VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

MECHANIKOS FAKULTETAS

POLIGRAFINIŲ MAŠINŲ KATEDRA

Paulius Sviackevičius

3D SPAUSDINAMO OBJEKTO, KURIAMO DERINANT PLASTIKĄ IR TAKIAS MEDŽIAGAS, SAVYBIŲ TYRIMAS
RESEARCH OF PROPERTIES OF 3D PRINTED OBJECT, PRESENTED IN A COMBINATION OF PLASTIC AND FLOWABLE SUBSTANCES

Baigiamasis magistro darbas

Spaudos inžinerijos studijų programa, valstybinis kodas 612H74001

Gamybos inžinerijos studijų kryptis

Vilnius, 2017

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Katedros vedėjas

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Paulius Sviackevičius

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BAIGIAMOJO MAGISTRO DARBO
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Atlikti 3D spausdinto sudėtinio objekto (derinančio savyje plastiką – norimai objekto formai palaikyti, ir takią medžiagą - reaguojančią į aplinkos poveikį) kintančių savybių tyrimą.
Komplektuoti tyrimams atlikti reikalingą įrangą (sukuriant reikiamą 3D spausdintuvą); Objekto formai 3D spaudos būdas – medžiagos ekstruzija (FDM/FFF) ; medžiaga – polimerai (PLA). Taki medžiaga magneto reologinis skystis.
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Author	**Paulius Sviackevičius**
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Thesis language: English

Annotation

"Smart" products occupy even greater space in our lives every day. Their abilities to accomplish extraordinary tasks brings new opportunities. More and more focus is being put into research and development of such products. This is where 3D printing steps in. In this work, rigidity was being tested of specimens, composed of stiff polymers (ABS, PETG) and maghetorheological liquid, under magnetic field of different strength. To manufacture these specimens, special RepRap style 3D printer was developed, which was based on Fused Filament Fabrication (FFF) and material extrusion principles. Specimens were mounted into stove and pulled to measure force of resistance. Magnetic field of different strength was created by using ceramic or neodymium magnets and by changing their position and orientation. Found relations between load and displacement were described in the work. A change in rigidity was found not only after changing magnet's place or type, but also after changing its orientation.

Keywords: 3D printing, smart, functional printing, magnetorheological, MR liquid

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Pavadinimas **3D spausdinto objekto, kuriamo derinant plastiką ir takias medžiagas, savybių tyrimas**

Autorius **Paulius Sviackevičius**
Vadovas **Eugenijus Jurkonis**

Kalba: anglų

Anotacija

Išmanieji produktai užima vis daugiau vietos mūsų gyvenimuose. Jų savybės atlikti jiems neįprastas, bet svarbias užduotis suteikia vis naujas galimybes. Vis daugiau dėmesio yra skiriama į tokių produktų kūrimą ir vystymą. Tuo tarpu 3D spausdinimas čia atveria naujas galimybes. Darbo metu buvo tiriama bandinių, sudarytų iš kieto polimero (ABS, PETG) ir magnetoreologinio skysčio, standumas, esant skirtingam magnetiniam laukui. Bandiniams pagaminti buvo sukurtas specialus RepRap tipo 3D spausdintuvas, pagrįstas kieto polimero ekstruzijos (FFF) ir skystos medžiagos ekstruzijos principais. Bandiniai buvo įtvirtinami į stovą ir tempiami, matuojant jų pasipriešinimo jėgą. Skirtingas magnetinis laukas buvo sukuriamas naudojant keramikinį ir neodyminį magnetą bei keičiant jų pozicijas. Gautos apkrovos priklausomybės nuo poslinkio aprašytos darbe. Pastebėtas standumo pokytis esant ne tik skirtingai magneto padėčiai ir jo stiprumui, bet ir jo orientacijai.

Prasminiai žodžiai: 3D spausdinimas, išmanusis, funkcionalusis spausdinimas, magnetoreologinis, MR skystis

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Mano darbo vadovas doc. dr. Eugenijus Jurkonis.

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(Parašas)

Paulius Sviackevičius

(Vardas ir pavardė)

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Abbreviations

3D – **Three D**imensional
AM – **A**dditive **M**anufacturing
RP – **R**apid **P**rototyping
DLP – **D**igital **L**ight **P**rocessing
CAD – **C**omputer-**A**ided-**D**esign
HD – **H**igh **D**efinition
ABS – Type of copolymer, made from **A**crylonitrile 1,3-**B**utadiene and **S**tyrene monomers.
PLA – **P**oly**L**actic **A**cid
PETG – **G**lycol-modified **P**oly**E**thylene **T**erephthalate
HIPS – **H**igh **I**mpact **P**oly**S**tyrene.
SFF – **S**olid **F**reeform **F**abrication
MEMS – **M**icro **E**lectro-**M**echanical **S**ystems
UPC – **U**niversal **P**roduct **C**ode
RFID – **R**adio-**F**requency **Id**entification
FDM – **F**used **D**eposition **M**odelling
FFF – **F**used **F**ilament **F**abrication
MR – **M**agneto**r**heological
HDD – **H**ard **D**isk **D**rive

Abstract

Smart materials have been known for a while now and are widely used. Parts and mechanisms with such materials enable them to possess abilities, which regular devices do not have. It allows one device to have functions, which would otherwise require a whole set of different machines, but production cost of such units is still high. This is where 3D printing steps in.

Additive manufacturing allows us to produce parts, would otherwise be impossible. It not only allows us to create objects of simpler design, but also reduces production cost and time, when small-batch production is required. Although AM industry has improved a lot in the past few decades, much research is still needed to improve these processes even further and allow the use of more materials. One of trending research directions is functional printing.

Functional printing allows fabricating parts, which would immediately be functional or have certain mechanical or chemical abilities. In other words, allows fabrication of smart materials. Such technologies often use several materials, which may be completely different, exempli gratia, solid and liquid, chemically active and inert, magnetically sensitive and not.

Aim of the work – to investigate properties of a designed model, composed of two different materials, one of which is visco-elastic fluid, under effects of external magnetic field. Investigate how stiffness of two-material composite model changes under different strength of external magnetic field.

Objectives:

1. Design a test model, which would be a composite of two different materials, stiff polymer, used in FDM/FFF processes and magnetorheological fluid.
2. Design and build a 3D printing system that is capable of printing with two different materials simultaneously to print designed models with.
3. Print designed models, comprised of stiff polymer and MR fluid.
4. Conduct experiments to investigate correlation between strength of active magnetic field and model's stiffness.

Presentation of results.

Sviackevičius, P., Verbickaitė, E., Jurkonis, E., *Research of properties of 3d printed object, presented in a combination of plastic and flowable substances,* 20th annual young scientist conference "Science – future of Lithuania", held on 2017 april 28th, VGTU.

I. INTRODUCTION

AM technologies

Additive manufacturing is an entirety of different technologies, including Rapid Prototyping and 3D printing, which all share similar principle of creating things. Rapid prototyping is oriented to fast and cheap production of parts, which could later be developed for mass production. Its ability to transform digital model into material form cheaply and rapidly makes this technology irreplaceable, whether it's used in manufacturing or household [3].

First successful additive manufacturing process by P.A. Ciraud (1972) was a method of melting powder by using energy lasers. Even though we can find traces of additive manufacturing in early topography and photosculpture 150 years ago, this technology reached its peak of momentum in late twentieth century.

Back in 1968 W.K.Swainson suggested a process to directly create 3 dimensional structure layer by layer by exposing light sensitive polymer at the intersection of two laser beams. Scientists at Battelle laboratory managed to successfully create spatial object using this method. Such object can be created by photochemically crosslinking or washing polymers, when each layer is exposed to light at the intersection of two laser beams. Scientists we able to construct required equipment, but it didn't had a successful market entry simply because this manufacturing process was not commercially auspicious.

In 1971 P.A. Ciraud suggested powder based additive manufacturing process, which has every modern AM aspect. When using this method consumed materials must be able to melt at least partially. During printing process powder material is positioned onto matrix by a movable dispensing print-head by using gravitation, magnetostatics or electrostatics, then laser, electron or plasma beam heats up the powder causing it to melt and bind together with previously created layers. To speed up manufacturing process, additional laser can be used simultaneously, which are crossed at the material melting point, thus focusing more energy in one point [1].

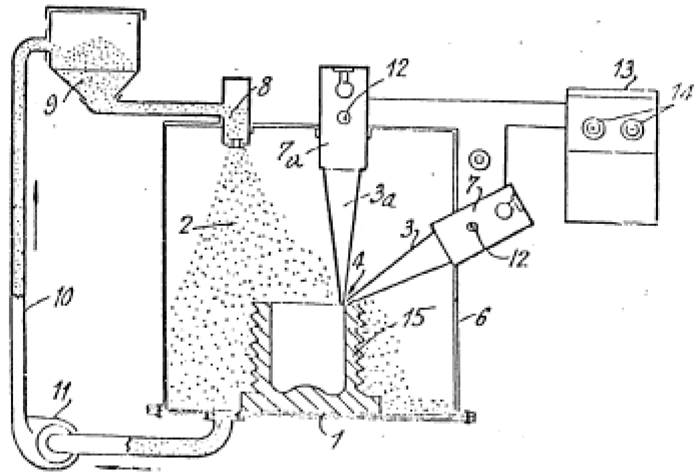

Fig.1 A method of AM by melting powder material, suggested by Ciraud.

Main difference between additive manufacturing and subtractive manufacturing is that during the process of AM building material is being added rather than taken away. During the AM process objects are being made by adding building material layer by layer, resulting in far less material consumption and simpler manufacturing process. During production up to 99% of material stays inside the final product which leads to extremely low amounts of wasted material compared to traditional manufacturing processes. Manufacturing products layer by layer also simplifies their designs and offers possibilities to create geometrical shapes, which are impossible to create using other methods.

Innovation of this method comes from its simplicity, because every person, who possess basic knowledge of AM and has access to 3D printing can make desired product by firstly creating its digital model or downloading it from internet and secondly printing it himself/herself or finding local 3D printing services provider. Much focus is being put into developing printing materials in the field of material science, which introduces additional printable materials as a result. In addition, this technology finds its way in various fields: household, mass-production, manufacturing, nanotechnologies, medicine, oil and military industries, et cetera.

3D printing

Recently, market demands have changed drastically. Today products must be offered in several different forms and adjusted to different sides of market. Products have become adjusted not only to each customer individually, but also for different occasions. Products are becoming more complex and their lifespan – shorter. To catch up with this pace of daily growing market demands manufacturing processes must become even shorter. That's where 3D printing technologies steps in. Much focus is being put into not only to improve current methods, but also develop even new ones.

Even though many new technologies arise, there are few main methods of 3D printing which have successfully withstood throughout history against rising challenges of time and market and set a foundation for present and future ones [2].

In 2009, during conference, international committee ASTM F42 described AM process as “combining materials to create objects from 3D digital model layer by layer, opposite to subtractive technologies. Said committee also described 7 major categories of additive manufacturing grouping current and future AM technologies [3]:

- **Material Jetting**
- **Binder Jetting**
- **Photopolymer Vat**
- **Powder Bed Fusion**
- **Material Extrusion**
- **Directed Energy Deposition**
- **Sheet Lamination**

Every category may have several, somehow different application methods and may include more than one technology which already exists, but all of technologies which share same category will be based on the same concept. This also applies to almost any technology, which may be invented in the future. So far, from the moment AM was categorised this way, no exceptions needed to be made due to newly invented AM methods.

Fused Deposition Modelling/Fused Filament Fabrication (FDM/FFF)

In 1982 Stratasys filed a patent for FDM technology [4]. Technology described there is one of the most popular AM technologies nowadays, used both in household and within makers. Main reason, why this technology is so popular, compared to its “siblings”, is simplicity and price. After Statasys patent’s licence came to an end this technology became available to everyone, thus allowing it to develop further even faster and forcing its price to come down drastically. Printers of this technology far less complicated than those of other technologies. Having basic knowledge in mechanics and electronics person is able to build a printer by himself. Commercial printers, on the other hand, are already built, set up for work and come as plug-and-play machines. These machines usually cost more, but don’t require assembling and that much maintenance.

In this work a FFF, or Fused Filament Fabrication type machine was used to fabricate test specimens. This is not an entirely different 3D printing method, but it should not be confused with

FDM, although they work in same way. Even though both technologies are virtually the same, FFF refers to a RepRap style machine. FFF name was a form of counter-action, initiated by makers community as an attempt to fight Statasys patent, which forbade the unlicensed use of FDM technology. Because of open source 3D printer movement, called RepRap and many enthusiasts this technology was able to improve rapidly and continues to do so today.

Most important part of a FDM printer is heating chamber, which heats up the supplied plastic up to its melting temperature. It is then extruded through calibrated print head. This process is completely controlled by computer and by using additional stepper motors said print head can be positioned to extrude viscous plastic in three dimensions. Often, a platform with controlled heating elements is used to help printing object stay in fixed place until the end of fabrication. If stepper motor is connected to heating platform (also called heat bed), it can also move along one axis, X, Y or Z moving object being printed alongside. Sometimes additional print-head is used, that allows printing support structures. These are usually printed from different kind of material, soluble in substance, in which the former material is not. Otherwise the supporting structures can be easily removed mechanically [3]. When using soluble materials to print support structures, various combinations of popular plastics can be taken of which one dissolves in certain fluid and other does not, exempli gratia, ABS and HIPS, PLA and ABS. This is possible, because ABS is soluble in acetone and HIPS is soluble in limonene, while PLA is resistant to both of those liquids. Another popular, but more expensive solution is PVA filament, which completely dissolves in water.

Material extrusion

Today there are many different technologies based on the principle of material extrusion. Even though its inception was technology, which used different masks for different layers to block UV light at unnecessary spots, thus solidifying photopolymer only where needed, today we can see bigger variety of materials used. Most of the technologies, which print using viscous materials, can be assigned to this category, but they can differentiate by the principle, how material is solidified, that is if it’s not intentionally left in liquid state. Most common systems solidify photopolymer using UV, IR or visible light. As an alternative, materials can be solidified using temperature, which dries out the bonding liquid, but in that case, material shrinkage should be taken into consideration, because by vaporising bonding liquid we are reducing the overall volume.

Main part of this technology is also its print head which uses pjezoceramics or pressure to push out viscous material. Stepper motors are used to move print head along X, Y and Z axis (variations are available) to create spatial structure. Second most important part is material solidifying system.

It can be UV laser, thermo-chamber or any other variation which is able to solidify printed material. One of the most popular material extrusion systems nowadays are InkJet and PolyJet. These technologies are, in fact, most similar to traditional printing, because machines work in the same way as office inkjet printers do, except former ones have added Z axis and solidifying system to harden photopolymer.

As noted earlier, extruded materials can be other than just photopolymers. That’s why there are additional technologies appearing alongside InkJet and PolyJet, which also print with liquid materials. Nevertheless, various viscous materials, possessing electric, magnetic or visco-elastic abilities, can be printed. One of such methods is Solid Freeform Fabrication or SFF for short. Exempli gratia, this method brings the possibility to print in viscous paste, consisting of 50% solid aluminium particles [9].

It might be possible to print infill structures using viscous materials. In that case, liquid shouldn’t be solidified and parts contours should be printed out of another, probably solid material. Also, structure should be absolutely tight, so that liquid infill material would stay inside. The machine, used to print these kinds of structures, should be hybrid, using several different 3D printing methods. To achieve a fine synergy of such different technologies would be a challenge.

Functional printing

In multi-material printing, usually printer of one specific technology (usually FDM), having several print-heads and capable of printing different material simultaneously is used. In other words, printers capable of printing different materials simultaneously are usually based on same method, can print relatively similar materials and, if put simply, have more than one print-head of same kind.

But recently research and development started focusing into so called multifunctional printing, during which different technologies and materials are being combined to produce final product. Especially high interest is being put into research on 3D printing with electronic components, conductor insertions and fully functional electronic parts such as MEMS even though its development “boomed” 20 years ago. Also much interest is being put into RFID and predictions are made that it will completely replace usual UPC systems in 20 years [10]. One approach to functional printing is combining stereolithography with direct printing and fabricating object which has electronic parts inserted during the print [5]. Another suggested approach is to print base using FDM technology, machine conductor channels, fill them with electrically conductive ink, place electronic components and cure the ink [6]. Research is being focused to overcome the challenge to print low resistance conductive insertions as it appears to be easier said than done. Even though conductive filaments can be found for sale at local retail store, due to their high resistance it makes it difficult to use them as conductors in electrical systems. To counter that, research has been done to print conductor containing bronze or silver particles using InkJet technology [7-8].

Products produced by such methods may be called smart products. Of course, name like this is nothing new, since almost every household appliance or, in fact, any functioning device nowadays can often be called smart. But this is no fancy way of advertising products. Adjective “smart” means said part or product possesses some kind of property which somewhat similar to intuitive thinking. In coding language it may be described as doing a task only if certain conditions are met. Depending on environment said material currently is, it can change its colour, structural parameters (stiffness or viscosity). One of the materials of such kind are magnetorheological fluids, or just MR fluids. When taking production of such products into consideration, 3D printing has a big potential by simplifying production itself, lowering the cost and time required [11].

Polymers used in FDM/FFF

ABS

ABS is one of the first filaments to be used in 3D printing industry. This copolymer consists of Acrylonitrile, Butadiene and Styrene monomers (chemical formula $(C_8H_8)_x{\cdot}(C_4H_6)_y{\cdot}(C_3H_3N)_z)$). The exact amounts for each monomer may vary depending on manufacturer thus influencing final properties of ABS, but proportions vary roughly around 25% of acrylonitrile, 25% of butadiene and 50% of styrene. ABS is made by polymerizing styrene and acrylonitrile in the presence of butadiene [12]. This copolymer is amorphous, which means, as most polymers, it doesn’t have a strict melting point and has a glass transition point of 105°C. It should be noted that glass transition point marks a temperature, from which bonds inside polymer start loosening up and polymer itself becomes more and more viscous, therefore its maximum usage temperature is usually quite lower, in this case being 80°C [13].

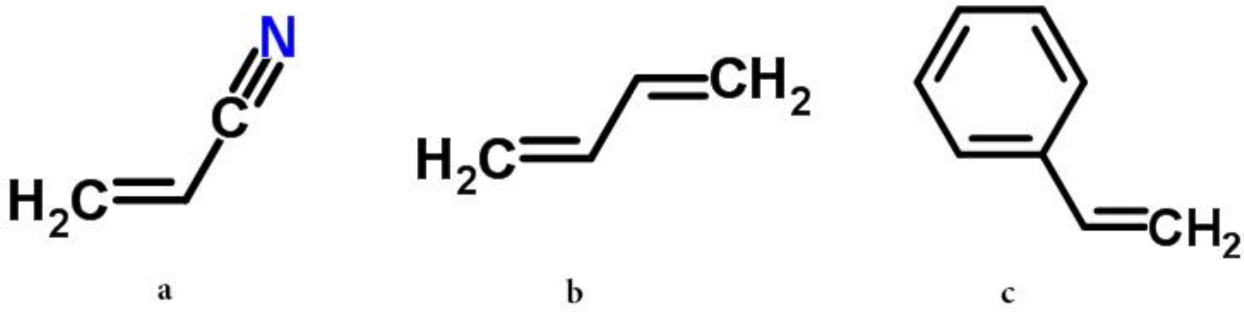

Fig.2 ABS monomers: (a) – acrylonitrile, (b) – 1,3-butadiene, (c) – styrene [23]

ABS is known to possess good impact resistance and toughness properties, by having tensile strength of 41 MPa, tensile modulus of 2.3 GPa and impact strength of 347 J/m, but low resistance to flames. Depending on proportions of each monomer, values of its properties might change slightly, because each monomer brings its own specific properties to the final copolymer. Acrylonitrile gives heat and chemical resistances and strength; Butadiene brings higher impact strength, toughness, low-temperature property retention and flexibility; Styrene gives rigidity, glossy finish and ease of processability [12]. Also, new monomers can be added to gain additional properties, but that leads to lower monomer proportions, thus weaker original properties. If glass fibres are added, polymer becomes stronger and its operating temperature rises.

