DESIGN AND ANALYSIS OF A BENDING MECHANISM PRODUCED BY FDM TECHNOLOGY

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DOI: 10.17973/MMSJ.2022_06_2022018

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In today's age of technical and technological development, the market requires many products, with an emphasis not only on price but also on quality. To meet these requirements, new technologies and production processes are constantly being developed. These technologies and processes lead to modernization of equipment, the purpose of which is to increase production efficiency and productivity. The ever-increasing expectations of economic development place demands on labour productivity, accuracy, quality, reliability, and create a large room for application of various transmission systems. These demands may be met by using advanced technologies in combination with upgraded original equipment and mechanisms. The focus of this article is on the mechanisms that work on the principles of bending member, enabling their rapid prototyping. This paper contributes to the topic with design of bending mechanisms and with the subsequent simulation of the functionality and evaluation of the respective results.

KEYWORDS

3D simulation, additive technologies, CAD software, mechanism, materials

1 INTRODUCTION

Mechanisms are parts of machines that consist of members moving with one degree of freedom and a clearly defined motion. They are used to transfer mechanical energy and capable of changing the type or speed of motion. Where transfer of energy, i.e. power, is concerned, it is possible to say that the mechanism is a device or a machine used for facilitating the physical labour of a man through work of the machine [Nam 2020]. The mechanisms can be divided in three ways. The first division considers design features of mechanisms and the second division considers the mechanisms function [Xu 2020]. The third division of mechanisms is explained in more detail in the next chapter of this paper. The above classifications are very important because a designer must be able to construct a mechanism and the mechanism must play a certain role in the machine or equipment. Mechanism division by their function is very challenging because there are a number of mechanism types found in machines and equipment in use today [Zhang 2019]. Machines and mechanisms should be able to perform sufficient motion or useful work. In order to fulfil these tasks, the mechanisms must be correctly designed in terms of motion of their individual parts and the mechanism strength. This means that they do not deform, break, or crack in course of their activities. The theory of machines and mechanisms deals with these issues [Liu 2019]. Due to complexity of their designs, mechanisms have often been confused with conventional articulated mechanisms. Another reason for the rise of bending mechanisms is that they enable to be rapidly prototyped using 3D printing. The main goal of this paper is to examine the principle and method of the bending mechanisms functionality [Wang 2019]. Under the influence of CAD material analysis, design has become simpler and, therefore, practically used to a greater extent. An integral part of the production process is FDM printing, in simple terms, referred to as 3D printing. This technology makes use of gradual melting of the material that is supplied to the printer mechanism, such as plastic, the so-called plastic fibre. A more frequently used name the user may encounter is the filament. The whole printing process is simple and is based on gradual unwinding of the plastic fibre from the spool placed on the printer. Under the influence of high temperature, the printhead, or the extruder, converts this solid plastic into a mouldable mass, used for producing a physical model of the part. The practical part maps the process of CAD designing of bending mechanisms with an explanation of the procedure of mechanism design, all the way to its simulation [Pandis 2019 and Shanmugam 2021]. The mechanisms can be divided, for example, according to the type of energy carrier. Under energy carrier we mean a set of material particles of any shape, size, and physical or chemical properties. Electrons, atoms, molecules, semi-finished products, workpieces and the like can be mentioned as an example [Xu 2020]. The mechanism consists of a system of interconnected bodies, of which one body is immovable, and is called a frame. This member captures the resulting reaction forces or moments that arise during the transformation of motion. The members of the mechanism that drive the mechanism are called drive elements. The other members of the mechanism are called driven elements. The driven member that performs the required final motion is called the output member. The members of a mechanical system can be divided into simple or complex ones. The degree of the mechanism complexity is determined by the number of components to which the member is directly connected [Zhang 2019].

1.1 Bending mechanisms

In practice, we know types of mechanisms, such as hydraulic, pneumatic, latching, stepping, damping, braking mechanisms and others. In this article, we will focus on bending mechanisms. Bending mechanisms can be defined as mechanisms that transmit or transform motion, force, or energy through at least one bending body in the mechanism assembly. The bending mechanism transmits its motion thanks to flexible members and, thus, does not use any articulated joints. The replacement of the articulated joints by the bending member is shown in Fig. 1. [Liu 2019].

