VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS
MECHANIKOS FAKULTETAS
POLIGRAFINIŲ MAŠINŲ KATEDRA

Edita Verbickaitė

3D SPAUSDINTŲ OBJEKTŲ GEOMETRINIŲ NUOKRYPIŲ TYRIMAS SPAUSDINANT FFF TECHNOLOGIJA
RESEARCH OF GEOMETRICAL DEVIATIONS IN 3D PRINTED OBJECTS PRINTED WITH FFF TECHNOLOGY

Baigiamasis magistro darbas

Spaudos inžinerijos studijų programa, valstybinis kodas 621H74001

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Spaudos būdas – medžiagos ekstruzija (FDM/FFF); medžiaga – poliaktidiniai polimerai (PLA). Pagrindiniai įtakos kriterijai: spausdinimo greitis, medžiagos ekstruzijos purkštuko skersmuo, temperatūriniai spausdinimo rėžimai.
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Kristaps Bumbulis, tecninės paramos pirkėjams vadybininkas, Mass Portal SIA, Pulka street 3/11, Riga, LV-1007

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Annotation

Fused filament fabrication (FFF) machines are increasingly being used by manufacturers and makers to produce parts for functional use. Apparently, the control of accuracy and surface finish quality becomes crucial for this technology. The goal of this study was to present an investigation of printing parameters on dimensional accuracy and determining the optimal surface finish of a part built by the Fused filament fabrication (FFF) process. Defined by the Design of Experiment (DOE) main factors for investigation were chosen: nozzle temperature (170°C and 230°C levels), feed-rate (50% and 100% levels) and nozzle diameter (from 0,25mm, 0,4mm, to 0,6mm). Experiments were conducted with these parameters and 12 test targets were printed and replicated. 2k statistic factorial design was used to analyze data and determine significant factors. Comparative analysis was used to verify geometrical and dimensional accuracy.

Keywords: Process improvement, 3D printer, Polylactic acid, dimensional accuracy, visual inspection, design of experiments.

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Pavadinimas **3D spausdintų objektų geometrinių nuokrypių tyrimas spausdinant FFF technologija.**
Autorius **Edita Verbickaitė**
Vadovas **Eugenijus Jurkonis**

Kalba: anglų

Anotacija

3D spausdinimas užima svarbią vietą šių laikų technologijų vystymesi. Šia technologija yra susidomėję ne tik gamybininkai, bet ir individualūs vartotojai, tačiau su detalių paviršiaus kokybe ir matmenų netikslumais susiduria abi žmonių grupės. Šio tyrimo pagrindinė idėja - ištirti šių, taip greitai augančių, technologijų tikslumą ir kokybę, atsispindinčią spausdintose detalėse. Tyrimas koncentruojamas į tiesioginio išpurškimo technologijas (FFF), polilaktinės rūgšties polimerą (PLA) ir spausdinimo parametrų efektą atspausdintų modelių paviršiaus kokybei ir geometrinių matmenų nuokrypiams. Tyrimo metu buvo panaudotas metodas, kuriuo pasirinkti parametrai buvo išskiriami į aukšto ir žemo lygius: purkštuko temperatūrą (170°C ir 230°C), spausdinimo greitį (50% ir 100%) ir purkštuko skersmenį (0,25mm, 0,4mm, 0,6mm). Dvylika tokio pačio dizaino spausdinių su pritaikytais skirtingais parametrais buvo atspausdinti ir dubliuoti. 2k statistinis faktorialinis metodas buvo pritaikytas išskirti didžiausią įtaką darančius parametrus. Lyginamoji analizė buvo atlikta siekiant ištirti atsiradusius geometrinius nuokrypius.

Prasminiai žodžiai: Proceso optimizavimas, 3D spausdintuvas, PLA, matmenų tikslumas, paviršiaus kokybės analizė, lyginamoji analizė

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Mano darbo vadovas doc. dr. Eugenijus Jurkonis.

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(Parašas)

Edita Verbickaitė
(Vardas ir pavardė)

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List of abbreviations

AM – Additive Manufacturing
FFF – Fused Filament Fabrication
FDM – Fused Deposition Modelling
MEM – Melt Extrusion Manufacturing
DOE – Design of Experiments
SLA - Stereolithography
CAD - Computer-Aided Design
CAM – Computer - Aided Manufacturing
3D – Three Dimensional
PLA - Polylactic acid
DIY – Do it yourself
STEM - Science,Technology, Engineering, and Mathematics
PA – Polymide
STL - StereoLithography
ABS - Acrylonitrile Butadiene Styrene
PET - Polyethylene Terephthalate
HIPS - High Impact Polystyrene
ASA - Acrylonitrile Styrene Acrylate

ABSTRACT

3D printing era has been rapidly growing over the last few years. Additive manufacturing technologies (AM) became irreplaceable in prototyping and parts manufacturing. AM technologies allow having unimaginable flexibility of geometric forms and structures. It helps to extend the capabilities of other technologies and connect several science fields into multidisciplinary process. Apparently, the control of accuracy and surface finish quality becomes crucial for this technology. Many studies have investigated how to obtain optimal parameters, better printer calibration process, how to evaluate quality of standardized test targets, and printing performance. Even though many studies have been done there are limitations due to lack of knowledge of main factors which influences printing process. Researchers are still trying to adopt benchmarking procedures due to replicability problem and eliminate dimensional inaccuracy. The goal of this research was to present an investigation of printing parameters on dimensional accuracy and determining the optimal surface finish of a part built by the Fused filament fabrication (FFF) process. Defined by the Design of Experiment (DoE) main factors for investigation were chosen: nozzle temperature (170°C and 230°C levels), feed-rate (50% and 100% levels) and nozzle diameter (from 0,25 mm, 0,4 mm, to 0,6 mm). A set of 12 test targets, obtained from combinations of selected parameters, were printed and replicated on a Rep-Rap Prusa i3 printer in PLA material. 2^k statistic factorial design and ANOVA were used to analyse data and determine significant factors. Comparative analysis and visual inspection were used to check surface finish quality. This master thesis shows how certain parameters affect geometrical and dimensional accuracy and surface finish. Statistic factorial method shows significant factors for test targets and the optimum settings are proposed.

Presentation of results

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Conferences and published work

Edita Verbickaite, Jurkonis, E., Sviackevicius, P., *RESEARCH OF 3D PRINTED OBJECT DIMIENSIONS INFLUENCE ON SURFACE PRECISION,* Scientific-practical conference” Innovations in publishing, printing and multimedia technologies 2016”. Collection of articles. 90-95psl. ISSN 2029-4638, Kaunas, held on 14 April 2016.

1. REVIEW OF LITERATURE

1.1 Growth of 3D printing industry

Over the past decade, additive manufacturing has been taking a huge place in world's production market. It is interesting to see how new firms, which include some of the world's biggest companies, as well as new start-ups, are shaping the industry. Compared to last year, new faces led the industry pack, like EOS and Envision TEC were GE Aviation, HP, Carbon, Mark forged and Additive Industries. Yet do not need to forget the mayor players of this industry like Stratasys and 3D Systems. All of them taking care of different sectors and trying to bring additive manufacturing into new level. For example, 3D systems announced the expansion in such fields like jewelry, dental and industrial casting markets. Stratasys operates in the healthcare, aerospace, automotive and education markets. Organovo is know as company, which uses 3D bio printing technology, and create three-dimensional functional human tissues for medical research and surgical and therapeutic applications [30]. As Wohlers Associated pointed out "This wave of development and commercialization is putting pressure on the established producers of AM systems" [39].

However, it's need to mention, that since the expiration of some critical patents of fused deposition modelling (FDM) there is rapid growth in open source 3-D printer movement caused by RepRap. Low cost 3D printers have filled the market when fused filament fabrication (FFF) term had appeared. Technology became not just attractive, but affordable to makers, small businesses, schools and universities. Do-it-yourself (DIY) projects, hobbies and educational activities at schools has received much more attention. One of the biggest impacts of low-cost 3D printers is in the particular Science, Technology, Engineering and Mathematics (STEM) education. Small businesses are engaging in bringing 3D printing capabilities to educational institutions. As it seems the future workforce would bring outstanding outcomes because small businesses have implemented 3D printing in current education [18].

Resent survey such The State of 3D Printing 2016 (Sculpteo, 2016) shows specific analysis of 3D printing fields. More than 1000 professional respondents from 53 different countries across Europe (55%), United States (39%), (5.1%), and Africa (1%) were questioned online. People from 19 different industries, across consumer goods, industrial products, high-tech, services, entertainment, and electronics. Survey shows that dominant material in 2016 for 3D Printing is plastics, attributable to demand for low cost parts production and growing adoption of rapid prototyping. Of the many types of plastics available, polyamide (PA) is the most prevalent. Additional materials include resins (26%), metals (23%), multicolour/Sandstone (13%) and wax (8%).Fig.1 [6].

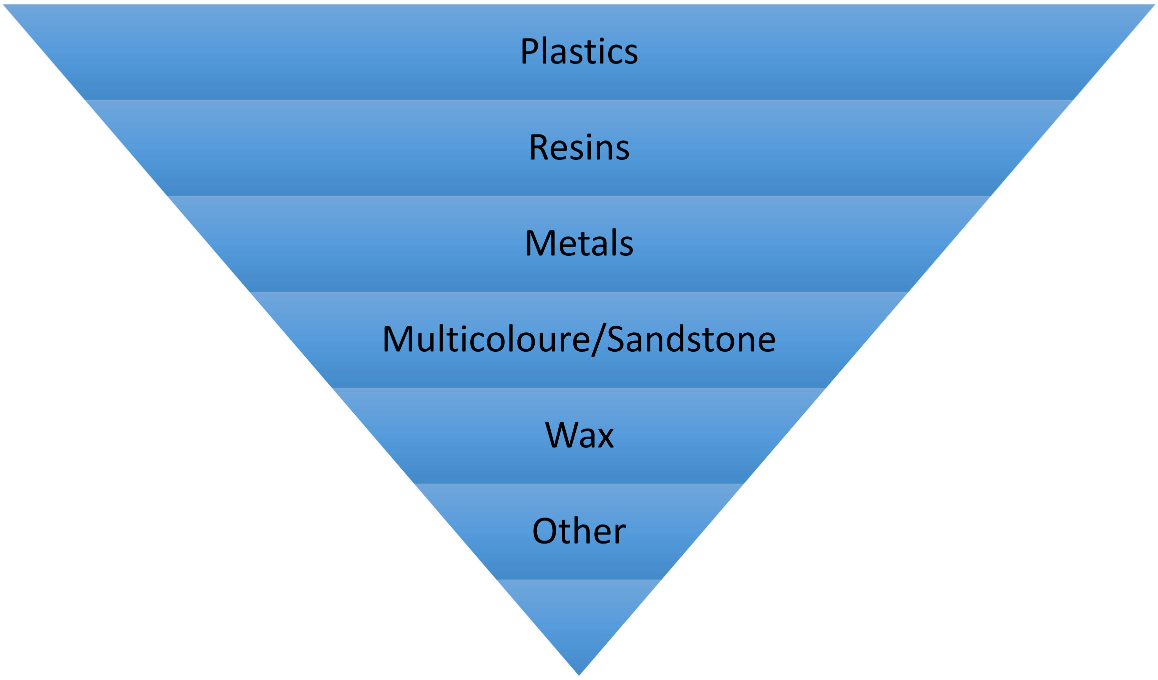


Fig. 1. Top 3D printing materials 2016

Previous survey is related to the very first survey of 3D printing community back then in 2012. People were ask what types of printers they have used. The half of the respondents used open source printers [21].

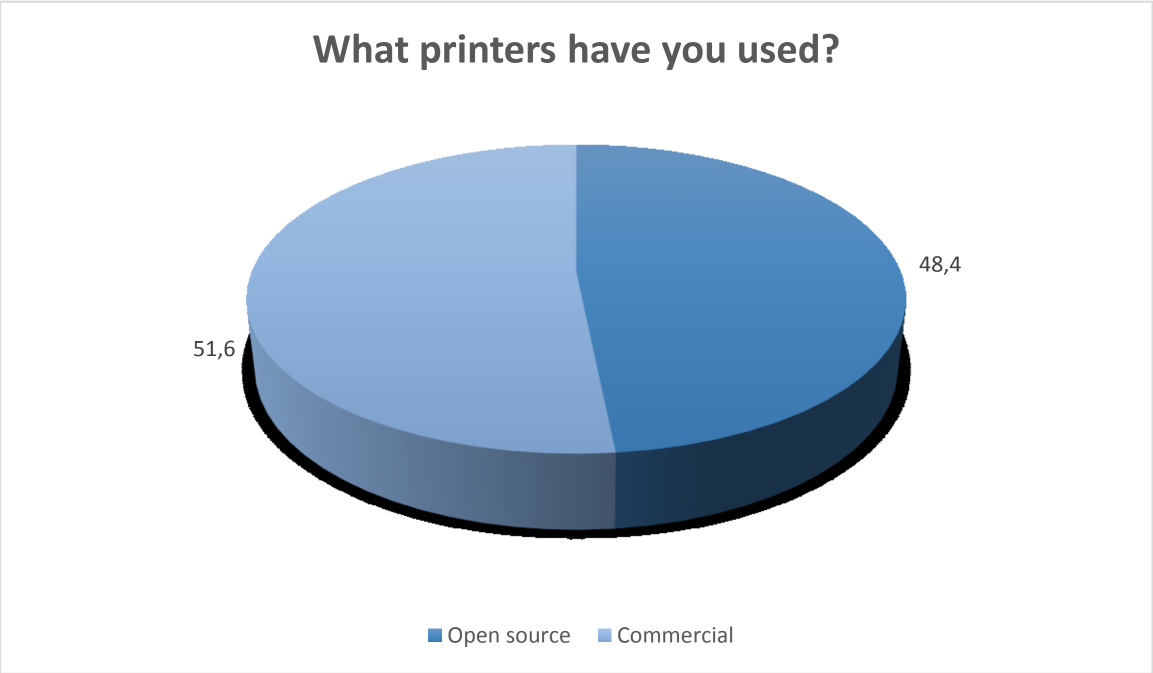


Fig. 2. First survey on the 3D printing community

It means that fused filament technology became available and affordable to more and more people. Even a few years ago, it was clear that open source 3D printers would play a big role in the future of the industry.

1.2 Additive manufacturing common principles

AM processes are revolutionizing traditional manufacturing methods and demonstrating its advantages in rapid, art-to-part capability for making high-value, complex, and individually customized parts. Additive processes showing abilities for making parts that are even more difficult or impossible to make with traditional production processes e.g., parts with complex geometries, engineered porosity, or lattice structures. Yet additive processes are having an inadequacy in part accuracy, surface finish, materials and material properties, process speed, and standards [34].

Nevertheless, additive manufacturing techniques are different depending on many mechanical, material, application factors, the basic approach can be adopt, which can be described as follows:

- The model or part is modelled with Computer-aided design (CAD) or Computer-aided manufacturing (CAM) systems. The model supposed to have closed curves to become a solid object. It is important for AM systems that model will have enclosed volume.
- The solid model or part is next converted to STL (Stereolithography) file format, which originated from 3D Systems and common to all AM technologies.
- A computer program as Slicer or other slicing program analysis the model converted into .STL file format and *slices* model into cross sections. Automatically adapting to solidification either liquids, powder or plastic and then combining to 3D model [5].

AM Unique Capabilities

The layer-by-layer based additive process of AM leads to unique capabilities in comparison with most other manufacturing processes. These days any kind of shape is virtually possible and it is a challenge to traditional manufacturing techniques. The need of complexity is increasing that is why additive manufacturing is taking a place and trying to fill it. Some of it is described below:

- Hierarchical complexity: features can be designed with shape complexity across multiple size scales.
- Functional complexity: functional devices (not just individual piece-parts) can be produced in one build.
- Material complexity: material can be processed one point, or one layer, at a time as a single material or as a combination of materials.

Looking into today's market complexity enabled production of end-use products or parts, but the prime importance here is material complexity of which applications are taking the advantage [12].

Classification

There are seven formulated categories of standards that classify the range of Additive Manufacturing processes. Made by American Society for Testing and Materials (ASTM) group "ASTM F42 – Additive Manufacturing" [26]. Most common classification is based on processes, which are in baseline technology such as lasers, printer technology, extrusion technology, etc. "The seven process categories are presented here:

- Vat photopolymerization: processes that utilize a liquid photopolymer that is contained in a vat and processed by selectively delivering energy to cure specific regions of a part cross-section.
- Powder bed fusion: processes that utilize a container filled with powder that is processed selectively using an energy source, most commonly a scanning laser or electron beam.
- Material extrusion: processes that deposit a material by extruding it through a nozzle, typically while scanning the nozzle in a pattern that produces a part cross-section.
- Material jetting: ink-jet printing processes.
- Binder jetting: processes where a binder is printed into a powder bed in order to form part cross-sections.
- Sheet lamination: processes that deposit a layer of material at a time, where the material is in sheet form.
- Directed energy deposition: processes that simultaneously deposit a material (usually powder or wire) and provide energy to process that material through a single deposition device" [12].

1.2.1 FFF technology

Fused filament fabrication or FFF technology is not common to hear or find between scientific researches. Even though it is equal to the term FDM, which is the most recognised and known in 3D printing industry. FDM is a trademark of Stratasys, Inc.the first company that patented the technology [8] and still remains the leading company in the world of extrusion AM systems [38]. Due to this trademark, manufacturers and makers of open-source systems have referred to this general process as "fused filament fabrication" or FFF [15]. It is difficult to keep up with technology development each day news things appear. For example MEM or melt extrusion manufacturing has been recently developed in China is similar to extrusion AM pioneers [14].

FFF working principle

FFF machines as FDM machines have extruder head with nozzle, which can be changeable in different diameters. The purpose of the nozzle is deposit-heated filaments. Some of these machines have multiple nozzles, which programed to extruded different material considering of the part structure, ones deposit part material others for support materials. All movements of extruder head are controlled with computer numerical control system. The extruder head is moved to the coordinates X/Y/Z positions for placing the material. The heated filament is pushed throw heated nozzle, but in smaller diameter. To force the filament out in precise amount the extruded uses torque and pinch system. Deposited material cools and solidifies on the model where the material is laid down. Printing layer-by-layer continuously until the part is fully built [7].

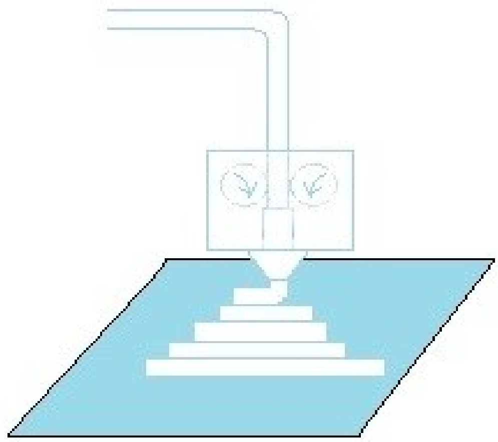


Fig. 3. FFF working principle

Limitations of FFF

FFF technology limitations are very similar to FDM. Build speed, accuracy, material density are main factors, which appears as disadvantage in using this technology. The actual produced shape is dependent on the nozzle, acceleration, and deceleration characteristics and the viscoelastic behaviour of the material as it solidifies [12].

