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***A. Rakishev[1], B. Donenbayev[2], K. R. Jamaludin[3]***
[1,2]Abylkas Saginov Karaganda Technical University,
Republic of Kazakhstan, Karaganda;
[3]Universiti Teknologi Malaysia, Malaysia, Kuala Lumpur;
*e-mail: a.rakishev@kstu.kz

## *STUDY OF THE MECHANICAL CHARACTERISTICS OF FDM (3D PRINTED) PARTS: EMPIRICAL AND COMPUTATIONAL METHODS*

*Fused deposition modelling, alternatively referred to as Fused Filament Fabrication, is an additive manufacturing technique that has garnered significant attention across various industries due to its diverse applications. This research investigates the ultimate tensile strength and elastic modulus of 3D-printed Polylactic acid samples, following the ISO-527-2-2012 standard. The mechanical performance of the created parts is considered from both experimental and computational points of view. The finite element method within the ANSYS environment was employed for computer-based load and strength calculations.*

*Tensile specimens are fabricated using the Fused deposition modelling approach. The experimental outcomes were utilised to derive all the essential engineering constants required for evaluating the mechanical behaviour. The validity of the theoretical model has been confirmed through a comprehensive comparison with a substantial volume of experimental data, exhibiting mean errors of approximately 1 %.*

*The objective of this research is to assess the effectiveness and efficacy of analytical models in predicting the structural and mechanical behaviour of components produced through fused deposition modelling.*

*Keywords: additive technology, fused deposition modelling (FDM), PLA, mechanical properties, analytical model.*

**Introduction**

Achieving optimal product quality and affordability, coupled with rapid production timelines and competitive pricing while adhering to safety standards and other benchmarks, is essential for maintaining competitiveness in the worldwide manufacturing arena. A crucial aspect of product development is the engineering design journey, beginning with requirement identification and culminating in a prototype primed for manufacturing. The industrial perspective has shifted from conventional product development approaches to additive technology, owing to the substantial capacity of additive manufacturing techniques to curtail product development cycles and expenses.

Additive technologies, commonly known as 3D printing, have demonstrated significant relevance and potential across various scientific disciplines. These technologies involve creating three-dimensional objects by adding material layer by layer, as opposed to traditional subtractive manufacturing methods that involve cutting away material from a solid block.

Additive technologies are extensively used in scientific research for rapid prototyping and iterative design. Scientists and researchers can quickly create physical models of complex structures, devices, or experimental setups, allowing them to visualise and test ideas more effectively. Also, additive technologies can fabricate intricate and complex geometries that are challenging or impossible to produce using traditional manufacturing methods. This is particularly valuable in fields such as aerospace, materials science, and nanotechnology. It should also be noted that 3D printing enhances science education by providing tangible, hands-on experiences. It enables students and the general public to interact with physical models, enhancing understanding and engagement in various scientific concepts. One of the main advantages Additive technologies are explored for sustainable practices, such as recycling plastics to create 3D printing filament and fabricating energy-efficient components. Overall, additive technologies have a broad and transformative impact on scientific research, offering innovative solutions across diverse disciplines and fostering new avenues for exploration and discovery.

There are seven categories of additive manufacturing (AM) processes [1]. These categories are based on the type of energy source and the materials used. Thus, parts can be printed using various additive manufacturing processes, including Material Extrusion, Photopolymerization, Jetting, Lamination, and other techniques. Each of these processes has its own unique characteristics, advantages, and limitations, making them suitable for different applications and industries. These processes offer a wide range of options for AM. As mentioned earlier each process has its own advantages, such as speed, accuracy, material compatibility, and post-processing requirements. The choice of which process to use depends on factors like the intended application, material requirements, part complexity, and production volume.

As technology continues to evolve, new AM processes and variations are being developed, expanding the possibilities for creating complex and functional parts through additive manufacturing. It's essential to stay up-to-date with the latest advancements in the field to make informed decisions about which process to use for a particular project [2].

Among AM processes Material Extrusion is an inexpensive, faster printing method and widely used technique. It is often referred to as Fused Deposition Modelling (FDM) or Fused Filament Fabrication (FFF). There are several reasons for its popularity, namely, accessibility and affordability, material variety, ease of use, build volume and scalability, diverse applications, post-processing options, open-source community. FDM uses a variety of thermoplastic materials that are extruded through a heated nozzle to build up layers and create 3D objects. The choice of material depends on the specific application, functional requirements, and desired properties of the final part. The mechanical properties of different Fused Deposition Modelling materials can vary significantly. Each material has its own set of strengths, weaknesses, and characteristics that make it suitable for specific applications.

