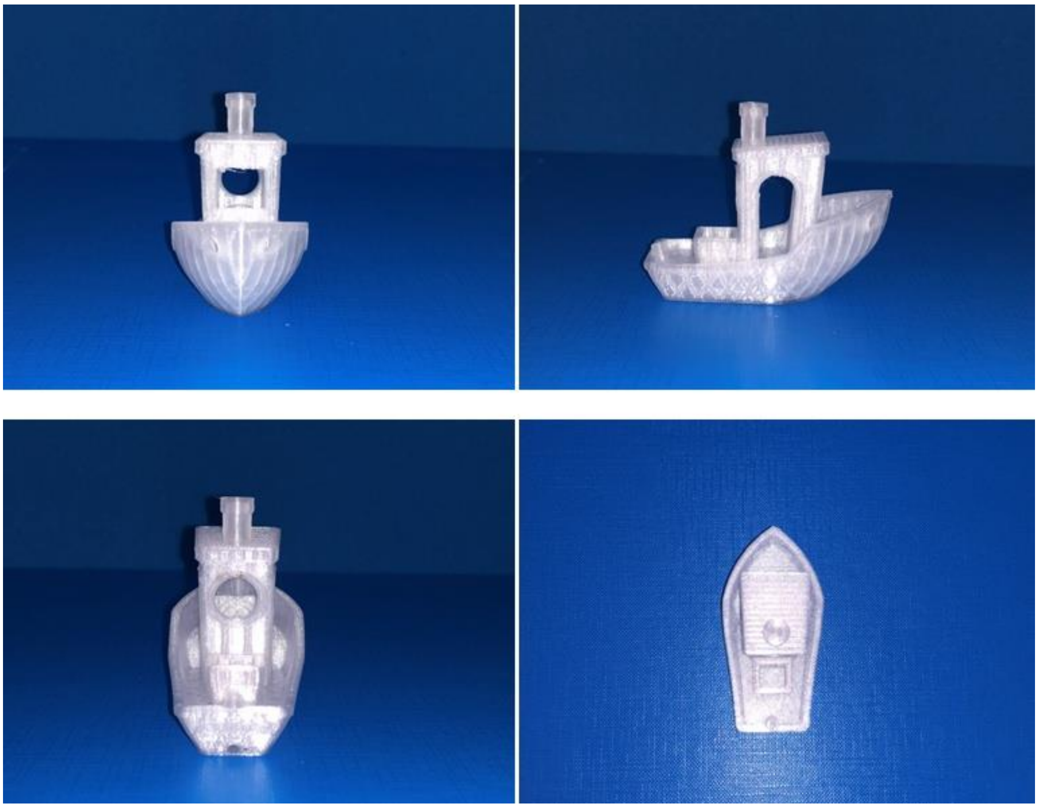

Figure 76. The first print of nGen

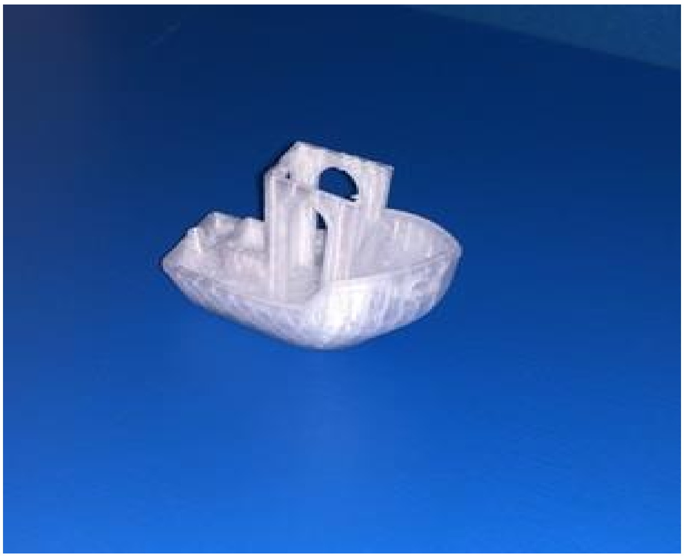

Figure 77. The second print of nGen

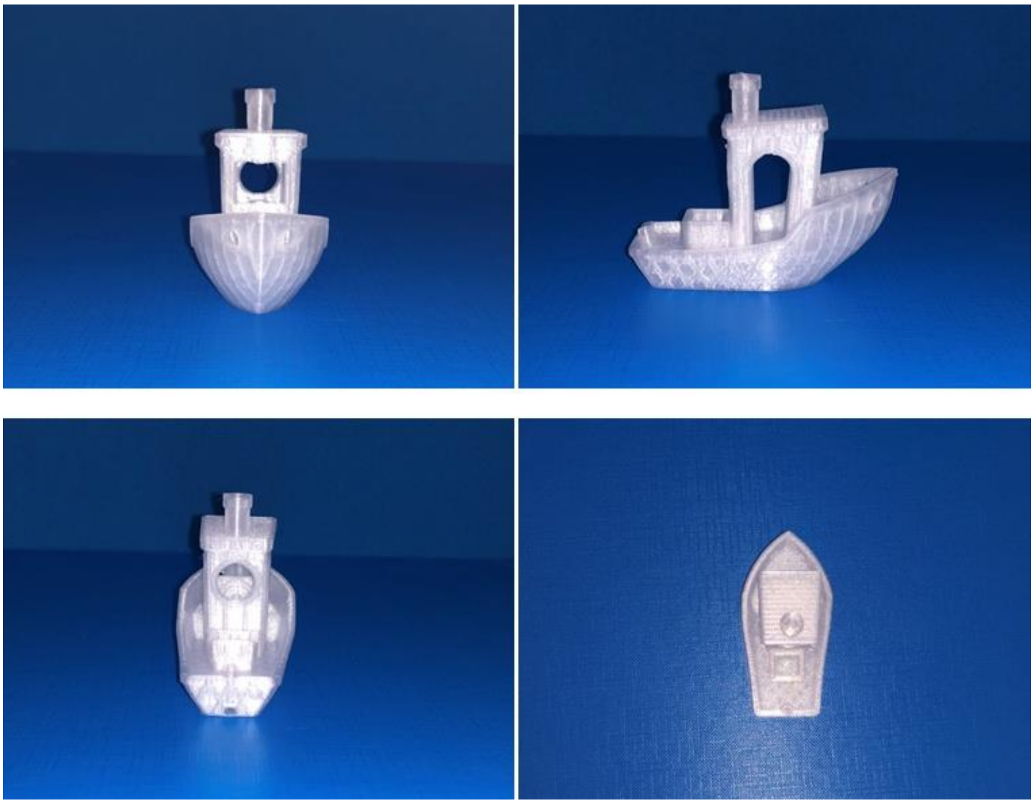

Figure 78. The third print of nGen

Figure 79. The 4th print of nGen

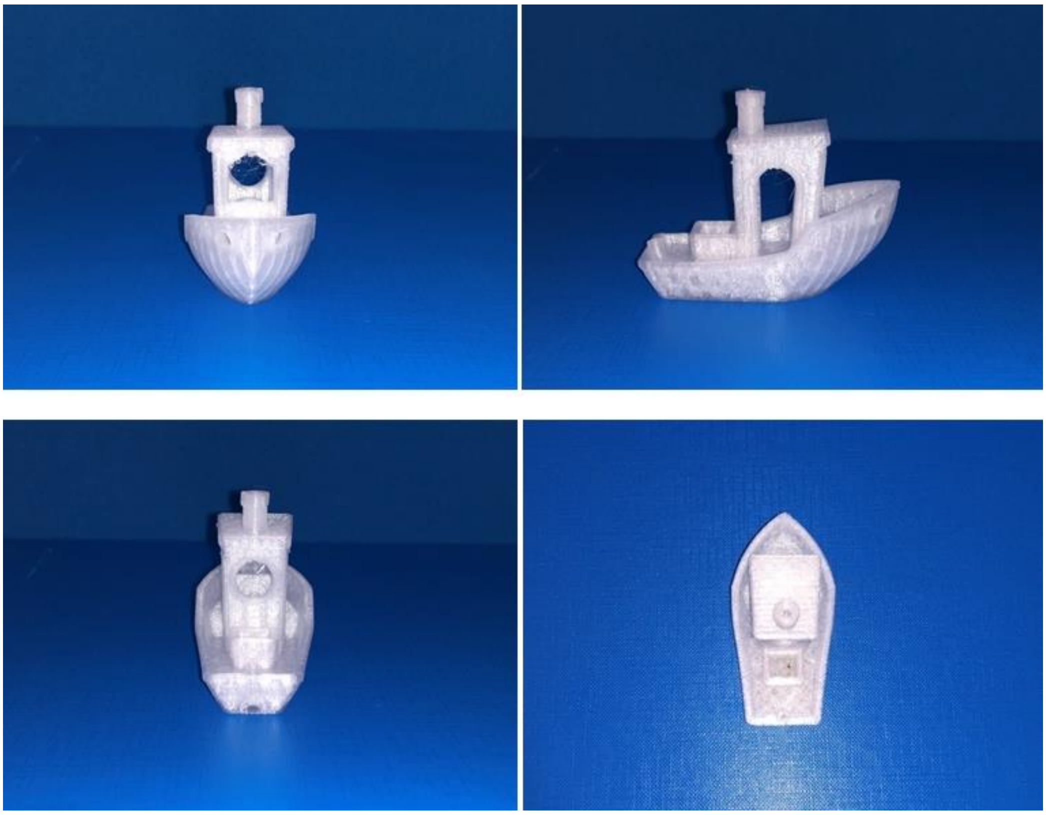

Figure 80. The first print of PC-Plus

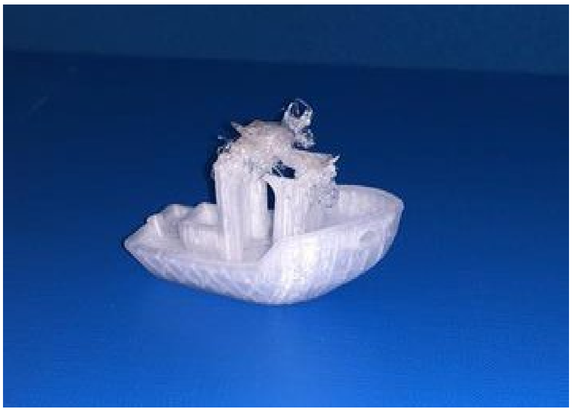

Figure 81. The second print of PC-Plus

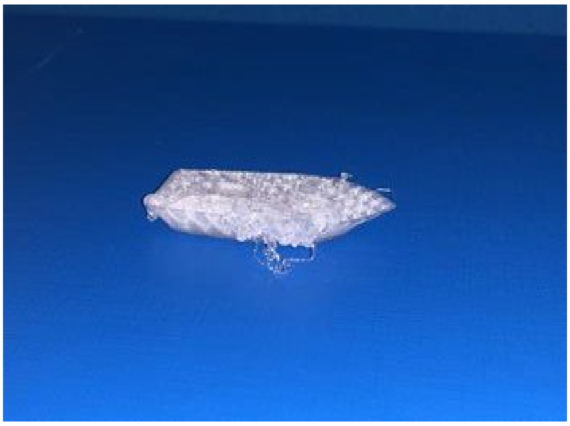

Figure 82. The third print of PC-Plus

Figure 83. The 4th print of PC-Plus

Figure 84. The first print of TPU green

Figure 85. The second print of TPU green

Figure 86. The third print of TPU green

Figure 87. The 4th print of TPU green

Figure 88. The 5th print of TPU green

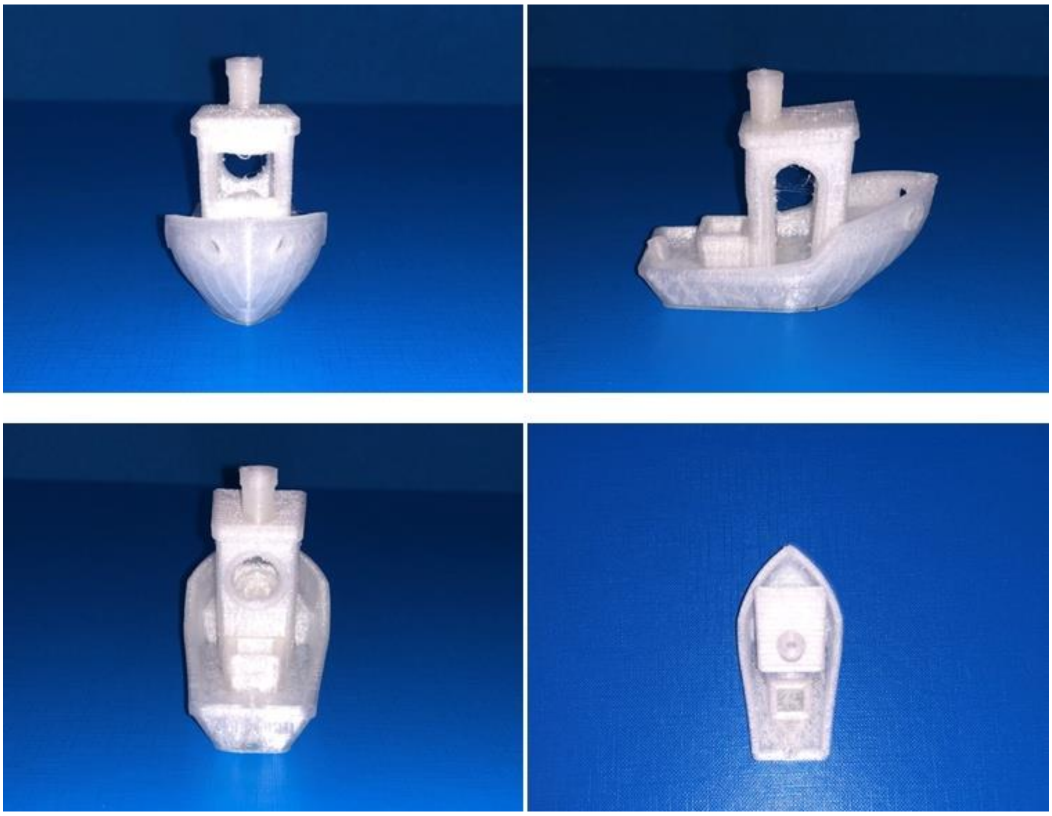

Figure 89. The first print of TPU transparent

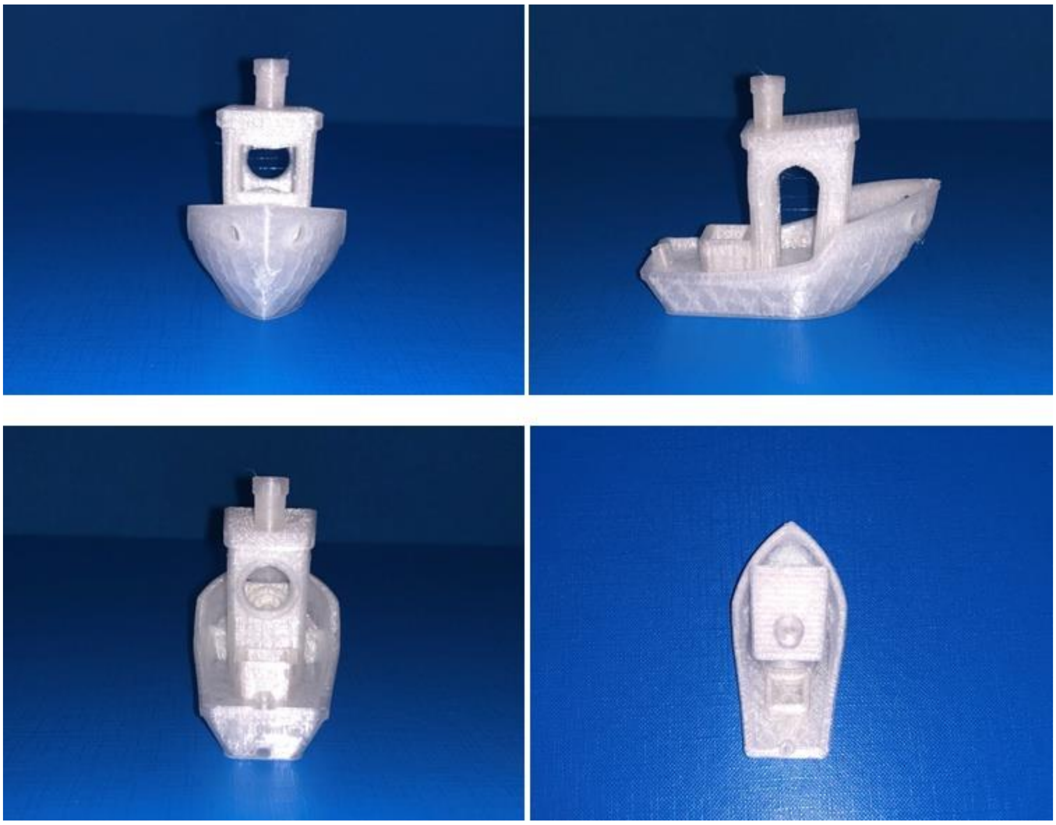

Figure 90. The second print of TPU transparent

Figure 91. The first print of ASA black

Figure 92. The second print of ASA black

Figure 93. The third print of ASA black

Figure 94. The first print of ASA natural

Figure 95. The second print of ASA natural

Figure 96. The first print of ApolloX

Figure 97. The second print of ApolloX

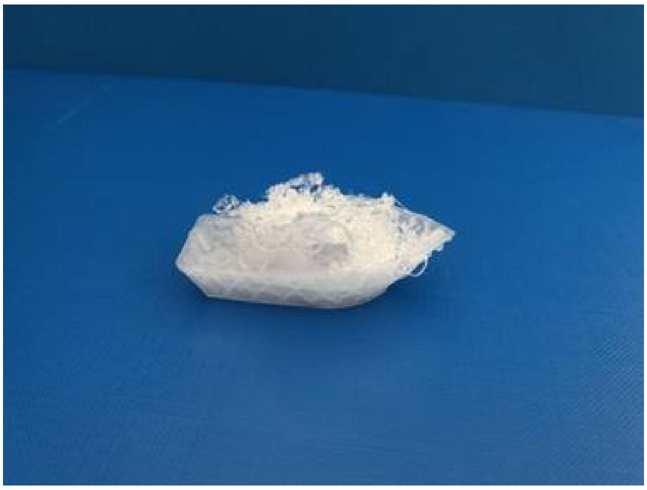

Figure 98. The first print of PP

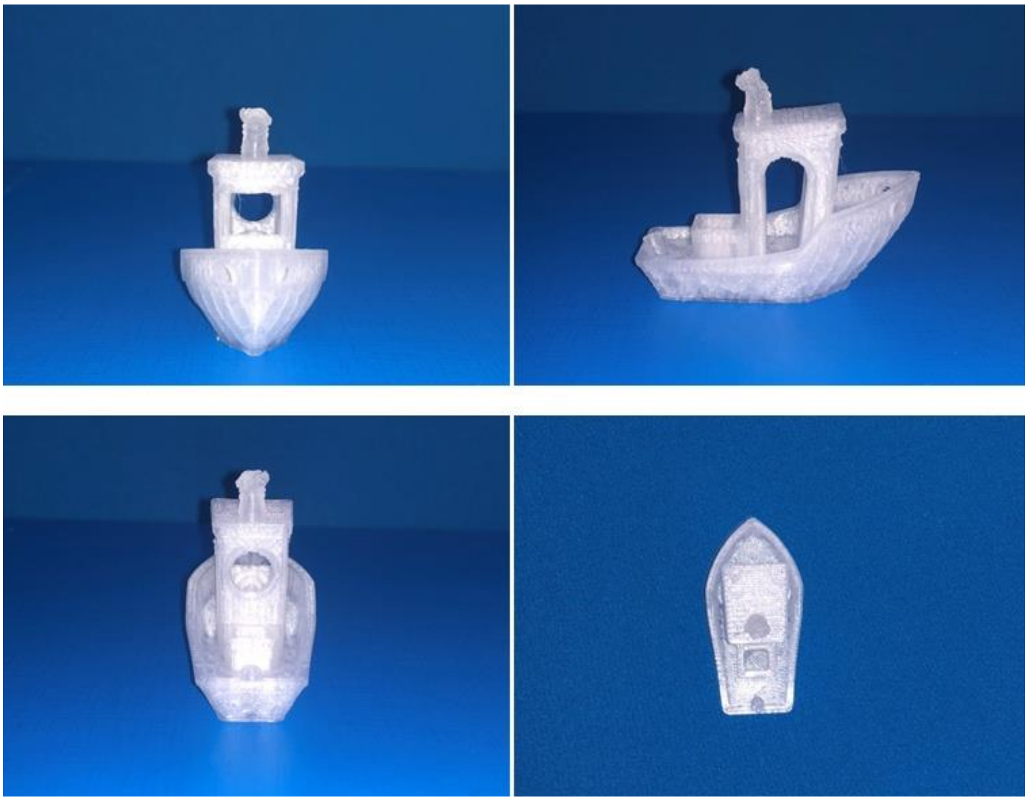

Figure 99. The second print of PP

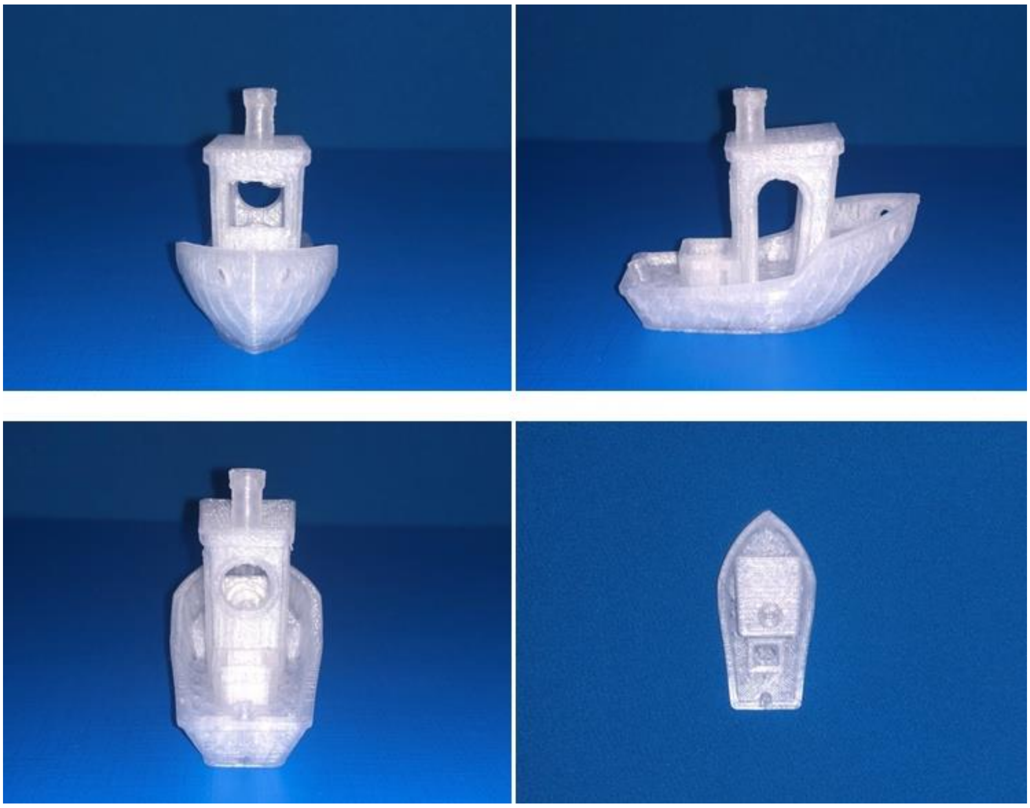

Figure 100. The third print of PP

Figure 101. The first print of Copperfill PLA (AprintaPro)

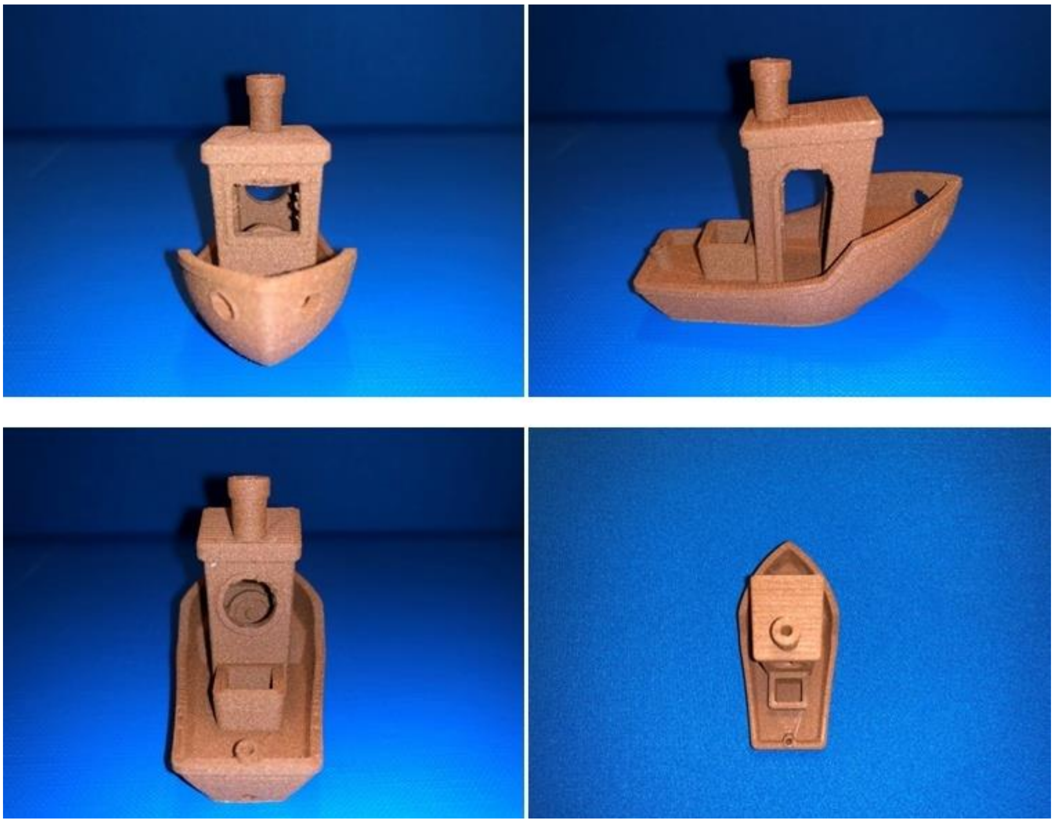

Figure 102. The second print of Copperfill PLA (AprintaPro)