When left under the presence of UV light (including sunlight), like many other polymers, its structure will degrade over time, becoming even weaker as time passes. It is known throughout 3D printing community, that ABS is soluble in acetone, which makes it very easy to add gloss finish to final product, “glue” broken parts together or even help with adhesion problems when printing. It is also possible to use ABS as support material and submerge printed part into acetone to easily dissolve all of the support structures.

Apart from 3D printing ABS is widely used in various applications. Most well know example is LEGO bricks. Other than that, it is used to make car body parts, wheel covers, musical instruments, computers keyboards, housings for electronical applications and power-tools, et cetera.

Fig.3 Example of 3D printed object in ABS.

Fig.4 LEGO bricks are example of the use of ABS polymer [28].

PLA

After years of frustrating printing with ABS and many attempts to solve its “warping” problems 3D printing community was introduced with PLA filament, also known as polylactic acid. Polylactic acid is a first biodegradable polymer which is often made from corn starch. It is mainly composed of lactide monomer. Two ways to produce PLA polymer is by condensation of lactic acid or by ring-opening polymerization of the cyclic lactide dimer. The former, though, has some difficulties removing traces of water, left after condensation, thus affecting the final density of polymer [14].

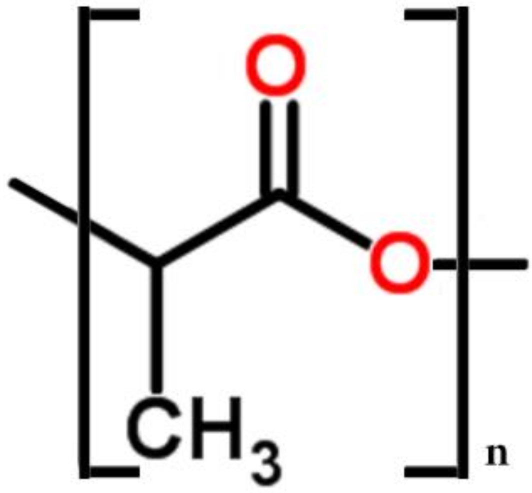

Fig.5 Chemical structure of PLA polymer [23]

Depending on how polymer was processed and what temperatures it endured, it can be either amorphous or semi-crystalline, which means its properties might change slightly. Its density might differ from 1,250 g/cm^3 to 1.490 g/cm^3. It possesses a glass transition point (T_g) of ~58°C and melting range from 130°C to 230°C. Compared to ABS, it has higher tensile strength of ~64 MPa, but much lower tensile elongation at break point of 0.5% to 9.2% [15] (compared to ABS of 1.0% to 57% [13]). Normal printing temperatures are 180°-230°C for extruder and 60°-65°C for heatbed. The facts, that printing temperatures for this polymer are much lower than those of ABS, it doesn't possess ability to "warp" and synergises well with good cooling system, this polymer is very easy to print, thus is much more desirable for 3D printing community. Although it's easy to print with, because of its lesser mechanical properties it may not be chosen over ABS, when mechanically challenging parts are to be printed.

PLA is favoured for its biodegradable tag. Although it may retain its molecular strength and structure under normal use conditions, it will degrade within months when exposed to high temperature and humidity. This happens mainly because of hydrolysis, which breaks down chemical chains into smaller ones until they are consumable by bacteria [14]. For this reason polylactic acid can be used to make biodegradable bottles, bags, containers or even surgical support structures, which eventually break down inside patients body and degrade when healing circle is almost over.

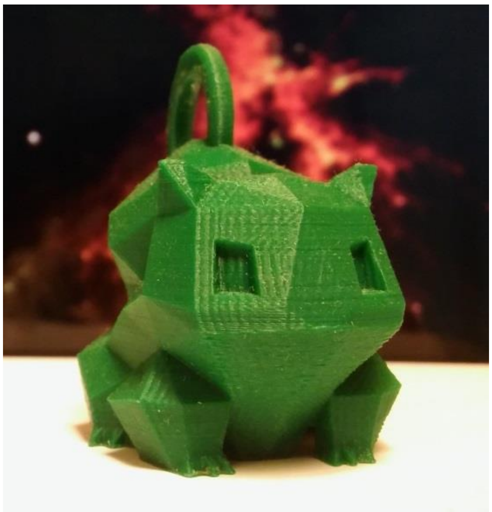

Fig.6 Example of 3D printed object in PLA.

PET

Polyethylene terephthalate, sometimes also called as polyester, or just PET is one of the most popular polymers in the world. Even though it has been used for quite a while, it was introduced into 3D printing industry as a filament only recently, with added glycol monomer (PETG). It consists of long chains of polymerised ethylene terephthalate monomers (chemical formula $C_{10}H_8O_4$). It is processed from dimethyl terephthalate (or terephthalic acid) and ethylene glycol. It is done in two stages, first – a solution polymerisation and second – melt polymerisation, which is done under partial vacuum or inert gas.

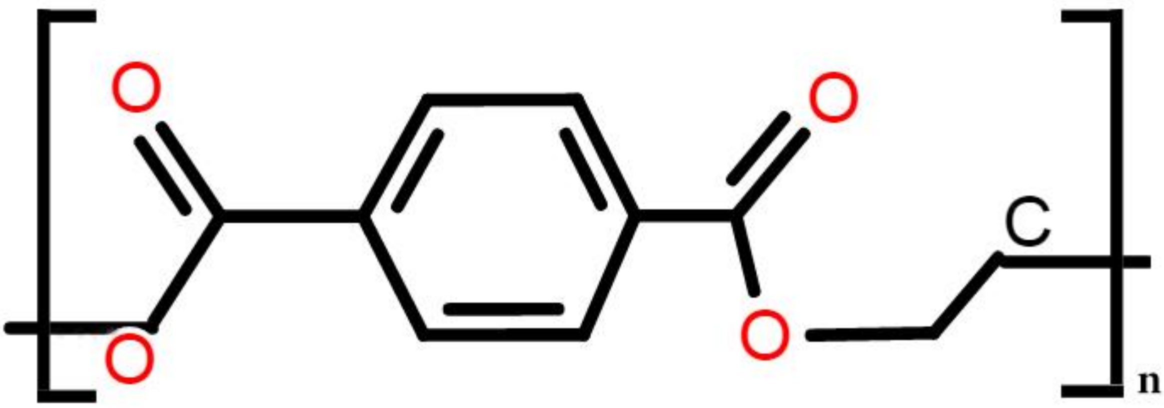

Fig.7 Chemical structure of polyethylene terephthalate.[23]

Depending on it processing and temperature history, it can be either amorphous of semi-crystalline. Taking that into account, it can be opaque of semi-transparent. It possesses tensile strength of 55-75MPa, tensile modulus of 9,96 GPa and impact strength of 101 J/m [12]. Compared to ABS and PLA it seems to be much stronger, but not as impact resistant as ABS. When bent it tends not to break like PLA would, but rather bend all the way creating “white spot” and the bend point. Often it would take many attempts to break thinner part by bending it back and forth, which tells about its resistance to weariness. In comparison, PLA tends to break shortly after the beginning of bend and ABS most of the time bends all the way, but breaks, when reaching 180° bend. PET's glass transition point is at 67-81°C. It is non-toxic, chemically inert and makes very good moisture barrier material. When printing, extruder should be heated to 230°-260°C and heatbed to 70°-85°C. Within 3D printing community it is often referred as "easy to print as PLA, but strong as ABS". This is because it possesses very little "warping", like PLA, and with good cooling system can be bridge printed easily, and has much higher tensile strength.

PET is widely used in 3D printing, injection moulding and blow moulding. In fact, because of its good water resistance properties, it's one of the most commonly used polymers to make soft-drink bottles. It is also used to make films, but mostly it's used to make food packages, due to its lightweight, non-toxic and shatterproof properties.

Fig.8 Example of 3D printed object in PETG.

Parameter	ABS	PLA	PET
Extruder temperature	230°-260°C	180°-230°C	240°-260°C
Heatbed temperature	100°C	60°C	70°C
Warping	Moderate	Almost none	Small
Soluble in acetone?	Yes	No, but damages integrity	No
Tensile strength	41MPa	50MPa	65MPa
Glass transition point	105°C	58°C	75°C
Water absorption	Small	Moderate	Almost none
Density	1,07g/cm^3	1,3g/cm^3	1,38g/cm^3
Relative flexibility	Medium	Low	High

Table 1. Main properties of polymers, compared to each other.

Magnetorheological fluids

Magnetorheological fluids are relatively new. First time a magnetorheological (MR) fluid was synthesised in 1964. For a while all of the information was classified, but after a decade or so information was available to the public, which lead to many experiments with these kinds of fluids. Not only experiments, regarding fluid's rheological properties, squeeze behaviour, applications and such were conducted [16, 17, 18, 19], but also various squeeze-film and semi-active dampers, magnetic field controlled capacitor devices with these kinds of fluids were developed [20, 21, 22]. Such applications mostly involve electrically adjustable dampers and breaks.

MR fluid consists of magnetic dipolar particles, like those of Fe_3O_4, suspended in carrier liquid, which is usually organic oil. Such liquid is not electrically conductive, but due to small particles of iron oxides, which tend to be ~10nm (categorised as ferrofluids) or 0,1-1µm (categorised as magnetorheological fluids) it possesses magnetic properties. Under no presence of magnetic field, fluid is viscous and acts as a liquid, but when external magnetic field is applied, particles inside the fluid organise in orderly fashion alongside magnetic field lines.

Fig.9 Magnetorheological fluid: without external magnetic field – (left), with external magnetic field – (right).

This leads to one of the most important MR fluid‘s poperty – to change its viscosity according to strength of magnetic field. This property allows fluid to be so effitient in MR breaks, since strength of breaking can be easily controlled by electromagnets.

II. EXPERIMENT

Aim of the work, objectives.

Aim of the work – to investigate properties of a designed model, composed of two different materials, one of which is visco-elastic fluid, under effects of external magnetic field. Investigate how stiffness of two-material composite model changes under external magnetic field of different strength.

Objectives:

- Design a test model, which would be a composite of two different materials, stiff polymer, used in FDM/FFF processes and magnetorheological fluid.
- Design and build a 3D printing system, capable of printing in two different materials simultaneously, to print designed models with.
- Print designed models, comprised of stiff polymer and MR fluid.
- Conduct experiments to investigate correlation between strength of active magnetic field and model's stiffness.

Equipment

Günter

To produce test objects, comprised of two different materials, AM machine named Günter was built. Its name is a tribute to its inception, which took place during internship in Germany. Günter is a RepRap type 3D printer with movable heat-bed along Z axis and extruder carriage, moving according to CoreXY principle.

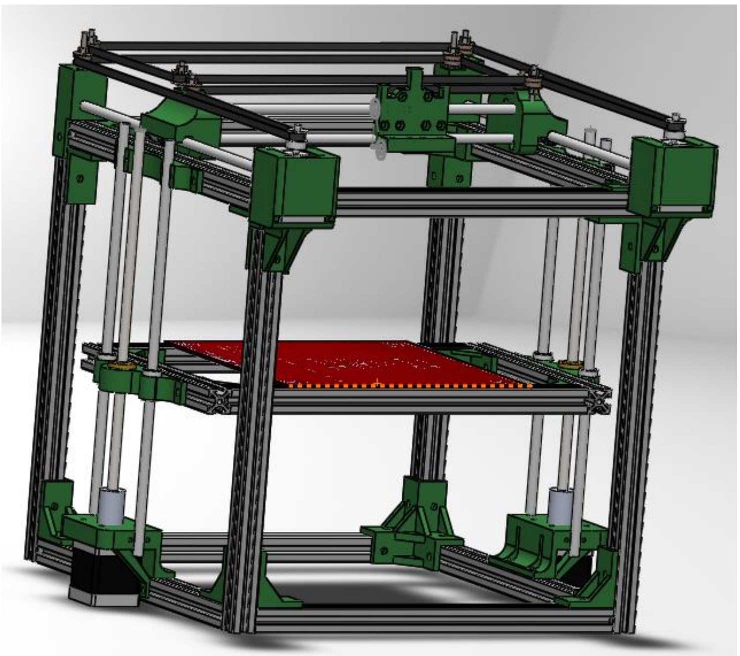

Fig. 10 Günter in its alpha stage.

CoreXY is a kind of belt-driven system, which ensures good belt tension in both positive and negative axis at the same time. This reduces the backlash and teeth-jumping, which happens in regular belt-driven one axis transmissions. As the name suggests, this system simultaneously controls movements in two axes, rather than just one. It uses two stepper motors and two belts. When stepper motors are turning in same direction, extruder carriage is moving along X axis. When stepper motors are moving in opposite direction, carriage is moving along Y axis [27].

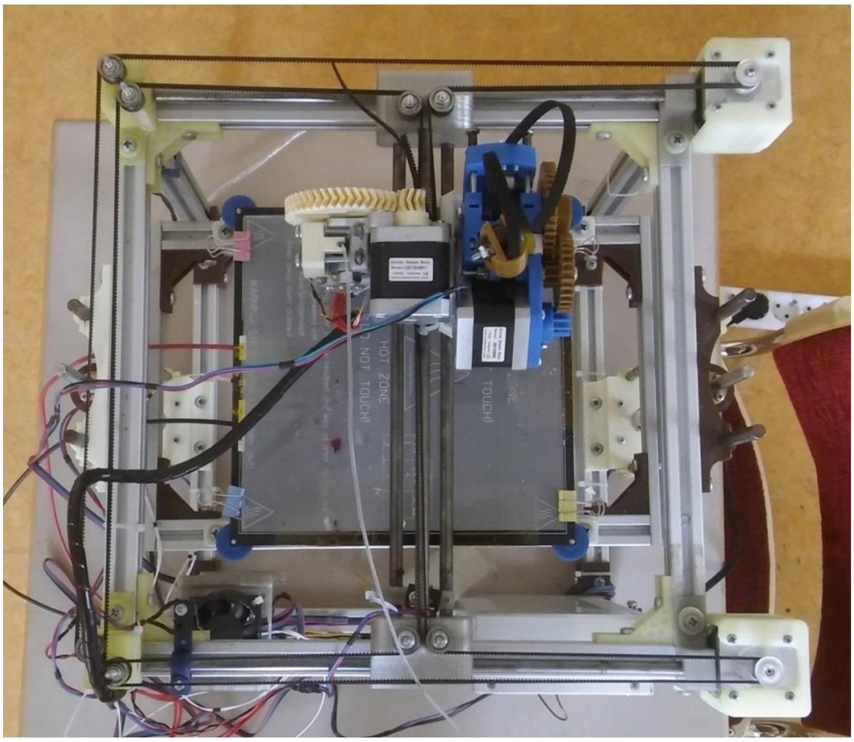

Fig.11 Extruder carriage designed to move according to CoreXY principle.

Extruder carriage is equipped with FFF technology direct extruder and belt-driven paste extruder, all of which are open-source models for RepRap printers [24].

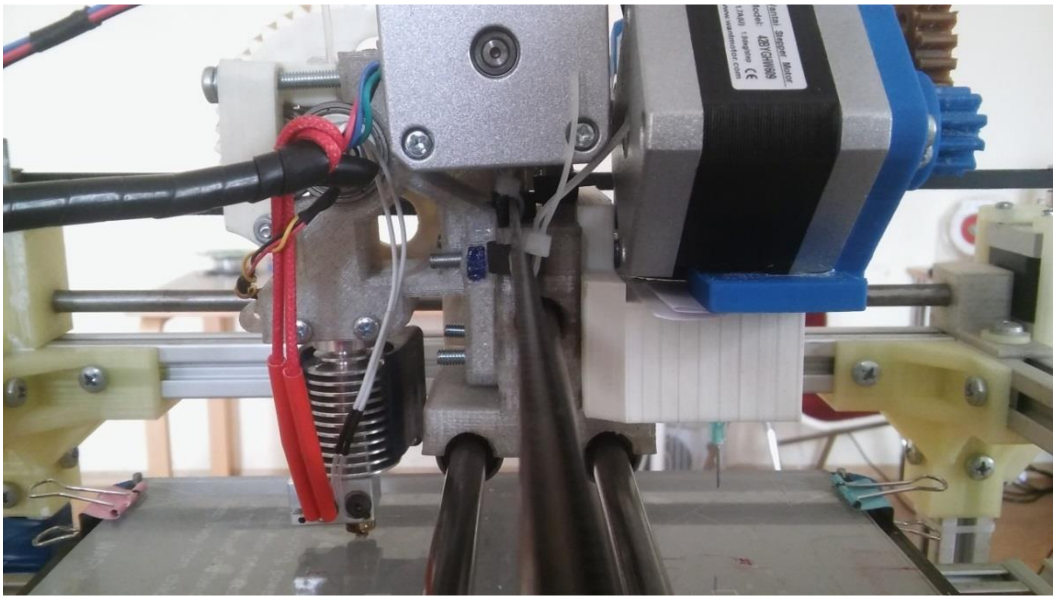

Fig.12 Extruder carriage equipped with direct filament extruder and paste extruder.

Rest of the connecting components were designed specifically for this printer (see appendix for bill of materials) and printed with 3D printer. Due to major vibrations occurring during the print, the print-head is limited to very slow travel and print accelerations of 600mm/s^2. Because it's a very early stage of this printer's development, its design must be improved a lot to solve such problems.

3D printing software

To operate FFF printer 3 different programs must be used, putting 3D modelling software aside, which would make the fourth one. These three groups are:

1) 3D printer firmware
2) Digital model slicing software
3) 3D printer controlling software

3D printing firmware is a package of code lines, which are the foundation of printer's functionality. Based on this code printer is able to transform various G-Code commands into precise actions. It's like operating system of a personal computer. Just like in computers, firmware software might change from printer to printer, but RepRap printers are mostly run on Marlin package, which is based on Sprinter firmware. Marlin firmware supports RAMPS, RAMBo, Ultimaker, BQ, and several other Arduino-based 3D printers.

Firmware, used in this work, was Marlin, uploaded to Arduino computer with RAMPS1.4 shield.