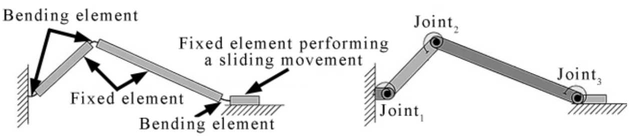

Figure 1. The bending mechanism principle

Although it may seem that the construction of bending mechanisms is very simple, the opposite is true. The use of bending mechanisms began to be abandoned precisely because of the complexity of construction due to the increasing demands on the mechanisms. Today's understanding of bending mechanisms is much better and more advanced also thanks to modern technologies such as computer technology and material fatigue analysis. These modern technologies thus help to simplify the process of mechanism construction. Thanks to this, mechanisms are again used anywhere from state of the art equipment with high accuracy to simple, everyday equipment. Their application varies from small micro-devices to large machines. It is often said that a rigid and robust structure is needed, but rigidity and strength are two different properties. In some cases, both properties are needed, such as in bridge construction and others. Therefore, people often think that if the material is rigid, it must be strong and vice versa. However, this is not the case. Strength refers to resistance to failure, while rigidity refers to resistance to deflection of the material when bent [Wang 2019].

2 MATERIAL AND METHODS

A When discussing general properties of materials, it is assumed that the final product will exhibit isotropic behaviour. The term isotropic denotes constant characteristics in any direction and the same values at any point in the volume of the part. Such environment serves in particular as a basis for structural calculations in technical design. If the part is made in layers, it is not surprising that the part appears to be anisotropic. This means that the properties of the material vary in different directions. Properties parallel to the structure are different from properties perpendicular to it. The degree of anisotropy may vary from difficult to detect to a degree that can seriously affect the stability of the part. The degree of anisotropy can be influenced by design, mainly through changing the orientation of the part. The anisotropic effect is closely related to the way the adjacent layers are connected. The highest degree of anisotropy is a phenomenon we call delamination, which occurs during layer deposition [Shanmugam 2021]. As a subset of thermoplastic materials, materials of the FDM technology form strong interlayer bonds at or near the melting point and have a suitable composition and morphology. This results in low stress without deformation as soon as the material reaches room temperature. The material intended for FDM technologies must also have adequate flexural modulus and strength so that it can be formed into a wound fibre – the filament. It must also have a sufficiently low viscosity, so that in the expanded state it passes through the nozzle of the extruder, but at the same time, it must be able to create a well-defined width of the printed geometry at the speed of deposition. The melting properties of amorphous thermoplastics make them suitable for FDM technologies. These polymers, including the most commonly used ABS and PLA materials, melt over a wide temperature range, creating viscosity ideal for extrusion through the extruder nozzle [Pandis 2019]. ABS (acrylonitrile-butadiene-styrene) it is often used for interior car parts due to its excellent impact toughness in combination with a good mix of other required properties. In practice, several types of ABS resins and many special classes of alloyed or otherwise modified ABS materials are used to meet the necessary requirements [Billah 2020 and Ponsuriyaprakash 2020]. PLA material (polylactic acid) differs from most thermoplastic polymers in that it is obtained from renewable sources such as corn starch or sugar cane. In contrast, most plastics come from distillation and polymerization of non-renewable oil reserves. Therefore, PLA is also called bio plastic. In practice, it is used to make plastic films, bottles, and biodegradable medical devices such as screws and pins, which are expected to degrade biologically. PLA is classified as a thermoplastic polyester, which means that PLA can be heated to a melting point of about 150°C - 160 °C and then cooled and reheated without significant degradation. In 3D printing, and especially for users of FDM technologies, PLA is one of the basic materials for 3D printing. PLA fibres for 3D printing are produced in various colours [Farah 2016 and Harshitha 2019]. PET-G (Polyethylene terephthalate) it is one of the most commonly used thermoplastic polymers in the world, better known as polyester. It is a naturally transparent and semi-crystalline plastic that is most commonly used as a fibre for clothing and an effective moisture barrier. It is widely used for filling bottles. As a technical plastic, it is used jointly with other materials, such as laminates or carbon nanotubes, to increase the material strength. PET-G is one of extremely use-friendly materials for 3D printing. It is relatively strong and substantially flexible, so it is designed for components that need to combine flexibility and durability. PET has a reputation for emitting less odour than conventional 3D printing materials such as ABS and PLA [Durgashyam 2019 and Nguyen 2020]. The mechanism simulation was performed in the CAD program PTC Creo Parametric, with investigation of the stress-generating zones in the mechanism's material. The parts that changed the position under the load the most were examined, too. Before starting the simulation, mechanical and physical parameters of the material were selected in the program according to the type of material from which the mechanism was to be made. The material properties required by the program are listed in Tab. 1.