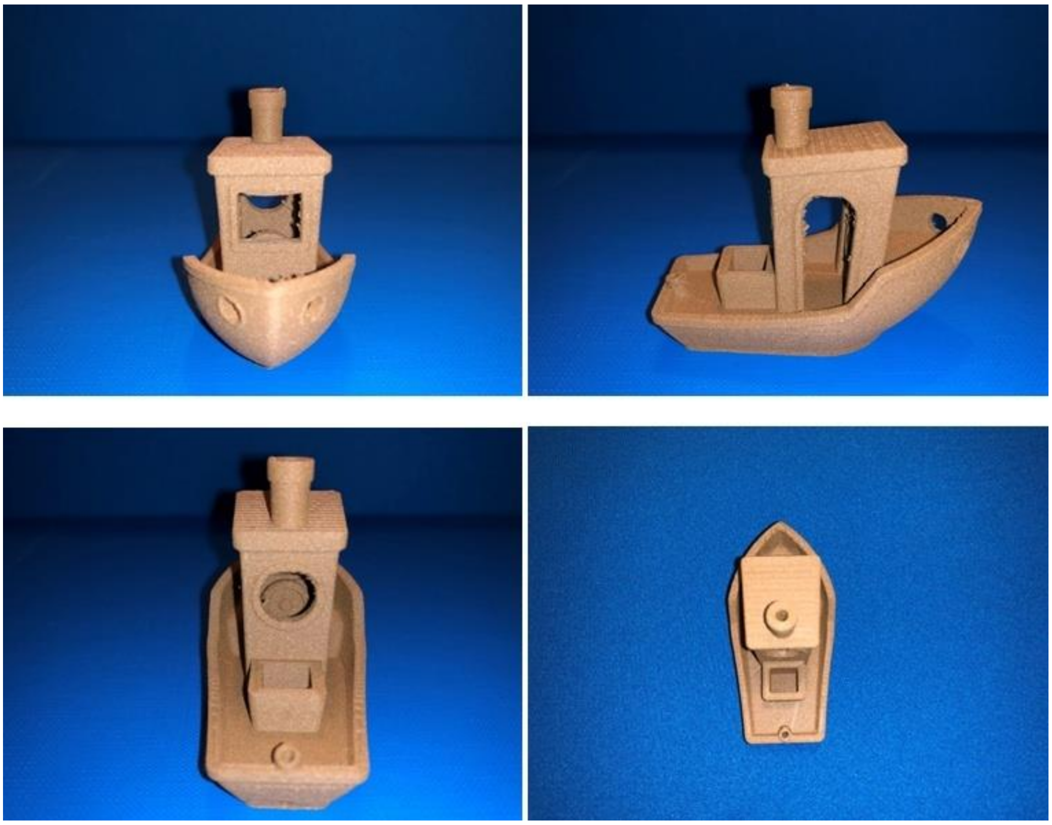

Figure 103. The first print of Bronzefill material

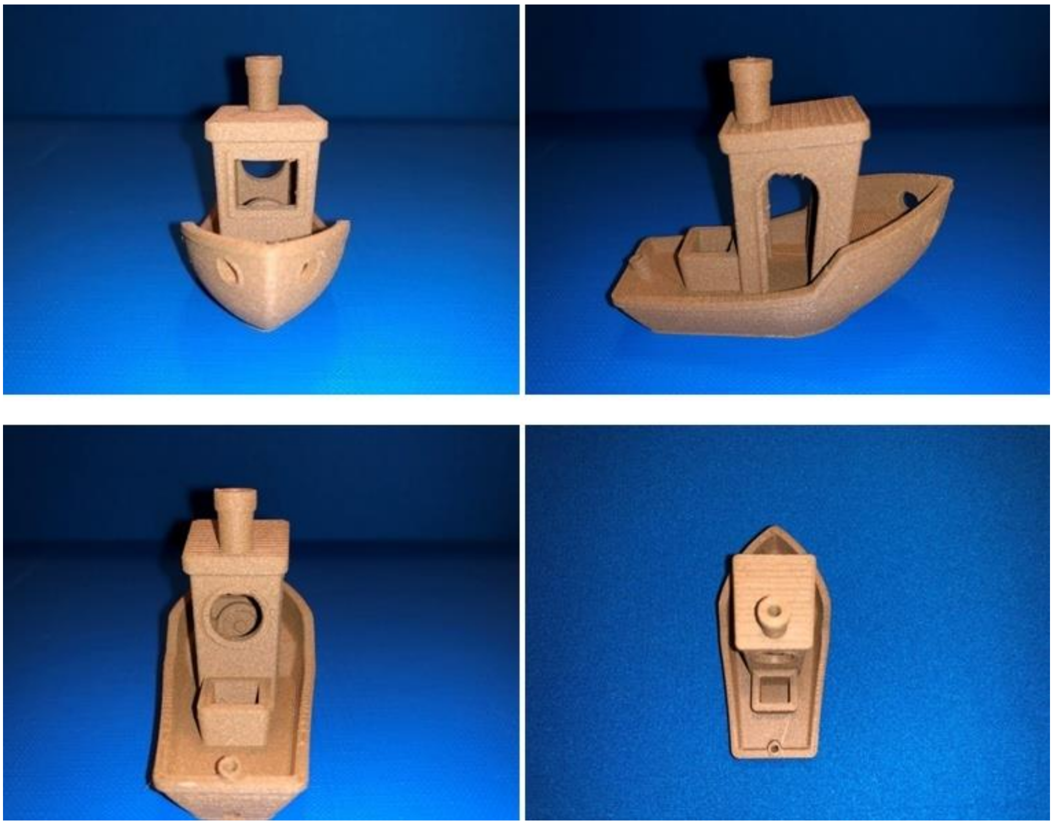

Figure 104. The second print of Bronzefill material

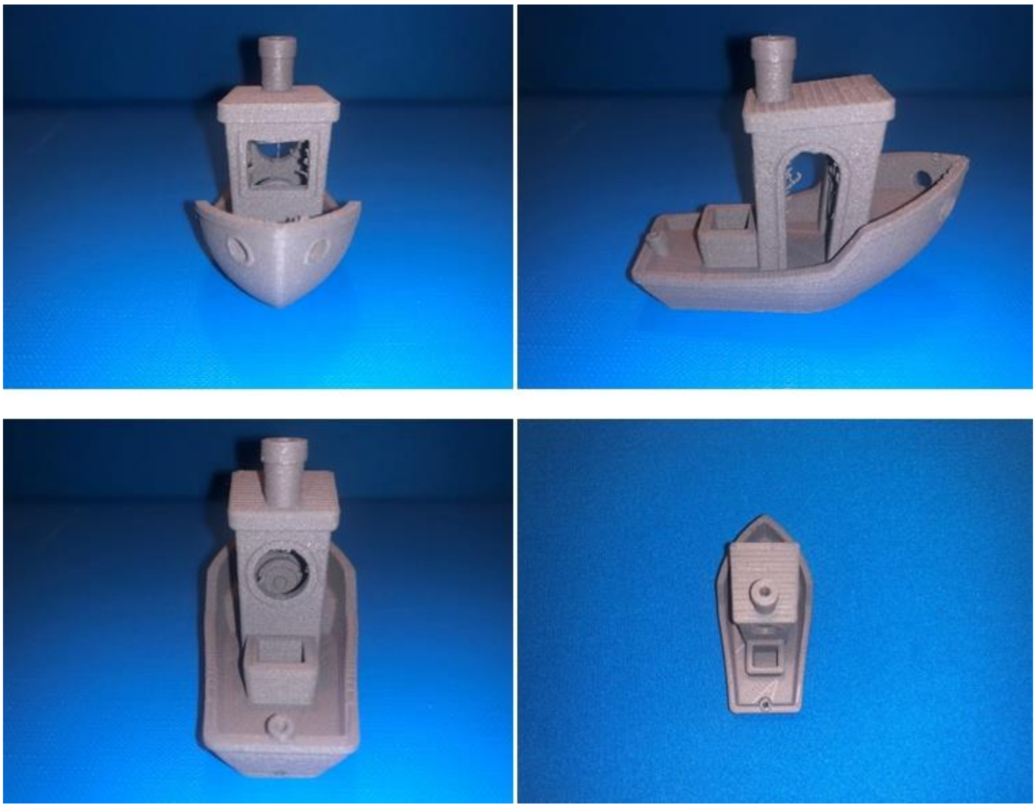

Figure 105. The first print of steelFill material

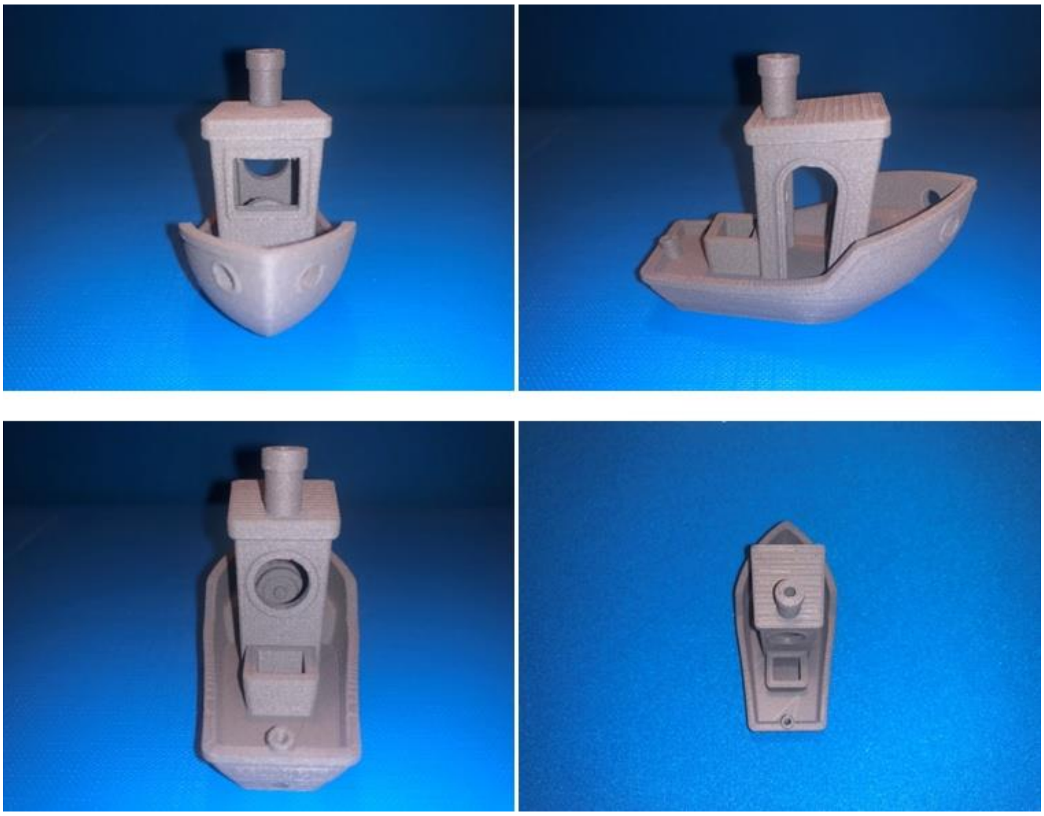

Figure 106. The second print of steelFill material

Figure 107. 3DBenchy printed with copperFill PLA (colorFabb)

Figure 108. The first print of GreenTEC Pro natural

Figure 109. The second print of GreenTEC Pro natural

Figure 110. The first print of GreenTEC Pro carbon

Figure 111. The second print of GreenTEC Pro carbon

Figure 112. The first print of CarbonFil material

Figure 113. The second print of CarbonFil material

Figure 114. The third print of CarbonFil material

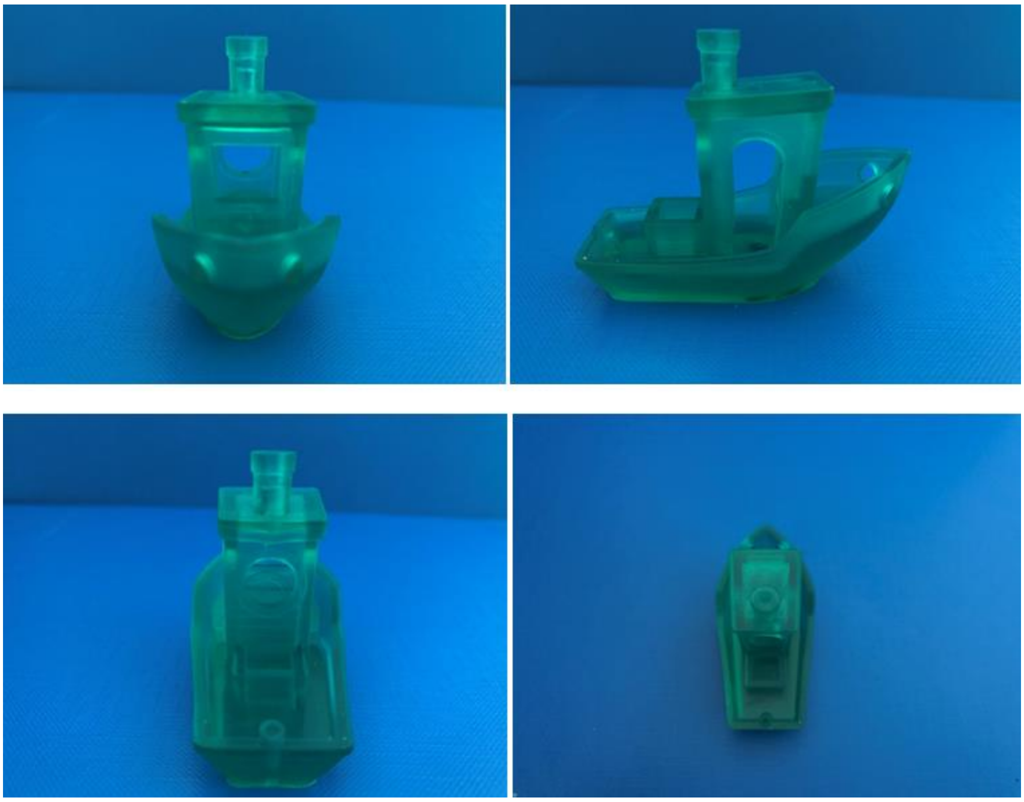

Figure 115. 3DBenchy printed with Anycubic Resin green

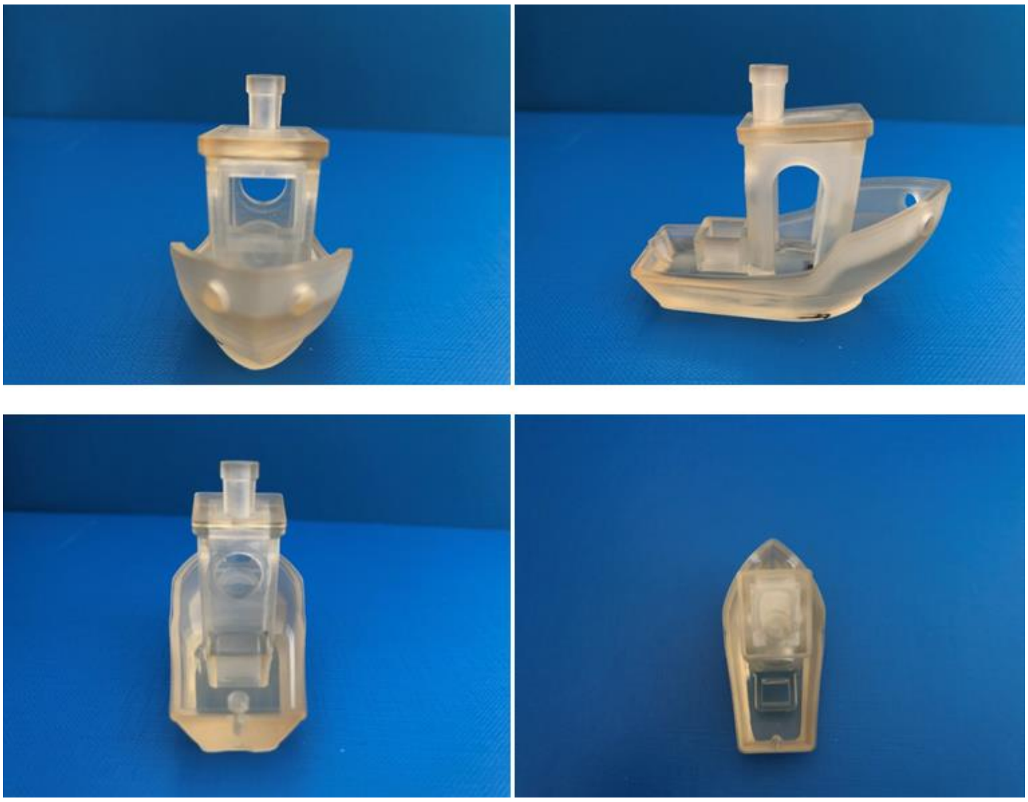

Figure 116. 3DBenchy printed with PrimaCreator Resin clear

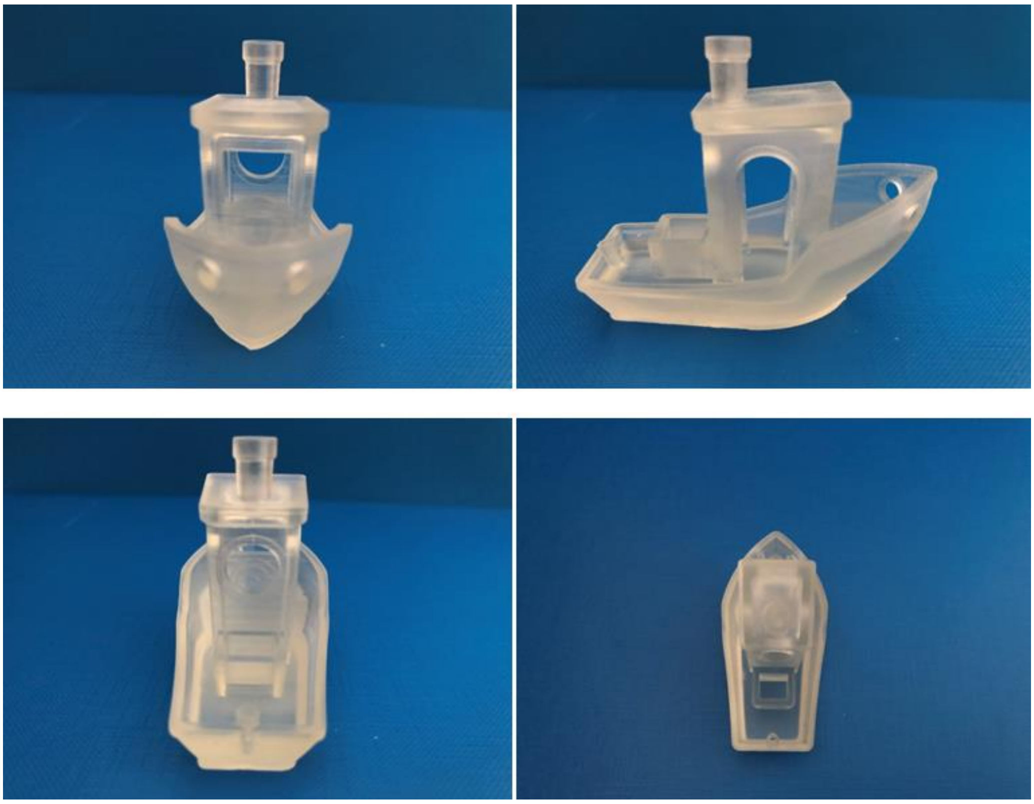

Figure 117. 3DBenchy printed with Wanhao Resin water washable clear

Figure 118. 3DBenchy printed with PhotoCentric3D UV Flexible Resin clear

8 Appendix A2

8.1 Data of Hounsfield units measurement

The complete and detailed data of Hounsfield units measurements of all the cylinders corresponding to Table 17.

The positions of all the cylinders on the plate are shown in Figure 31.

Table 24. Hounsfield units measurement of the cylinders on Plate C top side (include the HU of water)

Material	Slice	Position	Hounsfield units under different kV									
			70 kV		80 kV		100 kV		120 kV		140 kV	
			Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
StoneFil(Form futura, 285STONEFIL-PCLAY-0500)	**1**	**C 1**	**1555.65**	**31.39**	**1383.67**	**23.09**	**1162.36**	**17.18**	**1049.27**	**16.83**	**970.34**	**15.71**
	2	C 1	1592.42	26.36	1414.06	23.18	1186.33	16.73	1068.15	15.75	988.66	13.77
	3	C 1	1601.1	26.75	1418.3	19.66	1193.09	15.62	1071.99	14.87	992.05	12.11
	4	C 1	1600.95	25.56	1420.99	19.66	1194.57	14.72	1070.83	14.86	992.36	13.52
	5	C 1	1604.24	25.67	1421.16	17.99	1195.37	15.51	1072.22	15.04	991.79	13.24
	6	C 1	1603.59	29.05	1419.36	17.96	1196.09	15.85	1072.43	14.3	993.04	11.93
	7	C 1	1603.05	26.83	1418.4	20.76	1196.09	15.37	1072.49	14.54	993.46	13.07
	8	C 1	1607.98	28.08	1419.6	19.32	1195.59	16.27	1072.12	14.68	993.74	13.74
	9	C 1	1604.82	25.14	1420.17	19.02	1195.43	14.76	1072.49	14.45	992.84	14.1
	10	C 1	1604.41	28.21	1420.62	20.64	1194.14	15.27	1072.61	13.98	994.3	12.7
	11	C 1	1603.62	25.8	1421.64	20.43	1193.72	14.45	1073.57	11.65	994.7	12.46
	12	C 1	1602.52	26.02	1421.27	18.96	1194.79	15.13	1073.79	13.46	995.16	12.69
	13	C 1	1602.79	25.71	1421.24	17.95	1194.74	15.21	1073.67	14.16	994.11	13.76
	14	C 1	1601.68	26.36	1421.13	19.73	1194.96	14.87	1073.27	13.77	993.14	12.99
	15	C 1	1602.16	26.43	1420.13	18.98	1195.43	14.33	1071.55	14.85	992.81	12.24
	16	C 1	1601.67	23.85	1419.01	18.23	1195.69	14.21	1071.11	13.35	992.3	12.18
	17	C 1	1601.58	23.09	1418.88	21.12	1194.37	14.4	1070.05	13.22	991.69	12.28
Pegasus PP Ultralight(For	**1**	**C 2**	**-136.55**	**14.5**	**-157.05**	**9.48**	**-184.93**	**6.47**	**-198.55**	**6.31**	**-208.21**	**6.32**
	2	C 2	-155.16	15.36	-178.12	11.08	-206.15	5.78	-220.37	7.53	-231.56	5.82

mfutura, 285PEGAPP-NAT-0500)	3	C 2	-174.75	13.3	-197.54	10.45	-224.58	8.4	-237.33	8.12	-248.86	7.32
	4	C 2	-181.28	16.6	-200.07	11.25	-228.15	8.55	-240.23	9.1	-250.94	7.75
	5	C 2	-183.01	14.31	-203.42	10.21	-230.43	8.66	-244.75	7.42	-254.8	8.87
	6	C 2	-183.48	16.67	-207.33	10.7	-231.99	9.22	-246.51	7.35	-256.72	9.14
	7	C 2	-183.26	17.02	-206.95	11.18	-233.26	8.04	-245.38	7.35	-256.22	8.22
	8	C 2	-188.59	14.97	-211.16	10	-238.26	7.88	-250.35	7.55	-260.52	7.84
	9	C 2	-192.89	15.15	-212.04	9.57	-240.23	6.47	-252.03	7.45	-261.72	7.86
	10	C 2	-195.41	15.59	-214.37	9.09	-242.21	6.45	-255.83	6.75	-266.48	6.62
	11	C 2	-199.07	13.87	-220.57	10.56	-246.64	6.25	-258.96	6.19	-268.67	7.24
	12	C 2	-204.53	15.67	-224.43	10.29	-249.86	6.55	-262.78	7.46	-272.39	7.9
	13	C 2	-207.73	17.13	-228.45	9.94	-254.06	7.2	-266.76	6.74	-276.12	8.18
	14	C 2	-205.14	14.62	-226.18	11.43	-252.93	6.62	-265.36	7.04	-274.59	7.79
	15	C 2	-212.92	15.49	-232.76	10.86	-259.1	7.83	-272.43	8.29	-282.88	7.75
	16	C 2	-207.35	15.06	-229.18	10.09	-255.61	8.97	-267.29	7	-276.84	7.78
	17	C 2	-207.67	14.97	-230.92	11.38	-256.73	8.07	-269.23	7.44	-278.66	6.77
PLA(Ultimaker, 1612)	**1**	**C 4**	**195.42**	**19.69**	**200.76**	**11.47**	**204.82**	**8.53**	**207.58**	**8.55**	**208.41**	**7.94**
	2	C 4	199.63	16.57	205.89	11.26	207.87	8.34	212.43	7.92	212.58	6.66
	3	C 4	203.19	15.24	206.87	10.77	209.9	9.09	214.2	8.05	213.36	7.76
	4	C 4	202.44	18.46	205.51	11.61	209.98	8.32	214.44	7.25	214.51	8.15
	5	C 4	203.35	15.13	206.48	10.22	209.65	8.19	214.48	8.01	213.94	7.44
	6	C 4	201.14	20.06	205.33	11.58	208.86	7.19	212.75	8.42	213.49	7.45
	7	C 4	200.28	17.67	206.71	10.7	207.96	9.45	211.67	8.52	212.82	8.05
	8	C 4	200.79	17.72	207.04	12.44	207.49	7.56	212.4	9.17	212.57	8.44
	9	C 4	201.29	17.92	205.85	10.22	207.3	8.84	212.57	8.23	211.64	7.79
	10	C 4	199.53	15.51	204.56	11.87	206.01	7.4	212.64	7.47	211.46	9.2
	11	C 4	198.76	13.58	202.45	12.1	206.55	7.8	212.35	7.29	210.92	8.21
	12	C 4	195.88	17.19	201.25	12.58	207.03	8.24	211.92	8.28	211.14	7.33
	13	C 4	197.82	16.15	204.52	11.23	207.45	8.36	212	8.65	212.74	7.36
	14	C 4	200.74	15.19	204.14	11.36	207.28	10.07	213.52	8.15	212.77	7.99