1.2.2 Main parameters for FFF technology

It is unknown how many variable factors can influence printing process. Researchers are trying to investigate several or one at the printing time and compare results to broaden database. Most common are build parameters: the layer thickness, the raster angle and width, density, and the air gap. Ohers: print speed, layer thickness, and nozzle and platen temperature, cooling fan speed, infill densities and patterns. Here is discussed just two factors, which are taken into consideration in this master thesis.

The extrusion nozzle and its diameter defines the shape and size of extruded filament and smallest geometrical features, which can be produced. It is not possible to produce smaller features than nozzle diameter and have satisfactory strength. The pressure drop between the chamber and the surrounding atmosphere controls material flow through the nozzle. For understanding the process, it may be useful to see an example of the study about traditional screw-fed extrusion by Stevens and Covas [36]. Nozzle geometry, material viscosity and pressure drop describes the relation of mass flow through the nozzle. The temperature is prime factor for viscosity [12].

The speed of an extrusion system is dependable on two: the feed rate and the plotting speed. Feed rate made purpose to supply the material and the rate at which the liquefier can melt the material and feed it through the nozzle [12].

1.3 Mechanical limitations for part accuracy and quality

With understanding FFF technology, it is difficult to manage the accuracy of printed part. Resolution is a function systematically depending on the motors, which controls print head and how accurate the motor system is. The quality of the system design reflects to the quality of controlling algorithm and the print nozzle diameter. The model which is transported from CAD and building on the heating plate has limitations to its curvature because of limitation by the minimum step size of the stepper motors controlling x-y motion in the build plane [1] [2]. The width of a road is further limited by nozzle diameter and cannot be smaller than 1.2-1.5 times the size of the nozzle diameter [2]. This limitation is, at least, in part, due to die swelling of the melt, as it leaves the print nozzle, illustrated in Fig.4. Within the narrow nozzle opening, the melt is under stress, storing deformation material elastically. This stress is relaxed as the polymer leaves the nozzle, allowing release of the elastically stored energy resulting in radial expansion of the melt [19] Fig 4. Die swelling when the melt leaves the print nozzle and stresses are relaxed in radial expansion of the melt and limiting maximum resolution in an extrusion AM process [13].

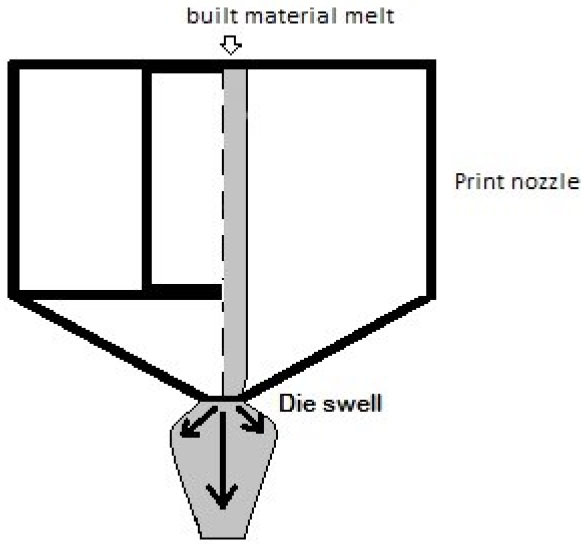


Fig. 4. Extrusion process through printing nozzle

Accuracy and resolution are, largely, a function of the ability accurately control the rate at which melted material leaves the deposition nozzle. Accounting for start, stop and acceleration or deceleration of the print head requires the ability to control the flow rate of material through the print Fig.5. Illustrating the extruded road with dimensional error appeared in the beginning and the end of the road. 1 - is the start of extrusion, 2 – under deposition acceleration print head, 3 – normal deposition/ steady print head velocity, 4 – over deposition decelerating print head, 5 – the end of the extrusion road.) [13].

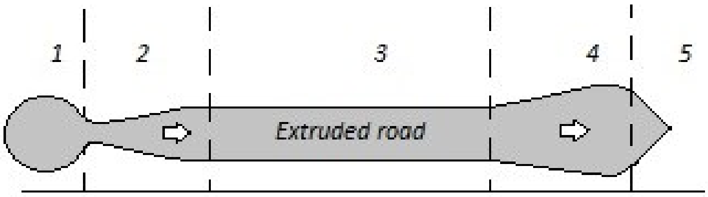


Fig. 5. Extruded road with dimensional errors

Sources of Inaccuracy

Material-dependent phenomena also play a role in accuracy, including shrinkage and residual stress-induced distortion. Repeatable shrinkage and distortion can be compensated by scaling the CAD model; however, predictive capabilities at present are not accurate enough to fully understand and compensate for variations in shrinkage and residual stresses that are scan pattern or geometry dependent. Quantitative understanding of the effects of process parameters, build style, part orientation, support structures, and other factors on the magnitude of shrinkage, residual stress, and distortion is necessary to enhance these predictive capabilities. In the meantime, for parts, which require a high degree of accuracy, extra material must be added to critical features, which is then removed via milling or other subtractive means to achieve the desired accuracy [12].

1.4 Test artefacts practiced in three-dimensional printing

To evaluate better machine performance and its processes need to use standardized test parts. There are several AM test part designs which were developed over past years. “Two types of methodologies for manufacturing metrology are used to evaluate the performance of a machine and/or a process: (1) through a series of direct measurements of machine and process characteristics, and (2) through measurements of manufactured test artefacts. A standardized test part mostly used for quantitatively evaluation. The comparison between different machines can be performed by producing the same standardized parts” [34].

Current artefacts

Benchmarking artefacts, as shown in Fig.6, are from previous researches and designed to test the limits of an individual AM process; within possibility of most suitable process and material combination. Artefact designers involve accuracy and repeatability of angled surface, geometric dimension in order to evaluate performance, such as form, accuracy, repeatability and surface finish.

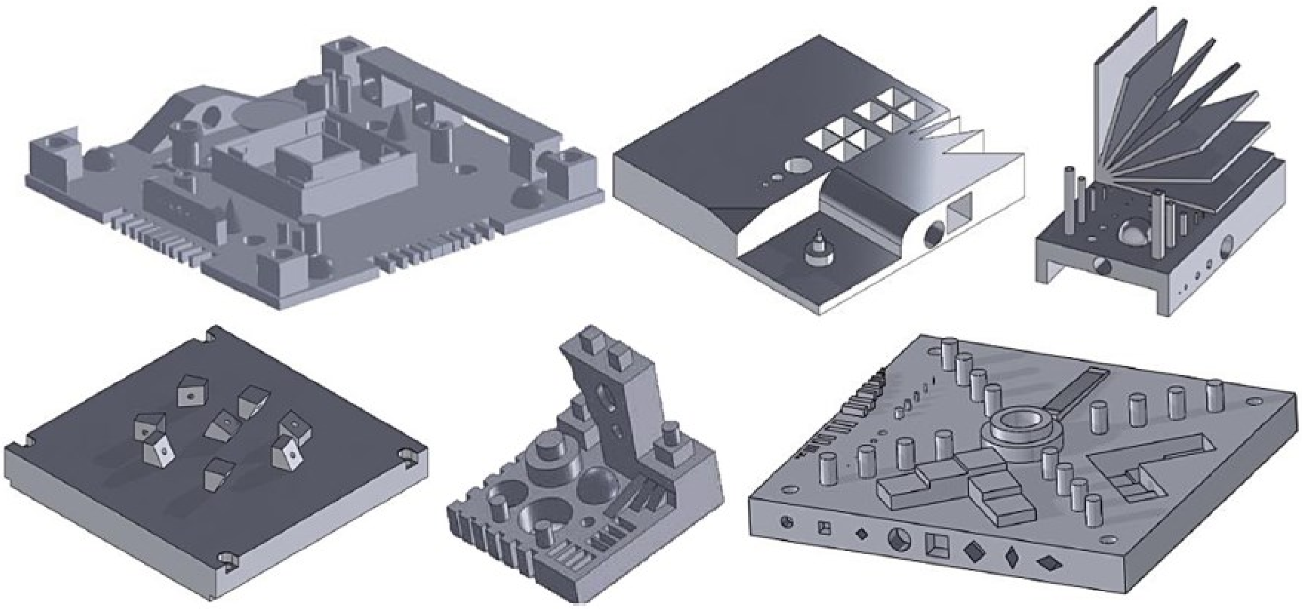


Fig. 6. Additive manufacturing test artefacts in order by (MaheshM, 2004) (Kruth J-P, 2005) (SantosEC, 2006) (Cavallini B) (W.Johnson, 2011) (S.Moylan, 2012).

AM benchmarking is classified in three different types as follows:

- Geometric Benchmark: used to measure the geometric features of a part (i.e. tolerances, accuracy, repeatability and surface finish).
- Mechanical Benchmark: used to analyse the mechanical properties (tensile strength, compressive strength, creep, etc).

- Process Benchmark: used to establish process related parameters (part orientation, support structures, layer thickness, speed, etc) [23].

Table 1. Geometric features and their intended purpose.

Feature	Purpose
Flat base	Flatness and straightness
Cube	Parallelism, linear accuracy and repeatability
Cylindrical hole	Roundness, cylindricity, accuracy and repeatability of radius (internal)
Sphere	Sphereness, relative accuracy and repeatability of a continuously changing sloping surface
Solid cylinder	Roundness, cylindricity, accuracy and repeatability of radius (external)
Hollow cylinder	Roundness, cylindricity and coaxially of cylinders
Cone	Sloping profile and taper
Angled surfaces	Angularity, accuracy and repeatability of angled surfaces

"Rules" for Test Artefacts

In early stage of SLA development, Richter and Jacobs defined an "ideal accuracy test part" to help provide better results in quantitative investigations. According to researchers, the standard test artefact would:

- be large enough to test the performance of the machine near the extremes of the platform as well
- be as near the centre,
- have a substantial number of small, medium, and large features,
- have both holes and bosses to aid in verifying beam width compensation,
- not take too long to build,
- not consume a large quantity of material,
- be easy to measure, and
- have many features of a "real" part (i.e., thin walls, flat surfaces, holes, etc.) [29].

Optimization methods

Shape optimization can be described as size optimization. Usually, bounding curves or surfaces are optimized to reach the similar geometrical objectives and constrains. For example, design variables are used such as positions of control vertices for curves or surfaces. Shape and size optimization are combined in order to optimize structures such as free-form shapes, also standard shapes (e.g., cylinders) with dimensions [12].

1.5 Research approach and experimental base

The research is based on *design of experiments* (DoE) method to understand effects and influence of main parameters to test target design, surface finish and obvious geometrical deviations. The discussion about basic principles, the strategy and guidelines for design experiment is needed due to understand the experimentation within this research. Also the Comparative or Benchmarking analysis based on dimensional comparisons of two or more comparable alternatives, processes, products, qualifications, sets of data, systems, or the like [10]. In this case, printed test targets dimensions and CAD model information are taken into consideration and the data of geometrical inaccuracy converted to deviations and have been visualized into graphs. Moreover, visual inspection is taking a serious part in this research, unlike the comparative analysis, at this section visible geometrical errors were analysed and compared.

1.5.1 DoE and factorial experiment

In order to evaluate the effect of the factors selected as well as any interaction effects between factors, mostly DoE approach is selected, when two levels associated with each factor. “Within the theory of optimization, an experiment is a series of tests in which the input variables are changed according to a given rule in order to identify the reason for the changes in the output response” [4].

Three basic principles of Statistical DoE:

Replication

- allows an estimate of experimental error
- allows for a more precise estimate of the sample mean value

Randomization

- cornerstone of all statistical methods
- “average out” effects of extraneous factors
- reduce bias and systematic errors

Blocking

- increases precision of experiment
- “factor out” variable not studied

In general, by using DoE, allows for researches to learn about the process which is investigated, screen important variables, build a mathematical model, obtain prediction equations, optimize the response (if required). Statistical significance is tested using ANOVA, and the prediction model is obtained using regression analysis. ANOVA is:" The one-way analysis of variance (ANOVA) is used to determine whether there are any statistically significant differences between the means of three or more independent (unrelated) groups" [24].

According to Montgomery, an experiment can have the following objectives:

- Determining which variables are most influential on the output (y) determining where to set the influential controllable factors (x) so that y is usually near the desired nominal value.
- Determining where to set the influential controllable factors (x) so that variability in y is small.
- Determining where to set the influential controllable factors (x) so that the effects of the uncontrollable variables z1, z2, …, zq are minimized [22].

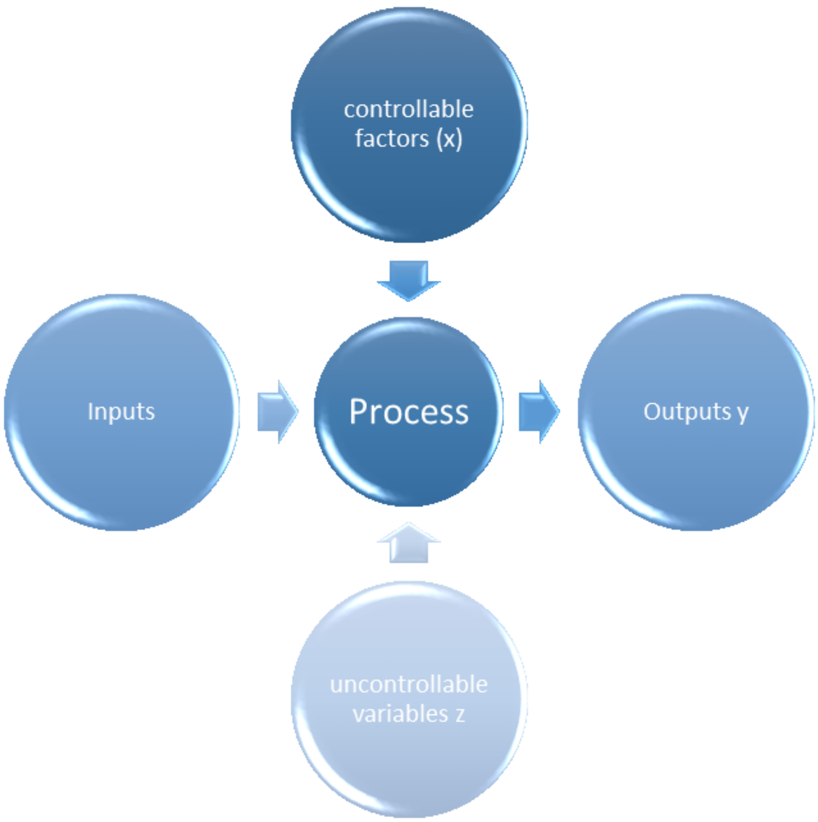


Fig. 7. General model of the process or system by (Montgomery, 2013)

Full factorial design is probably the most common and intuitive strategy of experimental design. In the most simple form, the two-level full factorial, there are k factors and L = 2 levels per factor. The samples are given by every possible combination of the factors values. Therefore, the sample size is N = 2k [4]. This approach compares both factor one's and two's level one results against each other and design of experiments the same for level two's approach. This design was selected for this research because it is shown to be best for experiments testing multiple factors.

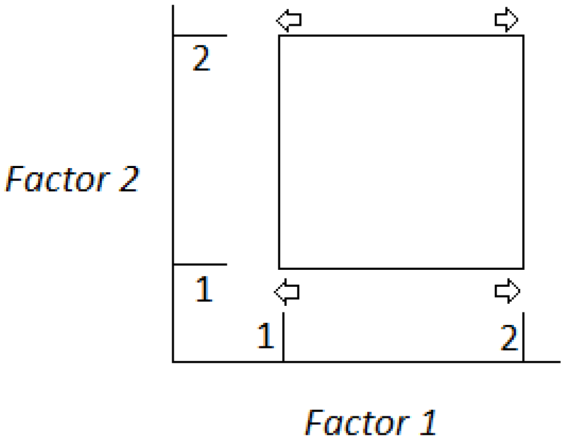


Fig. 9. Comparison of results leading to the factor 1 effect

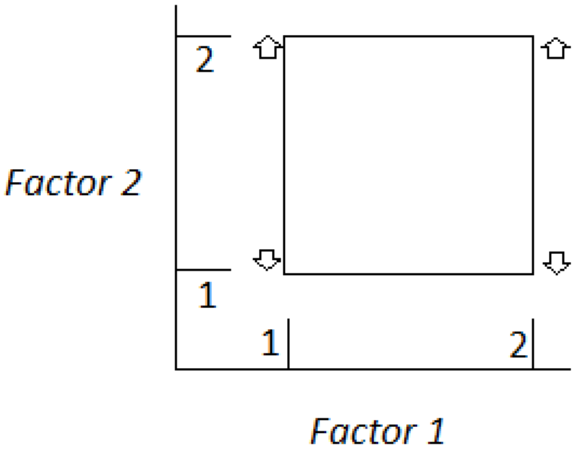


Fig. 8. Comparison of results leading to the factor 2 effect

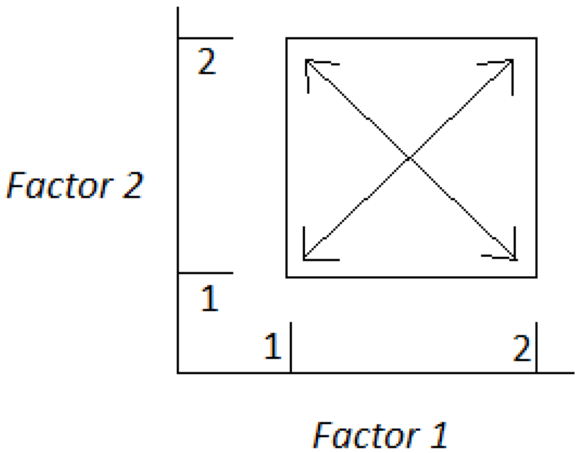


Fig. 10. Comparison of factors and their interaction

1.5.2 Schematic model of research

The set of guidelines is needed to every design experiment, also a well thought-out plan. Montgomery presents the guidelines below, which he encourages, researchers to follow in order to conduct properly designed experiments [22].