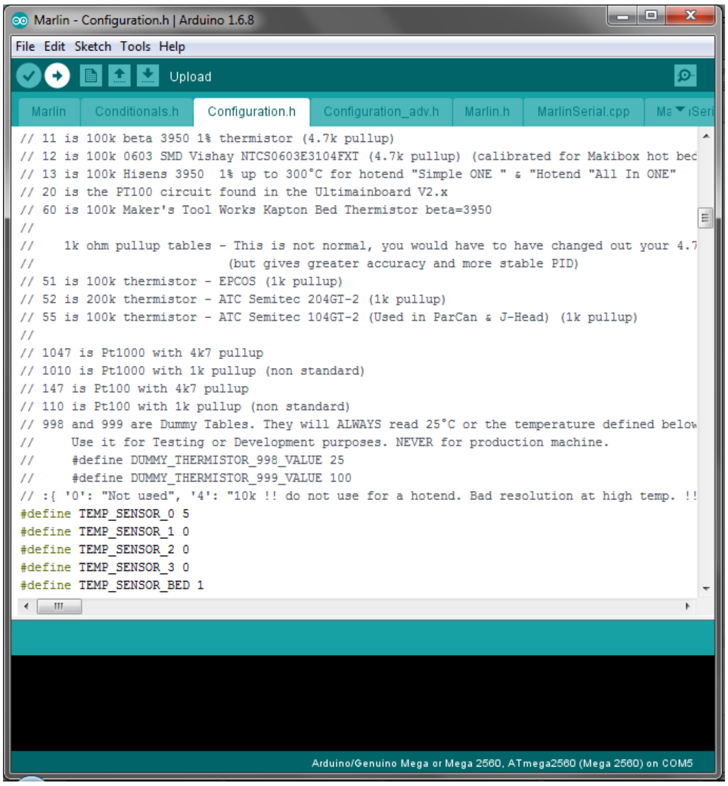

Fig.13 Arduino interface with Marlin firmware

Digital model slicing software is a program, designed to read digital 3D model, divide it in slices (layers) and generate G-Code commands, which would be read by printer to materialise digital model into physical form. In FFF technology, printers are building parts using lines of extruded filament. On each layer extruder is drawing contour of that layer, then infill and finally some assisting structures if needed. Since extruder's movement in space is based on vectors, this can be interpreted as coordinate commands, which are later interpreted as individual stepper motor commands for X,Y,Z and E axes (E stands for extruder stepper motor). To achieve all of this, slicing program first reads digital 3D model, then slices it into even (sometimes uneven) layers, simulates stepper motors movements and writes all of this into G-Code command lines. Often 3D printed parts vary from one to another and different approaches to slice them must be taken, since one method might work perfectly for one model, but bring awful results for another. To solve this problem software uses a set of parameters, which may be changed by user. These parameters define such variables as temperature, cooling, printing speed, line width, infill, et cetera. Examples of slicing software: Slic3r, Cura Engine, Skyforge, Kisslicer.

<u>Slicing program used in this work was Slic3r Prusa Edition 1.34.1.</u>

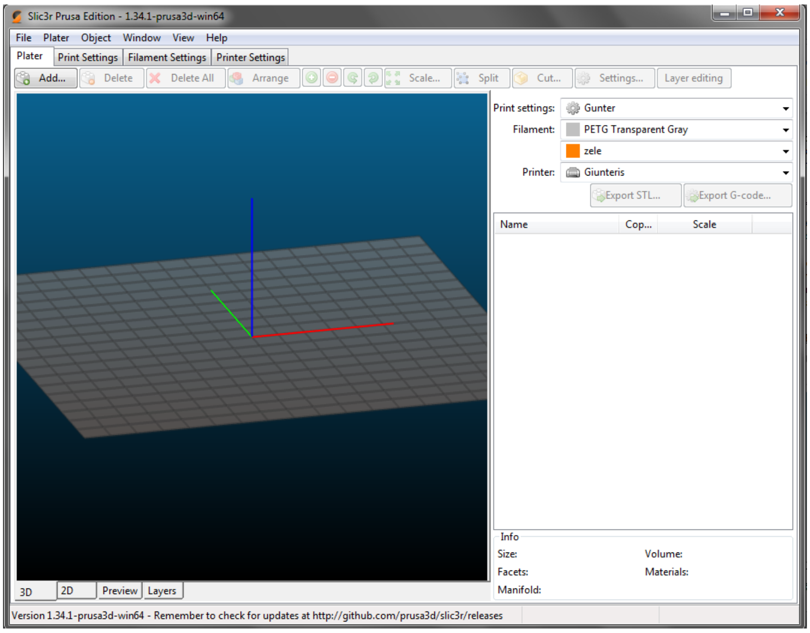

Fig.14 Slic3r Prusa Edition interface.

3D printer controlling software is designed to send generated G-Code commands one by one into printer. This software is unnecessary, if printer has SD card port and is able to read G-Code files from it. First, printer must be connected to another computer via USB cable, Bluetooth or WiFi signals, which has this software installed. Then, previously generated G-Code file is loaded into program, which later on starts sending G-Code commands into printer. Software usually allows controlling printer's basic functions, such as temperature, movement and cooling. This is useful when printer calibration or adjustments during printing process is in need. Also, some programs also have real-time simulation of printed part, which visually represents already sent commands. Examples of such software: Repetier-Host, Pronterface, Cura.

<u>3D printer controlling software used in this work was Repetier-Host v2.0.0</u>

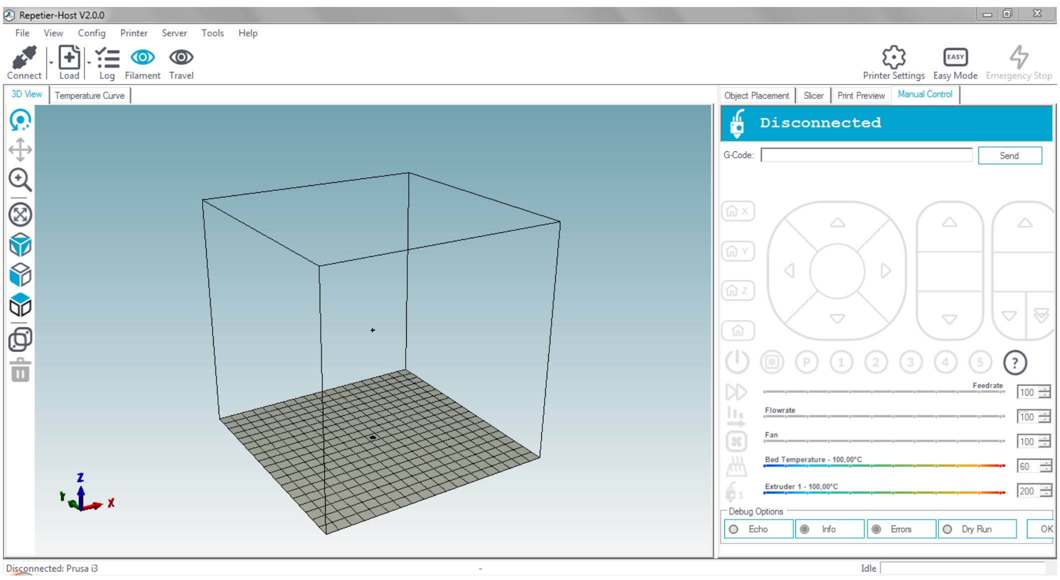

Fig.15 Repetier-Host software interface.

Tension stand

<u>Mecmesin Multitest 2,5-i.</u>

During experiments, a tensile test system was used to measure forces. Mecmesin brand system was used. Multitest 2.5-i is a system, that allows undergoing tensile and compresion tests. It allows measuring forces up to 2,5 kN. Main specifications of this machine are:

- Compression tester and tension testing
- Maximum load of 2500 N (550 lbf)
- Crosshead movement up to 590 mm (23.2") *
- Maximum sample diameter 134mm (5.28")
- 13 different loadcell capacities from 2 N to 2500 N (0.45 - 550 lbf)
- Load resolution of 1:6500
- Loadcell accuracy of ±0.1% of full scale
- Speed range of 1 - 1000 mm/min (0.04 - 39.4"/min) up to 2 kN 1 - 750 mm/min (0.04 - 30"/min) above 2 kN
- Weight 36 kg (79 lb)

Full specifications can be found in appendix section.

Fig.16 Multitest 2.5-i machine ready to begin testing.

Magnet

Magnets used in this experiment were:

1) One from a Hard Disk Drive. These kinds of magnets are found in HDD storage devices, where they are used as actuators to move read-write head. These magnets possess strong magnetic abilities, much stronger that those of classic ceramic type. Some people suggest that magnets used in HDD drives could be of neodymium type, but scientific proof in this work to confirm this is yet to be found.

Fig.17 HDD magnet used in experiment.

Fig.18 Magnetic field of HDD actuator magnet [25].

2) One from old speaker. These magnets are found in speakers and are responsible for creating vibrations of diafragma. These magnets are ceramic type and have lesser magnetic strength than neodydium magnets.

Fig.19 Whole speaker magnet used in experiment

Fig.20 Part of speaker magnet used in experiment.

Designed 3D models with two materials.

Model was designed using SolidWorks software. It's a cuboid with its dimensions being 100x10x1,5. Cuboid has different wall thickness of 0,5mm and 0,8mm, which creates a 98,4x8,4x0,5 void inside for MR fluid to fit. These dimensions were chosen as a compromise to ensure watertight structure and good flexibility, since thinner wall would yield greater flexibility, but it also would greatly increase the chances for gaps to appear between layers. Cross section of this model can be seen in the figure bellow.

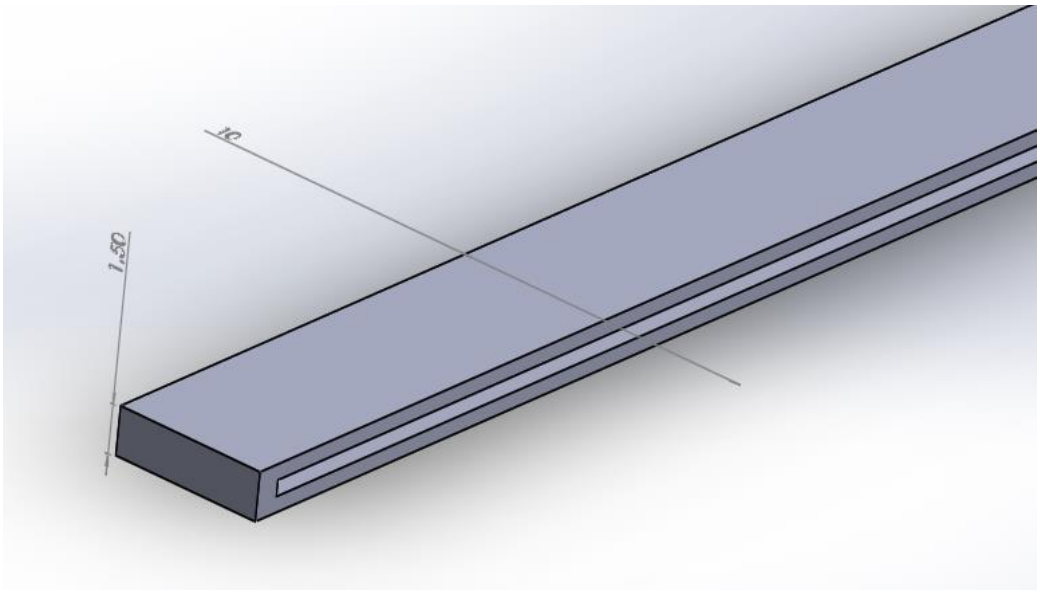

Fig.21 Cross section of test model, designed to be printed with two materials.

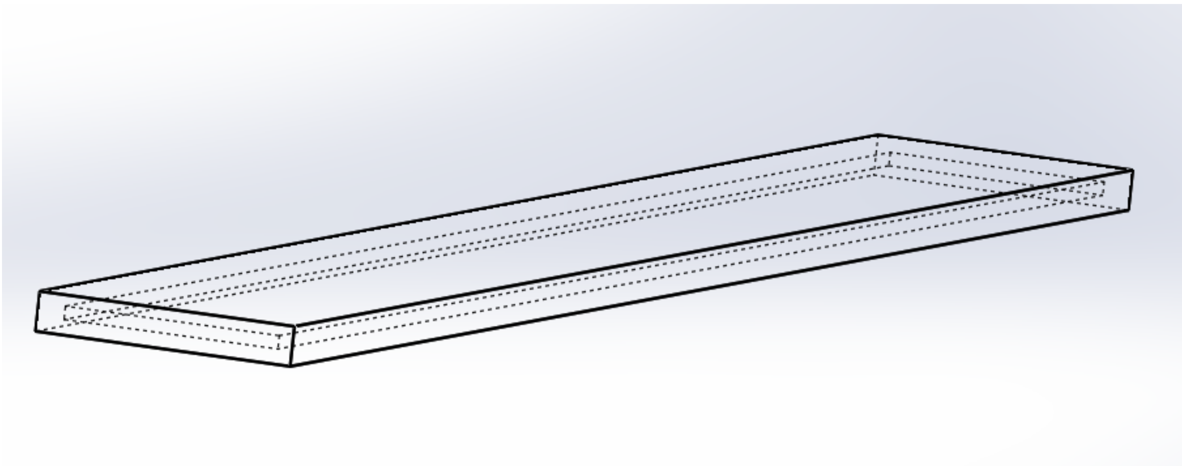

Fig.22 See-through model with visible hollow structure inside.

This model is designed to be printed out of plastic filament and its hollow part to be filled with MR fluid. Cylinder structure was also considered, but was rejected due to impossibility to print it perfectly when laid down and increased stiffness when printing oriented upwards Z axis.

Materials used to print test speciments.

Magnetorheological fluid

Magnetorheological fluid used these experiments is MRHCCS4-B. General properties of these fluids are somewhat similar, but depending on manufacturer, it can be composed of different size ferro-particles, have different proportions of particle and oil composition and may have different kind of carrier oil, although most of the time organic oils are used. This fluid, in particular, has a packing of 80%, hydrocarbon oil as carrier oil and its viscosity possesses thixotropic properties [26]. It can be speculated as to what abbreviations in its name mean, but in this case is irrelevant.

Fig.23 MR fluid inside a container with applied external magnetic field.

PETG and ABS filaments

Filament is a form in which plastic is load into FDM/FFF printer. It resembles a wire, but has a very strict diameter of 1.75mm or 2.85mm and small deviations (mostly around $\pm$0.02mm). Filament's quality is defined by how small its diameter deviations are and what is the purity of polymer. Since there can be filaments made from different kinds of polymers, some of the parameters, used in slicing software, might change. These parameters must be input when new filament is loaded into 3D printer. Said parameters are: diameter, extruder temperature, bed temperature and cooling settings. In this case, cooling settings are a little more complex than just one input, so to simplify this we will take only minimum and maximum cooling fan speed into consideration.

Below are shown the parameters, used for each filament. Take note that earlier, temperatures were suggested in ranges, but here they were taken as exact values. This is result of a choice of correct temperature to achieve decent quality.

Parameter	Value
Extruder multiplier	0.865
Extruder temperature	245°C
Bed temperature	100°C
Cooling	15%-50%

Table 2. Parameters for ABS filament.

Parameter	Value
Extruder multiplier	0.93
Extruder temperature	240°C
Bed temperature	70°C
Cooling	30%-80%

Table 3. Parameters for PETG filament.

Printing parameters

In order to 3D print objects, software needs to slice its digital model into even slices, which represent layers during the print. After that software calculates and generates G-code commands, which are later sent to printer. During slicing process, several parameters, which can be changed, are taken into consideration. Below are parameters, used in slicing digital model of the test specimen.

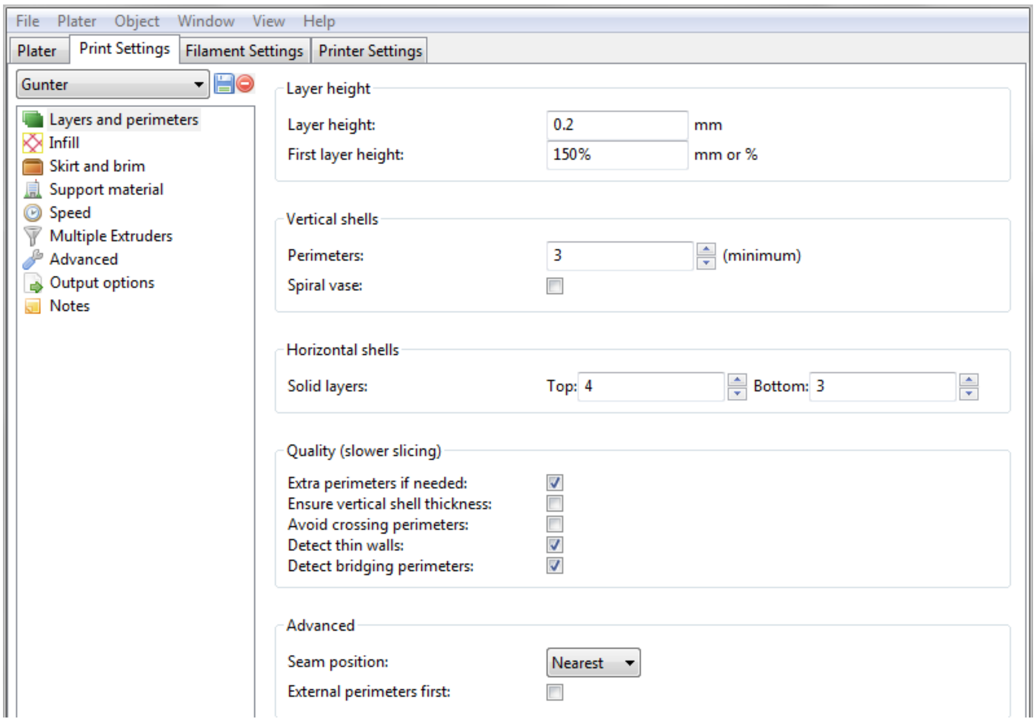

Fig.24 Parameters under 'Perimeters' tab.

