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THE EFFECT OF MULTI-MATERIAL PRINTING TO FLEXIBILITY

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Abstract: Currently, 3D printing is one of the popular technological production methods, mainly because it offers various options that affect the resulting properties of prints. The aim of the presented work is to manufacture a prosthetic finger with a PIP and DIP joint using multi-material 3D printing, which will allow to mimic the flexion of a physiological finger. The subject of this research and testing is the design of a combination of solid and flexible material for a monolithic finger model, which will allow the required bending in selected areas of the print.

1 Introduction

Additive manufacturing (AM), which is based on layer-by-layer material addition, provides an opportunity for producing multi-material components with customized geometry tailored material properties at different locations and tailored functionality. Current developments in Multiple Material Additive Manufacturing (MMAM) focus mainly on producing components with similar material properties [1,2], such as those consisting of polymer-polymer [3-5]; polymer composite with nano-and micro-particle filler [6,7]; metal-metal [8,9]. In the field of prosthetics and orthotics in the design of prostheses, orthoses and other aids, it is very important to choose a suitable material, resp. combinations of materials. This choice of different materials makes it possible to influence the resulting properties of the product, e.g. flexibility. The presented study deals with the selection of a suitable combination of materials for the production of a prosthetic finger model, which will allow the most realistic flexion of its individual links in the area of joints. Combination of suitably selected materials results in better properties and lower maintenance requirements for the prosthesis. The aim was to ensure sufficient flexibility of the printout, which was to be achieved by using a flexible material, with sustainability of the printout shape and ensuring bending in the desired direction, which ensured the choice of rigid material.

2 Material and methods

The design of a functional monolithic prosthetic finger consists of 3 segments, which are connected to each other by a PIP and a DIP joint. This model is designed as one piece, where different combinations of materials are in the areas of joints in order to achieve the most natural flexion. Two types of 3D printers were used for the additive manufacturing, which enable multi-material printing, namely the TEVO Tarantula - Prusa i3 printer and the Bioplotter Manufacturer. Hobby printer TEVO Tarantula is an FDM type that prints the filament supplied in the spool layer by layer by building on a bitmap according to a CAD model [10]. The second type is the Bioplotter Manufacturer dual printer with the possibility of printing low-temperature and high-temperature material. PLA (polylactic acid), TPE-E (thermoplastic elastomer) and LSR (silicone) were chosen as printing materials due to their suitable properties (Table 1) [11].

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Table 1 Properties of selected material filaments

	TPE	PLA	LSR
Tensile strength	26-43 MPa	65 MPa	7 MPa
Brittleness	1/10	7,5/10	>1/10
Thermal expansion coefficient	157µm/m-°C	68µm/m-°C	250 µm/m-°C
Density	1,19-1,23 g/cm³	1,24 g/cm³	1,10-1,50 g/cm³
Printability	6/10	9/10	5/10
Flexibility	high	low	high
Elasticity	high	low	extremely high
Impact resistance	high	low	medium
Fatigue resistance	high	very low	very high
Thermal resistance	low	low	low
Shrinkage	low	low	low
Recyclability	Y	Y	N
Bioabsorption	Y	Y	N
Biocompatibility	Y	Y	Y
Chemical resistance	Y	N	Y

3 Experiment

The experimental part deals with the combination of 3D printing of solid and flexible materials and their influence on bending. A key feature for achieving prosthetic finger flexion is the elasticity of the material. Elasticity in structural mechanics means that the material responds elastically to an applied load and when the load is removed it returns to its original shape. Flexibility is less well defined but means that the material will respond to loading by deforming without fracture but does not necessarily fully return to its original shape. The Young's modulus parameter, which is based on Hooke's law, was used to analyse the property. It describes the relationship between the deformation of a solid body caused by the action of stress and its magnitude.

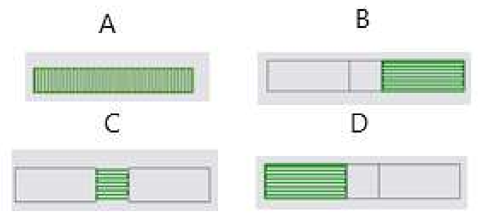
Table 2 The degree of elasticity of materials according to Young's modulus

Material	*Young's module*	Flexibility
PLA	3 500 MPa	Low flexibility
TPE - FilaFlex	95 MPa	High flexibility
TPE - Arnitel	250 MPa	Semi-flexibility
Silicone	3,3 MPa	High flexibility

In the first part of the experiment the combination of printing of low-temperature and high-temperature materials were verified. It was used a multi-cartridge printer Bioplotter Manufacturer. As a less flexible material with a high melting point, was chosen a mixture of PLA and PHB, which has the desired properties. The highly flexible low melting point material was Mapei's LSR silicone from Mapesil.

Table 3 The degree of elasticity of materials according to Young's modulus

	Layer number	Layer order	Material	Dimension	Position
A	3	1. 3. 5.	PLA	10x60 mm	Whole model
B	2	3. 4.	PLA	10x25 mm	Proximal part of specimen
C	2	3. 4.	LSR	10x10 mm	Joint part of model
D	1	2. 4.	PLA	10x25 mm	Distal part of specimen



For the purpose of our research work were made three specimens, which were modelled in Autodesk Meshmixer program. The first sample is in the shape of a square with dimensions of 20x20*mm*. It is a four-layer model, where the layers alternate in the order PLA, LSR, PLA, LSR. Sample No. 2 was designed to resemble the actual flexion of the finger, so the rigid parts are connected to each other via flexible joint parts. The combination of materials was only in the articulated part, where PLA alternates with LSR with the intention to increase the flexibility of the transition. Our designed model consisted of layering prisms PLA (low flexibility) and LSR (high flexibility), where the first, third, fifth layer is formed by PLA prism with dimensions 20x60*mm* and a second and fourth layer of LSR prisms with dimensions of 20x20*mm*. The square in the middle represents the joint, so it should provide the greatest flexibility during the bending. The ribbing of the lamellae during the alternation of the individual layers over the entire surface of the print is formed by the structure of the grid. The third sample was created by dimensional modification of sample no. 2. The design was based on the assumption that the narrowing of the layers will ensure better adhesion between the layers [12,13]. Dimensions of sample no. 3 are listed in Table 3.

