



**Kaunas University of Technology**  
Faculty of Mechanical Engineering and Design

**Research of dimensional accuracy and surface quality  
dependency on printing speed of FDM 3D printed parts**

Master's Final Degree Project

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**Laisvūnas Levinskas**

Project author

**Prof. dr. Vytautas Grigas**

Supervisor

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**Kaunas, 2019**



**Kaunas University of Technology**  
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# **Research of dimensional accuracy and surface quality dependency on printing speed of FDM 3D printed parts**

Master's Final Degree Project  
Mechanical Engineering (code 6211EX009)

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**Kaunas, 2019**



**Kaunas University of Technology**  
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## **Research of dimensional accuracy and surface quality dependency on printing speed of FDM 3D printed parts**

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I confirm that the final project of mine, Laisvūnas Levinskas, on the topic „Research of dimensional accuracy and surface quality dependency on printing speed of FDM 3D printed parts“ is written completely by myself; all the provided data and research results are correct and have been obtained honestly. None of the parts of this thesis have been plagiarised from any printed, Internet-based or otherwise recorded sources. All direct and indirect quotations from external resources are indicated in the list of references. No monetary funds (unless required by Law) have been paid to anyone for any contribution to this project.

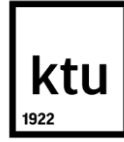
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**Kaunas University of Technology**

Faculty of Mechanical Engineering and Design

Study programme: MECHANICAL ENGINEERING 6211EX009

## **Task Assignment for Final Degree Project of Master's Studies**

**Student** – Laisvūnas Levinskas

**Title of the Project** – Research of dimensional accuracy and surface quality dependency on printing speed of FDM 3D printed parts

*(In English)*

FDM metodu 3D spausdintų detalių matmenų tikslumo ir paviršių kokybės tyrimas

*(In Lithuanian)*

### **1. Aim and Tasks of the Project –**

**Aim:** to test how increasing FDM 3D printer's speed characteristics affects dimensional accuracy and surface quality of the parts. **Tasks:** to analyse the working principle of fused deposition modeling (FDM) 3D printing technology and identify main specifications of 3D printers that affect printing speed; to develop a hypothesis on how these speed characteristics might affect dimensional accuracy and surface quality; conduct series of experiments to test how increasing speed affects dimensional accuracy and surface quality of 3D printed parts.

### **2. Initial Data –**

Extruder has non-linear extrusion and reduced relative output with increased flow rate.

### **3. Main Requirements and Conditions –**

Specimens printed at least by two different printers based on FDM technology have to be tested. The effect of maximal speed, acceleration and jerk (at least three different values each) has to be evaluated

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Study field and area (study field group): Technological Sciences, Mechanical Engineering,

Keywords: FDM, 3D printer, dimensional accuracy, surface quality, speed, relative output, non-linear extrusion

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### **Summary**

The impact of increased maximum speed, acceleration and jerk characteristics on dimensional accuracy and surface quality of FDM 3D printed parts has been determined.

The FDM 3D printing technologies and working principles of different 3D printers has been analyzed. Types of FDM 3D printers, their construction types and main motion characteristics identified. Research hypotheses have been developed and experiments designed according to possible surface imperfections caused by increased speed.

Experiments have been carried out in three main parts. First of all, the influence of increased maximum printing speed on 3D printed part dimensional accuracy and surface quality has been determined. Specimens on two different printers have been printed, measured and scanned for visual analysis. It has been determined that increasing maximum speed changes frequency of surface ringing artifact. High flow rate is a consequence of high speed and causes low relative output and non-linear behavior of the extruder. This result in reduced dimensional accuracy and lower surface quality. Next the influence of increased acceleration and jerk settings on printed part dimensional accuracy and surface quality has been determined. After printing and measuring specimens it has been concluded that increasing acceleration or jerk causes linear reduction in dimensional accuracy. Increasing acceleration and jerk at the same time has cumulative effect. Lastly the relative output of Anycubic i3 Mega 3D printer has been determined by extruding fixed length of filament and increasing speeds. Relative output is reduced as flow rate increases. Increasing nozzle temperature lowers reduction in relative output.

