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Use of additive manufacturing in interior product development

DIPLOMA THESIS

Bc. Iva Linhartová   **2016**

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Abstract

Linhartová, I. Use of additive manufacturing in interior product development. Diploma thesis, Brno, Mendel University in Brno, 2016.

Diploma thesis Use of additive manufacturing in interior product development is focused on researching whether there is a use for 3D printing and related technologies from theoretical as well as from practical site of the issue. It focuses on possibilities of layered manufacturing and related technologies, material possibilities and practical application in the field of interior products.
Practical part of the thesis consists of material and component testing.

Key words: additive manufacturing, 3D printing, material properties, furniture, interior

Abstrakt

Linhartová, I. Využití aditivní výroby při vývoji interiérového produktu. Diplomová práce, Brno, Mendelova univerzita v Brně, 2016.

Diplomová práce Využití aditivní výroby při vývoji interiérového produktu je zaměřena na výzkum praktického využívání 3D tisku a souvisejících technologií při vývoji a výrobě interiérových produktů a to jak z teoretického, tak z praktického hlediska. Zaměřuje se na možnosti využití 3D tisku a souvisejících technologií, zjištění a prověření materiálových možností a praktické aplikace v oblasti interiérových produktů.
V praktické části se práce zabývá testováním materiálu a součástky vyrobené za pomocí 3D tisku.

Klíčová slova: additive manufacturing, 3D tisk, materiálové vlastnosti, nábytek, interiér

Table of contents

I. INTRODUCTION

This diploma thesis focuses on new possibilities of production mainly in the field of furniture and interior products. The world of manufacturing is changing and all kinds of industries are adapting to new appearing technologies. Layered manufacturing is one of them, and as this technology is becoming more accessible, its place in many kinds of large to small productions is becoming more ensured.

We know about the technology of additive manufacturing and 3D printing for a while, but we still didn't adapt our thinking of manufacturing to it. Layered manufacturing is a completely new approach and industries need to adapt the basic thinking in order to use the potential of this technology in a full way. New technologies such as layered manufacturing are bringing many possibilities but most of them must be still discovered.

The aim of this work is to point out some of the additive technologies advantages but also draw backs and to point out some of the new technologies possible practical usage. Of course it is not my goal to reject traditional ways of production and at this stage of additive manufacturing technology development it is not even possible. My objective is to point out, that these methods of production could be a common tool for product development stages and a complementary manufacturing method aside with the traditional ones.

Because till now the technology of additive manufacturing was mainly used for fast prototyping, there was not a big focus on the material properties and not a sufficient research of the material properties done. However, some of industries already started to use additive manufacturing as a manufacturing method for the final product production.

In the theoretical part of this work there was a large literature review of the issue done. In order to understand the possibilities, understanding of the technology must be done. The practical part of the work followed up on the literature reviews' results.

II. GOALS

The main goal of this work is to point out some of the new technologies and their possible usage and application in development of an interior product. It mainly focuses on additive technologies and for its better understanding first a solid theoretical research and learning about this technology as well as about materials which are used along with additive manufacturing must be done.

One of the goals of this work is to find out more about the material properties of the most common and easily accessed material used when manufacturing a part on a 3D printer – ABS. Another goal is to test a component related to furniture or interior product made by using a very common additive manufacturing method – Fused deposition modelling (FDM).

Last goal is to evaluate all obtained information and data about this relatively new technology and determine whether there is a practical usage in a near future for additive technologies in furniture production and interior product development.

III. REVIEW OF PROBLEMATIC

1. Product development

The need to create a successful product in quite short time is evident, especially in nowadays competitive global environment. To compete on market, products need to be cheaper, of high quality, and fast adaptive to customer´s changing requirements. The solution to stay competitive in such a dynamic market remains to be the usage of the modern technologies, and this point has been proven in industry. In order for a company to be successful, there must be a continuous consistency of producing series of high quality products. To achieve such a high goal, attention must be paid especially to the product-definition and product-development stage.

Engineers often need to build prototypes to validate the concept of their designs. However, prototyping in the traditional way can be very time consuming and it is increasing the cost of the final product. Prototyping in fact became a weak spot of the product development process.

To produce a competitive product, engineering effort should be invested mainly to the product definition stage. It is obvious that when a product is at the definition stage it is very easy to make changes in its design, meanwhile when the product is developed further it becomes difficult to make changes. When a company tries to make a simple change at the production stages of a product, the cost will be larger than the cost of a change at design.[1]

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[1] LIOU, Frank W. *Rapid prototyping and engineering applications: a toolbox for prototype development*. Boca Raton: CRC Press, 2008, xxv, 535 p. Mechanical engineering Taylor, 210. ISBN 08-493-3409-8.

1.1. Product definition stage

The goal of every product designer is that once a product designed, it will work well. This goal is more likely to be achieved when the product is designed well and tested early; this early stage is called "product definition". In another words, the key to a good and functional design is to prototype early and prototype often.

The result of the product definition stage is customers´ needs translated into product design specifications. However, it could be more than that. Ideally the result of the product definition could be a well-evaluated prototype which confirms, that the customer required concept will work. This is the best way how to assure, that the new design of the product will be successful and money consuming changes in later product stages will not appear.[2]

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[2] LIOU, Frank W. *Rapid prototyping and engineering applications: a toolbox for prototype development*. Boca Raton: CRC Press, 2008, xxv, 535 p. Mechanical engineering Taylor, 210. ISBN 08-493-3409-8.

2. Rapid prototyping

As mentioned above, prototyping can be a very time-consuming process. Rapid prototyping as a modern technique has become a new trend in producing physical prototypes.

2.1.   What is prototyping?

"Prototypes are one of the most useful and cost-effective quality tools businesses have."[3]

The increasing trend in industry is to use simulation technologies such as virtual simulations and rapid prototyping as a part of product prototyping activities. Prototypes play a very important role in a product development. It is obvious that all kinds of products need prototypes and the better prototyping is, the better the final product is.

However, prototyping has a big influence of product cost, quality and time. It is very important, that prototypes are built with efficiency, so they add low-cost and short time-to-market to the final product. Furthermore, it is important that a prototype serves the purpose of the product development type.

The most common reasons to prototype are evaluation of product function, evaluation of product appearance or evaluation of changes, which have been made in the product design. This is why the material and process criteria have a huge importance. To keep cost to minimum when building a prototype, it is important to use cheap and available materials, which at the same time will still fulfil the same purpose as the original material of a product. With the same importance also the prototyping process

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[3] LIOU, Frank W. *Rapid prototyping and engineering applications: a toolbox for prototype development.* Boca Raton: CRC Press, 2008, xxv, 535 p. Mechanical engineering Taylor, 210. ISBN 08-493-3409-8.

must be chosen. In a case when a prototype is built to test the look of a product, it can be made from a very cheap material, whereas a prototype built to test its full function must be made from an appropriate material which serves its purpose.

Traditional prototyping methods allowed engineers to make a static model of their design. However these prototypes did not serve their purpose well, because they did not allow to test their usage and full function. In order to evaluate effectively the whole design concept and function, modern prototyping techniques, such as rapid prototyping and virtual testing, are needed for a successful product development.[4]

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[4] LIOU, Frank W. *Rapid prototyping and engineering applications: a toolbox for prototype development*. Boca Raton: CRC Press, 2008, xxv, 535 p. Mechanical engineering Taylor, 210. ISBN 08-493-3409-8.

3. Additive manufacturing

Although rapid prototyping is a commonly used term linked to methods of fast prototyping, this term is no longer accurate way to call the process of creating prototypes. The reason why is that nowadays this technology is commonly used not only for prototyping but also to create whole parts of final products. That's why the term additive manufacturing (AM) is more accurate and increasingly used.[5]

3.1. AM characteristics

The very basic principle of additive manufacturing (also "layered manufacturing") is evident from the term – it lies in adding material. AM is based on layered manufacturing – typically from the bottom up. Very thin layers are laid down one on another and when stuck together they create a 3D object. A model generated by three-dimensional Computer Aided System (3D CAD) can be manufactured directly without the need of fabrication process planning. Each layer is cross section of the component derived from the original 3D CAD data. It is obvious that additive technologies significantly simplify the process of producing 3D objects directly from CAD files. Other manufacturing processes need to determine all kinds of parameters like the order in which different parts should be manufactured, which tools and processes must be used and what additional works will be used to complete the manufactured part. Whereas additive manufacturing needs dimensional data and basic knowledge of how additive manufacturing machines work and knowledge of the possible materials used.

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[5] GIBSON, Ian, David W. ROSEN a Brent STUCKER. *Additive manufacturing technologies: rapid prototyping to direct digital manufacturing*. New York: Springer, 2010, xxii, 459 p. ISBN 14-419-1120-0.

The process of AM first needs a virtual model assembled in a CAD software, then this model is converted into STL format and then send to a machine for manufacturing of the finished product. These machines are usually referred to as "3D printers"[6],[7].

3.2.   Development of additive technologies

Even though additive technologies (AT) started to develop in the late eighties, we can say, that this technology is still in the start of its possible big expansion. However there has been a huge development forward in the field of AT through the years. The first commercially used fabrication system based on rapid prototyping is according to [8] dated to 1988. There is a huge difference in the amount of precision and strength which is possible to be achieved by using nowadays developed AT. Despite the fact, that nowadays there are devices capable of not only creating models from plastics, waxes and papers as before, but also from metals, composites and ceramics.

Large amount of approaches, which study how to create a model, were developed in the last 30 years of additive technologies progress. Methods vary depending on the use of materials, construction speed or strength requirements. The methods relevant to this work will be described later.

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[6] GIBSON, Ian, David W. ROSEN a Brent STUCKER. *Additive manufacturing technologies: rapid prototyping to direct digital manufacturing*. New York: Springer, 2010, xxii, 459 p. ISBN 14-419-1120-0.

[7] Additive Fabrication. *Custompartnet* [online]. 2008 [2014-10-09]. Available at: http://www.custompart-net.com/wu/additive-fabrication

[8] GIBSON, Ian, David W. ROSEN a Brent STUCKER. *Additive manufacturing technologies: rapid prototyping to direct digital manufacturing*. New York: Springer, 2010, xxii, 459 p. ISBN 14-419-1120-0.

3.3.   The generic additive manufacturing process

Using additive technology to produce a component always involves several steps, which are necessary for every component creation. The concrete number of steps and time needed for every step may vary depending on the complexity of a component, accuracy requirements, surface quality requirements and also on the chosen technology.

3.3.1. 3D CAD model creation

All parts manufactured by AT must begin with this phase. It is therefore necessary to create a CAD software model, or get it another way, such as 3D scanning. This software model will fully describe the external geometry. The model can be either volumetric or described by surfaces only. The only problem which may occur is that the surface of the model will be not completely closed – meaning that on one edge or in a place where several areas intersect, will be a split or a crack. However such a problem is often detected and removed immediately in the next step, which is a transfer to STL format.[9]

3.3.2. Conversion to STL

STL file format is connected to Stereolithography but it is also known as Standard Tessellation Language. STL format has become the standard input format for almost all devices that use additive manufacturing process and nearly every CAD system can output such a file format. STL file describes the external surfaces of the

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[9] GIBSON, Ian, David W. ROSEN a Brent STUCKER. *Additive manufacturing technologies: rapid prototyping to direct digital manufacturing*. New York: Springer, 2010, xxii, 459 p. ISBN 14-419-1120-0.

original CAD model and it is the basis for calculation of the slices. The surfaces are described by network of small triangular areas that approximate the original area.[10]

Figure 1. A CAD model on the left converted into STL format on the right

Because these triangles describe 3D shapes, each triangle has a direction. This direction is expressed by the normal of the triangle. Therefore there can be 2 identical triangles, but each facing an opposite direction (Figure 2). This fact can be reported as a mistake on a STL file in a case that there are inverted normals and the surface does not have a consistent direction.

[10] GIBSON, Ian, David W. ROSEN a Brent STUCKER. *Additive manufacturing technologies: rapid prototyping to direct digital manufacturing*. New York: Springer, 2010, xxii, 459 p. ISBN 14-419-1120-0.
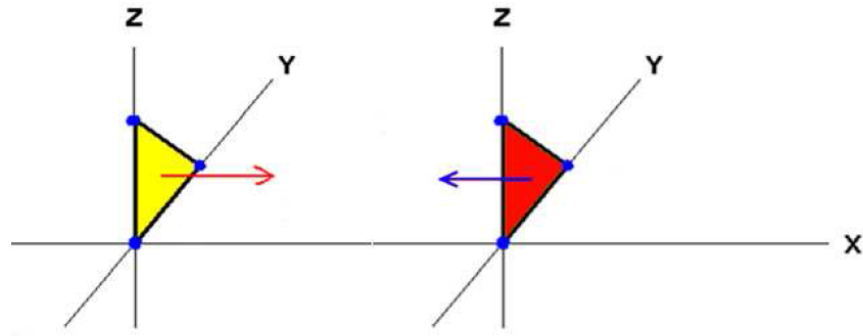
Figure 2. Identical triangles each facing an opposite direction

3.3.3. Transfer to AM machine and STL file manipulation

The created STL file can be sent directly to the target AM machine. Unfortunately this process does not work like in case of the inject printers – that we press a button and the work would be done. There re number of actions that must be done before the built itself starts. First, the orientation need to be specified, meaning the position in which the part will be printed. Often there is not only one product being printed at once, so it is also necessary to accurately deploy the models on the desktop of the printer. The software that printers are equipped, may have functions such as scaling components, adding identification marks (3D embossed characters) or even combining multiple models into one piece. [11]

3.3.4. Machine setup

The setup parameters can differ from a machine to machine but there will be at least some parameters that are specific to the process or machine used. So this phase dependent on the capabilities of each printer. Most of the printers are designed to run

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[11] GIBSON, Ian, David W. ROSEN a Brent STUCKER. *Additive manufacturing technologies: rapid prototyping to direct digital manufacturing*. New York: Springer, 2010, xxii, 459 p. ISBN 14-419-1120-0.

with several types of materials and variation in layer thickness. The layer thickness is one of the most important parameters determining the final product accuracy. Within the setting also the printing time, resolution, and other parameters can be affected. [12]

3.3.5. Built

All the previous stages of the generic AM process consisted of semi-automated tasks, that required considerable manual control, interaction, and decision making. When these steps are completed, the process goes to computer-controlled building phase. The printing itself then is fully automated, there is no need to interfere. From time to time we should only check if there are any error messages, for example in a case, that the building material is over. [13]

3.3.6. Post-processing

After the component is built can be removed from the printer. In the next step the supports must be removed from the model. The supports are often made from a different material than the model and they are used as a supportive structure. Furthermore if the model was fabricated from a photosensitive material, it must be cured to

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[12] GIBSON, Ian, David W. ROSEN a Brent STUCKER. *Additive manufacturing technologies: rapid prototyping to direct digital manufacturing*. New York: Springer, 2010, xxii, 459 p. ISBN 14-419-1120-0.

[13] GIBSON, Ian, David W. ROSEN a Brent STUCKER. *Additive manufacturing technologies: rapid prototyping to direct digital manufacturing*. New York: Springer, 2010, xxii, 459 p. ISBN 14-419-1120-0.

obtain full strength. Also various surface treatments may follow such as sanding, polishing or applying a protective coating, to increase the appearance and mostly durability of the product. [14]

3.3.7. Application

After post-processing the product is ready for use. It should be understood, that although the parts could be made of similar materials to those available from other manufacturing processes (like moulding and casting), parts may not behave according to standard material specifications. Some printing methods can create small pores with bubbles trapped inside the material, which can cause a failure under mechanical stress. Furthermore in almost every case the properties are also anisotropic. However the AM processes and materials are constantly improving and the AM technology develops extremely quick. [15]

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[14] Additive Fabrication. *Custompartnet* [online]. 2008 [2014-10-09]. Available at: http://www.custompart-net.com/wu/additive-fabrication

[15] GIBSON, Ian, David W. ROSEN a Brent STUCKER. *Additive manufacturing technologies: rapid prototyping to direct digital manufacturing*. New York: Springer, 2010, xxii, 459 p. ISBN 14-419-1120-0.

4. Additive manufacturing technologies

AM technologies can be according to [16] divided into three categories based on the form of the raw material. This raw material can be in a liquid, solid or powder foundation. Some of the most used methods will be described further.

4.1. Liquid-based systems

This kind of additive technologies typically use photo curable polymer resins. To form each part of a layer, selected portions of the resin are cured. Stereolithography (SLA), is the most common liquid-based additive process, which was also the first commercially available AT. The advantage of the photopolymer-systems is a good accuracy and an appearance similar to moulded parts. However, photo curable polymers have poor mechanical properties which may even become worse over time. UV protective coating must be applied in order to prevent degradation. Other liquid-based processes include Jetted Photopolymer and Ink Jet Printing. [17]

4.1.1. SLA – Stereolithography

Stereolithography is considered as the pioneer of the Rapid Prototyping industry. The term stereolithography was first used by the US company 3D Systems, which introduced the first commercial system in 1988. This technology works on a principle

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[16] LIOU, Frank W. *Rapid prototyping and engineering applications: a toolbox for prototype development*. Boca Raton: CRC Press, 2008, xxv, 535 p. Mechanical engineering Taylor, 210. ISBN 08-493-3409-8.

[17] Additive Fabrication. *Custompartnet* [online]. 2008 [2014-10-09]. Available at: http://www.custompart-net.com/wu/additive-fabrication

of solidifying a photosensitive resin by UV laser light layer by layer to create a 3D object. Resins used in SLA can be epoxy, vinyl ether or acrylate.