	PLA	PET-G
Density (g/cm3)	1.252	1.27
Poisson constant	0.36	0.37
Young's modulus [GPa]	3.4	2.1
Yield strength [MPa]	59	53
Strength limit [MPa]	73	48.8

Table 1. Material parameters [Nam 2020]

2.1 FDM Technology

With FDM technology, we create three-dimensional objects from CAD-generated wireframe or surface model data through doses of separate layers. The model is built to deposit layers from bottom to top. The main advantages of this technology include easy change of working material, low maintenance costs, unattended operation, compact size, and low working temperature. This method can be used to produce components from a variety of materials, including elastomers, ABS (acrylonitrile butadiene styrene) and wax castings. In the manufacturing process of a model, the fibre is fed through a heated element and becomes molten or semi-molten. The liquefied fibre is fed through a nozzle using a solid fibre as a piston. The material is deposited on a partially constructed part or heating pad. The nozzle head moves along the XY plane and deposits material according to the geometry of the currently printed layer. After the layer is deposited in the XY plane, the nozzle moves vertically in the Z plane in the direction of the start of depositing a new layer on the previous layer. The principle of FDM technology can be seen in Fig. 2. [Angelo 2020].

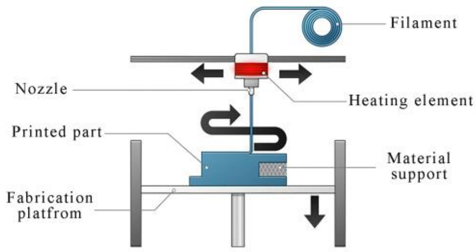

Figure 2. Principle of FDM technology

A simple clamp that uses the principles of a bending member was designed and simulated in the CAD program PTC Creo Parametric. In practice, the proposed mechanism fulfils the role of a simple clamp, which is to ensure the mutual position of the clamped part and the work bench. As already mentioned in the paper, bending mechanisms have a limited range of motion. The clamp, therefore, works properly when it repeatedly clamps the material of the same thickness. If the thickness of the material changes, it is also necessary to adjust the dimensions of the clamp. Several alternatives have been considered in the design of the component. The individual alternatives with modifications are shown in Fig. 3. When simulating the individual alternatives, attention will be paid to what effect the removal of a notch on the arm of the mechanism, or the removal of the groove, will have on the bending of the mechanism.

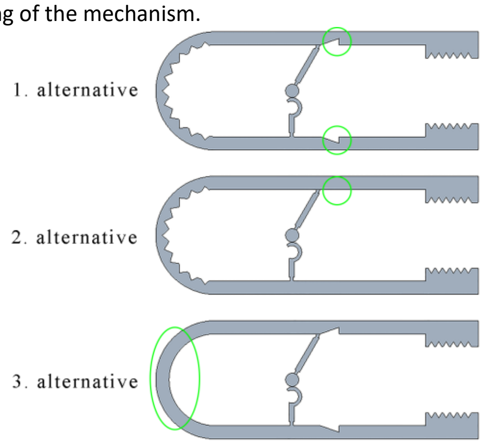

Figure 3. Proposed mechanism options

The parameters, which include the direction, the size, and the area on which the pressure acts, and the method of bonding, were chosen to simulate as much as possible the conditions occurring in practice. Fig. 4 shows the plot of the action of the force and the binding of the mechanism.

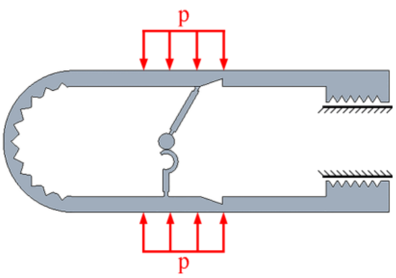

Figure 4. Site of load application and site of the bond

Fig. 5 shows the selection of the size, the direction, and the area of load application. The magnitude of the pressure applied was set at 5 kPa.