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### **Santrauka**

Nustatyta, kaip nuo maksimalaus spausdinimo greičio, pagreičio arba „jerk“ parametrų priklauso FDM technologija 3D spausdintų detalių matmenų tikslumas ir paviršiaus kokybė.

Atlikta literatūros šaltinių apžvalga ir išanalizuotos FDM 3D spausdinimo technologijos bei spausdintuvų veikimo principai. Išskirti pagrindiniai 3D spausdintuvų tipai, jų galimos konstrukcijos ir pagrindinės judesio charakteristikos. Nustatyta, kokius paviršiaus netobulumus sukelia pernelyg didelis spausdinimo greitis ir atitinkamai išsikeltos hipotezės bandymams atlikti.

Bandymai atlikti keliais etapais. Pirmiausia nustatyta, kokią įtaką detalių tikslumui turi maksimalus spausdinimo greitis. Dvejais skirtingais spausdintuvais atspausdintų bandinių matmenų tikslumas išmatuotas mikrometru, o paviršiaus kokybės analizė atlikta juos nuskenavus ir skenuotus vaizdus palyginus tarpusavyje. Gauta, kad padidinus maksimalų spausdinimo greitį pakinta detalių paviršiaus bangavimo dažnis. Dėl didelio spausdinimo greičio padidėja plastiko tekėjimo srautas, kuris nulemia sumažėjusią santykinę ekstruderio išeigą, bei nelinijinės ekstruzijos efektą. Dėl šių priežasčių sumažėja detalių matmenų tikslumas ir suprastėja paviršiaus kokybė. Taip pat nustatyta, kokią įtaką detalių tikslumui ir paviršiaus kokybei daro padidinti spausdinimo pagreičio ir „jerk“ parametrai. Atspausdinus ir išmatavus bandinius nustatyta, kad matmenų tikslumas tiesiškai mažėja didinant pagreičio arba „jerk“ parametrus. Matmenų tikslumas yra dar mažesnis, jei šie parametrai yra didinami kartu. Galiausiai ištirta 3D spausdintuvo „Anycubic i3 Mega“ ekstruderio santykinė išeiga. Tai atlikta ekstruduojant nustatyto ilgio plastiko giją vis didinant tiekimo greitį. Bandymų metu gauta, kad santykinė išeiga sumažėja, kuomet plastiko tekėjimo srautas didėja.

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## List of abbreviations and terms

### Terms:

**Fused Deposition Modeling (FDM)** – additive manufacturing process, where melted material is extruded in a pre-defined path layer-by-layer.

**Build platform** – flat horizontal surface on which first layer of molten plastic is extruded. It is often heated and can be called heated bed.

**Print head** – part of 3D printer's construction that is moved above the build platform and has a function of melting plastic and laying it in a path.

**Print head's gantry** – 3D printer's subframe that print head is attached to. Gantry is moving with print head and connecting it to main frame of 3D printer.

**Nozzle** – lowest part of the print head. Nozzle has an opening of specific diameter through which molten plastic exits. Diameter of the opening defines printing layer width.

**Extruder** – stepper motor and set of gears that push plastic filament through the print head.

**Plastic filament** – long and thin strand of plastic that pushed by extruder into the print head. Plastic filament can be considered as raw material for 3D printing and is stored coiled in a spool.

**Bowden tube** – tube through which plastic filament is guided. Most often it is made out of teflon and guides filament from extruder to the print head.

## Introduction

3D printing has become increasingly more popular over the last decade. Ability to quickly manufacture parts for everyday use, hobby or prototyping has proven to be very useful to many people. Furthermore, variety of plastics – stiff, flexible, food safe, water-soluble, UV resistant, etc. are available. Market has been filled with many 3D printers at different price points. Fused deposition modeling (FDM) 3D printing method is the most common due to relatively simple working principle, easy usage and cheap manufacturing. Despite having many positives, one negative is that it is still rather slow process. Even the smaller objects can take hours to manufacture, and larger parts – days. Printing speeds are usually kept around 60 mm/s, and even though it is easily possible to set it higher, part quality starts to deteriorate. Dimensional accuracy and surface quality is reduced.