	15	C 4	201.83	19.04	204.28	9.81	207.57	10.2	212.67	8.74	212.47	7.73
	16	C 4	203.12	14.78	205.53	11.77	208.69	9.48	212.93	7.58	212.5	7.62
	17	C 4	204.5	18.43	206.06	12.83	208.06	10.34	213.55	8.13	212.5	7.63
ApolloX(Form futura, 285APOX-WHITE-0750)	**1**	**C 5**	**84.4**	**15.25**	**91.22**	**12.23**	**98.7**	**7.46**	**103.78**	**8.31**	**104.63**	**6.93**
	2	C 5	84.56	17.16	92.41	13.3	99.89	7.65	103.97	7.82	106.41	7.78
	3	C 5	85.36	16.19	95.04	12.02	99.45	8.06	104.95	7.19	107.35	7.14
	4	C 5	87.23	14.06	94.2	13.24	98.03	8.18	104.03	7.96	106.6	6.55
	5	C 5	88.72	16.84	92.82	13.36	98.94	7.79	105.35	6.94	107.22	7.39
	6	C 5	88.5	17.41	91.79	13.41	99.04	9.37	105.52	7.35	106.96	7.75
	7	C 5	86.63	18	92.17	12.5	99.71	7.88	105.83	8.05	106.41	9.49
	8	C 5	87.48	17.31	92.43	11.57	99.56	8.8	105.76	7.82	106.53	8.79
	9	C 5	85.68	17.72	91.78	13.88	98.67	8.67	105.22	8.66	106.65	9.03
	10	C 5	83.52	16.65	90.23	12.38	98.05	7.79	104.12	8.79	107.55	8.74
	11	C 5	82.85	14.4	91.3	14.08	97.55	9.41	104.38	8.73	105.95	9.14
	12	C 5	85.03	16.27	91.81	12.26	98.87	10.14	104.4	9.36	104.66	9.16
	13	C 5	86.54	19.39	90.85	12.89	98.22	8.37	104.06	7.75	106.38	9.14
	14	C 5	82.87	19.44	91.54	11.1	96.34	7.41	103.17	8.32	104.37	8.36
	15	C 5	79.93	21.81	90.87	12.15	96.25	9.97	103.96	9.38	103.56	7.45
	16	C 5	82.26	17.08	90.95	12.35	97	10.09	103.46	8.02	103.23	7.65
	17	C 5	86.43	22.57	93.37	14.21	98.32	8.74	104.67	8.67	106.44	9.12
Nylon(Ultimaker, 1647)	**1**	**C 7**	**63.7**	**16.41**	**76.66**	**10.72**	**91.3**	**6.88**	**102.5**	**7.25**	**108.15**	**6.88**
	2	C 7	62.8	16.35	76.37	12	91.11	6.81	101.88	7.65	107.38	7.66
	3	C 7	59.5	17.87	76.1	10.17	89	8.17	100.81	8.42	105.04	8.3
	4	C 7	58.26	18.45	74.15	10.97	88.68	6.97	100.25	6.94	104.36	7.07
	5	C 7	55.64	19.53	73.95	11.46	89.66	8.18	101.21	7.43	105.04	8.61
	6	C 7	58.32	14.46	73.01	11.3	90.42	7.36	101.14	7.96	104.69	6.88
	7	C 7	59.55	17.67	74.12	13.61	91.15	7.87	101.16	9.19	104.77	7.7
	8	C 7	56.33	16.7	74.3	11.79	91.23	8.17	100.42	8.24	107.1	8.59
	9	C 7	59.11	17.77	73.95	11.88	89.61	9.66	101.82	7.56	107.62	8.03

	10	C 7	58.72	16.66	74.47	11.9	90.06	8.54	102.52	6.84	107.86	7.35
	11	C 7	59.4	15.12	72.79	11.73	89.35	9.49	101.29	6.96	106.94	6.69
	12	C 7	61.43	18.28	74.73	12.92	88.72	9.14	101.61	8.33	106.61	7.91
	13	C 7	59.49	18.78	75.26	10.79	89.7	7.97	101.79	6.98	105.63	7.86
	14	C 7	57.26	18.42	73.91	11.29	89.14	8.11	100.07	7.93	105.08	9.11
	15	C 7	56.27	20.38	74.3	12.34	89.07	9.57	100.67	9.54	106.34	8.17
	16	C 7	58.52	17.17	71.86	12.99	88.83	8.05	99.9	7.71	106.11	8.67
	17	C 7	62.78	17.29	75.35	13.5	90.33	8.02	101.91	7.78	105.49	8.91
PC-Plus (Polymaker, 70409)	**1**	**C 8**	**113.71**	**15.68**	**125.6**	**7.67**	**135.53**	**6.66**	**145.49**	**6.65**	**148.52**	**6.82**
	2	C 8	114.62	16.59	125.28	11.3	137.4	8.28	147.53	6.78	150.05	6.35
	3	C 8	116.6	15.41	126.15	9.83	137.89	6.73	147.12	6.1	150.39	6.73
	4	C 8	113.62	15.33	126.21	10.12	138.81	6.14	146.72	7.01	150.44	8.03
	5	C 8	112.91	16.99	126.81	12.82	139.08	7.17	146.87	7.89	151.37	6.89
	6	C 8	112.56	14.18	127.53	11.04	138.26	8.06	147.65	7.1	150.44	7.01
	7	C 8	114.35	16.08	124.94	9.1	137.02	7.95	145.84	8.16	149.44	6.58
	8	C 8	114.02	17.21	124.87	10.73	138.08	7.77	145.13	6.42	149.28	7.03
	9	C 8	114.78	14.11	126.77	12.06	138.68	7.42	146.18	6.77	150.04	6.66
	10	C 8	113.82	13.44	128.77	10.97	137.95	8.55	147.43	6.46	150.66	6.96
	11	C 8	114.38	17.87	127.99	8.7	138.03	7.5	147.97	6.82	151.67	5.97
	12	C 8	114.74	16.85	126.95	10.88	137.32	7.19	148.48	7.15	151.87	7.12
	13	C 8	114.36	16.47	126.72	10.11	137.79	5.56	148.2	6.05	150.82	6.65
	14	C 8	113.78	16.51	125.91	10.64	138.75	7.35	146.97	7.08	150.43	6.78
	15	C 8	113.7	17.8	126.36	10.63	138.7	8.62	146.95	8.15	151.07	6.24
	16	C 8	113.3	17.15	127.06	11.08	139.08	7.63	147.87	6.86	150.8	7.01
	17	C 8	116.68	17.72	127.29	11.88	137.47	6.89	148.05	8.2	151.05	6.49
HDglass(Form futura, 285HDGLA-CLEAR-0750)	**1**	**C 10**	**164.31**	**17.48**	**174.68**	**11.91**	**188.6**	**7.23**	**199.08**	**6.92**	**202.98**	**7.68**
	2	C 10	169.87	15.64	183.04	12.32	195.67	8.53	207.11	8.3	209.99	7.99
	3	C 10	171.48	18.14	184	9.88	197.78	8.18	206.75	8.39	210.51	7.8
	4	C 10	170.71	17.87	182.41	10.25	197.41	7.42	208.11	7.23	210.87	6.99

	5	C 10	171.51	16.4	182.47	12.32	195.47	8.44	207.88	8.15	211.04	7.81
	6	C 10	175.91	18.22	183.01	12.64	195.84	9.25	207.79	8.63	210.65	7.85
	7	C 10	171.03	15.95	181.86	13.92	195.87	5.81	205.09	9.24	209.01	8.08
	8	C 10	168.91	19.65	183.36	11.61	196.64	7.85	203.88	9.26	208.52	8.28
	9	C 10	170.11	17.09	183.06	12.77	195.64	9.89	204.83	8.69	208.26	8.95
	10	C 10	170.28	20.29	182.25	9.91	195.39	7.85	206.17	8	209.66	9.37
	11	C 10	170.62	22.12	182.29	12.81	194.87	7.97	205.31	7.98	208.43	8.5
	12	C 10	171.69	18.71	182.23	15.06	194.58	6.9	205.26	9.12	208.39	10.53
	13	C 10	167.82	19.38	182.63	11.7	194.52	8.01	205.28	7.48	207.8	8.38
	14	C 10	169.43	19.52	182.19	14.38	194.83	8.43	204.59	8.78	208.08	6.7
	15	C 10	169.29	19.48	182.41	13.49	195.5	6.42	204.82	8.14	208.93	9.06
	16	C 10	170.4	16.14	182.63	10.87	195.58	7.24	206.12	6.59	208.62	8.1
	17	C 10	169.39	17.77	183.06	11.7	195.32	8.42	205.61	9.34	209.55	9.31
TPU transparent(Extrudr, 9010241152001)	**1**	**C 11**	**63.56**	**16.28**	**75.91**	**11.79**	**89.05**	**8.47**	**100.12**	**7.76**	**103.24**	**8.27**
	2	C 11	59.03	18.19	73.38	13.03	86.55	8.86	97.56	8.63	102.58	8.65
	3	C 11	54.99	16.17	67.63	12.14	80.65	9.75	90.7	11.29	95.54	9.13
	4	C 11	47.44	14.86	59.28	14.57	72.39	11.23	82.57	12.27	87.74	9.12
	5	C 11	44.28	18.65	56.72	12.61	69.76	10.57	80.55	11.09	84.5	10.59
	6	C 11	43	16.41	54.14	14.27	67.91	10.45	78.94	9.44	83.74	11.13
	7	C 11	45.41	17.22	56.6	10.56	70.55	9.54	82.58	9.45	85.96	9.18
	8	C 11	54.74	13.32	65.23	14.1	81.14	10.36	91.79	8.45	94.01	9.4
	9	C 11	58.2	16.52	69.89	12.72	84.91	10.71	95.36	9.16	100.28	9.65
	10	C 11	63.89	23.66	74.47	16.79	89.1	12.33	99.75	10.5	105.83	11.49
	11	C 11	64.12	20.57	76.75	16.99	92.1	10.48	101.54	10.86	107.18	11.18
	12	C 11	70.33	18.44	77.66	15.51	93.74	11.37	104.06	12.69	109.2	11.26
	13	C 11	73.95	21.46	84.96	16.49	100.93	10.39	111.48	11.29	114.81	11.3
	14	C 11	76.85	20.65	90.84	17.09	107.04	10.28	116.96	11.13	119.93	10.56
	15	C 11	74.38	19.09	88.11	14.94	103.85	11.21	112.76	9.65	118.7	9.19
	16	C 11	73.14	15.65	84.16	12.98	100.67	9.56	110.74	7.84	115.95	8.19

	17	C 11	77.17	19.78	88.43	14.55	103.41	10.97	114.19	9.75	117.05	9.73
PLA Sparkly Silver(Eryone, GPLA-SILVER-175-1000)	**1**	**C 12**	**173.43**	**13.97**	**181.13**	**11.09**	**187.56**	**8.82**	**193.75**	**7.52**	**194.3**	**7.4**
	2	C 12	175.04	15.85	181.55	11.8	187.27	8.71	194.21	7.59	195.78	7.96
	3	C 12	170.33	16.32	178.63	12.27	185.63	8.2	192.84	8.72	194.03	8.08
	4	C 12	172.37	17.74	179.66	11.61	186.61	7.75	192.53	8.49	194.45	8.67
	5	C 12	175.66	16.98	179.83	10.38	188.15	8.67	194.07	8.77	196.75	8.59
	6	C 12	177.46	19.44	182.48	11.3	189.38	9	194.89	8.15	197.74	7.9
	7	C 12	180.29	19.68	183.4	11.42	190.82	7.57	196.33	8.34	198.84	6.82
	8	C 12	177.13	17.17	184.53	11.69	191.28	7.58	197.83	7.79	199.1	7.4
	9	C 12	175.94	19.18	185.33	11.36	190.13	8.77	198.04	8.31	199.54	7.81
	10	C 12	175.15	19.37	185.32	11.38	189.87	7.99	196.84	8.59	198.63	6.8
	11	C 12	172.97	14.34	182.6	11.95	189.71	8.03	195.8	8.25	198.32	8.47
	12	C 12	172.39	18.47	182.41	14.88	190.84	8.86	195.82	8.59	199.48	8.78
	13	C 12	172.57	18.83	182.02	13.28	188.82	9.06	196.04	8.73	198.18	8.53
	14	C 12	174.12	17.87	183.14	13.17	189.2	9.9	196.36	8.74	197.97	9.82
	15	C 12	173.34	18.85	181.79	14.08	189.87	9.2	194.16	7.9	198.06	9.07
	16	C 12	172.66	19.56	181.96	14.12	188.4	7.91	194.84	8.97	196.87	8.73
	17	C 12	169.93	21.3	181.06	12.8	185.36	10.23	192.36	8.85	194.15	9.12
HU of water on the periphery of the plate	1	Water_p	6.37	13.84	6.29	9.46	5.38	7.14	7.6	6.95	5.81	6.82
	2	Water_p	7.52	14.6	7.61	9.4	5.94	6.92	7.5	6.45	6.02	6.92
	3	Water_p	7.27	14	7.97	10.68	5.65	7.58	7.05	7.08	5.45	7.21
	4	Water_p	7.53	15.29	7.46	10.38	5.84	7.89	6.65	6.75	5.29	6.48
	5	Water_p	8.48	14.78	7.41	10.12	5.37	7.25	7	6.62	5.25	7.24
	6	Water_p	9.06	15.41	6.91	9.65	5.55	7.87	7.06	7.45	5.62	6.93
	7	Water_p	7.06	14.29	7.04	10.6	6.1	7.55	7.49	6.92	5.54	7.1
	8	Water_p	7.45	14.54	7.76	10.49	6.21	7.17	8	6.89	6.19	7.46
	9	Water_p	6.53	14.54	7.06	11.73	5.95	7.28	8.67	7.37	6.59	6.92
	10	Water_p	7.39	14.16	7.15	10.62	6.25	7.3	8	6.88	5.98	6.95
	11	Water_p	7.18	15.17	7.61	10.89	5.45	7.27	7.88	7.18	6.05	6.96

	12	Water_p	6.94	15.41	7.44	11.57	5.73	7.28	7.7	7.01	5.74	6.75
	13	Water_p	8.19	16.01	7.82	11.31	6.14	7.2	8.02	6.7	5.44	7.06
	14	Water_p	8.22	15.15	7.52	10.37	5.81	7.83	6.93	6.57	5.18	7.63
	15	Water_p	6.88	16.13	6.37	11.96	5.67	9.18	7.24	7.25	5.24	7.09
	16	Water_p	7.71	16.35	7.61	10.79	5.78	7.28	8.03	7.34	5.44	6.82
	17	Water_p	9.57	15.62	8.95	10.03	6.25	7.55	7.6	6.72	6.44	7.31
HU of water on the center of the plate	1	Water_c	-2.61	16.79	-3.81	11.74	-4.12	7.47	-2.8	7.13	-3.42	6.97
	2	Water_c	-1.1	17.09	-2.12	10.74	-3.48	7.07	-2.25	7.43	-3	7.59
	3	Water_c	-1.9	18.14	-2.18	12.98	-3.92	8.16	-2	7.84	-3.25	8.1
	4	Water_c	-3.28	19.3	-3.14	11.1	-4.28	8.62	-2.67	7.6	-3.65	6.99
	5	Water_c	-2.37	15.52	-1.87	11.29	-3.85	8.21	-2.3	7.33	-2.65	7.37
	6	Water_c	-3.26	17.47	-2.03	11.52	-3.56	8.33	-2.38	7.73	-3.24	7.17
	7	Water_c	-3.63	17.03	-3.3	11.93	-3.48	7.62	-1.55	7.03	-3.63	6.84
	8	Water_c	-2.73	18.67	-1.94	11.22	-2.89	8.13	-2.57	7.83	-2.81	7.3
	9	Water_c	-2.54	20.15	-2.56	12.59	-3.52	7.41	-2.32	8.3	-2.89	7.59
	10	Water_c	-2.53	19.98	-1.81	11.51	-4.17	7.58	-1.87	7.18	-3.2	7.11
	11	Water_c	-2.26	19.63	-2.21	10.64	-4.03	8.34	-2.13	8.03	-3.8	7.19
	12	Water_c	-1.63	17.12	-1.65	12.52	-3.7	7.87	-1.44	8.04	-3.2	7.44
	13	Water_c	-2.41	18.66	-2.32	11.57	-3.41	8.17	-1.57	7.43	-2.64	7.49
	14	Water_c	-1.66	20.59	-2.53	11.49	-3.88	8.49	-1.72	8.54	-3.06	8.13
	15	Water_c	-2.76	19.51	-2.71	13.02	-3.96	7.78	-2.52	8.42	-3.01	7.92
	16	Water_c	-3.48	16.83	-1.93	12.34	-4.06	7.37	-2.1	7.87	-3.05	7.26
	17	Water_c	-3.06	18.5	-3.46	13.07	-3.9	8.71	-1.55	7.67	-3.46	8.18

Table 25. Hounsfield units measurement of the cylinders on Plate C top side (HU of water subtracted)

Material	Slice	Position	Hounsfield units under different kV									
			70 kV		80 kV		100 kV		120 kV		140 kV	
			Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
StoneFil(Form futura, 285STONEFI L-PCLAY-0500)	**1**	**C 1**	**1549**	**34.3**	**1377**	**25.0**	**1157**	**18.6**	**1042**	**18.2**	**965**	**17.1**
	2	C 1	1585	30.1	1406	25.0	1180	18.1	1061	17.0	983	15.4
	3	C 1	1594	30.2	1410	22.4	1187	17.4	1065	16.5	987	14.1
	4	C 1	1593	29.8	1414	22.2	1189	16.7	1064	16.3	987	15.0
	5	C 1	1596	29.6	1414	20.6	1190	17.1	1065	16.4	987	15.1
	6	C 1	1595	32.9	1412	20.4	1191	17.7	1065	16.1	987	13.8
	7	C 1	1596	30.4	1411	23.3	1190	17.1	1065	16.1	988	14.9
	8	C 1	1601	31.6	1412	22.0	1189	17.8	1064	16.2	988	15.6
	9	C 1	1598	29.0	1413	22.3	1189	16.5	1064	16.2	986	15.7
	10	C 1	1597	31.6	1413	23.2	1188	16.9	1065	15.6	988	14.5
	11	C 1	1596	29.9	1414	23.2	1188	16.2	1066	13.7	989	14.3
	12	C 1	1596	30.2	1414	22.2	1189	16.8	1066	15.2	989	14.4
	13	C 1	1595	30.3	1413	21.2	1189	16.8	1066	15.7	989	15.5
	14	C 1	1593	30.4	1414	22.3	1189	16.8	1066	15.3	988	15.1
	15	C 1	1595	31.0	1414	22.4	1190	17.0	1064	16.5	988	14.1
	16	C 1	1594	28.9	1411	21.2	1190	16.0	1063	15.2	987	14.0
	17	C 1	1592	27.9	1410	23.4	1188	16.3	1062	14.8	985	14.3
Pegasus PP Ultralight (Formfutura,	**1**	**C 2**	**-143**	**20.0**	**-163**	**13.4**	**-190**	**9.6**	**-206**	**9.4**	**-214**	**9.3**
	2	C 2	-163	21.2	-186	14.5	-212	9.0	-228	9.9	-238	9.0
	3	C 2	-182	19.3	-206	14.9	-230	11.3	-244	10.8	-254	10.3

285PEGAPP-NAT-0500)	4	C 2	-189	22.6	-208	15.3	-234	11.6	-247	11.3	-256	10.1
	5	C 2	-191	20.6	-211	14.4	-236	11.3	-252	9.9	-260	11.4
	6	C 2	-193	22.7	-214	14.4	-238	12.1	-254	10.5	-262	11.5
	7	C 2	-190	22.2	-214	15.4	-239	11.0	-253	10.1	-262	10.9
	8	C 2	-196	20.9	-219	14.5	-244	10.7	-258	10.2	-267	10.8
	9	C 2	-199	21.0	-219	15.1	-246	9.7	-261	10.5	-268	10.5
	10	C 2	-203	21.1	-222	14.0	-248	9.7	-264	9.6	-272	9.6
	11	C 2	-206	20.6	-228	15.2	-252	9.6	-267	9.5	-275	10.0
	12	C 2	-211	22.0	-232	15.5	-256	9.8	-270	10.2	-278	10.4
	13	C 2	-216	23.4	-236	15.1	-260	10.2	-275	9.5	-282	10.8
	14	C 2	-213	21.1	-234	15.4	-259	10.3	-272	9.6	-280	10.9
	15	C 2	-220	22.4	-239	16.2	-265	12.1	-280	11.0	-288	10.5
	16	C 2	-215	22.2	-237	14.8	-261	11.6	-275	10.1	-282	10.3
	17	C 2	-217	21.6	-240	15.2	-263	11.1	-277	10.0	-285	10.0
	1	**C 4**	**189**	**24.1**	**194**	**14.9**	**199**	**11.1**	**200**	**11.0**	**203**	**10.5**
	2	C 4	192	22.1	198	14.7	202	10.8	205	10.2	207	9.6
	3	C 4	196	20.7	199	15.2	204	11.8	207	10.7	208	10.6
	4	C 4	195	24.0	198	15.6	204	11.5	208	9.9	209	10.4
	5	C 4	195	21.2	199	14.4	204	10.9	207	10.4	209	10.4
	6	C 4	192	25.3	198	15.1	203	10.7	206	11.2	208	10.2
	7	C 4	193	22.7	200	15.1	202	12.1	204	11.0	207	10.7
PLA(Ultimaker, 1612)	8	C 4	193	22.9	199	16.3	201	10.4	204	11.5	206	11.3
	9	C 4	195	23.1	199	15.6	201	11.5	204	11.0	205	10.4
	10	C 4	192	21.0	197	15.9	200	10.4	205	10.2	205	11.5
	11	C 4	192	20.4	195	16.3	201	10.7	204	10.2	205	10.8
	12	C 4	189	23.1	194	17.1	201	11.0	204	10.8	205	10.0
	13	C 4	190	22.7	197	15.9	201	11.0	204	10.9	207	10.2
	14	C 4	193	21.5	197	15.4	201	12.8	207	10.5	208	11.0
	15	C 4	195	25.0	198	15.5	202	13.7	205	11.4	207	10.5

	16	C 4	195	22.0	198	16.0	203	12.0	205	10.6	207	10.2
	17	C 4	195	24.2	197	16.3	202	12.8	206	10.5	206	10.6
ApolloX(Form futura, 285APOX-WHITE-0750)	**1**	**C 5**	**78**	**20.6**	**85**	**15.5**	**93**	**10.3**	**96**	**10.8**	**99**	**9.7**
	2	C 5	77	22.5	85	16.3	94	10.3	96	10.1	100	10.4
	3	C 5	78	21.4	87	16.1	94	11.1	98	10.1	102	10.1
	4	C 5	80	20.8	87	16.8	92	11.4	97	10.4	101	9.2
	5	C 5	80	22.4	85	16.8	94	10.6	98	9.6	102	10.3
	6	C 5	79	23.3	85	16.5	93	12.2	98	10.5	101	10.4
	7	C 5	80	23.0	85	16.4	94	10.9	98	10.6	101	11.9
	8	C 5	80	22.6	85	15.6	93	11.4	98	10.4	100	11.5
	9	C 5	79	22.9	85	18.2	93	11.3	97	11.4	100	11.4
	10	C 5	76	21.9	83	16.3	92	10.7	96	11.2	102	11.2
	11	C 5	76	20.9	84	17.8	92	11.9	97	11.3	100	11.5
	12	C 5	78	22.4	84	16.9	93	12.5	97	11.7	99	11.4
	13	C 5	78	25.1	83	17.1	92	11.0	96	10.2	101	11.5
	14	C 5	75	24.6	84	15.2	91	10.8	96	10.6	99	11.3
	15	C 5	73	27.1	85	17.0	91	13.6	97	11.9	98	10.3
	16	C 5	75	23.6	83	16.4	91	12.4	95	10.9	98	10.2
	17	C 5	77	27.4	84	17.4	92	11.5	97	11.0	100	11.7
Nylon(Ultimaker, 1647)	**1**	**C 7**	**57**	**21.5**	**70**	**14.3**	**86**	**9.9**	**95**	**10.0**	**102**	**9.7**
	2	C 7	55	21.9	69	15.2	85	9.7	94	10.0	101	10.3
	3	C 7	52	22.7	68	14.7	83	11.1	94	11.0	100	11.0
	4	C 7	51	24.0	67	15.1	83	10.5	94	9.7	99	9.6
	5	C 7	47	24.5	67	15.3	84	10.9	94	10.0	100	11.2
	6	C 7	49	21.1	66	14.9	85	10.8	94	10.9	99	9.8
	7	C 7	52	22.7	67	17.3	85	10.9	94	11.5	99	10.5
	8	C 7	49	22.1	67	15.8	85	10.9	92	10.7	101	11.4
	9	C 7	53	23.0	67	16.7	84	12.1	93	10.6	101	10.6
	10	C 7	51	21.9	67	15.9	84	11.2	95	9.7	102	10.1