- Recognition of and statement of the problem
- Selection of the response variables
- Choice of factors, levels, and ranges
- Choice of experimental design
- Performing the experiment
- Statistical analysis of the data
- Conclusions and recommendations

Step-by-step scheme of the experiment is shown below:

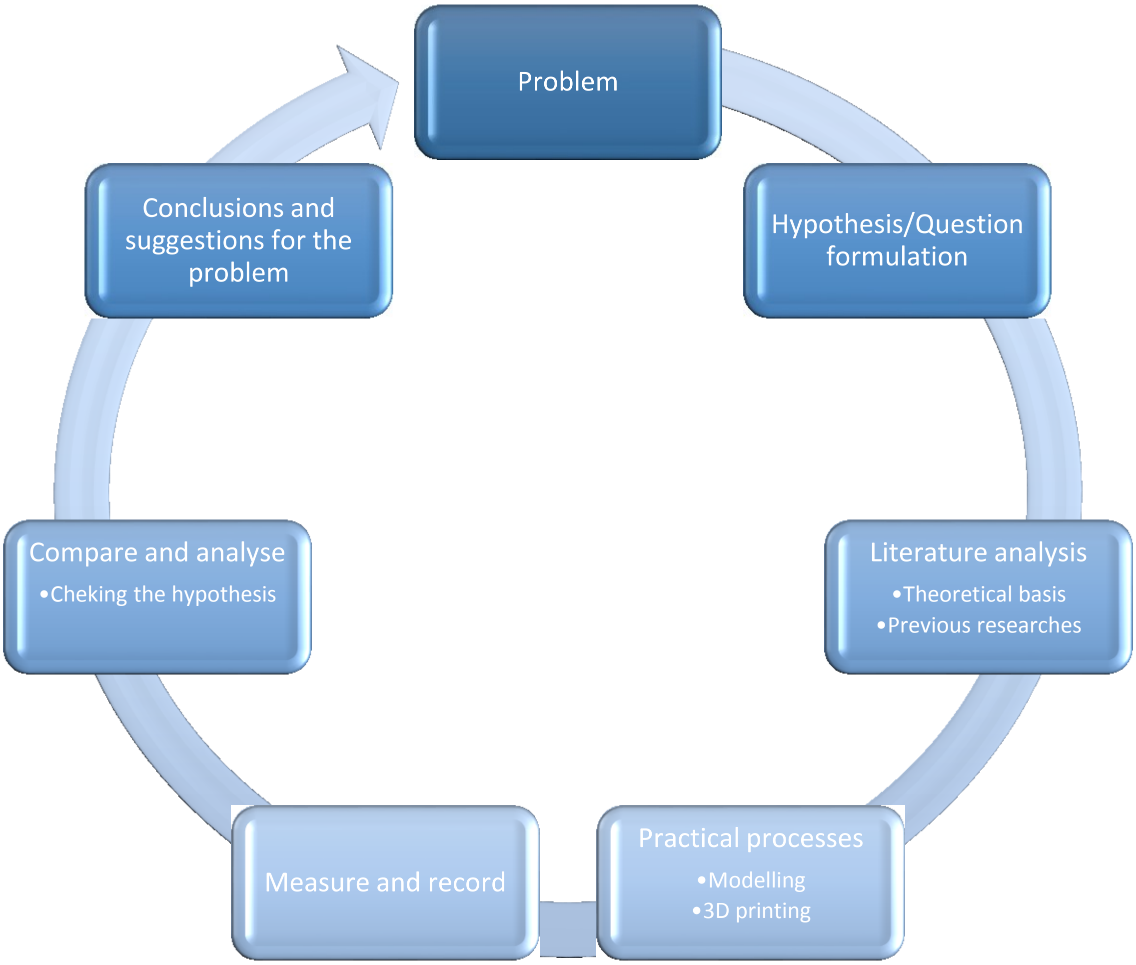


Fig. 11. Step-by-step experimental scheme

2. DESIGN AND REALIZATION OF EXPERIMENT

2.1 The statement of the problem and Research objective

Most of the researches are exploring complexity of geometrical shapes, new materials, and new mechanical solutions. Manufacturers and makers care about low cost and faster build speed. From scientific point of view, dimensional accuracy and finish surface quality have the prime importance, but still lack of knowledge in this field exists. Even makers need to know optimal parameter for the print parts that they could produce. Main factors, which is helping to solve surface quality and accuracy problems, are time, repetitive practice and records of the data. Additive manufacturing can take the advantage and use the replication principle to determine most common deviations and optimize the process.

The aim of thesis is to determine the optimum process parameters of open source, low cost 3D printers that can be used to print parts from PLA with both good surface finish and dimensional accuracy. Process parameters such as nozzle temperature, feed-rate, and nozzle diameter are taken into consideration. Specifically, this master thesis will attempt to answer the following questions:

- Does nozzle temperature effect dimensional accuracy and surface finish?
- Does feed-rate effect dimensional accuracy and surface finish?
- Does nozzle diameter effect dimensional accuracy and surface finish?

2.2 Research methodology

Reaching a success in scientific research multiple steps need to be done. The performance in investigation of FFF involves the modelling and fabricating of the test model. For this experiment FFF technology open-source 3D printer was used. The design of the test target is developed based on an objective to study the capability of FFF machine to produce the desired geometrical shapes. 24 test targets were built with different sets of printing parameters. PLA (Polylactic Acid) material was used in experiment. Environment temperature was 27˚C. As the flowchart Fig.12 below illustrates, the procedure was applied in the following steps and will be discussed in detail in the following sections:

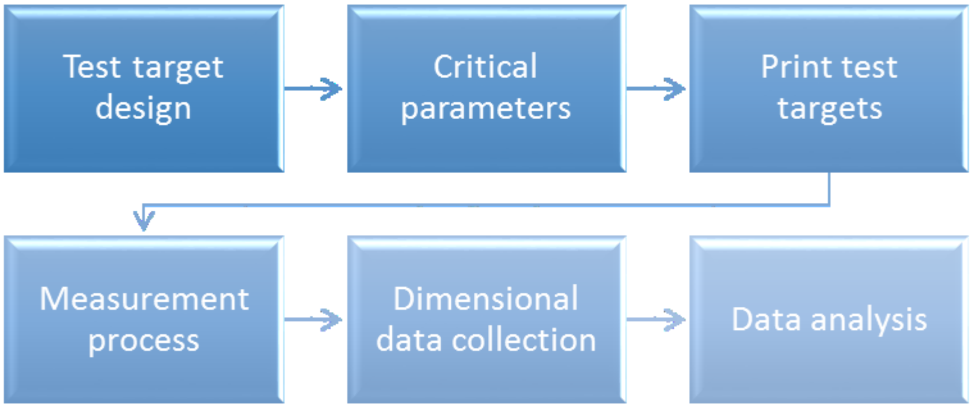


Fig. 12. Workflow of experimental procedures

2.3 Test target design and critical parameters

Due to primary master thesis goal to investigate the influence of nozzle temperature and feed-rate to dimensional accuracy and good surface finish, the rest of the parameters package were out of the experimental plan.

Firstly, test part Fig.13 was made by Solidworks2014 (3D computer-aided design (CAD)), has a variety of geometrical shapes and sizes that are common in our real life. All of them were made by following the standardized AM artefacts (Fig.6), which are shown in previous sectors.

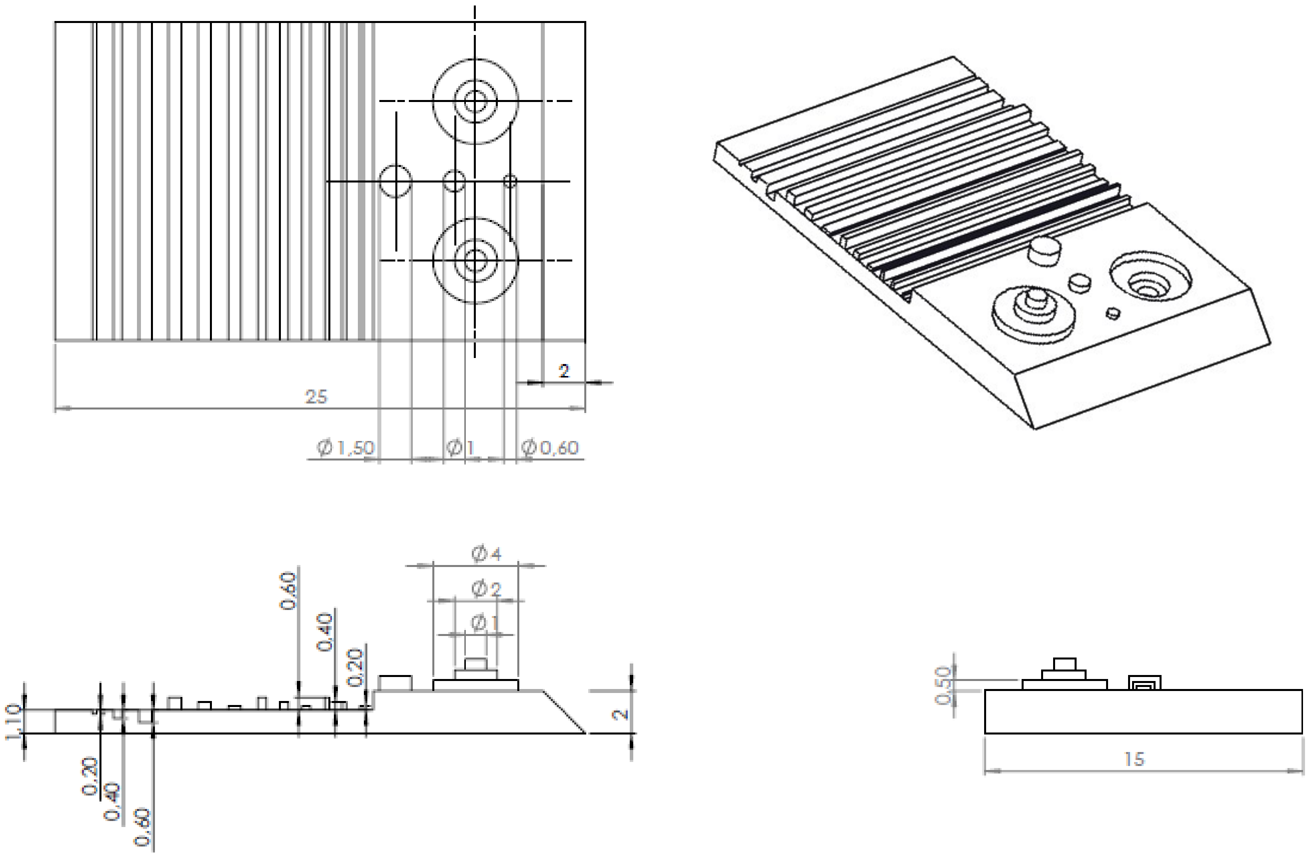


Fig. 13. Profiles of Test target for the experiment

Then CAD data was converted into standard triangular language (STL) format. Printed with a scale by 2 (Slicer program was used), due to capabilities of nozzle diameters for this experiment.

The variety of geometrical shapes and fundamental lines of the test target are marked in Solidworks 2014 environment:

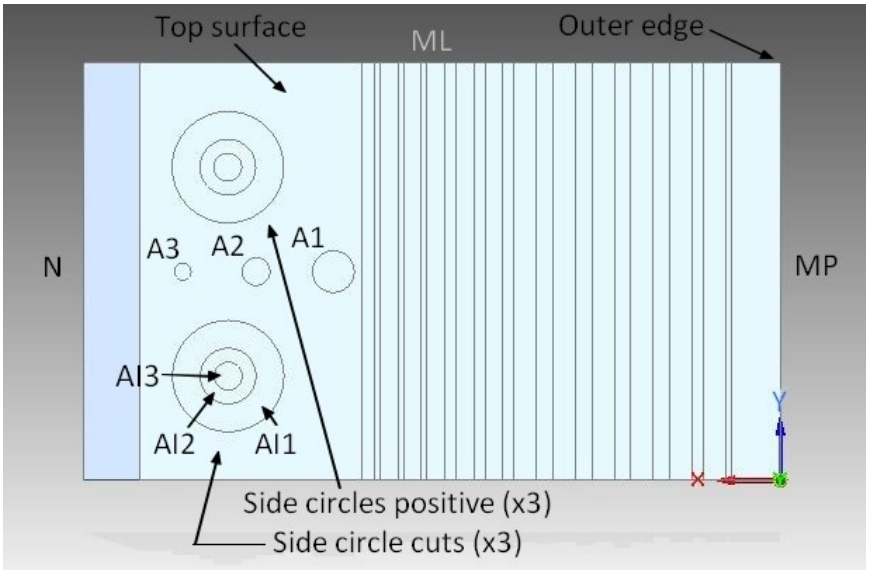


Fig. 14. Top view of test part

Features :

Facets(mm) N

Model length ML

Model width MP

Pins and circle cuts: A1, A2, A3, AI1, AI2, AI3

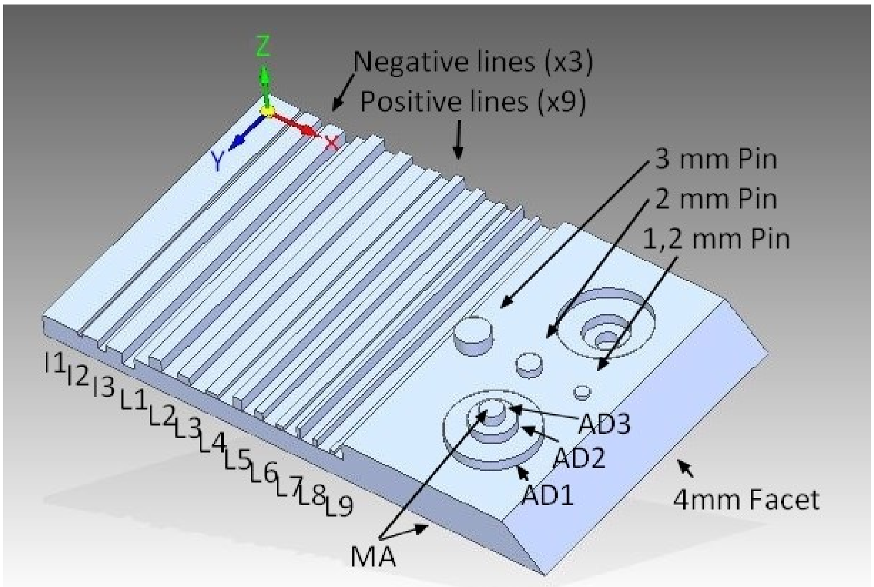


Fig. 15. Perspective view of the test part

Line(mm): L1, L2, L3, L4, L5, L6, L7, L8, L9

Cut(mm) I1, I2, I3

Model height MA

Circles AD1, AD2 ,AD3

Table 2. Test target features and dimensions

Feature	Size
Lines	9 lines with width and height(1,2 mm, 0,8 mm, 0,4 mm)
Negative lines(cuts)	3 with height and width (1,2 mm, 0,8 mm, 0,4 mm)
Main body: full length, width, height	(50 mm, 30 mm, 7 mm)
Facets	2 with height and width (4 mm)
Circles	Diameter (8 mm, 4 mm, 2 mm) Height (1 mm , 2 mm , 3mm)
Circle cuts	Diameter (8 mm, 4 mm, 2 mm) Height (1 mm , 2 mm , 3mm)
Pins	Diameter (1,4 mm, 0,8 mm, 0,4 mm) Height (3 mm, 2 mm, 1,2 mm)

Critical parameters

During printing process of the experiment, several parameters were kept constant, and just three changing parameters were examined. Constant parameters of the processes of this study are shown in Table 3.

Table 3. Printing parameters which were kept constant during the printing process

Parameter	Value
Infill [%]	100
Layer height [mm]	0,05
Bed Temp. [C]	60
Extrusion multiplier	0,8645
Fill pattern: rectilinear	

Three critical printing factors were chosen for this experiment; all consisting of different levels each, a high and a low. All values used in range for fused filament fabrication system :

- *Nozzle temperature* in two levels low and high (170°C and 230°C levels);
- *Feed-rate* in two levels low and high (50% and 100% levels);
- *Nozzle diameter* (from 0,25 mm, 0,4 mm, to 0,6 mm);

12 print test were produced and replicated for result verification. To sum up 24 in total. Using table 4. Different parameters combinations have been executed.

Table 4. Factors and levels used in the experiment

	Temperature		Feed-rate	
Diam.	170	230	50	100
0.25	+		+	
	+			+
		+	+	
		+		+
0.4	+		+	
	+			+
		+	+	
		+		+
0.6	+		+	
	+			+
		+	+	
		+		+

2.4 Print test targets

In this section, all experimental instruments used in whole research process with the goal to print test targets are described below:

3D Printer

For this master thesis, RepRap open-source, low price type printer was used. It has open frame, which makes easier to use: follow the print process and fix, if it is needed, withdraw finished parts, take care of mechanisms, and keep it clean. It has large build volume 10500 cm3 (25 x 21 x 20 cm), 0,25 mm, 0,6 mm, 0, 4mm nozzle (easily changeable) for 1,75 mm filament. It can produced parts from 0,05 mm layer height, and various material can be used like PLA, ABS, PET, HIPS, Flex PP, Ninjaflex, Laywood, Laybrick, Nylon, Bamboofill, Bronzefill, ASA, T-Glase, Carbon-fibers enhanced filaments, Polycarbonates. It is economical due to low average power consumption 70 W (printing PLA) or 110 W (printing ABS). It is very portable: exterior dimensions 42 x 42 x 38 cm, weight 6,5 kg [28].

Material

In today's world, Polylactic acid (PLA) has taken over the marketplace and push ABS filament from most favourite 3D printing filaments. A fermentation process using 100% annually renewable resources (such as corn starch or sugar cane) makes the starting material for the final polymer, lactic acid. The polymer will also rapidly degrade in the environment and the by-products are of very low toxicity, eventually being converted to carbon dioxide and water. It is even called “the green plastic” [9].

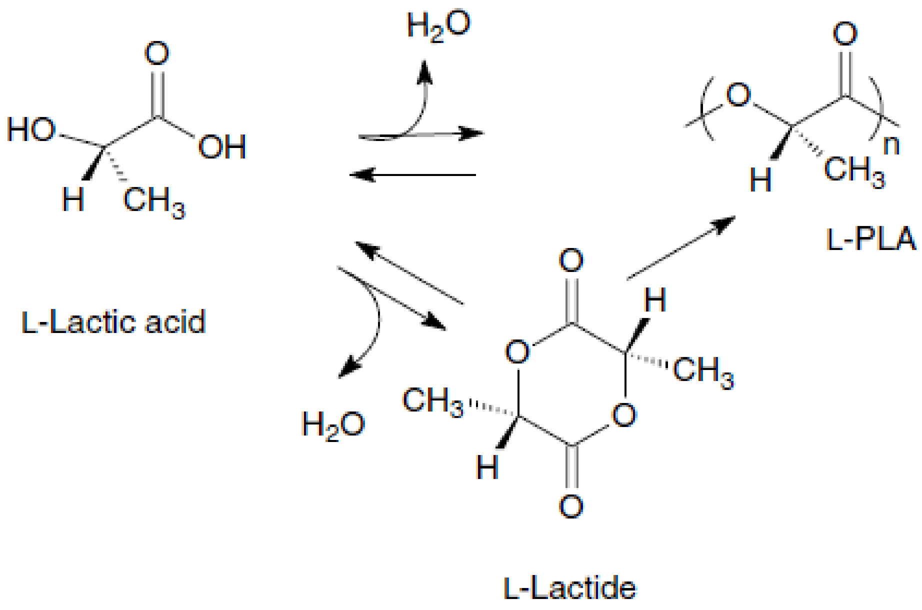


Fig. 16. Polymerization routes to polylactic acid.(David E. Henton, 2005m.)

