Optimization of parameters during filament extrusion

Tomáš Balint[1,a*], Jozef Živčák[1,b], Miroslav Kohan[1,c], Samuel Lancoš[1,d], Bibiána Ondrejová[1,e]

[1] Biomedical Engineering and Measurement Department, Faculty of Mechanical Engineering, Technical university of Košice, Letná 9, 042 00, SK

[a]tomas.balint@tuke.sk, [b]jozef.zivcak@tuke.sk, [c]miroslav.kohan@tuke.sk, [d]samuel.lancos@tuke.sk, [e]bibiana.ondrejova@tuke.sk

Keywords: Filament Extrusion, 3D Printing, PLA, 3D Printer, Filament Maker

Abstract. This scientific study brings new insights into the field of optimization of parameters in the extrusion of filaments from biodegradable materials. Extrusion is a production process in which metal or plastic materials are pushed through a rigid cross-sectional profile or matrix to form a continuous strip of shaped product (filament). The extrusion process begins by bringing the material in the form of granules, pellets or powders from the hopper to the extruder zone. One of the chapters contains a detailed description of the extrusion of filaments and optimization of parameters. Optimization of parameters consists of real designs and devices designed by the authors of this publication themselves. This study has a significant contribution in the field of material extrusion.

Introduction

Natural and synthetic polymers are considered biodegradable materials. Polymers can be broadly defined as macromolecules composed of covalently bonded monomers. Natural-based polymers include starch, chitosan, hyaluronic acid derivatives, collagen, fibrin gels, and silk. Undesirable properties of these polymers include low mechanical strength, unknown degradation rate, repellency and high physiological activity [1-4]. Various scientific studies show that synthetic polymers have a wide range of uses and satisfactory properties compared to natural polymers. An overview of biodegradable materials used in the extrusion of filaments and their possible applications is given in table 1.

Synthetic biodegradable polymers	Application
Poly(amino acids)	Medical products, tissue engineering, orthopaedic applications
Polymlinic acid (PLA), polyglycollic acid (PGA) and copolymers	Barrier membranes, controlled tissue regeneration (in dental applications), orthopaedic applications, stents, clamps, stitches, tissue engineering
Polyhydroxy butyrate (PHB), polyhydroxyvalerate (PHV) and copolymers	Long-term drug administration, orthopaedic applications, stents
Polydioxanone (PDO)	Fracture fixation, stitches

Table 1. Applications of biodegradable polymers

Extrusion is a manufacturing process in which metal or plastic materials are forced through a solid cross-sectional profile or die to form a continuous strip of shaped product (filament). The extrusion process begins with the introduction of material in the form of granules, pellets or powders from the hopper into the extruder zone. The melting process then begins through the heat generated by the mechanical energy supplied by the rotation of the screw and the heaters located along the head. The molten materials are then pressed into a die, which structures the materials into a hard pipe during the cooling process [5, 6].

Extrusion systems for the production of bioresorbable materials for clinical use

The extrusion manufacturing process is widely used for mixing polymeric materials. The process is highly flexible and enables a high degree of personalization of production. In twin-screw extrusion, the screws can be, for example, parallel or counter-current, interlocking or vice versa. In addition, the configurations of the augers themselves can be changed using various elements, blocks, to achieve specific mixing characteristics. In this extrusion process, raw materials can be solid substances (granules, powders). Large companies use industrial filament makers (extrusion systems), which excel in the large volume of extruded material and its precision. But in my research I will be using desktop extrusion systems at a good level. The desktop extrusion systems mentioned below are getting closer and closer in terms of quality to industrial extrusion systems. The Filabot EX2 extrusion system has a maximum extrusion temperature of 450°C, which means that all kinds of materials can be extruded, including high-temperature ones such as polycarbonate and even PEEK. Filament maker from 3devo company is an available extruder with a maximum extrusion temperature of 300°C and an extrusion speed of 250-600 mm per minute. We chose this extruder as the best option for extruding materials PLA/PHB/Thermoplastic starch and different concentrations of plasticizer, due to the precise composition of this extruder, the quality of the extruded materials and the extrusion temperature [7-10]. I am researching these materials as part of my dissertation. Extruder with high precision and maximum extrusion temperature of 300°C. Extrusion systems are mentioned in the following Fig. 1.

Fig. 1. Extrusion systems [10]

In industrial production, which uses more complex extrusion systems, unlike single-screw extrusion, a number of materials, both solid and liquid, are extruded by parallel two-screw extrusion (Fig.2). This provides maximum extrusion flexibility by allowing materials to be introduced into the melt at different stages or locations along the extruder cylinder. This brings a number of advantages:

• Possibility to add fibrous material to minimise fibre wear;

• Addition of shear or temperature-sensitive materials that can deteriorate if they pass through the entire extruder;

• Adding a plasticizer, liquid dye, stabiliser or lubricant.

Industrial extrusion systems are different from desktop extrusion systems in design and build quality. The barrel and screw of industrial extruders are made of high quality alloy steel with high hardness, strong corrosion resistance and long service life after nitrogen treatment. The automatic hydraulic inverter of the sieve can maintain the continuous production of the machine [11-14].