	11	C 7	52	21.4	65	16.0	84	12.0	93	10.0	101	9.7
	12	C 7	54	23.9	67	17.3	83	11.7	94	10.9	101	10.4
	13	C 7	51	24.7	67	15.6	84	10.7	94	9.7	100	10.6
	14	C 7	49	23.8	66	15.3	83	11.3	93	10.3	100	11.9
	15	C 7	49	26.0	68	17.2	83	13.3	93	12.0	101	10.8
	16	C 7	51	23.7	64	16.9	83	10.9	92	10.6	101	11.0
	17	C 7	53	23.3	66	16.8	84	11.0	94	10.3	99	11.5
PC-Plus (Polymaker, 70409)	**1**	**C 8**	**107**	**20.9**	**119**	**12.2**	**130**	**9.8**	**138**	**9.6**	**143**	**9.6**
	2	C 8	107	22.1	118	14.7	131	10.8	140	9.4	144	9.4
	3	C 8	109	20.8	118	14.5	132	10.1	140	9.3	145	9.9
	4	C 8	106	21.7	119	14.5	133	10.0	140	9.7	145	10.3
	5	C 8	104	22.5	119	16.3	134	10.2	140	10.3	146	10.0
	6	C 8	104	20.9	121	14.7	133	11.3	141	10.3	145	9.9
	7	C 8	107	21.5	118	14.0	131	11.0	138	10.7	144	9.7
	8	C 8	107	22.5	117	15.0	132	10.6	137	9.4	143	10.3
	9	C 8	108	20.3	120	16.8	133	10.4	138	10.0	143	9.6
	10	C 8	106	19.5	122	15.3	132	11.2	139	9.4	145	9.8
	11	C 8	107	23.4	120	13.9	133	10.4	140	9.9	146	9.2
	12	C 8	108	22.8	120	15.9	132	10.2	141	10.0	146	9.8
	13	C 8	106	23.0	119	15.2	132	9.1	140	9.0	145	9.7
	14	C 8	106	22.4	118	14.9	133	10.7	140	9.7	145	10.2
	15	C 8	107	24.0	120	16.0	133	12.6	140	10.9	146	9.4
	16	C 8	106	23.7	119	15.5	133	10.5	140	10.0	145	9.8
	17	C 8	107	23.6	118	15.5	131	10.2	140	10.6	145	9.8
HDglass(Form futura, 285HDGLA-CLEAR-0750)	**1**	**C 10**	**167**	**24.2**	**178**	**16.7**	**193**	**10.4**	**202**	**9.9**	**206**	**10.4**
	2	C 10	171	23.2	185	16.3	199	11.1	209	11.1	213	11.0
	3	C 10	173	25.7	186	16.3	202	11.6	209	11.5	214	11.2
	4	C 10	174	26.3	186	15.1	202	11.4	211	10.5	215	9.9
	5	C 10	174	22.6	184	16.7	199	11.8	210	11.0	214	10.7

	6	C 10	179	25.2	185	17.1	199	12.4	210	11.6	214	10.6
	7	C 10	175	23.3	185	18.3	199	9.6	207	11.6	213	10.6
	8	C 10	172	27.1	185	16.1	200	11.3	206	12.1	211	11.0
	9	C 10	173	26.4	186	17.9	199	12.4	207	12.0	211	11.7
	10	C 10	173	28.5	184	15.2	200	10.9	208	10.7	213	11.8
	11	C 10	173	29.6	185	16.7	199	11.5	207	11.3	212	11.1
	12	C 10	173	25.4	184	19.6	198	10.5	207	12.2	212	12.9
	13	C 10	170	26.9	185	16.5	198	11.4	207	10.5	210	11.2
	14	C 10	171	28.4	185	18.4	199	12.0	206	12.2	211	10.5
	15	C 10	172	27.6	185	18.7	199	10.1	207	11.7	212	12.0
	16	C 10	174	23.3	185	16.4	200	10.3	208	10.3	212	10.9
	17	C 10	172	25.7	187	17.5	199	12.1	207	12.1	213	12.4
TPU transparent(Extrudr, 9010241152001)	**1**	**C 11**	**66**	**23.4**	**80**	**16.6**	**93**	**11.3**	**103**	**10.5**	**107**	**10.8**
	2	C 11	60	25.0	76	16.9	90	11.3	100	11.4	106	11.5
	3	C 11	57	24.3	70	17.8	85	12.7	93	13.7	99	12.2
	4	C 11	51	24.4	62	18.3	77	14.2	85	14.4	91	11.5
	5	C 11	47	24.3	59	16.9	74	13.4	83	13.3	87	12.9
	6	C 11	46	24.0	56	18.3	71	13.4	81	12.2	87	13.2
	7	C 11	49	24.2	60	15.9	74	12.2	84	11.8	90	11.4
	8	C 11	57	22.9	67	18.0	84	13.2	94	11.5	97	11.9
	9	C 11	61	26.1	72	17.9	88	13.0	98	12.4	103	12.3
	10	C 11	66	31.0	76	20.4	93	14.5	102	12.7	109	13.5
	11	C 11	66	28.4	79	20.0	96	13.4	104	13.5	111	13.3
	12	C 11	72	25.2	79	19.9	97	13.8	106	15.0	112	13.5
	13	C 11	76	28.4	87	20.1	104	13.2	113	13.5	117	13.6
	14	C 11	79	29.2	93	20.6	111	13.3	119	14.0	123	13.3
	15	C 11	77	27.3	91	19.8	108	13.6	115	12.8	122	12.1
	16	C 11	77	23.0	86	17.9	105	12.1	113	11.1	119	10.9
	17	C 11	80	27.1	92	19.6	107	14.0	116	12.4	121	12.7

PLA Sparkly Silver(Eryone, GPLA-SILVER-175-1000)	**1**	**C 12**	**176**	**21.8**	**185**	**16.1**	**192**	**11.6**	**197**	**10.4**	**198**	**10.2**
	2	C 12	176	23.3	184	16.0	191	11.2	196	10.6	199	11.0
	3	C 12	172	24.4	181	17.9	190	11.6	195	11.7	197	11.4
	4	C 12	176	26.2	183	16.1	191	11.6	195	11.4	198	11.1
	5	C 12	178	23.0	182	15.3	192	11.9	196	11.4	199	11.3
	6	C 12	181	26.1	185	16.1	193	12.3	197	11.2	201	10.7
	7	C 12	184	26.0	187	16.5	194	10.7	198	10.9	202	9.7
	8	C 12	180	25.4	186	16.2	194	11.1	200	11.0	202	10.4
	9	C 12	178	27.8	188	17.0	194	11.5	200	11.7	202	10.9
	10	C 12	178	27.8	187	16.2	194	11.0	199	11.2	202	9.8
	11	C 12	175	24.3	185	16.0	194	11.6	198	11.5	202	11.1
	12	C 12	174	25.2	184	19.4	195	11.9	197	11.8	203	11.5
	13	C 12	175	26.5	184	17.6	192	12.2	198	11.5	201	11.4
	14	C 12	176	27.3	186	17.5	193	13.0	198	12.2	201	12.7
	15	C 12	176	27.1	185	19.2	194	12.0	197	11.5	201	12.0
	16	C 12	176	25.8	184	18.8	192	10.8	197	11.9	200	11.4
	17	C 12	173	28.2	185	18.3	189	13.4	194	11.7	198	12.3

Table 26. Hounsfield units measurement of the cylinders on Plate C bottom side (include the HU of water)

Material	Slice	Position	Hounsfield units under different kV									
			70 kV		80 kV		100 kV		120 kV		140 kV	
			Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Vinyl 303 (Fillamentum, VIN303_285_nat)	**1**	**C 1**	**1818.65**	**36.66**	**1539.93**	**29.74**	**1199.11**	**23.1**	**1011.18**	**19.24**	**890.75**	**16.98**
	2	C 1	1833.19	36.39	1550.14	27.49	1209.85	22.76	1018.3	19.31	897.65	17.4
	3	C 1	1833.77	34.45	1550.79	29.94	1213.72	22.78	1020.02	19.02	899.51	16.41
	4	C 1	1836.16	35.42	1554.38	29.14	1211.19	21.92	1021.52	18.92	900.24	17.72
	5	C 1	1835.45	33.7	1551.41	27.69	1210.4	21.04	1021.03	20.05	900.84	16.24
	6	C 1	1826.24	35.29	1547.38	28.62	1207.38	22.28	1020.28	19.08	901.41	15.68
	7	C 1	1818.09	36.66	1534.67	29.42	1202.52	22.21	1011.3	20.29	893.3	17.32
	8	C 1	1801.18	37.93	1520.1	29.74	1188.06	22.01	995.82	20.58	875.65	17.44
	9	C 1	1790.9	31.32	1506.15	25.61	1173.57	19.43	983.33	17.01	863.77	14.68
	10	C 1	1778.87	33.19	1498.82	25.17	1161.24	18.99	980.81	16.02	863.28	15.23
	11	C 1	1769.48	33.89	1501.38	28.93	1158.34	20.8	982.48	14.35	866.84	15.71
	12	C 1	1775.63	38.39	1503.99	28.27	1172.57	21.43	983.52	18.13	865.21	17.26
	13	C 1	1792.95	34.38	1519.74	29.13	1183.86	19.7	995.08	17.88	874.21	17.76
	14	C 1	1818.96	32.07	1537.83	27.94	1199.31	21.34	1011.84	18.75	891.47	17.2
	15	C 1	1842.55	35.72	1553.04	28.44	1212.1	20.05	1026.91	19.63	903.31	16.08
	16	C 1	1848.47	34.44	1563.84	28.53	1226.04	20.7	1032.84	20.33	908.74	16.13
	17	C 1	1845.05	36.98	1561.68	28.82	1224.03	22.9	1030.12	20.56	907.15	17.84
PP(Verbatim, 55951)	**1**	**C 2**	**-173.33**	**13.2**	**-158.82**	**11.77**	**-139.97**	**6.85**	**-127.59**	**6.99**	**-121.47**	**6.04**
	2	C 2	-178.16	11.12	-161.71	7.66	-140.95	6.86	-128.93	6.34	-123.02	5.43
	3	C 2	-177.69	12.73	-159.6	7.93	-140.04	5.94	-126.56	5.82	-121.34	5.63

	4	C 2	-178.74	11.98	-157.68	7.95	-142.88	5.58	-125.44	6.09	-120.79	5.45
	5	C 2	-176.23	11.67	-157.64	7.31	-144.46	6.41	-125.27	6.56	-118.37	6.29
	6	C 2	-178.09	14.33	-150.06	9.05	-142.94	5.84	-116.92	6.77	-109.87	6.41
	7	C 2	-172.36	14.62	-150.38	8.85	-139.81	5.78	-119.29	5.93	-114.07	5.41
	8	C 2	-171.96	15.45	-163.77	10.37	-142.87	6.41	-131.31	5.94	-128.18	7.64
	9	C 2	-179.61	16.38	-169.89	11.14	-149.99	7.17	-136.93	7.41	-133.16	8.14
	10	C 2	-194.37	16.26	-161.35	11.18	-146	6.99	-128.56	7.03	-125.33	7.68
	11	C 2	-190.49	20.64	-156.37	12.02	-154.08	7.68	-124.93	6.03	-122.67	7.11
	12	C 2	-185.29	16.28	-161.97	10.99	-156.35	8.05	-131.04	7.42	-126.72	7.71
	13	C 2	-183.52	13.33	-167.01	9.57	-145.48	6.28	-136.21	6.94	-129.9	5.93
	14	C 2	-170.18	13.82	-159.67	8.24	-143.14	5.67	-127.89	5.45	-122.72	5.62
	15	C 2	-171.13	11.99	-150.11	7.77	-136.73	6.38	-116.71	4.82	-112.14	5.23
	16	C 2	-181.83	10.95	-156.82	6.7	-125.31	4.98	-121.65	5.47	-117.5	4.56
	17	C 2	-182.62	9.11	-164.69	6.61	-130.03	5.11	-129.86	5.18	-124.5	4.31
CarbonFil(Formfutura, 175CARBFIL-BLCK-0500)	**1**	**C 4**	**102.22**	**13.89**	**116.33**	**11.95**	**129.1**	**10.61**	**138.16**	**9.09**	**143.23**	**8.8**
	2	C 4	104.95	16.99	119.93	12.34	130.91	10.06	141.06	9.37	145.99	9.45
	3	C 4	101.6	18.08	120.92	13.34	126.94	9.41	142.21	10.69	145.03	9.92
	4	C 4	106.07	15.67	122.26	13.91	131.95	9.06	143.76	10.12	147.82	9.85
	5	C 4	105.72	14.08	121.4	13.96	130.35	10.85	143.36	10.27	149.45	11.44
	6	C 4	109.32	18.62	129.27	13.72	128.98	10.86	152.62	10.11	155.7	9.81
	7	C 4	116.01	15.98	133.88	12.99	140.45	9.97	156.95	10.31	159.67	9.33
	8	C 4	125.18	18.41	128.5	14.41	139.2	9.14	149.62	10.04	155.13	10.91
	9	C 4	97.72	17.25	122.31	15.37	130.94	9.97	142.43	10.94	144.4	10.49
	10	C 4	88.63	18.6	121.05	13.4	133.88	11.52	140.3	10.81	142.26	9.8
	11	C 4	91.27	20.19	106.48	13.63	116.12	10.41	126.77	9.74	127.87	8.98
	12	C 4	83.4	17.73	100.6	13.35	94.48	8.98	121.61	9.14	123.15	10.55
	13	C 4	84.59	16.53	102.16	12.18	101.68	8.97	121.15	8.67	122.2	10.08
	14	C 4	128.4	16.77	131.38	11.47	138.3	9.99	153.11	10.17	153.6	11.11
	15	C 4	147.14	13.22	163.94	11.06	184.54	10.82	187.97	10.46	189.73	11.18

	16	C 4	152.52	12.95	168.37	8.85	204.21	7.82	191.77	7.83	193.49	7.41
	17	C 4	134.12	13.97	144.77	11.55	165.14	11.69	165.33	12.53	169.3	11.86
colorFabb_XT(colorFabb, 8719033553019)	**1**	**C 5**	**184.13**	**13.92**	**198.82**	**9.45**	**209.64**	**9.05**	**218.78**	**7.02**	**223.33**	**7.19**
	2	C 5	188.13	14.7	203.88	11.48	214.12	7.72	225.65	7.43	227.49	7.27
	3	C 5	183.18	15.62	204.01	12.58	210.95	7.48	225.68	6.99	229.02	7.65
	4	C 5	181.41	15.95	197.47	8.73	208.25	8.01	218.89	6.94	221.32	7.54
	5	C 5	184.08	15.27	195.19	8.98	206.53	7.7	217.19	7.47	222.25	7.93
	6	C 5	191.28	17.43	209.51	9.94	211.4	7.87	231.78	6.99	236.68	8.06
	7	C 5	202.51	16.86	217.96	11.32	220.69	7.97	239.77	8.06	241.28	7.11
	8	C 5	190.38	22.26	208.17	12.19	212.77	10.18	224.13	9.65	229.72	8.98
	9	C 5	159.28	22.29	202.57	15.33	211.32	12.54	218.84	10.3	220.97	9.3
	10	C 5	184.82	22.06	206.56	15.92	218.89	11.73	223.63	9.8	226.09	9.7
	11	C 5	199.33	26.58	209.32	15.37	219.97	9.89	224.58	9.54	229.13	9.21
	12	C 5	196.41	22.63	202.56	13.49	200.89	11.28	219.04	10.41	223.3	8.63
	13	C 5	181.96	20.82	194.11	12.66	177.64	9.4	209.51	9.71	212.27	10.44
	14	C 5	203.9	16.52	217.06	10.28	220.87	9.37	237.45	7.82	237.22	8.73
	15	C 5	198.7	13.16	213.85	9.13	245.92	7.45	235.84	6.08	236.46	6.6
	16	C 5	184.34	12.33	197.72	7.64	225.61	5.84	220.6	5.3	223.86	6.84
	17	C 5	176.12	9.93	188.36	6.67	204.44	6.16	211.4	5.4	214.76	6.11
EasyWood(Formfutura, 285EWOOD-BIRCH-0500)	**1**	**C 7**	**185.26**	**16.27**	**188.53**	**11.16**	**195.52**	**8.96**	**197.87**	**8.79**	**198.43**	**10.64**
	2	C 7	193.92	19.02	198.66	13.95	200.72	9.51	207.28	8.73	208.29	8.68
	3	C 7	199.66	16.76	206.57	11.15	208.72	8.53	216.42	7.83	215.79	8.69
	4	C 7	197.48	16.17	204.23	10.16	206.21	7.23	214.07	6.73	214.6	6.92
	5	C 7	187.99	18.97	191.32	18.18	193.77	15.02	200.53	14.39	200.17	15.79
	6	C 7	202.82	17.86	197.23	17.11	196.52	13.81	207.36	13.47	207.28	14.15
	7	C 7	220.86	14.8	225.25	13.61	221.95	8.54	234.01	7.56	239.39	7.2
	8	C 7	203.33	21.21	220.74	13.36	221.15	9.54	225.3	7.5	228.24	7.58
	9	C 7	196.13	18.82	210.05	14.25	213.99	10.75	214.36	9.23	215.87	8.8
	10	C 7	211.7	26.72	212.53	13.52	210.79	10.51	215.77	8.53	217.53	9.07

	11	C 7	217.53	21.2	215.41	13.24	209.28	9.9	219.76	9.57	221.94	9.47
	12	C 7	192.52	27.77	192.46	20.38	163.05	16.15	193.72	16.3	198.23	17.87
	13	C 7	188.18	22.34	190.69	18.37	171.92	14.51	193.3	14.07	192.77	13.1
	14	C 7	221.15	15.15	227.94	11.86	242.29	8.72	236.04	7.62	237.24	8.05
	15	C 7	216.79	12.45	238.57	8.68	244.17	7.36	248.8	6.47	247.4	6.88
	16	C 7	208.03	9.59	221.29	8.5	223.24	5.72	230.36	5.12	226.09	5.32
	17	C 7	199.54	8.37	204.4	7.68	209.11	6.35	214.23	5.26	214.89	5.72
glowFill(color Fabb, 8719033555136)	**1**	**C 8**	**497.06**	**17.39**	**454.24**	**12.38**	**397.16**	**9.4**	**366.54**	**9.9**	**342.45**	**8.33**
	2	C 8	500.29	15.35	460.18	14.44	401.3	9.4	369.47	9.3	345.44	8.42
	3	C 8	497.09	16.38	460.52	15.02	401.16	10.18	369.97	9.07	348.67	8.75
	4	C 8	494.52	15.93	455.89	11.57	397.6	9.5	367.13	9.58	344.7	8.19
	5	C 8	499.7	18.3	454.56	11.64	395.77	9.83	367.47	9.58	344.75	8.91
	6	C 8	502.61	21.94	457.94	13.73	398.08	11.13	372.29	11.41	349.09	9.61
	7	C 8	500.43	19.14	463.18	14.4	405.41	9.45	376.43	9.52	356.1	9.19
	8	C 8	492.87	19.55	450.96	12.89	398.19	10.2	362.58	10.6	340.06	8.26
	9	C 8	470.1	21.06	437.67	12.4	385.61	11.31	352.5	10.59	328.86	9.37
	10	C 8	476.97	25.2	443.51	16.41	386.58	9.98	355.44	10.1	333.93	9.33
	11	C 8	486.94	25.34	445.25	13.89	374.2	10.79	356.46	9.67	337.15	8.81
	12	C 8	477.35	23.04	440.48	15.95	354.39	11.91	352.33	9.77	330.96	10.96
	13	C 8	476.11	21.22	435.59	14.93	380.92	11.06	346.39	9.92	322.02	9.87
	14	C 8	500.11	15.3	454.94	13.44	407.21	10.25	367.21	9.74	344.82	8.75
	15	C 8	504.72	15.82	473.84	12.49	422.37	9.71	388.15	8.73	362.68	8.92
	16	C 8	498.68	13.66	466.63	11.13	409.78	8.03	378.56	7.39	352.55	8.03
	17	C 8	492.29	13.96	452.84	10.5	397.65	8.11	365.8	7.9	341.75	7.91
nGen(colorFabb, 8719033554733)	**1**	**C 10**	**102.94**	**16.91**	**113.52**	**11.86**	**131.06**	**7.73**	**139.91**	**7.28**	**143.6**	**6.98**
	2	C 10	103.92	19.53	113.91	10.46	130.72	7.12	141.43	7.89	144.95	7.91
	3	C 10	99.56	17.86	117.11	10.35	129.86	7.72	143.34	7.57	147.44	8.41
	4	C 10	97.94	17.4	114.48	10.97	127.43	7.57	139.77	7.05	145.06	7.91
	5	C 10	105.99	19.34	112.63	9.7	123.59	6.32	137.69	7.25	143.42	8.53

	6	C 10	110.56	15.38	116.64	9.9	127.14	8.38	142.99	8.68	149.32	7.31
	7	C 10	108.34	20.45	124.69	9.03	134.62	9.04	150.48	8.89	159.22	7.69
	8	C 10	103.34	17.51	115.13	11.79	132.34	8.32	138.39	6.99	144.12	9.38
	9	C 10	82.96	21.76	107.7	15.41	119.6	10.59	129.1	8.76	131.98	9.44
	10	C 10	91.75	21.44	114.93	14.06	124.9	9.91	136.16	9.05	140.52	9.64
	11	C 10	108.24	23.73	118.4	12.61	122.28	9.95	140.37	9.92	145.83	9.87
	12	C 10	98.76	22.67	115.24	12.83	98.81	8.84	137.16	8.46	141.4	9.26
	13	C 10	96.05	19.29	103.87	13.71	112.88	8.36	125.26	8.52	129.63	8.97
	14	C 10	114.76	15.93	121.87	10.34	142.07	8.69	147.86	7.44	151.99	6.86
	15	C 10	112.98	13.39	135.11	10.74	158.13	7.38	161.87	7.52	160.81	6.67
	16	C 10	99.13	12.6	118.13	8.53	140.7	5.75	144.59	5.78	145.49	6.27
	17	C 10	94.45	11.44	109.19	7.66	128.62	5.22	135.96	5.44	140.1	5.11
corkFill(color Fabb, 8719033555327)	**1**	**C 11**	**159.5**	**16.47**	**167.39**	**11.01**	**174.35**	**7.56**	**181.62**	**7.6**	**184.07**	**7.6**
	2	C 11	158.46	15.54	166.4	10.93	174.09	8.06	182.2	7.92	184.62	7.43
	3	C 11	157.72	13.79	169.15	12.19	173.41	7.93	185.34	8.6	187.36	8.53
	4	C 11	155.99	13.24	166.9	10.73	171.64	7.96	181.65	7.34	184.47	6.39
	5	C 11	159.72	13.22	165.23	11.05	170.47	6.78	181.64	6.03	183.94	5.9
	6	C 11	157.46	14	171.99	10.75	172.48	8.43	188.47	8.25	195.31	7.31
	7	C 11	158.15	17.43	173.16	12.07	178.45	6.87	190.52	9.22	197.44	7.82
	8	C 11	157.3	22.21	160.61	11.03	172.22	8.04	177.74	8.42	179.54	8.22
	9	C 11	144.64	19.18	152.99	12.31	162.37	9.18	168.96	8.74	169.92	8.84
	10	C 11	131.68	20.89	158.14	15.51	164.5	8.21	174.12	9.41	177.05	8.85
	11	C 11	147.35	27.11	162.5	13.66	157.52	8.69	177.22	9.83	181.54	9.95
	12	C 11	144.36	22.52	158.06	13.83	148.46	9.18	174.81	9.25	178.33	9.93
	13	C 11	145.74	17.79	153.19	10.94	164.3	8.11	167.5	7.76	169.65	8.37
	14	C 11	162.95	15.92	163.84	10.21	170.83	7.63	179.48	6.25	181.64	7.47
	15	C 11	164.93	14.68	177.14	10.02	187.95	7.38	195.8	7.19	195.36	6.8
	16	C 11	155.94	12.71	168.5	7.14	193.7	6.66	185.5	6.62	187.22	6.1
	17	C 11	153.45	12.54	163.5	8.21	180.23	5.7	180	6.25	182.24	5.83

PET(Innofil3d natural, Pet-0301b075)	**1**	**C 12**	**254.26**	**18.44**	**262.96**	**15.21**	**272.2**	**7.63**	**277.77**	**7.14**	**278.72**	**9.2**
	2	C 12	256.58	18.66	264.87	10.91	273.01	7.21	279.15	7.76	280.86	8.18
	3	C 12	257.72	19.79	269.26	12.81	272.21	8.15	282.72	8.84	284.2	8.46
	4	C 12	253.44	19.6	264.88	11.9	270.31	8.16	278.47	8.02	278.51	9.57
	5	C 12	256.06	16.63	260.09	11.4	267.99	7.04	275.56	6.35	277.52	7.64
	6	C 12	260.52	17.86	267.84	12.62	270.48	9.27	283.85	8.28	291.17	7.65
	7	C 12	260.92	19.3	277.23	14.42	277.23	7.66	291.44	7.95	295.18	7.51
	8	C 12	256.15	16.86	259.8	13.75	267.62	8.62	272.52	8.03	273.94	8.84
	9	C 12	230.94	23.1	251.65	15.08	253.14	11.64	264.35	10.55	264.32	9.03
	10	C 12	231.51	23.7	257.54	16.32	262.68	11.6	269.92	10.81	269.63	11.41
	11	C 12	254.3	22.13	260.72	15.38	265.93	9.34	272.78	10.21	275.3	11.23
	12	C 12	249.47	25.42	260.7	16.6	242.62	9.51	272.49	8.5	276.35	10.01
	13	C 12	244.17	23.53	251.93	12.21	249.72	8.76	262.88	9.97	264.7	7.77
	14	C 12	270.36	14.27	271.11	10.52	275.03	8.22	284.74	6.85	285.41	6.38
	15	C 12	269.3	12.91	280.74	10.1	298.81	8.31	295.62	6.55	293.69	6.28
	16	C 12	255.57	14.09	264.53	9.4	293.05	6.35	280.3	6.72	281.45	6.49
	17	C 12	250.37	11.32	261.07	8.34	274.05	6.68	274.83	5.94	276.54	5.35
HU of water on the periphery of the plate	1	Water_p	8.44	14.23	8.08	10.71	8	7.64	8.14	6.86	6.65	7.19
	2	Water_p	8.89	13.21	10.6	10.3	9.56	6.97	10.43	7.41	8.8	7.3
	3	Water_p	8.51	15.14	12.36	10.75	8.45	7.24	12.36	6.77	10.77	7.25
	4	Water_p	6.38	13.79	10.04	8.8	6.05	6.65	10.13	7.07	8.67	6.83
	5	Water_p	11.3	13.64	9.39	9.01	4.81	6.7	9.65	7.33	8.49	7.53
	6	Water_p	14.46	14.39	18.24	10.98	7.35	6.5	18.05	8.26	19.03	7.11
	7	Water_p	19.27	17.51	24.61	12.43	14.27	7.16	25.08	10.32	23.84	10.36
	8	Water_p	14.69	16.71	14.97	14.38	12.67	10.12	12.6	9.92	10.21	9.97
	9	Water_p	5.91	19.08	10.73	16.97	6.75	12.71	6.79	11.6	3.61	12.47
	10	Water_p	5.19	25.51	16.78	16.35	11.72	12.44	14.4	12.16	10.37	12.07
	11	Water_p	16.61	27.27	19.28	16.15	7.7	20.38	16.69	11.73	14.3	12.04
	12	Water_p	11.5	22.21	11.04	14.76	-9.02	10.78	8.42	9.37	7.67	9.54