PLA by its structure is more rigid than ABS, which means printed objects are slightly brittle [27]. Primary benefits are good strength, user-friendly, durability, and some impact resistance.

- Ideal for consumer products, small toys, higher print speeds, smoother layer;
- Very limited flexibility;
- Not soluble;
- Less sturdy than ABS;
- Refer to manufacturer guidelines for food safety;
- General print temperature range is 170°C – 230°C;
- Minor shrinkage during cooling, less sensitive compared to ABS;
- No Heated bed required;
- Printing difficulty is easy, once temperature, bed height and speed are set [27];

Printing process

After selection of critical parameters, further experiment process was to print test targets, which were prepared in .STL file format. STL object information:

Shells:	**1**	Points:	**571**	Edges:	**1707**
Faces:	**1138**	Volume:	**0,5323 cm³**	Surface:	**10,3401 cm²**

Dimensions:	X	Y	Z
Minimum:	-25,00 mm	-15,00 mm	0,00 mm
Maximum:	25,00 mm	15,00 mm	7,00 mm
Size:	50,00 mm	30,00 mm	7,00 mm

Analyse

Manifold:	Not computed
Normals:	Not computed
Intersecting triangles:	Not computed
Highly Connected Edges:	Not computed
Loop Edges:	Not computed

Fig. 17. STL object information

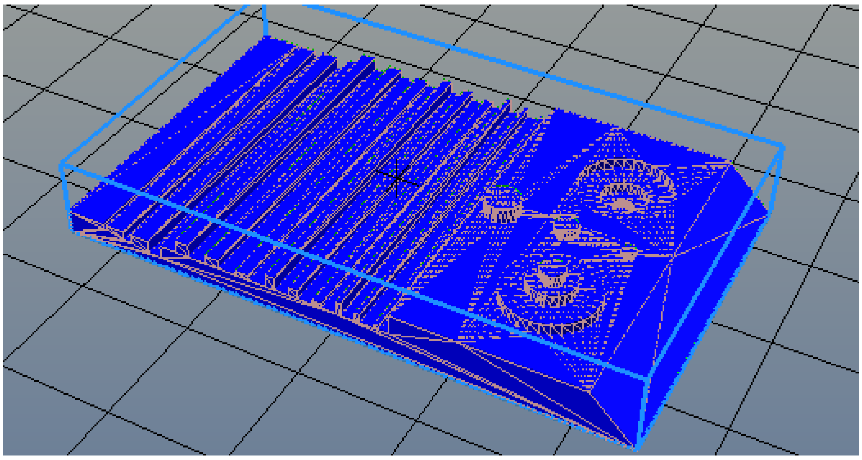


Fig. 18. STL object information

Using Slicer program test target was *sliced* and needed printing parameters were adopted. Average printing time of one target approximately was 48min. Estimated time for complete printing process was 19 hours. There was no need to use post-printing processes because test targets were printed in decent quality for further steps.

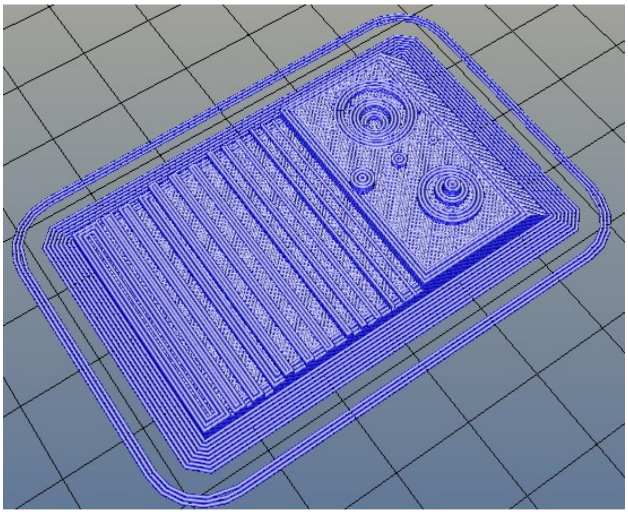


Fig. 19. Test target sliced in layers

2.5 Measurement process and instruments

Printed test targets were measured using a Digital Calliper with a resolution of 0.01 mm and comparison between CAD designs and actual test targets proceeded to detect dimensional inaccuracy of the process. All geometrical features mentioned in previous chapters were measured with respect to length, width roundness, height, depth per test. In table 5, the difference between the nominal and measured dimensions called deviations. For comparative analysis portable MAGNIFIER - WALTEX 8X Desk Magnifier (Size: 42 x 35 x 43 (mm)) was used. It has 0.875" diameter lens, 8X magnification power with scale. Digital test target images were captured and focussed perfectly using the adjustable focus mechanism for visual surface quality verification.

2.6 Dimensional and visual data collection

All geometrical features, which was shown in previous sectors, were measured three times and average value was taken into data, which was used in two different analysis: factorial and comparative. Printed test targets were grouped into blocks by nozzle diameter Fig.20.

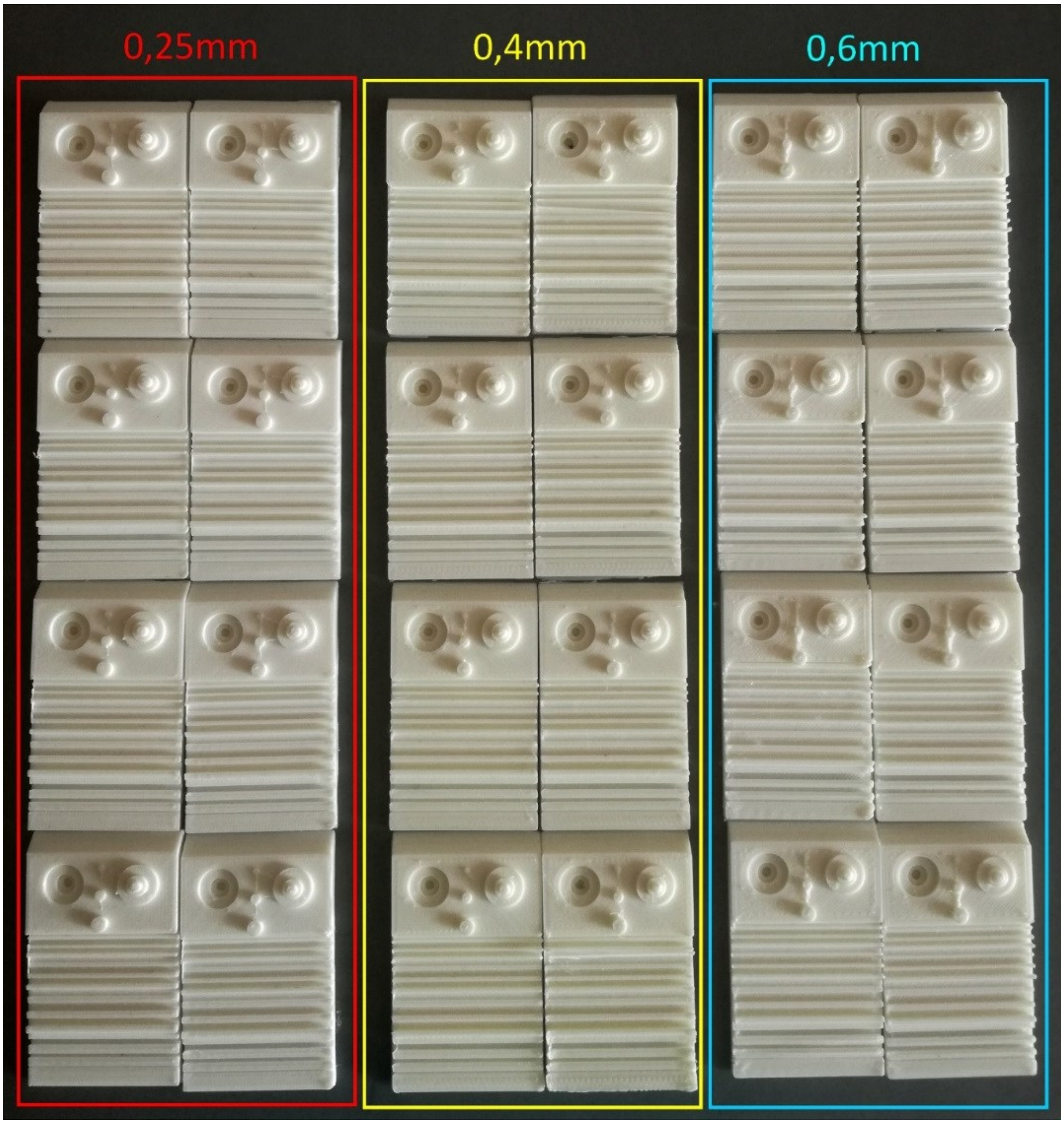


Fig. 20. Actual 3D test parts printed with 0,25mm, 0,4mm, 0,6mm nozzle diameter

For comparative analysis, visual inspection process were executed and consisted of these built parameters: raster, contour, air gap, raster width, contour raster gap and contour width. Fig 21. shows the scheme of a test target single layer.

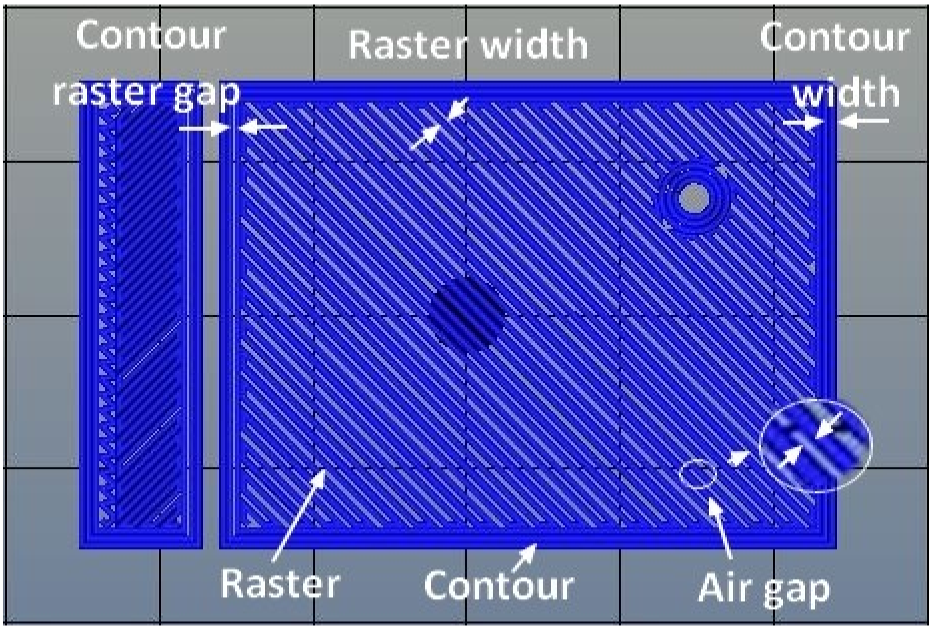


Fig. 21. Scheme of the single layer of built parameters

2.6.1 Excel data collection

Measurements from test targets were recorded and collected to excel sheets (Appendix A, B, C). Printed test targets were numbered by the sequence of printing. The original targets have been numbered 1, 2, 3… and replicas 1_1, 2_1, 3_1 etc. Excel tables consist of information such as: target numbers, geometrical features, temperature [˚C], feed-rate[mm/s], nominal height and width [mm], measured height and width [mm], deviations(difference between the nominal value and the measured value) of height and width [mm]. Data for factorial design was used from positive fundamental lines. For better results, deviations of 9 lines dimensions were taken into average value and put it to ANOVA analysis.

Table 5. Fundamental line measurements in excel table

		Temperature	Feedrate	Nominal height	Nominal width	Measured height	Meausured width	Dev H	Dev W
Targ.Nr.	Feature	deg C	mm/s	mm	mm	mm	mm	mm	mm
					1				
	Line(mm)								
1	L1	230	100	1,2	1,2	1,26	1,33	0,06	0,13
1	L2	230	100	0,8	1,2	0,88	1,32	0,08	0,12
1	L3	230	100	0,4	1,2	0,49	1,33	0,09	0,13
1	L4	230	100	1,2	0,8	1,23	0,94	0,03	0,14
1	L5	230	100	0,8	0,8	0,84	0,82	0,04	0,02
1	L6	230	100	0,4	0,8	0,77	0,78	0,37	-0,02
1	L7	230	100	1,2	0,4	1,19	0,45	-0,01	0,05
1	L8	230	100	0,8	0,4	0,84	0,45	0,04	0,05
1	L9	230	100	0,4	0,4	0,52	0,45	0,12	0,05

Comparative analysis covered (a) negative lines (cuts), (b) main model body length, width, height, (c) circles, circle cuts and pins dimensional deviations. Differences between digital and actual dimensions have been visualized in graphs shown below in results section.

Table 6. (a) Negative fundamental lines

	Cut(mm)								
1	I1	230	100	0,4	0,4	0,34	0,37	-0,06	-0,03
1	I2	230	100	0,8	0,8	0,78	0,75	-0,02	-0,05
1	I3	230	100	1,2	1,2	1,25	1,24	0,05	0,04

Table 7. (b) Main model body measurements

	Main body								
	Facets(mm)								
1_1	N	170	100	4	4	4,15	4,13	0,15	0,13
	Model length			Nominal length		Measured length		Dev ML	
1_1	ML	170	100	50		48,6		-1,4	
	Model width			Nominal width		Measured width		Dev MP	
1_1	MP	170	100	30		29,3		-0,7	
	Model height			Nominal height		Measured height		Dev MA	
1_1	MA	170	100	7		7,3		0,3	

Table 8. (c) Circles, circle cuts and pins

	Circles and Cuts			Nominal height	Nominal diameter	Measured height	Measured diameter	Dev H	Dev D
1	AD1	230	100	1	8	1	7,44	0	-0,56
1	AD2	230	100	1	4	0,91	3,66	-0,09	-0,34
1	AD3	230	100	1	2	1,04	1,96	0,04	-0,04
1	A1	230	100	1,4	3	1,36	2,7	-0,04	-0,3
1	A2	230	100	0,8	2	0,85	1,8	0,05	-0,2
1	A3	230	100	0,4	1,2	0,45	1,1	0,05	-0,1
1	AI1	170	100	1	8	1,34	7,8	0,34	-0,2
1	AI2	170	100	1	4	0,83	3,72	-0,17	-0,28
1	AI3	170	100	1	2	0,78	1,75	-0,22	-0,25

2.7 Design of the experiment

Minitab 17

Minitab 17 is a comprehensive statistical calculation software. It focuses on the utilization of Minitab Statistical Software tools and features from a manufacturing, engineering and business process perspective. Provides access to a complete set of statistical tools, including descriptive Statistics, Hypothesis Tests, Confidence Intervals and Normality Tests, Gage R&R, Destructive Testing, Gage Linearity and Bias, Attribute Agreement, Variables and Attribute Control Charts, Capability Analysis for Normal, Non-normal and Attribute data [35]. Letting to generate a variety of full and fractional factorial designs using Minitab’s intuitive DoE interface: Design of Factorial Experiments; Normal Effects Plot and Pareto of Effects; Power and Sample Size; Main Effect, Interaction, and Cube Plots; Centre Points; Overlaid Contour Plots; Multiple Response Optimization [20]. It can be used to uncover the relationships between variables and identify important factors affecting the quality of products and services. Statistical significance of these factors is established with analysis of variance (ANOVA). Graphical tools help identify the impact of each factor on the desired outcomes and reveal abnormalities in the data.

For the analysis of the 24-run factorial design, dimensional deviations response variables were analysed using the Minitab 17 software. The procedure for the analysis of deviations response variable was performed as follows:

- The design of experiment were chosen
- Factors and Reponses were inserted
- The effects were calculated.
- Significant effects were chosen from the graph.
- Statistical model was fit to the data.
- Model Diagnostic analysis was performed.
- The Model Graphs were analysed.

For full factorial design, three factors were selected for this experiment. Two of them consisting of two levels each a high and a low (nozzle temperature and feed-rate) they are more likely associated with the physical state of the thermoplastics. Nozzle diameter as fixed factor had three values variations (0,25 mm, 0,4 mm, 0,6 mm).

Table 9. Printing parameters and their levels used for factorial design

Factor	Units	Low	High
Nozzle temperature	[°C]	170	230
Feed-rate [mm/s]	[%]	50	100
Nozzle diameter	[mm]	25; 40; 60	

Input variables for this study were fundamental line design height and design width. Output variables were response variable (Dev H) and response variable (Dev W). Controllable factors been investigated: nozzle temperature, fees-rate. Uncontrollable was nozzle diameter. The metrics of the experiment are illustrated in Fig. 22.

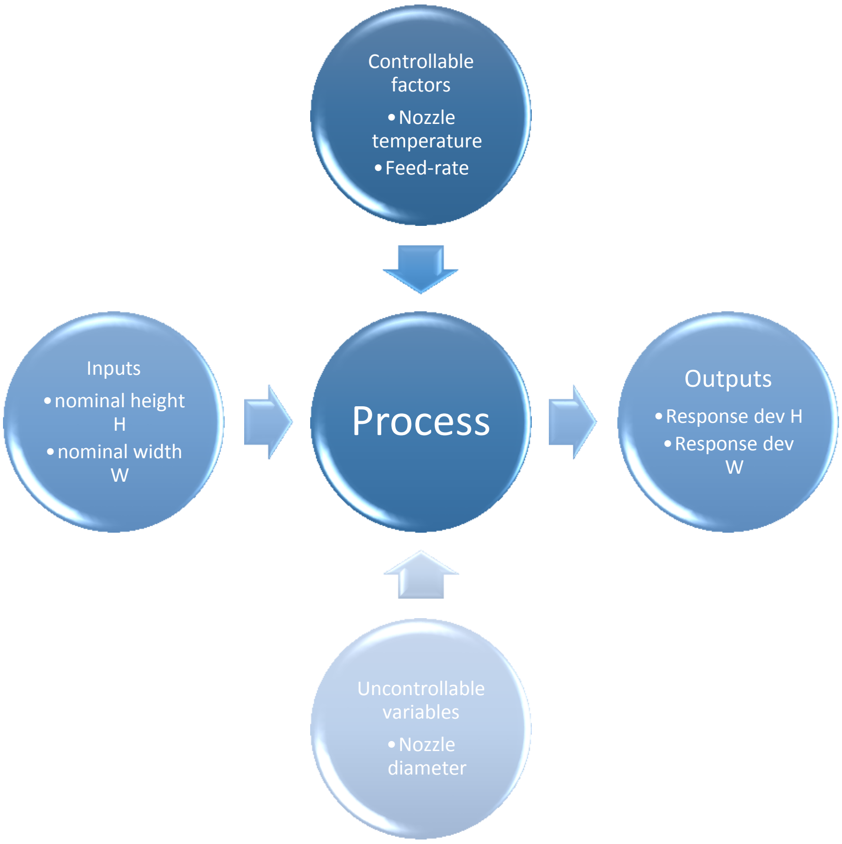


Fig. 22. Analyzed metrics of experiment

Analysis of variance

Generation of DoE – full factorial design table and analysis of ANOVA were performed for each test part (24 runs) of nine fundamental lines average values of height and width. Main effects and interaction plots generated from statistical software were initially consulted for both the Dev H and Dev W response variables to verify whether or not the factors had an effect on the dimensional change.