The process converts 3D digital image data into very thin cross-sections thus the layers are defined. The system consists of an Ultra-Violet Laser, a vat of photo-curable liquid resin, and a controlling system. The vat filled with a resin contains a vertically moving platform which supports the part under construction. The platform is lowered into the resign, such that the surface of the platform is a layer-thickness (typically about 0,1 mm) below the surface of the resin. The laser beam then traces the boundaries and fills in the cross-section of the model, hardening precisely where the light hits the surface. [18]
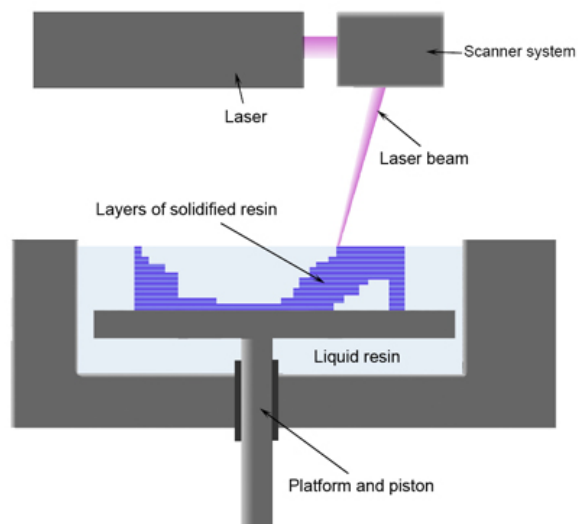

Figure 3. Simplified SLA apparatus

[18] LIOU, Frank W. *Rapid prototyping and engineering applications: a toolbox for prototype development*. Boca Raton: CRC Press, 2008, xxv, 535 p. Mechanical engineering Taylor, 210. ISBN 08-493-3409-8.

4.1.2. PolyJet

PolyJet technology is patented by company Object Geometries. Principle of this technology is a combination of jetting molten material and stereolithography. The process starts with applying molten plastic which immediately cools and solidifies on the platform. Then the layer is nearly instantly cured by UV lamp and all in one pass of the printhead. This is the main advantage from classic SLA – there is no need of UV curing chamber and it is saving time. PolyJet technology is offering a very big accuracy. The modern 3D printers using PolyJet technology can print in extremely thin layers (0,016 mm) and thus produce highly detailed and accurate physical prototypes. [19]
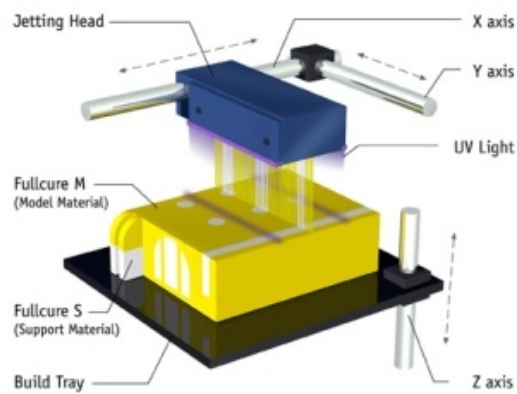

Figure 4. PolyJet method scheme patented by Object Geometries

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[19] LIOU, Frank W. *Rapid prototyping and engineering applications: a toolbox for prototype development*. Boca Raton: CRC Press, 2008, xxv, 535 p. Mechanical engineering Taylor, 210. ISBN 08-493-3409-8.

4.2. Powder-based systems

Powder systems deposit a bed of powder layer-by-layer. An inject head moves across the powder bed, depositing selectively a liquid bending material. A thin layer of powder is spread across the completed section and the process is repeated with each layer adhering to the last. When the model is completed, the "de-powdering" process starts and the unbound powder is removed. Usage of powdered material enables parts to be fabricated using polymers, metals, or ceramics. Mechanical properties of these parts are better and more stable. Other powder-based processes include Direct Metal Laser Sintering (DMLS) and Three Dimensional Printing (3DP)[20].

4.2.1. DMLS – Direct Metal Laser Sintering

DMLS was developed together by Rapid Product Innovations (RPI) and EOS GmbH in 1994. DMLS was the first commercial rapid prototyping method to produce metal parts in a single process. This technology uses a high power laser beam to sinter powdered material, typically metal, with properties of the original material. The beam is automatically aimed at points in space defined by a 3D model and it binds the material together and creates a solid part. Main advantage is this technology is material properties of the finished part and also big accuracy (metal powder diameter 0,02 mm). DMLS produces 95% dense steel compared to Selective Laser Sintering which produces 75% dense steel. Current material options are alloy steel, stainless steel, tool steel, aluminium, bronze, cobalt-chrome, and titanium. [21]

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[20] Additive Fabrication. *Custompartnet* [online]. 2008 [2014-10-09]. Available at: http://www.custompart-net.com/wu/additive-fabrication

[21] Direct Metal Laser Sintering. *Custompartnet* [online]. [2015-01-20]. Available at: http://www.custompart-net.com/wu/direct-metal-laser-sintering

4.2.2. SLS – Selective Laser Sintering

SLS was developed at the University of Texas in Austin and later patented 1989 and sold by DTM Corporation. The basic concept of SLS is similar to Stereolithography. A moving laser beam is selectively sintering powdered composite material (polymer or metal) according to a computer 3D model and creating cross-sections of the built part. The parts are built on a platform that adjusts in height which is equal to the thickness of the layer being built. The metal composite material contains also of a polymer binder which has to be burned off afterwards in a furnace at temperature of 900 °C. Material options for SLS are nylon, glass-filled nylon, polyamide, polystyrene, elastomers and the mentioned metal composite.[22]

SLS is suitable for creating parts for almost any purpose. The biggest advantage of this method is that the model has according to (El-Gizawy, Corl, and Graybill, 2015) 100% strength in all axes. With other methods there is often a problem with the strength in the Z axis, which is a direction of the material layering.

4.2.3. FDM – Fused Deposition Modelling

Fused Deposition Modelling is the most common extrusion-based additive manufacturing method. FDM works with a material in a solid state, which is either in a form of wound fibres or granulate. FDM uses a heating chamber to liquefy polymer which is fed to the system as a filament. The biggest advantage of this technology is a wide range of possible materials to use and the major strength of FDM is good mechanical properties of the final parts. Parts made using FDM are amongst the strongest in the polymer-based AM processes group. On the other side the biggest

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[22] Selective Laser Sintering. *Custompartnet* [online]. [2015-01-20]. Available at: http://www.custompart-net.com/wu/selective-laser-sintering

disadvantage of this technology is the build speed. The speed and acceleration of the plotting heads is somehow smaller than other systems. As mentioned above, FDM has a wide range of materials including bioplastics and also some biocompatible materials, which allows to use the parts made by this technology in medicine.[23],[24].

4.3.   Other related techniques

With using the AM for creating physical prototypes and parts come other techniques related to the field. In a whole process of additive manufacturing we might use techniques such as virtual prototyping using computer-aided engineering, laser scanning of a part, optimization using computational approaches and also technologies for physical testing of the final part. Almost all techniques mentioned includes a process called reverse engineering.

Related definitions:

A **point cloud** is a complex of data points in a three-dimensional coordinate system represented by coordinates X, Y, Z. Point cloud often represents external surface of an object. [25] **3D scanner** in general is a device which examines a physical object in order to collect data about its shape and appearance. The collected data is then used to create a digital 3D model. **CMM** (Coordinate Measuring Machine) is a contact type 3D scanner, which examines an object by physical touch thus collecting data. **Laser scanner** is a non-contact type 3D scanner, that uses laser light to examine a physical object. **CT** (computed tomography) is a computer-aided process, which uses

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[23] GIBSON, Ian, David W. ROSEN a Brent STUCKER. Additive manufacturing technologies: rapid prototyping to direct digital manufacturing. New York: Springer, 2010, xxii, 459 p. ISBN 14-419-1120-0.

[24] FDM Thermoplastics. *Stratasyscom* [online]. [2015-01-20]. Available at: http://www.stratasys.com/materials/fdm

[25] Point Cloud. In: *Wikipedia: the free encyclopedia* [online]. San Francisco (CA): Wikimedia Foundation, 2001-[cit. 2015-01-20]. Available at: http://en.wikipedia.org/wiki/Point_cloud

x-rays to create a three-dimensional model of a scanned object both external and internal. [26]

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[26] 3D Scanner. In: *Wikipedia: the free encyclopedia* [online]. San Francisco (CA): Wikimedia Foundation, 2001-[cit. 2015-01-20]. Available at: http://en.wikipedia.org/wiki/3D_scanner#Triangulation

5. The past and current state of the issue

The question of practical usage of 3D printing, or additive manufacturing, is a highly disscussed topic through many industries. In the world of furniture design, some new movements can be spot aside the "traditional" usage of 3D printing, like visual prototyping or creating exclusive designer pieces. Many designers and design studios are trying to discover the practical usage of 3D printing by different applications and concepts. Therefore many had come to a similar conclusion, which is not using this method of manufacturing to produce the whole piece of furniture, but using only 3D printed parts together with traditional furniture materials such a wooden composites. Printing the whole product always leads to production of a very expensive piece, while using only small 3D printed parts as joints to create a furniture piece can beneficiate its design and actually lead to creating an affordable piece.

The practical usage these days seems to be the usage of 3D printing as a complementary manufacturing method. The designer movement is to reduce the design of a furniture piece to a single connector or a joint, or a set of joints, which can be 3D printed.

5.1. Interior products and 3D printing

Many designers and design studios are trying to work with 3D printing and discover the practical usage of this technology in interior product industry. For this chapter I chose some practical examples of usage of 3D printed components as part of furniture. Most of the designs are using 3D printed components as a kind of fittings replacement. However with these LEGO-like designs the question of the components strength and mechanical properties comes. In a design of a furniture piece they work as fittings and most of the mechanical load lies on them. This issue must be investigated because in a case that the 3D printed pieces have poor properties the furniture does not have to be completely safe for common usage. For the purpose of this work, there are some of these examples of using 3D printing as a complementary method to produce a furniture piece bellow.

The ANICE stool

ANICE stool is a project made by designer Arthur Schmitt. The stool is made by using a 3D printed core, which users can download on a public website Thingiverse. This project was made to show the practical and affordable usage of 3D printed components. This way an owner of a commercial 3D printer can make his own piece of furniture just by printing the most important part, the connector, which is ready in a CAD file.[27] However the design of the connector does not solve the problem how to mount the seat desk of the stool.
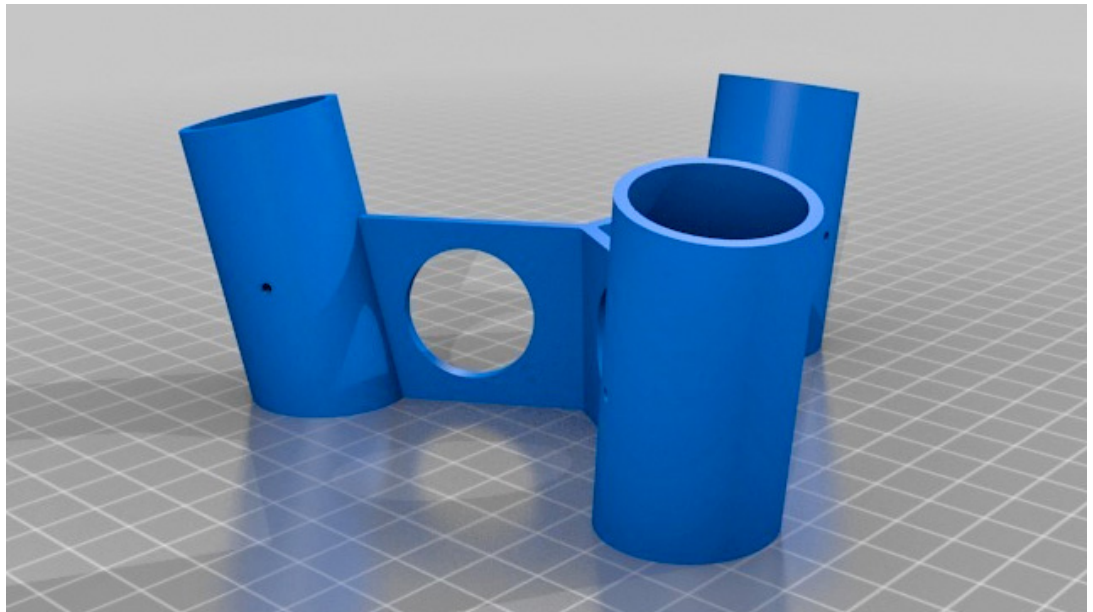
Figure 5. Connector for the ANICE stool design

[27] ANICE stool. *Thingiversecom*. [online] [2016-03-20] Available at: http://www.thingiverse.com/thing:246236

Keystones

Keystones is a collection of 3D printed connectors. Furniture pieces can be assembled together just by using one of the connectors and couple of solid wood bars. The designer's concept of Keystones reduces the furniture making process only to the need to print a connector. Furniture becomes a compact piece which can be made on-location. These connectors hold together various components of a given piece of furniture without the need for joinery skills.[28]

Figure 6. One fo the Keystones connector

[28] Create customized furniture designs 3D-printed wood connectors. Solidsmackcom. [online] [2016-03-20] Available at: http://www.solidsmack.com/design/create-customized-furniture-designs-3d-printed-wood-connectors/

LINK furniture system

LINK is a furniture concept designed by Tamas Boldiszar. It consists of plywood sheets and sets of 3D printed connectors which allow its users to design and create their own pieces of furniture with various combinations of the elements. The modular elements of the system are made of plywood and custom parts, connectors, are 3D printed by FDM printing technology. The connectors are secured by using a screw. The description of the LINK system also points out that since the printers are using thermoplastics, the material can be remelted and reprinted. This concept means that the furniture can be redesigned without using new materials. LINK combines new technologies and sustainable design, which as a combination could be the general future design concept. [29]

Figure 7. LINK furniture system

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[29] Modular furniture system. Marvelbuilding.com. [online] [2016-03-20] Available at: //www.marvelbuilding.com/modular-furniture-system-3d-printed-connectors-link.html

3D Printed Furniture by Dirk Vander Kooij

Dutch designer Dirk van der Kooij constructed a robot which uses similar technology as 3D printing to make pieces of furniture out of reclaimed material. His famous design – the Endless chair won the Dutch design award in 2011.[30] The robot can make this chair within 3 hours, which is approx. 40 times faster than traditional 3D printing, however it uses extremely big diameter of the nozzle, which could lead to much poorer mechanical properties of the whole piece. The chair weighs 12 kg

Figure 8. Chair of Dirk van der Kooij printed out of reclaimed material

[30] Endless chair. Dirkvanderkooij. [online] [2016-03-20] Available at: http://www.dirkvanderkooij.com/collections/collection/products/endless-chair-2010

Batoidea Chair by Peter Donders

Batoidea Chair is made by using 3D printing as a complementary technology of production. The production of this chair, which breaks with convention and is made of aluminium casting, would have been virtually impossible in terms of economic aspects without the use of 3D print technology. The chair production process places great demands on 3D printing and the cast, as the design consists of a very thin-walled aluminium cast structure. [31]

Figure 9. Batoidea Chair by Peter Donders

[31] Designer chair. Voxeljetde. [online] [2016-03-20] Available at: http://www.voxeljet.de/en/case-studies/case-studies/designer-chair/

One_Shot.MGX foldable stool by Patrick Jouin

The One_Shot.MGX is a foldable stool which is manufactured by selective laser sintering as one complete piece; the stool emerges from the machine in its final form, complete with hinges that are concealed by the structure of the stool itself. [32] The model is a winner of Good Design Award 2008 and it is shown in several art museums all around the world.

Figure 10.One_Shot.MGX in folded and unfolded form

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[32] MGX model. Mgxbymaterialisecom. [online] [2016-03-20] Available at: https://mgxbymaterialise.com/principal-collection/families/mgxmodel/detail/detail/45

6. Materials

In the beginning of AM technologies development, there were several problems with the usage of original materials which were far from ideal for this new application. For example the models created from early photo curable resins were very brittle and powders used degraded quickly – simply the manufactured parts were weak and with this fact came many limitations. However, as the technology developed, the understanding came and materials were developed specifically to meet AM technologies requirements. The result s that parts made by AM technologies are now much more accurate, stronger and longer lasting. [33]

The following chapters include overviews of some current material possibilities and trends in the AM technologies, however it should be noted, that the information could be outdated very soon because of the rocket speed development of AM.

6.1. Material requirements for AM

- **Form proper feedstock** – raw AM materials must be able to come in a form suitable for each AM process and technology
- **Processability** – material must be proccessable for the fabricators
- **Post-processability as needed** – there must be post-processing possibilities
- **Acceptable service properties** – mechanical, physical and chemical properties of the processed material must suit its applications requirements

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[33] GIBSON, Ian, David W. ROSEN a Brent STUCKER. Additive manufacturing technologies: rapid prototyping to direct digital manufacturing. New York: Springer, 2010, xxii, 459 p. ISBN 14-419-1120-0.

6.2.   AM material family

The charts bellow illustrate the basic materials used by the additive manufacturing technologies. AM materials divide into two basic groups – homogeneous materials and composites (heterogenous), composed by more than one material in order to suit the technology of production.
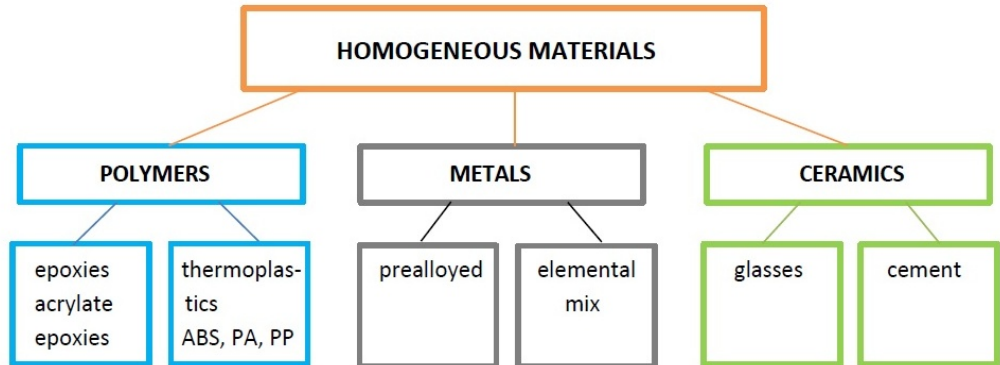
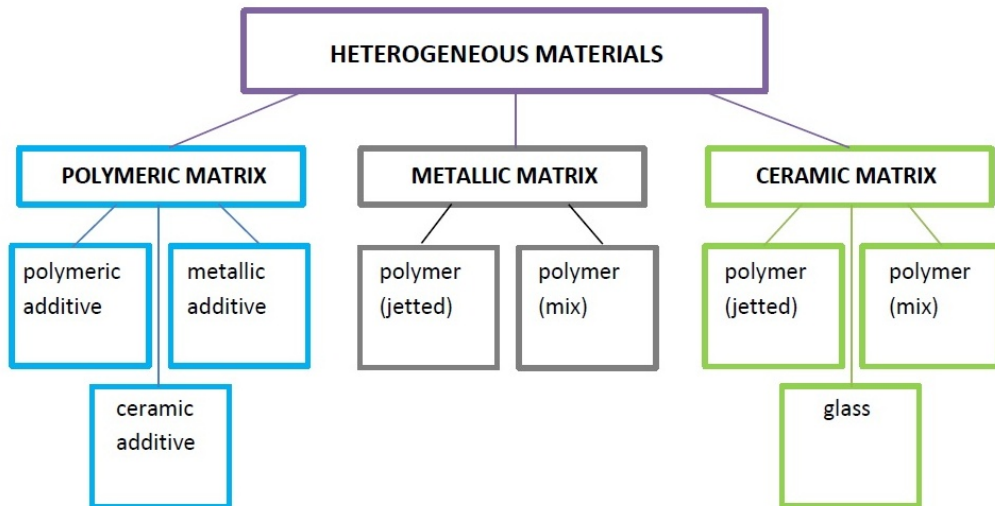Figure 11. Homogenous materials

Figure 12. Heterogeneous materials

Other material groups belonging to the AM material family:

- Composites
- Binders (temporary, permanent)
- Support structures
- Graded structures
- Multi-materials

6.3. AM materials vs. technologies

The table bellow illustrates the basic overview of additive manufacturing technologies and related materials.

