The influence of 3D-printing technological conditions on the performance properties of master models

A. Dvoryankin[1], *I.* Nefelov[1], and *N.* Baurova[1*]

[1]Moscow Automobile and Road Construction State Technical University (MADI), 64 Leningradsky Ave., 125319 Moscow, Russia

Abstract. The influence of 3D-printing technological conditions on the performance properties of master models has been investigated. It is shown that strength properties of master models depend significantly on two parameters: layer thickness and percentage of filling. Recommendations on the choice of 3D-printing conditions for manufacturing master models, as well as products based on master models, are presented.

1 Introduction

Additive technologies originated in the 1980s, but have become more widespread around the world in the last 10 years [1]. This pace of development has been facilitated by the use of additive technologies in various industries, such as engineering, medicine, aircraft and automotive industry, production of essential commodities, as well as the use of 3D printers for private use. As a rule, thermoplastic polymers are used as the main materials in 3D-printing technologies [2-5], however, papers where thermosetting material is the basis of polymer matrix have been published recently [6-11].

In mechanical engineering, additive technologies can be effectively combined with casting [1, 12, 13]. Casting is used for the production of both large and small parts. The production of parts by casting requires the observance of initially specified parameters as well as the consideration of processability and accuracy requirements of the part [1, 14].

Compared to traditional production methods, the use of casting combined with 3D-printing can significantly reduce labour input, cost, and the production cost of manufactured products [12, 15]. At the same time, in order to produce products that meet all the requirements of the consumer, 3D-printing methods should be carefully selected for casting technologies. There are 4 main methods of 3D-printing (Table 1).

Table 1. 3D-printing Methods and Their Features.

3D-printing Methods	Features
Binder Jetting	- The cladding sand is applied in layers, and each following layer is coated with a binder and sintered by laser. - This method reduces the cost and labour input in series production.

* Corresponding author: nbaurova@mail.ru

 https://doi.org/10.1051/e3sconf/202337601018

	- The high cost of equipment. - The manufactured moulds can be sent for metal pouring immediately after production. - Attachment of the method to a single material.
Selective Laser Sintering (SLS)	- The polystyrene is layer-by-layer sintered under the influence of the laser, until the original master model is obtained (at a temperature of 100 to 120°C). - It can be used to produce master models of the most complex geometric shapes and sizes. - The high cost of equipment. - The final models are highly durable and have a clean surface. - The master models for the casting mould are made separately.
Stereolithography	- The light-sensitive resin (photopolymer) cures under UV to form the specified 3D-model. - It can be used to produce master models with complex geometries. - Due to the emission of harmful substances from photopolymer resin, a protective, airtight box should be installed on the printer. - The final master model can be used as a standard product.
Fused Deposition Modeling	- ABS or PLA plastic melted at 180 to 220°C is applied to the contour of the part. - It can be used to produce master models of the most complex geometries and sizes. - Supporting material is used to avoid poor quality models. - Easy selection of printing material. - The quality of the master models is determined by the print mode.

Based on the literature review and previous studies, FDM technology has been identified as the most suitable for use in conjunction with casting because of the ease of producing master models for casting methods such as investment casting and burn-out casting, the models produced have high strength and surface purity [14-18].

However, for the production of the final parts and their application in the relevant industries, it is necessary to precisely set the parameters of 3D-printing at the initial stage. Therefore, in order to fully apply 3D technology with casting, it is necessary to determine the impact of 3D-printing modes on the quality and anti-adhesion properties of manufactured master models. This is the aim of the present study.

2 Methodology and results of experimental studies

Two dependent experiments were carried out to determine the best printing conditions.

The first experiment was aimed at selecting the print modes at which the finished master models would have the best strength.

GOST 4651-2014 "Plastics. Compression test method" was used to print three groups of samples, and in each group one of the parameters affecting the course of the 3D-printing process was changed.

Also, based on the literature review and previous studies, six following parameters that have the greatest impact on the quality of printed master models have been identified [13, 17]:

- Material. When starting the printing process, it is necessary to choose a material that meets the requirements for the final model. There are many types of ABS-plastic today and each has a weighty set of characteristics, ranging from melting point to environmental influences.