Next, an ANOVA general linear method was conducted for both response variables and studied to determine if the null hypothesis could be rejected and the alternative hypothesis accepted. For analysis, the common α-level of 0.05 is chosen. A null hypothesis is generally assumed true and the factors do not influence the system, p-value for the printing process factors are greater than the chosen α-level of 0.05. In contrast, the alternative hypothesis assumes the factors do influence the process and will be accepted if the null hypothesis is rejected and the p-value is less than 0.05. All residual plots for making assumptions for complete printing process were made.

3. RESULTS

3.1 Results of visual inspection

The comparative analysis has been applied to study the effect of printing process failures and geometrical errors such as air gaps, raster width variations, contour raster gap and contour width, which influences the surface finish quality.

The set of investigated test targets are shown below. Each of one was inspected visually.

Test targets printed with 0,6mm nozzle diameter (digital images with 8X magnification)

a)

b)

Comparing these two targets a) and b) printed in high-level temperature (230˚C) and low/high level of feed-rate (1^{st} at 50%, 2^{nd} 100%) the difference is quiet obvious. On 2^{nd} test target small air gaps and contour raster gaps have appeared, which means the spacing between toolpaths increases, effectively replacing some of the material filled areas with air. Left overs of nozzle retraction trajectory are visible and contour line became evident.

c)

d)

c) and d) Printed in low-level temperature (170◦C) and low/high level of feed-rate (1st at 50%, 2nd 100%) the similarities are obvious. Both test targets have big air gaps and contour raster gaps appeared. Left overs of nozzle retraction trajectory are visible. Contour width became separated from the model and affects bigger value of contour raster. These geometrical errors has significant impact for surface finish quality of test target. Compared to a) and b) the difference of surface finish quality is undeniable.

Fig. 23. Test targets printed 0,6mm in different parameters: a) T=230, F=50 b)T=230, F=100 c) T=170, F=50 d)T=170, F=100

Test targets printed with 0,4mm nozzle diameter (digital images with 8X magnification)

a)

b)

Comparing these two targets a) and b) printed in high-level temperature (230˚C) and low/high level of feed-rate (1^{st} at 50%, 2^{nd} 100%) the differences are not really visible. On 1^{nd} test target no significant errors have appeared. Some leftovers of nozzle retraction trajectory are visible, but insignificant. However on 2^{nd} test target just barely visible air gaps appeared.

c)

d)

c) and d) Printed in low-level temperature (170˚C) and low/high level of feed-rate (1st at 50%, 2nd 100%) the difference is incontestable. Both test targets have visible material extrusion trajectory made by nozzle and leftovers of nozzle retraction trajectory. Compared with test targets printed with the same parameters just with bigger nozzle, the surface finish quality is more acceptable.

Fig. 24. Test targets printed 0,4mm in different parameters: a) T=230, F=50 b)T=230, F=100 c) T=170, F=50 d)T=170, F=100

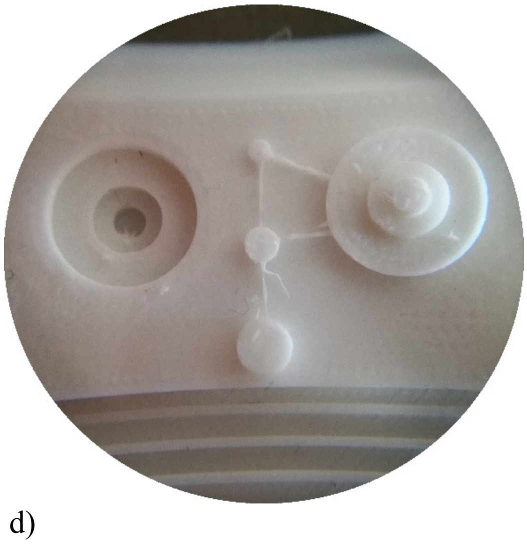
Test targets printed with 0,25mm nozzle diameter (digital images with 8X magnification)

a)

b)

Comparing these two targets a) and b) printed in high-level temperature (230˚C) and low/high level of feed-rate (1st at 50%, 2nd 100%) only differ from one another. No significant air gaps, contour raster gaps, or other geometrical errors except small amount leftovers of nozzle retraction trajectory, but that does not have any effect for surface finish quality. It looks like a solid model.

c)



d)

c) and d) Printed in low-level temperature (170˚C) and low/high level of feed-rate (1st at 50%, 2nd 100%). Both test targets have no significant air gaps, contour raster gaps, or other geometrical errors, except small amount of leftovers of nozzle retraction trajectory. Leftovers can't be considered to have any effect on surface finish quality. If compared to the test targets printed with higher temperature these test targets have lower quality, however, looks more precise than test targets printed with 0,4mm or 0,6mm nozzle.

Fig. 25. Test targets printed 0,25mm in different parameters: a) T=230, F=50 b)T=230, F=100 c) T=170, F=50 d)T=170, F=100

3.2 Data Collection, Analysis and Comparative data

Dimensional accuracy was evaluated based on the measurements of individual part features and comparing nominal values to the original CAD file. Main graphs are showing deviations of negative lines(cuts) (I1, I2, I3), model length (ML), width (MP) and height (MA), circles (AD1, AD2, AD3), circle cuts (AI1, AI2, AI3) and pins (A1, A2, A3). Dimensional inaccuracy are easily visible in graphs, where model length and width are represented and values are smaller than nominal ones. These observations lead to the evidence of material shrinkage process and requires a solution on how to maintain nominal values in an actual model. Value of model height is greater than nominal; this is due to substitution of extrusion road process. Positive circle are the highest feature of the model and the place where extrusion road ends which seems to be related to inaccuracy of the model height. This requires a solution, for instance additional model that would be the highest print on the printing plate.

Dimensional accuracy of circles and circle cuts were investigated by two size variations: circle height and diameter. Measured values were subtracted from nominal and obtained deviations converted to percentage values and average was taken for better identification. Two general trends are easily visible from the graphs. Firstly, measured height of circles and pins are seem to be greater than nominal value. Second trend is that the measurements percentage deviations on average overall of circle diameters seem to be lower than the planned or theoretical size, which identify shrinkage of polymer and their density, which varies from one temperature value to another.

Dimensional accuracy of negative lines (cuts) were investigated by two size variations: line depth and width. Deviations were calculated and converted to percentage to investigate a holistic view dimensional inaccuracy in this model feature. Average percentage value was taken into consideration and showed in visual form. Deviations varies between -20% and 25% and unpredictable spikes in the charts are visible. No dependency were detected that means it can be caused by many other factors. Graphs describing comparative analysis are shown below:

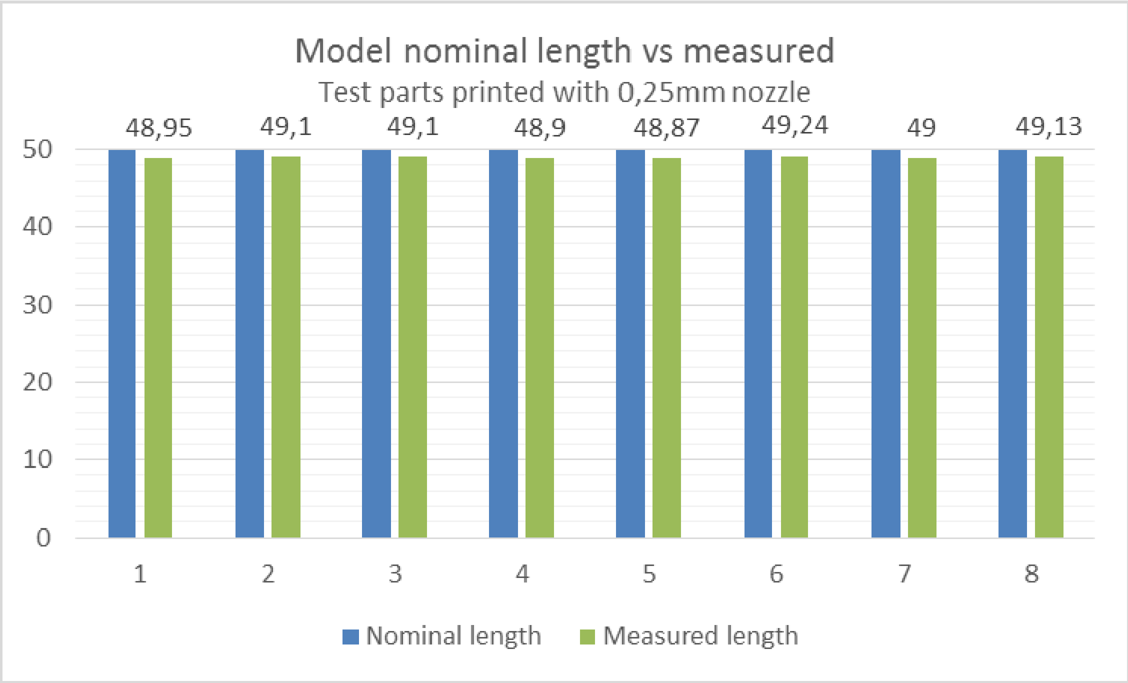


Fig. 26. Model nominal length vs measured, test part printed with 0,25mm nozzle

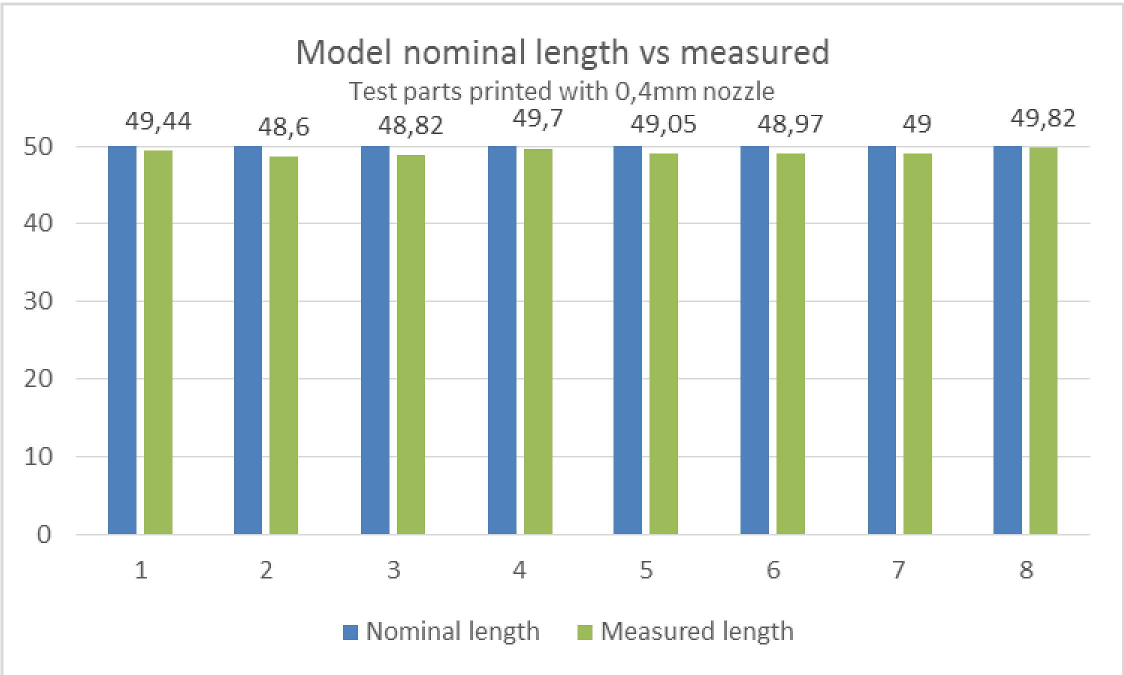


Fig. 27. Model nominal length vs measured, test part printed with 0,4mm nozzle

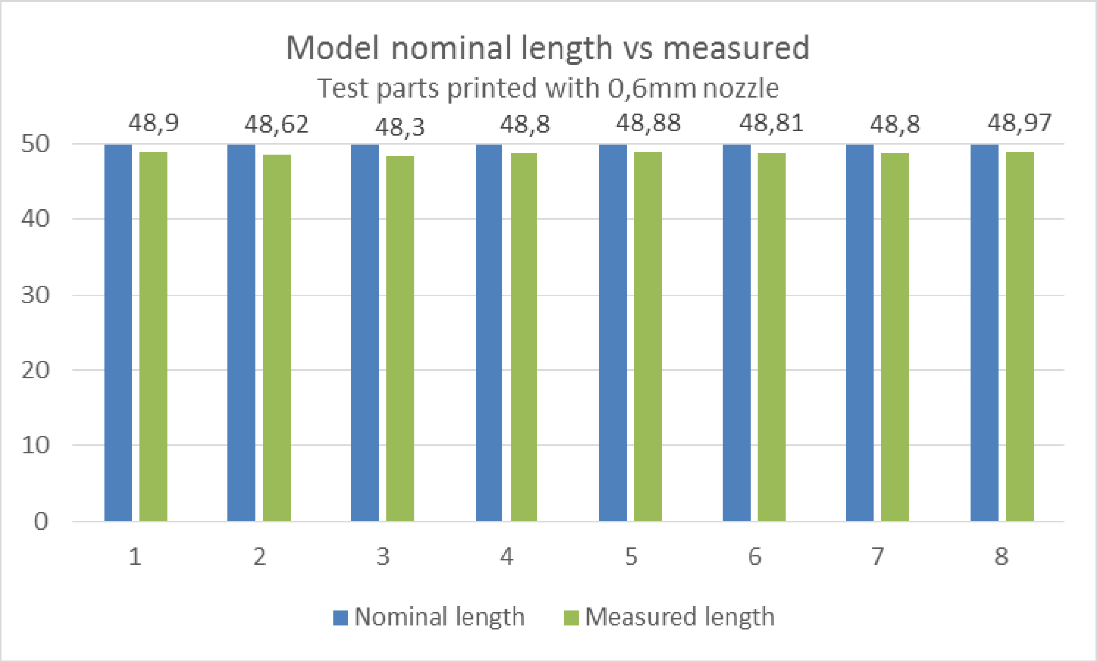


Fig. 28. Model nominal length vs measured, test part printed with 0,6mm nozzle

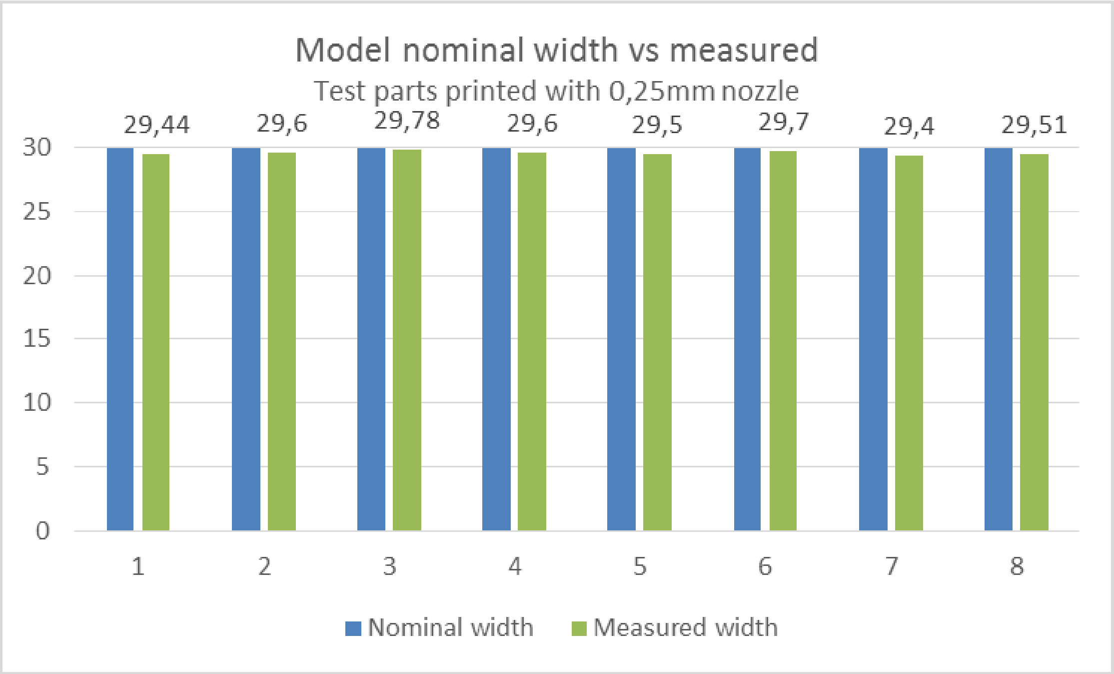


Fig. 29. Model nominal width vs measured, test part printed with 0,25mm nozzle

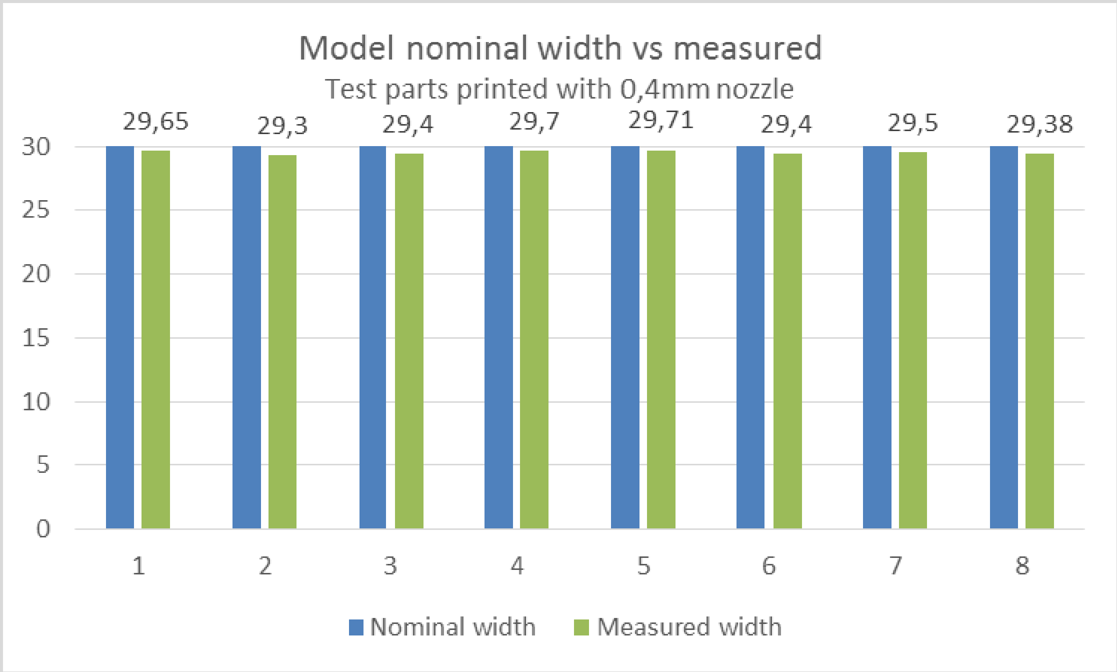


Fig. 30. Model nominal width vs measured, test part printed with 0,4mm nozzle

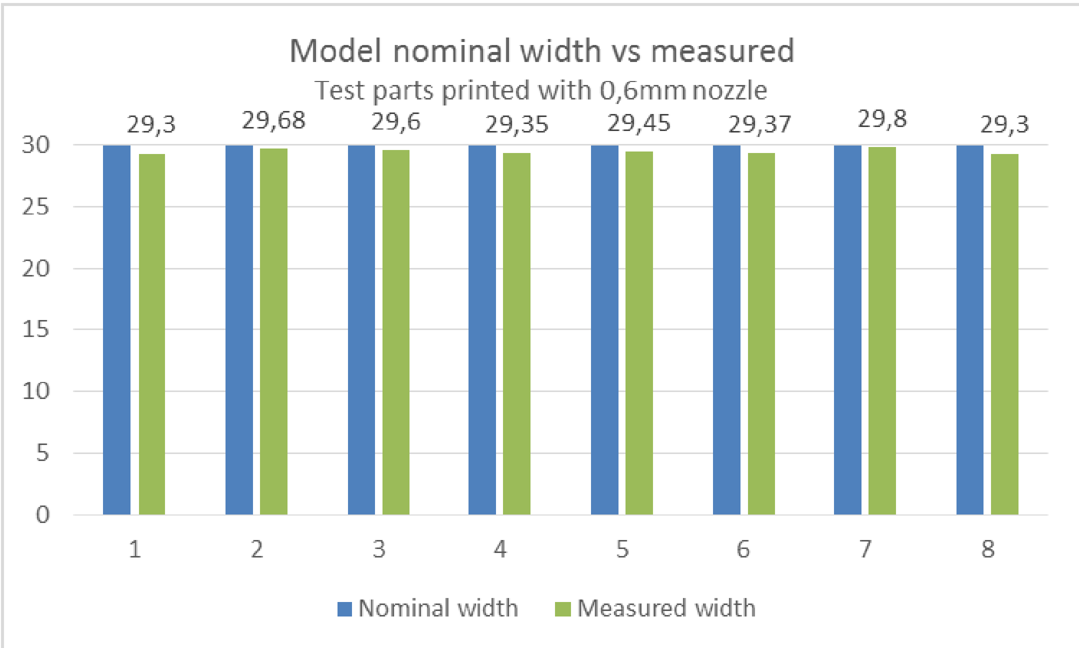


Fig. 31. Model nominal width vs measured, test part printed with 0,6mm nozzle

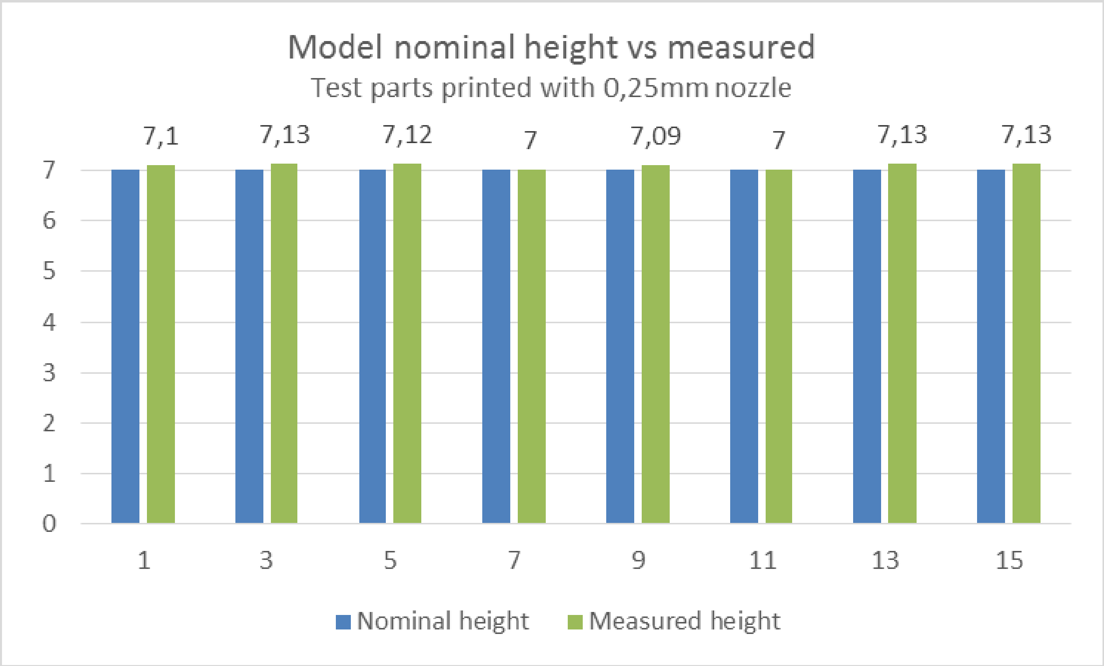


Fig. 32. Model nominal height vs measured, test part printed with 0,25mm nozzle

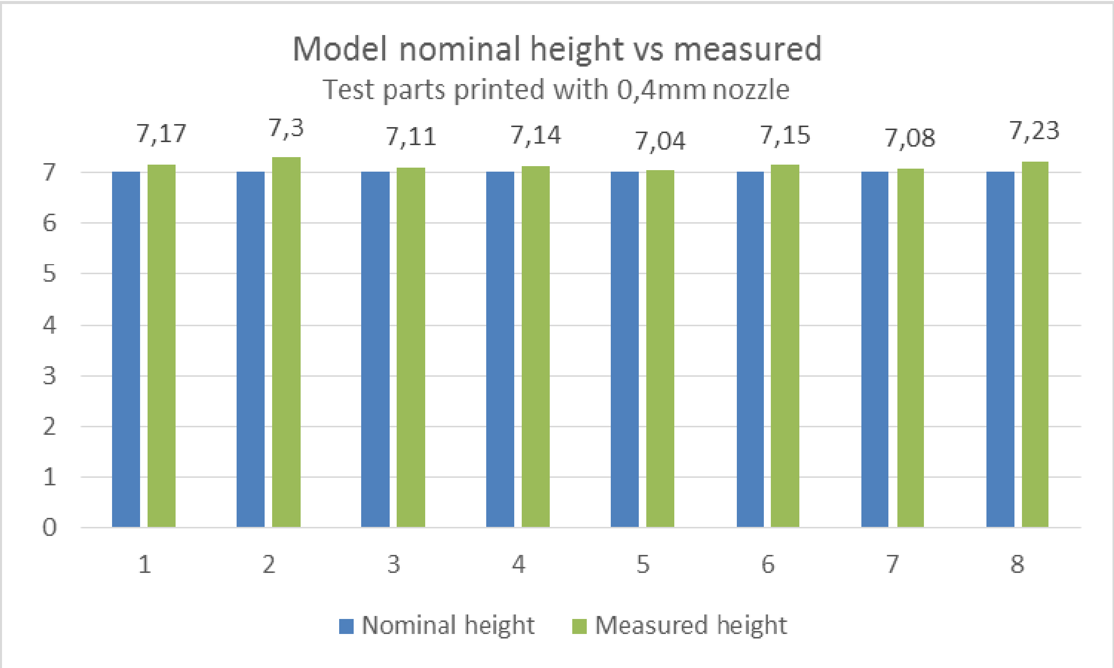


Fig. 33. Model nominal width vs measured, test part printed with 0,4mm nozzle

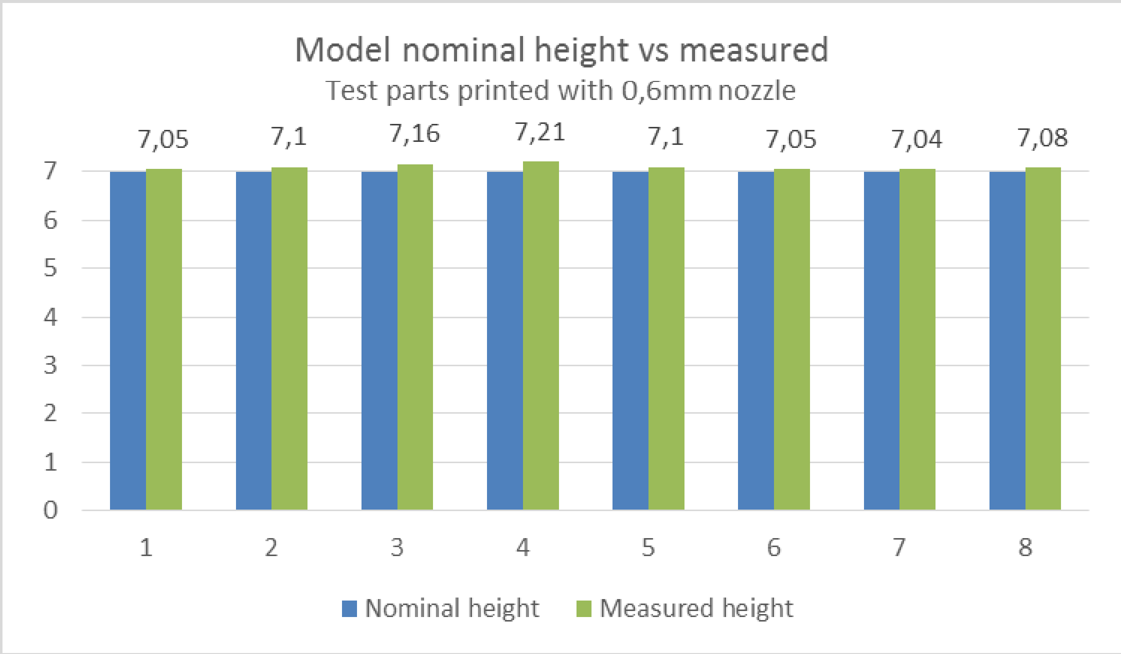


Fig. 34. Model nominal width vs measured, test part printed with 0,6mm nozzle

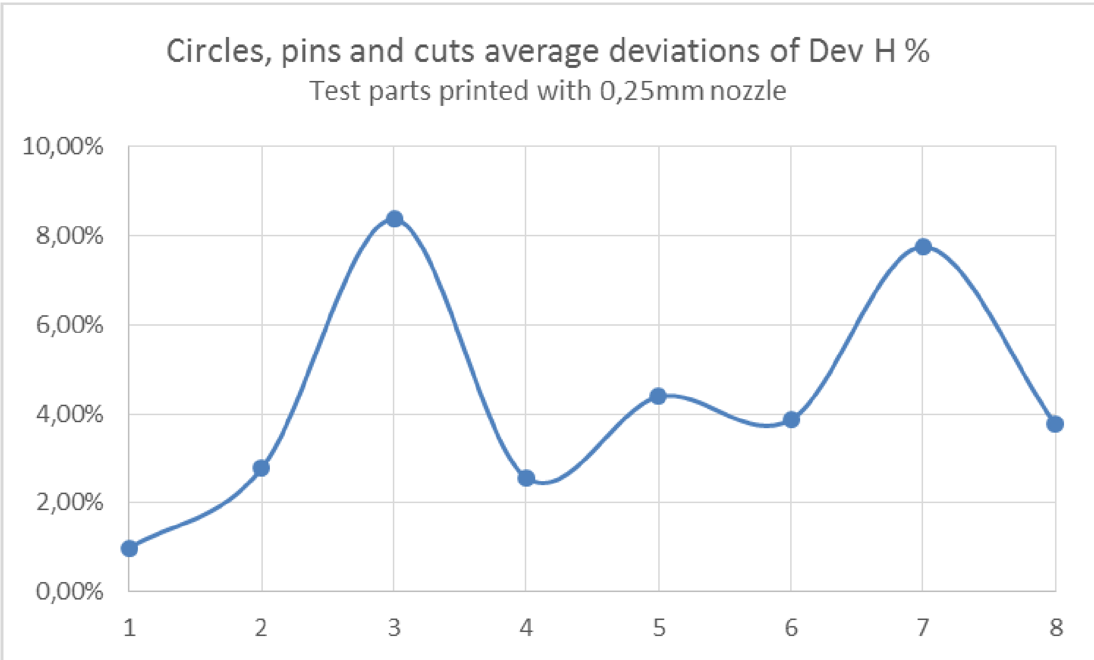


Fig. 35. Circles, pins and cuts average H deviations printed with 0,25mm nozzle

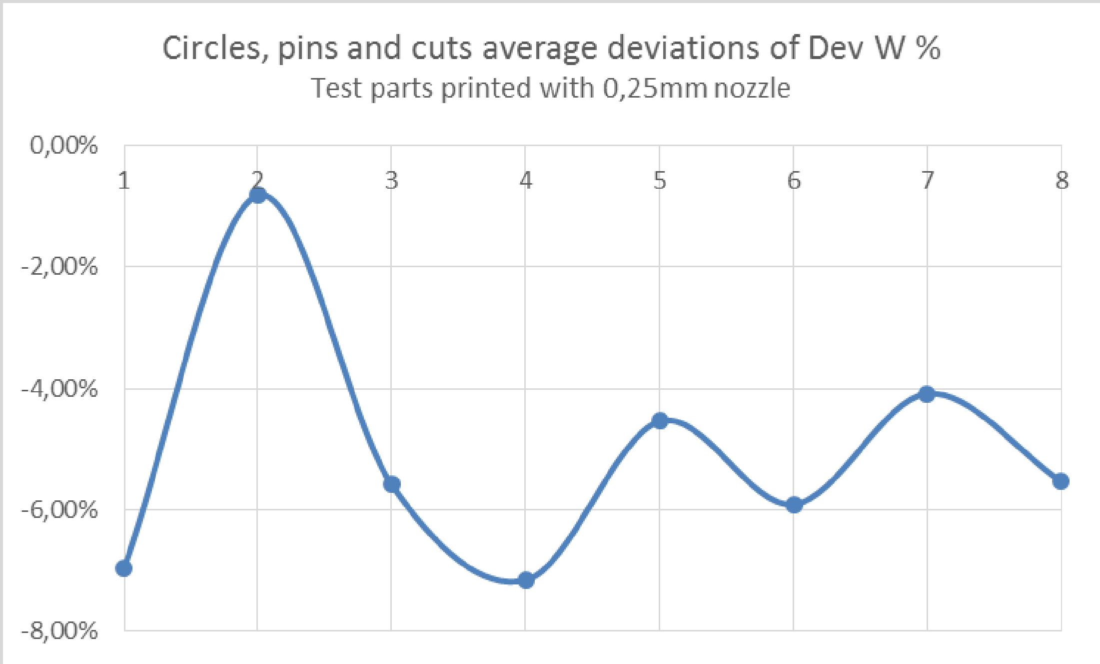


Fig. 36. Circles, pins and cuts average diameter deviations printed with 0,25mm nozzle

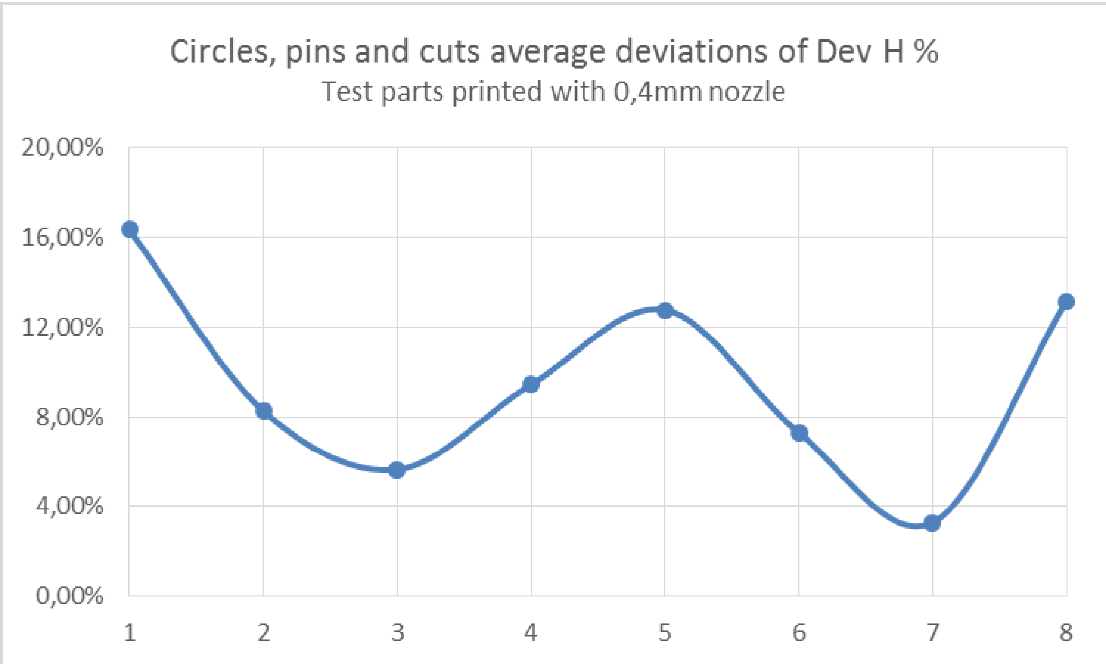


Fig. 37. Circles, pins and cuts average H deviations printed with 0,4mm nozzle

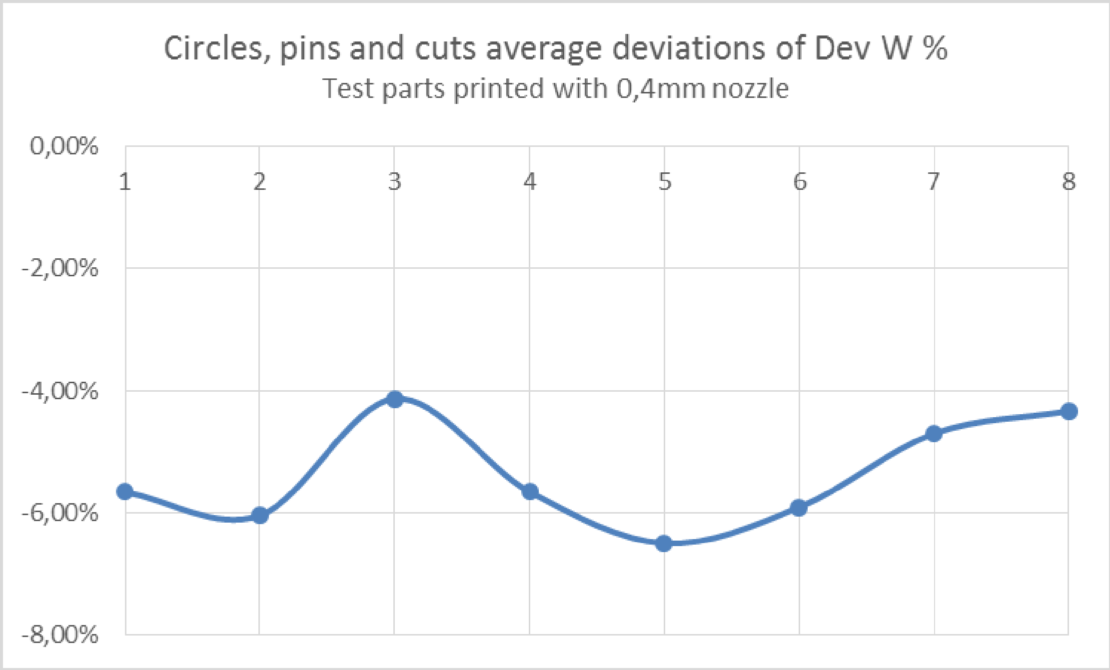


Fig. 38. Circles, pins and cuts average diameter deviations printed with 0,4mm nozzle