Knowing speed to accuracy relation could help choose optimal settings for minimal time spent printing, maximum dimensional accuracy and best visual appearance. Such knowledge would also help designers and manufacturers of 3D printers to make educated engineering decisions when designing 3D printers. Better printers with high printing speed would be beneficial to save time, allow more manufactured parts per time, reduce electricity costs by reducing time needed to heat build platform and the nozzle.

The aim of the project is to find out how FDM 3D printer's speed characteristics affects dimensional accuracy and surface quality of the parts.

To achieve this aim the following tasks should be solved:

- to analyse the working principle of fused deposition modeling (FDM) 3D printing technology and identify main specifications of 3D printers that affect printing speed;
- to develop a hypothesis on how these speed characteristics might affect dimensional accuracy and surface quality;
- conduct series of experiments to test how increasing speed affects dimensional accuracy and surface quality of 3D printed parts.

## **1. Literature analysis of FDM 3D printing technology**

In this chapter literature analysis on FDM 3D printing technology will be carried out. Firstly, overview of several most relevant scientific papers and articles, then analysis of working principle, types of FDM 3D printers and lastly required software.

### **1.1. Analysis of previous research**

No scientific research on dimensional accuracy and surface quality dependency on printing speed of 3D printed parts has been found. However, some research has been done on FDM 3D printed part's surface quality in general. One of the more comprehensive research papers is Surface Roughness Quality and Dimensional Accuracy by Mohammad S. Alsoufi and Abdulrhman E. Elsayed [1]. In this research authors propose an analysis of surface roughness and dimensional accuracy of parts manufactured using desktop FDM 3D printers. Rectangular specimens of dimensions 40 mm (L) × 40 mm (W) × 15 mm (H) have been printed and measured using contact-type surface profilometer test-rig and electronic digital calipers.

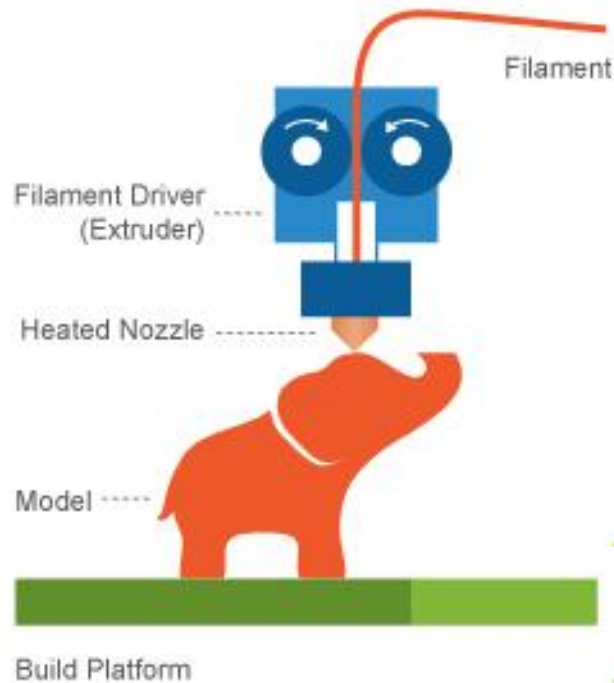
Results show that PLA plastic exhibits better surface smoothness and dimensional accuracy when compared to ABS. Specimens from PLA and ABS has comparable dimensional error in horizontal dimensions. However, specimens from PLA had 2% error in vertical axis, while ABS plastic had as much as 18% error in vertical axis. Reason for this is that ABS plastic has a tendency to shrink much more when cooling and consequently warp. Knowing these results allowed to choose best plastic to use in the experiments – PLA.

Some research has been done on jerk and its effects on corner quality by Daniel Halvorson. He wrote an article “A Solid Foundation for: High-Quality Corners” [2] where he tested various jerk values and visually inspected specimen appearance. Even though specimen's measurements were not taken out, he still discovered that reducing jerk reduces surface ringing, but significantly increases corner swell. And increasing jerk reduces corner swell, but introduces surface ringing. This article showed that it is reasonable to expect reduced dimensional accuracy at corners when changing jerk setting.