Fig. 2. Industrial extrusion system [12]

Twin-screw extruders are commonly used in modern industry. Based on the relative direction of rotation of their screws, these extruders can be divided into two types: co-rotating and counter-rotating. In a co-rotating twin-screw extruder, the maximum speed is reached at the tips of the screw, while in counter-rotating twin-screw extruders, the maximum speed is reached in the area of the feed. However, the counter-current mechanism generates a greater increase in pressure, making it more efficient at extrusion. Single- and twin-screw extruders were compared by a scientific team led by scientist Senanayake as part of design research aimed at a simplified extruder for less developed countries. The advantage of single-screw extruders is their simplicity of construction, but they are more likely to become clogged with material than twin-screw extruders. Furthermore, the single-screw extruder is the most common type of extruder and offers relatively low investment costs for companies dealing with the extrusion of materials intended for biodegradable purposes. If higher production and higher performance are required, twin-screw extruders are used. The easiest way to increase the throughput of the extruder is to increase the speed of the screw. This easy solution usually results in poor melt quality caused by exceeding the melting capacity of the screw design and degradation caused by high melt temperature. Using a smaller diameter screw can offer several advantages to achieve higher throughput at a higher screw speed [15].

Optimization of parameters during biomedical filament extrusion

After thorough research into materials and extrusion systems, we proceeded to extrude the biomedical filament on equipment from the 3devo company. The filament was produced from medically certified pellets in an optimized laboratory environment in a laminar box designed and engineered by this scientific team. Fig. 3 shows the filament production process.

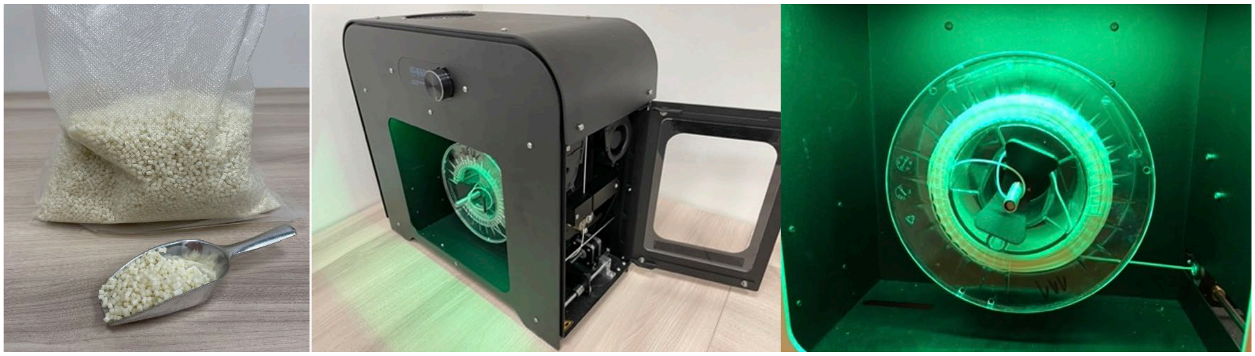

Fig 3. Filament production process

We managed to optimize all necessary extrusion parameters. The laminar box equipped with a filter and cooling has fulfilled its purpose (Fig. 4).

Fig. 4. Biomedical laminar box

As part of improving the quality of the production of biomedical filaments, we proceeded to our own laminar box design. We made the model of the laminar box in the 3D modeling program SketchUp. The laminar itself stands out with its simple and purposeful design. Compact dimensions ensure trouble-free handling when operating the filament maker in the production process. A sterile environment is ensured by isolation. It is made of aluminum profiles and plexiglass with a thorough connection. Air recovery in the laminar box is provided by twelve fans that supply and remove air. Laminar boxes can be equipped with UV light, which has the task of sterilizing the working environment of the laminar box. The UV light unit is equipped with a timer and a sensor that prevents exposure to UV radiation when the door is lifted [16].

Conclusion

This scientific study brings important significant knowledge in the field of materials, production and optimization of parameters in the filament production process. For a better orientation in the given issue, the extrusion of biomedical filament on a desktop device from the company 3devo is described. Filament maker Composer 450 is a device for the production of filaments, on which it is possible to mix several materials. Production took place in an air-conditioned room at a temperature of 18°C. The material for the production of biomedical filaments was delivered in the form of granules, vacuum-sealed in an opaque package. Nevertheless, we dried the material in a dryer from 3devo. We set the drying temperature at 160°C for 180 minutes. We optimized this entire process with the help of a device designed by us. The laminar box can also be defined as a laboratory station intended for work in dust-free, sterile conditions. The use of laminar boxes is wide-ranging. Laminar boxes are mainly used in optical, laser, semiconductor and electronic technology applications. The design of the laminar box is designed to prevent contact with the external environment and thus ensure the protection of researchers as well as the researched material. The entire article is briefly divided from the materials to the output in the form of a new product.