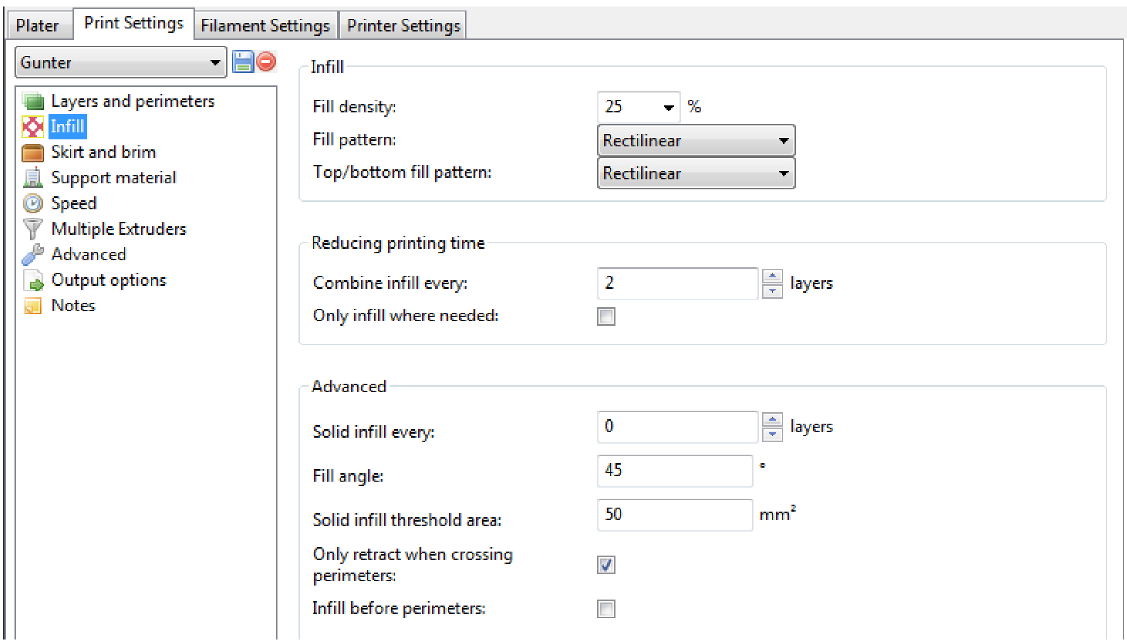

Fig.25 Parameters under 'Infill' tab

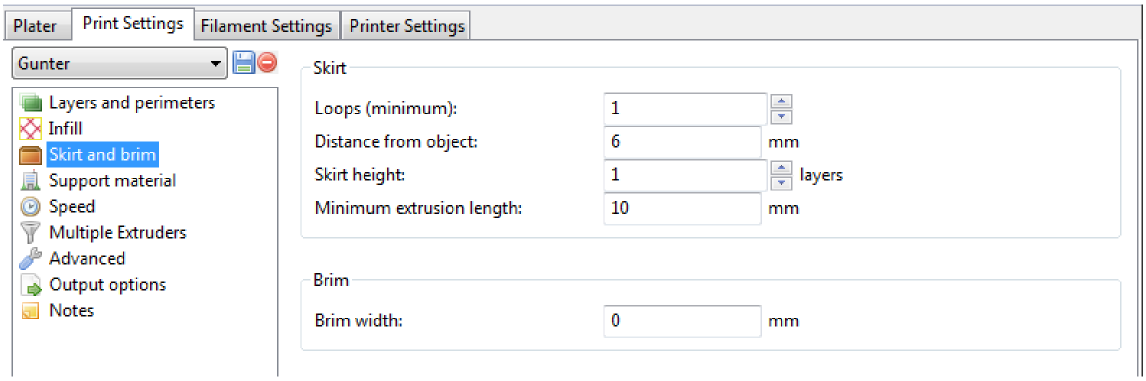

Fig.26 Parameters under 'Skirt and brim' tab

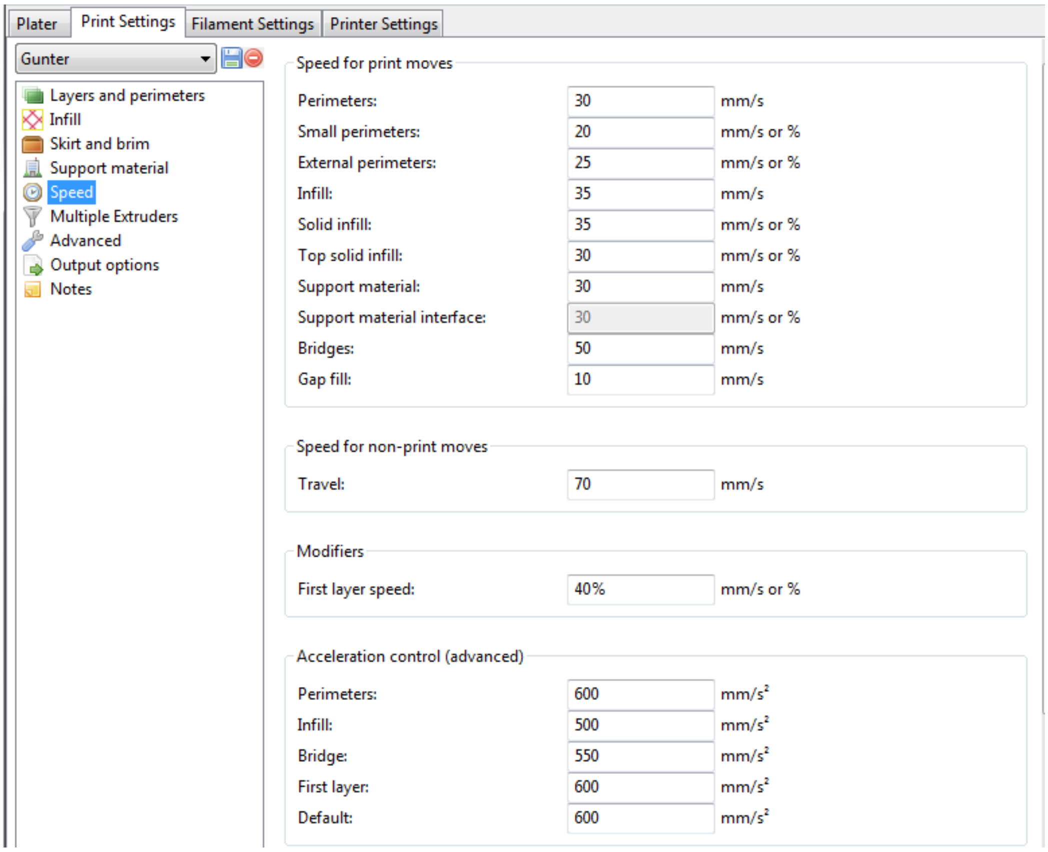

Fig.27 Parameters under 'Speed' tab

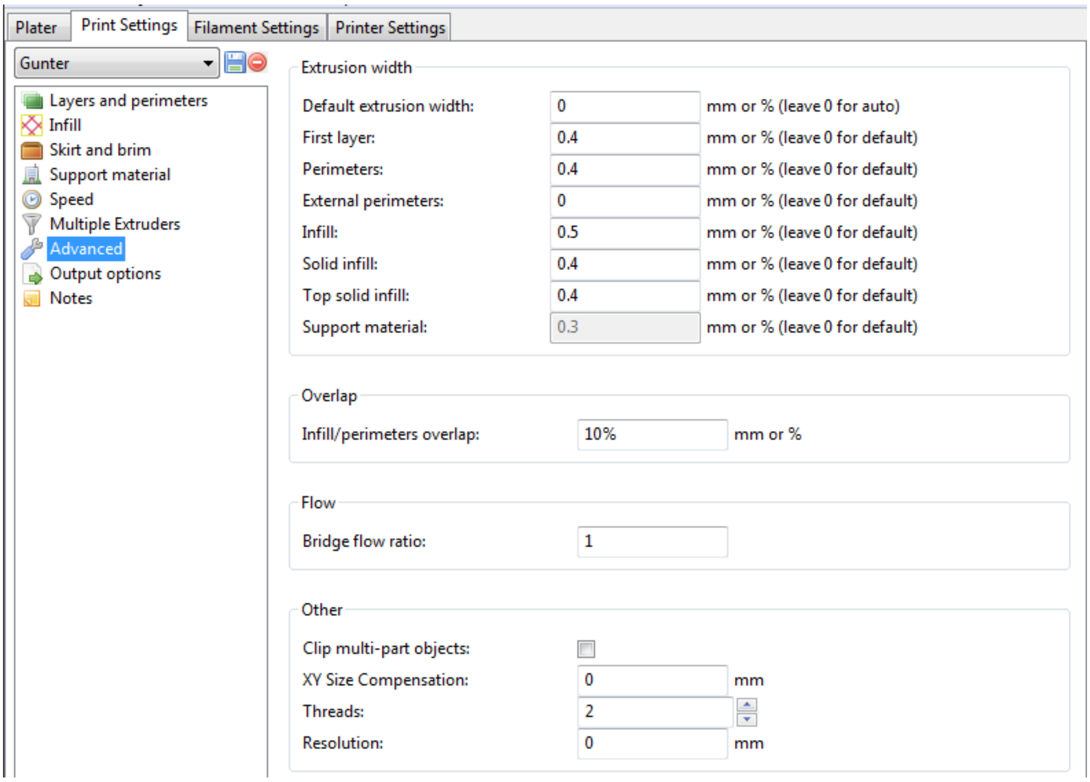

Fig.28 Parameters under 'Advanced' tab

Take note, that some of the parameter tabs were skipped. This is because they were either irrelevant or not used for this print.

Slicing. Evaluation of different orientations

In order to print something, first, its model must be sliced. Since FFF method prints objects layer by layer, final product's mechanical properties often are different along Z axis. Usually parts tend to be weaker and if flexible material is used it tends to be stiffer along Z axis. Because of this, object orientation evaluation is very important step before slicing. Before printing test specimens, three different orientations were considered, until right one was chosen. It will be discussed, why orientation chosen was the best one, and why other ones would have been a poor choice.

Firstly, orientation like in the figure bellow would not only produce a part that would be much stiffer and brittle, but also it would be increasingly difficult to preserve correct shape as we would advance in layers. This is because part, when printed, would start to oscillate according to extruder movements and amplitude of these oscillations would increase with height.

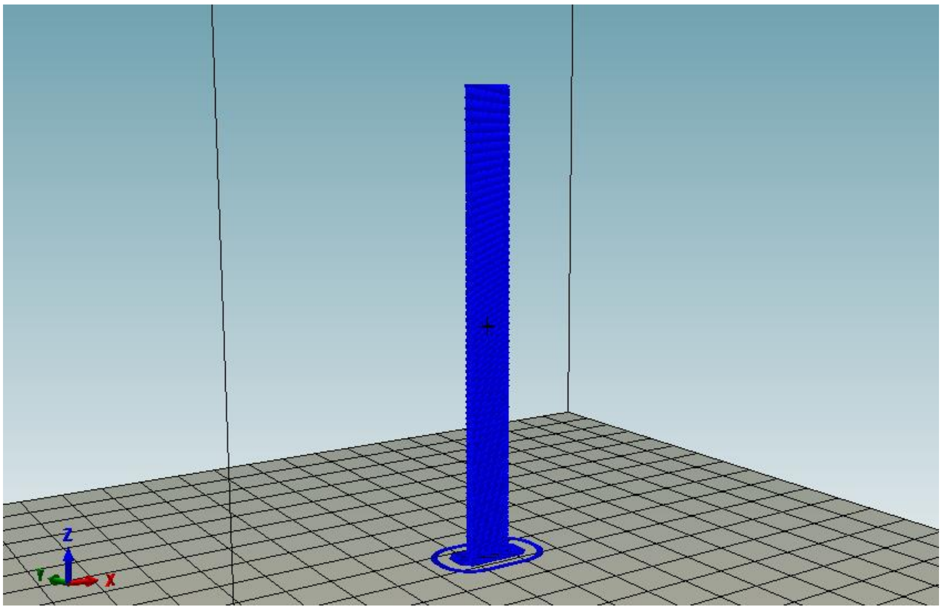

Fig.29 Sliced model positioned along Z axis.

It is known, that 3D printed parts possess increased stiffness along Z axis, because of the "stacked" layers. If this orientation is chosen, whole specimen would be created this way (see figure below). Increased specimen's stiffness would require more sensitive equipment to read any changes in stiffness during the experiment.

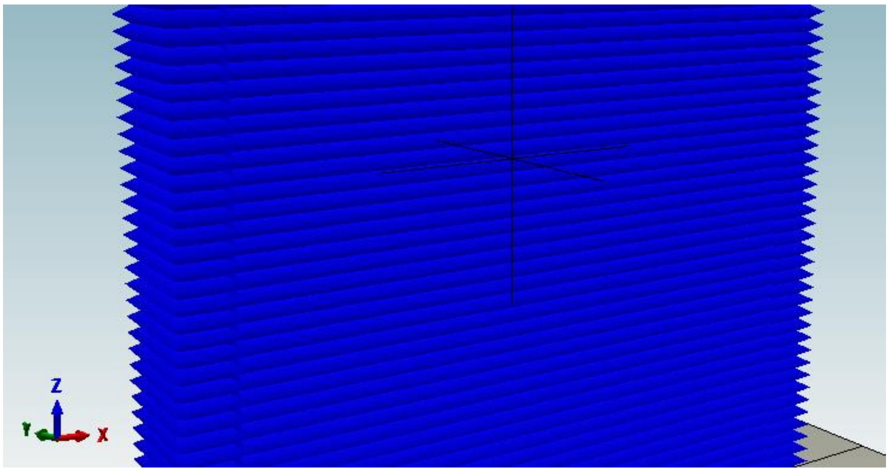

Fig.30 Close-up of Z-axis oriented slicing.

Secondly, orientation as shown in the figure bellow was considered. Although this would have yield excellent flexibility, but it would have been very challenging to print like this.

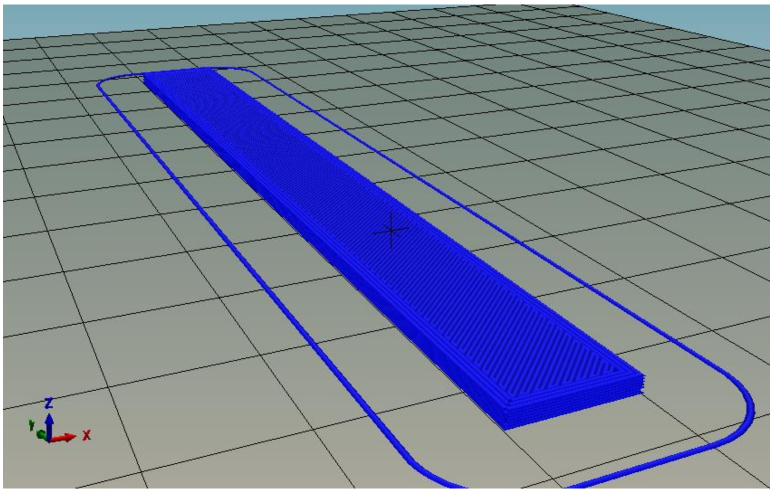

Fig.31 Sliced model positioned flat on the surface.

As seen in the figure bellow, model has an empty void inside. To print layers, which are directly above said void would require one of two things: support structures or excellent bridging abilities. Support structure is not an option, because it would be impossible to remove and would occupy space, which is reserved for MR fluid. Bridging would be the only option here, but to ensure watertight structure, layers, required for “ceiling”, would need to be increased, which would lead to reduced flexibility.

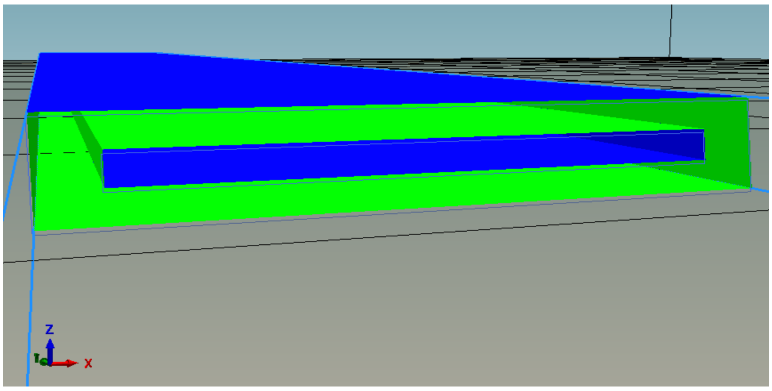

Fig.32 Close-up cross section view of model, positioned flat on the surface.

Third option is as shown in figure bellow. This grants good flexibility and doesn’t require any complex bridging. The only “tricky” part is, again, top layers, which are directly above empty space inside the part. It requires some bridging, but distances between two walls are very short, so it’s a quite simple task.

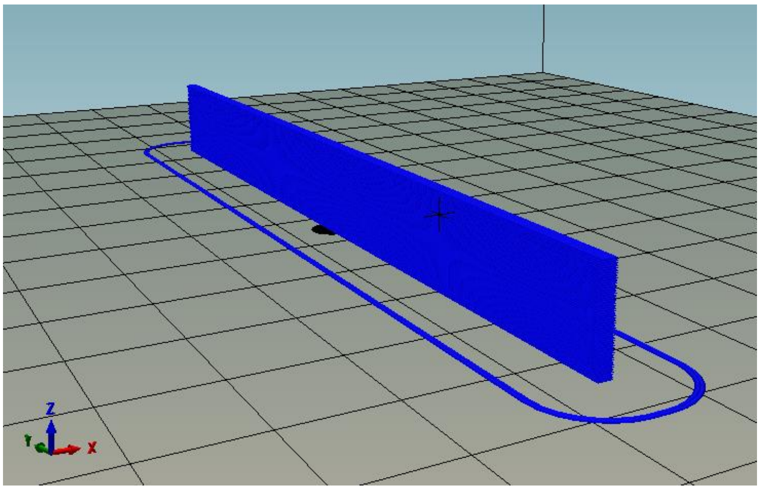

Fig.33 Sliced model, positioned on its thin side.

Layers would be stacked as shown in figure bellow.

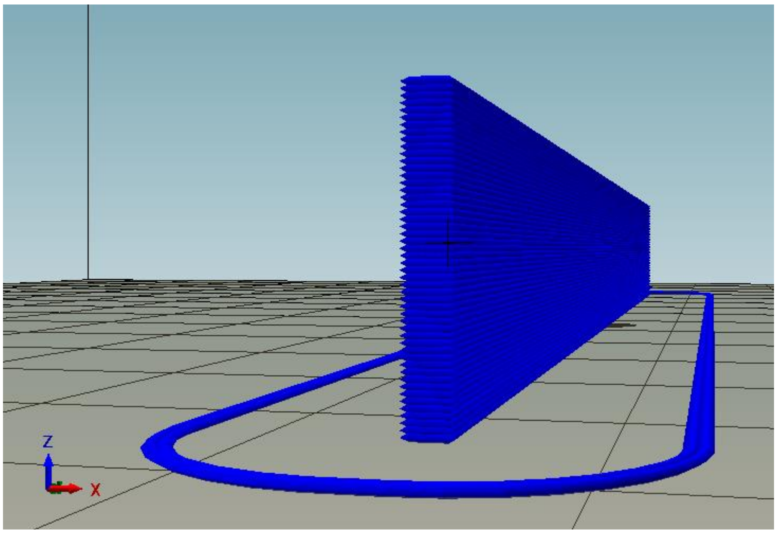

Fig.34 Close-up layer configuration of sliced model.

After evaluating all of previously described options, decision was made to print specimens oriented as shown in figure bellow. This allows us to preserve good flexibility, required to observe any changes during the experiment, and is the least complicated way to fabricate the specimen from the rest of discussed options.

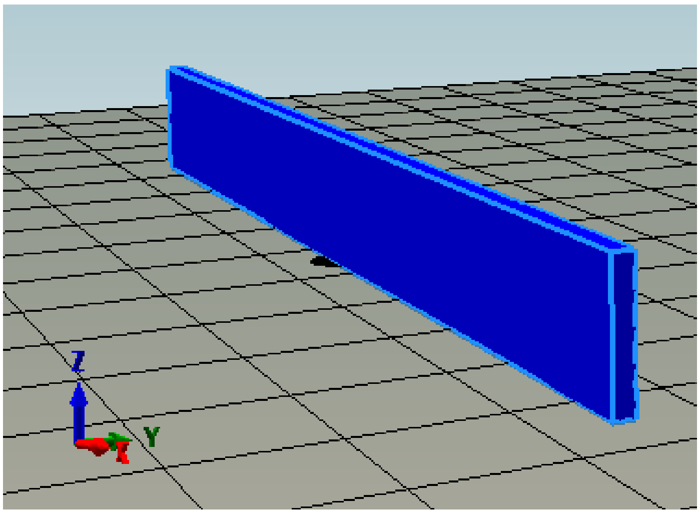

Fig.35 Printing orientation of experimental model.

Printing, results and problem solving

First test specimens were printed out of PETG filament. Of course, as it was first attempt to print object from such different kinds of materials, it failed. Soon, it was realised, that only way to figure out how to successfully fabricate part from solid and liquid materials is trial by error. First specimen failed to print because one layer of PETG had some of the MR fluid smudged on, which didn't allow further layers to bind with previous ones.

1st attempt failed. Reason: layer of filament, when coated with MR fluid, loses ability to bind with the next one.

Fig.36 #1 specimen. Failed and incomplete. Top view.

Fig.37 #1 specimen. Failed and incomplete. Side view.

Second specimen printed brought better results. Printed part was successfully finished and filled with MR fluid, but it wasn't watertight. MR fluid inside would spill through part's walls when the specimen is bent at least a little. Leakage spots were attempted to be fixed with superglue, but due to oily nature of MR fluid, it was very difficult to do so. In the figure a major MR fluid spill can be seen to the right of the centre.