This article uses Polylactic Acid (PLA) material as an example. PLA is a widespread and environmentally friendly bioplastic derived from renewable resources like cornstarch or sugarcane. It's easy to print, has low warping, and is suitable for a wide range of applications. The print material plays a key role in the mechanical properties of the manufactured part. This article proposes to conduct a study in order to determine the mechanical properties of parts manufactured by FDM and compare the results with a computer model. Currently, numerous studies have been made by different researchers [3-7]. Kumar and Singh [3] use multi-objective optimization to examine mechanical characteristics of PLA. The accepted mechanical properties of PLA were unified by optimising the FDM process parameters using Taguchi method. Croccolo et al. [8] compares obtained experimental data with an analytical model which was developed to predict the strength and the stiffness characteristics of FDM parts. Obtained model was compared with experimental and affirmed.

Current study investigates simulation models of specimens that previously were tested under different axial loads. Considering the works observed earlier, the relevance of the work is proved by the theoretical and practical significance of the topic.

**Materials and Methods**

This article mainly explores the mechanical properties of parts that are made using 3D printing. The experimental process includes samples made of polylactic acid, as was mentioned earlier a widely used material for FDM parts. The selected filament belongs to Filamentive and has a diameter of 2.85 mm in white colour. All samples were printed on an Ultimaker S5 printer with one nozzle. The nozzle was 0.8 mm in diameter. A Cura program was used to obtain the G-code. It is also known that print settings have an impact on part quality [9–11]. For this reason, all print parameters were constant for all samples. At the same time, past experience and recommendations from equipment producers were taken into account in order to set parameters. Sample density was set at 100 %.

The schematic diagram and dimensions of the samples were indicated in Figure 1. ISO-527-2-2012 standard was taken into consideration to prototype the 3D model of the tensile test specimens in the CAD software. The experiments were conducted on a Hounsfield-H10Ks universal testing machine with a capacity of 10 kN. The uniaxial test is one of the most commonly performed tests in the field of mechanical testing of materials. This test is designed to assess the mechanical properties of a material under different forces. It provides valuable information about how a material responds to applied loads, allowing it to determine various mechanical characteristics. This information is crucial for material selection, design, and ensuring the safety and reliability of various engineering applications.

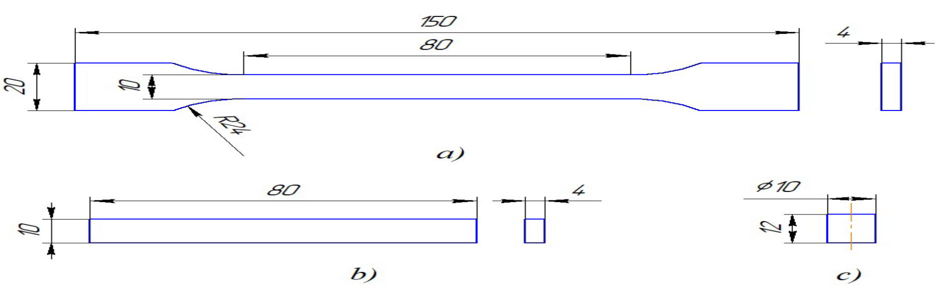


Figure 1 – Tensile specimen dimensions (mm)

In addition to the experimental model for strength assessment, a computer model was also built by means of the ANSYS program. Computer simulations can be utilised to predict and analyse the behaviour of material and structures under different conditions. This software program is based on the finite element method (FEM). The finite element method is a numerical technique used to solve complex engineering and mathematical problems by breaking down a continuous system into smaller, more manageable elements. However, it's important to note that the accuracy of the simulation heavily relies on the accuracy of the input data and assumptions made during the modelling process.

Calculation scheme of the sample outlined on Figure 2. One end of the part is rigidly fixed, the second end is subjected to a vertical tensile force of 2466 N.

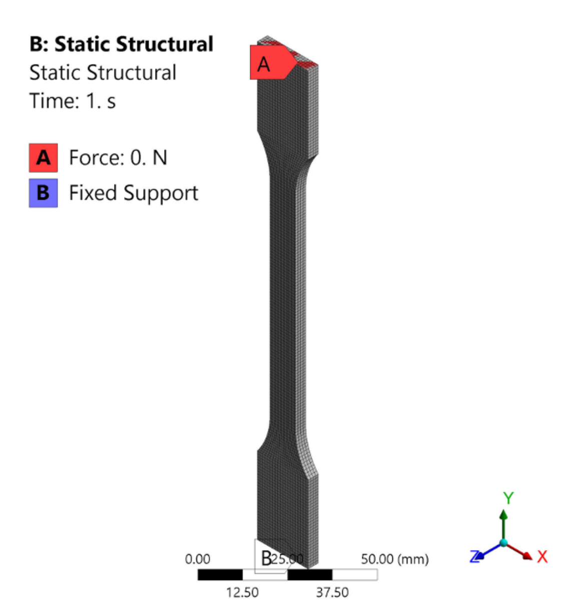


Figure 2 – Specimen boundary conditions for tension

Young's modulus was adopted on the basis of engineering tests of 5 samples and corresponds to the arithmetic mean. Other values of the boundary conditions are presented in Table 1.