Table 1 AM materials/technologies

AM technology:	FDM - Fused Deposition Modelling	Stereolithography and material jetting	Laser sintering	DMLS - Direct Metal Laser Sintering
Materials:	ABS	Acrylics	Nylon 11 and 12 (PA)	Tool steel
	Polycarbonate	Acrylates	Polystyrene	Stainless steel
	PC/ABS blend	Epoxies	Polypropylene	Aluminium alloys
	PLA (polyactic acid)	"ABS-like" (jetting)	Polyester	Co-Cr alloys
	PEI (polyetherimide)		PEEK (polyetheretherketon)	Nickel alloys
	Nylon co-polymer		Thermoplastic polyurethane	Titanium alloys
			Nylon 6	Gold
				Silver

6.4. Plastics

Plastics are currently the most widely used materials in AM. There is a big amount of different plastics which can be used in AM; we divide them into two general categories – thermoplastics and photopolymers. Thermoplastics are commonly used by the FDM technology whereas photopolymers by the PolyJet technology.

6.4.1. Properties of FDM thermoplastics

Table 2 Properties of FDM thermoplastics [34]

Plastics used in FDM - Thermoplastics									
Properties	**ABSplus**	**ABSi**	**ASA**	**Nylon 12**	**PC**	**PC-ABS**	**PC-ISO**	**PPSF/PPSU**	**Ultem 9085**
Layer Thickness [mm]									
0,330									
0,254									
0,177									
0,127									
Tensile Strength [MPa]	33,0	37,0	33,0	48,0	68,0	34,0	57,0	55,0	71,6
Flexural Strength [MPa]	58,0	62,0	60,0	69,0	104,0	59,0	90,0	110,0	115,1
Heat Deflection [°C]	96	87	-	82	138	110	133	189	153
Young´s Modulus [MPa]	2200	1920	2010	1310	2300	1810	2000	2100	2200
Unique Properties	Variety of colour options	Translucent material	UV-stable	Fatigue resistant, high elongation at break	High tensile strength	High impact resistance	ISO 10993 certified	High heat and chemical resistance	FST (flame, smoke, toxicity) certified material

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[34] FDM Thermoplastics. Material spec sheets. *Stratasyscom* [online]. [2015-02-25]. Available at: http://www.stratasys.com/materials/fdm

6.4.2. FDM plastics vs. their standard forms – mechanical properties

Table 3 FDM plastics vs. their standard forms – mechanical properties [35],[36]

Comparison of mechanical properties - FDM plastics vs. standard plastics											
Properties	ABS plus (FDM)	ABSi (FDM)	ABS (extrusion, injection, blow moulding)	ASA (FDM)	ASA (extrusion, injection, blow moulding)	Nylon 12 (FDM)	PA 12 (Polyamide/Nylon)	PC (FDM)	PC (extrusion and moulding)	PC-ABS (FDM)	PC-ABS (extrusion and injection moulding)
Tensile Strength [MPa]	33,0	37	51,7	33	50	68	69	68	72,4	34	51
Flexural Strength [MPa]	58,0	62	73,1	60	79,2	49	85	104	93,1	59	89
Young´s Modulus [MPa]	2200	1920	2340	2010	2600	1310	2600	2300	2440	1810	2620
	ABS (FDM)/ABS			ASA (FDM)/ASA		Nylon 12/PA 12		PC (FDM)/PC		PC-ABS(FDM)/ PC-ABS	
Tensile Strength	71%			66,%		98%		93%		66%	
Flexural Strength	84%			75%		57%		111%		66%	
Young´s Modulus	82%			77%		50%		94%		69%	

[35] FDM Thermoplastics. Material spec sheets. *Stratasyscom* [online]. [2015-02-25]. Available from: http://www.stratasys.com/materials/fdm

[36] CES EduPack 2005, Granta Design Limited, Cambridge, UK. (c) Granta Design.

6.4.3. Overview of most commonly used plastics in FDM machines

FDM manufacturing technology is the most common additive manufacturing technology among desktop printers. Many large commercial printers and also popular printers such as the Makerbot, Reprap, Cubix, and Printrbot are all using FDM technology. The most popular materials FDM works with are PLA and ABS.

ABS (Acrylonitrile Butadiene Styrene)

Acrylonitrile Butadiene Styrene is a thermoplastic resin usually used for injection moulding applications. ABS and its modifications generally possess medium strength and performance at medium cost. ABS is tough, hard and rigid and has good chemical resistance and dimensional stability.

ABS as a polymer can take many forms and can be engineered to vary in its properties according to the desired way of application. ABS is widely used in additive manufacturing for functional applications because it matches 80% of the properties of the real injected production material. Models made from ABS are in general very accurate but they have intermediate level of printed details. However the surface of the models made from ABS is quite rougher compared to other materials. Of course there are different versions and commercial filament brands of ABS used in different AM technologies and printers. FDM ABS is the most widely used version, which is both office friendly and suitable for professional applications. [37]

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[37] ABS plus. *Stratasyscom* [online]. [2015-02-25]. Available at: http://www.stratasys.com/materials/fdm
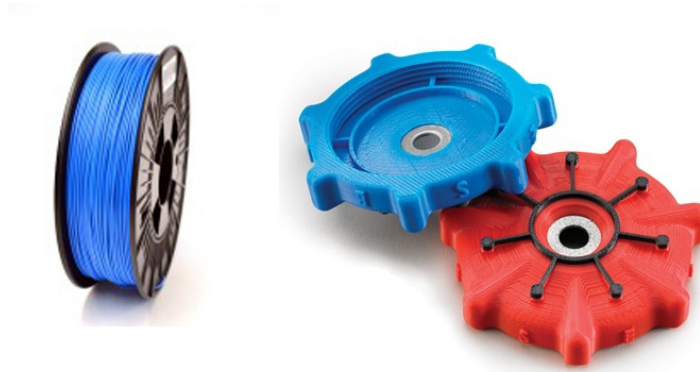
Figure 13. ABS Plus filament and manufactured functional parts

PLA (polylactide)

PLA is a biodegradable polymer which can be derived from renewable resources, such as corn starch. PLA is potentially a very useful material, it is harder than ABS and melts at a lower temperature (around 180°C to 220°C). However ABS gives higher quality surface over PLA. PLA is dimensionally stable and relatively cheap, which gives it a popular plastic for home printers. [38]

ASA (Acrylonitrile Styrene Acrylate)

ASA is a thermoplastic developed as an alternative to ABS. It was vas developed with some improvements of its properties such as weather resistance. In its controversial form is widely used in the automotive industry as well as in several other outdoor applications. In its form developed for FDM technology this material has the best aesthetics from the FDM material family. It is widely used for building durable prototypes and also for its UV stability. [39],[40]

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[38] PLA - RepRapWiki. *Repraporg.* [online]. [2016-03-25]. Available at: http://reprap.org/wiki/PLA

[39] Acrylonitrile Styrene Acrylate (ASA). *Prospectorcom* [online]. [2015-02-25]. Available at: http://plastics.ulprospector.com/generics/8/acrylonitrile-styrene-acrylate-asa

[40] ASA. *Stratasyscom* [online]. [2015-02-25]. Available at: http://www.stratasys.com/materials/fdm/asa

PA (Polyamide, Nylon)

PA has many forms of this material used in additive manufacturing, mostly in FDM machines. Very popular form is Nylon 12, which is a filament material developed by Stratasys. Compared to other materials Nylon 12 has great elongation at break and fatigue resistance. PA in general is good for applications which demand high fatigue endurance, high impact strength and chemical resistance. It is used in aerospace and automotive applications and custom production tooling. [41]

PC (Polycarbonate)

Polycarbonate is the most widely used industrial thermoplastic. PC used in controversial processes is a choice for applications where required excellent impact resistance and high clarity of the material. Those unique properties resulted in applications such as bulletproof windows, break resistant lenses, compact discs, etc. PC is used in FDM machines to produce functional prototypes and even end-use parts for its high tensile and flexural strength. [42]

PC-ABS

This material aims to provide strength and heat resistance of PC combined with the flexibility of ABS. PC-ABS filament was developed by Stratasys and it is used in FDM machines for applications like power-tool prototyping and industrial equipment manufacturing. [43]

Plastic filaments ISO certified

There are materials developed specifically to meet ISO 10993 medical grade requirements. These materials are biocompatible and sterilizable and can be used in

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[41] FDM Nylon 12. *Stratasyscom* [online]. [2015-02-25]. Available from: http://www.stratasys.com/materials/fdm/nylon

[42] PC. *Stratasyscom* [online]. [2015-02-25]. Available at: http://www.stratasys.com/materials/fdm/pc

[43] PC-ABS. *Stratasyscom* [online]. [2015-02-25]. Available at: http://www.stratasys.com/materials/fdm/pc-abs

medical applications such as bone replacements or medical devices. One example of such a material is PC-ISO developed by Stratasys which used in FDM machines and it is the strongest most heat-resistant biocompatible material available with FDM technology. Second example is nylon 618 developed by Taulman 3D with the same purpose and applications. [44],[45]

PPSF/PPSU (Polyphenylsulfone)

PPSF has the biggest heat and chemical resistance from all FDM materials. It is typically used in automotive, aerospace and plumbing applications. PPSF parts are mechanically superior and also dimensionally accurate. Because PPSF is also steri-lizable, it can be used in medical applications. Because of its excellent properties it is often used in high-end engineering applications. [46]

ULTEM 9085 – polyetherimide (PEI)

Another filament material used in FDM machines developed by Stratasys. UL-TEM 9085 is a high performance thermoplastic with quite impressive mechanical and thermal properties. Because this material is flame retardant and it has high strength-to-weight ratio it is not only used in functional testing, manufacturing tooling but also in direct digital manufacturing of end-use parts including aircraft interior compo-nents. [47]

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[44] PC-ISO. *Stratasyscom* [online]. [2015-02-25]. Available at: http://www.stratasys.com/materials/fdm/pc-iso

[45] 618 Specifications. *Taulman3dcom* [online]. [2015-02-28]. Available at: http://taulman3d.com/618-fea-tures.html

[46] PPSF/PPSU. *Stratasyscom* [online]. [2015-02-25]. Available at: http://www.stratasys.com/materi-als/fdm/ppsf-ppsu

[47] Ultem 9085. *Stratasyscom* [online]. [2015-02-25]. Available at: http://www.stratasys.com/materials/fdm/ul-tem-9085

Figure 14. A ventilation component manufactured by an FDM machine using ULTEM 9085

6.4.4. Overview of most comonlly used plastics in PolyJet machines

PolyJet manufacturing technology produces highly realistic, functional 3D models in a wide range of materials with properties from rigid to rubber and opaque to transparent. Machines using PolyJet technology can print in extremely thin layers (0,016 mm) and though offer a very good accuracy of the components.

Digital materials

Digital materials are UV cured materials used in AM, which are produced by PolyJet machines. We can define Digital Materials as composite materials with predetermined visual and mechanical properties. These materials are created by jetting simultaneously up to three PolyJet based resins. Materials are mixed together in order to create a new one suitable for a specific application with unique mechanical properties. They can be mixed in specific concentrations and structures. [48]

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[48] PolyJet Materials. *Stratasyscom* [online]. [2015-02-28]. Available at: http://www.stratasys.com/~/media/Main/Secure/Material%20Specs%20MS/PolyJet-Material-Specs/PolyJetMaterialsBrochure-08-13.pdf

Digital ABS

Digital ABS is a material used in PolyJet machines, which was developed by Stratasys. This material was designed to simulate standard ABS plastics by combining high-temperature resistance with toughness. The main advantage of Digital ABS is high resolution combined with getting closer to the properties of thermoplastics. Using of this material is suitable for parts that require PolyJet technology's highest possible impact resistance and shock absorption. Digital ABS is suitable for applications such as functional prototypes, manufacturing tools, moulds and injection moulds and parts of higher temperature use in general. [49]

Other PolyJet materials

There are many PolyJet plastics developed in order to suit specific requirements or to simulate properties of standard plastics. There are PolyJet Transparent plastics which are developed to simulate properties of PMMA for applications which require full or partial transparency.

PolyJet Polypropylene is group of photopolymer materials developed to simulate polypropylene. These materials can offer improved toughness, dimensional stability or flexibility and strength.

Another group of PolyJet materials are rubber-like materials, which offer various ways of elastomer characteristics: elongation at break, tear resistance and high tensile strength.

There are also medical rapid prototyping materials in the PolyJet family. PolyJet photopolymer MED610 has a biocompatible material which is known for its high

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[49] Digital ABS. *Stratasyscom* [online]. [2015-02-28]. Available at: http://www.stratasys.com/materials/polyjet/digital-abs

dimensional stability and colourless transparency. This material is suitable for medical applications requiring prolonged skin contact such as dental aids.[50]

Figure 15. 3D printed hearing and dental aids

6.5. Metals

As mentioned earlier in the work, the use of metal alloys in additive layer manufacturing is mainly connected with Direct Metal Laser Sintering. Powdered metal is arranged in layers and fused together by a high-power laser. These parts created by using DMSL have excellent mechanical properties and the material of the produced parts is a fully dense metal. There are also other metal 3D printing processes which use a binder, even though they produce parts which are not fully dense metal with this fact related mechanical properties.

Stainless steel

Stainless steel is characterized by very good corrosion resistance and mechanical properties in general, especially high toughness and ductility, and it is widely used in

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[50] PolyJet Materials. *Stratasyscom* [online]. [2015-02-28]. Available at: http://www.stratasys.com/materials/polyjet

many engineering applications. Used in additive manufacturing this material is ideal for creating functional parts, small series products and not only prototyping. In general stainless steel is ideal for applications which require high corrosion resistance but also sterilizability, which predetermines this material for wide range of medical applications.[51]

Figure 16. 3D-printed bottle opener

Figure 17. 3D printed bone replacement implant

Titanium alloy

Pre-alloyed Ti_6Al_4V alloy in fine powder form, which is characterized by having excellent mechanical properties and corrosion resistance combined with low specific weight and biocompatibility. Parts produced by additive manufacturing using titanium alloys are ideal for high-performance engineering applications, which require the combination of high mechanical properties and low specific weight, such as aerospace, motor racing, and also production of biomedical implants. [52]

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[51] DMLS/DMLM Materials. Stainless Steel Material data sheet. *Dmlsnet* [online]. [2015-03-10]. Available at: http://dmls.net/materials/

[52] DMLS/DMLM Materials. Titanium Material data sheet. *Dmlsnet* [online]. [2015-03-10]. Available at: http://dmls.net/materials/

Cobalt-chrome-molybdenum based super-alloy

Cobalt Chrome Alloy $Co_{28}Cr_6Mo$ is a powder mixture developed for laser-sintering additive manufacturing systems. This kind of superalloy is known for having excellent mechanical properties such as strength and hardness and also high corrosion and temperature resistance. These alloys are commonly used in biomedical applications (dental and medical implants) and also in high-temperature engineering applications such as engines in aero industry. These laser-sintered parts are characterized by a fine, uniform crystal grain structure. Using this material is ideal for applications like functional metal prototypes, small series products, parts requiring high mechanical properties in elevated temperatures (500-1 000 °C), parts requiring high corrosion resistance and as mentioned above, applications requiring biocompatibility. [53]
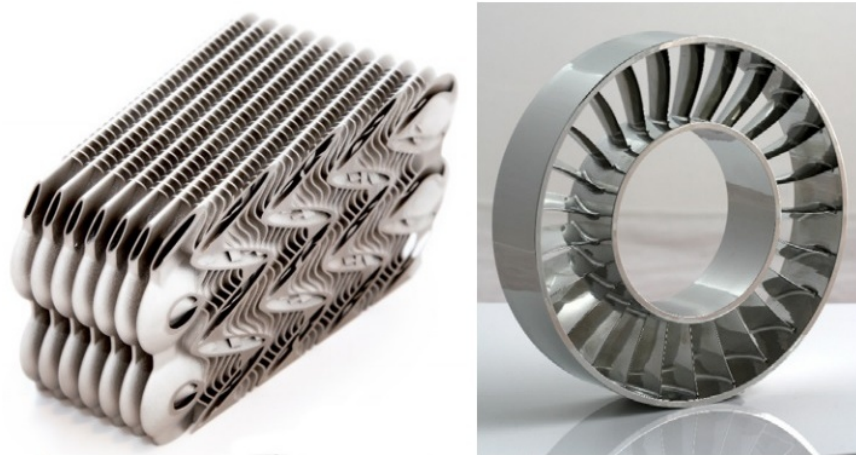
Figure 18. Cobalt-chrome-molybdenum 3D printed prototype parts for aero engines.