2nd attempt failed. Specimen was completely printed, but its structure wasn't watertight, which cause MR fluid to come through.

Fig.38 #2 specimen. Complete but faulty. Side view.

Third specimen was also printed from PETG filament. Progress could already be seen. Part was successfully printed, but still some MR fluid leakage could be seen, although this time overall quality was much better. MR fluid spills can be seen on the left bottom side and to the right from the centre in the figure 39. This specimen can be brought into testing, but only until a portion of MR fluid is gone, which would cause significant deviations in results.

3rd attempt partially succeeded. Specimen completely printed, but still some minor MR fluid spills can be seen.

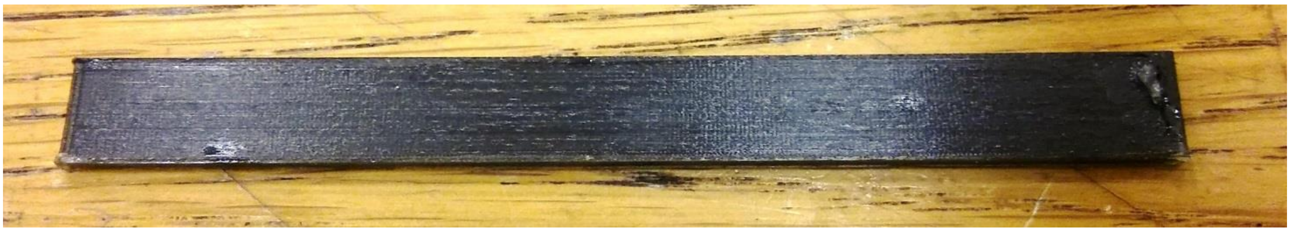

Fig.39 #3 specimen. Complete, but faulty. Side view.

Fourth and the final specimen, printed from PETG filament brought the best results within family of PETG specimens. It was fully printed and showed only a minor signs of MR fluid leakage. Even though whole structure wasn't purely watertight, this could be ignored, since deformations, happening during the experiment, would be too small to cause escape of any significant amount of MR fluid. Superglue fix was avoided this time in fear not to change specimen's stiffness, since dried superglue is much stiffer than PETG polymer.

4th attempt succeeded. Part was printed successfully with only insignificant leakiness.

Fig.40 #4 specimen. Successful with insignificant faults. Side view.

Fifth specimen was printed from ABS. This decision, to switch to another filament, was based on two reasons:

1) To finally solve leakage problems.
2) To have a specimen, from another polymer, to compare.

First attempt to print it was already successful. It had two faulty spots, but they were easily fixed with a solution of ABS and acetone. In the figure, two spots can be seen where dissolved ABS was applied. Also, whole structure was coated with acetone to ensure it's completely sealed.

5th attempt successfully completed. Specimen was coated with acetone and two faulty spots were sealed with dissolved ABS.

Fig.41 #5 specimen. Complete and sealed with acetone.

Sixth specimen was printed without MR fluid to be filled manually. Since MR fluid wasn't involved during the print it came out in good quality, but because ABS was used as a filament, the results of warping can be seen in the figure bellow. A small hole was designed on the side, through which syringe needle could fit. Whole structure was coated with acetone to remove any minor holes, which might have appeared during the print. MR fluid was then injected with syringe manually. Finally, hole was sealed with dissolved ABS. Specimen without MR fluid and fluid being injected can be seen in the figures bellow.

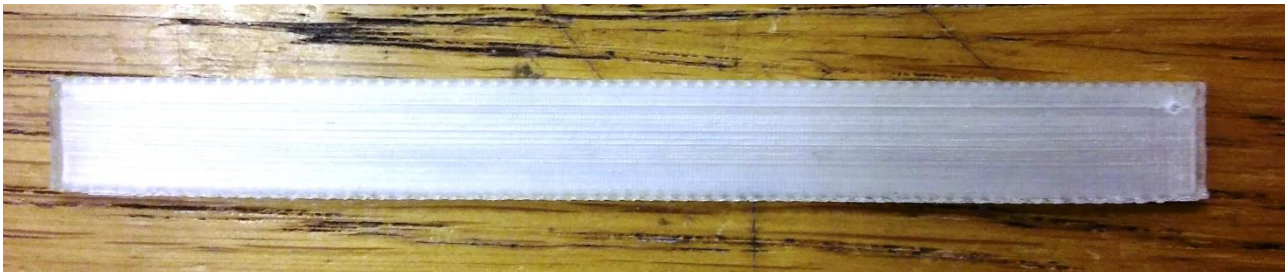

Fig.42 ABS specimen without MR fluid.

Fig.43 MR fluid being manually injected into specimen.

Experimental stage. Success and failure.

NOTE: to avoid misunderstandings when analysing graphs later on, following experiments will be listed in the order they were done.

Experiment was carried out in several different ways in order to investigate nature of such two-material composites as much as possible in given circumstances. At all times specimen was fixed at one end and pulled upwards using string at the other. Magnet was placed at various positions and force, required to pull specimen, was measured. Experiment was also carried out to investigate, if string, used in experiments, had any significant elongation at all (experiment #2). It was found, that elongation, appearing in the string is, in fact, very small. It was decided, that occurring deviation due to this elongation is insignificant and can be ignored.

Experiment #1.

At first, ABS and PETG specimens were taken into control test to see their default rigidity when no external magnetic field is applied.

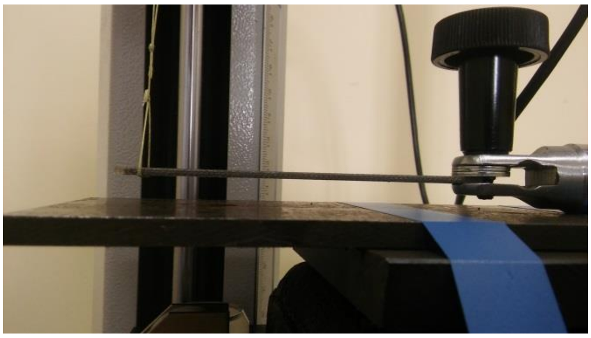

Fig.44 ABS specimen ready for control test.

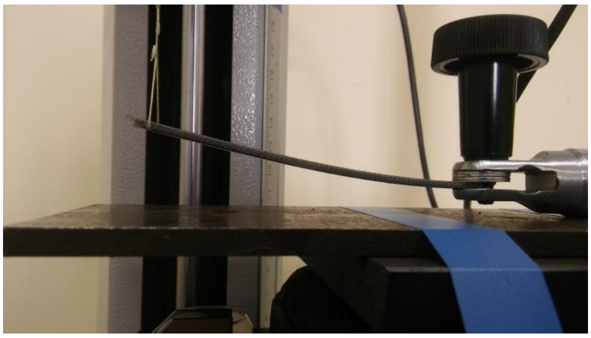

Fig.45 ABS specimen during control test run.

Experiments #3, 4, 5, 6 and 7.

Then, metal plate was graduated with lines, with 10mm step.

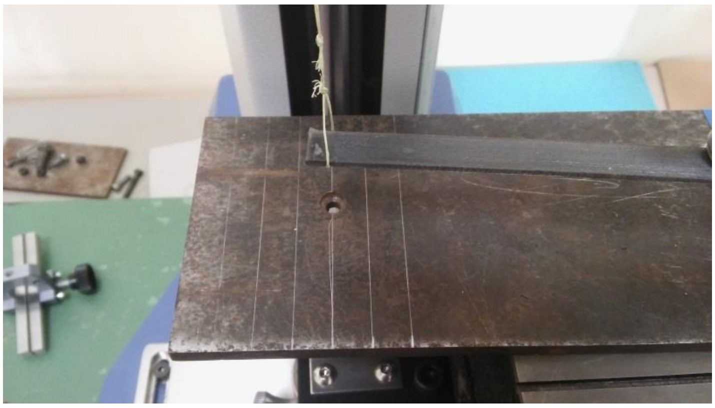

Fig.46 Graduated plate in a step of 10mm.

This scale was later used to place ceramic magnet accordingly. Tests were carried out to see, how specimen‘s stiffness change, when magnet position is changed horizontally. 0mm offset position was chosen as a point, where magnet‘s right edge was as the same point as specimen‘s end. Magnet was moved by 10mm each time and test was carried out again. It was done so for 0, 10, 20, 30 and 40mm offsets.

Fig.47 Magnet placed at 0mm offset. Experiment #3

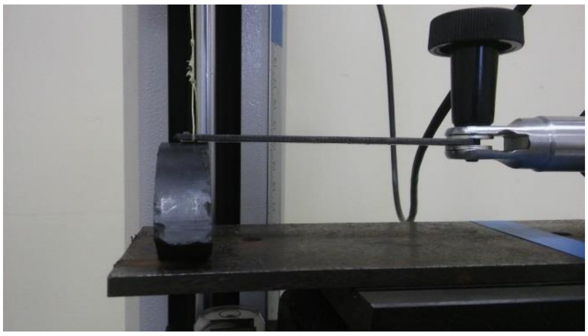

Fig.48 Magnet placed at 10mm offset. Experiment #4

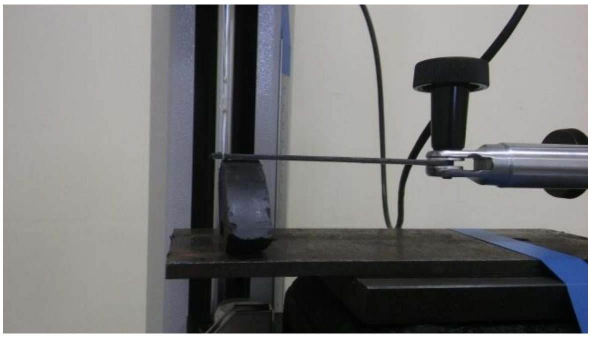

Fig.49 Magnet placed at 20mm offset. Experiment #5

Fig.50 Magnet placed at 30mm offset. Experiment #6.

Experiment #8.

Another stage of experiment was initiated. A HDD magnet was placed on metal plate and specimen was lowered so that it would touch the magnet and would be at completely horizontal position at the same time. Like in the previous experiments one edge was fixed and the other one was being pulled upwards. Force, required to pull specimen at the given distance, was measured. Both of the specimens were tested.

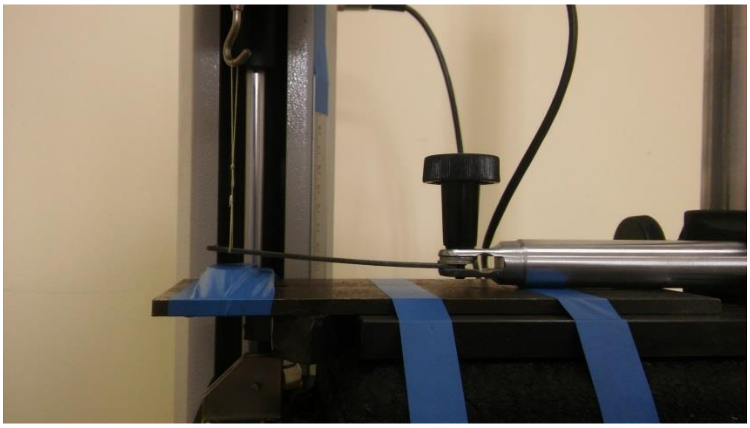

Fig.51 HDD magnet placed underneath specimen.

Experiment #9.

Worth to mention, that experiment was also carried out with two different magnets to see, what difference would be visible between magnets of different strength.

Data processing

All of the data gathered during the experiment was saved in excel format. During tension process, data gathering frequency was set to lowest rate of 50Hz, but given, that one cycle lasted 60 seconds, data accumulated was unnecessarily big and therefore needed to be filtered.

For this task, algorithm was created within excel interface, to find “step” values:

=IF({current value}={previous value};NONE;{current value}).

Created algorithm checked, if current value is the same as previous one and if so, it was taken out. If value was different than previous one, it meant a “step” value, which was left. This was done for “Load” column. For “Displacement” column following formula was applied:

=IF({Load value}=NONE;NONE;{Displacement value}).

This formula checked, if corresponding "Load" value was tagged as "None", if so, displacement's value was also given such tag, otherwise it was left untouched. Later, all of the cells that contained "NONE" were removed leaving only step values.

Processed data was significantly sparser. Of course, this algorithm didn't filter cases of alternating values, when two values alternate between each other over and over again, but this was easily solved later, when drawing graphs. Example of alternating values in "Load" column can be seen in the figure 52. Displacement values are proportionally increasing, while Load values are "jumping" randomly. This is caused by over-sensitive machine cell, which tend to cause noise at the very start of experiment cycle.

Load	Displacement
N	mm
0,001253883044	0,00000
0,001253883044	0,00000
0,002507766088	0,00000
0,001253883044	0,00000
0,000000000000	0,00000
0,000000000000	0,00000
0,002507766088	0,00000
0,001253883044	0,00000
0,001253883044	0,00167
0,001253883044	0,00333
0,003761649132	0,00667
0,002507766088	0,01167
0,003761649132	0,01417
0,003761649132	0,01750
0,003761649132	0,02167
0,003761649132	0,02583
0,003761649132	0,02833
0,003761649132	0,03250
0,005015542110	0,03500
0,003761649132	0,03833
0,003761649132	0,04333
0,005015542110	0,04583

Fig.52 Example of alternating values.

III. RESULTS

Data and Graphs

Full collected data of every experiment can be found in appendix section. Data is saved in excel format. Unfortunately, due to massive data line count in each experiment, it cannot be displayed here practically. Therefore it can be found in attached CD.

In this section graphs can be found, which visualise results of every experiment. As described in previous section, experiments were numbered in the order they were done. Same numbering sequence is used in this section. Summary and commentary of these graphs are to be found in next section.

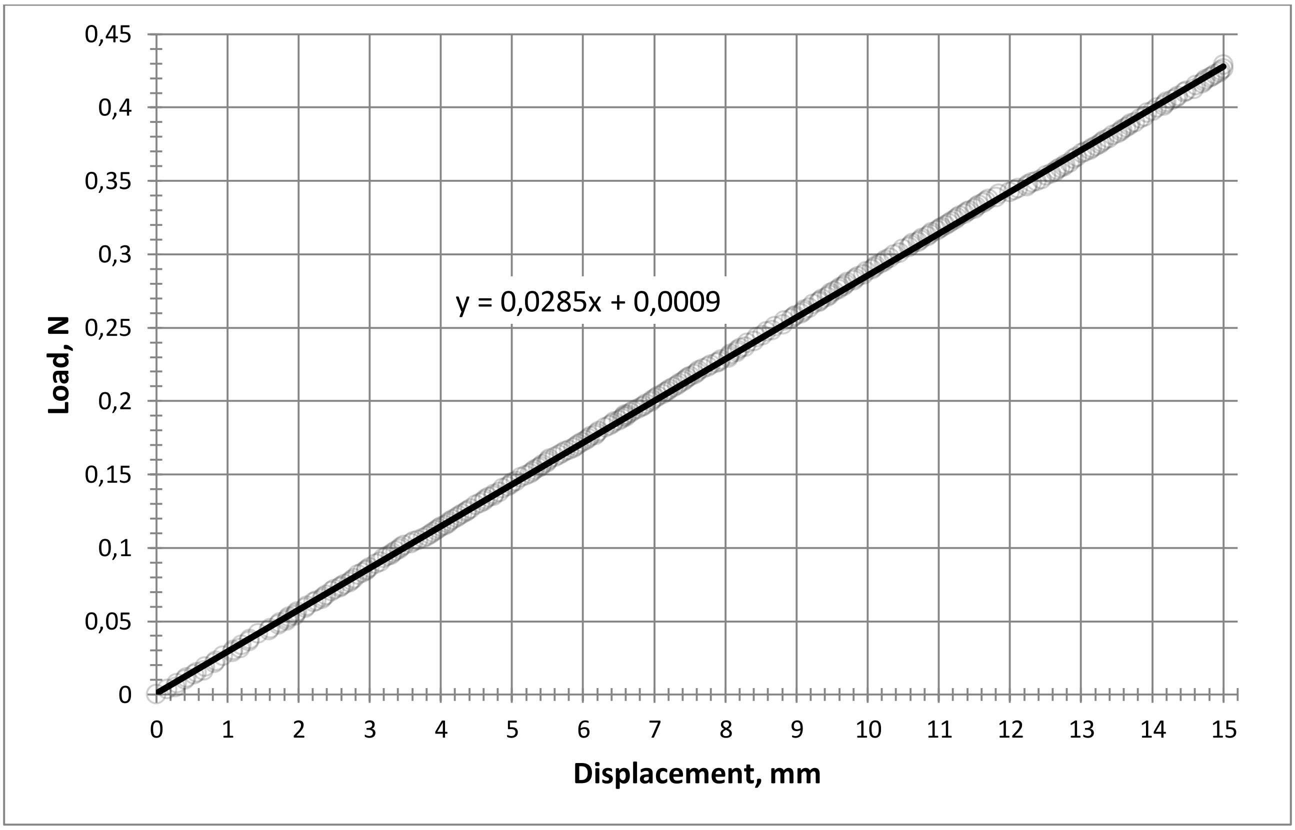

Fig.53 Stiffness of ABS control group. Experiment #1.

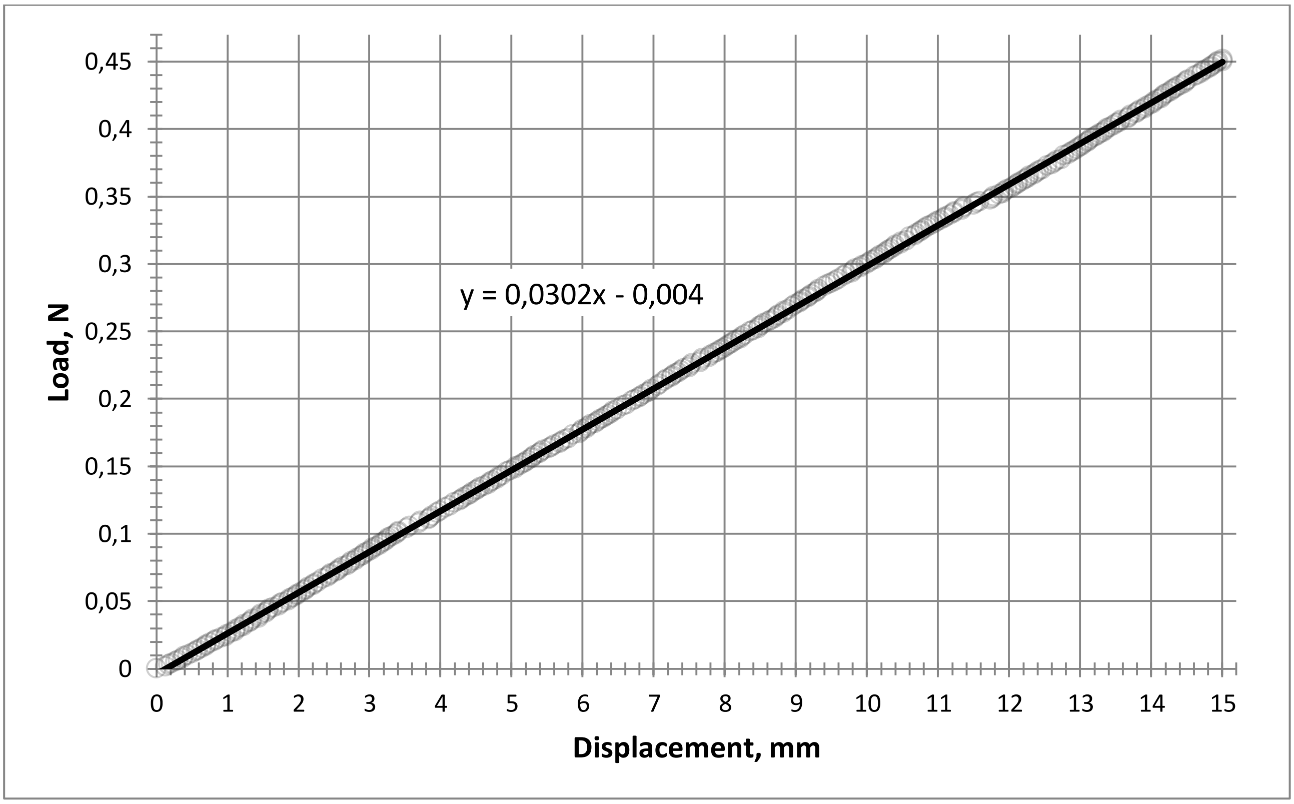

Fig.54 Stiffness of PETG control group. Experiment #1.