- Printing temperature. If the temperature is set too low, the plastic will not melt, quickly clogging the printer's nozzle and stopping the printing process. If the temperature is set too high the plastic will burn.

- Filling percentage. This parameter determines the strength of the model as well as the amount of material required for printing.

- Fill type. Depending on the model configuration, this parameter varies, as each model requires a different type of filling. In addition, correct selection of this parameter will prevent various types of deformation during printing.

- Layer thickness. This parameter affects the quality of the layer fusion. If it is set too high, the printed layer will take too long to harden, which may cause the model to pull away from the work surface when the next layer is applied, or shift the size of the model. If this setting is set too low, it will take longer time to print the model.

- Print speed. This parameter is the last one to be set as it is based on the selection of the previous parameters. For example, if a temperature is low, a filling percentage approaching 100% and a high layer thickness is selected, the minimum print speed will be set to fully sinter the applied layers.

In this paper, the experimental investigations varied the print layer thickness, filling percentage and print speed.

Initially, three groups of samples were made using a Magnum Creative 2Pro 3D-printer, with two parameters being fixed and one of the parameters being changed. As a result, in each group of samples, only one of the selected parameters was changed. Thus, 45 samples with a nominal size of 10x10x10mm were produced from ABS-plastic.

The obtained samples were cleaned of supporting materials after printing, and then were sent to the UTS-110M-50 universal machine for testing. Based on the compression results of 5 samples of each type (at a compression rate of 2 mm/min), the ultimate strength was determined by the arithmetic mean. The test results are presented in Table 2.

Table 2. Test Results on the Influence of 3D-printing Parameters on the Strength Properties of Samples.

Group No.	Test Results				
	Layer thickness. mm	**Percentage of filling.%**	**Print speed. mm/s**	**Absolutely compressive force. H**	**Tensile strength. MPa**
the1st sample group	0.06	100	45	7035.3	70.35
	0.12	100	45	6521.96	65.21
	0.2	100	45	6085.52	60.85
the 2nd sample group	0.06	80	45	5333.24	53.33
	0.06	60	45	4548.58	45.48
	0.06	40	45	3352.74	33.52
the 3rd sample group	0.06	100	15	6775.26	67.75
	0.06	100	30	7071.36	70.71
	0.06	100	60	6762.2	67.62

Based on the data obtained, it can be concluded that the strength properties of the master models are most significantly influenced by two parameters: the thickness of the layer and the percentage of filling.

It has been determined that the best 3D-printing parameters for master models are as follows:

- layer thickness - 0.06 mm;
- filling percentage - 40%, 60%, 80%, 100%;
- printing speed - 15 mm/s, 30 mm/s, 45 mm/s, 60 mm/s.

Further tests were conducted to determine the anti-adhesion resistance of the silicone materials traditionally used in the manufacture of master models and moisture resistance.

https://doi.org/10.1051/e3sconf/202337601018

Based on the results of the first stage, seven series of 30x30x10 mm nominal size samples were produced on a Magnum Creative 2 Pro 3D printer, using 3D Printer Filament ABS (Black) Strong with the best set of printing parameters determined in the first stage.

In order to determine the adhesion resistance, silicone material was applied to the samples, the silicon samples were kept at room temperature for 72 hours, weighed, and then the silicone layer was mechanically removed and weighed again.

At the final stage, after evaluating the anti-adhesion properties, tests were carried out to determine the moisture resistance of the specimens with residual unremoved silicone. After removal of the silicone layer, the samples were incubated for 90 days in sealed containers with water (the samples were completely immersed in water for the entire time), then dried for 48 hours and weighed again. The test results are shown in Table 3.

The samples of the first (100% filling, 45 mm/s print speed) and second (80% filling, 45 mm/s print speed) samples show a very slight increase in mass after the test.

The samples of the third (60% filling, 45 mm/s printing speed) and fourth (40% filling, 45 mm/s print speed) series after testing have the worst anti-adhesive properties and the greatest weight gain, which is explained by the swelling of silicone remaining in the pores of the sample in contact with water.

Samples of the fifth (100% filling percentage, 15 mm/s printing speed), sixth (100% filling percentage, 30 mm/s printing speed) and seventh (100% filling percentage, 60 mm/s printing speed) series after testing have fairly good anti-adhesive properties, but at the same time due to the increase in mass recorded satisfactory moisture resistance.