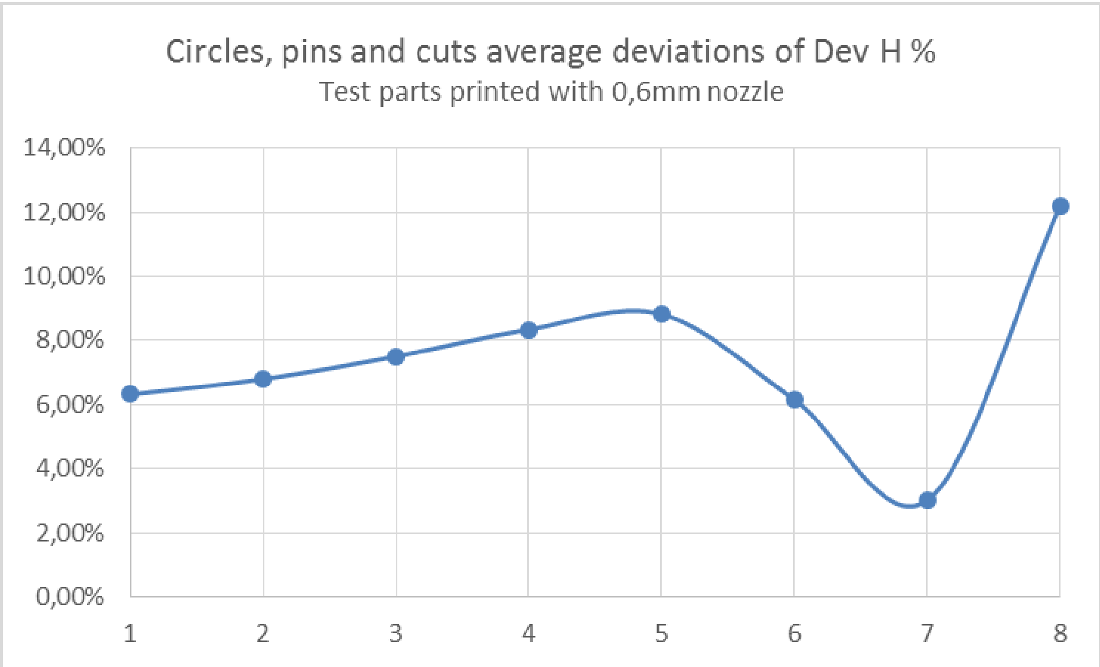


Fig. 39. Circles, pins and cuts average H deviations printed with 0,6mm nozzle

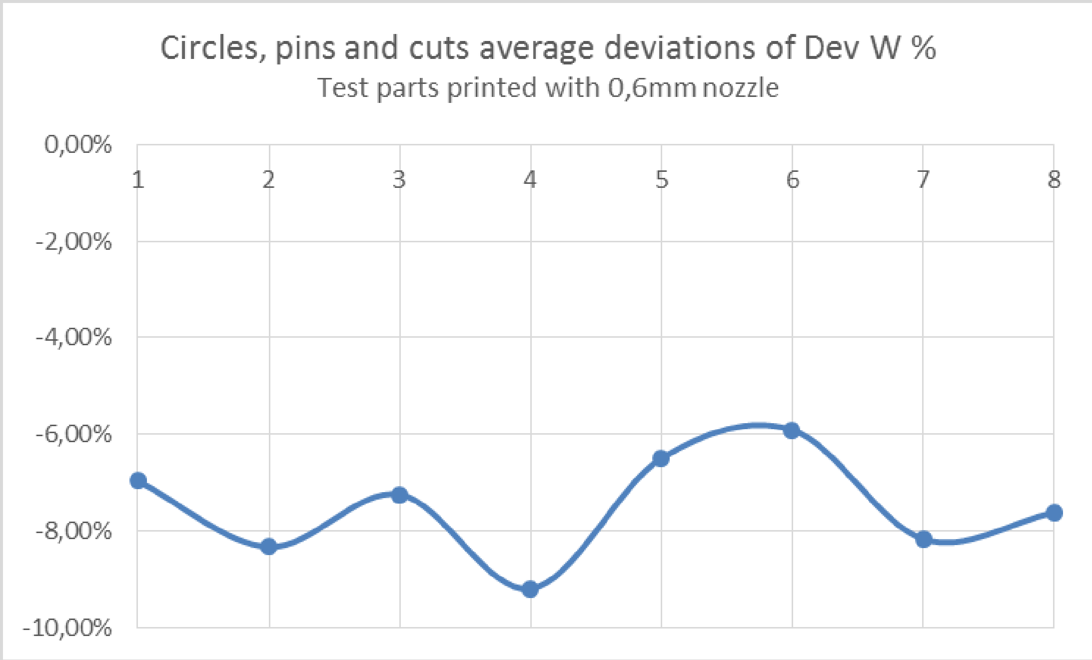


Fig. 40. Circles, pins and cuts average diameter deviations printed with 0,6mm nozzle

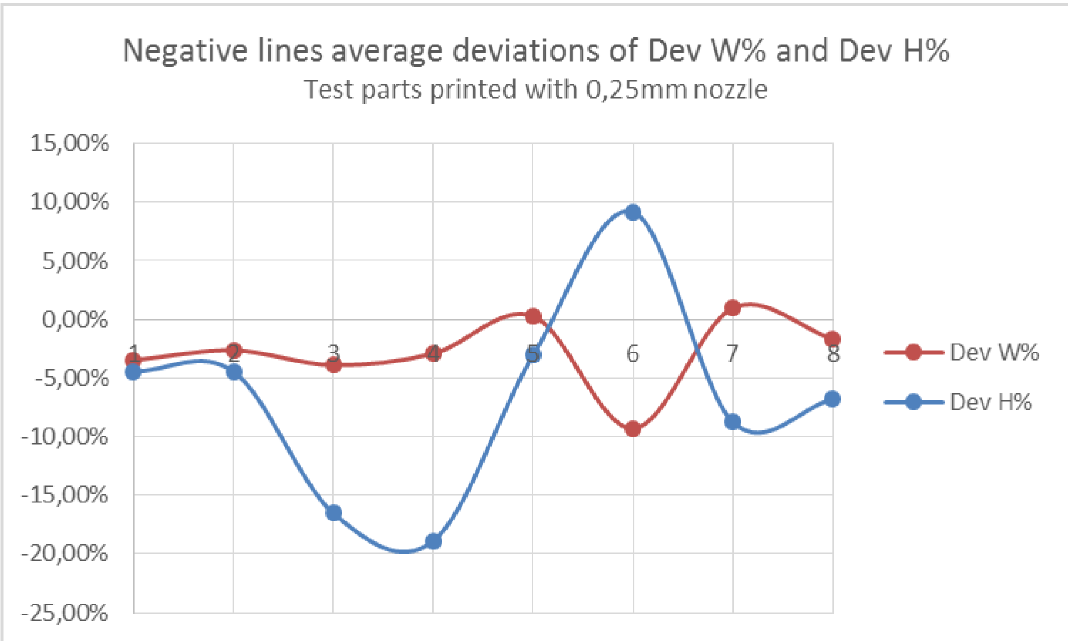


Fig. 41. Negative lines average deviations of Dev W and Dev H percentage (0,25mm nozzle)

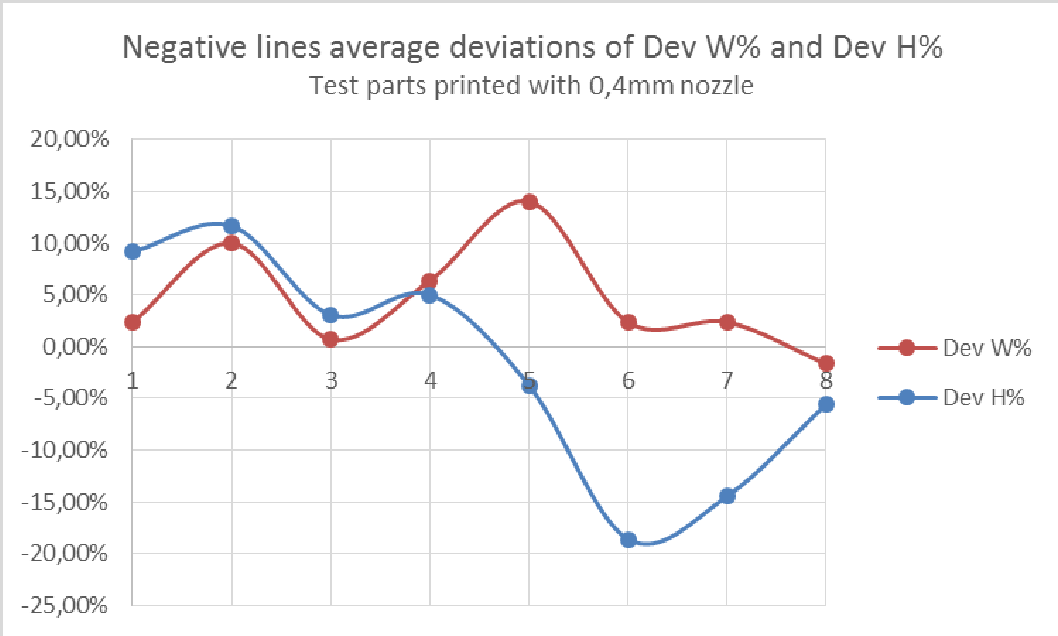


Fig. 42. Negative lines average deviations of Dev W and Dev H percentage (0,4mm nozzle)

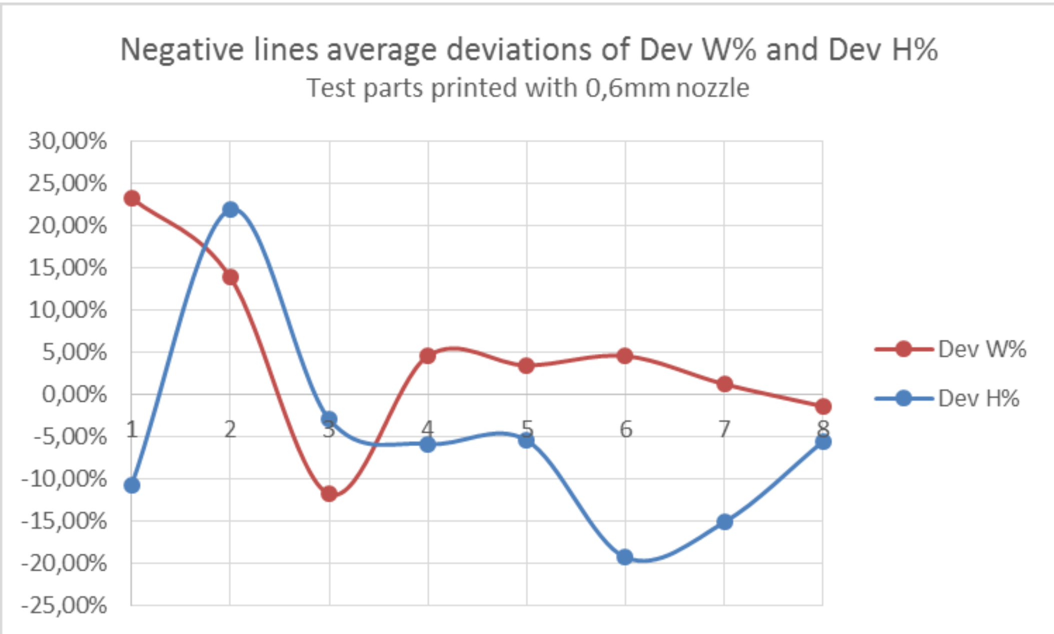


Fig. 43. Negative lines average deviations of Dev W and Dev H percentage (0,6mm nozzle)

3.3 Expected Results and Output of the Study

Full factorial design table and ANOVA analysis for 24 runs are shown in Table 10. First column of the table states the randomized order of experiment, while in the second column a standard order is shown as defined by the software. There was no need for blocking and value is equal to 1. The columns (C5, C6, C7) are factors of nozzle temperature, feed-rate and nozzle diameter. In the last two columns, the averages of fundamental lines heights (Dev H) and widths (Dev W) deviations are shown.

General Linear Model: Dev H versus Nozzle D; Temp; Feed-rate and Dev W versus Nozzle D; Temp; Feed-rate are shown in tables which consist of factor information, analysis of variance, model summary, coefficients from which model assumptions can be made, regressions equation, fits and diagnostics for unusual observations. The four-in-one residual plot displays four different residual plots together in one graph window. The comparisons of these residual plots let to determine the assumptions of the analysis and prove or reject the questions raised before.

Analysis of variance for Dev H (Table 12), showed a dominant, statistically significant effect of nozzle diameter and nozzle temperature both have p=0.00. This means the null hypothesis can be rejected, because p-value is less than 0.05. However, the feed-rate seem to be insignificant, because the p-value are greater than the chosen p=0,495. A half-normal plot in Fig.44 are showing the same observations. For the deviations of Dev H data, the residuals appear to follow a straight line. No evidence of non-normality, skewness, outliers, or unidentified variables exists.

Analysis of variance for Dev W (Table 18), as well proved to be statistically significant effect of nozzle diameter and nozzle temperature both have p=0.00. The feed-rate seem to be insignificant too, because the p-value are greater than the chosen p=0,663. A half-normal plot in Fig.45 are showing observations for the deviations of Dev W data, the residuals appear to follow a straight line as well as in Dev H data. As it can be seen, Dev H has a greater deviations than Dev W. Common range between deviations in residual plots for Dev H is from -0,08 to 0,08. It is almost double than in Dev W where common range is from -0,04 to 0,04. Fig 44 and Fig 45.

Plots of main effects for Dev H and Dev W have proved the numbers. Feed-rate had no significant influence, because the variance of means are close to zero for Dev W and positive effect for Dev H, but values are small to have an effect. Fig 47.Nozzle temperature seem to has stronger effect on printing in z coordinate, the line is steeper for Dev H than for Dev W. The nozzle diameter has the same trend the bigger nozzle is, the smaller mean value have appeared. The greater values for dimensional inaccuracy had parts printed with 0,25 mm nozzle, and the obvious shrinkage of material and smaller dimensions of the features appeared on parts printed with 0,6 mm nozzle.

By comparing these values, it can be seen that reasonable parameter estimation was achieved. Not all factors were found to be significant in the general linear ANOVA’s, making it easier to draw conclusions.

Table 10. Design of experiment of Minitab17 environment

	StdOrder	RunOrder	PtType	Blocks	Temperature[degC]	Feedrate[mm/s]	Nozzle diameter[mm]	Dev H	Dev W
1	20	1	1	1	230	50	40	0,0477778	0,012222
2	4	2	1	1	170	100	25	0,0922222	0,045556
3	16	3	1	1	170	100	25	0,0077778	0,052222
4	14	4	1	1	170	50	40	-0,0355556	0,016667
5	21	5	1	1	230	50	60	-0,0011111	-0,017778
6	3	6	1	1	170	50	60	-0,0711111	-0,063333
7	11	7	1	1	230	100	40	0,0200000	0,003333
8	8	8	1	1	230	50	40	0,0433333	0,013333
9	10	9	1	1	230	100	25	0,0911111	0,074444
10	1	10	1	1	170	50	25	-0,0211111	0,051111
11	15	11	1	1	170	50	60	-0,0977778	-0,104444
12	13	12	1	1	170	50	25	0,0388889	0,014444
13	23	13	1	1	230	100	40	0,0300000	0,017778
14	6	14	1	1	170	100	60	-0,0422222	-0,074444
15	2	15	1	1	170	50	40	0,0100000	-0,016667
16	9	16	1	1	230	50	60	0,0155556	-0,051111
17	7	17	1	1	230	50	25	0,0977778	0,092222
18	17	18	1	1	170	100	40	0,0222222	-0,013333
19	24	19	1	1	230	100	60	0,0033333	-0,014444
20	19	20	1	1	230	50	25	0,0822222	0,073333
21	12	21	1	1	230	100	60	0,0722222	-0,044444
22	22	22	1	1	230	100	25	0,0133333	0,064444
23	18	23	1	1	170	100	60	-0,0488889	-0,094444
24	5	24	1	1	170	100	40	-0,0377778	-0,034444

Analysis of variance

General Linear Model: Dev H versus Nozzle D; Temp; Feed-rate

Method

Factor coding (-1; 0; +1)

Table 11. Factor information (Dev H)

Factor	Type	Levels	Values
Temperature	Fixed	2	170; 230
Feed-rate	Fixed	2	50; 100
Nozzle diameter	Fixed	3	25; 40; 60

Table 12. Analysis of Variance (Dev H)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Nozzle D	1	0,020218	0,020218	17,88	0,000
Temperature	1	0,020352	0,020352	18,00	0,000
Feed-rate	1	0,000546	0,000546	0,48	0,495
Error	20	0,022615	0,001131		
Lack-of-Fit	8	0,008317	0,001040	0,87	0,564
Pure Error	12	0,014298	0,001192		
Total	23	0,063731			

Table 13. Model Summary (Dev H)

S	R-sq	R-sq(adj)	R-sq(pred)
0,0336269	64,51%	59,19%	47,90%

Table 14. Coefficients (Dev H)

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0,0982	0,0211	4,65	0,000	
Nozzle D	-0,002024	0,000479	-4,23	0,000	1,00
Temp.					
170	-0,02912	0,00686	-4,24	0,000	1,00
Feed-rate					
50	-0,00477	0,00686	-0,69	0,495	1,00

Table 15. Regression Equation (Dev H)

Temp	Feedrate	
170	50	Dev H = 0,0643 - 0,002024 Nozzle D
170	100	Dev H = 0,0738 - 0,002024 Nozzle D
230	50	Dev H = 0,1225 - 0,002024 Nozzle D
230	100	Dev H = 0,1321 - 0,002024 Nozzle D