Table 1 – Linear parameters of PLA specimens

| Young's Modulus, MPa | Poisson's Ratio | Bulk Modulus, MPa | Shear Modulus, MPa |
|---|---|---|---|
| 2964 | 0.3 | 2470 | 1140 |

**Result and Discussion**

The aim of this research is to assess the mechanical characteristics of components produced using the FDM technique through a combination of experimental and computational approaches. Tensile, flexural and compression loads were applied to the specimens in figure 1.

Figure 3 represents the tensile and flexural test results for the set of specimens investigated in this study. As indicated in this diagram, the specimens exhibit tensile strengths of 61, 62.5, 61.9, 61.9, and 61.5 MPa (with a standard deviation of 0.5 MPa). In this manner, it can be asserted that the trials are reliable.

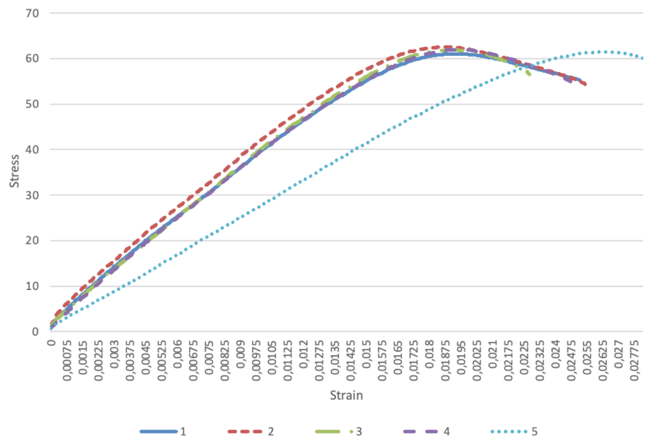


Figure 3 – Stress-strain curves for PLA samples

Additionally, the empirical results align with the values presented in previous studies conducted by other researchers [12, 13].

The numerical technique yielded a normal stress of 62.43 MPa along the Y-axis at the midpoint of the estimated sample length (Figure 4). Thus, the value of the numerical method slightly exceeds the arithmetic mean value of the stress obtained on the basis of the experiment on 0.67 MPa.

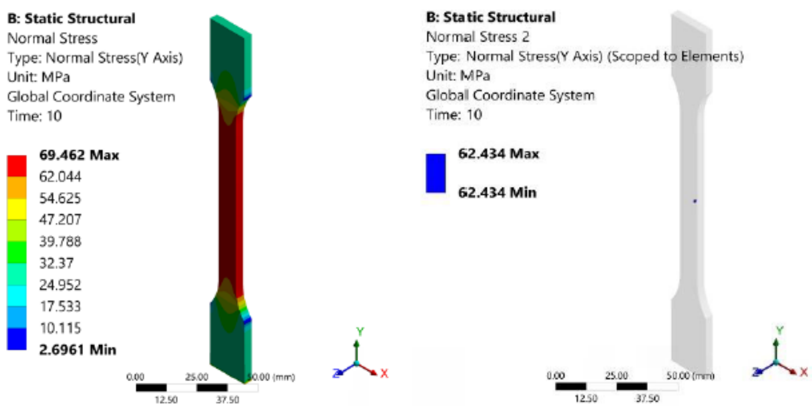


Figure 4 – Y-axis normal stress and its value at the midpoint of the estimated sample length

This problem was solved in a linear formulation, where Hooke's law is satisfied, and this is obvious from Figure 5. For evaluation purposes, we can determine the Young's Modulus utilising the following equation:

$$E = \frac{\delta_{comp}}{\varepsilon_{comp}} = \frac{62.434}{2.1064 \cdot 10^{-2}} = 2964\ MPa$$

As a result, the same average value is obtained, which was obtained empirically.