	13	Water_p	7.41	20.66	3.69	12.48	-6.51	12.82	-0.32	9.2	-0.43	8.45
	14	Water_p	20.59	16.1	18.31	16	16.13	13.93	17.94	14.35	15.71	13.57
	15	Water_p	18.26	11.68	26.6	9.37	27.11	11.86	27.26	7.92	22.4	6.26
	16	Water_p	8.59	10.27	13.16	8.45	21.1	9.03	13.64	6.78	10.25	6.07
	17	Water_p	5.33	10.18	6.26	7.21	10.41	7.75	6.28	5.2	4.36	5.28
HU of water on the center of the plate	1	Water_c	2.3	18.52	2.57	11.45	1.08	10.16	1.97	9.2	0.76	9.77
	2	Water_c	1.34	16.29	1.68	11.82	-0.68	7.66	1.42	6.94	0.55	7.85
	3	Water_c	0.18	17.6	3.81	10.55	-1.6	7.67	3.96	8.28	2.91	7.82
	4	Water_c	-1.52	16.01	-0.63	11.69	-2.56	7.54	1.37	7.35	-0.11	6.84
	5	Water_c	1.16	15.76	-1.23	10.14	-4.94	6.53	0.56	6.79	-0.96	6.8
	6	Water_c	5.56	17.99	6.86	11.14	-1.35	7.63	7.65	7.39	9.91	7.57
	7	Water_c	8.19	17.17	14.26	12.19	6.45	7.8	13.92	8.65	16.57	9.18
	8	Water_c	5.56	19.2	3.13	13.93	2.27	9.27	2.37	8.96	1.58	9.17
	9	Water_c	-11.83	20.85	-4.36	13.44	-7.97	9.24	-5.54	8.96	-8.98	8.52
	10	Water_c	-12.62	21.34	2.47	14.93	-3.2	9.4	1.44	9.12	-0.78	8.89
	11	Water_c	0.6	22.65	6.03	14.62	-3.75	10.81	5.03	9.85	3.49	9.15
	12	Water_c	-3.07	20.64	1.53	13.4	-25.63	8.59	-0.22	8.18	-2.29	9.22
	13	Water_c	-5.49	18.29	-8.56	10.96	-15.21	9.7	-10.6	7.86	-13.1	8.48
	14	Water_c	13.02	15.83	7.49	11.13	5.37	8.56	7.72	8.06	4.69	7.68
	15	Water_c	12.79	13.2	18.35	9.58	21.62	8.51	18.87	7.18	14.07	6.41
	16	Water_c	1.84	11.56	5.41	7.88	14.78	6.8	5.73	6.16	2.55	6.1
	17	Water_c	-3.23	11.46	-1.89	7.79	2.27	5.95	-0.86	5.64	-2.72	5.21

Table 27. Hounsfield units measurement of the cylinders on Plate C bottom side (HU of water subtracted)

Material	**Slice**	**Position**	**Hounsfield units under different kV**									
			70 kV		**80 kV**		**100 kV**		**120 kV**		**140 kV**	
			Mean	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
Vinyl 303 (Fillamentum, VIN303_285_nat)	**1**	**C 1**	**1810**	**39.3**	**1532**	**31.6**	**1191**	**24.3**	**1003**	**20.4**	**884**	**18.4**
	2	C 1	1824	38.7	1540	29.4	1200	23.8	1008	20.7	889	18.9
	3	C 1	1825	37.6	1538	31.8	1205	23.9	1008	20.2	889	17.9
	4	C 1	1830	38.0	1544	30.4	1205	22.9	1011	20.2	892	19.0
	5	C 1	1824	36.4	1542	29.1	1206	22.1	1011	21.3	892	17.9
	6	C 1	1812	38.1	1529	30.7	1200	23.2	1002	20.8	882	17.2
	7	C 1	1799	40.6	1510	31.9	1188	23.3	986	22.8	869	20.2
	8	C 1	1786	41.4	1505	33.0	1175	24.2	983	22.8	865	20.1
	9	C 1	1785	36.7	1495	30.7	1167	23.2	977	20.6	860	19.3
	10	C 1	1774	41.9	1482	30.0	1150	22.7	966	20.1	853	19.4
	11	C 1	1753	43.5	1482	33.1	1151	29.1	966	18.5	853	19.8
	12	C 1	1764	44.4	1493	31.9	1182	24.0	975	20.4	858	19.7
	13	C 1	1786	40.1	1516	31.7	1190	23.5	995	20.1	875	19.7
	14	C 1	1798	35.9	1520	32.2	1183	25.5	994	23.6	876	21.9
	15	C 1	1824	37.6	1526	29.9	1185	23.3	1000	21.2	881	17.3
	16	C 1	1840	35.9	1551	29.8	1205	22.6	1019	21.4	898	17.2
	17	C 1	1840	38.4	1555	29.7	1214	24.2	1024	21.2	903	18.6
PP(Verbatim, 55951)	**1**	**C 2**	**-182**	**19.4**	**-167**	**15.9**	**-148**	**10.3**	**-136**	**9.8**	**-128**	**9.4**
	2	C 2	-187	17.3	-172	12.8	-151	9.8	-139	9.8	-132	9.1
	3	C 2	-186	19.8	-172	13.4	-148	9.4	-139	8.9	-132	9.2

	4	C 2	-185	18.3	-168	11.9	-149	8.7	-136	9.3	-129	8.7
	5	C 2	-188	18.0	-167	11.6	-149	9.3	-135	9.8	-127	9.8
	6	C 2	-193	20.3	-168	14.2	-150	8.7	-135	10.7	-129	9.6
	7	C 2	-192	22.8	-175	15.3	-154	9.2	-144	11.9	-138	11.7
	8	C 2	-187	22.8	-179	17.7	-156	12.0	-144	11.6	-138	12.6
	9	C 2	-186	25.1	-181	20.3	-157	14.6	-144	13.8	-137	14.9
	10	C 2	-200	30.3	-178	19.8	-158	14.3	-143	14.0	-136	14.3
	11	C 2	-207	34.2	-176	20.1	-162	21.8	-142	13.2	-137	14.0
	12	C 2	-197	27.5	-173	18.4	-147	13.5	-139	12.0	-134	12.3
	13	C 2	-191	24.6	-171	15.7	-139	14.3	-136	11.5	-129	10.3
	14	C 2	-191	21.2	-178	18.0	-159	15.0	-146	15.4	-138	14.7
	15	C 2	-189	16.7	-177	12.2	-164	13.5	-144	9.3	-135	8.2
	16	C 2	-190	15.0	-170	10.8	-146	10.3	-135	8.7	-128	7.6
	17	C 2	-188	13.7	-171	9.8	-140	9.3	-136	7.3	-129	6.8
CarbonFil(Formfutura, 175CARBFIL-BLCK-0500)	**1**	**C 4**	**94**	**19.9**	**108**	**16.0**	**121**	**13.1**	**130**	**11.4**	**137**	**11.4**
	2	C 4	96	21.5	109	16.1	121	12.2	131	11.9	137	11.9
	3	C 4	93	23.6	109	17.1	118	11.9	130	12.7	134	12.3
	4	C 4	100	20.9	112	16.5	126	11.2	134	12.3	139	12.0
	5	C 4	94	19.6	112	16.6	126	12.8	134	12.6	141	13.7
	6	C 4	95	23.5	111	17.6	122	12.7	135	13.1	137	12.1
	7	C 4	97	23.7	109	18.0	126	12.3	132	14.6	136	13.9
	8	C 4	110	24.9	114	20.4	127	13.6	137	14.1	145	14.8
	9	C 4	92	25.7	112	22.9	124	16.2	136	15.9	141	16.3
	10	C 4	83	31.6	104	21.1	122	17.0	126	16.3	132	15.5
	11	C 4	75	33.9	87	21.1	108	22.9	110	15.2	114	15.0
	12	C 4	72	28.4	90	19.9	104	14.0	113	13.1	115	14.2
	13	C 4	77	26.5	98	17.4	108	15.6	121	12.6	123	13.2
	14	C 4	108	23.2	113	19.7	122	17.1	135	17.6	138	17.5
	15	C 4	129	17.6	137	14.5	157	16.1	161	13.1	167	12.8

	16	C 4	144	16.5	155	12.2	183	11.9	178	10.4	183	9.6
	17	C 4	129	17.3	139	13.6	155	14.0	159	13.6	165	13.0
colorFabb_XT(colorFabb, 8719033553019)	**1**	**C 5**	**176**	**19.9**	**191**	**14.3**	**202**	**11.8**	**211**	**9.8**	**217**	**10.2**
	2	C 5	179	19.8	193	15.4	205	10.4	215	10.5	219	10.3
	3	C 5	175	21.8	192	16.5	203	10.4	213	9.7	218	10.5
	4	C 5	175	21.1	187	12.4	202	10.4	209	9.9	213	10.2
	5	C 5	173	20.5	186	12.7	202	10.2	208	10.5	214	10.9
	6	C 5	177	22.6	191	14.8	204	10.2	214	10.8	218	10.7
	7	C 5	183	24.3	193	16.8	206	10.7	215	13.1	217	12.6
	8	C 5	176	27.8	193	18.9	200	14.4	212	13.8	220	13.4
	9	C 5	153	29.3	192	22.9	205	17.9	212	15.5	217	15.6
	10	C 5	180	33.7	190	22.8	207	17.1	209	15.6	216	15.5
	11	C 5	183	38.1	190	22.3	212	22.7	208	15.1	215	15.2
	12	C 5	185	31.7	192	20.0	210	15.6	211	14.0	216	12.9
	13	C 5	175	29.3	190	17.8	184	15.9	210	13.4	213	13.4
	14	C 5	183	23.1	199	19.0	205	16.8	220	16.3	222	16.1
	15	C 5	180	17.6	187	13.1	219	14.0	209	10.0	214	9.1
	16	C 5	176	16.0	185	11.4	205	10.8	207	8.6	214	9.1
	17	C 5	171	14.2	182	9.8	194	9.9	205	7.5	210	8.1
EasyWood(Formfutura, 285EWOOD-BIRCH-0500)	**1**	**C 7**	**177**	**21.6**	**180**	**15.5**	**188**	**11.8**	**190**	**11.2**	**192**	**12.8**
	2	C 7	185	23.2	188	17.3	191	11.8	197	11.5	199	11.3
	3	C 7	191	22.6	194	15.5	200	11.2	204	10.4	205	11.3
	4	C 7	191	21.3	194	13.4	200	9.8	204	9.8	206	9.7
	5	C 7	177	23.4	182	20.3	189	16.4	191	16.1	192	17.5
	6	C 7	188	22.9	179	20.3	189	15.3	189	15.8	188	15.8
	7	C 7	202	22.9	201	18.4	208	11.1	209	12.8	216	12.6
	8	C 7	189	27.0	206	19.6	208	13.9	213	12.4	218	12.5
	9	C 7	190	26.8	199	22.2	207	16.6	208	14.8	212	15.3
	10	C 7	207	36.9	196	21.2	199	16.3	201	14.9	207	15.1

	11	C 7	201	34.5	196	20.9	202	22.7	203	15.1	208	15.3
	12	C 7	181	35.6	181	25.2	172	19.4	185	18.8	191	20.3
	13	C 7	181	30.4	187	22.2	178	19.4	194	16.8	193	15.6
	14	C 7	201	22.1	210	19.9	226	16.4	218	16.2	222	15.8
	15	C 7	199	17.1	212	12.8	217	14.0	222	10.2	225	9.3
	16	C 7	199	14.1	208	12.0	202	10.7	217	8.5	216	8.1
	17	C 7	194	13.2	198	10.5	199	10.0	208	7.4	211	7.8
glowFill(color Fabb, 8719033555136)	**1**	**C 8**	**489**	**22.5**	**446**	**16.4**	**389**	**12.1**	**358**	**12.0**	**336**	**11.0**
	2	C 8	491	20.3	450	17.7	392	11.7	359	11.9	337	11.1
	3	C 8	489	22.3	448	18.5	393	12.5	358	11.3	338	11.4
	4	C 8	488	21.1	446	14.5	392	11.6	357	11.9	336	10.7
	5	C 8	488	22.8	445	14.7	391	11.9	358	12.1	336	11.7
	6	C 8	488	26.2	440	17.6	391	12.9	354	14.1	330	12.0
	7	C 8	481	25.9	439	19.0	391	11.9	351	14.0	332	13.8
	8	C 8	478	25.7	436	19.3	386	14.4	350	14.5	330	12.9
	9	C 8	464	28.4	427	21.0	379	17.0	346	15.7	325	15.6
	10	C 8	472	35.9	427	23.2	375	15.9	341	15.8	324	15.3
	11	C 8	470	37.2	426	21.3	367	23.1	340	15.2	323	14.9
	12	C 8	466	32.0	429	21.7	363	16.1	344	13.5	323	14.5
	13	C 8	469	29.6	432	19.5	387	16.9	347	13.5	322	13.0
	14	C 8	480	22.2	437	20.9	391	17.3	349	17.3	329	16.1
	15	C 8	486	19.7	447	15.6	395	15.3	361	11.8	340	10.9
	16	C 8	490	17.1	453	14.0	389	12.1	365	10.0	342	10.1
	17	C 8	487	17.3	447	12.7	387	11.2	360	9.5	337	9.5
nGen(colorFabb, 8719033554733)	**1**	**C 10**	**101**	**25.1**	**111**	**16.5**	**130**	**12.8**	**138**	**11.7**	**143**	**12.0**
	2	C 10	103	25.4	112	15.8	131	10.5	140	10.5	144	11.1
	3	C 10	99	25.1	113	14.8	131	10.9	139	11.2	145	11.5
	4	C 10	99	23.6	115	16.0	130	10.7	138	10.2	145	10.5
	5	C 10	105	24.9	114	14.0	129	9.1	137	9.9	144	10.9

	6	C 10	105	23.7	110	14.9	128	11.3	135	11.4	139	10.5
	7	C 10	100	26.7	110	15.2	128	11.9	137	12.4	143	12.0
	8	C 10	98	26.0	112	18.2	130	12.5	136	11.4	143	13.1
	9	C 10	95	30.1	112	20.4	128	14.1	135	12.5	141	12.7
	10	C 10	104	30.3	112	20.5	128	13.7	135	12.8	141	13.1
	11	C 10	108	32.8	112	19.3	126	14.7	135	14.0	142	13.5
	12	C 10	102	30.7	114	18.6	124	12.3	137	11.8	144	13.1
	13	C 10	102	26.6	112	17.6	128	12.8	136	11.6	143	12.3
	14	C 10	102	22.5	114	15.2	137	12.2	140	11.0	147	10.3
	15	C 10	100	18.8	117	14.4	137	11.3	143	10.4	147	9.3
	16	C 10	97	17.1	113	11.6	126	8.9	139	8.4	143	8.7
	17	C 10	98	16.2	111	10.9	126	7.9	137	7.8	143	7.3
corkFill(color Fabb, 8719033555327)	**1**	**C 11**	**157**	**24.8**	**165**	**15.9**	**173**	**12.7**	**180**	**11.9**	**183**	**12.4**
	2	C 11	157	22.5	165	16.1	175	11.1	181	10.5	184	10.8
	3	C 11	158	22.4	165	16.1	175	11.0	181	11.9	184	11.6
	4	C 11	158	20.8	168	15.9	174	11.0	180	10.4	185	9.4
	5	C 11	159	20.6	166	15.0	175	9.4	181	9.1	185	9.0
	6	C 11	152	22.8	165	15.5	174	11.4	181	11.1	185	10.5
	7	C 11	150	24.5	159	17.2	172	10.4	177	12.6	181	12.1
	8	C 11	152	29.4	157	17.8	170	12.3	175	12.3	178	12.3
	9	C 11	156	28.3	157	18.2	170	13.0	175	12.5	179	12.3
	10	C 11	144	29.9	156	21.5	168	12.5	173	13.1	178	12.5
	11	C 11	147	35.3	156	20.0	161	13.9	172	13.9	178	13.5
	12	C 11	147	30.5	157	19.3	174	12.6	175	12.3	181	13.6
	13	C 11	151	25.5	162	15.5	180	12.6	178	11.0	183	11.9
	14	C 11	150	22.5	156	15.1	165	11.5	172	10.2	177	10.7
	15	C 11	152	19.7	159	13.9	166	11.3	177	10.2	181	9.3
	16	C 11	154	17.2	163	10.6	179	9.5	180	9.0	185	8.6
	17	C 11	157	17.0	165	11.3	178	8.2	181	8.4	185	7.8

PET(Innofil3d natural, Pet-0301b075)	**1**	**C 12**	**252**	**26.1**	**260**	**19.0**	**271**	**12.7**	**276**	**11.6**	**278**	**13.4**
	2	C 12	255	24.8	263	16.1	274	10.5	278	10.4	280	11.3
	3	C 12	258	26.5	265	16.6	274	11.2	279	12.1	281	11.5
	4	C 12	255	25.3	266	16.7	273	11.1	277	10.9	279	11.8
	5	C 12	255	22.9	261	15.3	273	9.6	275	9.3	278	10.2
	6	C 12	255	25.3	261	16.8	272	12.0	276	11.1	281	10.8
	7	C 12	253	25.8	263	18.9	271	10.9	278	11.7	279	11.9
	8	C 12	251	25.6	257	19.6	265	12.7	270	12.0	272	12.7
	9	C 12	243	31.1	256	20.2	261	14.9	270	13.8	273	12.4
	10	C 12	244	31.9	255	22.1	266	14.9	268	14.1	270	14.5
	11	C 12	254	31.7	255	21.2	270	14.3	268	14.2	272	14.5
	12	C 12	253	32.7	259	21.3	268	12.8	273	11.8	279	13.6
	13	C 12	250	29.8	260	16.4	265	13.1	273	12.7	278	11.5
	14	C 12	257	21.3	264	15.3	270	11.9	277	10.6	281	10.0
	15	C 12	257	18.5	262	13.9	277	11.9	277	9.7	280	9.0
	16	C 12	254	18.2	259	12.3	278	9.3	275	9.1	279	8.9
	17	C 12	254	16.1	263	11.4	272	8.9	276	8.2	279	7.5

Table 28. Hounsfield units measurement of the cylinders on Plate B top side (include the HU of water)

Material	**Slice**	**Position**	**Hounsfield units under different kV**									
			70 kV		**80 kV**		**100 kV**		**120 kV**		**140 kV**	
			Mean	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
PLA mineral(Fiberlogy, PLA-MIN-NATUR-285-085)	**1**	**C 1**	**733.15**	**16.95**	**663.07**	**12.83**	**577.51**	**11.55**	**532.51**	**9.96**	**500.16**	**9.4**
	2	C 1	743.28	17.19	673.18	11.41	585.92	9.88	540.53	9.7	507.94	8.49
	3	C 1	743.99	16.57	675.63	11.42	588.44	8.99	542.87	8.77	510.64	8.29
	4	C 1	743.95	14.92	676.91	11.14	588.55	9.08	543.57	9.16	510.31	9.26
	5	C 1	744.11	15.37	677.47	11.18	588.6	9.23	544.59	8.55	511.13	7.98
	6	C 1	743.75	15.54	677	10.42	589.25	9.21	544.43	8.62	511.23	7.72
	7	C 1	744.13	13.68	676.16	12.45	589.43	9.08	542.64	8.21	510.4	7.25
	8	C 1	743.18	15.05	675.03	10.63	588.03	10.1	542.71	8.52	510.4	8.06
	9	C 1	742.06	14.87	674.4	11.49	588.2	8.77	541.79	8.13	509.77	8.56
	10	C 1	742.94	11.94	674.35	12.49	587.76	8.13	541.35	8.29	509.63	8.43
	11	C 1	744.53	14.23	673.41	10.84	588.1	8.59	541.64	7.5	510.48	9.18
	12	C 1	743.97	12.77	674.42	11.25	587.43	8.65	541.18	7.9	510.1	8.07
	13	C 1	743.28	14.49	675.2	11.32	587.55	8.52	541.83	8.59	510.61	7.82
	14	C 1	743.41	17.64	673.13	11.39	586.46	8.5	542.29	8.57	510.36	7.99
	15	C 1	742.42	14.1	673.4	10.73	586.85	9.17	541.63	8.18	509.43	7.12
	16	C 1	742.77	14.51	673.85	11.01	586.48	9.1	542.11	7.86	508.85	7.97
	17	C 1	742.07	14.33	672.3	11.32	587.13	8.13	541.35	8.31	509.97	8.16
HIPS(ICE Filaments, 29548)	**1**	**C 2**	**-84.53**	**9.46**	**-68.62**	**6.34**	**-49.26**	**5.08**	**-35.15**	**4.97**	**-30.18**	**4.66**
	2	C 2	-86.38	8.98	-68.57	7.35	-49.35	4.66	-35.66	5.3	-30.68	5.23
	3	C 2	-84.3	11.09	-67.84	7.05	-50.12	4.18	-35.6	4.35	-29.57	5.03

	4	C 2	-84.65	9.47	-67.79	6.42	-49.61	3.99	-34.65	5.33	-29.84	5.44
	5	C 2	-83.26	9.62	-68.13	7.7	-50.04	4.31	-35.42	5.43	-30.12	5.17
	6	C 2	-82.77	10.22	-67.26	7.06	-50.46	4.8	-35.32	5.27	-29.85	4.9
	7	C 2	-83.91	9.03	-68.42	7.06	-50.71	4.78	-37.06	5.19	-31.27	4.74
	8	C 2	-86.77	10.32	-69.52	6.83	-51.18	4.68	-37.64	4.87	-31.64	5.14
	9	C 2	-86.61	8.57	-70.48	6.28	-51.42	5.51	-37.46	4.46	-31.88	5.07
	10	C 2	-86.47	9.29	-70.33	5.76	-50.78	4.77	-36.91	4.7	-31.91	4.53
	11	C 2	-86.71	10.47	-69.61	6.58	-50.62	4.38	-36.45	4.71	-31.4	4.41
	12	C 2	-87.38	9.9	-70.43	6.37	-51.68	5.16	-36.79	4.9	-32.31	4.14
	13	C 2	-88.76	9.3	-71.01	6.15	-51.38	4.84	-38.67	4.76	-32.85	5.74
	14	C 2	-90.29	9.39	-72.08	6.87	-52.42	4.9	-39.44	4.46	-33.72	5.75
	15	C 2	-91.14	9.14	-72.91	6.33	-53.08	4.55	-39.95	4.93	-34.8	5.16
	16	C 2	-89.51	7.88	-72.58	7.55	-53.44	4.76	-40.43	5.01	-35.89	4.85
	17	C 2	-90.42	9.4	-73.79	6.03	-54.25	5.23	-41.36	4.55	-35.68	4.88
Anycubic Resin green (AB-POT048)	**1**	**C 4**	**121.68**	**9.35**	**135.03**	**8.28**	**146.23**	**6.59**	**156.17**	**6.62**	**159.3**	**6.97**
	2	C 4	121.55	10.61	135.01	9.41	147.36	7.43	157.13	7.41	159.95	6.66
	3	C 4	120.78	18.76	134.15	16.04	145.8	14.91	155.9	16.81	158.57	17.62
	4	C 4	119.94	22.1	132.83	21.9	145.3	21.18	155.12	21.35	157.48	22.9
	5	C 4	123.3	13.33	135.47	12.18	147.8	11.02	157.13	10.06	159.63	10.52
	6	C 4	123.11	17.15	134.73	14.96	147.21	14.92	155.58	14.78	158.85	16.18
	7	C 4	120.63	22.6	133.28	19.53	145.66	21.72	154.71	23.1	157.04	22.74
	8	C 4	121.16	22.66	133.62	18.19	145.1	20.4	155.54	21.44	157.25	20.29
	9	C 4	122.73	13.36	136.4	12.82	146.36	12.14	157.13	10.4	159.57	10.99
	10	C 4	121.08	20.43	135.21	19.31	145.17	20.31	155.06	20.37	158.48	20.19
	11	C 4	121.5	18.04	135.31	19.48	145.39	19.76	155.93	18.67	157.9	19.69
	12	C 4	120.98	19.27	132.45	20.35	145.3	20.77	154.84	20.77	158.1	20.97
	13	C 4	119.57	20.14	133.19	20.29	144.52	19.13	154.78	20.35	156.99	20.19
	14	C 4	118.55	18.83	133.63	18.67	144.65	18.26	153.9	18.13	156.65	17.76
	15	C 4	120.15	19.44	133.19	17.16	143.88	16.29	154.17	16.62	156.34	16.94