Philippe Carrier published three part article named “Printing at 300 mm/s” (Part 1 – Basics and hardware, Part 2 – Calculations, Part 3 – Firmware and tests) [3]. Article in depth explains relevant specifications and settings of 3D printers that need to be considered when printing at high speeds. Besides frame rigidity and stepper motors one of the most important considerations is the extruder. More specifically its ability to extrude required amount of plastic at a given speed or flow rate. During high flow rate moments extruder exhibits low relative output which results in under-extrusion. Author of articles also did a series of calculations to determine stepper motor rotational speeds, optimal layer height, etc. One of more relevant calculations is required stepper torque for X and Y axes. Printer used in these articles had print head which moves in X axis and built platform which moves in Y axis. Philippe Carrier calculated that load on Y axis's stepper motor could be at least twice as big as on X axis's. This indicates that printers that have low moving mass could potentially have better print quality.

## 1.2. FDM 3D printing basics

FDM stands for Fused deposition modeling. It is additive manufacturing process where melted plastic material is extruded in a pre-defined path layer-by-layer. Figure 1 shows fundamental parts that make FDM 3D printer.

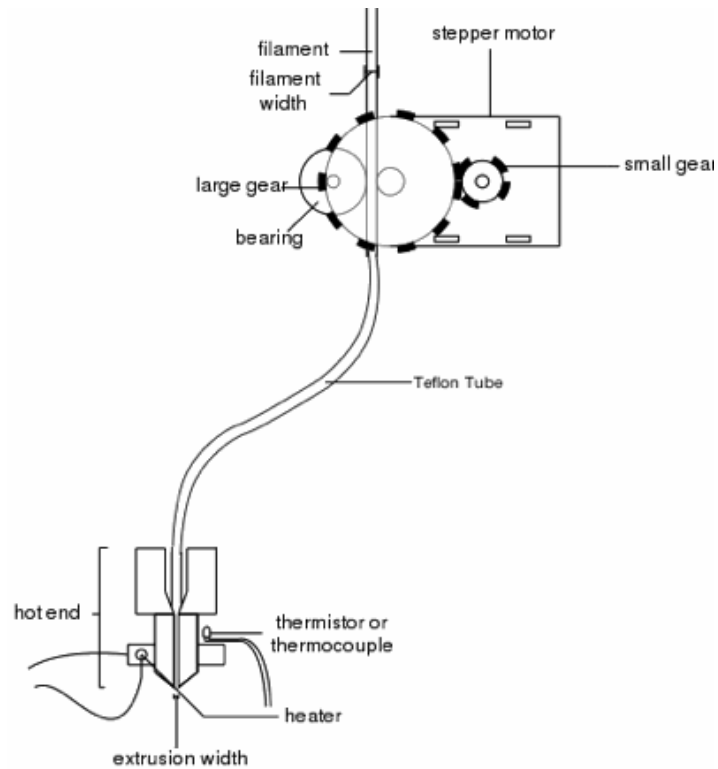


**Fig 1.** FDM 3D printing principle [4]

Extruder uses torque to turn gears which pull plastic filament from spool (not shown) and pushes it into the heated nozzle. Molten plastic is then placed in a line onto build platform. Lines eventually form layers which shape 3D model. Resolution of 3D printed part is defined by nozzle diameter and layer height. Most common nozzle diameter is 0,4 mm and is often not changed, because it requires an experienced user to change the nozzle. 0,4 mm is used because it strikes good balance between quality and printing speed. Layer height can be changed in software for every model individually. Most common range is between 0,1 mm and 0,3mm. Lower layer height offer better vertical resolution, but result in much longer printing times. Figure depicts a direct extruder, where extruder moves together with the nozzle. However, there are a couple of different extrusion types which will be analyzed in the next section.