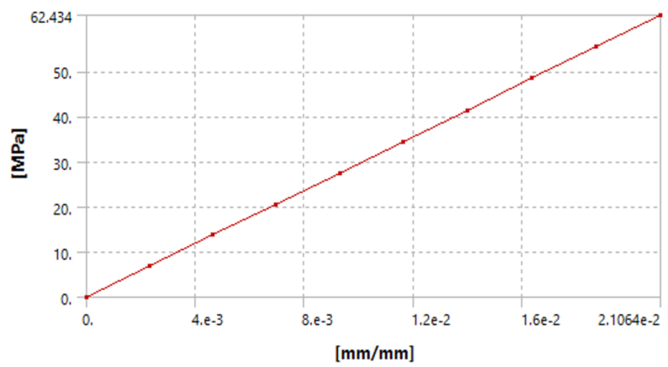


Figure 5 – Graph of stress versus relative longitudinal strain at the midpoint of a PLA sample

**Conclusions**

The primary outcome of the research paper revolves around the potential to forecast the mechanical characteristics of Fused Deposition modelled components through the utilisation of empirical data. Using experimentally derived mechanical attributes, a linear formulation was employed to conduct a numerical computation. The variance between the two techniques was negligible, constituting a mere 1 % disparity.

The suggested analytical model holds the potential to serve as a valuable instrument for FDM designers and manufacturers. Specifically, it can offer guidance in assessing attainable strength or stiffness by adjusting parameters related to the components.

Hence, it is feasible to employ analytical models for foreseeing the structural performance of FDM components or similar types of AM components, relying on material characteristics. As a result, these analytical models can support the 3D printing procedure, thereby mitigating the necessity for time-intensive and expensive conventional experimental methods.

REFERENCES

1 ISO/ASTM52900 Additive Manufacturing – General Principles – Terminology. West Conshohocken, PA: ASTM International; 2015.

2 **Parikh, H. H., Jadav, R., Joshi, P.** 3-D Printing: A Review of Manufacturing Methods, Materials, Scope and Challenges, and Applications//Lecture Notes in Mechanical Engineering, 2023 P. 243–256.

3 **Kumar, K., Singh, H.** Multi-Objective Optimization of Fused Deposition Modeling for Mechanical Properties of Biopolymer Parts Using the Grey-Taguchi Method//Chinese Journal of Mechanical Engineering. 2023. – 36:30

4 **Khalili, A., Kami, A., Abedini, V.** Tensile and Flexural Properties of 3D-Printed Polylactic Acid/Continuous Carbon Fiber Composite // Mechanics of Advanced Composite Structures 10. 2023. – 407 – 418.

5 **Cerda-Avila, S. N., Medellín-Castillo, H. I. and Lim, T.** Analytical models to estimate the structural behaviour of fused deposition modelling components//Rapid Prototyping Journal, 2021. – Vol. 27 № 4, P. 658–670.

6 **Cuan-Urquizo, E., Barocio, E., Tejada-Ortigoza, V., Pipes, R. B., Rodriguez, C. A., Roman-Flores, A.** Characterization of the Mechanical Properties of FFF Structures and Materials : A Review on the Experimental, Computational and Theoretical Approaches//Materials 2019, 12(6), 895.

7 **Bragaglia, M., Cecchini, F., Paleari, L., Ferrara, M., Rinaldi, M., Nanni, F.** Modeling the fracture behavior of 3D-printed PLA as a laminate composite : Influence of printing parameters on failure and mechanical properties // Composite Structures, Volume 322, 2023, 117379.

8 **Croccolo, D., De Agostinis, M., Olmi, G.** Experimental characterization and analytical modelling of the mechanical behaviour of fused deposition processed parts made of ABS-M30//Comput. Mater. Sci. 79, 506–518. – 2013.

9 **Xu, J., Xu, F., Gao, G.** The Effect of 3D Printing Process Parameters on the Mechanical Properties of PLA Parts//Journal of Physics: Conference Series, 2133 (2021) 012026, doi:10.1088/1742-6596/2133/1/012026.

10 **Chacón, J. M., Caminero, M. A., García-Plaza, E. and Núñez, P. J.** Additive manufacturing of PLA structures using fused deposition modelling: Effect of process parameters on mechanical properties and their optimal selection//Materials & Design, (2017) Volume 124, P.143–157.

11 **Chen, Y. K., Shi, T. C. and Zhang, J. H.** Influence of Printing Parameters on Properties of Fused Deposition Modeling ABS Samples Engineering Plastics Application, 2019. – 47. – 47–52.

12 **Laureto, J. J., Pearce, J. M.** Anisotropic mechanical property variance between ASTM D638-14 type i and type iv fused filament fabricated specimens. Polym. Test. 2018, 68, 294–301.