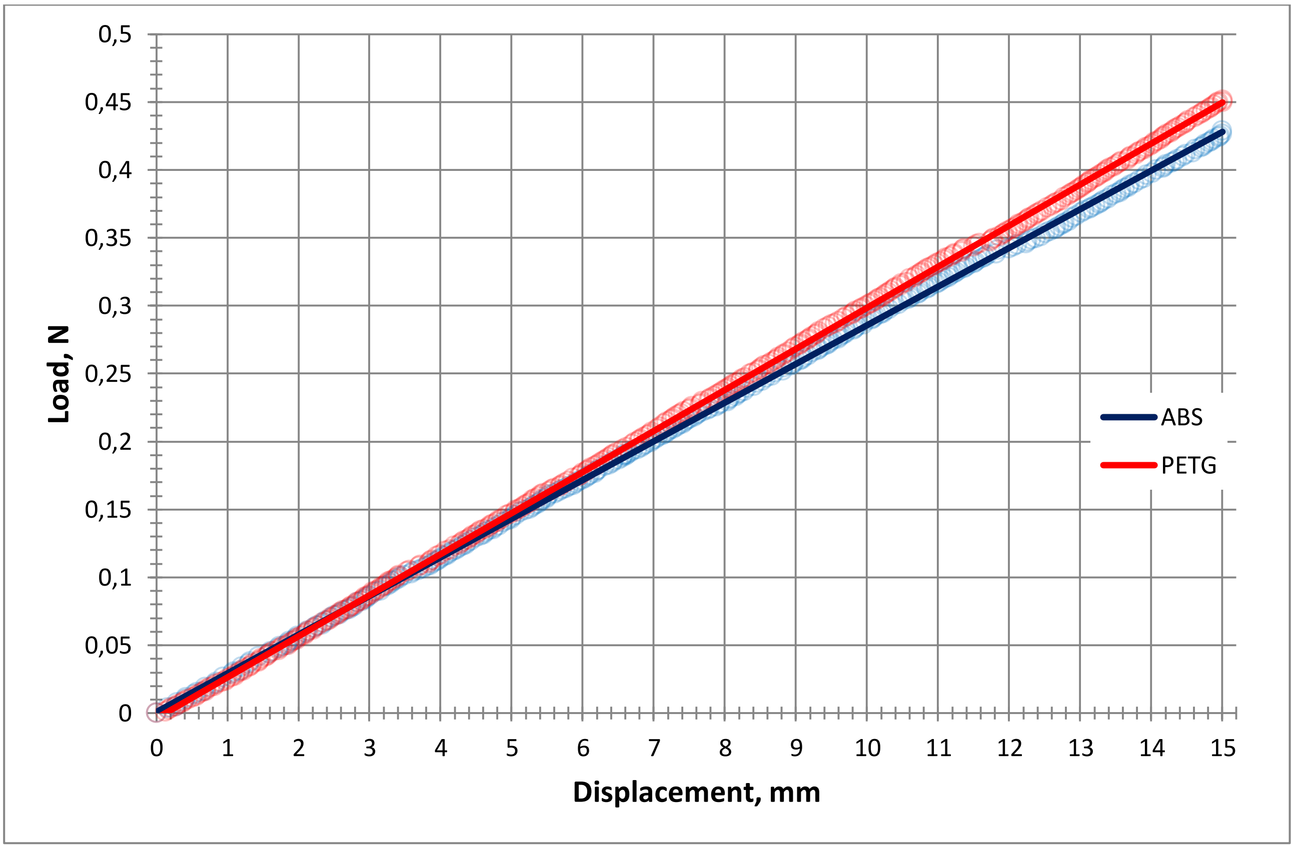

Fig.55 Control group stiffness of ABS specimens, compared to PETG specimens. Experiment #1

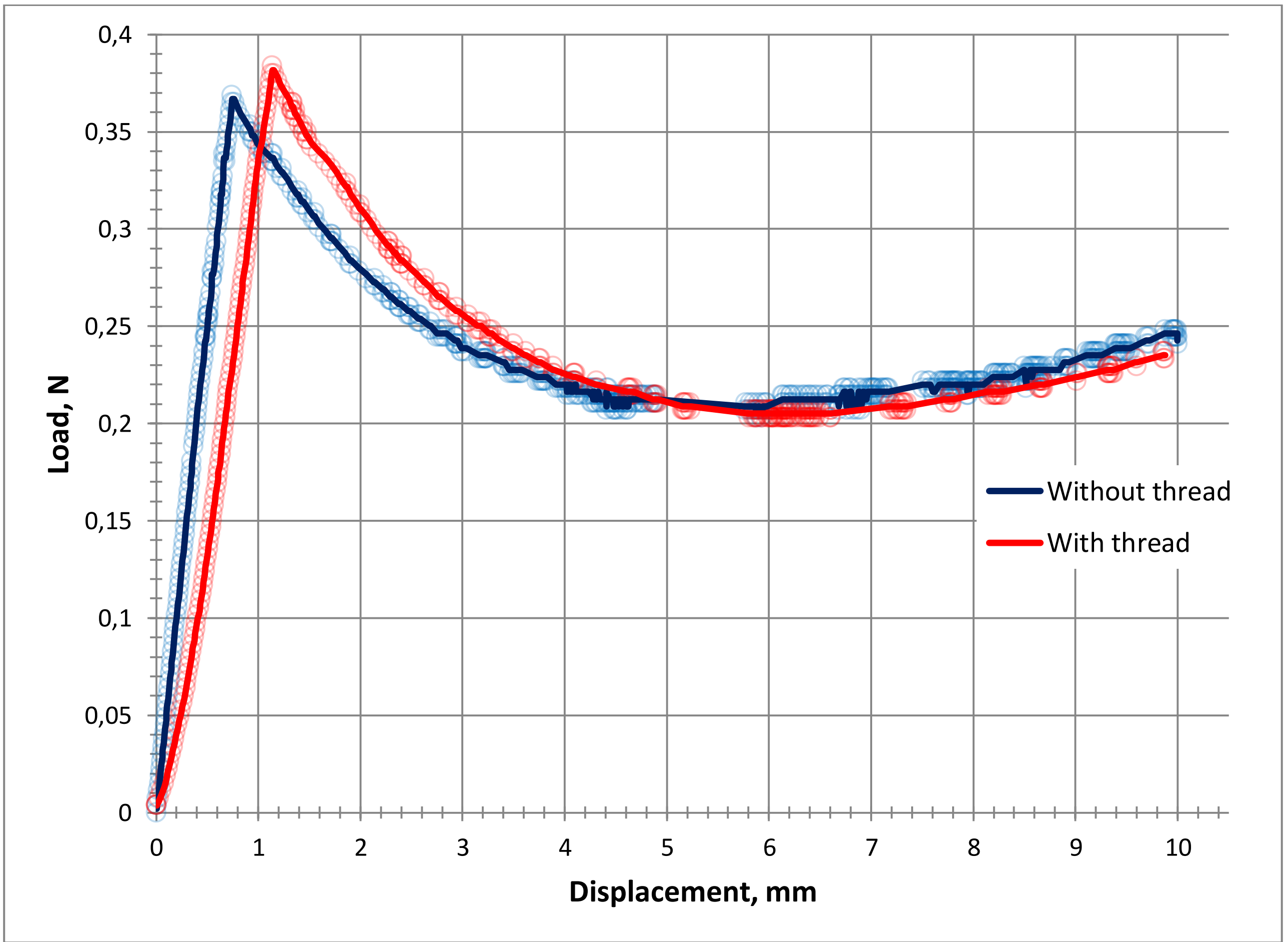

Fig.56 Visible data inaccuracy when using string to pull specimen. Experiment #2

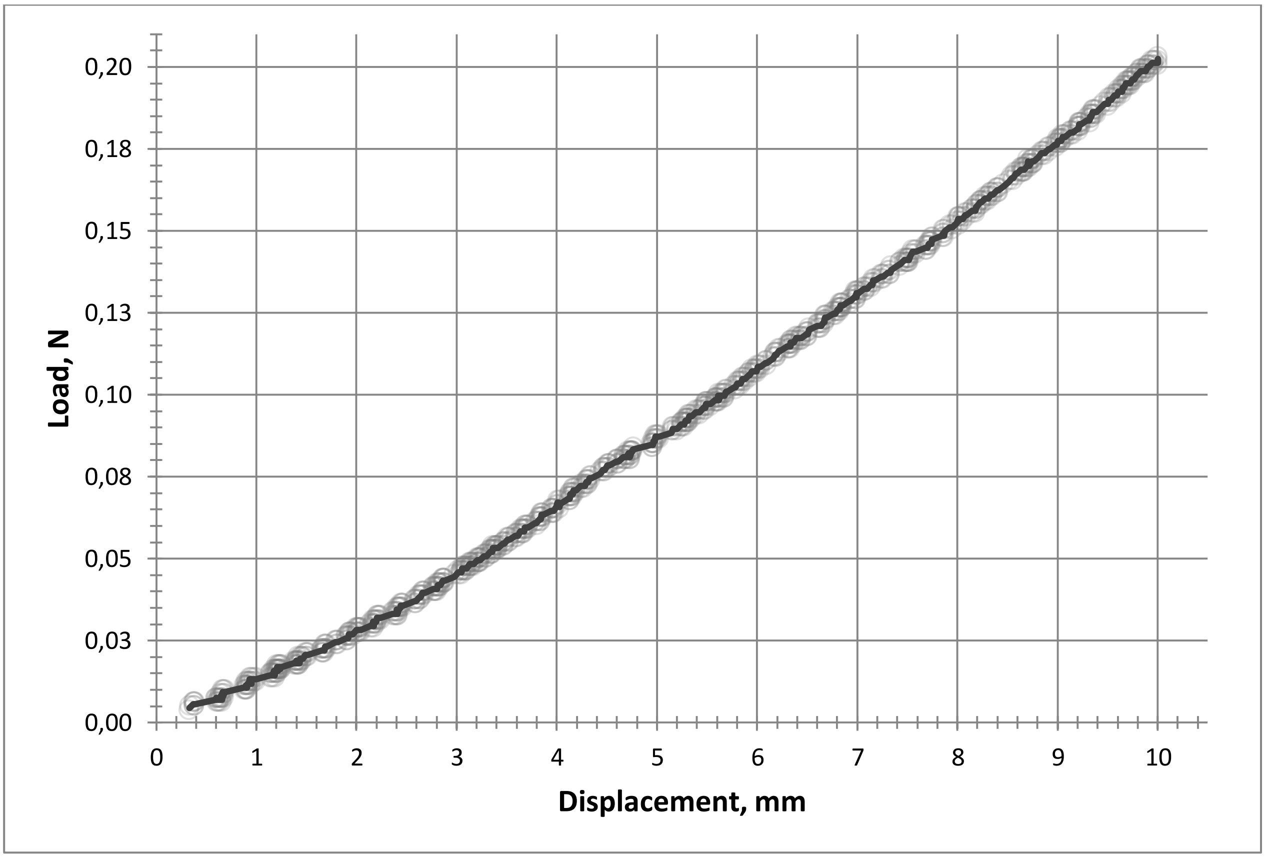

Fig.57 Stiffness of PETG specimen under effects of magnetic field. 0mm offset. Experiment #3

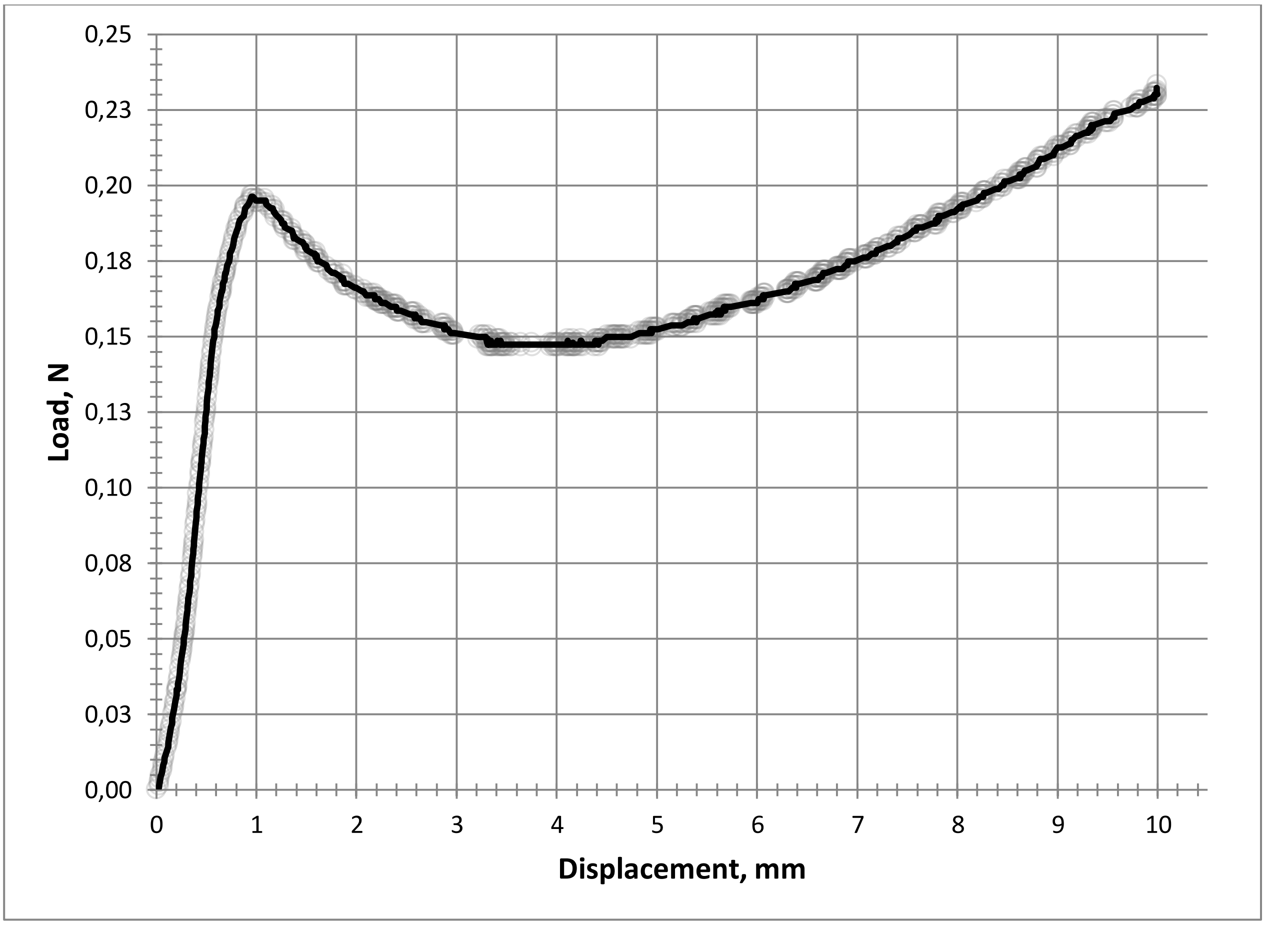

Fig.58 Stiffness of PETG specimen under effects of magnetic field. 10mm offset. Experiment #4

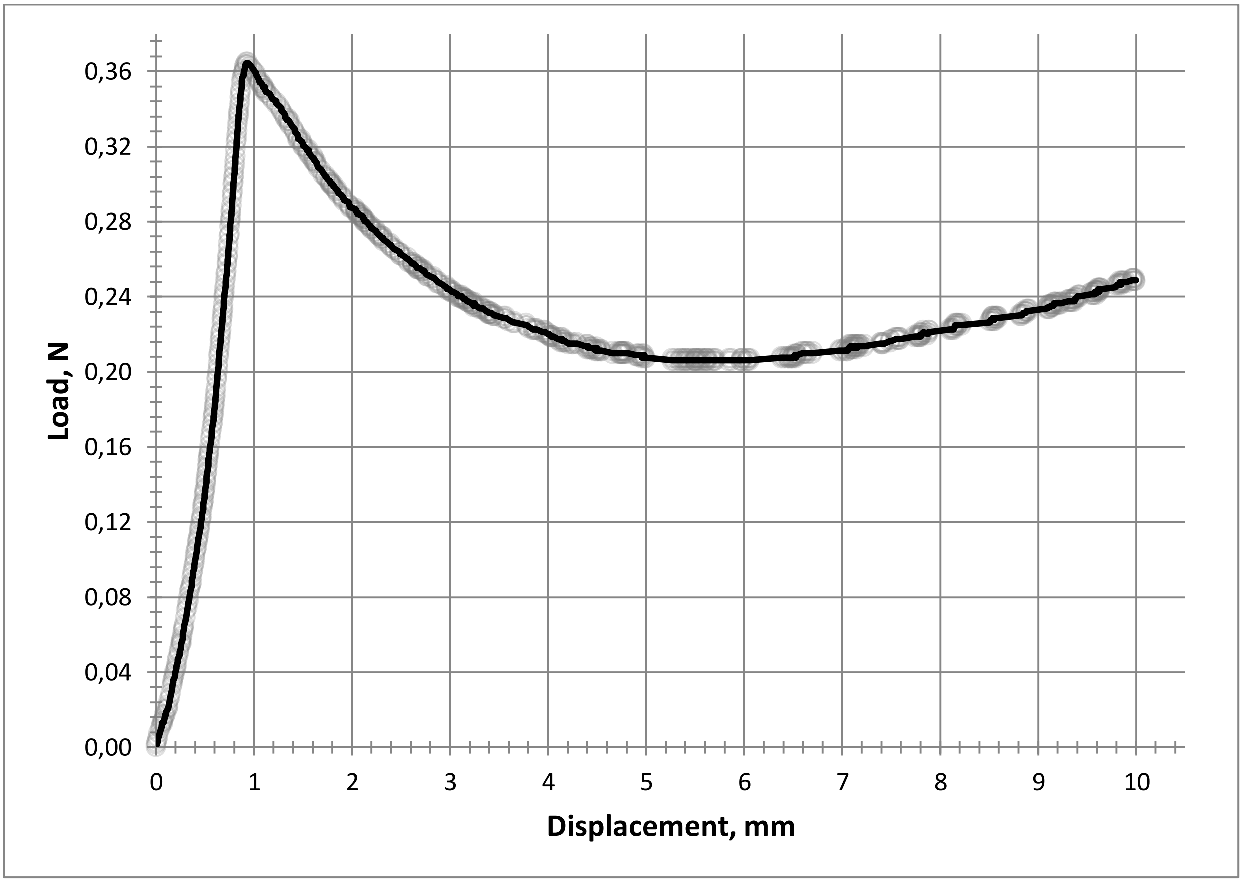

Fig.59 Stiffness of PETG specimen under effects of magnetic field. 20mm offset. Experiment #5