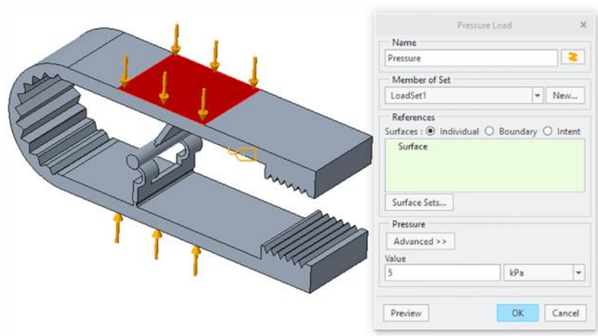

Figure 5. Selected size, direction, and area of pressure

The type of binding was adapted to the most authentic simulation course. A rigid bond was applied to one of the mechanism's arm Fig. 6 a) and a sliding bond was used for the second arm, i.e., with the possibility of deflection in the Z axis by a specified constant Fig. 6 b).

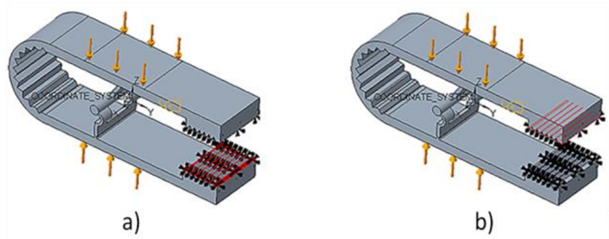

Figure 6. Display of bonds and pressure

3 RESULTS AND DISCUSSION

The left side of Fig. 7 – Fig. 12 shows the individual stresses that arise upon exposure to pressure. The right side of these figures shows the displacements occurring during the mechanism's movement. The results are evaluated according to a given colour scale. Red represents the highest degree of stress and displacement. Blue indicates parts without stress or displacement. The resulting images in the simulation were taken at the time when the mechanism was fully locked under the checked arm. The 1st option has been made with all the elements accounted for, i.e., its design includes a notch on the arm and also a groove on the arc of the mechanism. Fig. 7 and Fig. 8 show the observed effect of these elements on the mechanism.

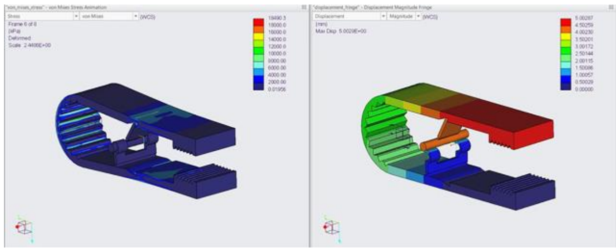

Figure 7. Simulation results – 1st option, PLA material

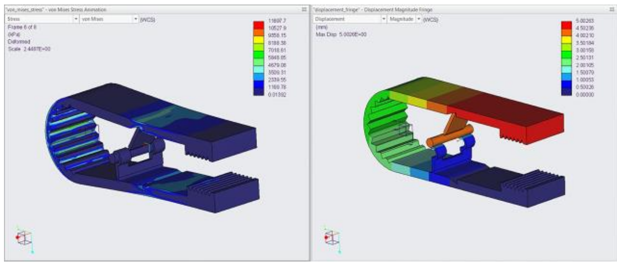

Figure 8. Simulation results – 1st option, PET-G material

It can be observed from the colour scale that the highest stress rate for PET-G material is 11 697,7 kPa, while in simulation of the mechanism made of PLA material, the stress value reaches 18 490,3 kPa. This indicates that it is possible to reduce the generated stress values through the use of the material. Using the colour scale and the places indicated in the picture, the most stressed zones were found. In both cases, these zones are located at the apex of the groove triangle. In Option 2, the notch was removed from the mechanism's arm. The effect of notch removal on the stress generated in the part can be seen in Fig. 9 and Fig. 10.