13 **Dobos, J., Hanon, M. M., Oldal, I.** Effect of infill density and pattern on the specific load capacity of FDM 3D-printed PLA multi-layer sandwich, J Polym Eng 2022. – 42(2), 118–128.

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***А. Ракишев[1], Б. Доненбаев[2], Х. Р. Джамалудин[3]**
[1,2]Әбілқас Сағынов атындағы Қарағанды техникалық университеті,
Қазақстан Республикасы, Қарағанды қ.;
[3]Малайзия технология университеті, Малайзия, Куала-Лумпур.
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## FDM (3D БАСЫЛҒАН) БӨЛШЕКТЕРІНІҢ МЕХАНИКАЛЫҚ СИПАТТАМАЛАРЫН ЗЕРТТЕУ: ЭМПИРИКАЛЫҚ ЖӘНЕ КОМПЬЮТЕРЛІК ӘДІСТЕР

*Балқытып тұндырумен үлгілеу, сонымен қатар жіпті балқытумен жасау әдісі, аддитивті өндіріс әдісі болып табылады. Әртүрлі пайдалану мүмкіндіктеріне байланысты өндірістің әр саласында үлкен қызығушылыққа ие. Бұл жұмыста ISO-527-2-2012 стандартына сәйкес 3 D басып шығарылған полилактикалық қышқыл (PLA) үлгілерінің созылу күші мен серпімділік модулі зерттеледі. Жасалған бөлшектердің механикалық сипаттамалары тәжірибелік жағынан да, есептелген жағынан да қарастырылады. Компьютердің жүктемесі мен беріктігін есептеу үшін ANSYS бағдарламасында соңғы элементтер әдісі қолданылды.*

*Тәжірибе үлгілері балқытып тұндыру тәсілі арқылы дайындалды. Тәжірибе нәтижелері механикалық сипаттамаларды бағалау үшін қажетті барлық негізгі инженерлік константаларды алу үшін пайдаланылды. Теориялық модельдің дұрыстығы шамамен 1 % орташа қателерді көрсететін эксперименттік деректердің мәнімен жан-жақты салыстыру арқылы расталды.*

*Бұл зерттеудің мақсаты балқытып тұндырумен үлгілеу арқылы алынған компоненттердің механикалық қасиетерін болжаудағы аналитикалық үлгінің тиімділігін бағалау болып табылады.*

*Кілтті сөздер: аддитивті технологиялар, балқытып тұндыру әдісі (FDM), PLA, механикалық қасиеттер, аналитикалық үлгі.*

***А. Ракишев[1], Б. Доненбаев[1], Х. Р. Джамалудин[2]**
[1,2]Карагандинский технический университет имени
Абылкаса Сагинова, Республика Казахстан, г. Караганда;
[3]Университеты технологий Малайзии, Малайзия, Куала-Лумпур.
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## ИССЛЕДОВАНИЕ МЕХАНИЧЕСКИХ ХАРАКТЕРИСТИК FDM ДЕТАЛЕЙ (3D ПЕЧАТИ): ЭМПИРИЧЕСКИЕ И КОМПЬЮТЕРНЫЕ МЕТОДЫ

*Моделирование с наплавлением, также называемое изготовлением наплавленных нитей, представляет собой метод аддитивного производства, который привлек значительное внимание в различных отраслях промышленности из-за его разнообразных применений. В этой работе* *исследуются предельная прочность на разрыв и модуль упругости образцов полимолочной кислоты (PLA), напечатанных на 3D-принтере, в соответствии со стандартом ISO-527-2-2012. Механические характеристики созданных деталей рассматриваются как с экспериментальной, так и с расчетной стороны. Метод конечных элементов в среде ANSYS использовался для компьютерных расчетов нагрузки и прочности.*

*Образцы для растяжения изготавливаются с использованием подхода моделирования наплавления. Экспериментальные результаты были использованы для получения всех основных инженерных констант, необходимых для оценки механического поведения. Обоснованность теоретической модели была подтверждена путем всестороннего сравнения со значительным объемом экспериментальных данных, демонстрирующих средние ошибки примерно 1 %.*

*Целью данного исследования является оценка эффективности и действенности аналитических моделей при прогнозировании структурного и механического поведения компонентов, полученных с помощью моделирования методом послойного наплавления.*

*Ключевые слова: аддитивные технологии, метод послойного наплавления (FDM), PLA, механические свойства, аналитическая модель.*

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67-36-69

e-mail: kereku@tou.edu.kz
nitk.tou.edu.kz