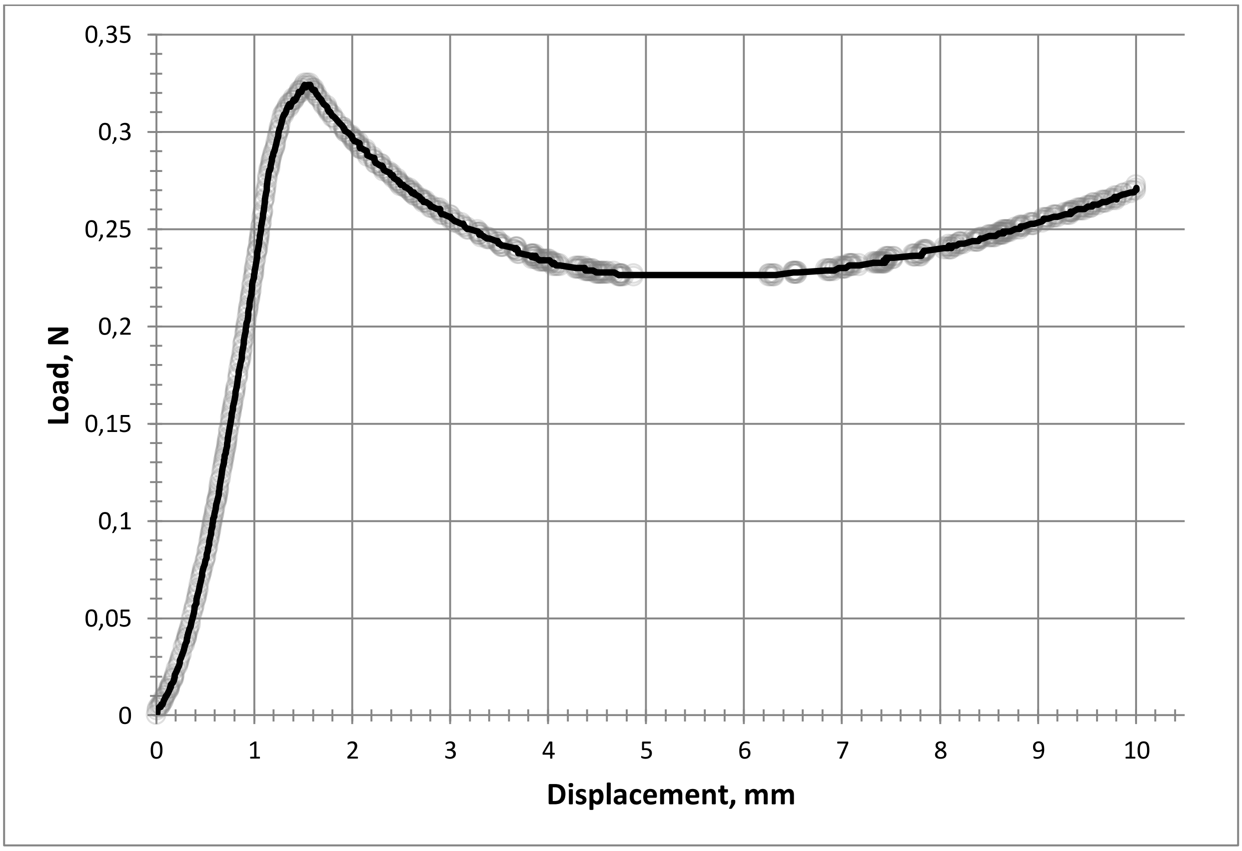

Fig.60 Stiffness of PETG specimen under effects of magnetic field. 30mm offset. Experiment #6

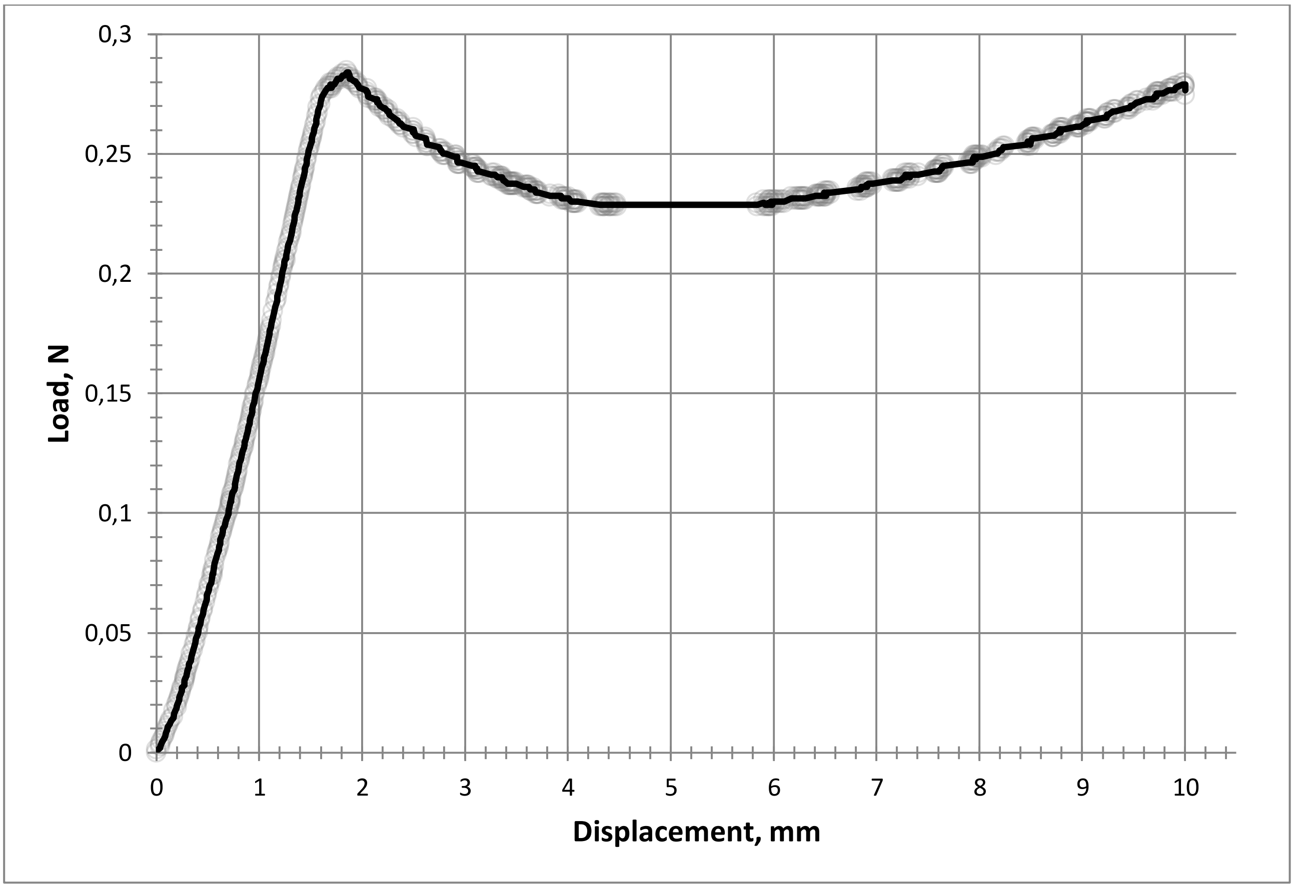

Fig.61 Stiffness of PETG specimen under effects of magnetic field. 40mm offset. Experiment #7

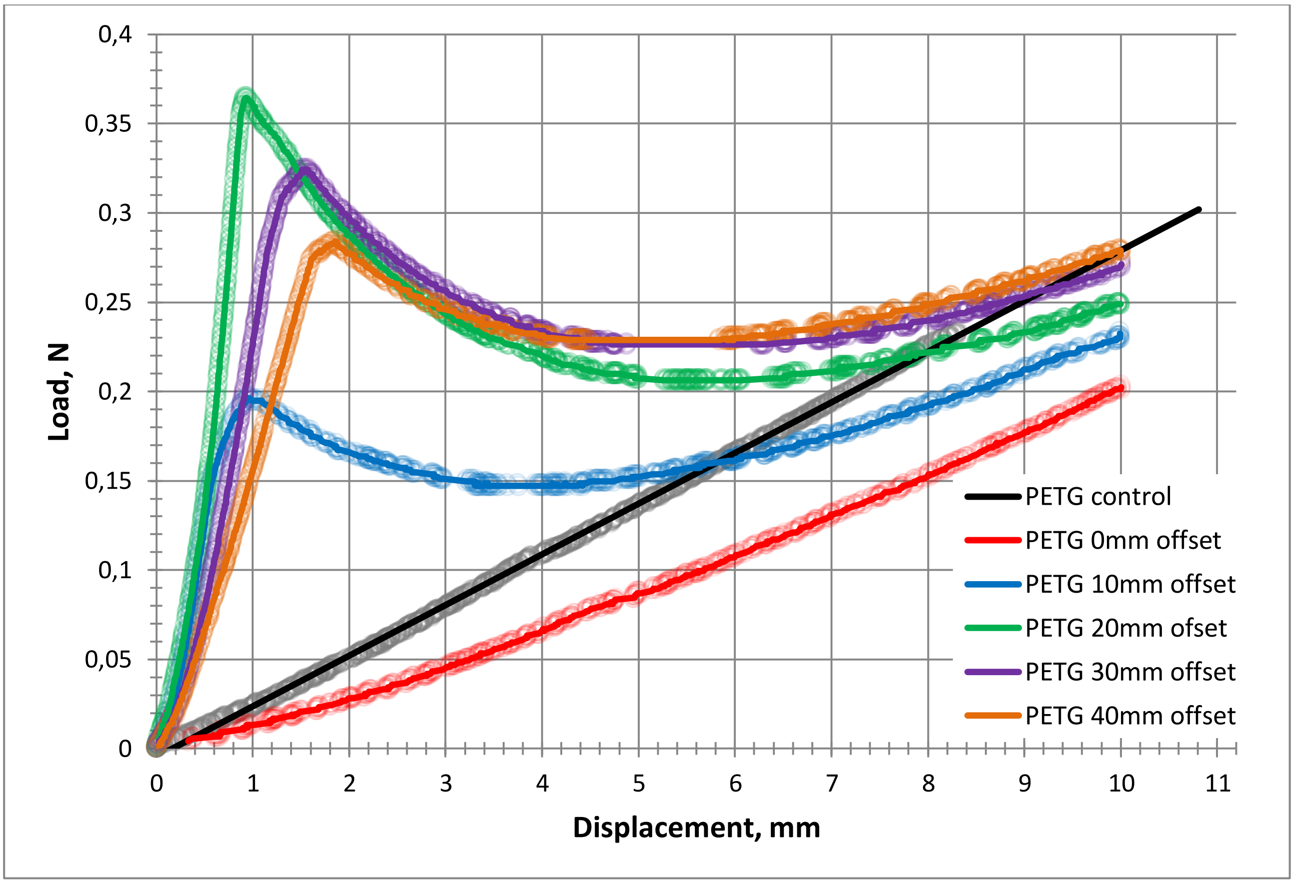

Fig.62 Compared data of all 3-7 experiments and PETG control test.

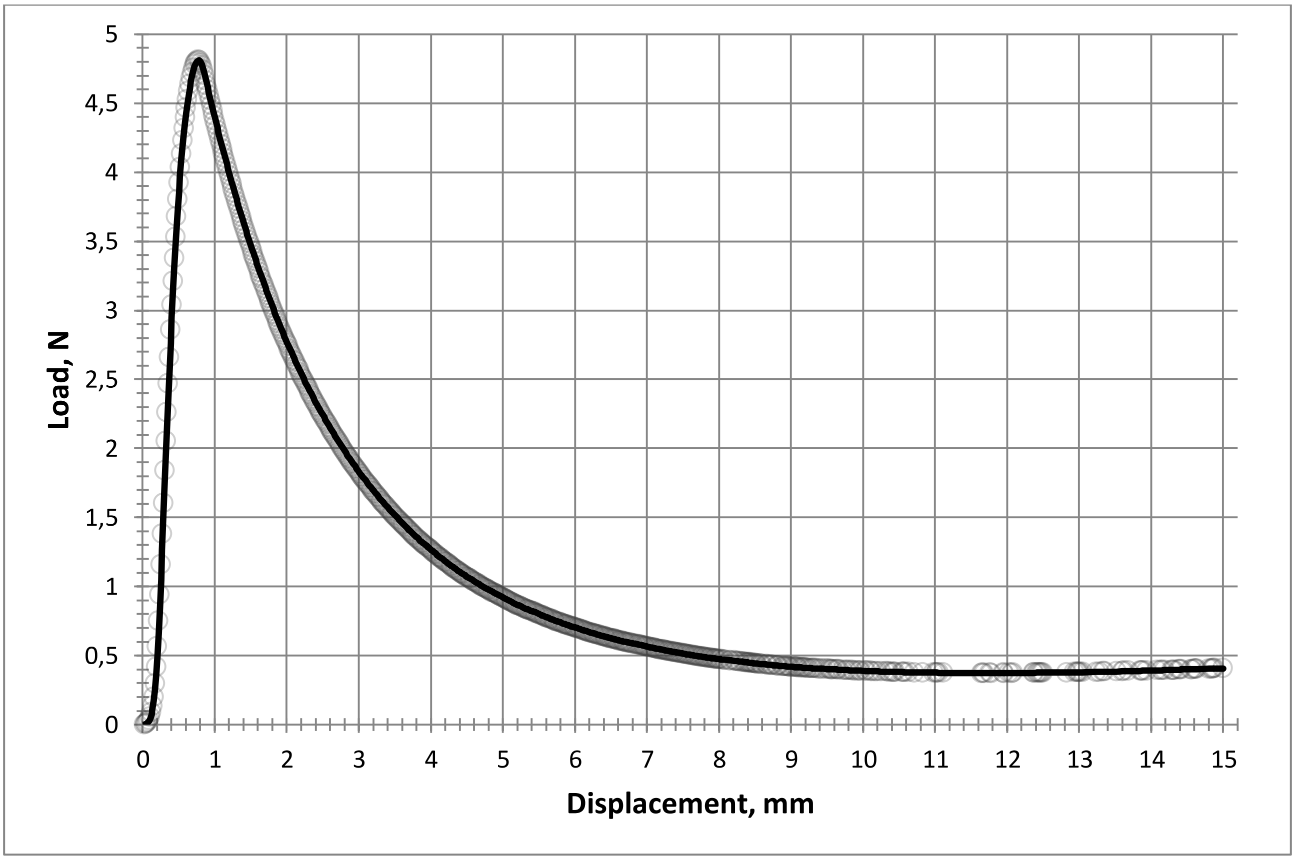

Fig.63 Force generated when pulling ABS specimen with neodymium magnet underneath. Experiment #8.

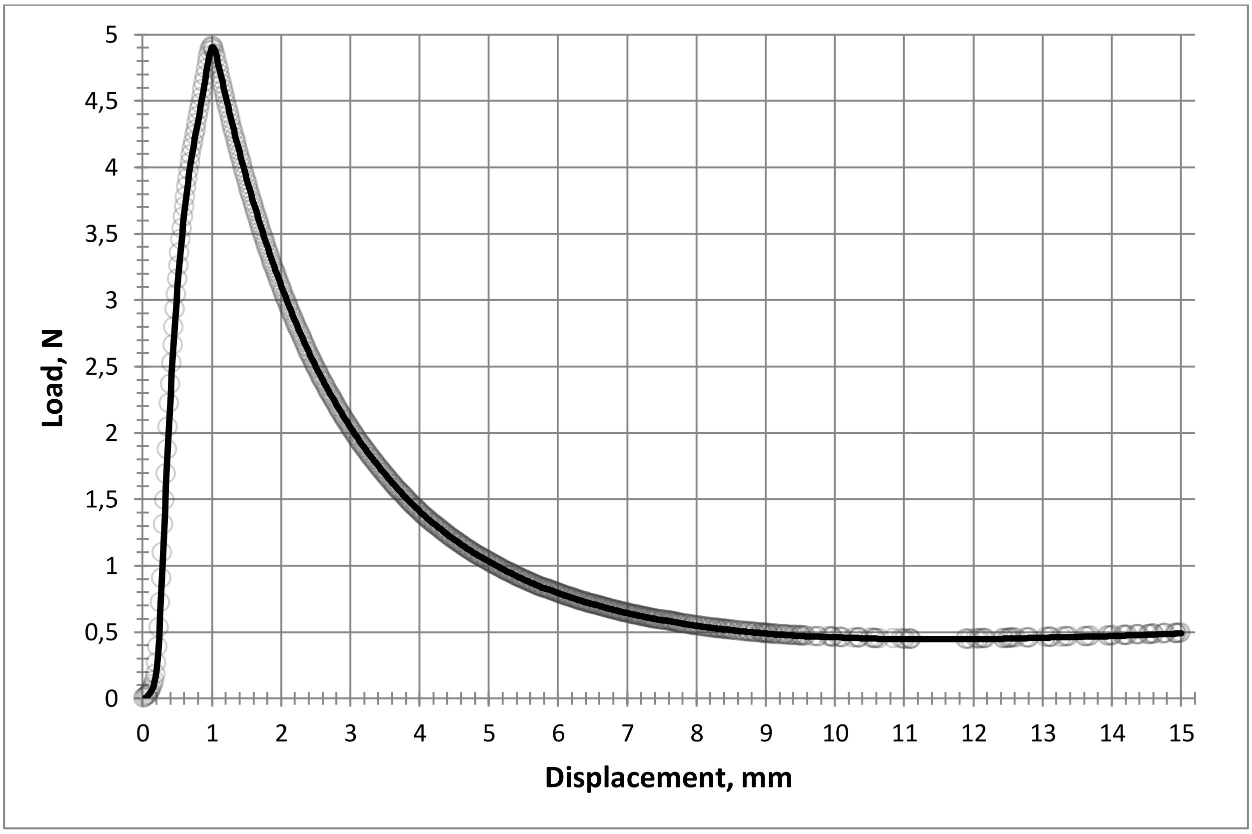

Fig.64 Force generated when pulling PETG specimen with neodymium magnet underneath. Experiment #8.