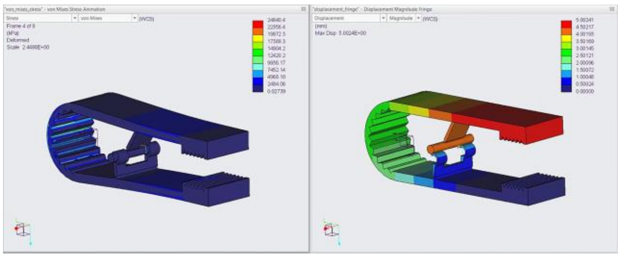

Figure 9. Simulation results – 2nd option, PLA material

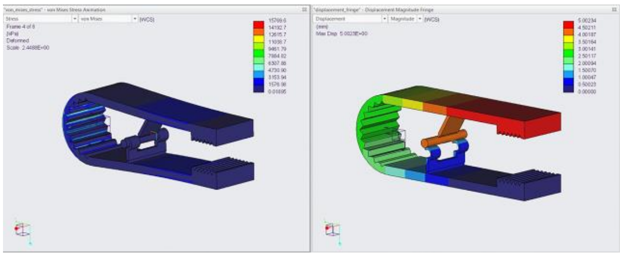

Figure 10. Simulation results – 2nd option, PET-G material

In the design of the 3rd option, changes were made by removing the grooves on the arc of the mechanism. The results of the simulation can be seen in Fig. 11 and Fig. 12.

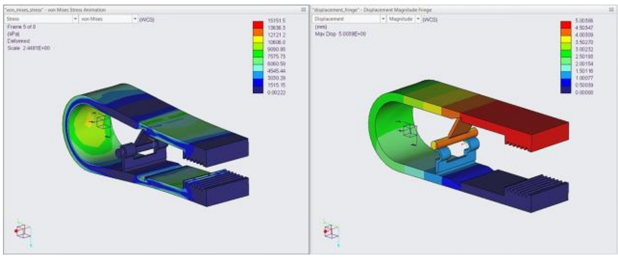

Figure 11. Simulation results – 3rd option, PLA material

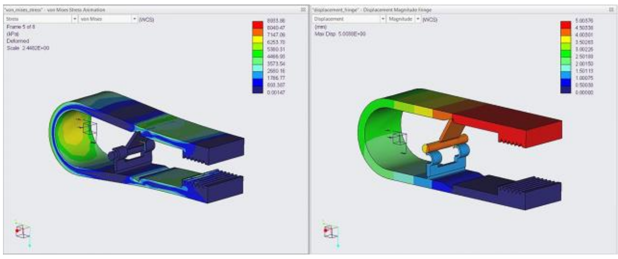

Figure 12. Simulation results – 3rd option, PET-G material

With this option, it can be noticed that the mechanism is, compared to the previous two options, fully locked only in frame 5 from 8 frames. This suggests that the grooves on the mechanisms arc affected its locking. As was the case with the previous mechanisms here, too, can be seen that the highest stress value of the PET-G material is 8 933,86 kPa, i.e., it is lower than in the PLA material, the stress value of which is 15 151,5 kPa. The reduction in stress is due to the removal of part of the highest stress generation, i.e., the gearing on the mechanism arc. In the 1st option, the highest stress value of 18 490 kPa is observed for the PLA material. The stress rate for the PLA material in the second option is 24 840 kPa. The value of the 2nd option thus shows an obvious increase in stress for PLA material and also PET-G compared to the 1st option. It is also possible to notice differences in the results on the distribution of stress on the arm. While in the 1st option the stress is partly concentrated on the notch, in the 2nd option the entire stress is distributed on the mechanism arm Fig. 13.

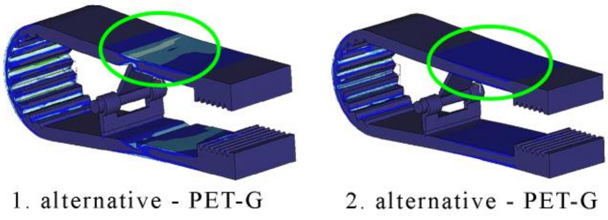

Figure 13. Notch stress concentration

Removal of the notch and distribution of force on the arm resulted in an even greater generation of stress on the groove. Fig. 14 shows the point of greatest stress where the zone of action is coloured in red.

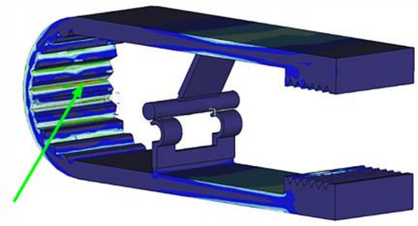

Figure 14. Comparing changes in stress

The stress distribution results show that the removed groove has the effect of generating a larger stress zone on the mechanisms arm. Fig. 15 shows the differences in stress distribution on the arm.