## 1.3. Extrusion types

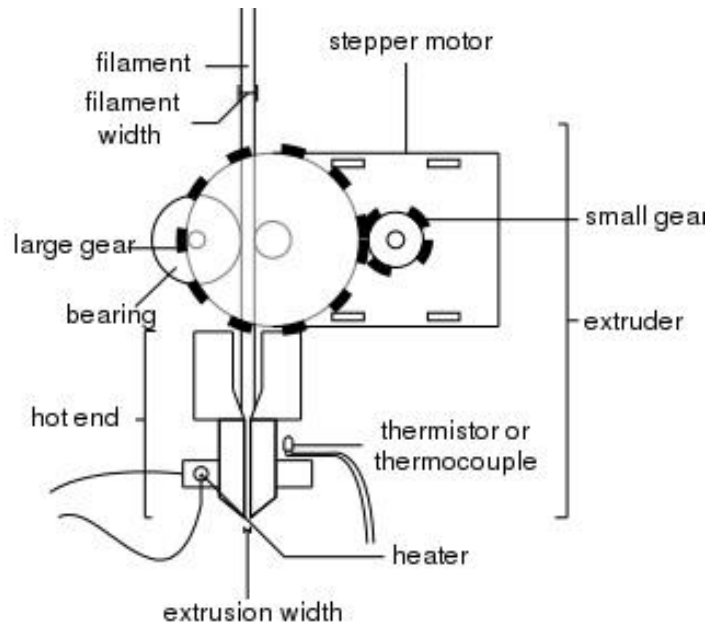
There can be printers that use bowden extruder or direct extruder. Main difference between these types is where extruder is placed in relation to print head. In Bowden type extruder motor is placed rigidly on non-moving part of the frame and feeds filament into the hot end via a teflon (a.k.a. bowden) tube. Basic principle is shown in figure 2.



**Fig 2.** Bowden extrusion principle [5]

Figure shows relevant parts of bowden extruder. As mentioned previously, the most important feature is bowden (teflon in the figure) tube which guides filament plastic from the extruder into the print head's hot-end. Extruder is attached rigidly somewhere on the frame of 3d printer. Tube has internal diameter larger than diameter of the plastic filament. Usually around 2 mm for 1,75 mm filaments. Ideally gap would be smaller to reduce backlash, but there are always some tolerances for tubes and also filament itself. Filament must slide freely in the tube, otherwise it might cause bad quality 3D prints or fail completely. Tube is flexible and can have varying lengths depending of placement of the extruder. Again, it is considered that shorter is better to reduce backlash.

Next extrusion type is direct extrusion. The main defining feature of this type is that extruder is attached directly to the hot end. In this case, extruder is part of a print head and moves together with a hot end. Basic principle is shown in figure 3.



**Fig 3.** Direct extrusion principle [5]

When it comes to printing speed, it is considered that bowden type extruder allows for higher speeds. This is because print head is lighter and does not have added mass of heavy extruder stepper motor. Lower moving mass means lower momentum and lower loads on the frame when accelerating and decelerating potentially reducing overshoot and surface ringing [6].

On the other hand, direct drive extruder potentially has greater accuracy of how much filament is being pushed into the nozzle. Since distance between extruder and nozzle is much shorter there is much less backlash when compared to bowden type extruder.

#### **1.4. FDM 3D printer form factors**

3D printers exist in variety of form factors, each having their own advantages and disadvantages and potential print quality. Two main types of FDM 3D printers are cartesian and delta printers.

##### **1.4.1. Delta printers**

Delta printers (Fig 4) are increasingly more popular due to efficient use of print space and speeds. They have fixed build platform and extruder is moved using three motors. Since extruder assembly is designed to be as light as possible, these printers are potentially faster compared to cartesian printers [8].



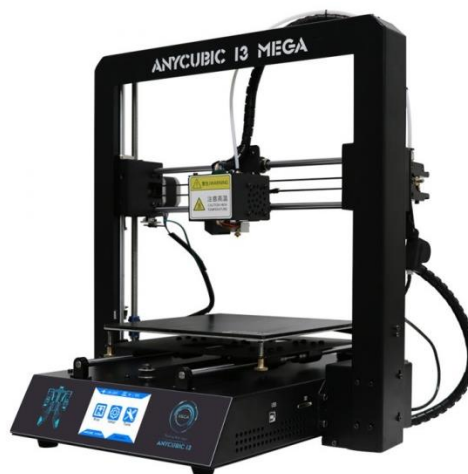
**Fig 4.** Delta 3D printer Anycubic Kossel plus [7]

However, difficult calibration process caused by complicated navigation in delta's 3D space, means that it is not easy to print dimensionally accurate parts. Delta printers are only possible with Bowden extruder which may further limit their application.

#### **1.4.2. Cartesian printers**

In 3D printers, X and Y axes travel longest distances and are the most important when it comes to speed. These axes are moving the fastest, therefore reducing their moving mass should be the most important goal. Most often extruder is moved in two axes and build platform is moved in a third axis. This is where these printers could be divided into several sub-types depending on which axes are their main, i.e. in which two axes nozzle is moved.