	16	C 4	123.7	10.07	132.93	7.82	145.76	5.81	155.87	6.54	158.48	6.73
	17	C 4	123.93	9.42	134.24	7.77	146.35	6.88	156.31	6.7	158.15	6.28
PrimaCreator Resin clear(PV-RESIN-B405-0500-CL)	**1**	**C 5**	**140.13**	**14.02**	**153.59**	**10.3**	**164.52**	**7.74**	**173.47**	**10.25**	**175.42**	**7.97**
	2	C 5	143.12	13.38	154.62	10.99	165.98	8.77	175.14	9.12	177.48	8.76
	3	C 5	143.34	10.24	155.92	9.75	167.46	6.28	175.98	6.21	179.27	6.7
	4	C 5	143.46	13.46	154.7	12.53	166.5	12.66	175.36	12.1	177.66	12.62
	5	C 5	143.27	14.18	154.67	12.05	165.67	12.27	174.67	12.97	177.48	12.71
	6	C 5	141.15	21.72	152.72	21.38	163.36	22.19	172.55	21.96	175.12	22.87
	7	C 5	143.18	12.22	155.77	9.89	165.88	9.4	175.89	8.71	178.36	9.51
	8	C 5	145.15	11.21	156.42	8.61	167.15	7.19	175.41	5.74	179.05	6.36
	9	C 5	143.88	12.25	156.02	10.42	166.17	8.49	175.08	9.62	178.27	9.65
	10	C 5	144.64	11.82	156.96	10.1	165.77	7.98	175.41	7.77	178.33	7.86
	11	C 5	143.11	11.15	156.32	8.95	166.09	6.73	175.39	6.22	178.88	7.39
	12	C 5	144.04	11.36	154.4	7.69	165.95	6.88	174.74	6.97	178.39	6.47
	13	C 5	143.78	12.5	154.41	9.4	165.32	8.87	174.09	8.61	176.73	8.73
	14	C 5	143.95	9.96	154.81	9.11	165.33	6.14	174.76	6.66	177.65	6.19
	15	C 5	143.7	11.74	153.26	10.06	164.65	7.41	174.27	8.05	176.24	7.72
	16	C 5	142.88	11.23	152.51	9.36	163.9	7.12	172.98	7.85	174.87	7.2
	17	C 5	144.02	9.87	152.83	8.83	163.7	6.52	172.11	6.61	174.88	6.41
PhotoCentric 3D UV Flexible Resin clear(PHODCL01UVFLEX)	**1**	**C 7**	**121.16**	**10.92**	**133.38**	**6.42**	**144.61**	**5.9**	**153.93**	**5.99**	**155.44**	**5.61**
	2	C 7	123.29	9.33	135.19	8.16	145.71	5.48	154.99	6.03	157.71	6.34
	3	C 7	124.4	10.8	135.58	7.26	145.29	7.1	155.3	6.79	157.67	5.36
	4	C 7	124.72	10.98	135.17	7.47	146.45	6.36	155.31	6.04	157.87	5.41
	5	C 7	125.78	10.29	135.84	7.51	146.61	5.61	155.57	5.67	158.69	6.08
	6	C 7	125.7	10.69	135.96	6.89	146.49	5.76	155.37	5.46	158.57	6.1
	7	C 7	124.17	11.38	134.94	7.12	146.14	5.74	154.67	6.03	157.45	5.64
	8	C 7	123.1	12.05	134.88	7.54	145.12	5.5	154.84	6.28	157.05	6.38
	9	C 7	121.15	10.86	135.52	7.15	146.04	5.78	154.79	6.17	157.25	6.21
	10	C 7	121.73	10.53	136.61	6.78	146.06	5.89	154.67	6	157.72	5.04

	11	C 7	121.89	10	135.3	8.63	145.13	6.59	153.59	6.08	157.64	5.9
	12	C 7	122.64	9.48	133.67	7.95	145.22	5.73	154.27	5.66	157.54	6.47
	13	C 7	122.82	10.25	133.45	7.59	144.71	6.52	154.34	5.68	156.7	6.12
	14	C 7	122.95	10.83	133.75	8.2	144.95	5.35	153.87	5.83	157.1	5.98
	15	C 7	123.83	9.66	133.01	6.64	145.06	5.83	153.26	5.68	156.68	5.47
	16	C 7	121.86	8.6	133.53	6.54	144.34	5.86	153.48	5.35	156.78	5.25
	17	C 7	121.04	12.36	135.1	7.66	144.48	5.46	155.04	4.81	157.88	5.46
ABS(Verbatim , 55019)	**1**	**C 8**	**-8.75**	**9.23**	**7.9**	**6.57**	**23.7**	**5.79**	**35.05**	**5**	**39.7**	**4.68**
	2	C 8	-7.43	9.42	7.02	6.98	23.38	4.82	35.16	4.29	39.91	5.3
	3	C 8	-7.52	10.6	7.61	5.66	23.33	4.75	35.79	4.58	39.73	4.93
	4	C 8	-7.11	9.46	7.78	5.43	24.91	4.69	35.59	4.19	39.94	4.26
	5	C 8	-7.31	10.24	7.18	5.72	24.04	6	36.1	5.55	41.07	4.32
	6	C 8	-7.11	9.89	6.73	6.61	23.72	4.91	35.78	5.06	40.57	4.66
	7	C 8	-7.4	9.89	6.82	7	23.14	4.56	35.34	5.08	39.91	4.91
	8	C 8	-8.61	9.62	7.05	7	23.65	4.44	35.28	5.23	39.31	4.84
	9	C 8	-8.05	9.87	6.79	5.98	24.14	5.18	34.15	4.92	39.11	4.94
	10	C 8	-7.76	9.13	6.54	7.61	23.06	4.87	34.63	5.18	38.74	5.19
	11	C 8	-7.34	7.85	6.84	7.05	22.77	4.79	34.69	5.29	39.13	5.4
	12	C 8	-7.05	8.31	6.24	6.91	22.48	5.18	34.55	4.46	39.43	5.3
	13	C 8	-8.26	8.15	6.77	6.76	22.3	4.98	34.82	4.92	39.62	4.95
	14	C 8	-7.08	8.24	7.75	6.67	23.12	5.24	35.11	4.95	40	4.09
	15	C 8	-8.22	10.76	6.7	6.07	22.58	5.14	34.42	4.36	39.95	4.21
	16	C 8	-7.56	8.84	7.68	5.84	23.38	4.71	35.25	4.68	40.39	4.77
	17	C 8	-6.4	9.01	9.41	6.09	25.04	5.69	37.25	5.14	42.41	5.05
GreenTEC Pro Carbon(Extrudr, 901024142697	**1**	**C 10**	**350.03**	**12.13**	**344.38**	**9.53**	**332.42**	**8.14**	**332.17**	**8.76**	**324.03**	**7.45**
	2	C 10	368.08	11.64	359.11	8.53	348.56	6.32	345.08	6.51	338.86	5.89
	3	C 10	370.74	13.05	362.15	9.05	350.42	7.11	346.49	6.46	340.82	5.98
	4	C 10	371.05	11.7	364.16	9.5	351.47	5.55	348.3	6.06	342.24	6.22
	5	C 10	371.93	14.5	363.7	10.18	351.46	6.02	348.12	6.23	342.36	6.77

3)	6	C 10	369.94	12.49	362.81	8.63	351.49	7.4	348.55	6.89	342.47	7.36
	7	C 10	370.42	13.19	361.4	8.4	351.81	7.28	347.79	6.19	342.72	5.93
	8	C 10	369.97	13.08	361.35	9.57	350.71	6.01	347.72	6.29	342.09	6.51
	9	C 10	371.51	11.97	363.09	7.95	350.67	6.23	347.55	7.03	343.35	5.54
	10	C 10	370.21	10.96	362.38	8.68	351.16	6.31	348.39	6.78	343.58	6.14
	11	C 10	369.84	12.03	364.52	7.39	351.49	6.16	347.99	7.43	344.06	7.43
	12	C 10	369.77	10.63	364.3	8.49	351.63	6.67	347.51	6.5	342.27	5.81
	13	C 10	368.36	11.75	362.34	9.02	351.98	6.98	347.69	6.02	342.75	6.13
	14	C 10	369.82	11.79	362.03	8.45	351.66	6.44	348.33	7.29	344.19	6.11
	15	C 10	370	11.55	363.18	8.14	351.88	6.52	348.07	6.19	342.82	6.5
	16	C 10	369.35	12.01	363.65	8.37	351.81	6.74	348.46	6.62	343.06	6.32
	17	C 10	370.44	13.53	363.75	8.82	352.55	7.58	349.11	5.71	343.39	5.89
Metal Filament Aluminium (AptoFun, B01ITNXRWD)	**1**	**C 11**	**224.76**	**11.58**	**225.65**	**9.2**	**220.06**	**6.4**	**225.17**	**6.13**	**220.88**	**6.82**
	2	C 11	250.89	13.24	249.25	9.19	244.35	6.58	245.81	6.3	241.81	6.42
	3	C 11	252.18	12.85	251.16	6.77	246.07	5.59	247.79	5.38	243.96	5.8
	4	C 11	255.21	12.95	250.1	7.44	247.24	6.23	248.28	5.81	245.84	5.59
	5	C 11	253.69	12.64	251.46	8.38	247.12	5.7	248.73	6.67	245.6	6.22
	6	C 11	253.56	11.69	251.99	8.79	246.88	5.6	248.69	6.11	245.31	4.98
	7	C 11	255.27	12.18	253.28	8.09	247.79	6.54	248.43	5.89	245.66	5.85
	8	C 11	255.85	11.16	251.92	7.93	247.7	6.99	248.88	6.21	244.93	6
	9	C 11	255.87	12.37	251.95	6.69	247.92	6.16	248.87	6.8	245.62	5.32
	10	C 11	254.84	12.88	251.67	7.64	246.38	5.32	248.77	5.28	245.73	5.65
	11	C 11	254.45	12.73	251.65	7.62	247.29	7.81	248.76	5.8	246.34	5.94
	12	C 11	253.16	13.92	251.96	6.93	248.29	5.97	248.62	5.66	245.92	4.99
	13	C 11	253.52	11.39	252.83	8.14	248.28	5.87	248.64	5.96	246.82	5.34
	14	C 11	255.46	10.99	251.92	8.21	247.79	6.45	249.46	6.03	245.53	5.52
	15	C 11	254.01	11.33	251.95	8.63	248.91	6.03	249.13	5.05	246.06	5.3
	16	C 11	255.12	12.96	251.89	10.3	248.57	5.94	249.33	5.65	246.76	5.44
	17	C 11	255.24	11.83	253.6	7.88	249.94	5.75	248.37	5.87	246.45	5.48

Wanhao Resin water washable clear(23453)	**1**	**C 12**	**139.31**	**12.13**	**150.48**	**8.22**	**161.82**	**6.09**	**172.67**	**6.13**	**175.06**	**7.45**
	2	C 12	138.09	13.05	150.09	8.51	161.06	6.29	172.02	7.25	173.07	7.02
	3	C 12	136.52	12.87	150.84	9.89	161.15	7.55	171.18	7.5	173.97	6.25
	4	C 12	139.43	11.68	150.85	9.23	161.64	7.78	170.99	7.28	173.92	6.37
	5	C 12	136.85	11.86	149.26	9.33	161.11	7.21	171.56	6.74	172.99	7.31
	6	C 12	137.67	11.22	149.26	8.97	161.03	5.8	170.67	6.87	173.52	8.25
	7	C 12	138.6	10.81	148.91	7.78	161.46	5.91	170.51	6.31	173.76	7.47
	8	C 12	138.29	12.39	149.1	8.23	161.68	7.24	170.25	7.21	173.71	7.05
	9	C 12	137.3	10.64	148.91	8.22	161.86	6.32	171.67	6.77	173.39	6.75
	10	C 12	137.6	11.44	148.27	8.32	161.95	6.18	172.34	6.54	174.01	6.12
	11	C 12	136.59	13.76	149.39	7.35	162.08	6.9	172.51	7.2	174.49	7.19
	12	C 12	137.54	11.72	149.59	8.23	161.36	5.88	172.3	6.62	174.58	6.29
	13	C 12	137.67	11.14	149.55	8.25	162.16	6.26	172.7	6.77	175.14	5.94
	14	C 12	137.62	12.61	148.25	9.08	160.3	7.61	170.27	7.68	173.41	7.87
	15	C 12	125.72	21.52	135.88	20.26	147.29	20.75	156.69	24.34	158.42	23.67
	16	C 12	101	31.28	109.72	30.14	118.73	33.48	124.81	34.77	126.77	35.34
	17	C 12	62.59	28.11	64.91	30.53	69.82	33	71.62	33.25	73.2	35.32
HU of water on the periphery of the plate	1	Water_p	3.42	10.28	3.78	6.95	2.58	4.64	4.24	5	2.5	5.1
	2	Water_p	3.86	9.86	3.44	6.29	2.56	4.77	4.35	5.2	2.22	5.46
	3	Water_p	4.38	9.11	4.34	7.13	2.71	5.48	5.2	5.16	2.74	5.13
	4	Water_p	4.89	9.81	4.64	7.06	3.4	5.41	5.49	4.95	3.04	4.68
	5	Water_p	4.34	9.7	4.74	7.05	3.31	5.23	5.3	4.95	3.19	4.52
	6	Water_p	4.59	9.66	4.47	7.05	3.16	5	4.71	4.8	3.22	5.04
	7	Water_p	4.78	9.45	4.74	7.33	3.11	4.49	4.82	4.89	2.9	5.06
	8	Water_p	4.26	9.48	4.2	7.05	2.78	5.19	4.67	5.1	3.03	5.21
	9	Water_p	4.09	9.5	4.18	7.09	2.67	5.2	4.88	4.76	3.05	4.54
	10	Water_p	3.34	10.44	4.26	6.91	2.79	4.99	4.86	5.05	3.3	4.76
	11	Water_p	3.99	9.94	4.19	7.1	2.53	4.91	5.01	4.79	3.14	5.22
	12	Water_p	3.74	9.06	4.07	6.39	2.25	4.75	4.83	4.81	3.21	4.97

	13	Water_p	4.01	9.33	4.17	7.33	2.51	5.1	4.92	5.25	3.14	4.92
	14	Water_p	3.47	9.31	4.48	6.79	2.69	5.16	4.83	5.13	3.04	4.86
	15	Water_p	4.04	9.52	4.55	6.91	2.78	5.14	4.88	4.73	2.69	4.87
	16	Water_p	4.34	10.29	4.41	6.48	2.94	5.21	4.81	4.97	2.83	4.69
	17	Water_p	5.06	9.98	5.26	6.95	3.32	5.03	5.08	4.85	3.51	4.69
HU of water on the center of the plate	1	Water_c	-3.54	11.01	-3.28	7.15	-4.82	5.63	-2.73	5.31	-4.53	5.57
	2	Water_c	-3.62	10.38	-3.39	7.18	-5.3	5.39	-2.96	5.3	-4.59	5.14
	3	Water_c	-3.61	11.06	-3.03	6.99	-5.12	5.71	-2.4	5.11	-4.54	5.07
	4	Water_c	-2.45	11.2	-3.31	7.44	-4.02	5.02	-2.3	5.7	-4.61	5.35
	5	Water_c	-2.61	11.95	-2.99	7.44	-4.63	5.46	-2.4	5.32	-4.46	4.92
	6	Water_c	-2.71	11.5	-2.76	6.87	-4.42	5.19	-3	5.3	-4.08	5.17
	7	Water_c	-3.53	11.02	-2.47	7.15	-4.43	5.07	-2.49	5.01	-4.31	4.89
	8	Water_c	-4.33	11.68	-3.07	8.03	-5	5.3	-2.59	5.57	-4.46	5.45
	9	Water_c	-4.42	10.76	-3.8	7.41	-4.92	4.95	-2.36	4.8	-4.27	4.91
	10	Water_c	-3.37	11.12	-3.68	6.82	-4.94	5.13	-2.31	4.96	-4.1	5.23
	11	Water_c	-3.1	11.88	-2.83	7.12	-4.82	4.81	-2.17	4.91	-3.9	5.64
	12	Water_c	-3.21	11	-3.26	6.72	-4.87	5.08	-1.87	5.19	-4.17	5.16
	13	Water_c	-3.6	10.43	-3.27	7.86	-4.52	5.34	-2.5	5.33	-4.33	5.16
	14	Water_c	-2.97	11.56	-3.21	7.15	-4.2	5.18	-2.5	5.23	-4.58	5.34
	15	Water_c	-2.6	10.9	-3.69	7.28	-4.27	5.59	-2.67	5.15	-3.74	5.37
	16	Water_c	-2.68	11.09	-3.37	7.1	-4.63	5.01	-2.71	4.87	-4.06	4.93
	17	Water_c	-2.07	10.73	-2.8	7.99	-4.18	5.22	-1.98	5.4	-3.54	5.22

Table 29. Hounsfield units measurement of the cylinders on Plate Btop side (HU of water subtracted)

Material	Slice	Position	Hounsfield units under different kV									
			70 kV		80 kV		100 kV		120 kV		140 kV	
			Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
PLA mineral(Fiberlogy, PLA-MIN-NATUR-285-085)	**1**	**C 1**	**730**	**19.8**	**659**	**14.6**	**575**	**12.4**	**528**	**11.1**	**498**	**10.7**
	2	C 1	739	19.8	670	13.0	583	11.0	536	11.0	506	10.1
	3	C 1	740	18.9	671	13.5	586	10.5	538	10.2	508	9.7
	4	C 1	739	17.9	672	13.2	585	10.6	538	10.4	507	10.4
	5	C 1	740	18.2	673	13.2	585	10.6	539	9.9	508	9.2
	6	C 1	739	18.3	673	12.6	586	10.5	540	9.9	508	9.2
	7	C 1	739	16.6	671	14.4	586	10.1	538	9.6	508	8.8
	8	C 1	739	17.8	671	12.8	585	11.4	538	9.9	507	9.6
	9	C 1	738	17.6	670	13.5	586	10.2	537	9.4	507	9.7
	10	C 1	740	15.9	670	14.3	585	9.5	536	9.7	506	9.7
	11	C 1	741	17.4	669	13.0	586	9.9	537	8.9	507	10.6
	12	C 1	740	15.7	670	12.9	585	9.9	536	9.2	507	9.5
	13	C 1	739	17.2	671	13.5	585	9.9	537	10.1	507	9.2
	14	C 1	740	19.9	669	13.3	584	9.9	537	10.0	507	9.4
	15	C 1	738	17.0	669	12.8	584	10.5	537	9.4	507	8.6
	16	C 1	738	17.8	669	12.8	584	10.5	537	9.3	506	9.2
	17	C 1	737	17.5	667	13.3	584	9.6	536	9.6	506	9.4
HIPS(ICE Filaments, 29548)	**1**	**C 2**	**-88**	**14.0**	**-72**	**9.4**	**-52**	**6.9**	**-39**	**7.0**	**-33**	**6.9**
	2	C 2	-90	13.3	-72	9.7	-52	6.7	-40	7.4	-33	7.6
	3	C 2	-89	14.4	-72	10.0	-53	6.9	-41	6.7	-32	7.2

	4	C 2	-90	13.6	-72	9.5	-53	6.7	-40	7.3	-33	7.2
	5	C 2	-88	13.7	-73	10.4	-53	6.8	-41	7.3	-33	6.9
	6	C 2	-87	14.1	-72	10.0	-54	6.9	-40	7.1	-33	7.0
	7	C 2	-89	13.1	-73	10.2	-54	6.6	-42	7.1	-34	6.9
	8	C 2	-91	14.0	-74	9.8	-54	7.0	-42	7.1	-35	7.3
	9	C 2	-91	12.8	-75	9.5	-54	7.6	-42	6.5	-35	6.8
	10	C 2	-90	14.0	-75	9.0	-54	6.9	-42	6.9	-35	6.6
	11	C 2	-91	14.4	-74	9.7	-53	6.6	-41	6.7	-35	6.8
	12	C 2	-91	13.4	-75	9.0	-54	7.0	-42	6.9	-36	6.5
	13	C 2	-93	13.2	-75	9.6	-54	7.0	-44	7.1	-36	7.6
	14	C 2	-94	13.2	-77	9.7	-55	7.1	-44	6.8	-37	7.5
	15	C 2	-95	13.2	-77	9.4	-56	6.9	-45	6.8	-37	7.1
	16	C 2	-94	13.0	-77	9.9	-56	7.1	-45	7.1	-39	6.7
	17	C 2	-95	13.7	-79	9.2	-58	7.3	-46	6.7	-39	6.8
Anycubic Resin green (AB-POT048)	**1**	**C 4**	**118**	**13.9**	**131**	**10.8**	**144**	**8.1**	**152**	**8.3**	**157**	**8.6**
	2	C 4	118	14.5	132	11.3	145	8.8	153	9.1	158	8.6
	3	C 4	116	20.9	130	17.6	143	15.9	151	17.6	156	18.4
	4	C 4	115	24.2	128	23.0	142	21.9	150	21.9	154	23.4
	5	C 4	119	16.5	131	14.1	144	12.2	152	11.2	156	11.4
	6	C 4	119	19.7	130	16.5	144	15.7	151	15.5	156	16.9
	7	C 4	116	24.5	129	20.9	143	22.2	150	23.6	154	23.3
	8	C 4	117	24.6	129	19.5	142	21.0	151	22.0	154	20.9
	9	C 4	119	16.4	132	14.6	144	13.2	152	11.4	157	11.9
	10	C 4	118	22.9	131	20.5	142	20.9	150	21.0	155	20.7
	11	C 4	118	20.6	131	20.7	143	20.4	151	19.3	155	20.4
	12	C 4	117	21.3	128	21.3	143	21.3	150	21.3	155	21.6
	13	C 4	116	22.2	129	21.6	142	19.8	150	21.0	154	20.8
	14	C 4	115	21.0	129	19.9	142	19.0	149	18.8	154	18.4
	15	C 4	116	21.6	129	18.5	141	17.1	149	17.3	154	17.6

	16	C 4	119	14.4	129	10.2	143	7.8	151	8.2	156	8.2
	17	C 4	119	13.7	129	10.4	143	8.5	151	8.3	155	7.8
PrimaCreator Resin clear(PV-RESIN-B405-0500-CL)	**1**	**C 5**	**137**	**17.4**	**150**	**12.4**	**162**	**9.0**	**169**	**11.4**	**173**	**9.5**
	2	C 5	139	16.6	151	12.7	163	10.0	171	10.5	175	10.3
	3	C 5	139	13.7	152	12.1	165	8.3	171	8.1	177	8.4
	4	C 5	139	16.7	150	14.4	163	13.8	170	13.1	175	13.5
	5	C 5	139	17.2	150	14.0	162	13.3	169	13.9	174	13.5
	6	C 5	137	23.8	148	22.5	160	22.7	168	22.5	172	23.4
	7	C 5	138	15.4	151	12.3	163	10.4	171	10.0	175	10.8
	8	C 5	141	14.7	152	11.1	164	8.9	171	7.7	176	8.2
	9	C 5	140	15.5	152	12.6	164	10.0	170	10.7	175	10.7
	10	C 5	141	15.8	153	12.2	163	9.4	171	9.3	175	9.2
	11	C 5	139	14.9	152	11.4	164	8.3	170	7.9	176	9.0
	12	C 5	140	14.5	150	10.0	164	8.4	170	8.5	175	8.2
	13	C 5	140	15.6	150	11.9	163	10.2	169	10.1	174	10.0
	14	C 5	140	13.6	150	11.4	163	8.0	170	8.4	175	7.9
	15	C 5	140	15.1	149	12.2	162	9.0	169	9.3	174	9.1
	16	C 5	139	15.2	148	11.4	161	8.8	168	9.3	172	8.6
	17	C 5	139	14.0	148	11.2	160	8.2	167	8.2	171	7.9
PhotoCentric 3D UV Flexible Resin clear(PHODCL01UVFLEX)	**1**	**C 7**	**118**	**15.0**	**130**	**9.5**	**142**	**7.5**	**150**	**7.8**	**153**	**7.6**
	2	C 7	119	13.6	132	10.3	143	7.3	151	8.0	155	8.4
	3	C 7	120	14.1	131	10.2	143	9.0	150	8.5	155	7.4
	4	C 7	120	14.7	131	10.3	143	8.3	150	7.8	155	7.2
	5	C 7	121	14.1	131	10.3	143	7.7	150	7.5	156	7.6
	6	C 7	121	14.4	131	9.9	143	7.6	151	7.3	155	7.9
	7	C 7	119	14.8	130	10.2	143	7.3	150	7.8	155	7.6
	8	C 7	119	15.3	131	10.3	142	7.6	150	8.1	154	8.2
	9	C 7	117	14.4	131	10.1	143	7.8	150	7.8	154	7.7
	10	C 7	118	14.8	132	9.7	143	7.7	150	7.8	154	6.9

	11	C 7	118	14.1	131	11.2	143	8.2	149	7.7	155	7.9
	12	C 7	119	13.1	130	10.2	143	7.4	149	7.4	154	8.2
	13	C 7	119	13.9	129	10.6	142	8.3	149	7.7	154	7.9
	14	C 7	119	14.3	129	10.6	142	7.4	149	7.8	154	7.7
	15	C 7	120	13.6	128	9.6	142	7.8	148	7.4	154	7.3
	16	C 7	118	13.4	129	9.2	141	7.8	149	7.3	154	7.0
	17	C 7	116	15.9	130	10.3	141	7.4	150	6.8	154	7.2
ABS(Verbatim, 55019)	**1**	**C 8**	**-12**	**13.8**	**4**	**9.6**	**21**	**7.4**	**31**	**7.1**	**37**	**6.9**
	2	C 8	-11	13.6	4	9.4	21	6.8	31	6.7	38	7.6
	3	C 8	-12	14.0	3	9.1	21	7.3	31	6.9	37	7.1
	4	C 8	-12	13.6	3	8.9	22	7.2	30	6.5	37	6.3
	5	C 8	-12	14.1	2	9.1	21	8.0	31	7.4	38	6.3
	6	C 8	-12	13.8	2	9.7	21	7.0	31	7.0	37	6.9
	7	C 8	-12	13.7	2	10.1	20	6.4	31	7.1	37	7.1
	8	C 8	-13	13.5	3	9.9	21	6.8	31	7.3	36	7.1
	9	C 8	-12	13.7	3	9.3	21	7.3	29	6.8	36	6.7
	10	C 8	-11	13.9	2	10.3	20	7.0	30	7.2	35	7.0
	11	C 8	-11	12.7	3	10.0	20	6.9	30	7.1	36	7.5
	12	C 8	-11	12.3	2	9.4	20	7.0	30	6.6	36	7.3
	13	C 8	-12	12.4	3	10.0	20	7.1	30	7.2	36	7.0
	14	C 8	-11	12.4	3	9.5	20	7.4	30	7.1	37	6.4
	15	C 8	-12	14.4	2	9.2	20	7.3	30	6.4	37	6.4
	16	C 8	-12	13.6	3	8.7	20	7.0	30	6.8	38	6.7
	17	C 8	-11	13.4	4	9.2	22	7.6	32	7.1	39	6.9
GreenTEC Pro Carbon(Extrudr, 901024142697	**1**	**C 10**	**354**	**16.4**	**348**	**11.9**	**337**	**9.9**	**335**	**10.2**	**329**	**9.3**
	2	C 10	372	15.6	363	11.1	354	8.3	348	8.4	343	7.8
	3	C 10	374	17.1	365	11.4	356	9.1	349	8.2	345	7.8
	4	C 10	374	16.2	367	12.1	355	7.5	351	8.3	347	8.2
	5	C 10	375	18.8	367	12.6	356	8.1	351	8.2	347	8.4