Acknowledgement
This scientific study was created thanks to support under the Operational Program Integrated In-frastructure for the project "Center for Medical Bioadditive Research and Production (CEMBAM), code ITMS2014 +: 313011V358, co-financed by the European Regional Development Fund" and also thanks to support under the Op-erational Program Integrated Infrastructure for the project: Open Scientific Community for Mod-ern Interdisciplinary Research in Medicine (OPENMED), code ITMS2014 +: 313011V455, co-financed by the European Regional Development Fund and thanks to support under the Opera-tional Program Integrated infrastructure for the project: Center for Advanced Therapies of Chronic Inflammatory Diseases of the Musculoskeletal System (CPT ZOPA), code ITMS2014 +: 313011W410, co-financed by the European Regional Development Fund.

References

[1] Zeeratkar, M., D. De Tulio, M., Percoco, G., 2021. Fused Filament Fabrication (FFF) for Manufacturing of Microfluidic Micromixers, an Experimental Study on the Effect of Process Variables in Printed Microfluidic Micromixers. In: Micromachines. Vol. 12(8), pp. 858. https://doi.org/10.3390/mi12080858

[2] Hasegawa, K.; Matsumoto, M.; Hosokawa, K.; Maeda, M., 2016. Detection of methylated DNA on a power-free microfluidic chip with laminar flow-assisted dendritic amplification. In: Anal. Sci., 32, pp. 603-606. https://doi.org/10.2116/analsci.32.603

[3] Ou, J.; Moss, G.R.; Rothstein, J.P., 2007. Enhanced mixing in laminar flows using ultrahydrophobic surfaces. In: Phys. Rev. E, 76, 016304. https://doi.org/10.1103/PhysRevE.76.016304

[4] A. Aghaei Araei, I. Towhata., 2014. Impact and cyclic shaking on loose sand properties in laminar box using gap sensors . In: Soil Dyn Earthq Eng. Vol. 66 , pp. 401-414. https://doi.org/10.1016/j.soildyn.2014.08.004

[5] Ueng TS, Chen CH, Peng LH, Li WC., 2006. Large-scale shear box soil liquefaction testing on shaking table - preparation of large sand specimen and preliminary shaking table test. In: Proceedings of the National Center for Research on Earthquake Engineering; Taiwan.

[6] M. Khabbazian, V.N. Kaliakin, C.L. Meehan., 2010. Numerical study of the effect of geosynthetic encasement on the behaviour of granular columns. In: Geosynthetics International. Vol. 17. pp. 132-143. https://doi.org/10.1680/gein.2010.17.3.132

[7] Tagliavini G., Solari F., Montanari R., 2016. CFD simulation of a co-rotating twin-screw extruder: Validation of a rheological model for a starch-based dough for snack food. In: Proceedings of the International Food Operations and Processing Simulation Workshop, FoodOPS. https://doi.org/10.1515/ijfe-2017-0116

[8] Pearson J.R.A., Petrie C.J.S. The flow of a tubular film. Part 1. Formal mathematical representation. J. Fluid Mech. 1970;40:1-19. doi: 10.1017/S0022112070000010. https://doi.org/10.1017/S0022112070000010

[9] Pearson J.R.A., Petrie C.J.S. The flow of a tubular film. Part 2. Interpretation of the model and discussion of solutions. J. Fluid Mech. 1970;42:609-625. doi: 10.1017/S0022112070001507. https://doi.org/10.1017/S0022112070001507

[10] Vlachopoulos J., Sidiropoulos V., 2017. Reference Module. In: Materials Science and Materials Engineering. Elsevier.

[11] Wilczyński K., Lewandowski A., Wilczyński K.J., 2012. Experimental study for starve-fed single screw extrusion of thermoplastics. In: Polym. Eng. Sci. 2012;52:1258-1270. doi: 10.1002/pen.23076. https://doi.org/10.1002/pen.23076

[12] Gautam A., Choudhury G.S., 1999. Screw configuration effects on residence time distribution and mixing in twin-screw extruders during extrusion of rice flour. J. Food Process. Eng. 1999;22: pp. 263-285. https://doi.org/10.1111/j.1745-4530.1999.tb00485.x

[13] Kao S.V., Allison G.R. Residence time distribution in a twin screw extruder. Polym. Eng. Sci. 1984;24:645-651. doi: 10.1002/pen.760240906. https://doi.org/10.1002/pen.760240906

[14] Altomare R.E., Ghossi P., 1986. An Analysis of Residence Time Distribution Patterns in A Twin Screw Cooking Extruder. In: Biotechnol. Vol.2, pp. 157-163. https://doi.org/10.1002/btpr.5420020310

[15] Gonçalves N.D., Teixeira P., Ferrás L.L., Afonso A.M., Nõbrega J.M., Carneiro O.S., 1849. Design and optimization of an extrusion die for the production of wood-plastic composite profiles. In: Polym. Eng. Sci. Vol. 55, pp. 1855. https://doi.org/10.1002/pen.24024

[16] Bahaa S., Mohammad, A. Et al., 2021. Gaining a better understanding of the extrusion process in fused filament fabrication 3D printing: a review. In: The International Journal of Advanced Manufacturing Technology. Vol.114, pp. 1279-1291. https://doi.org/10.1007/s00170-021-06918-6