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[53] DMLS/DMLM Materials. CobaltChrome MP1 Material data sheet. *Dmlsnet* [online]. [2015-03-10]. Available at: http://dmls.net/materials/

Nickel alloy

Nickel based heat resistant alloy in powder form characterized by having good tensile, fatigue, creep and rupture strength at temperatures up to 700 °C. This material is ideal for applications which require high temperature, chemical and corrosion resistance such as turbine engine parts, chemical and process industry parts and other high-end engineering applications. [54]

Aluminium alloy

Aluminium alloy in powder form, which is typically casting alloy with good casting and dynamic properties. Aluminium alloys are typically used in AM for parts with thin walls and complex geometry. It offers good strength, hardness and dynamic properties and is therefore also used for parts that are subject to high loads. This material is ideal for applications which require a combination of good thermal properties and low weight and it is used for applications like direct manufacturing of functional prototypes, small productions runs and user-specific products manufacturing. [55]

6.6. Other material possibilities

There are many companies which develop and fabricate filaments for 3D printing and every year there are more and more material possibilities appearing. Most of the materials are composites or mixtures based on polymers or resins. New trend in filaments developing are materials which make the product look like or feel like it is made from the actual materials – real world materials.

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[54] DMLS/DMLM Materials. Nickel Alloy Material data sheet. *Dmlsnet* [online]. [2015-03-10]. Available at: http://dmls.net/materials/

[55] DMLS/DMLM Materials. Alluminium Alloy Material data sheet. *Dmlsnet* [online]. [2015-03-10]. Available at: http://dmls.net/materials/

Sandstone

Models made using the "sandstone" filament called LayBrick (developed by cc-products) have the desired stone-like effect and they do not look like they are made from plastic. The filament is compatible with FDM machines and it is made from thermoplastic polymer (co-polyesters), which is used as a binder, and combined with very fine milled chalk powder. The sandstone filament is very sensitive on the printing temperatures – the higher the temperature the rougher the print. This material is also quite brittle so it is only ideal for applications like visual models or prototypes. [56]

Wood-based

Wood-based filament material called Laywood (developed by cc-products) is wood-polymer composite and it contains 40% recycled wood and 60% binding polymers. Printing at various temperatures provides a finished product with different colours - 190˚C for light coloured wood and 230 ˚C for dark coloured wood. Objects made from Laywood have the wood-like appearance and they even smell like wood. Afterwards the finished objects can be also processed like wood – cut, grinded or coated. Even though the material is presented as eco-friendly, it is a very questionable fact. The point that is uses recycled wood is making it eco-friendlier than other plastic filaments materials, but as a wood-polymer composite it raises a big question mark about the final stages of its life cycle. [57]

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[56] LAYBRICK. *3dersorg* [online]. [2015-03-18]. Available at: http://www.3ders.org/articles/20130527-laybrick-a-new-rough-3d-printer-filament-near-zero-warp.html

[57] Wood filament LAYWOOD-D3. *3dersorg* [online]. [2015-03-18]. Available at: http://www.3ders.org/articles/20130204-wood-filament-laywoo-d3-suppliers-and-price-compare.html

Figure 19. 3D printed objects using Laywood

Carbon fibres containing

There are several materials on the market which combine carbon fibres into 3D printing filament. These filaments intergrade up to 20% carbon fibre into a polymer binder. Such filament materials are characterised by quite high stiffness, dimensional stability and accuracy, heat resistance and good functionality. These characteristics make this material ideal for aerospace, automotive and prototyping industries applications. [58]

Experimental materials

Filaments producing companies are also working on some experimental materials, which are quite innovative and unusual. Bronze filament is a visual purpose filament – it has actual appearance of bronze. BronzeFill is a mixture of PLA and bronze

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[58] XT-CF20. *Colorfabbcom* [online]. [2015-03-21]. Available at: http://colorfabb.com/xt-cf20

powder. Very similar filaments are copperFill and brassFill, which are also mixtures of PLA with copper or brass powder. Another experimental material is bambooFill – material based on PLA containing 20% of recycled bamboo fibres. GlowFill is a material which is again based on PLA but it contains concentrated phosphorescent pigment so the material glows in the dark. [59]

Figure 20. Glowfill filament

[59] Special filaments. *Colorfabbcom* [online]. [2015-03-21]. Available at: http://colorfabb.com/special-filaments

7. AM possibilities and drawbacks

Additive manufacturing, commercially known a 3D printing, has developed a reputation of its massive potential in almost every industry and market, including machinery industry, medical/dental, automotive, aerospace, robotics and even consumer market. Additive manufacturing processes are becoming more and more relevant in medicine and especially in the dental market, where the customization, which is one of the biggest advantages of AM, is necessary and required. AM is nowadays used by all major companies and most of them have their own development centres focusing on AM development. GE (General Motors) has predicted [60] 14% annual growth for additive manufacturing through 2017. The primary potential of additive process still remains in the ability to shorten cycle times and rapidly transform concepts into physical products. Also there is no limit for additive processes in the design geometries and shapes – AM gives designers a great new range of possibilities. However additive processes are well suited for highly customized applications, there is still relatively low volume if actual applications – the technology is not necessarily well suited for all applications. Objects which are very large or objects with simple geometries requiring high volume production runs (e.g. ten thousand units) are currently still better served by traditional manufacturing processes. With this way of thinking we can say that additive manufacturing technology is very usable as a complementary manufacturing technology rather than a replacement of the traditional manufacturing processes.

The list of industries, which are adopting or experimenting with 3D printing, is increasing every year and currently the technology has expanded the most into the low-end and consumer areas. It has been applied in such areas as furniture, fashion, jewellery and even food. Also the consumer oriented hardware – home 3D printers –

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[60] Additive manufacturing. *Americasgecapitalcom* [online]. [2015-03-21] Available at: http://www.americas.ge-capital.com/GECA_Document/Additive_Manufacturing_Fall_2013.pdf

are becoming cheaper and so within reach of many consumers. There is also a big potential of lower costs of the 3D printing materials and filaments.[61]

We can summarize the main advantages of AM into following points:

- **Short product preparatory period** – after finishing the digital model of the product and creating STL file, developers can create a prototype of the product immediately. Also as soon as the product is printed, the testing of its properties can begin – so it is obvious that this process is saving a big amount of time.

- **Few shape limits** – objects of almost any shape which can be designed in a CAD software can be also produced by additive manufacturing.

- **Less material waste** – the technology is opposed to subtractive manufacturing which produce waste in general. Because AM uses only so much material which is actually needed, there is very little material wasted.

- **The more complicated the better** – in applications where is advantageous to use more complicated shapes it saves money. It actually cost less to print more complex part instead of a simple cube of the same size. The more complex or less solid objects can be manufactured faster and cheaper with AM.

- **Adjustable material properties** – while using polymers as the materials for 3D printing, there is a possibility to adjust the final material properties or even to create a composite suitable the specific application using 2 printing heads with 2 different materials.

- **Parts which are difficult to produce by traditional manufacturing processes** – either because of its shape, time consumption or other limitations some parts can be more effective when produced by AM instead of a traditional manufacturing techniques.

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[61] Additive manufacturing. *Americasgecapitalcom* [online]. [2015-03-21] Available at: http://www.americas.ge-capital.com/GECA_Document/Additive_Manufacturing_Fall_2013.pdf

The main drawbacks of AM we can summarize into following points:

- **High cost of the production** – large parts are quite slow to make, the high-quality additive manufacturing machines are still very expensive, and good quality materials are also quite expensive. Simply some parts are still more cost effective to produce by traditional processes.
- **Long build time** – most of the printers lay down the material at a speed of one to five cubic inches per hour, so depending on the part being manufactured the build time can prolong to non-acceptable amount. So again sometimes using the traditional manufacturing processes can be much faster.
- **Poor mechanical properties** – this characteristic is being associated with AM from the start. Because the material is layered, there are weak points in every layer connecting spot. Also the layering causes defects and geometry inaccuracies.
- **Limited part size** – the most machines can not print objects larger than 30-50 cm. Of course the larger the machine is and the larger objects it can print, the more it costs. There are machines which can print objects of several meters in size but there are only prototypes made for their purpose.
- **One at a time** – parts can be only printed one at a time, which is a big disadvantage from economic point of view. No large production runs can be possibly done with AM.
- **Post processing** – most of AM technologies require post-processing – the surface is lower quality than other manufacturing methods. [62]

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[62] Pros and cons of Additive Manufacturing. *Compositesmanufacturingmagazinecom.* [online]. [2015-03-21] Available at: http://compositesmanufacturingmagazine.com/2014/10/pros-cons-additive-manufacturing/

IV.   METHODOLOGY

The practical part of this work should briefly demonstrate the usage of additive manufacturing and related techniques in an interior product development. The objective of AM is to produce finished components as well suitable for potential end-use in a product and to produce components, which are suitable for testing their properties as a part of a product development. With this trend the need of thorough understanding of the mechanical properties of the materials and the overall behaviour of the parts produced by layered manufacturing comes. The parts of end-use as well as the parts intended for testing must be not only durable, but the mechanical properties of the components must meet the in-service loading requirements. For that reason, the properties of chosen component were also tested on assumed service-life loading.

1. Material testing

As mentioned above, the need to understand the material properties of AM materials is obvious and with this fact naturally the need for material testing comes.

1.1. Material choice

As the material of focus the FDM plastics were chosen – firstly because FDM is a widely and commercially used AM technology, secondly it is an affordable technology for small businesses. Plastics have a wide field of usage in the furniture industry and the field of interior products and as well they are the best materials for visual models making. One of the most common plastic in the industry is ABS, which is a very versatile plastic. For the material testing was therefore chosen FDM ABS from Stratasys – ABSplus-P430.

1.2. Approach and expectations for properties characteristics

According to the nature of the layered manufacturing there is the expectation of quasi-anisotropic (plane isotropy) properties. According to [63] mechanical properties of FDM materials depend on fibre orientation (raster angle) in each layer and stacking of various layers. Also the porosity, occurrence of air bubbles, the fibre diameter (layer thickness) and the printing speed and temperature affect the mechanical properties of the material. This is why we have tested ABS material in two principal directions (assuming plane isotropy) as well as component printed in two directions in respect to model geometry.

1.3. Testing method

The material was tested for compressive strength for the contrast to the more commonly measured tensile strength, which is also the mechanical property most commonly included in material lists. The standard test method for compressive strength for polymers matrix composite materials in the USA is ASTM D695 (Figure 21) that is analogy of compression test according to ČSN 49 0110 for testing wood. The procedures in both testing methods do not differ in principle. In the actual test method used, there was a small modification first in the specimen geometry, second in the speed of testing. The test specimen was established as a cube 0,02 x 0,02 x 0,02 m and the testing speed was 0,004 m/min and constant. All mechanical tests were carried out using the Universal testing machine ZWICK Z050 and a data acquisition system to collect the results.

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[63] El-Gizawy, A., Corl, S. and Graybill, B. (2015). *Process-induced Properties of FDM Products*. 1st ed. [ebook]. [2015-03-21] Available at: http://www.stratasys.com/~/media/Main/Files/FDM%20Test%20Reports/Process-induced%20Properties%20of%20FDM%20Products.pdf
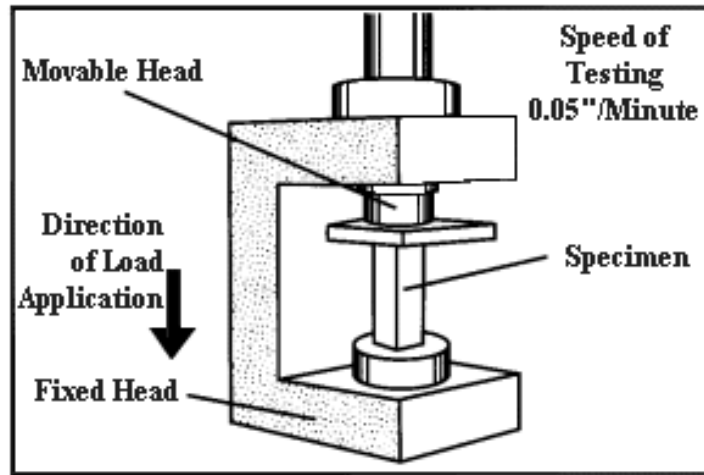
Figure 21. ASTM D695

Two raster angles were used for the test – 0° and 90° (Figure 13). Two specimens were tested along the filaments and two across the filaments to determine the differences in their mechanical properties (strength, elastic modulus and Poisson's ratios).
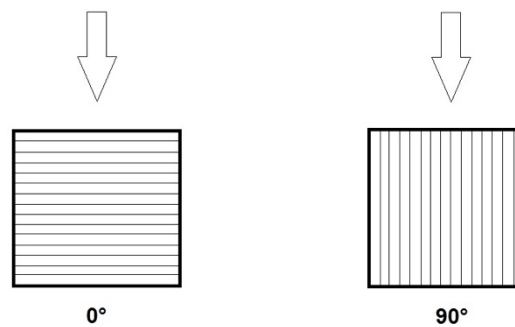
Figure 22. 0° raster and 90° raster with the load direction

1.3.1. ZWICK Z050 universal testing machine

ZWICK Z050 was used for compression test of the material specimens as well as for the compression test of the 3D-printed component. ZWICK Z050 is universal test equipment with mechanical movement of the upper crossbeam. Maximum load force of the machine is 50 kN with a shift range of 0.001 - 500 mm.min^{-1}. The testing

machine is controlled by the Zwick testXpert software, which is used also for data evaluation.

1.4. Normal elastic moduli determination

First step was collecting data from the Zwick testXpert software. This data was used for further calculations. From the collected data the stress-strain curve can be constructed. From the stress-strain curve the modulus of elasticity was obtained as depicted in Fig. 24.
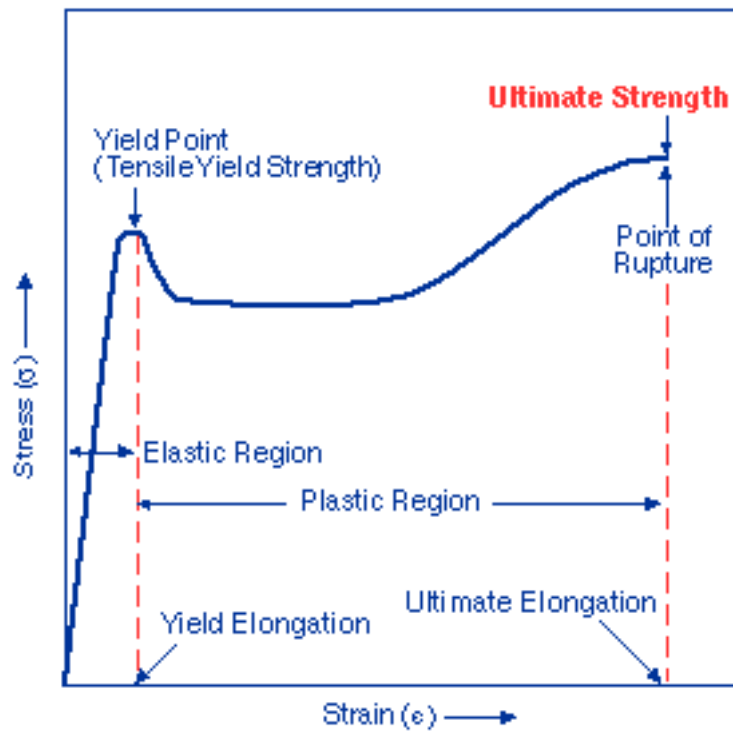
Figure 23. A typical stress strain curve of a thermoplastic
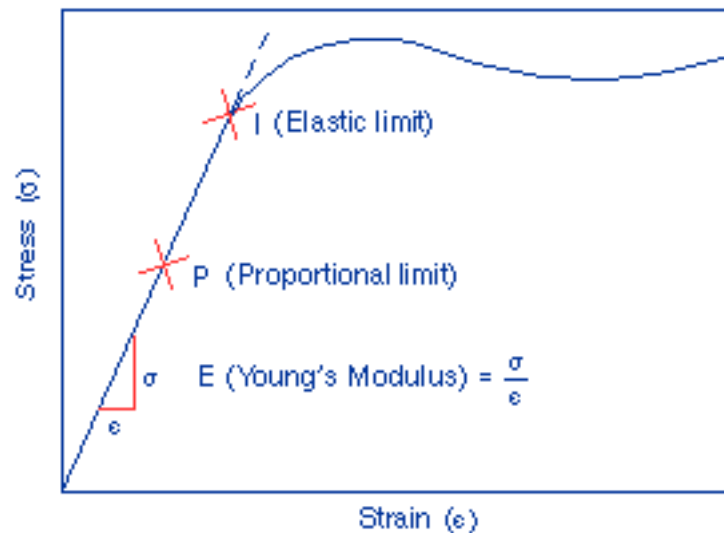
Figure 24. Detail of the elastic region; same curve as in Figure 23

Young's modulus E, is a measure of stiffness of an elastic material. It is defined as the ratio of stress o corresponding strain (relative deformation) in a material under tension or compression as follows:

$$Young's\ modulus = \frac{stress}{strain} = E = \frac{\sigma}{\varepsilon}$$

Where ε is strain [-] and σ is stress [Pa] defined as follows:

$$Stress = \frac{force}{area} = \sigma = \frac{F}{A}$$

$$Strain = \frac{difference\ between\ lengths}{original\ length} = \varepsilon = \frac{(l - l_{0)}}{l_0}$$

To determine E, following formula was used:

$$E = \frac{(\sigma_2 - \sigma_1)}{(\varepsilon_1 - \varepsilon_2)} * 100 * 4^*$$

*value of coefficient (3-5) is used due to acquisition of strain using-crosshead

1.5. Optical measurement using DIC

Digital Image Correlation (DIC) is a non-contact optical technique used for measuring strains. DIC compares a series of grey-scale images of a sample at different stages of deformation, tracks pixels' movement in the region of interest (Fig. 13) and calculates displacement and strain by the use of correlation algorithm. DIC consists of a temporally stable low noise digital camera, zoom objective and PC software. Before mechanical tests, stochastic pattern was applied on the sample surface in order to enable the DIC algorithm calculate their movement. During the test, consecutive pictures were taken by the camera using Vic-Snap software. Images are later transferred to PC and are analysed through correlation algorithm by using a relevant software – Vic 2D 2009.[64] Pattern was created by applying a spray colour on the specimens to provide contrast to correlate images well (Figure 26, 27). Full fields of strains (ε_{xx}, ε_{yy} and ε_{yx}) were calculated and data exported to Microsoft Excel 2013.