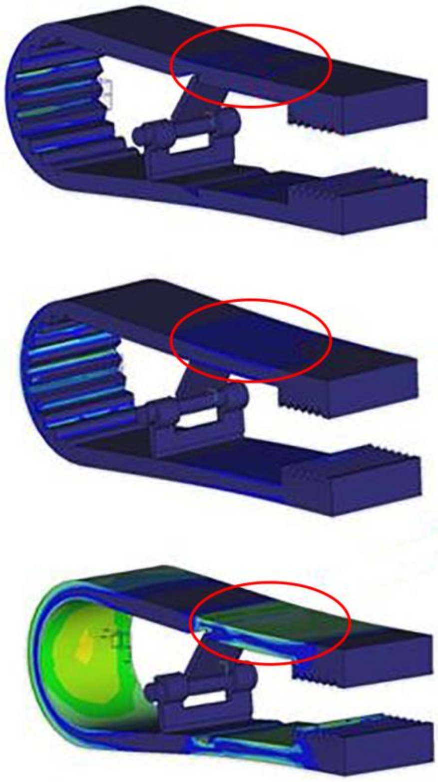

Figure 15. Stress distribution on the frame

Fig. 16 shows the individual bending mechanisms created by FDM technology. Two different types of plastics were used to print the bending mechanisms, namely PLA and PET-G. In practice, the individual bending mechanisms are used for clamping construction templates in the production of wooden doors and their frames.

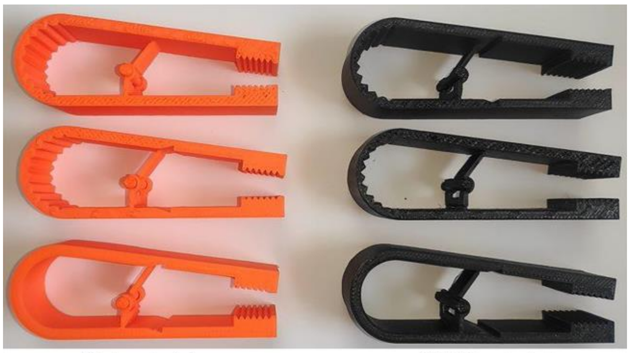

Figure 16. Locked bending mechanisms

Due to better clarity of the obtained results, the individual stress and displacement results for each alternative and material are shown in Tab. 2.

	1. alternative		2. alternative		3. alternative	
	PLA	PET-G	PLA	PET-G	PLA	PET-G
Stress (kPa)	18490,3	11697,7	24840,4	15769,6	15151,5	8933,86
Displacement (mm)	5,00287	5,00263	5,00241	5,00234	5,00386	5,00376

Table 2. Results of individual measurements

4 CONCLUSIONS

The article points out aspects affecting functionality of bending mechanisms, their complexity, and the extent of knowledge that the designer must apply when designing the mechanism so that the proposed mechanism can be used in practice. The designer must, therefore, design the mechanism in such a way that it has sufficient flexibility and, at the same time, strength of the bending member and that it does not get damaged, deformed, cracked, or change the accuracy of the required movement during its operation. The present article discussed the functionality of bending mechanisms in greater detail, as well as the basic rules the designer must follow. The practical part of the paper presented a specific proposal of the mechanism on which the simulation was performed in the CAD program PTC Creo Parametric. Using the simulation, the places of the highest stress generation in the mechanism were determined, which were evaluated using a colour scale. The work pointed out the differences in stress generation when using PLA and PET-G material, which can be utilized to select a suitable material for production. The effect of the mechanism's modification on its functionality and bending has been demonstrated. The expected growth of the use of bending mechanisms in the future gains relevance with the improvement of software analysis of the mechanism's behaviour and the subsequent possibility of rapid prototyping. There is also a constant progress in materials research. In future research, we plan to produce the same alternatives to the individual bending mechanisms from various plastic materials. The research will be extended to porous structures. This means that the internal volume of the individual components will be filled with different porous structures with different volume ratios. It will be interesting to observe how the stress on individual components changes with different volume ratio and different porous structures. We would like to achieve material savings while maintaining the mechanical properties of the individual alternatives and then progress in the study of porous structures can also have a positive impact on the design and usability of bending mechanisms.

ACKNOWLEDGMENTS

The authors thank the Ministry of education of Slovak Republic for supporting this research by the grant KEGA no. 038TUKE-4/2021, VEGA no. 1/0051/20 and project APVV-18-0316.