Due to simple construction XZ-type (Fig 5) printer is probably the most common. Especially in desktop/consumer space.

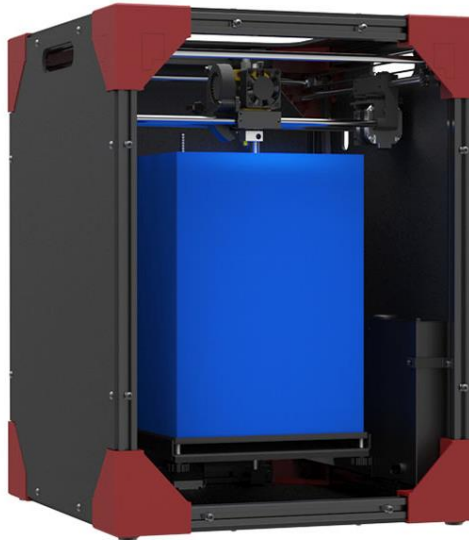


**Fig 5.** XZ-type cartesian 3D printer Anycubic i3 Mega [9]



Here build platform is moving in Y axis and it is this types biggest drawback. Build platform itself is already pretty heavy when compared to printhead. When printing, mass is being continuously added to the platform which further increases its mass. In addition, if printing tall and narrow parts, plastic part not being perfectly stiff itself may start to wobble in Y axis.

XY-type (Fig 6) printers, as the name implies, move extruder in X and Y axes. Z axis is used to move build platform.



**Fig 6.** XY-type cartesian 3D printer Anycubic 4 Max [10]

Such system is inherently faster than XZ-type printers, because heavy build platform with printed model is moved in slow Z axis, and lighter print head assembly is moved in main X and Y axes. Reduced mass and inertia of the print head assembly should allow for higher acceleration and faster prints while maintaining dimensional accuracy and surface quality. Even more so on large volume printers. However, having a direct extruder on XY-type printer might negate mass advantage over XZ-type. There are also many other considerations. Even same type of printers from different makers can manufacture better or worse quality prints depending on frame rigidity, component quality and pre-set settings like acceleration and jerk.

It has been established that lower moving mass should improve printed part quality. However, it is not easy to test this statement experimentally. That is because 3D printers are already assembled machines and changing their configuration would be hardly an easy task. Testing with different model printers with different configurations is not feasible, because even slight changes in frame construction or drive system could have big effect making results incomparable. However, in Newtonian mechanics momentum of an object is the product of velocity and mass. And Newtons second law states that force is a product of mass and acceleration. This means, that we can still test effects of increased momentum by increasing speed and acceleration and keep mass constant.

At this point most typical FDM 3D printer hardware configurations have been identified. Next main motion characteristics will be described.

## **1.5. Motion characteristics of FDM 3D printers**

There are several main characteristics that impact how quickly FDM 3D printer's print head moves at any given moment. These characteristics affect printing time and also printed part's quality in different ways.

In this project, it is considered that: parameters that when changed, directly affect how quickly 3D printer's print head moves at any moment are speed parameters. In addition to maximum printing speed, acceleration and jerk will be also considered as speed parameters, even if they don't correspond to maximum speed.

### **1.5.1. Maximum speed**

Maximum speed is velocity that print head can reach, measured in mm/s. This parameter can easily be changed in slicer software, but is often limited in 3D printer's firmware to 300 mm/s. Printer never reaches maximum speed instantly, there is always some acceleration set. If acceleration setting is low and printed lines are short, then print head may not even reach maximum speed. Maximum speed directly impacts printing time, but common assumption is that setting it too high would reduce quality of manufactured parts [11]. Therefore, often it is set at around 60 mm/s for most plastic filaments. One of the goals of this project is to test how exactly increased speeds affect quality of the parts.