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[64] Lin, S. (2015). *Strain Measurement by Digital Image Correlation.* 1st ed. [ebook] Sweden: Royal Institute of Technology, p.15. Available at: http://www.desy.de/f/students/2015/reports/SenLin.pdf [Accessed 17 Apr. 2016].

$$Poisson's\ ratio = -\frac{strain\ in\ direction\ of\ load}{strain\ in\ right\ agle\ to\ load}$$

$$\mu = -\frac{\varepsilon_{xx}}{\varepsilon_{yy}}$$
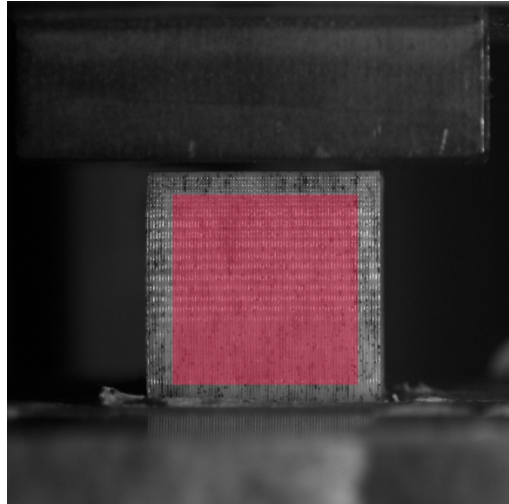
Figure 25. The region of interest for calculating strains
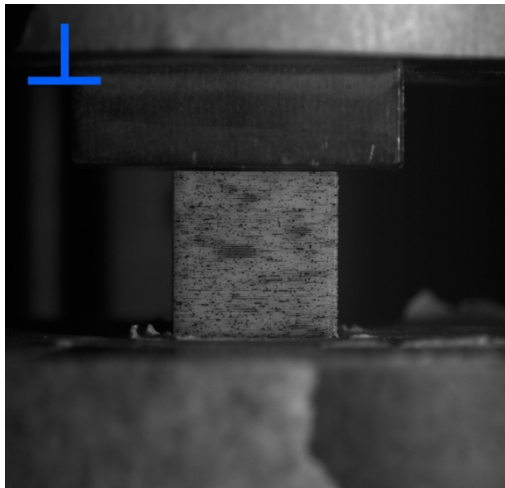
Figure 26. Specimen with tested across the filaments
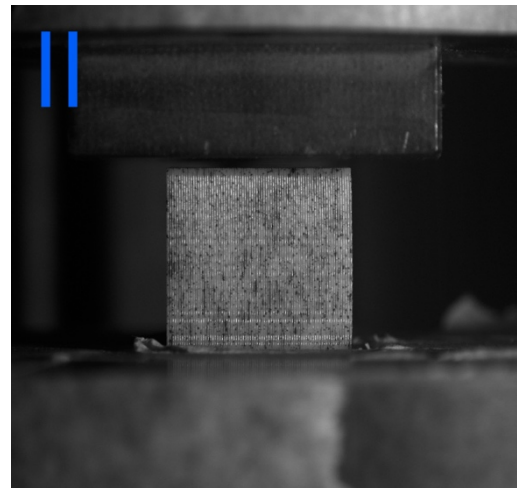
Figure 27. Specimen tested along the filaments

1.6. Shear elastic moduli determination

After calculating the Young's modulus and Poisson's ratios, the values could be used for calculation of Shear elastic modulus determination. The formula was following:

$$G = \frac{E}{2(1 + \mu)}$$

2. Component testing

Another part of the work was to test a 3D printed component used in furniture constructions. The component was tested virtually by creating a numerical model and then also physically on the universal testing machine ZWICK Z050.

2.1. The component

In accordance to the research done in the theoretical part of the work, 3D printed connector for 90° degrees furniture joint was chosen (Figure 3). This connector was designed by Ollé Gellért[65] as a part of his collection of 3D printed furniture joints. Consumers can actually buy the STL files of his design online[66], print them on their home printers and construct a furniture piece using 8 mm plywood sheets. But can this concept work? The displayed product using these connectors is a bookshelf, which put in practical use must hold on under a suitable amount of load for its design and intended usage.

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[65] Print To Build, 3D printed joint collection. Behancenet. [online] [2016-20-03] Available at: https://www.behance.net/gallery/27812109/Print-To-Build-3D-printed-joint-collection

[66] Print to build joint collection. Cults3dnet. [online] [2016-20-03] Available at: https://cults3d.com/en/various/print-to-build-joint-collection

Figure 28. Bookshelf built using the 3D printed connectors
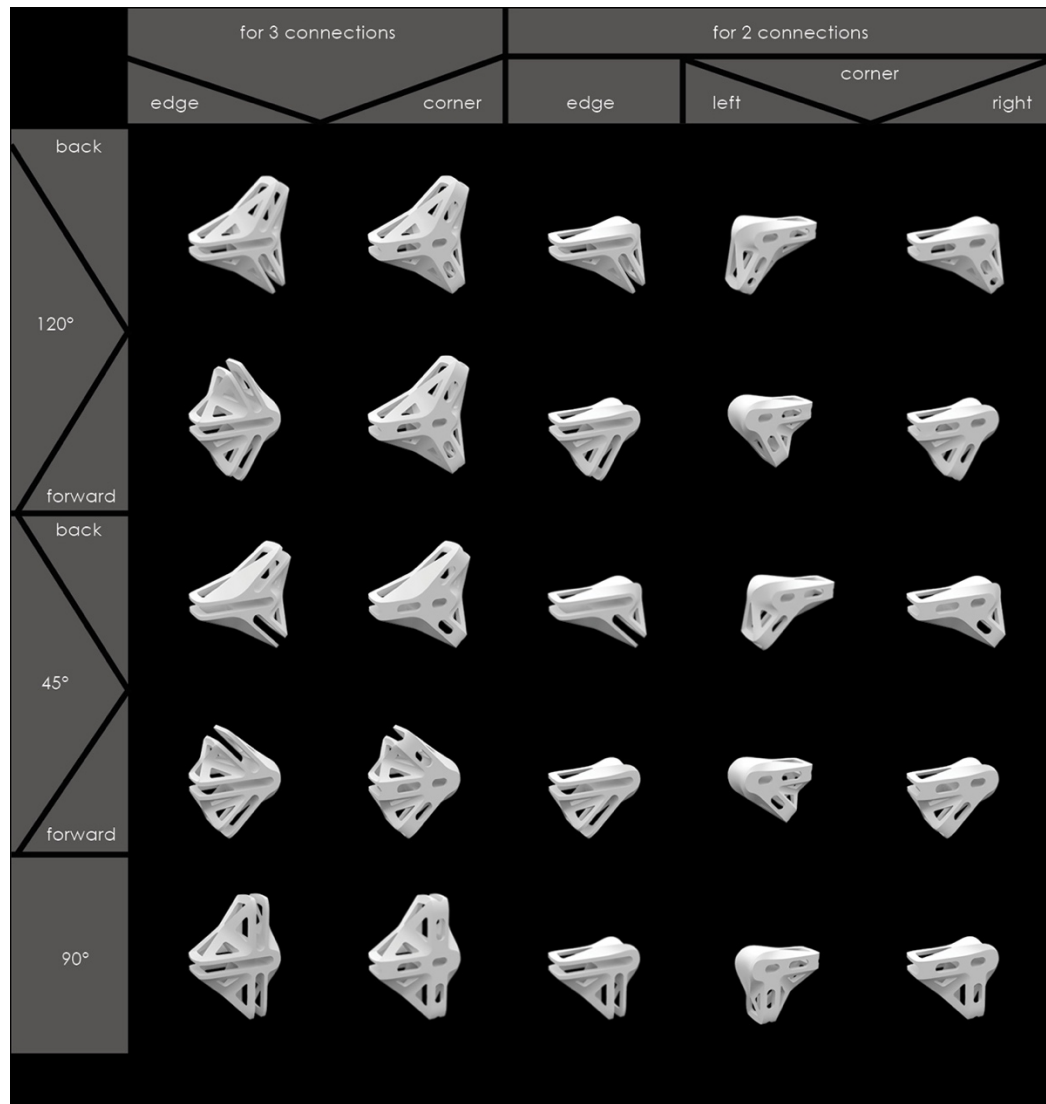
Figure 29. The collection of connectors

2.2. Virtual testing

The objective was to analyse the numerical (finite element) model of the component printed in two different directions (axial direction of the layers and lateral direction of the layers).

2.2.1. Import of STL to ANSYS ICEM CFD

First step was to import the geometry file of the component to meshing software ANSYS ICEM CFD 13.0. ICEM is an extension of the meshing capabilities in ANSYS Meshing. ICEM can be used outside of ANSYS Workbench to mesh from "dirty" CAD or faceted geometry such as STL, to mesh large or complex models, or to Hexa mesh. ICEM creates output to a variety of computational fluid dynamics (CFD) and finite element analysis (FEA) solvers.

Second step was to generate volume from faceted geometry file (STL), a network of tetrahedra (Figure 4). Text file / script is generated from ICEM, which is then imported to ANSYS Mechanical. Imported model after meshing using tetrahedral element is depicted in Fig. 30.
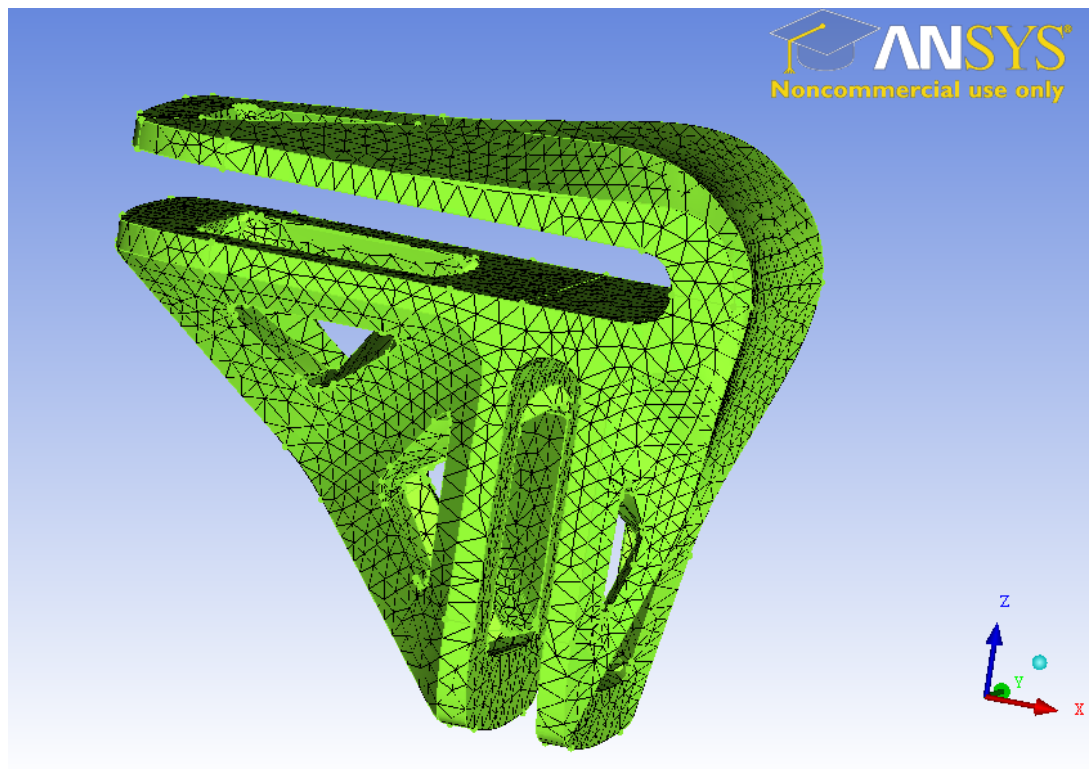
Figure 30. Mesh generated in ANSYS ICEM CFD 13.0

2.2.2. Import to ANSYS Mechanical

After importing the file from ICEM to ANSYS 15.0, first step was to find out the quality and characteristics of finite element mesh. The volume was meshed by two different kind of elements – shell elements and solid elements. However, only the solid elements were desired to stay in the FE model. There were two types of elements found in the volume – type 1 and type 2, which means that the object consists of the surface shell elements that have to be cleared out from the mesh. Therefore, the second step was to clear the volume from the shell elements, then to check the thoroughness of the process and repeat the operation again till there is only one type of element left. Next step was to set material characteristics, which were set as plane isotropic (the anisotropic character of the material was settled by the load settings in the next step), see Table 4.

Finally, boundary conditions were applied to the model. Upper part was loaded by the displacement; the bottom part was constrained against displacement in all direction. The loading was made in the angle reflecting the physical test. In order to find out the difference in behaviour of parts printed in different directions (layer directions), the analysis was done twice. The process of set up was identical till the point of material set up. To model behaviour of the component with axial and lateral layer direction (relative to the jaws of the component), relevant values of Young's modulus, Poisson's ratio and Shear elastic modulus were set. Points of attachment were set in the end of the component jaws.

Table 4 Load settings for model 1 and model 2

Value	Model 1	Model 2	
EX	2100	1700	[Mpa]
EY	2100	1700	[Mpa]
EZ	1700	2100	[Mpa]
PRXY	0,41	0,41	-
PRYZ	0,41	0,41	-
PRXZ	0,41	0,41	-
GXY	900	600	[Mpa]
GYZ	900	600	[Mpa]
GXZ	600	900	[Mpa]
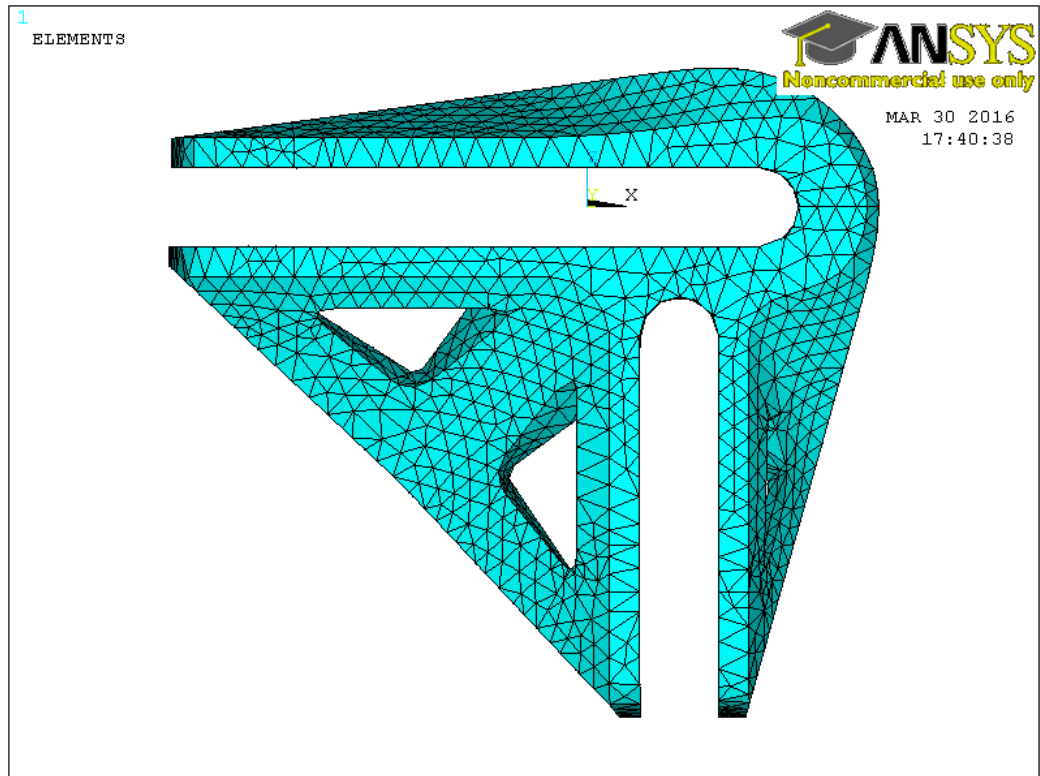
Figure 31. Import to ANSYS 15.0

2.3. Component testing - compression test

To make this experiment, ZWICK universal testing machine was used and data were collected by using the control software Zwick testXpert. For the compression test of the component special test mounts (Figure 32) must have been used. These test mounts were used analogically as in the work of Šimek (2008) and Kořený (2007).[67],[68] which were focused on mechanical properties of furniture joints. The testing mounts were assembled to Zwick machine using standard bolts.
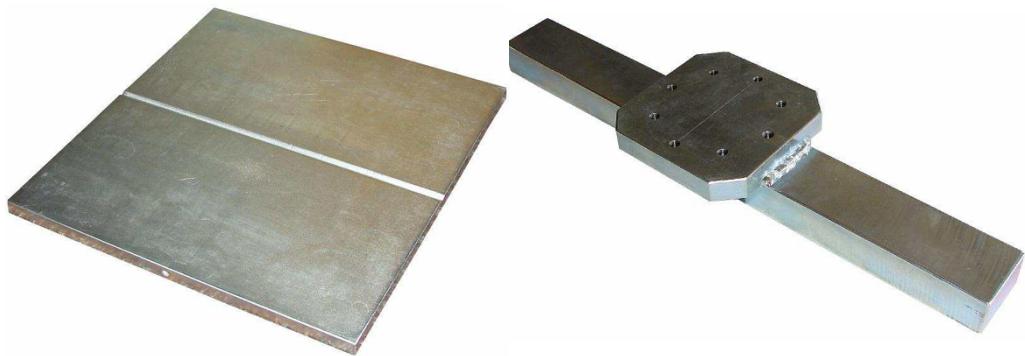
Figure 32. Test mounts – the base and the cross bar

[67] ŠIMEK, M. 2008. Mechanické vlastnosti nejpoužívanějších demontovatelných spojů korpusového nábytku. Dissertation. Mendelova univerzita v Brně. Brno, 120 p.