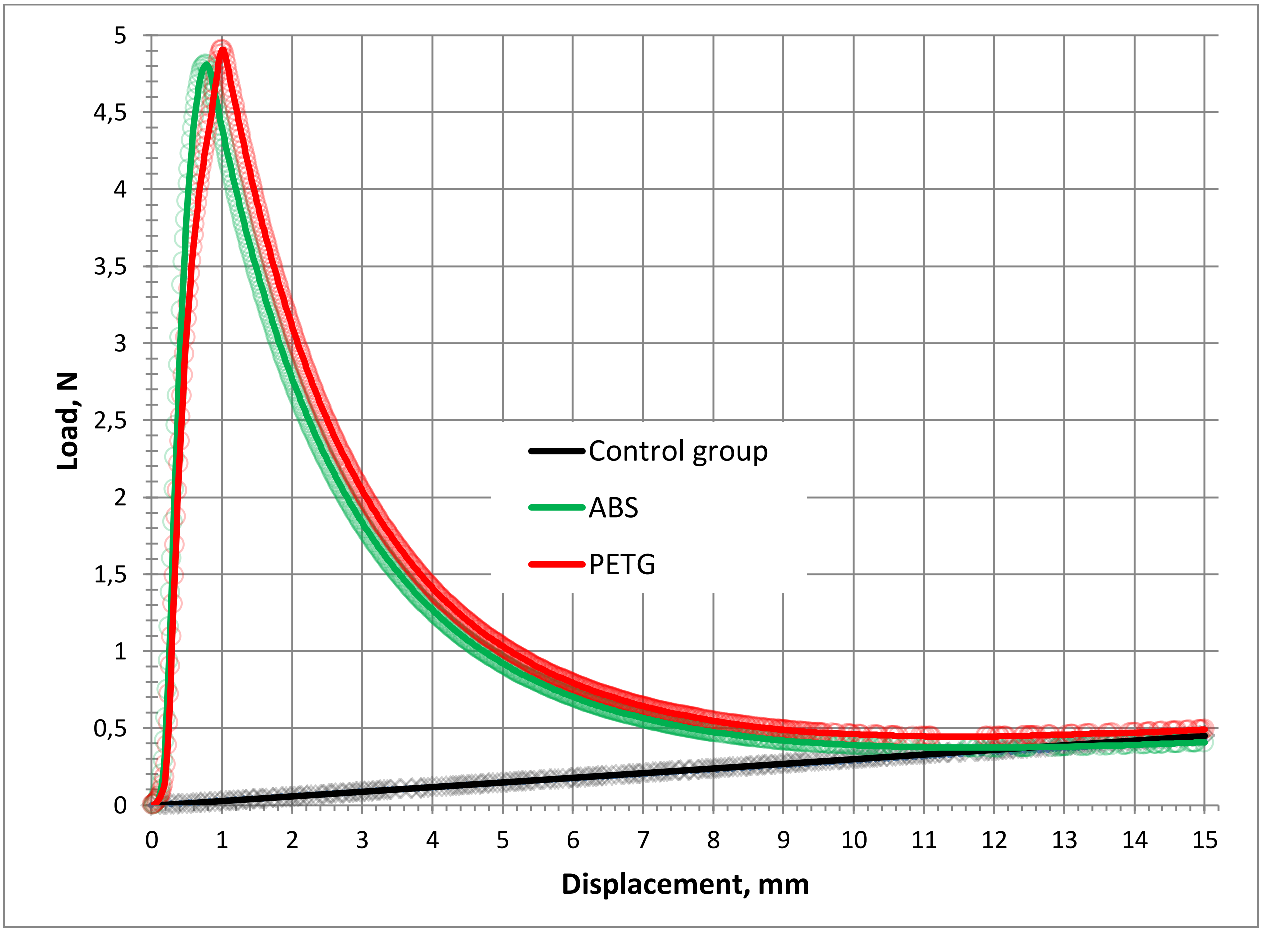

Fig.65 ABS and PETG load graphs compared to control group.

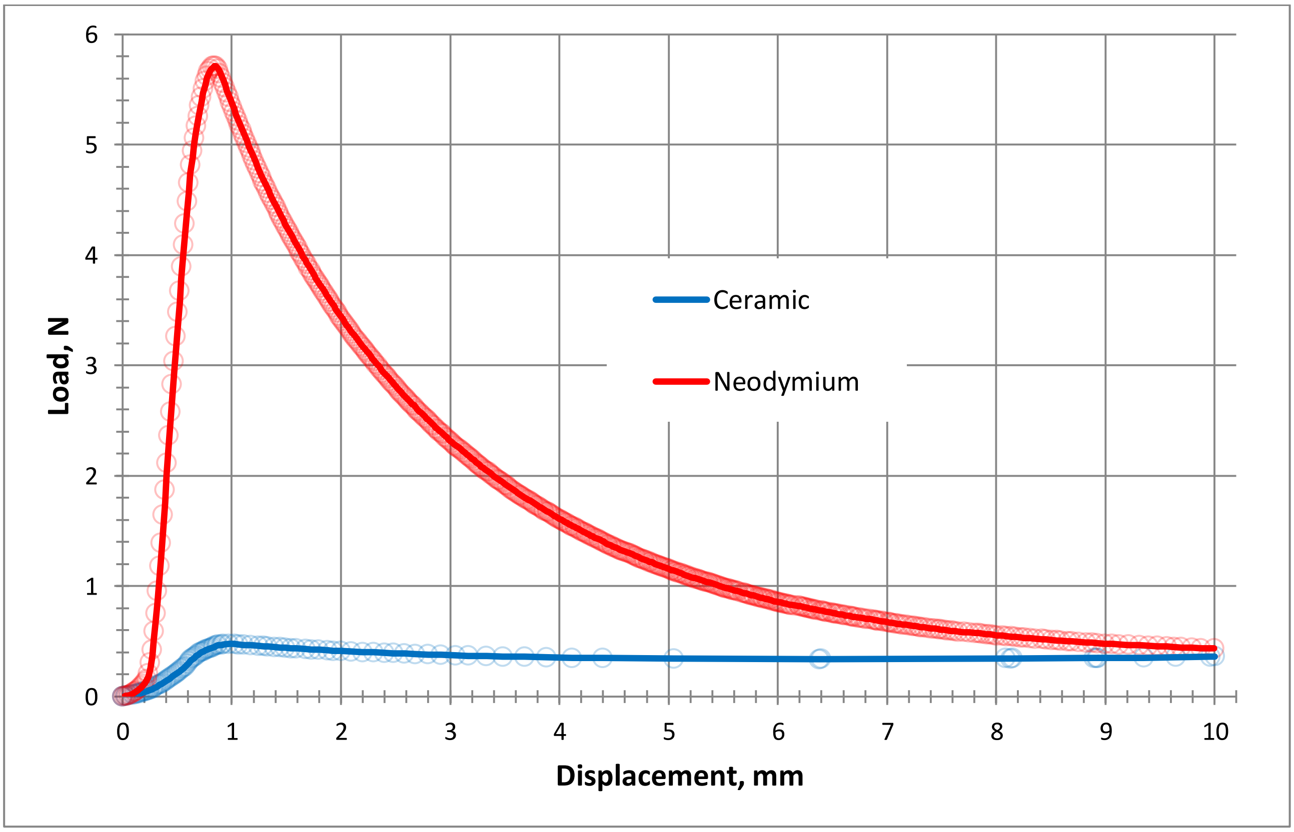

Fig.66 ABS specimen stiffness under effects of neodymium and ceramic magnets. Experiment #9

Results summary

Experiment #1.

This experiment was meant to set “base” statistics for specimens both made from ABS and PETG under no effects of magnetic field whatsoever, so that results of other experiments could be compared accordingly. As expected, results showed linear relation between displacement and load, as shown in figures 53 and 54. Its linear function can be described as y=0,0285x, while PETG was y=0,0302x. Although linear relation in control group’s results was expected, they were still surprising. It seemed that ABS specimen possessed better flexibility abilities. In figure 55, difference between forces, required to pull specimen a certain distance, can be clearly seen. Although, at 15mm displacement forces differ in less than 0,03N, ABS specimen was a bit more flexible. PETG was the first polymer chosen to be carcass of specimen, because of its ability to bend without breaking in half, which lead to assumption, that it had better flexibility than ABS. This was proven to be false.

Experiment #2.

A thread between cell’s hook and specimen was used, because some experiments were impossible to be done otherwise. For this matter said thread was tested for elongation, which could interfere with results. Unfortunately, differently from the rest of experiments, only one test run was done for each instance, which didn’t allow forming statistical average. This caused a lot of visible “jumping values” which were mentioned earlier. Also, greater deviations needed to be considered.

It can be seen in the figure 56 that results differ a little bit, but taking all of the points, mentioned earlier, into consideration, it was decided, using thread might cause no significant deviations and this is why. When 3-5 samples are done for one experiment, their results differ in same way. For this reason it was decided to undergo more than 1 sample in order to gather more data, derive statistical average and lessen possible deviations. Of course, this could also have been done in this case, but due to human error, some of the sample data from this experiment was lost. Though, small thread elongation can be seen, particularly at the function’s peak. Sample “without thread” possesses a very sharp peak, while “with thread” has its peak smoothen a little bit.

Experiment #3.

As seen in the figure 57 ceramic magnet placed with 0mm offset may seem to have very little effect on PETG specimen. A slight curve is seen along the way from displacement of 0mm to 10mm. Although visually it might seem very similar to control group’s graph, but taken a look at the values it can be seen that there is an obvious decrease in Load values. At 10mm displacement load value is slightly above 0.2N, while in control graph it is close to 0.3N.

Up until ~5mm displacement a curve, bent downwards, can be seen. This indicates effect of magnetic field, which reduced needed force to pull specimen. From 5mm displacement a more linear function can be observed, which might indicate, that magnetic field has very little effect at this point and most of the resistance force is generated from specimen's natural stiffness.

Experiment #4.

Right up until 1mm displacement a rapid increase in load can be seen. Peak of this section is a point, when specimen is completely separated from the surface of magnet. Because structure of specimen is not rigid, when it is pulled away from touching magnet it's not lifting evenly. First, the point where string is applied is lifting up, bending that part up, while rest of the specimen continue to touch surface of magnet. As more the specimen is being pulled, the more it is bent and more of it breaks away from surface of magnet until it completely breaks away from surface of magnet. That point is the peak of rapid rise of load, seen at the start of graph. From 1mm we can see that load is gradually lowering for a while, until it starts to get close to control values. It can be seen that peak of this graph is at 10mm, meaning that force, needed to break away is lesser than that which is needed to bend specimen 10mm, but even there, where effects of magnet should be close to none, specimen is still showing more flexibility than at control test.

Experiment #5.

First section of this graph, until 1mm, has much more sudden jump in generated load. It reaches a peak of 0.36N and starts to gradually fall. Taken a closer look, we can see that until around 0.16N point, graph is more like a curve than a straight line. Somewhere between 5-6mm we can see, that specimen escapes magnetic field, which pulls it towards magnet and starts to get closer to its control values.

Experiment #6.

A small curve, at the very beginning seems to be much smaller. Also, specimen seems to break away from magnet only at ~1,5mm. This is due to magnet being placed in such position that requires specimen to be bent more for it to break away from magnet's surface. Getting close to peak values we can see, that there is a strange "nudge" in the graph. Reason for this is unknown, but it's possible that this is due to some kind of "misbehaviour", which might cause incorrect readings, maybe thread shifting or something similar, which shouldn't happen in general. Once again, it appears 5-6mm range is where specimen starts to catch up with its natural stiffness, cause graph to go up again.

<u>Experiment #7.</u>

By looking at figure's 61, we can see that beginning of graph is very similar to previous one. 1,5-1,8mm is the point of complete breakaway from magnet's surface with exact same nudge. At this point it's hard to say, if it's because of some kind of error, or because of magnets offset. Breakaway is at ~1,8mm, which is even further, than during previous experiment. After load peak value specimen travels considerably short distance, until magnetic field effect is no longer visible in the graph.

In figure 62 we can see results of experiments from 3 to 7 compared together along with control test results. It appears that all of said experiments showed some interesting results. At 10mm displacement, load values are lower than that of control run. It may be possible, that due to the way magnet was positioned, it generated such magnetic field, which pulled specimens downwards, when they were close enough, but at one point (which seem to differ, depending on magnet's offset) starting to generate force of opposite vector, pushing specimen upwards, thus reducing resistance. This only applies to 0, 10 and 20mm offsets. 30mm and 40mm offsets seem to lack this "feature" and their graphs get close to control values. 0mm offset shows reduced load values during whole test run with its value at 10mm displacement differing from control values by ~0.07N.

<u>Experiment #8.</u>

Principe of this experiment is exactly the same as previous one, except this time much stronger magnet was used. Result of this can be clearly seen as the peak of graphs, seen in figures 63 and 64 is much higher, almost at 5N. From breakaway point a gradual decrease in load values can be seen for both graphs, until point is reached, where magnetic field influence is no longer visible. From that point graph starts to catch up with its control stiffness. In figure 65 we can see both ABS and PETG specimen graphs compared with added control group graph. It seems that PETG breakaway point is at 1mm displacement, while ABS is a little bit sooner, somewhere around 0,8mm. This is quite interesting, because it shows ABS specimen not only needed less force to break away from magnet's surface, but also was bent less while doing it. Of course, there is possibility, that this is not more than a mechanical error, like different amounts of MR fluid inside specimens.

<u>Experiment #9.</u>

In figure 66 we can see a difference between neodymium and ceramic magnets in work. When ceramic magnet is in use, it requires approximately 0,5N force to break it away from magnet, while neodymium magnet requires almost 5,8N force, which is more than 10 times bigger. Despite that difference, in both instances graphs seem to get closer to same value, which is specimen's control stiffness. Another difference can be seen in distance, at which magnetic field seize to influence specimen's stiffness in any significant way. For ceramic magnet that distance is approximately 5-6mm, while for neodymium it's approximately 11,5mm (taken from figure 65).

Conclusions

- Specimens, consisting of stiff polymer and visco-elastic MR fluid were successfully designed and manufactured. Specimens printed from ABS are more watertight, have less printing errors, are easier to maintain and possess better flexibility than those, made from PETG polymer.
- RepRap 3D printer, capable of printing two different materials, filament and visco-elastic material, simultaneously was successfully designed and built.
- Rigidity of specimen, when pulled by a positive Y axis vector force, was measured during all of experiments. Rigidity of control groups for ABS and PETG specimens can be described as linear functions y=0,0285x and y=0,0302x respectively, where *y* is force (N) and *x* is displacement (mm).
- Magnet orientation and position affects specimen's stiffness along positive Y axis in different way.0mm magnet offset reduces specimen's stiffness all of the time; 10mm and 20mm offsets create negative Y axis vector force while very close to magnet and slowly changes to positive Y axis vector force at the end, changing specimen's stiffness respectively; 30mm and 40mm offsets create only negative Y axis vector force at first, which eventually fades away as distance from magnet grows. 0mm offset, which is when magnet is placed next to specimen, creates greatest positive Y axis vector force, which increases specimen's flexibility.
- Load/Displacement graphs for specimens, while magnetic field is in effect are composed of 3 parts. First is breaking away from magnet's surface, where load is rapidly increasing, while displacement changes a little. Specimen here is being manipulated by two different vector forces, which gradually bends specimen, where it is in contact with magnet, until it completely breaks away. Second, after breakaway point, which resembles traditional magnetic-field-strength/distance graph, until the point, where magnetic field's force is lower than specimen's natural stiffness. Third, where graph starts getting closer to specimen's control stiffness.
- Load values are directly influenced by strength of magnet used.
- Thread string used in experiments had very little influence on results, thus was ignored.

Applicability

Composites of two completely different materials, such as used in these experiments can be defined as “smart materials”. These materials can change their properties depending on environment they’re in, or indicate certain changes in same environment. These particular composites can be used in situations, where variable rigidity is needed, exempli gratia, shoe insoles for sportsmen, where insole is soft when jumping, but hard when making a step; prosthetics, where different stiffness is needed to pick up brittle, soft or heavy things; seats; grabbers.

Various pressure actuators can be equipped with such composite parts allowing them to have adjustable sensitivity or threshold. Actuators or sensors, which detect change in temperature, acidity (pH), humidity, etc. may be developed and used in a form of accessory.

Dampers, breaks and other similar systems, in which MR fluids have already been applied, can be further improved with such composites allowing their construction or manufacturing process to be simplified.

Various mechanical units can be entirely changed with single composite part, which would function in entirely same way and would have much simpler construction.

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Presentation of results.

Sviackevičius, P., Verbickaitė, E., Jurkonis, E., *Research of properties of 3d printed object, presented in a combination of plastic and flowable substances*, 20th annual young scientist conference “Science – future of Lithuania”, held on 2017 april 28th, VGTU.

Appendix

Specification of Mecmesin Multitest 2.5-I system

MultiTest-*i*		0.5	1	2.5	5	10	25	50
TEST FRAME								
Rated capacity	N	500	1000	2500	5000	10000	25000	50000
	kgf	50	100	250	500	1000	2500	5000
	lbf	110	220	550	1100	2200	5500	11000
Number of ballscrews		1	1	1	1	2	2	2
Speed range	mm/min	1 - 1000	1 - 1000	1 - 1000*	1 - 500	1 - 1000	1 - 1000**	1 - 400***
	in/min	(0.04 - 40)	(0.04 - 40)	(0.04 - 40)	(0.04 - 20)	(0.04 - 40)	(0.04 - 40)	(0.04 - 15)
Crosshead speed accuracy		±0.2% of indicated speed						
Distance between columns		-	-	-	-	400 mm (15.7″)	400 mm (15.7″)	420 mm (16.5″)
Throat depth†		67 mm (2.6″)	67 mm (2.6″)	67 mm (2.6″)	95 mm (3.7″)	-	-	-
Vertical daylight ††		1359 mm (53.5″)	1159 mm (45.6″)	590 mm (23.2″)	710 mm (28.0″)	1140 mm (44.9″)	1140 mm (44.9″)	1330 mm (52.4″)
Height		1710 mm (67.3″)	1510 mm (59.4″)	941 mm (37″)	1082 mm (42.6″)	1500 mm (59.1″)	1500 mm (59.1″)	1981 mm (76″)
Width		290 mm (11.4″)	290 mm (11.4″)	290 mm (11.4″)	328 mm (12.9″)	826 mm (32.5″)	826 mm (32.5″)	864 mm (34″)
Depth		414 mm (16.3″)	414 mm (16.3″)	414 mm (16.3″)	526 mm (20.7″)	542 mm (21.3″)	542 mm (21.3″)	572 mm (22.5″)
Weight		38 kg (84 lbs)	36 kg (79 lbs)	22 kg (49 lbs)	38 kg (84 lbs)	140 kg (309 lbs)	140 kg (309 lbs)	285 kg (628 lbs)
Max. power requirement		120 watts	200 watts	250 watts	150 watts	450 watts	450 watts	450 watts
Voltage		230 V AC 50 Hz or 110 V AC 60 Hz						
LOAD MEASUREMENT								
Available loadcell ranges	N	2 to 50000 (14 models)						
	kgf	0.2 to 5000 (14 models)						
	lbf	0.45 to 11000 (14 models)						
Loadcell measurement accuracy		±0.1% of full scale for loadcells from 2 N to 2.5 kN ±0.2% of full scale for loadcells from 5 kN to 50 kN						
Loadcell measurement resolution		1:6500						
DISPLACEMENT								
Crosshead travel††		1200 mm (47.3″)	1000 mm (39.4″)	500 mm (19.7″)	590 mm (23.2″)	950 mm (37.4″)	950 mm (37.4″)	1100 mm (43.3″)
Positional accuracy per 300 mm (11.81″) of travel		±130 μm (±0.005″)				±100 μm (±0.004″)		
Displayed resolution		±0.01 mm (±0.0004″)						

SOFTWARE	
Digital display of load/length/speed	Yes
Communication with test stand	Via RS232 port or USB port (converter supplied)
Computer requirements	100 Mb available HD, CD-ROM plus available RS232 port/USB port
Operating system (OS)	Compatible OS installed as listed; Windows® 2000, XP & 7
Sampling rate	Selectable from 1 kHz, 500 Hz, 100 Hz, 50 Hz and 10 Hz
Secondary input	Event Input (switch), Digital control I/O Ports
Data output	LPT1 (Printer port), RS232 Port (direct or via USB/Network converter in ASCII format) ASCII file (Export to spreadsheet, SPC package etc...)

* 2.5 kN - above 2 kN, the recommended maximum speed is 750 mm/min (30 in/min)
** 25 kN - above 10 kN, the recommended maximum speed is 500 mm/min (20 in/min)
*** 50 kN - above 25 kN, the recommended maximum speed is 250 mm/min (10 in/min)
† Measured on centre line of loadcell
†† Measured without loadcell or grips