### **1.5.2. Acceleration**

Acceleration is how quickly print head increases its movement speed, measured in  $\text{mm/s}^2$ . This parameter can be changed in slicer software by inserting additional command lines at the start of gcode. Sometimes it can be changed directly within printer's user interface if manufacturer allows, or by flashing custom firmware to the printer with changed default values. Manufacturers often set acceleration of 3D printers at  $1000 \text{ mm/s}^2$  to  $3000 \text{ mm/s}^2$ . Setting acceleration low (e.g.  $1000 \text{ mm/s}^2$  or less) would force nozzle to approach corner at a slower rate before starting movement in a new direction, reducing its momentum. And in theory, lower the momentum, lower the overshoot amount and less surface ringing. Setting acceleration high can be beneficial to reduce printing time and reduce corner swell effect by reducing amount of time nozzle moves slowly or is stationary. Ideally, acceleration would be as high as possible, so that printing time is at its lowest and printing speed is as close to constant as possible. In reality, it is difficult to achieve - there many hardware limitations. Firstly, force is needed to accelerate printhead and NEMA 17 stepper motors used in 3D printers typically have only about 0,5 Nm of holding torque [12]. Secondly, processing chip inside 3D printer with stepper motor drivers have to be fast enough to process increased data rates that come with high acceleration. Then frame, print head's gantry, belt and pulley system have to be not only strong, but more importantly rigid enough not to flex when print head accelerates and decelerates. Lastly, extruder has to be able to provide required amount of plastic at the right time. How exactly increasing acceleration affects 3D printed parts will be tested during the experiments.

### **1.5.3. Jerk**

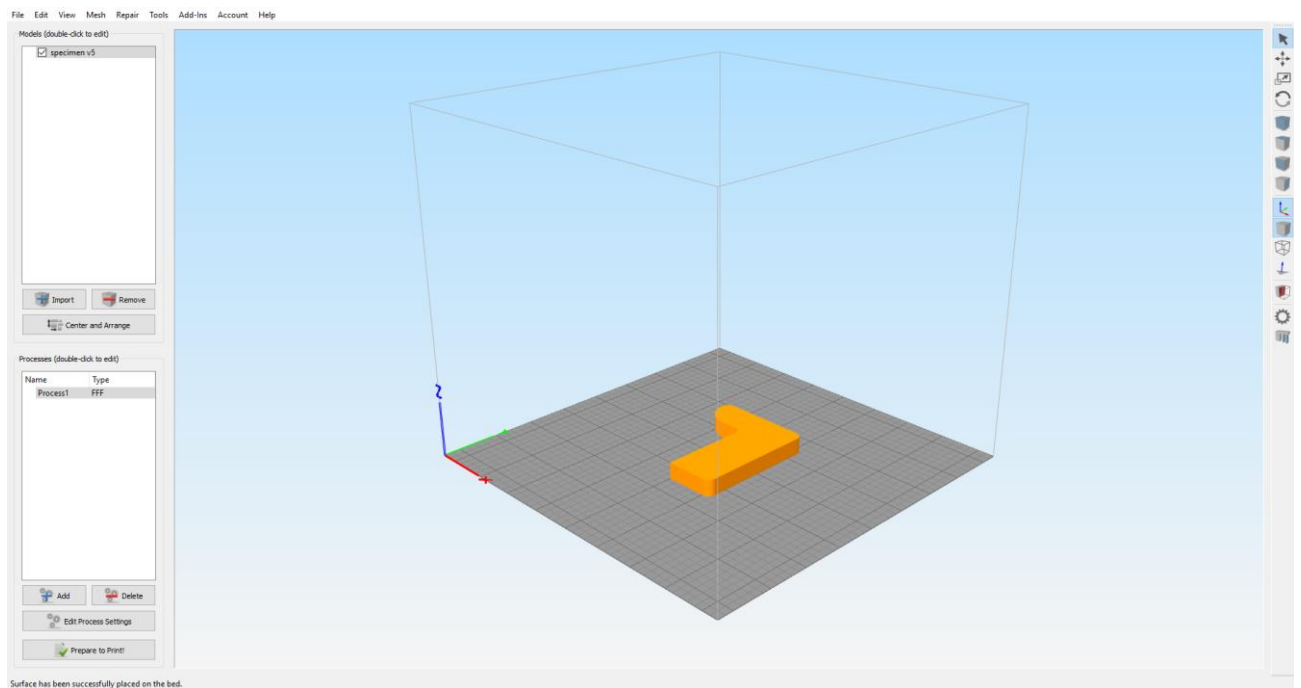
Jerk in physics is rate of change of acceleration. However, in 3D printing this parameter has different meaning. It defines minimum speed at which acceleration is applied. Measured in mm/s. Below set jerk value no acceleration is applied. For example, if jerk is set to 10 mm/s, then print