REFERENCES

[Billah 2020] Billah, K.M.M., Lorenzana, F.A.R., Martinez, N.L., Wicker, R.B., Espalin, D. Thermomechanical characterization of short carbon fibre and short glass fibre-reinforced ABS used in large format additive manufacturing. Additive Manufacturing, 2020, Vol. 35, 101299. https://doi.org/10.1016/j.addma.2020.101299.

[Angelo 2020] Angelo, L., Di Stefano, P., Dolatnezhadsomarin, A., Guardiani, E., Khorram, E. A reliable build orientation optimization method in additive manufacturing: the application to FDM technology. International Journal of Advanced Manufacturing Technology, 2020, Vol. 108, pp. 263-276. https://doi.org/10.1007/s00170-020-05359-x.

[Durgashyam 2019] Durgashyam, K., Indra Reddy, M., Balakrishna, A., Satyanarayana, K. Experimental investigation on mechanical properties of PETG material processed by fused deposition modeling method. Materials Today: Proceedings, 2019, Vol. 18, pp. 2052-2059. https://doi.org/10.1016/j.matpr.2019.06.082.

[Farah 2016] Farah, S., Anderson, D.G., Langer, R. Physical and mechanical properties of PLA, and their functions in widespread applications - A comprehensive review. Advanced Drug Delivery Reviews, 2016, Vol. 107, pp. 367-392. https://doi.org/10.1016/j.addr.2016.06.012.

[Harshitha 2019] Harshitha, V., Rao, S.S. Design and analysis of ISO standard bolt and nut in FDM 3D printer using PLA and ABS materials. Materials Today: Proceedings, 2019, Vol. 19, pp. 583-588. https://doi.org/10.1016/j.matpr.2019.07.737.

[Liu 2019] Liu, D., Zuo, J., Wang, J., Li, P., Duan, K., Zhang, D., Guo, S. Bending failure mechanism and strengthening of concrete-filled steel tubular support. Engineering Structures, 2019, Vol. 198, 109449. https://doi.org/10.1016/j.engstruct.2019.109449.

[Nam 2020] Nam, J., Jo, N., Kim, J.S., Lee, S.W. Development of a health monitoring and diagnosis framework for fused deposition modeling process based on a machine learning algorithm. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2020, Vol. 234, pp. 324-332. https://doi.org/10.1177/0954405419855224.

[Nguyen 2020] Nguyen, D.M., et al. Synergistic influences of stearic acid coating and recycled PET microfibres on the enhanced properties of composite materials. Materials, 2020, Vol. 13, pp. 1-16. https://doi.org/10.3390/ma13061461.

[Pandis 2019] Pandis, P.K., Papaioannou, S., Koukou, M.K., Vrachopoulos, M.G., Stathopoulos, V.N. Differential scanning calorimetry based evaluation of 3D printed PLA for phase change materials encapsulation or as container material of heat storage tanks. Energy

Procedia, 2019, Vol. 161, pp. 429-437. https://doi.org/10.1016/j.egypro.2019.02.088.

[Ponsuriyaprakash 2020] Ponsuriyaprakash, S., Udhayakumar, P., Pandiyarajan, R. Experimental Investigation of ABS Matrix and Cellulose Fibre Reinforced Polymer Composite Materials. Journal of Natural Fibres, 2020, pp. 1-12. doi.org/10.1080/15440478.2020.1841065.

[Shanmugam 2021] Shanmugam, V., et al. Fatigue behaviour of FDM-3D printed polymers, polymeric composites and architected cellular materials. International Journal of Fatigue, 2021, Vol. 143, 106007. https://doi.org/10.1016/j.ijfatigue.2020.106007.

[Wang 2019] Wang, L., Liu, X., Saleemi, S., Zhang, Y., Qiu, Y., Xu, F. Bending properties and failure mechanisms of three-dimensional hybrid woven spacer composites with glass and carbon fibres. Textile Research Journal, 2019, Vol. 89, pp. 4502-4511. https://doi.org/10.1177/0040517519837730.

[Xu 2020] Xu, S., Huang, J., Liu, J., Ma, Y. Topology optimization for FDM parts considering the hybrid deposition path pattern. Micromachines, 2020, Vol. 11, pp. 1-22. https://doi.org/10.3390/mi11080709.

[Zhang 2019] Zhang, B., Liao, Z., Yang, P., Liao, H. Robotic visible forceps manipulator with a novel linkage bending mechanism. Journal of Mechanisms and Robotics, 2019, Vol. 11. https://doi.org/10.1115/1.4041941.

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