3)	6	C 10	373	17.0	366	11.0	356	9.0	352	8.7	347	9.0
	7	C 10	374	17.2	364	11.0	356	8.9	350	8.0	347	7.7
	8	C 10	374	17.5	364	12.5	356	8.0	350	8.4	347	8.5
	9	C 10	376	16.1	367	10.9	356	8.0	350	8.5	348	7.4
	10	C 10	374	15.6	366	11.0	356	8.1	351	8.4	348	8.1
	11	C 10	373	16.9	367	10.3	356	7.8	350	8.9	348	9.3
	12	C 10	373	15.3	368	10.8	357	8.4	349	8.3	346	7.8
	13	C 10	372	15.7	366	12.0	357	8.8	350	8.0	347	8.0
	14	C 10	373	16.5	365	11.1	356	8.3	351	9.0	349	8.1
	15	C 10	373	15.9	367	10.9	356	8.6	351	8.1	347	8.4
	16	C 10	372	16.3	367	11.0	356	8.4	351	8.2	347	8.0
	17	C 10	373	17.3	367	11.9	357	9.2	351	7.9	347	7.9
Metal Filament Aluminium (AptoFun, B01ITNXRWD)	**1**	**C 11**	**228**	**16.0**	**229**	**11.7**	**225**	**8.5**	**228**	**8.1**	**225**	**8.8**
	2	C 11	255	16.8	253	11.7	250	8.5	249	8.2	246	8.2
	3	C 11	256	17.0	254	9.7	251	8.0	250	7.4	249	7.7
	4	C 11	258	17.1	253	10.5	251	8.0	251	8.1	250	7.7
	5	C 11	256	17.4	254	11.2	252	7.9	251	8.5	250	7.9
	6	C 11	256	16.4	255	11.2	251	7.6	252	8.1	249	7.2
	7	C 11	259	16.4	256	10.8	252	8.3	251	7.7	250	7.6
	8	C 11	260	16.2	255	11.3	253	8.8	251	8.3	249	8.1
	9	C 11	260	16.4	256	10.0	253	7.9	251	8.3	250	7.2
	10	C 11	258	17.0	255	10.2	251	7.4	251	7.2	250	7.7
	11	C 11	258	17.4	254	10.4	252	9.2	251	7.6	250	8.2
	12	C 11	256	17.7	255	9.7	253	7.8	250	7.7	250	7.2
	13	C 11	257	15.4	256	11.3	253	7.9	251	8.0	251	7.4
	14	C 11	258	16.0	255	10.9	252	8.3	252	8.0	250	7.7
	15	C 11	257	15.7	256	11.3	253	8.2	252	7.2	250	7.5
	16	C 11	258	17.1	255	12.5	253	7.8	252	7.5	251	7.3
	17	C 11	257	16.0	256	11.2	254	7.8	250	8.0	250	7.6

Wanhao Resin water washable clear(23453)	**1**	**C 12**	**143**	**16.4**	**154**	**10.9**	**167**	**8.3**	**175**	**8.1**	**180**	**9.3**
	2	C 12	142	16.7	153	11.1	166	8.3	175	9.0	178	8.7
	3	C 12	140	17.0	154	12.1	166	9.5	174	9.1	179	8.0
	4	C 12	142	16.2	154	11.9	166	9.3	173	9.2	179	8.3
	5	C 12	139	16.8	152	11.9	166	9.0	174	8.6	177	8.8
	6	C 12	140	16.1	152	11.3	165	7.8	174	8.7	178	9.7
	7	C 12	142	15.4	151	10.6	166	7.8	173	8.1	178	8.9
	8	C 12	143	17.0	152	11.5	167	9.0	173	9.1	178	8.9
	9	C 12	142	15.1	153	11.1	167	8.0	174	8.3	178	8.3
	10	C 12	141	16.0	152	10.8	167	8.0	175	8.2	178	8.1
	11	C 12	140	18.2	152	10.2	167	8.4	175	8.7	178	9.1
	12	C 12	141	16.1	153	10.6	166	7.8	174	8.4	179	8.1
	13	C 12	141	15.3	153	11.4	167	8.2	175	8.6	179	7.9
	14	C 12	141	17.1	151	11.6	165	9.2	173	9.3	178	9.5
	15	C 12	128	24.1	140	21.5	152	21.5	159	24.9	162	24.3
	16	C 12	104	33.2	113	31.0	123	33.9	128	35.1	131	35.7
	17	C 12	65	30.1	68	31.6	74	33.4	74	33.7	77	35.7

Table 30. Hounsfield units measurement of the cylinders on Plate B bottom side (include the HU of water)

Material	Slice	Position	70 kV		80 kV		100 kV		120 kV		140 kV	
			Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
GreenTEC Pro natural(Extrudr, 9010241426034)	**1**	**C 1**	**377.58**	**11.74**	**368.5**	**8.87**	**355.79**	**6.68**	**351.58**	**6.33**	**345.71**	**6.47**
	2	C 1	377.5	11.32	368.35	10.58	354.96	7.07	351.09	7.02	344.68	6.24
	3	C 1	377.27	10.36	368.57	10.45	354.56	6.14	350.14	6.8	345.14	6.87
	4	C 1	376.28	8.59	369.29	8.26	354.82	6.46	350.48	7.43	344.87	6.36
	5	C 1	377.29	9.1	368.64	8.7	355.94	7.32	351.02	7.05	344.43	6.69
	6	C 1	376.63	11.81	368	8.9	355	7.5	350.42	7.31	344.16	6.82
	7	C 1	377.24	12.43	368.49	9.37	354.96	7.26	350.7	6.77	344.55	6.41
	8	C 1	376.8	10.15	367.13	7.94	354.76	6.78	350.83	7.18	344.67	6.68
	9	C 1	376.74	10.87	368.45	8.25	354.55	7.24	350.39	6.63	344.52	6.67
	10	C 1	377.14	12.24	369.27	8.04	355.23	8.69	351.46	7.06	344.02	6.13
	11	C 1	377.58	12.02	369.01	8.49	354.35	6.95	350.7	6.68	344.13	6.53
	12	C 1	376.93	11.82	368.05	8.48	354.56	6.42	350.78	6.72	344.16	5.89
	13	C 1	377.17	11.38	369.03	7.49	355.59	5.82	351.07	6.94	345.05	6.94
	14	C 1	376.91	10.64	368.09	7.52	355.74	5.47	350.86	6.39	344.59	6.14
	15	C 1	382.37	10.17	372.54	8.51	358.89	6.58	353.35	6.71	346.79	6.09
	16	C 1	395.18	9.44	382.93	9.26	366.66	8.82	358.87	5.96	352.29	6.46
	17	C 1	347.34	10.48	328.1	6.82	315.53	5.99	307.61	6.22	302.18	5.61
ASA(Fillamentum, natural 00118)	**1**	**C 2**	**-37.7**	**8.89**	**-21.52**	**6.13**	**-4.91**	**4.26**	**7.1**	**6.28**	**12.37**	**4.17**
	2	C 2	-37.38	8.75	-22.43	6.44	-5.46	4.91	7.38	4.92	11.4	4.91
	3	C 2	-37.07	8.5	-22.89	6.81	-6.09	5.65	6.63	4.53	11.08	4.8

	4	C 2	-38.12	8.71	-22.94	6.17	-6.02	5.5	6.13	4.89	10.93	4.81
	5	C 2	-37.21	8.7	-23.73	6.5	-6.72	4.35	5.77	4.74	10.13	4.63
	6	C 2	-38.32	9.38	-23.82	6.29	-6.42	4.53	6.25	4.77	10.15	4.92
	7	C 2	-39.15	8.15	-22.79	5.7	-6.3	5.25	5.68	4.69	10.8	4.32
	8	C 2	-38.37	9.76	-21.95	5.74	-5.49	4.44	6.11	4.41	10.56	4.2
	9	C 2	-38.73	8.74	-21.83	6.02	-5.66	4.05	6.74	4.33	10.81	4.63
	10	C 2	-39.33	10.67	-22.92	5.93	-5.73	4.67	7.65	5.21	11.39	5.32
	11	C 2	-37.02	9.75	-23.43	7.32	-5.44	4.44	7.45	4.69	11.24	4.72
	12	C 2	-37.09	8.14	-23.2	6.5	-4.61	3.63	7.32	5.23	11.35	4.08
	13	C 2	-37.11	8.72	-21.68	7.09	-4.34	4.53	7.64	4.93	11.29	4.55
	14	C 2	-36.24	8.46	-21.89	5.12	-4.41	5.39	7.3	4.32	12.09	4.31
	15	C 2	-36.64	8.8	-21.01	6.25	-4.59	4.66	7.43	5.01	12.37	5.17
	16	C 2	-34.92	7.92	-21.21	6.34	-4.2	5.4	7.78	4.77	13.37	4.73
	17	C 2	-25.85	10.32	-15.13	7.17	-2.29	5.79	7.65	5.3	11.38	4.14
VeroBlue Stratasys (OBJ-03204)	**1**	**C 4**	**124.67**	**8.11**	**132.81**	**7.27**	**146.01**	**5.86**	**155.15**	**4.44**	**157.63**	**5.53**
	2	C 4	124.15	8.53	133.41	6.92	146.36	5	154.63	5.57	157.37	4.74
	3	C 4	122.58	8.77	133.41	6.44	145.44	5.55	154.29	5.59	157.28	5.25
	4	C 4	121.24	9.54	134.53	6.89	144.29	5.39	155.19	5.4	157.69	5.39
	5	C 4	121.14	9.62	134.04	7.01	143.94	5.36	155.46	4.24	157.33	5.41
	6	C 4	121.18	8.82	133.81	7.18	144.85	5.39	154.9	5.2	157.45	5.28
	7	C 4	120.96	9.76	133.93	6.69	144.96	4.92	154.44	4.7	157.66	5.18
	8	C 4	120.37	9.86	132.94	6.61	144.55	4.69	154.47	5.71	157.55	5.5
	9	C 4	122.04	8.89	133.6	6.58	145.31	5.01	154.25	4.83	157.41	5.14
	10	C 4	121.13	8.16	133.55	7.22	145.8	4.89	154.45	5.24	157.22	4.91
	11	C 4	120.52	9.28	133.66	7.09	144.52	4.98	153.8	5.79	157.29	4.84
	12	C 4	120.84	7.95	133.91	6.62	144.73	4.81	153.55	5.16	156.08	5.52
	13	C 4	121.11	8.83	132.44	5.99	144.81	5.59	153.68	5.4	156.7	5.1
	14	C 4	119.74	8.79	132.76	6.36	144.92	5.69	153.73	5.7	157.74	5.26
	15	C 4	119.99	10.59	132.63	6.68	143.8	5.06	154.21	4.92	156.85	5.07

	16	C 4	120.92	10.51	132.13	6.2	144.22	5.14	153.53	4.55	156.11	4.81
	17	C 4	115.01	9.38	124.79	6.21	136.77	4.84	145.52	5.22	147.58	5.11
Vero PureWhite Stratasys (OBJ-03327)	**1**	**C 5**	**162.62**	**9.71**	**169.45**	**8.43**	**175.56**	**5.68**	**182.49**	**5.77**	**183.02**	**5.31**
	2	C 5	161.58	9.87	168.66	7.5	175.73	5.8	181.6	5.73	182.39	5.4
	3	C 5	161.54	9.54	168.91	8.08	175.57	5.43	181.55	5.28	182.77	5.76
	4	C 5	160.34	10.78	170.77	7.13	175.1	5.23	181.93	5.33	182.2	5.2
	5	C 5	160.38	10.62	168.76	7.71	174.78	5.45	181.13	5.22	181.73	4.53
	6	C 5	162.32	9.3	169.02	8	174.8	5.39	181.34	5.6	181.94	4.74
	7	C 5	161.16	9.99	168.74	7.57	175.21	5.58	181.22	5.19	182.52	5.57
	8	C 5	161.42	9.47	169.12	8.15	175.79	5.02	182.12	5.93	182.68	5.13
	9	C 5	162.57	9.4	169.37	7.67	175.27	4.68	182.54	5.55	182.77	5.32
	10	C 5	160.66	10.19	170.01	7.93	175.29	5	182.44	4.7	182.34	4.66
	11	C 5	161.45	9.1	169.23	8.05	175.3	5.65	181.28	5.1	181.74	5.65
	12	C 5	163.03	9.33	168.26	6.95	175.49	5.26	181.53	5.34	182.04	5.62
	13	C 5	162.19	9.4	168.1	7.22	175.29	4.95	181.43	4.74	182.4	6
	14	C 5	160.98	9.93	168.48	7.03	175.34	5.19	180.65	4.85	182.54	5.19
	15	C 5	160.71	11.52	169.06	6.89	174.51	4.47	180.2	5.47	182.28	5.17
	16	C 5	159.03	10.36	168.46	7.52	173.11	4.66	179.54	5.92	181.66	5.48
	17	C 5	147.05	9.91	153.62	7.6	159.48	4.85	165.38	6.11	166.58	6.41
Formlabs form 2 elastic resin Formlabs(RS-F2-ELCL-01)	**1**	**C 7**	**21.78**	**9.08**	**33.43**	**7.75**	**47.31**	**5.7**	**58.67**	**4.91**	**61.85**	**5.79**
	2	C 7	20.13	9.25	33.01	6.46	47.03	4.9	57.27	5.3	61.51	5.26
	3	C 7	20.72	9.15	33.86	6.46	45.72	5.26	57.21	4.83	60.94	4.83
	4	C 7	20.8	9.89	32.83	6.98	46.04	4.89	56.58	5.76	60.29	4.99
	5	C 7	18.28	9.44	32.22	6.87	45.98	4.4	56.66	5.4	60.73	5.24
	6	C 7	17.05	8.61	32.37	7.17	45.64	5.27	56.72	5	60.74	5.62
	7	C 7	18.42	9.71	32.47	7.39	44.86	4.97	56.41	4.98	60.48	5.8
	8	C 7	19.52	10.92	33.44	6.83	45.94	5.39	55.97	4.62	60.58	5.11
	9	C 7	20.28	9.12	32.39	7.05	46.36	6.11	57.22	5.43	60.06	5.09
	10	C 7	20.48	7.86	31.97	7.04	47.16	6.04	56.62	5.61	60.5	5.17

	11	C 7	20.76	7.99	32.48	6.79	46.59	5.31	56.36	4.63	61.04	5.16
	12	C 7	19.44	9.12	32.01	6.36	45.98	5.36	56.61	5.18	60.82	5.04
	13	C 7	20.55	10.59	32.84	7.35	46.42	5.63	57.57	5.53	60.24	5.39
	14	C 7	22.4	9.04	33.84	7.47	46.05	4.98	57.48	5.13	59.86	5.88
	15	C 7	21.69	10.01	33.16	7.1	46.6	4.92	57.6	5.19	61.21	5.6
	16	C 7	22.52	11.11	34.42	7.15	47.68	4.69	57.88	6.16	61.84	6.17
	17	C 7	21.48	10.68	31.76	6.91	43.04	5.48	52.52	6.43	55.74	5.19
Formlabs form 2 flexible resin Formlabs (RS-F2-FLGR-02)	**1**	**C 8**	**72.09**	**9.37**	**84.94**	**6.95**	**97.67**	**4.86**	**106.61**	**4.27**	**109.3**	**4.78**
	2	C 8	71.05	8.96	84.47	6.69	95.98	5.06	105.58	4.79	108.77	5.52
	3	C 8	71.1	9.99	83.87	7.29	95.67	4.87	105.38	5.09	108.52	4.47
	4	C 8	70.21	9.41	83.89	6.93	96.47	5.5	104.97	4.68	108.65	5.38
	5	C 8	71.77	9.58	83.61	6.6	95.76	5	104.85	4.75	109.03	5.55
	6	C 8	72.72	9.78	83.96	6.03	95.48	4.84	105.06	4.89	108.62	4.88
	7	C 8	71.42	8.8	83.86	7.4	95.09	4.81	104.77	4.94	107.63	4.62
	8	C 8	71.42	9.49	83.82	6.31	95.6	4.99	105.04	4.68	107.92	5.13
	9	C 8	71.88	8.91	84.2	6.59	95.61	4.9	105.44	4.72	108.37	4.67
	10	C 8	73.53	10.55	84.05	6.37	95.52	5.3	106	4.28	108.59	4.98
	11	C 8	72.94	10.53	83.01	6.14	94.92	5.11	106.01	4.13	108.73	4.36
	12	C 8	71.75	9.59	83.17	7.09	95.84	5.17	106	5.08	108.63	5.06
	13	C 8	70.36	11.47	83.51	6.59	96.18	4.96	105.16	4.75	108.42	5.07
	14	C 8	72.31	9.38	82.7	6.97	95.97	5.13	104.98	5.29	108.49	5.43
	15	C 8	72.67	9.96	83.6	6.86	96.29	5.32	105.7	5.74	108.46	5.3
	16	C 8	71.36	9.83	81.76	6.3	93.79	5.3	103.01	5.82	106.31	5.42
	17	C 8	47.8	10.42	51.9	9.84	59.62	8.49	64.34	9.06	65.94	8.87
TangoPlus Stratasys (OBJ-03224)	**1**	**C 10**	**56.42**	**12.06**	**67**	**6.79**	**77.56**	**5.4**	**88.16**	**6.1**	**90.53**	**5.24**
	2	C 10	53.83	11.38	65.74	7.41	77.01	4.73	86.92	5.38	89.84	5.2
	3	C 10	53.02	11.8	64.39	7.53	77.39	5.63	87.76	4.74	90.83	5.46
	4	C 10	52.35	9.86	64.53	7.99	77.41	5.8	86.94	4.87	89.36	4.71
	5	C 10	53.96	11.07	65.77	7.37	76.39	5.3	87.43	4.98	90.11	5.13

	6	C 10	53.45	9.36	64.74	7.64	76.96	4.69	86.9	5.28	90.39	4.77
	7	C 10	53.6	11.33	65.77	7.55	77.01	5.02	86.72	5.57	90	6.31
	8	C 10	53.18	10.2	66.63	7.33	77.64	4.26	88.37	4.98	90.15	5.45
	9	C 10	53.54	10.23	65.43	7.26	78.36	5.52	87.29	5.08	89.89	4.91
	10	C 10	54.04	10.63	64.26	7.49	78.15	5.38	87.45	5.42	90.33	4.73
	11	C 10	53.19	10.5	64.57	6.27	78.6	4.02	87.21	4.7	90.28	5.2
	12	C 10	53.48	10.72	65.07	6.08	77.95	4.88	86.79	5.61	89.77	5.16
	13	C 10	54.83	10.48	65.52	7.55	77.88	4.74	87.57	5.42	89.78	4.86
	14	C 10	53.55	11.02	65.66	7.7	77.34	5.42	87.61	4.68	89.88	4.41
	15	C 10	54.43	10.08	65.58	6.73	77.6	5.52	87.26	4.31	90.21	5.63
	16	C 10	54.41	11.63	64.74	7.36	76.14	5.8	86.87	5.22	89.48	5.41
	17	C 10	52.68	9.92	63.29	7.01	73.69	4.87	83.89	4.86	87.11	5.28
Formlabs form2 clear resin (RS-F2-GPCL-04)	**1**	**C 11**	**107.96**	**9.6**	**118.78**	**9.06**	**132.44**	**5.4**	**141.23**	**5.52**	**146.08**	**4.75**
	2	C 11	106.32	11.27	117.5	7.84	131.59	5.24	141.6	5.53	145.97	5.74
	3	C 11	106.28	10.99	118	8.62	131.3	4.87	141.49	5.42	145.19	5.56
	4	C 11	107.09	9.85	117.61	9.22	131.19	5.08	141.44	5.47	145.08	4.95
	5	C 11	105.59	11.15	118.3	6.53	130.9	6.25	141.43	4.49	144.63	5.26
	6	C 11	104.76	9.52	118.45	7.16	130.22	5.73	141.21	5.05	144.2	5
	7	C 11	105.57	10.02	118.71	7.04	130.58	5.51	141.25	5.42	144.41	5.95
	8	C 11	107.01	10.22	118.38	7.28	131.61	5.04	141.58	5.47	143.78	5.49
	9	C 11	105.35	9.55	118.33	7.8	131.96	5.06	142.04	5.39	144.26	5.4
	10	C 11	106.47	10.86	118.33	6.63	131.38	5.15	141.31	6.04	143.9	4.85
	11	C 11	104.8	10.82	117.79	7.95	130.36	5.48	141.3	5.4	144.45	4.97
	12	C 11	105.41	10.86	117.52	7.22	131	4.89	140.83	4.98	144.01	5.42
	13	C 11	105.95	12.08	118.62	6.91	131.33	5.32	140.97	5.16	144.52	5.66
	14	C 11	106.11	9.81	119.16	6.45	131.44	4.95	141.08	5.74	144.33	4.99
	15	C 11	106.4	11.04	117.83	6.24	131.12	5.17	141.36	5.15	144.89	5.17
	16	C 11	106.26	9.78	119.1	7.95	130.54	5.34	141.55	5.31	144.26	6.18
	17	C 11	106.64	10.44	117.98	7.52	130.31	5.21	140.72	5.53	143.87	5.01

VeroClear Stratasys (OBJ-03271)	**1**	**C 12**	**101.55**	**9.99**	**114.91**	**7.92**	**129.81**	**5.02**	**140.29**	**6.19**	**143.57**	**5.19**
	2	C 12	101.09	11.84	112.6	8.31	129.67	5.12	140	5.29	142.74	5.53
	3	C 12	100.91	10.09	112.94	8.8	128.25	7	139.61	6.68	142.6	6.61
	4	C 12	102.36	10.22	115.32	6.1	129.66	5.95	140.75	5.63	144.48	5.28
	5	C 12	102.66	10.14	114.84	7.4	129.35	5.08	139.98	5.16	144.38	4.44
	6	C 12	102.62	11.4	114.59	7.58	129.22	5.08	141.09	5.17	144.15	5.24
	7	C 12	100.7	10.26	114.9	8.75	129.19	5.22	141.19	5.13	143.23	6
	8	C 12	101.9	10.21	116.32	7.56	129.72	5.49	141.38	5.93	143.39	4.32
	9	C 12	102.11	9.31	115.81	6.81	130.46	5.48	140.95	4.9	144.02	4.93
	10	C 12	102.91	11.71	115.51	7.1	130.16	5.18	139.92	4.9	144.01	5.61
	11	C 12	100.79	11.82	114.19	7.23	129.36	4.63	139.26	4.71	143.26	5.28
	12	C 12	99.47	10.9	113.7	7.06	129.49	5.39	139.53	5.12	142.35	4.62
	13	C 12	101.02	11.74	114.51	7.18	129.01	5.26	139.55	4.76	143.86	4.63
	14	C 12	102.77	11.16	116.12	7.6	128.21	5.3	139.55	4.48	143.47	4.55
	15	C 12	100.51	10.94	114.31	7.37	129.02	4.53	140.29	5.15	143.63	4.94
	16	C 12	100.52	11.13	114.22	7.05	128.45	5.29	139.42	5.4	142.47	5.89
	17	C 12	98.56	11.81	110.61	9.45	125.97	5.45	136.91	6.4	139.78	5.12
HU of water on the periphery of the plate	1	Water_p	4.03	9.59	5.06	6.65	3.2	5.32	5.16	4.54	2.98	5.1
	2	Water_p	4.82	8.99	5.28	6.17	2.9	5.12	4.74	4.92	2.92	4.5
	3	Water_p	4.35	9.67	4.8	6.7	2.81	4.97	4.44	4.93	3.25	4.81
	4	Water_p	4.18	9.99	4.84	7.48	3.01	5.38	5.08	5.09	3.46	5.07
	5	Water_p	4.66	9.7	4.4	6.76	2.42	5.38	5.11	4.51	3.29	4.63
	6	Water_p	4.51	10.21	4.09	6.91	2.69	4.78	5.04	4.47	3.24	5.02
	7	Water_p	4.41	9.76	4.07	7.5	2.36	4.98	4.95	4.98	3.55	4.91
	8	Water_p	4.66	9.77	4.84	6.73	2.71	5.35	5.12	4.96	3.67	4.72
	9	Water_p	4.56	9.93	4.6	6.64	2.86	4.43	4.89	4.68	3.01	5.18
	10	Water_p	4.21	9.58	4.21	7.01	3.39	5.19	4.79	4.77	3.06	4.78
	11	Water_p	4.56	9.44	3.99	6.69	3.21	4.54	4.63	5.09	2.89	5.23
	12	Water_p	5.2	9.43	4.7	6.11	3.4	4.61	4.9	4.65	2.79	5.14