Table 16. Fits and Diagnostics for Unusual Observations (Dev H)

Obs	Dev H	Fit	Resid	Std Resid	
7	0,0133	0,0815	-0,0681	-2,24	R
12	0,0722	0,0106	0,0616	2,04	R
22	0,0922	0,0232	0,0690	2,27	R

R Large residual

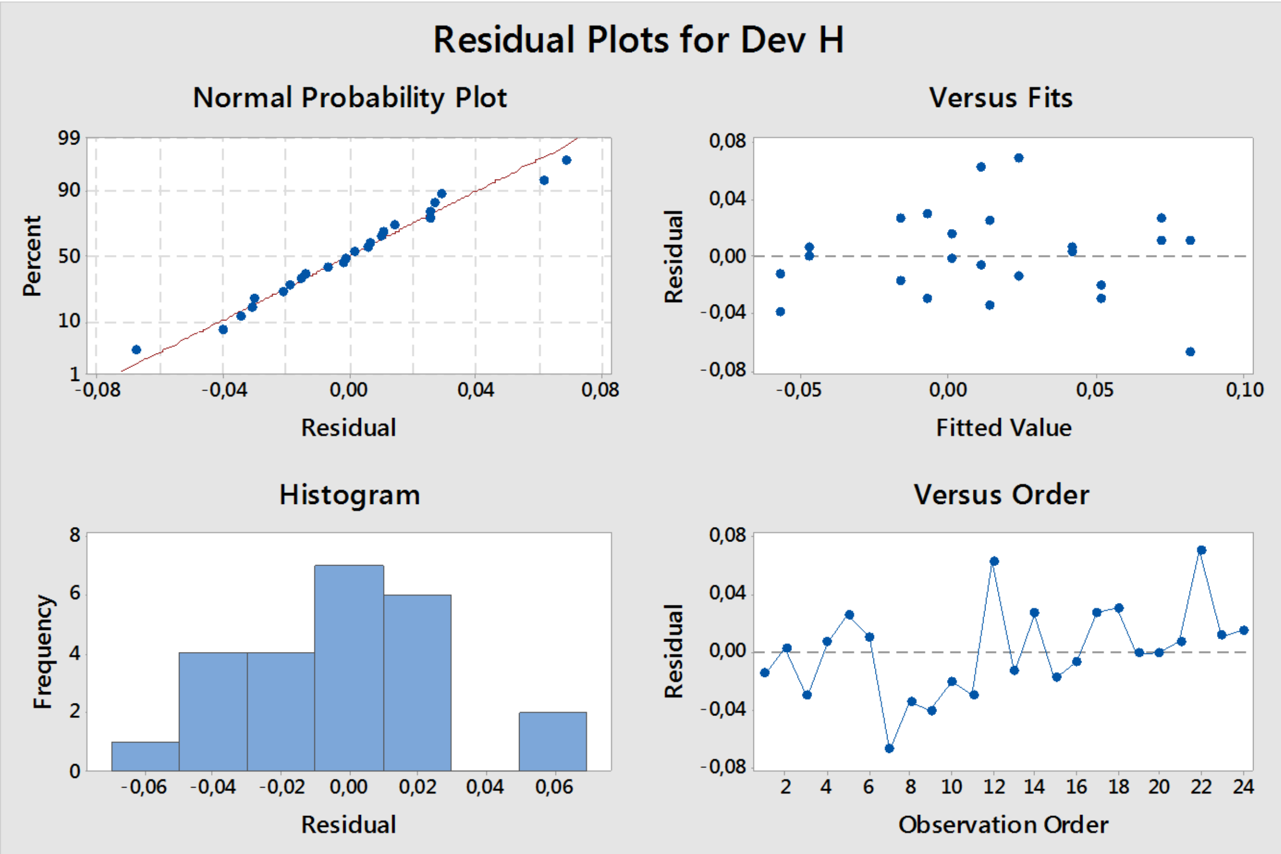


Fig. 44. Diagrams of residuals for Dev H

General Linear Model: Dev W versus Nozzle D; Temp; Feed-rate

Method

Factor coding (-1; 0; +1)

Table 17. Factor information (Dev W)

Factor	Type	Levels	Values
Temperature	Fixed	2	170;230
Feed-rate	Fixed	2	50;100
Nozzle diameter	Fixed	3	25;40;60

Table 18. Analysis of Variance (Dev W)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Nozzle D	1	0,053917	0,053917	177,89	0,000
Temperature	1	0,008230	0,008230	27,16	0,000
Feed-rate	1	0,000059	0,000059	0,20	0,663
Error	20	0,006062	0,000303		
Lack-of-Fit	8	0,002205	0,000276	0,86	0,574
Pure Error	12	0,003857	0,000321		
Total	23	0,068269			

Table 19. Model Summary (Dev W)

S	R-sq	R-sq(adj)	R-sq(pred)
0,0174094	91,12%	89,79%	87,11%

Table 20. Coefficients (Dev W)

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0,1378	0,0109	12,62	0,000	
Nozzle D	-0,003306	0,000248	-13,34	0,000	1,00
Temp.					
170	-0,01852	0,00355	-5,21	0,000	1,00
Feed-rate					
50	0,00157	0,00355	0,44	0,663	1,00

Table 21. Regression Equation (Dev W)

Temp	Feedrate	
170	50	Dev W = 0,1209 - 0,003306 Nozzle D
170	100	Dev W = 0,1177 - 0,003306 Nozzle D
230	50	Dev W = 0,1579 - 0,003306 Nozzle D
230	100	Dev W = 0,1548 - 0,003306 Nozzle D

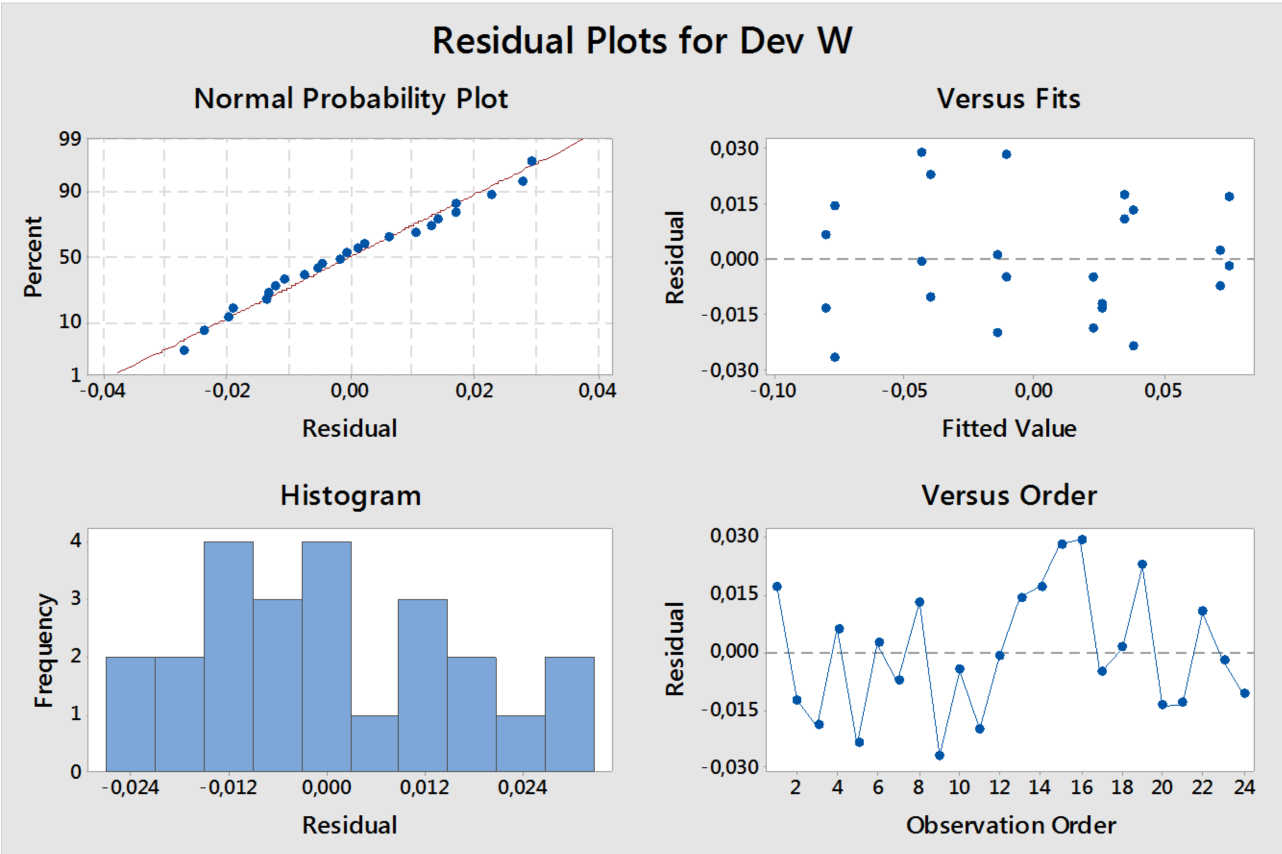


Fig. 45. Diagrams of residuals for Dev W

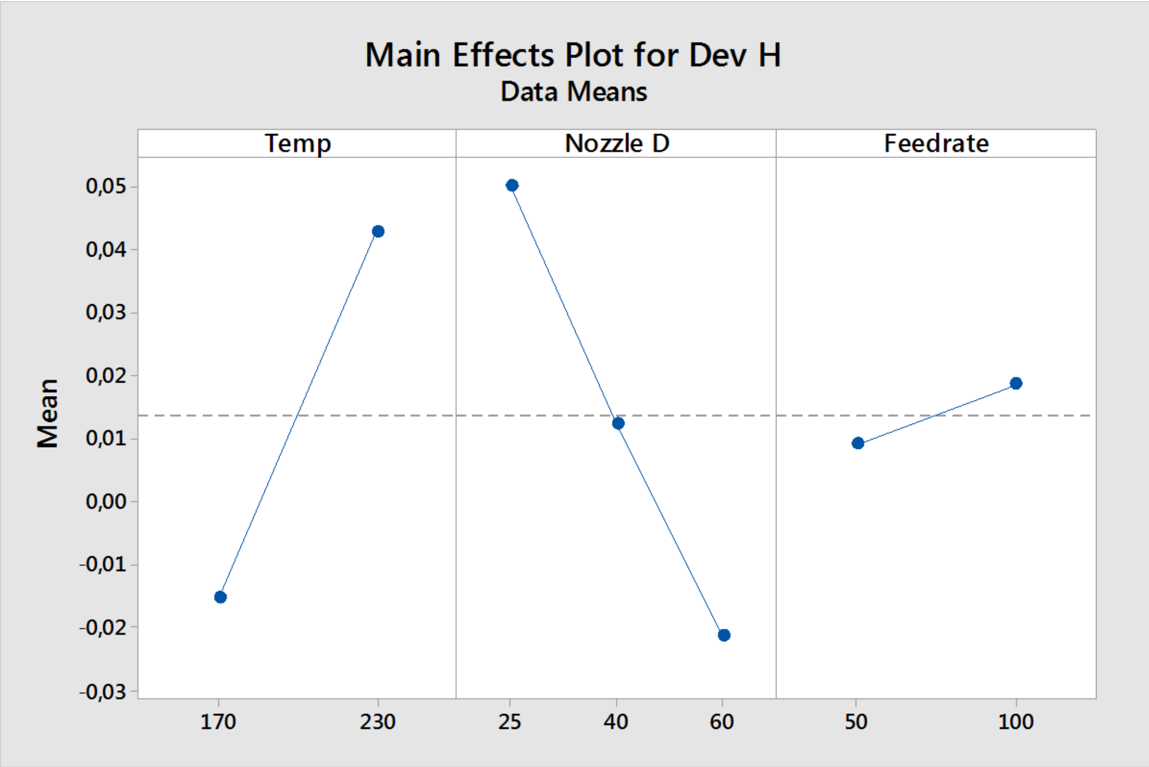


Fig. 46. Influence of nozzle temperature, feed-rate and nozzle diameter on Dev H dimensional accuracy

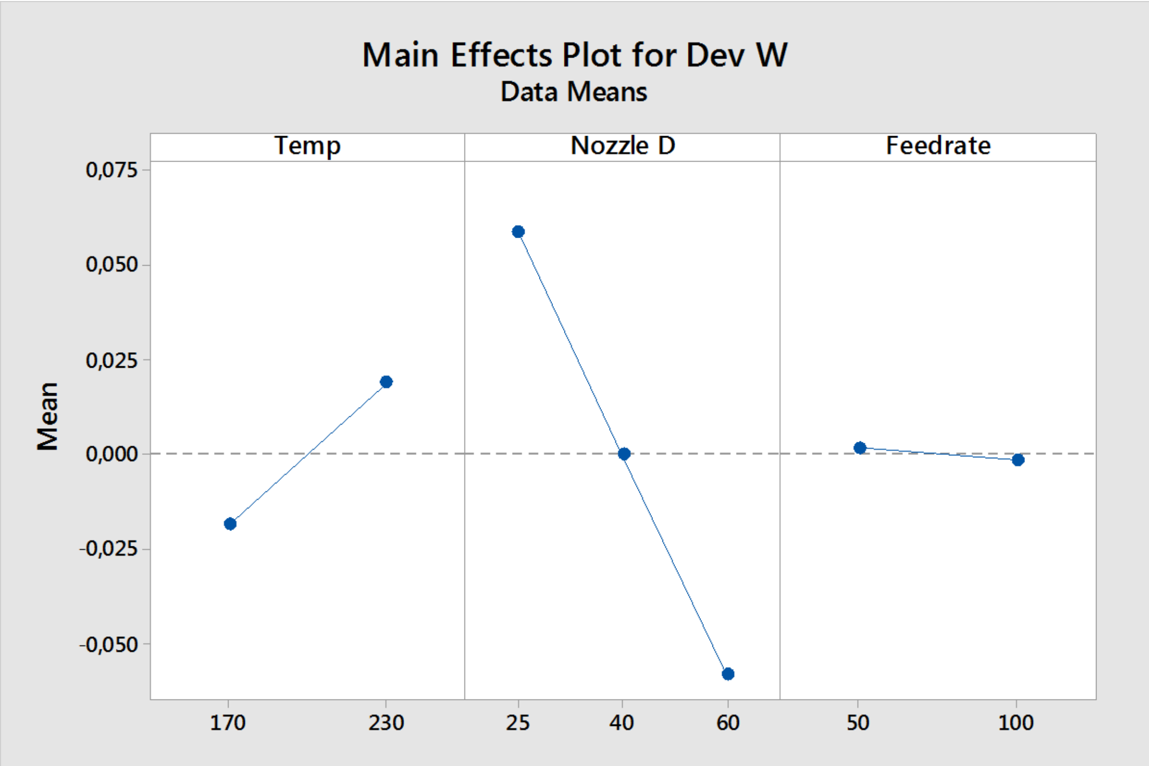


Fig. 47. Influence of nozzle temperature, feed-rate and nozzle diameter on Dev W dimensional accuracy

4. CONCLUSIONS AND SUGGESTIONS

In this Master thesis, an open-source 3D printer (Prusa i3) was studied. Test targets were prepared with Solidworks2014 CAD program and converted to STL file format. Slicer slicing software was used for printing process and printing parameters adoption. Printing parameters were chosen for understanding the impact on the surface finish and dimensional accuracy properties of test targets printed in PLA.

Visual inspection

The results discussed here were compared through visual inspection and two tendencies were observed. Best surface finish quality with almost no geometrical errors showed that parts printed with 0,25 mm nozzle diameter. Test target printed with highest (230˚C) nozzle temperature and lower (50%) feed-rate appeared to be the most precise and qualitative in a whole set. Considering test parts printed with 0,4 mm and 0,6 mm common geometrical errors visually seem to be evident. Parts printed in highest temperature and lowest feed-rate seem to have the better surface finish quality, but not the same as parts printed with 0,25 mm nozzle diameter. All set of test targets were studied and the worse quality test target had inadmissible geometrical errors for quality definition and printed with 0,6mm nozzle diameter with lowest (170˚C) temperature and highest feed-rate value. Nevertheless feed-rate factor did not have a significant impact on test targets surface finish. Significant differences are observed just between different temperatures. These observations lead to conclusion that the smaller nozzle and higher temperature leads to the formation of more accurate and qualitative surface finish of the part.

Comparative data

Comparative data shows obvious evidence of material shrinkage problem. Almost all graphs are showing deviations of negative lines (cuts), model length, width, circle, circle cuts and pins values are smaller than nominal ones. For instance comparing model length average deviations sorted by nozzle diameter the results are: - 1,8% (for 0,25 mm nozzle), -1,64% (for 0,4 mm nozzle), -2,48% (for 0,6 mm nozzle). The model width values are -3,5%, -1,63%, -1,7% by the same sequence of nozzle diameter. As it can be seen, all values are negative. This requires a solution how to maintain nominal values in printed models. The only feature, which showed measured values greater than nominal, was model height; this is due to substitution of extrusion road process. This problem could be solved if additional model would be printed at the same time ant be one layer higher.

ANOVA

Analysis of variance for Dev H and Dev W showed a dominant, statistically significant effects of nozzle temperature and nozzle diameter on surface finish and dimensional accuracy (Dev H: p=0,000), (Dev W p=0,000). No significance was found for feed-rate (Dev H p=0,495), (Dev W p=0,663) which are greater than ($p>0.05$). Residual plots also confirms the significance of nozzle temperature and diameter (Fig. 44, Fig.45). Main diagrams of effects (Fig. 46, Fig.47) show that higher nozzle temperature for Dev W has mildly effect for dimensional accuracy(from -0,02 to 0,02), while for Dev H has a pronounced effect and deviations are higher(-0,02 to 0,045). Feed-rate had no significant influence, the variance of means are relatively small even or close to zero for Dev W. However for Dev H feed-rate seem to have positive deviations form 0,01 to 0,02. The nozzle diameter seem to indicate the process of stress, which influence the melt going through narrow nozzle opening. This shows the effects for both responses Dev H and Dev W, where 0,6 mm nozzle diameter determine negative values and 0,25 mm positive values. To sum up, fundamental lines' width is more accurate than height and it is effected by nozzle temperature and nozzle diameter, which can be called critical parameters.

4.1 Applicability

FFF/FDM technology is one of the additive manufacturing technologies with great potential towards functional parts manufacturing. This research was designed to fill the gaps and broaden the database of optimum printing parameters. The results of this research will help manufacturers and makers in creating parts with higher dimensional accuracy and provide the values for fabricating parts with better surface finish quality. With these observations FFF technology users can benefit by saving time and cost when determining printing process and built parameters, which will suit their needs.

4.2 Future research

The future aim of this work is to investigate additional process parameters, for instance build orientation and get deeper knowledge of shrinkage factor, to study holistically the relationship and interactions of all critical FFF/FDM process parameters. Moreover, the development of non-linear model predictions would lead to multi-objective optimization algorithms.

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6. APPENDIX