[68] KOŘENý, A., 2007. Mechanické vlastnosti demontovatelných nábytkových spojů (Bachelor thesis). LDF, MZLU v Brně. 58 p.

The test was carried out in joint angle as depicted in Fig. 33.
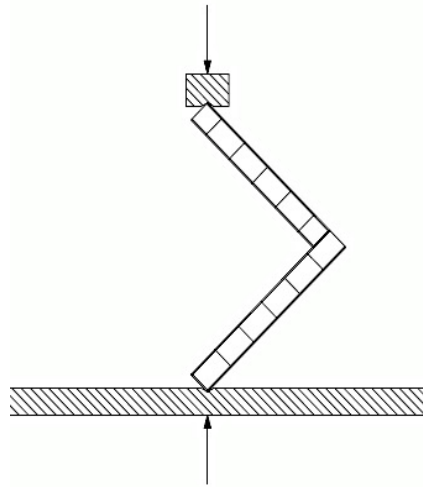
Figure 33. Scheme of the compression test

Component

The component was printed on Ultimaker 2+ Extended[69] printer (Figure 34), filament used was ABS Extrafil from Fillamentum (Figure 35), thickness of the layer was 0,25 mm on first component and 0,20 mm on the second component.

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[69] Ultimaker 2+ Extended. Ultimakercom. [online] [2016-03-10]. Available at: https://ultimaker.com/en/products/ultimaker-2-plus#Ultimaker-2-Extended+
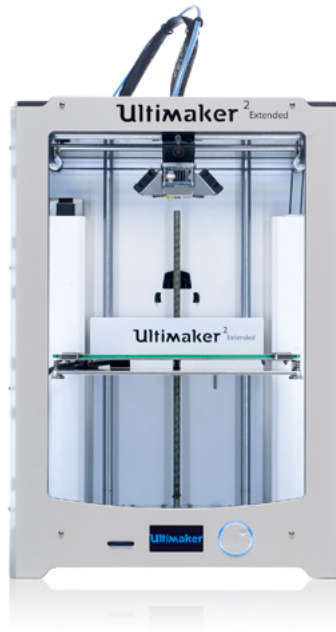
Figure 34. Ultimaker 2+ Extended 3D printer

Properties of ABS filaments for 3D printing:

Specific Gravity (ASTM D1505):	1,04 g/cm^3
Ductility (ASTM D638):	22 %
Strength (ASTM D638):	36 MPa
Working temperature:	220 - 240 °C
Hot pad:	80 - 100 °C

Filaments ABS Extrafill for 3D printing are produced on the extrusion line with a continuous measurement of the outer diameter of 1,75 mm (or 2,85 mm).

Tolerance for diameters +/- 0,05 mm.

Figure 35. Extract from ABS Extrafil material datasheet

The whole printed components are showed in Fig. 36. As we may see, the orientation and width of the printing is not clearly visible by naked eye. It requires close look.

Figure 36. Printed components

The whole experimental setup is showed in Fig. 37. As we may see, the plywood is not fully inserted into the connector. It was inserted to the maximal value of human force. The complete push of plywood inside the connector happened during the test.
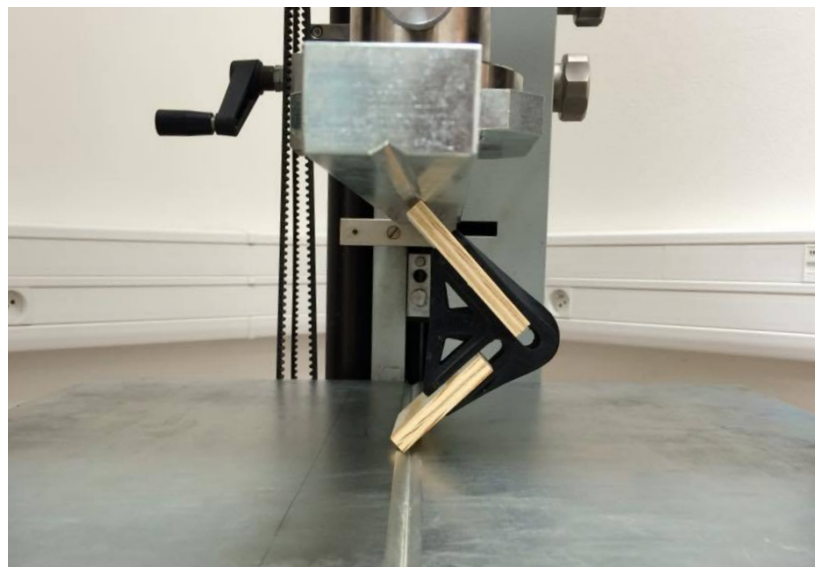
Figure 37. Compression test on ZWICK test machine

V. RESULTS AND DISCUSSION

This work focused on collection of activities that are part of additive manufacturing and rapid prototyping. The work is not deep analysis of particular problems, but, on the other hand, tries to map all needed techniques to solve particular problem. In this work, the problem is to design, physically and numerically test component for furniture construction. The partial problems of this "cycle" is to test properties of used material – ABS.

In order to inspect the mechanical properties of ABS 3D printed material properly there would have to be more tests done. There are many factors which influence the properties of the material and therefore the printed part. Furthermore tests of different combinations of these factors would have to be done in order to understand the 3D printed material thoroughly. Factors like layer/filaments orientation, layer thickness, orientation of the build, pattern of infill, amount of infill, number of shells and their thickness, speed of build, temperature of build, colour of the filament, and last but not least the type of printer and supplier of the filament used are all very important to consider as far as the influence of the material properties goes. However for the purpose of this work only two factors were chosen to be inspected. First was influence of layers' orientation and second was influence of layer thickness. First factor was inspected on a specimen; second factor was inspected on an actual 3D printed component. Nonetheless, from the literature review and tests, it is clear that material is homogenous and quite isotropic – it has plane isotropy. For such materials, there is not such a demand in number of samples, as there is for instance for wood and wood-based materials.

1. Influence of layer orientation on stiffness

Two specimen of transverse layer orientation and two specimen of longitudinal layer orientation were tested on the application of load (compressive strength). The results of that listed in Table 6 confirms the plane isotropy that is not significant.

1.2. Visual analysis of the surface response

The two groups of specimen reacted to the compressive load in a similar way (Figure 38, 39). The accumulated stresses lead to inner layer cracking or de-lamination, which were significantly more visible on the specimen tested on compressive strength with longitudinal layer orientation (Figure 39). The specimens in Figure 39 show buckling of fibres with plastic deformation of the region between the fibre breaks. Also de-bonding between the fibres occurs, which is caused by the increasing deformation and overall stress-strain behaviour of the specimens. These deformed fibres may lose the load carrying capacity and the zones where generated further strain result into bending till fracture.

In the other couple of specimen, tested with transverse layer orientation, any cracks on the surface did not occur, however there were buckles of the layers and fibres visible, and also light vertical areas, which could have been caused by deformation and disruptions of the fibres (Figure 38).
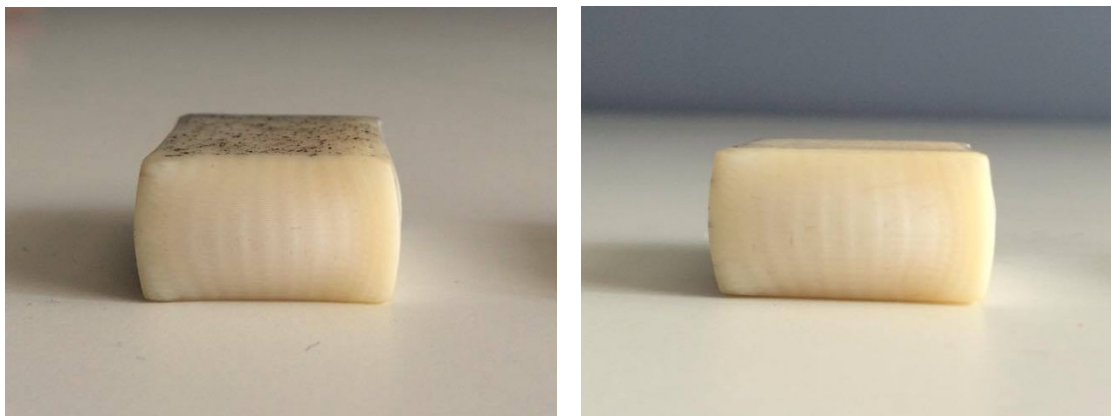
Figure 38. Specimens tested on compressive strength, transverse direction
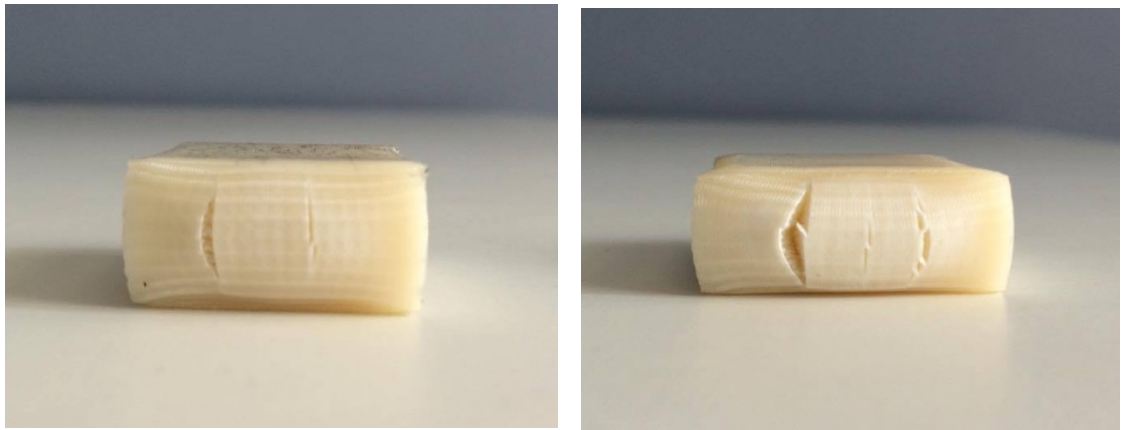
Figure 39. Specimens tested on compressive strength, longitudinal direction

Figure 40. Deformation process in time on images that were used for DIC analysis

1.3. Failure analysis

The stress strain behaviour (Figure 41) of specimen under compression starts like linear, then continues nonlinearly and inelastic due to generation of cracks and densification. When the specimen reaches the peak stress, the resisting stress decreases and strain increases. At the stress-stress diagram (Figure 41) there can be spot a small difference between the behaviour of the two groups of specimens. As we see, the ultimate strength (maximal stress) did not occur due to densification process. This phenomenon is similar to the loading of wood perpendicularly to grain in radial direction. Ultimate conventional strength of the specimen tested on compression load transverse direction is slightly higher than of the ones tested in longitudinal direction.ε
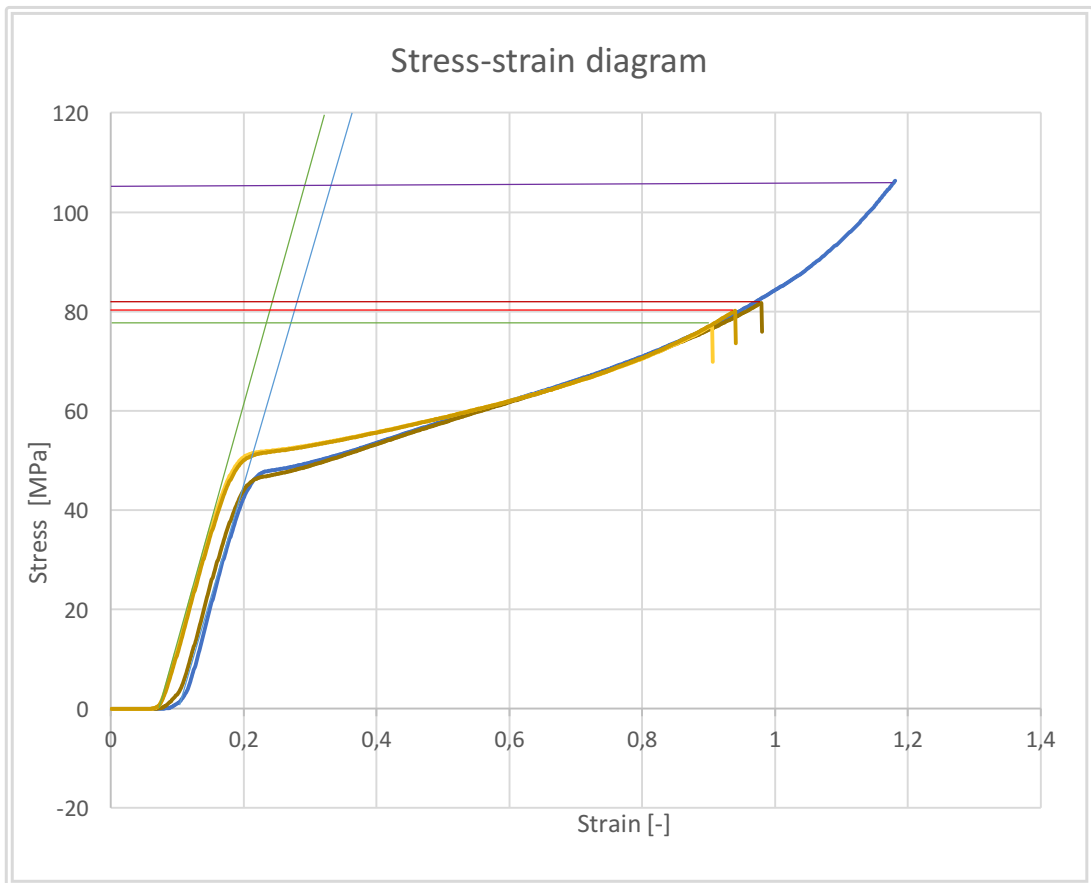
Figure 41. Results of compression test, stress-strain curves of all specimen

1.2. Calculation of Poisson's ratios, Elasticity moduli and Shear elastic moduli

Values calculated and obtained from testing on ZWICK and from DIC are shown in Table 5. The specimen group with transverse fibre orientation showed about 38% higher Elastic modulus value than the specimen group with longitudinal fibre orientation. The values of Poisson's ratios also vary accordingly. The Poisson's ratios are quite high and are falling into category of polymers-to-rubbers (rubber has Poisson's ratio nearly 0.5). The Poisson's ratios were calculated based on huge amount of data (approx. 100 000 values) because of full-field measurement. Consequently they should have statistical validity for the material, even despite lower number of specimens.

Table 5 Specimens characteristics

Specimen_num	Fmax	{epsilon}-F max	EMod	Density	Weight	W{lo Rm}	Specimen thickness a0	Specimen width b0	Length	Note
	N	%	MPa	kg/m³	g	Nmm	mm	mm	mm	
1	31 266,08	64,28	688,98	941	7,752	202 818,09	20,14	20,13	20,33	xy
2	32 182,13	66,70	690,66	951	7,749	211 941,02	20,01	20,06	20,30	xy
3	33 122,41	69,54	700,49	945	7,750	218 611,20	20,30	19,96	20,23	yx
4	43 010,32	83,69	719,63	952	7,747	298 353,84	20,28	19,95	20,11	yx

Table 6 Calculation of Elasticity moduli, Poisson ratios and Shear moduli

	strain		F		E	mean(exx)	mean(eyy)	μ	G
	[%]		[MPa]		[MPa]				[MPa]
	14s	21s	14s	21s					
transver1(xy axis)	6.04254	9.17346	4.90867	25.7401	2 661.38	0.00535027	- 0.0135675	0.394345	954.35
transver2 (xy axis)	6.04433	9.17585	5.53786	26.5786	2 687.61	0.00413476	- 0.0103741	0.398566	960.84
longitud1 (yx axis)	6.04269	9.17406	0.942995	14.9131	1 784.54	0.0151482	- 0.0363498	0.416734	629.81
longitud2 (yx axis)	6.04328	9.4563	0.121886	13.2341	1 536.73	0.00131508	- 0.003223344	0.407986	545.72

The horizontal strain (ε_{xx}) computed by DIC is showed in Fig. 42. For clarity, only elastic strain is showed. We may see, the maximum is located in the middle of the sample (approx. 5.7 %).
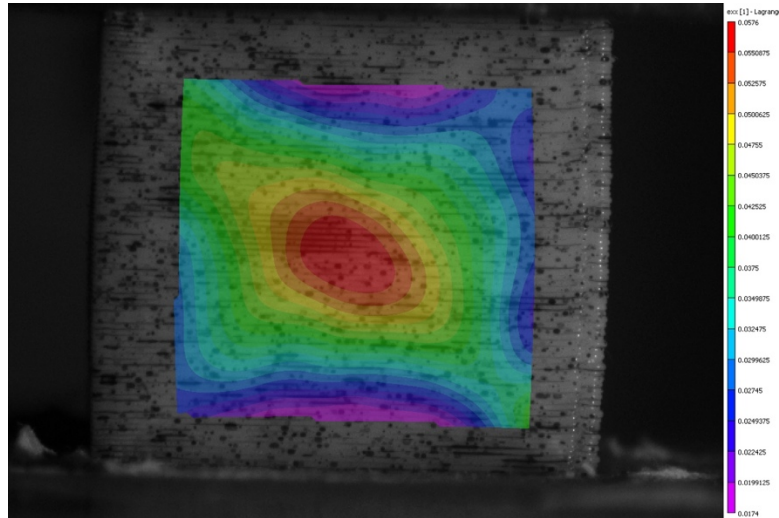
Figure 42. Normal strain in horizontal direction (ε_{xx}) at transverse loading