4 Results

During the experiment, the adhesion between their individual layers is the biggest problem with the prints made of several materials. Silicone only binds to another silicone or LSR. Another problem is that the Bioplotter can print multiple material filaments at the same time, but the materials must belong to different groups in terms of their printing temperature. For these reasons, the type of LSR and PLA or other high-temperature material used was evaluated as unsuitable bonding materials. The experiment further showed that the reason for the lack of adhesion between the silicone and the PLA mixture is the presence of hydrogen bonds in the chemical structure of the silicone, which weaken the ionic and covalent bonds necessary for the cohesion of the layers.

Specimen no. 1 was necessary to print with a contour, because of an unsuitable bend occurs around the z-axis. The flexibility of this sample is sufficient for the needs of the experiment, but the persistent problem of layer adhesion precludes its use.

In the second specimen, it can be seen that the linear lines of the structure overlap and a grid is formed. This and conjunction with the alternation of the filament materials, provides the desired bend in the joint area and not outside it. However, the most serious drawback is the adhesion of the layers of different materials, and there was also the breakage of the lamellae at the bending point.

The design of specimen no. 3 was approached in order to eliminate the lack of adhesion between the layers. The dimensions were modified and the last LSR layer was covered with a PLA layer (Figure 1). Although greater cohesiveness between the layers was visible in the bending test, it was found that the problem of adhesion was not eliminated. In this sample, an increased brittleness of the material is observed compared to the previous one. The lamellae break not only at the junction of the contour and the ribbing, but also in the area of the ribbing itself and, to the greatest extent, on the side which was printed out first.

Figure 1 Prints of the combination of LSR and PLA / PHB mixture, Left - first specimen, second specimen, third specimen

5 Discussion

Flexibility as a property describes the relationship between the deformation of a solid body caused by stress and its magnitude. The higher the Young's modulus, the greater the stress required to achieve the same deformation [14].

In the process of combining materials, the addition of PHB to the PLA mixture ensures an improvement in post-process stability by 20% compared to pure PLA [15]. This mixture also shows better properties in terms of material flexibility. In the combination of LSR and PLA / PHB, the biggest problem was the lack of adhesion between the layers. This is because of the intermolecular adhesive forces of silicone are weak. Although the angle between the PLA and the silicone was in the range of 0 °-45 °, the layers held together only by solidification and mutual pressure. It should be noted that this material does not adhere to other materials due to its chemical structure. Ionic and covalent forces are important for adhesion. Due to the hydrogen bond present in the silicone molecule, these bonds are weakened. Thus, the ionic and covalent bonds between the silicone molecules and the PLA + PHB mixture are not strong enough to provide the desired interlayer adhesion [10]. This insufficiently strong bond thus results in poor cohesion of the silicone and PLA mixture layers used in the experiment. To improve this problem, it is recommended to use a combination of silicone with silicone or a PLA mixture with materials that bond well with it or another printing method.

The biggest problem was the jamming of the filament in the extruder, which resulted in its unusability in printing, when testing the TPE-U Filaflex and when testing the flexibility of the printout. This was caused by the flexibility of the coil. The utilisation this material or any other material with a comparable modulus of elasticity for manufacturing, it is necessary to specifically adjust the print settings for a particular printer. Printing with TPE Arnitel proved to be suitable. The reason for the better printing process than the TPE-U variant was the higher value of the Young's modulus. The higher the Young's modulus of the material, the greater the stress required to achieve the same deformation [14].

The next possible solution could be to replace the LSR material (the group of acetic silicones), with a hybrid (acetic-neutral cured) silicone, which provides better adhesive properties. Such a material could be a polyether adhesive - ChemSet MS - 10. This material is used as a substitute for acetic silicone where a stronger binder is needed for industrial applications while maintaining the flexible properties offered by the LSR material group.

Another solution would be to replace both materials. It can be used a high-temperature material for the Bioplotter, for example ABS, which bonds well with the TPE material. An example of a suitable elastomer would be Polabond series 6401-6402, which would be exchanged for the LSR used [16].

6 Conclusion

The aim of the presented work was to imitate the flexion of the finger. It was based on the null hypothesis that the combination of solid and flexible material could result in flexion of the finger prosthesis. For this purpose, the Bioplotter multi-material printer was chosen as one of the manufacturing options. The selected materials were a mixture of PLA and PHB and LSR of the sanitary silicone type. The hypothesis was not confirmed due to the fact that the adhesion between the layers of materials with a different chemical structure was not sufficient.

FDM printing of the materials described above has proven successful. TEVO Tarantula - Prusa i3 printer was used to print specimens from Arnitel and Filaflex. This variant is very suitable for printing simple and small designs, as it has a printing bed with dimensions of 200mm x 200mm x 200mm. This platform is even heating and can be set from 60 to 120 °C. It can print models from materials such as PLA, ABS, PTEG, wood filament, TPE, PVE. The smallest possible layer thickness is 50 microns with a nozzle diameter of 1.75 mm and a print speed of 150 *mm/s* [10].

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