	13	Water_p	4.61	9.93	3.89	6.83	3.4	5.06	4.67	5.08	3	5.36
	14	Water_p	4.98	9.22	4.33	6.29	3.07	4.96	4.64	4.53	3.11	5.36
	15	Water_p	4.61	9	4.28	7.11	3.05	4.74	4.9	4.9	2.93	5.26
	16	Water_p	5.07	10.29	4.55	6.71	3.03	5	4.65	4.83	3.12	4.98
	17	Water_p	4.48	8.7	4.61	6.6	2.46	4.89	4.3	4.54	2.74	4.75
HU of water on the center of the plate	1	Water_c	-1.16	11.61	-2.04	7.09	-2.86	5.67	-1.52	5.31	-2.93	5.43
	2	Water_c	-2.5	10.8	-2.83	7.75	-3.78	4.89	-2.05	5.15	-3.59	5.2
	3	Water_c	-2.76	10.54	-3.01	7.12	-4.5	4.79	-1.92	5.06	-3.59	5.08
	4	Water_c	-2.3	10.63	-2.69	7.21	-4.56	5.46	-2.08	5	-3.94	5.11
	5	Water_c	-1.63	10.52	-2.88	6.91	-4.76	4.98	-1.96	5.03	-4.13	5.14
	6	Water_c	-2.04	10.19	-2.75	6.86	-4.24	4.96	-1.89	5.18	-4.29	5.01
	7	Water_c	-3.13	10.87	-2.87	7.39	-4.07	5.07	-2.04	5.31	-3.62	5.15
	8	Water_c	-2.38	10.42	-2.95	7.58	-4.56	4.76	-2.33	4.86	-3.96	4.91
	9	Water_c	-2.58	10.54	-2.26	7.57	-4.08	5.15	-2.14	4.82	-3.76	4.87
	10	Water_c	-2.2	10.22	-3.41	7.03	-4.31	5.14	-2.08	4.78	-4.55	5.28
	11	Water_c	-2.3	10.79	-2.89	7.04	-4.1	4.88	-2.44	4.77	-4.24	5.04
	12	Water_c	-2.1	9.72	-3.03	6.73	-4.57	4.61	-2.51	4.48	-4.11	5.04
	13	Water_c	-2.28	11.25	-2.46	7.43	-4.2	5.28	-1.94	5.18	-3.83	5.08
	14	Water_c	-2.87	9.44	-2.77	7.11	-4.22	5.2	-2.38	4.76	-4.11	4.82
	15	Water_c	-2.73	10.87	-3.9	7.16	-4.24	5.06	-2.4	4.8	-3.97	5.03
	16	Water_c	-3.31	10.99	-3.23	7.02	-4.1	5.15	-2.65	5.21	-4.32	5.28
	17	Water_c	-3.56	10.74	-2.53	7.15	-4.18	4.96	-2.15	4.79	-3.73	5.05

Table 31. Hounsfield units measurement of the cylinders on Plate B bottom side (HU of water subtracted)

Material	Slice	Position	Hounsfield units under different kV									
			70 kV		80 kV		100 kV		120 kV		140 kV	
			Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
GreenTEC Pro natural(Extrudr, 9010241426034)	**1**	**C 1**	**374**	**15.2**	**363**	**11.1**	**353**	**8.5**	**346**	**7.8**	**343**	**8.2**
	2	C 1	373	14.5	363	12.2	352	8.7	346	8.6	342	7.7
	3	C 1	373	14.2	364	12.4	352	7.9	346	8.4	342	8.4
	4	C 1	372	13.2	364	11.1	352	8.4	345	9.0	341	8.1
	5	C 1	373	13.3	364	11.0	354	9.1	346	8.4	341	8.1
	6	C 1	372	15.6	364	11.3	352	8.9	345	8.6	341	8.5
	7	C 1	373	15.8	364	12.0	353	8.8	346	8.4	341	8.1
	8	C 1	372	14.1	362	10.4	352	8.6	346	8.7	341	8.2
	9	C 1	372	14.7	364	10.6	352	8.5	346	8.1	342	8.4
	10	C 1	373	15.5	365	10.7	352	10.1	347	8.5	341	7.8
	11	C 1	373	15.3	365	10.8	351	8.3	346	8.4	341	8.4
	12	C 1	372	15.1	363	10.5	351	7.9	346	8.2	341	7.8
	13	C 1	373	15.1	365	10.1	352	7.7	346	8.6	342	8.8
	14	C 1	372	14.1	364	9.8	353	7.4	346	7.8	341	8.2
	15	C 1	378	13.6	368	11.1	356	8.1	348	8.3	344	8.0
	16	C 1	390	14.0	378	11.4	364	10.1	354	7.7	349	8.2
	17	C 1	343	13.6	323	9.5	313	7.7	303	7.7	299	7.4
ASA(Fillamentum, natural 00118)	**1**	**C 2**	**-42**	**13.1**	**-27**	**9.0**	**-8**	**6.8**	**2**	**7.7**	**9**	**6.6**
	2	C 2	-42	12.5	-28	8.9	-8	7.1	3	7.0	8	6.7
	3	C 2	-41	12.9	-28	9.6	-9	7.5	2	6.7	8	6.8

	4	C 2	-42	13.3	-28	9.7	-9	7.7	1	7.1	7	7.0
	5	C 2	-42	13.0	-28	9.4	-9	6.9	1	6.5	7	6.5
	6	C 2	-43	13.9	-28	9.3	-9	6.6	1	6.5	7	7.0
	7	C 2	-44	12.7	-27	9.4	-9	7.2	1	6.8	7	6.5
	8	C 2	-43	13.8	-27	8.8	-8	7.0	1	6.6	7	6.3
	9	C 2	-43	13.2	-26	9.0	-9	6.0	2	6.4	8	6.9
	10	C 2	-44	14.3	-27	9.2	-9	7.0	3	7.1	8	7.2
	11	C 2	-42	13.6	-27	9.9	-9	6.4	3	6.9	8	7.0
	12	C 2	-42	12.5	-28	8.9	-8	5.9	2	7.0	9	6.6
	13	C 2	-42	13.2	-26	9.8	-8	6.8	3	7.1	8	7.0
	14	C 2	-41	12.5	-26	8.1	-7	7.3	3	6.3	9	6.9
	15	C 2	-41	12.6	-25	9.5	-8	6.6	3	7.0	9	7.4
	16	C 2	-40	13.0	-26	9.2	-7	7.4	3	6.8	10	6.9
	17	C 2	-30	13.5	-20	9.7	-5	7.6	3	7.0	9	6.3
	1	**C 4**	**121**	**12.6**	**128**	**9.9**	**143**	**7.9**	**150**	**6.4**	**155**	**7.5**
	2	C 4	119	12.4	128	9.3	143	7.2	150	7.4	154	6.5
	3	C 4	118	13.1	129	9.3	143	7.5	150	7.5	154	7.1
	4	C 4	117	13.8	130	10.2	141	7.6	150	7.4	154	7.4
	5	C 4	116	13.7	130	9.7	142	7.6	150	6.2	154	7.1
	6	C 4	117	13.5	130	10.0	142	7.2	150	6.9	154	7.3
VeroBlue Stratasys (OBJ-03204)	7	C 4	117	13.8	130	10.1	143	7.0	149	6.8	154	7.1
	8	C 4	116	13.9	128	9.4	142	7.1	149	7.6	154	7.2
	9	C 4	117	13.3	129	9.3	142	6.7	149	6.7	154	7.3
	10	C 4	117	12.6	129	10.1	142	7.1	150	7.1	154	6.9
	11	C 4	116	13.2	130	9.7	141	6.7	149	7.7	154	7.1
	12	C 4	116	12.3	129	9.0	141	6.7	149	6.9	153	7.5
	13	C 4	117	13.3	129	9.1	141	7.5	149	7.4	154	7.4
	14	C 4	115	12.7	128	8.9	142	7.5	149	7.3	155	7.5
	15	C 4	115	13.9	128	9.8	141	6.9	149	6.9	154	7.3

	16	C 4	116	14.7	128	9.1	141	7.2	149	6.6	153	6.9
	17	C 4	111	12.8	120	9.1	134	6.9	141	6.9	145	7.0
Vero PureWhite Stratasys (OBJ-03327)	**1**	**C 5**	**159**	**13.6**	**164**	**10.7**	**172**	**7.8**	**177**	**7.3**	**180**	**7.4**
	2	C 5	157	13.4	163	9.7	173	7.7	177	7.6	179	7.0
	3	C 5	157	13.6	164	10.5	173	7.4	177	7.2	180	7.5
	4	C 5	156	14.7	166	10.3	172	7.5	177	7.4	179	7.3
	5	C 5	156	14.4	164	10.3	172	7.7	176	6.9	178	6.5
	6	C 5	158	13.8	165	10.6	172	7.2	176	7.2	179	6.9
	7	C 5	157	14.0	165	10.7	173	7.5	176	7.2	179	7.4
	8	C 5	157	13.6	164	10.6	173	7.3	177	7.7	179	7.0
	9	C 5	158	13.7	165	10.1	172	6.4	178	7.3	180	7.4
	10	C 5	156	14.0	166	10.6	172	7.2	178	6.7	179	6.7
	11	C 5	157	13.1	165	10.5	172	7.2	177	7.2	179	7.7
	12	C 5	158	13.3	164	9.3	172	7.0	177	7.1	179	7.6
	13	C 5	158	13.7	164	9.9	172	7.1	177	6.9	179	8.0
	14	C 5	156	13.6	164	9.4	172	7.2	176	6.6	179	7.5
	15	C 5	156	14.6	165	9.9	171	6.5	175	7.3	179	7.4
	16	C 5	154	14.6	164	10.1	170	6.8	175	7.6	179	7.4
	17	C 5	143	13.2	149	10.1	157	6.9	161	7.6	164	8.0
Formlabs form 2 elastic resin Formlabs(RS-F2-ELCL-01)	**1**	**C 7**	**18**	**13.2**	**28**	**10.2**	**44**	**7.8**	**54**	**6.7**	**59**	**7.7**
	2	C 7	15	12.9	28	8.9	44	7.1	53	7.2	59	6.9
	3	C 7	16	13.3	29	9.3	43	7.2	53	6.9	58	6.8
	4	C 7	17	14.1	28	10.2	43	7.3	52	7.7	57	7.1
	5	C 7	14	13.5	28	9.6	44	7.0	52	7.0	57	7.0
	6	C 7	13	13.4	28	10.0	43	7.1	52	6.7	58	7.5
	7	C 7	14	13.8	28	10.5	43	7.0	51	7.0	57	7.6
	8	C 7	15	14.7	29	9.6	43	7.6	51	6.8	57	7.0
	9	C 7	16	13.5	28	9.7	44	7.5	52	7.2	57	7.3
	10	C 7	16	12.4	28	9.9	44	8.0	52	7.4	57	7.0

	11	C 7	16	12.4	28	9.5	43	7.0	52	6.9	58	7.3
	12	C 7	14	13.1	27	8.8	43	7.1	52	7.0	58	7.2
	13	C 7	16	14.5	29	10.0	43	7.6	53	7.5	57	7.6
	14	C 7	17	12.9	30	9.8	43	7.0	53	6.8	57	8.0
	15	C 7	17	13.5	29	10.0	44	6.8	53	7.1	58	7.7
	16	C 7	17	15.1	30	9.8	45	6.9	53	7.8	59	7.9
	17	C 7	17	13.8	27	9.6	41	7.3	48	7.9	53	7.0
Formlabs form 2 flexible resin Formlabs (RS-F2-FLGR-02)	**1**	**C 8**	**68**	**13.4**	**80**	**9.6**	**94**	**7.2**	**101**	**6.2**	**106**	**7.0**
	2	C 8	66	12.7	79	9.1	93	7.2	101	6.9	106	7.1
	3	C 8	67	13.9	79	9.9	93	7.0	101	7.1	105	6.6
	4	C 8	66	13.7	79	10.2	93	7.7	100	6.9	105	7.4
	5	C 8	67	13.6	79	9.4	93	7.3	100	6.6	106	7.2
	6	C 8	68	14.1	80	9.2	93	6.8	100	6.6	105	7.0
	7	C 8	67	13.1	80	10.5	93	6.9	100	7.0	104	6.7
	8	C 8	67	13.6	79	9.2	93	7.3	100	6.8	104	7.0
	9	C 8	67	13.3	80	9.4	93	6.6	101	6.6	105	7.0
	10	C 8	69	14.3	80	9.5	92	7.4	101	6.4	106	6.9
	11	C 8	68	14.1	79	9.1	92	6.8	101	6.6	106	6.8
	12	C 8	67	13.4	78	9.4	92	6.9	101	6.9	106	7.2
	13	C 8	66	15.2	80	9.5	93	7.1	100	7.0	105	7.4
	14	C 8	67	13.2	78	9.4	93	7.1	100	7.0	105	7.6
	15	C 8	68	13.4	79	9.9	93	7.1	101	7.5	106	7.5
	16	C 8	66	14.2	77	9.2	91	7.3	98	7.6	103	7.4
	17	C 8	43	13.6	47	11.8	57	9.8	60	10.1	63	10.1
TangoPlus Stratasys (OBJ-03224)	**1**	**C 10**	**58**	**16.7**	**69**	**9.8**	**80**	**7.8**	**90**	**8.1**	**93**	**7.5**
	2	C 10	56	15.7	69	10.7	81	6.8	89	7.4	93	7.4
	3	C 10	56	15.8	67	10.4	82	7.4	90	6.9	94	7.5
	4	C 10	55	14.5	67	10.8	82	8.0	89	7.0	93	6.9
	5	C 10	56	15.3	69	10.1	81	7.3	89	7.1	94	7.3

	6	C 10	55	13.8	67	10.3	81	6.8	89	7.4	95	6.9
	7	C 10	57	15.7	69	10.6	81	7.1	89	7.7	94	8.1
	8	C 10	56	14.6	70	10.5	82	6.4	91	7.0	94	7.3
	9	C 10	56	14.7	68	10.5	82	7.5	89	7.0	94	6.9
	10	C 10	56	14.7	68	10.3	82	7.4	90	7.2	95	7.1
	11	C 10	55	15.1	67	9.4	83	6.3	90	6.7	95	7.2
	12	C 10	56	14.5	68	9.1	83	6.7	89	7.2	94	7.2
	13	C 10	57	15.4	68	10.6	82	7.1	90	7.5	94	7.0
	14	C 10	56	14.5	68	10.5	82	7.5	90	6.7	94	6.5
	15	C 10	57	14.8	69	9.8	82	7.5	90	6.5	94	7.5
	16	C 10	58	16.0	68	10.2	80	7.8	90	7.4	94	7.6
	17	C 10	56	14.6	66	10.0	78	7.0	86	6.8	91	7.3
Formlabs form2 clear resin (RS-F2-GPCL-04)	**1**	**C 11**	**109**	**15.1**	**121**	**11.5**	**135**	**7.8**	**143**	**7.7**	**149**	**7.2**
	2	C 11	109	15.6	120	11.0	135	7.2	144	7.6	150	7.7
	3	C 11	109	15.2	121	11.2	136	6.8	143	7.4	149	7.5
	4	C 11	109	14.5	120	11.7	136	7.5	144	7.4	149	7.1
	5	C 11	107	15.3	121	9.5	136	8.0	143	6.7	149	7.4
	6	C 11	107	13.9	121	9.9	134	7.6	143	7.2	148	7.1
	7	C 11	109	14.8	122	10.2	135	7.5	143	7.6	148	7.9
	8	C 11	109	14.6	121	10.5	136	6.9	144	7.3	148	7.4
	9	C 11	108	14.2	121	10.9	136	7.2	144	7.2	148	7.3
	10	C 11	109	14.9	122	9.7	136	7.3	143	7.7	148	7.2
	11	C 11	107	15.3	121	10.6	134	7.3	144	7.2	149	7.1
	12	C 11	108	14.6	121	9.9	136	6.7	143	6.7	148	7.4
	13	C 11	108	16.5	121	10.1	136	7.5	143	7.3	148	7.6
	14	C 11	109	13.6	122	9.6	136	7.2	143	7.5	148	6.9
	15	C 11	109	15.5	122	9.5	135	7.2	144	7.0	149	7.2
	16	C 11	110	14.7	122	10.6	135	7.4	144	7.4	149	8.1
	17	C 11	110	15.0	121	10.4	134	7.2	143	7.3	148	7.1

VeroClear Stratasys (OBJ-03271)	**1**	**C 12**	**103**	**15.3**	**117**	**10.6**	**133**	**7.6**	**142**	**8.2**	**147**	**7.5**
	2	C 12	104	16.0	115	11.4	133	7.1	142	7.4	146	7.6
	3	C 12	104	14.6	116	11.3	133	8.5	142	8.4	146	8.3
	4	C 12	105	14.7	118	9.4	134	8.1	143	7.5	148	7.3
	5	C 12	104	14.6	118	10.1	134	7.1	142	7.2	149	6.8
	6	C 12	105	15.3	117	10.2	133	7.1	143	7.3	148	7.2
	7	C 12	104	14.9	118	11.5	133	7.3	143	7.4	147	7.9
	8	C 12	104	14.6	119	10.7	134	7.3	144	7.7	147	6.5
	9	C 12	105	14.1	118	10.2	135	7.5	143	6.9	148	6.9
	10	C 12	105	15.5	119	10.0	134	7.3	142	6.8	149	7.7
	11	C 12	103	16.0	117	10.1	133	6.7	142	6.7	148	7.3
	12	C 12	102	14.6	117	9.8	134	7.1	142	6.8	146	6.8
	13	C 12	103	16.3	117	10.3	133	7.5	141	7.0	148	6.9
	14	C 12	106	14.6	119	10.4	132	7.4	142	6.5	148	6.6
	15	C 12	103	15.4	118	10.3	133	6.8	143	7.0	148	7.1
	16	C 12	104	15.6	117	9.9	133	7.4	142	7.5	147	7.9
	17	C 12	102	16.0	113	11.9	130	7.4	139	8.0	144	7.2

Table 32. Hounsfield units measurement of the cylinder on Plate Atop side (include the HU of water)

Material	Slice	Position	Hounsfield units under different kV									
			70 kV		80 kV		100 kV		120 kV		140 kV	
			Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
RGD 525Stratasys(OBJ-03256)	**1**	**C 1**	**114.94**	**8.69**	**127.09**	**7.13**	**137.66**	**6.36**	**147.13**	**6.24**	**150.26**	**6.07**
	2	C 1	108.97	9.14	121.26	7.76	132.65	4.8	140.43	5.44	143.15	5.34
	3	C 1	108	10.25	118.76	6.66	131.15	5	139.73	5.64	142.36	5.37
	4	C 1	108.7	9.66	118.35	6.33	130.21	5.16	140.1	4.9	142.16	5.25
	5	C 1	108.99	8.61	118.16	6.53	130.34	5.2	140.17	5.12	141.56	4.65
	6	C 1	108.8	8.4	119.08	6.13	130.21	4.86	139.77	5.16	141.72	4.29
	7	C 1	108.92	10.48	120.43	6.06	131	4.84	139.89	4.58	142.84	5.01
	8	C 1	110.18	9.99	120.29	5.76	130.43	4.94	140.21	5.34	142.89	5.23
	9	C 1	109.47	10.76	119.53	6.54	131.23	4.67	140.83	5.5	142.52	5.37
	10	C 1	108.69	9.18	120.57	6.86	131.43	5.07	141.25	5	142.5	5.01
	11	C 1	109.62	9.74	120.51	7.36	131.84	4.5	140.69	6.05	143.06	5.09
	12	C 1	110.05	10.24	121.14	6.68	131.95	5.55	140.75	5.01	142.91	5.3
	13	C 1	110.19	11.09	119.93	6.6	132.18	4.68	141.09	5.14	142.68	5.27
	14	C 1	110.75	9.11	120.95	6.56	132.67	5.51	141.28	5.35	144.2	4.58
	15	C 1	110.35	9.1	120.86	5.45	132.85	4.43	142.45	5	145.17	5.33
	16	C 1	111.23	9.18	121.69	6.62	133.39	4.92	143.71	5.35	146.36	4.91
	17	C 1	111.17	10.68	123.71	6.49	133.93	5.9	144.61	4.55	147.71	4.9
	18	C 1	114.77	10.5	127.95	6.45	136.84	4.28	148.33	4.87	151.64	5.08
HU of water on the periphery of	1	Water_p	4.5	8.99	4.76	6.77	3.22	4.63	4.75	4.55	3.08	4.73
	2	Water_p	4.7	9.85	4.53	6.36	3.08	5.1	4.92	4.82	3.16	4.76
	3	Water_p	5.65	9.1	4.57	6.55	2.88	4.94	4.86	4.88	3.69	4.81

the plate	4	Water_p	5.06	9.68	4.66	6.16	2.96	4.53	4.92	5.04	3.68	4.92
	5	Water_p	4.56	9.28	5.05	7.01	2.91	4.61	5.24	4.81	4.16	4.97
	6	Water_p	5.43	9.13	4.73	6.39	3.02	4.83	5.37	4.66	3.98	4.92
	7	Water_p	4.85	8.81	5.19	6.97	3.57	5.03	5.6	4.77	3.81	5.4
	8	Water_p	4.33	9.54	4.98	6.91	3.78	4.54	5.71	5.13	3.85	5.12
	9	Water_p	5.16	10.41	4.84	7.17	3.4	5.17	4.8	5.06	3.49	4.74
	10	Water_p	4.07	10.1	4.75	7.07	3.49	5.23	4.72	4.94	3.14	4.72
	11	Water_p	4.58	10.28	4.54	6.28	3.55	5.05	4.85	4.76	3.51	4.95
	12	Water_p	5.05	9.37	4.86	6.35	3.56	5.02	5.34	4.72	3.49	4.82
	13	Water_p	5.34	9.19	4.9	6.83	3.11	5.12	5.35	4.92	3.9	5.03
	14	Water_p	5.26	9.93	5.3	6.7	3.24	5.18	5.57	4.96	4.08	5.33
	15	Water_p	5.33	9.83	5.53	6.53	3.33	4.9	5.73	4.88	4.23	5.34
	16	Water_p	5.18	9.67	5.64	7.08	3.67	5.03	6.05	4.91	4.29	5.7
	17	Water_p	4.61	9.38	5.78	7.89	4.1	5.71	6.46	5.47	4.42	5.66
	18	Water_p	6.16	9.58	6.48	6.97	4.71	5.79	6.9	5.57	5.53	5.46
HU of water on the center of the plate	1	Water_c	-1.94	10.44	-2.35	6.99	-3.04	5.02	-0.96	4.9	-2.57	5.16
	2	Water_c	-2.11	10.02	-0.83	7.73	-2.93	5.14	-1.35	4.96	-2.68	5.11
	3	Water_c	-1.5	9.87	-1.08	7.04	-3.19	4.93	-1.38	4.75	-3.14	4.97
	4	Water_c	-0.53	10.84	-1.41	7.09	-2.75	4.72	-1.26	5.01	-3.01	5.19
	5	Water_c	-1.27	11.5	-1.22	8.28	-3.04	4.76	-0.55	4.87	-2.62	5.17
	6	Water_c	-0.87	10.68	-1.9	7.27	-3.68	4.68	-1.21	4.72	-2.34	5.12
	7	Water_c	-1.21	9.99	-0.56	7.36	-3.47	5.05	-0.47	5.28	-2.16	5.19
	8	Water_c	-1.51	10.65	-1.15	7.04	-2.96	5.49	-0.98	4.72	-2.96	5.29
	9	Water_c	-2.29	10.76	-2.35	7.63	-3.37	5.1	-1.8	4.92	-3.31	5.35
	10	Water_c	-2.28	10.39	-2.31	6.87	-3.32	5.25	-1.65	4.98	-3.27	5.33
	11	Water_c	-1.62	10.65	-1.96	6.65	-2.96	4.98	-1.15	4.96	-3.02	5.15
	12	Water_c	-1.32	10.82	-2.32	7.52	-2.94	5.07	-0.83	4.68	-2.85	5.38
	13	Water_c	-1.95	10.51	-1.8	7.37	-3.5	4.61	-1.07	4.99	-3.08	5.22
	14	Water_c	-2.07	10.71	-2.13	6.99	-3.03	5.21	-1.06	4.83	-2.63	4.94

	15	Water_c	-1.67	9.93	-2.34	6.98	-3.22	5	-0.96	4.78	-2.42	4.94
	16	Water_c	-1.32	10.3	-1.59	7.03	-2.58	4.66	-1.12	4.86	-2.99	5.03
	17	Water_c	-1.51	10.66	-1.83	7.26	-3.06	4.7	-0.64	4.93	-2.64	5.39
	18	Water_c	-0.94	10.12	-1.2	7.03	-2.42	4.58	-0.77	5.16	-2.27	4.77

Table 33. Hounsfield units measurement of the cylinder on Plate Atop side (HU of water subtracted)

Material	**Slice**	**Position**	**Hounsfield units under different kV**									
			70 kV		**80 kV**		**100 kV**		**120 kV**		**140 kV**	
			Mean	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
RGD 525Stratasys(OBJ-03256)	**1**	**C 1**	**110**	**12.5**	**122**	**9.8**	**134**	**7.9**	**147**	**7.7**	**147**	**7.7**
	2	C 1	104	13.4	117	10.0	130	7.0	140	7.3	140	7.2
	3	C 1	102	13.7	114	9.3	128	7.0	140	7.5	139	7.2
	4	C 1	104	13.7	114	8.8	127	6.9	140	7.0	138	7.2
	5	C 1	104	12.7	113	9.6	127	6.9	140	7.0	137	6.8
	6	C 1	103	12.4	114	8.9	127	6.9	140	7.0	138	6.5
	7	C 1	104	13.7	115	9.2	127	7.0	140	6.6	139	7.4
	8	C 1	106	13.8	115	9.0	127	6.7	140	7.4	139	7.3
	9	C 1	104	15.0	115	9.7	128	7.0	141	7.5	139	7.2
	10	C 1	105	13.6	116	9.9	128	7.3	141	7.0	139	6.9
	11	C 1	105	14.2	116	9.7	128	6.8	141	7.7	140	7.1
	12	C 1	105	13.9	116	9.2	128	7.5	141	6.9	139	7.2
	13	C 1	105	14.4	115	9.5	129	6.9	141	7.1	139	7.3
	14	C 1	105	13.5	116	9.4	129	7.6	141	7.3	140	7.0

	15	C 1	105	13.4	115	8.5	130	6.6	142	7.0	141	7.5
	16	C 1	106	13.3	116	9.7	130	7.0	144	7.3	142	7.5
	17	C 1	107	14.2	118	10.2	130	8.2	145	7.1	143	7.5
	18	C 1	109	14.2	121	9.5	132	7.2	148	7.4	146	7.5