In Fig. 43, we may see shear strain (ε_{xy}) with significantly visible shear angle. For perfectly isotropic materials, this angle is 45°. We see that our layered material has almost this value, i.e. negative and positive shear strains are almost located in corners of tested samples
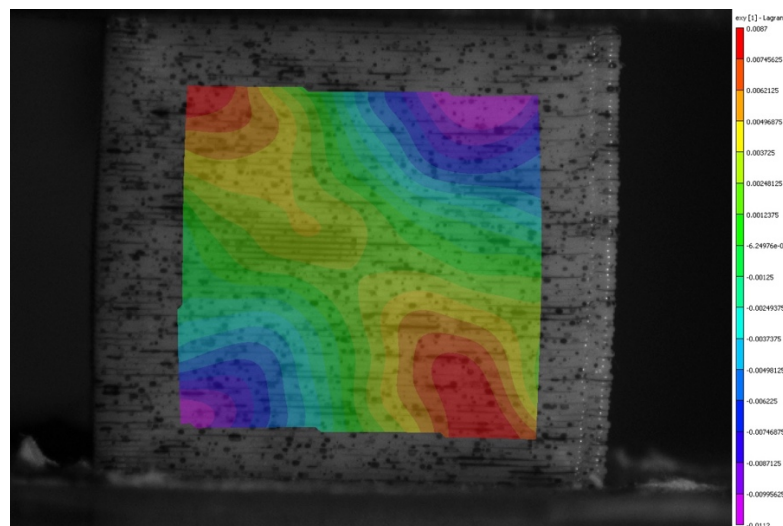
Figure 43. Shear strain fields (ε_{xy}) at transverse loading

Similar distribution as ε_{xy} is obtained for ε_{yy}, as we can see from Fig. 44.
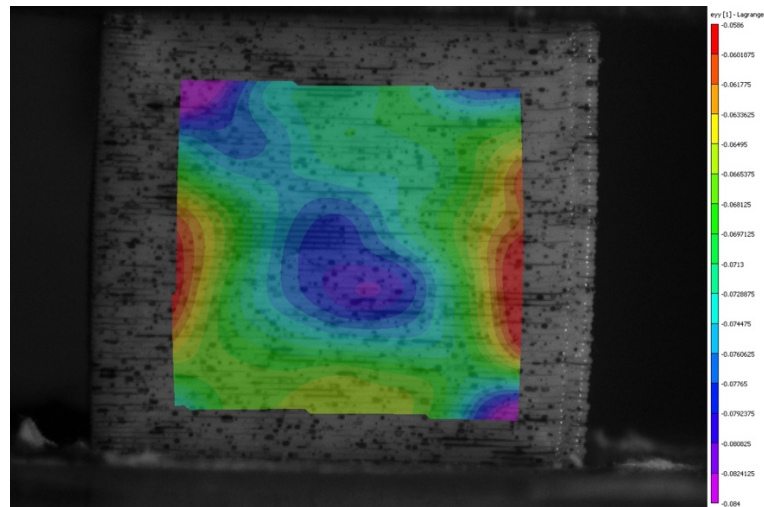
Figure 44. Normal strain in vertical direction (ε_{yy}) at transverse loading

The displacement in horizontal direction (U) is showed in Fig. 45. It shows symmetric distribution of pixels' movement due to Poisson's phenomenon which cause by plane isotropy in this mode of loading.
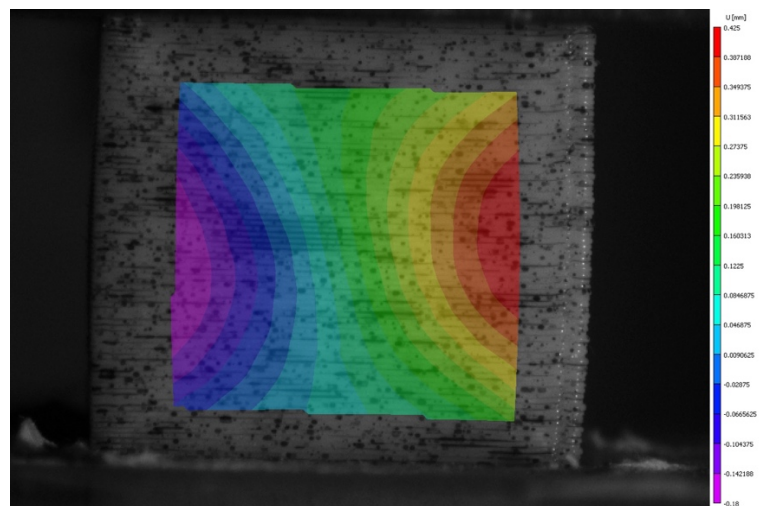
Figure 45. Displacement in horizontal direction (U) at transverse loading

Vertical component of displacement (V) is showed in Fig. 46. The almost parabolic distribution of contours is cause by inherent fault of compressive tests that are

not able to reduce friction between material and testing clamps. This "fault" is always present at testing materials in compression, so it does not invalidate results.
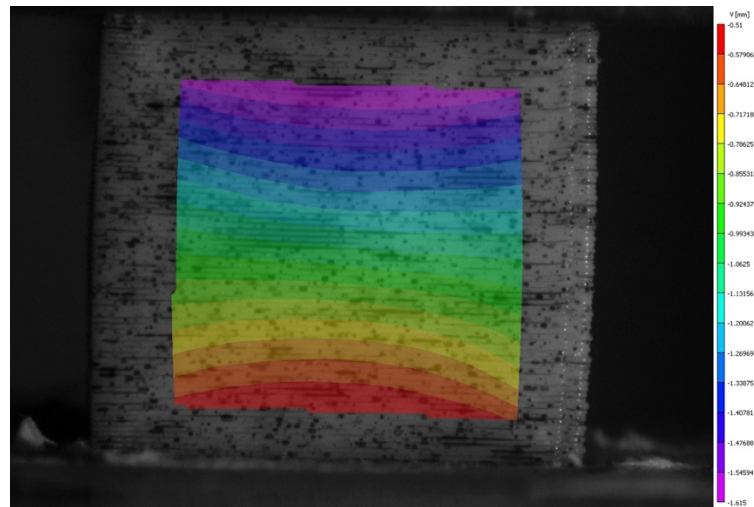
Figure 46. Displacement in horizontal direction (V) at transverse loading

The complementary set of results, but for specimen with vertical alignment of fibres with loading force is showed in Figures 47 to 51. The most of results correspond to those showed above and, therefore, do not need any other comments.
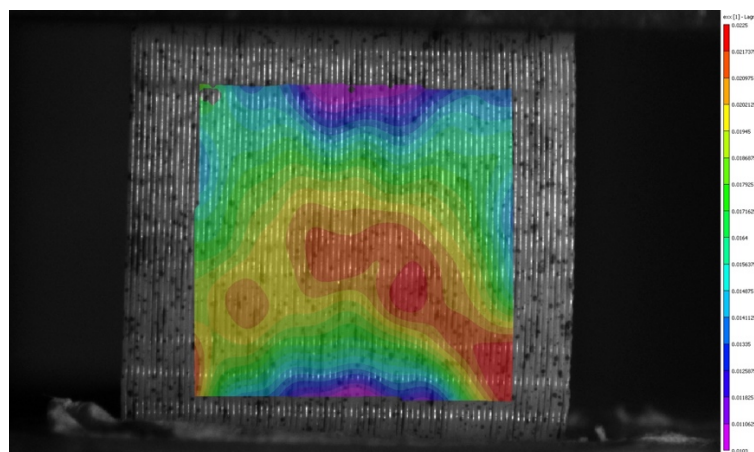
Figure 47. Normal strain in horizontal direction (ε_{xx}) at longitudinal loading
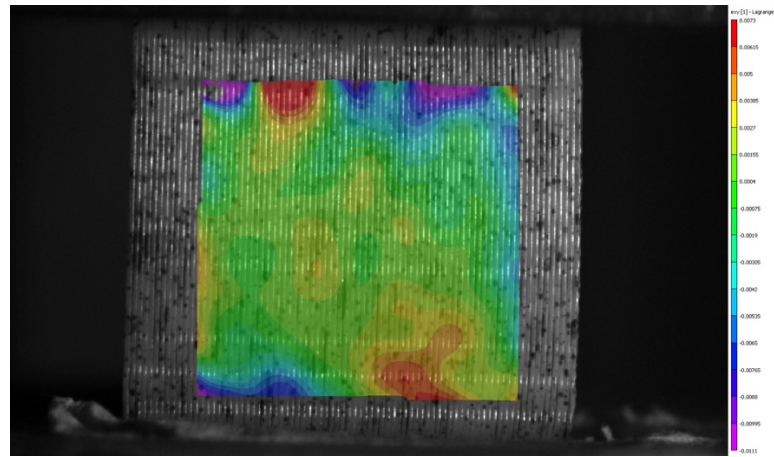
Figure 48. Shear strain fields (ε_{xy}) at longitudinal loading
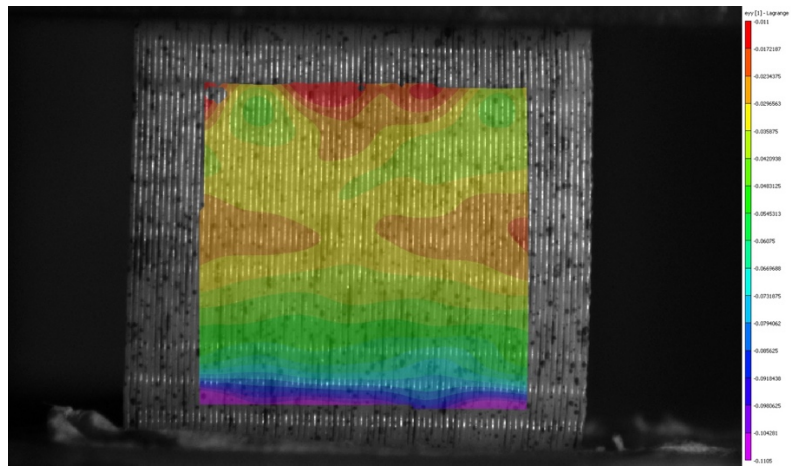
Figure 49. Normal strain in vertical direction (ε_{yy}) at longitudinal loading
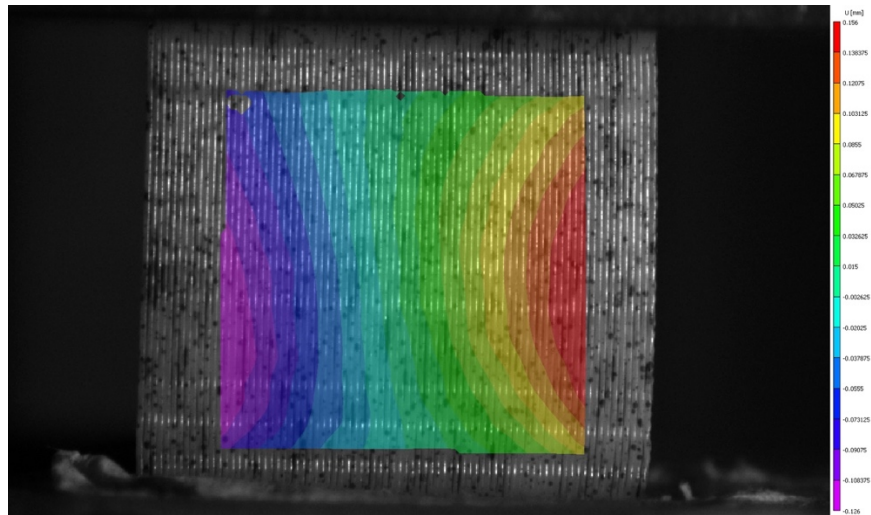
Figure 50. Horizontal displacement (U) at longitudinal loading
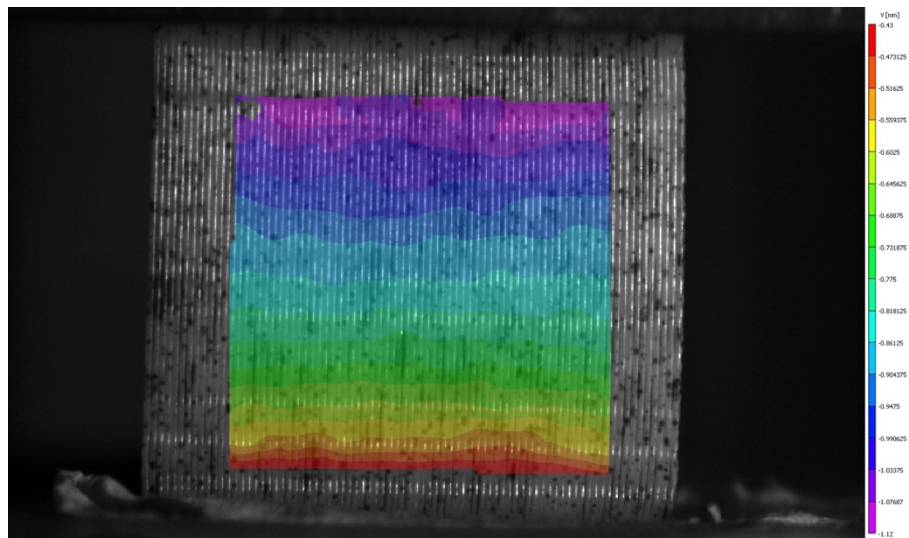
Figure 51. Horizontal displacement (V) at longitudinal loading

2. Influence of layer thickness on stiffness

To analyse the influence of layer thickness on stiffness of the component, two 3D printed components were tested in compression with different layer thickness. First component was printed using layer thickness of 0,20 mm, second 0,25 mm. According to different studies dedicated to the influence of layer thickness on 3D printed material's mechanical properties (for example [70], [71] etc.), the thinner the layer is, the better overall stiffness of the material.

2.1. Visual analysis of the component's surface response

Making visual evaluation of the surface of the component, the difference in the layer thickness can be spotted. Surface of the component printed with thicker layer seems more rough and inaccurate. Component with layer thickness of 0,25 mm had more visible cracks along the fibres (Figure 53). Fibres in the more stressed areas of the component's geometry were buckled or de-laminated (Figure 52, Figure 53). Part of the jaw cracked along the fibres and fall off. The compressive stress influence was mostly visible on the downer jaw of the component, which buckled to the sides as the component was loaded gradually. The component with layer thickness of 0,20 mm had a bigger buckling of the jaw, because it holds under bigger compressive force.

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Figure 52. Component with layer ness of 0,20 mm

Figure 53. Component with layer thick- thickness of 0,25 mm

2.2. Failure analysis

On the working diagrams (Figure 54 and Figure 55) obtained by analysing data from the Zwick test pert software we can see the approximate characteristics of the two components with different layer thickness and their stress behaviour.

The peak stress of the component with layer thickness of 0,20 mm was approximately 22% higher than the peak stress of the component with 0,25 mm layer thickness. The maximum force for component with 0,20 mm layer thickness was 424 N, and the maximum force for the component with 0,25 mm layer thickness was 334 N.
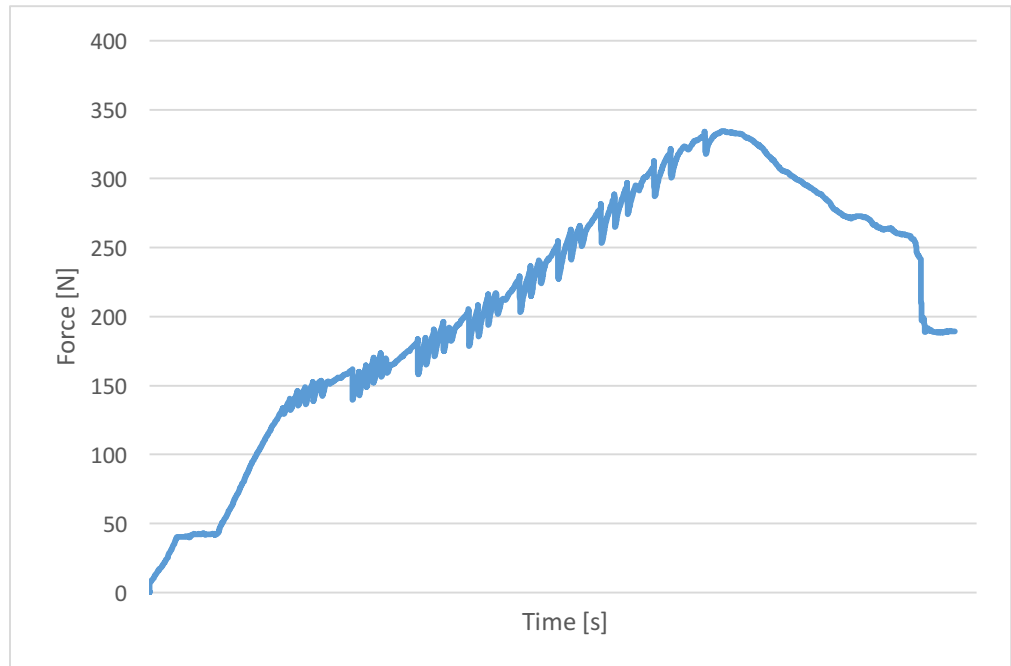
Figure 54. Working diagram of the compressive test, component with layer thickness 0,20 mm
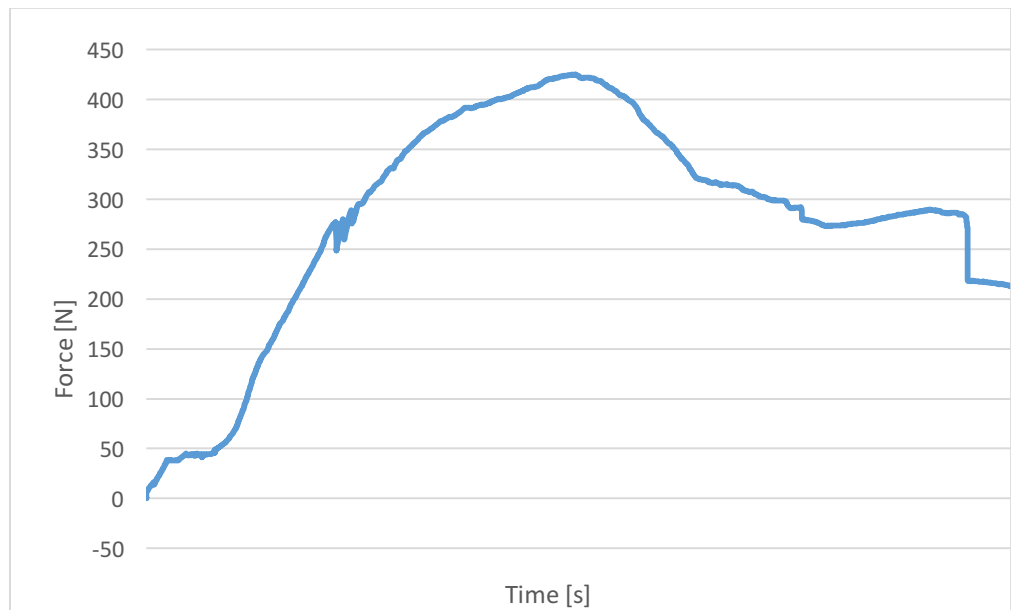
Figure 55. Working diagram of the compressive test, component with layer thickness 0,25 mm