Table 3. Changes in Sample Mass Before and After Testing.

Series No.	Print modes			Sample mass before test. g	Sample mass after testing			Mass gain. %
	Layer thickness. mm	Filling. %	Print speed. mm/s		Before silicone removal	After silicone removal	After 90 days in water	
1	0.06	100	45	9.03	11.07	9.03	9.1	0.78
2	0.06	80	45	7.56	8.97	7.56	7.59	0.4
3	0.06	60	45	5.90	7.79	5.98	6.11	3.56
4	0.06	40	45	4.44	5.62	4.56	4.59	3.38
5	0.06	100	15	8.89	9.83	8.89	8.98	1.01
6	0.06	100	30	9.03	10.20	9.03	9.13	1.11
7	0.06	100	60	9.13	10.76	9.13	9.33	2.19

Thus, based on the anti-adhesion tests, it was determined that the samples with the lowest filling percentages (№3, №4, table 3) had high porosity, which subsequently led to poor ant-iadhesion properties and increased weight due to accumulation of silicone in the pores and inability to remove it mechanically later on.

3 Conclusion

Based on the data obtained, the best parameters for 3D-printing the master models were determined:

- layer thickness - 0.06 mm;
- filling percentage - at least 80%;
- print speed - not more than 45 mm/s.

Acknowledgments

The material was prepared under research project No. FFSFM-2020-0011, experimental studies were carried out using the equipment of the MADI Collaborative Use Centre.

References

1. V.A. Valetov, *Additive technologies (state and prospects). Study guide* (ITMO University, St. Petersburg, 2015)
2. A.S. Borodulin, A.N. Kalinnikov, IOP Conference Series: Materials Science and Engineering **709(2)**, 022038 (2020)
3. A.S. Borodulin, A. Kalinnikov, A. Kharaev, S. Shcherbin, IOP Conference Series: Materials Science and Engineering **302(1)**, 012062 (2019)
4. R.C. Bazheva, A.S. Borodulin, A.N. Kalinnikov, A.M. Charaev, IOP Conference Series: Materials Science and Engineering **683(1)**, 012051 (2019)
5. A.N. Kharaev, R.C. Bazheva, M.V. Begiexa et al, Polymer Science – Series D **12(1)**, 24-28 (2019)
6. E.O. Platonova, E. Vlasov et al, Journal of Applied Polymer Science **136(33)**, 47869 (2019)
7. I.V. Bessonov, M.N. Kopitsyna, A.V. Polezhaev et al, Polymer Science-Series D **9(1)**, 17-21 (2016)
8. L.P. Kobets, A.S. Borodulin, G.V. Malysheva, Fibre Chemistry **48(4)**, 311-315 (2016)
9. P.P. Maung, T.L. Htet, G.V. Malysheva, IOP Conference Series: Materials Science and Engineering **709(2)**, 022041 (2020)
10. C. Yanyan, V.A. Nelyub, G.V. Malysheva, Polymer Science-Series D **12(3)**, 296-299 (2019)
11. P.A. Belov, A.S. Borodulin, L.P. Kobets, G.V. Malysheva, Polymer Science-Series D **9(2)**, 205-208 (2016)
12. A.I. Rudskoy et al, *Additive technologies* (Publishing House of the Polytechnic Institute. un-ta, St. Petersburg, 2016)
13. V.A. Zorin, M.I. Timchenko, Mechanization of construction **79(1)**, 5-8 (2018)
14. K. Kun, *Reconstruction and Development of a 3D Printer Using FDM Technology*, URL: https://www.researchgate.net/publication/269474018 FDM 3D Printing Technology in Manufacturing Composite_Elements
15. J. Kang, *The role and impact of 3D printing technologies in casting*, URL: https://www.researchgate.net/publication/318176485 The role and impact of 3D printing technologies in casting
16. I.S. Nefelov, N.I. Baurova, Polymer Science – Series D **12(1)**, 77-79 (2019)
17. I.S. Nefelov, N.I. Baurova, Journal of Physics: Conference Series **1990(1)**, 012072 (2021)
18. A.I. Rudskoi, N.I. Baurova, Russian Metallurgy **13**, 1378-1383 (2019)