3. Influence of the build orientation

To analyse an influence of layer orientation when 3D printing a component, numerical models with parametrical options were created. Only material model was defined parametrically. The geometry was made based on import (see above). Two numerical (FE) models were compared between each other. The displacement in Z axis direction is showed in Fig. 56. We see, that the most deflected (displaced) parts of the component is top and bottom, meanwhile the centre (red colour) is rather static. All results below are showed in RSYS = 11 that considers rotation of forces. So the results are not depicted with respect to geometrical axis of specimen.
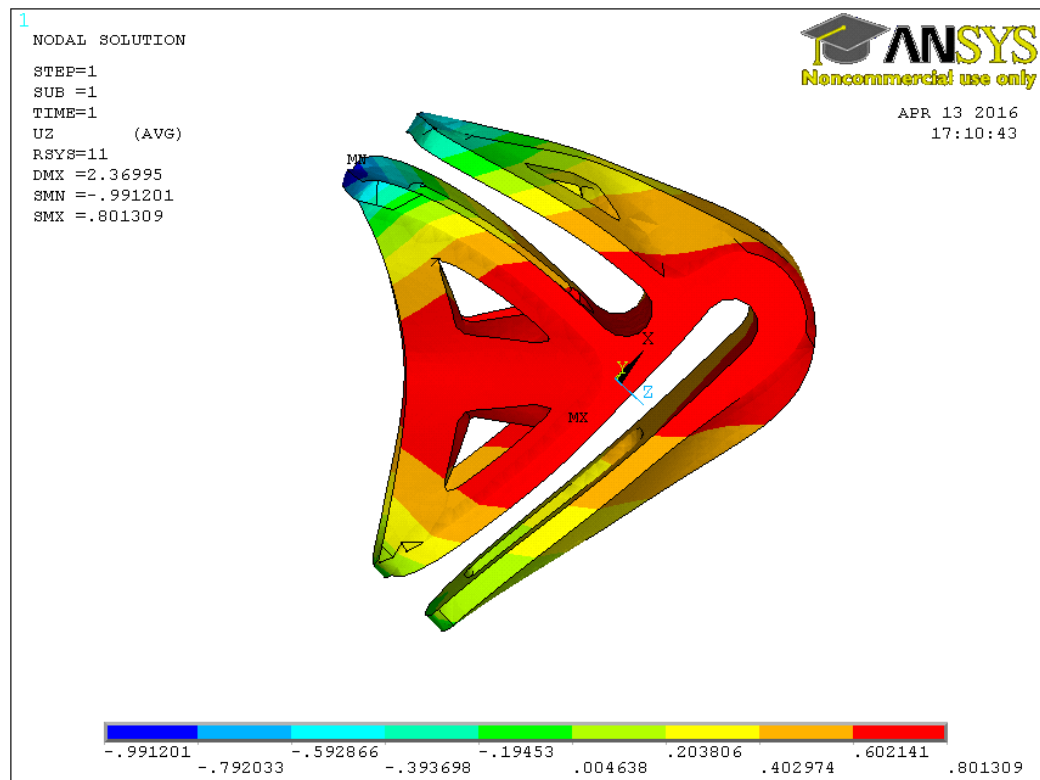
Figure 56. Displacement in Z axis direction in [mm]

Displacement in X axis direction is depicted in Fig. 57 (horizontally in the Figure). We see there a symmetric distribution given by boundary conditions.
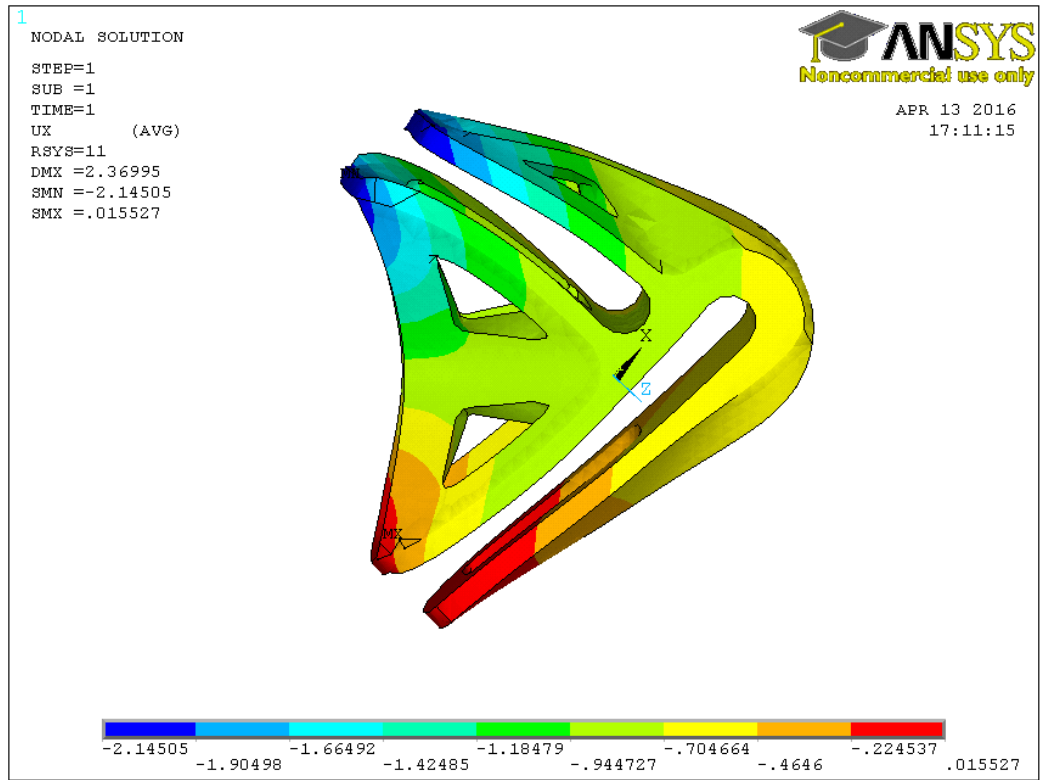
Figure 57. Displacement in X axis direction in [mm]
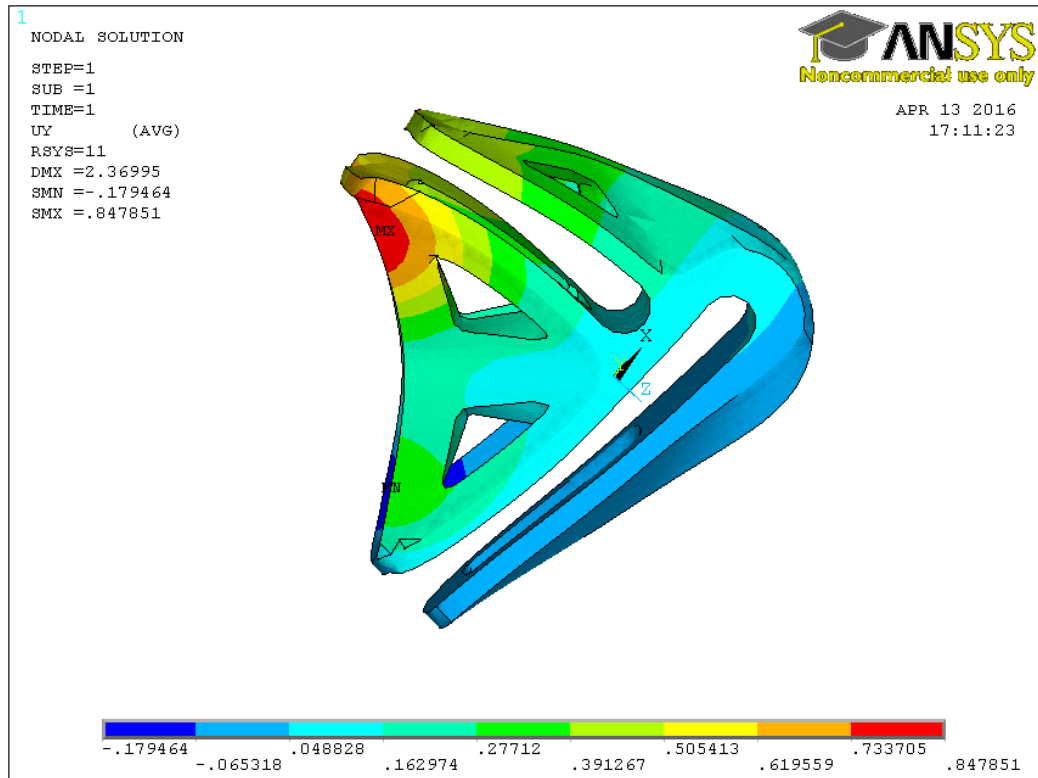
Figure 58. Displacement in Y axis direction in [mm]

Because we have nearly isotropic material mode, we may use also energetic criteria for assessing stress peaks. For this purpose, we plotted von Misses stress that shows where the scalar stress is the highest. In other words, it shows where is the highest potential for failure of the material. As we see from Fig. 59, the highest stress is on the top of the sample. This stress is called singular stress and is invalid stress that occurs due to a fact the area forces are acting at, are approaching zero. If we exclude these parts of the component from the mode, we may see where component is likely to failure. It is the vertical rib that experience stress about 70 Mpa. As we showed in Fig. 52 and Fig. 53, the failure really first occurred at vertical ribs by delamination. Our model is homogeneous, so it can not explain and characterize the delamination phenomenon.
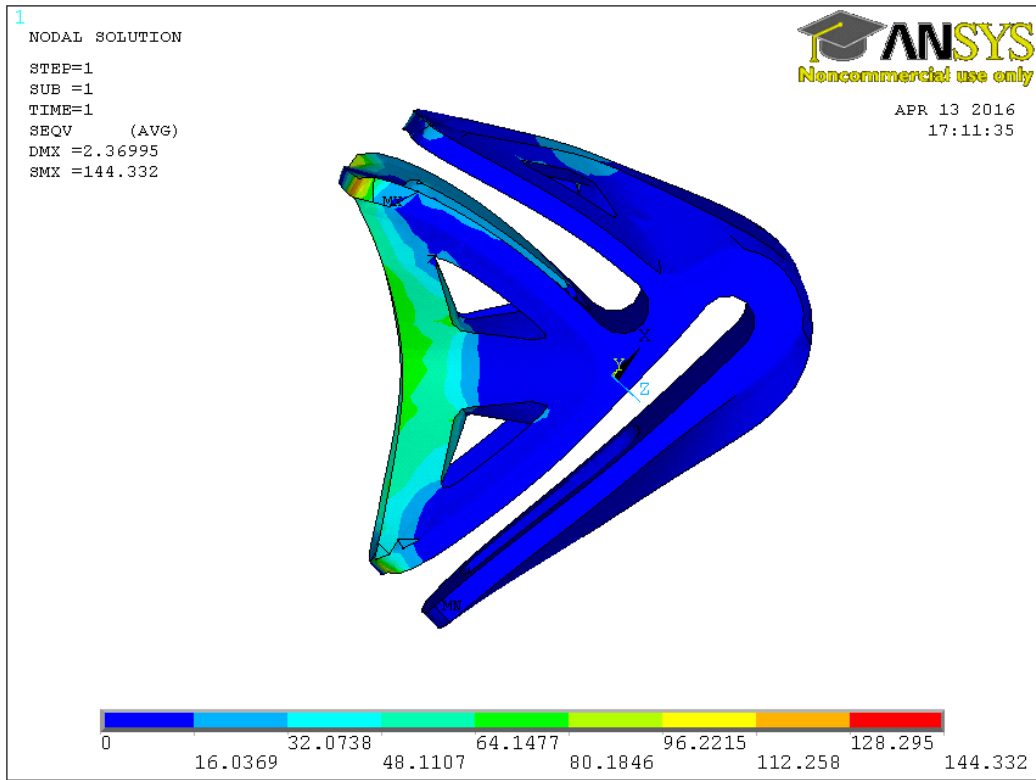
Figure 59. Von Misses stress for the component [MPa]

V.   SUMMARY

Based on defined objectives of this work, there was quite a large review of the topic done and all kinds of sources studied in the theoretical part. It is clear that additive manufacturing has a potential to become a part (small or large) of manufacturing processes in all kind of industries, furniture industry including. However additive processes are well suited for highly customized applications, there is still relatively low volume of actual applications. Products which are very large or products with simple geometries requiring high volume production runs (e.g. ten thousand units) are currently still better served by traditional manufacturing processes and probably it will stay that way. However the potential of bigger usage of AT could be to use the technology as a complementary one, besides the classic methods of production. The technology of layered manufacturing does not offer a cheap method of production yet, which is probably its biggest drawback. The reason why the potential of this technology is not being fully developing yet, could be the point, that we need to adapt our way of thinking to it. The product development process needs to adapt to the logic of this technology from the first idea, design, prototyping to way of production and product life cycle.

Second part of the literature review was focused on materials used in AM and mainly materials used together with the chosen AT – the Fused Deposition Modelling technology. According to the nature of the layered material there was the expectation of quasi-isotropic (plane isotropy) properties.

Based on the theoretical part of the thesis, two factors of influence on material properties of 3D-printed material and component were chosen in the practical part of the thesis to analyse. To verify the expectation mentioned above and to analyse partly the amount of diversity between the properties, we have tested 3D-printed ABS material in two principal directions (assuming plane isotropy) as well as component printed in two directions in respect to model geometry. Two specimen of different layer orientation were tested on compressive strength and the results showed, that the plane isotropy is not actually that significant. To analyse the influence of layer thick-

ness on stiffness of the component, two 3D printed components were tested in compression with different layer thickness and the results confirmed that the thinner the layer is, the better overall stiffness of the material. However to analyse this factors' influence properly, tests with more components of different layer thickness would need to be done. To analyse the rate of influence of layer orientation on a 3D-printed component, numerical models with parametrical options were created where only the material model was defined parametrically. The numerical model revealed the highest potential for failure of the material and where the component was likely to failure. At the compression test of the 3D-printed component failure first occurred at vertical ribs of the component by delamination, as it was expected according to the numerical model. However the model was homogeneous, so it could not characterize the occurred delamination.

Although the tests in the practical part of the work were quite limited on number of samples, the influence on the chosen factors is quite evident from the results. Wider analysis of the issue was not done due to high material and time consuming demands.

V. SHRNUTÍ

Na základě stanovených cílů této práce byl proveden literární přehled a rešerše všech dostupných zdrojů zvoleného tématu. Je zřejmé, že AM má potenciál stát se součástí malých i velkých výrobních procesů napříč průmyslovým spektrem, nábytkářský průmysl nevyjímaje. Procesy AM jsou vhodné zejména pro produkci vysoce personalizovaných výrobků, avšak ve skutečnosti jejich aplikace stále není příliš rozšířená. Produkce výrobků velkých rozměrů, výrobků s jednoduchou geometrií a výrobků, které vyžadují velké výrobní série (například deset tisíc kusů), je v současné době stále lépe obsloužena tradičními výrobními postupy a pravděpodobně to tak zůstane i do budoucna. Potenciál širšího využití AT by mohl spočívat ve využití této technologie výroby jako doplňkové, tedy vedle tradičních způsobů výroby. Technologie "vrstvené výroby" stále nenabízí levný způsob produkce, což je pravděpodobně stále jejím největším nedostatkem. Důvodem, proč potenciál tohoto způsobu produkce ještě nebyl plně rozvinut, by mohl být fakt, že jsme této technologii ještě nepřizpůsobili náš způsob uvažování. Proces vývoje produktu se musí totiž logice této technologie přizpůsobit od prvopočátku nápadu, návrhu, prototypu produktu, způsobu výroby až po uvažování o konci životního cyklu výrobku.

Druhá část literárního přehledu byla zaměřena na materiály, které se používají společně s technologiemi AM, a to zejména s vybranou technologií Fused Deposition Modelling. V závislosti na povaze vrstveného materiálu byly očekávány kvazi-izotropní vlastnosti materiálu (rovinná izotropie).

Na základě rešerše byly vybrány dva faktory vlivu na materiální vlastnosti 3D-vytisknutého materiálu a ty byly analyzovány v praktické části práce. Aby bylo možné alespoň z části ověřit výše zmíněné očekávané vlastnosti materiálu, a také analyzovat míru diverzity mezi vlastnostmi v různých směrech, testovali jsme vzorky ABS materiálu vytištěného na 3D tiskárně ve dvou hlavních směrech (s předpokladem rovinné isotropie). Dále jsme testovali konkrétní součástku s předpokladem, že byla vytištěná ve dvou různých směrech, s ohledem na geometrii modelu. Dvě skupiny vzorků s různou orientací vrstev byly testovány na pevnost v tlaku a získané výsledky ukázaly rozdíly ve vlastnostech v různých směrech podle principu rovinné

izotropie. Dále dvě 3D-vytištěné součástky byly testovány na pevnost v tlaku za účelem zjištění vlivu tloušťky vrstvy na tuhost a výsledky potvrdily předpoklad, že čím menší tloušťka vrstvy materiálu, tím větší celková tuhost. Avšak abychom náležitě ověřili vliv tohoto faktoru, musely by být provedeny zkoušky více součástek s větší diverzifikací tlouštěk vrstev. Za účelem zjištění míry vlivu směru tisku vytištěné součástky byly vytvořené numerické modely a parametricky definovány materiálové vlastnosti. Numerický model ukázal místo s největším potenciálem porušení materiálu a součástky. 3D-vytištěná součástka byla vystavena tlakové zkoušce. K porušení došlo v místě, které bylo předpokládáno na základě numerického modelu. Model však kvůli svému homogennímu charakteru nemohl popsat rozvláknění, ke kterému došlo při porušení materiálu.

Přestože zkoušky v praktické části práce byly provedeny s malým počtem vzorků, vliv vybraných faktorů na materiálové vlastnosti je poměrně zřejmý. Širší analýza problematiky nebyla provedena v důsledku vysokých materiálových a časových nároků.

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