head will instantly jump from 0 to 10 mm/s and then start accelerating at set acceleration until it reaches maximum speed. Conversely print head will decelerate to 10 mm/s and then instantly go to 0 mm/s when stopping. Obviously, this would mean infinite acceleration between 0 and 10 mm/s which is physically impossible. This is only what controller tells stepper motors to do, which causes steppers to accelerate and decelerate at maximum rate they are capable of. Manufacturers tend to set jerk to 10 mm/s or 20mm/s.

Setting jerk higher would reduce printing time somewhat, but not as much as increasing acceleration. The main reason this feature is used, is to prevent corner swell by maintaining higher average speed while cornering. It is assumed that high jerk just like high acceleration causes surface ringing therefore these two parameters will be tested alongside.

## 1.6. Slicing software and printer firmware overview

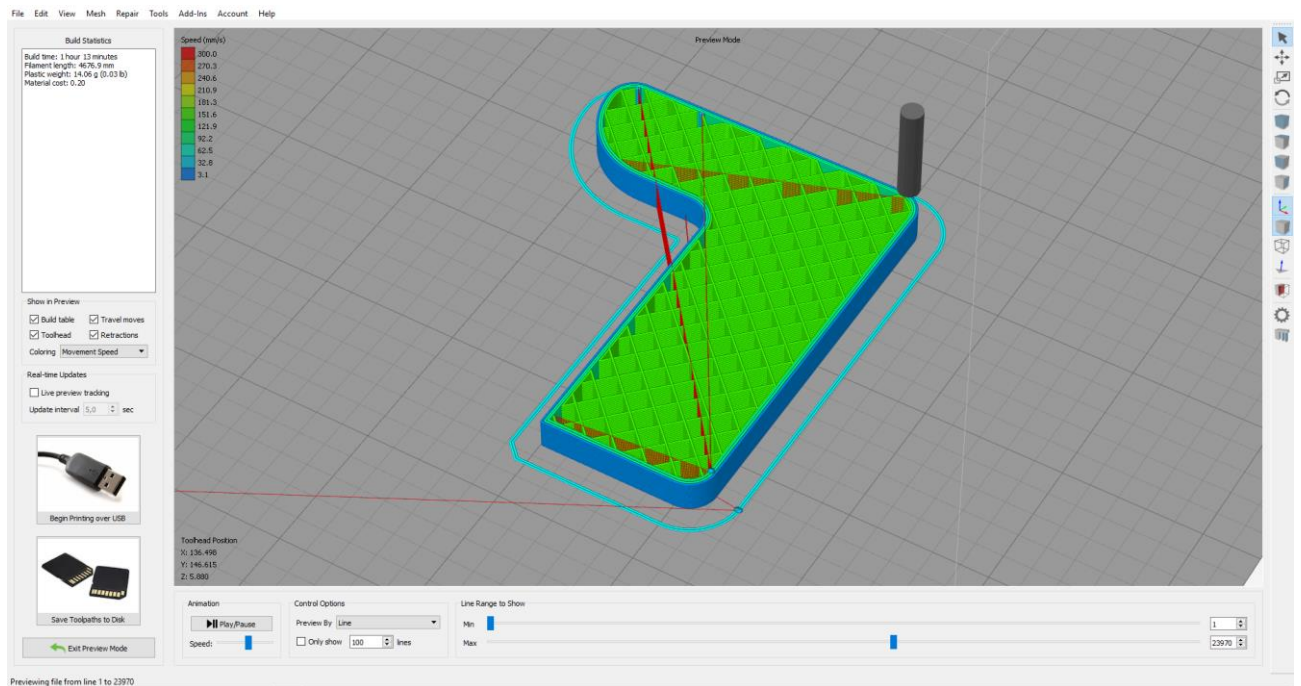
All FDM 3D printers today print using gcode file format. Gcode contains information about print head coordinates, speed, flow rate, temperature and other information. Slicer software converts 3D models from typical stl format to gcode. There are many applications available like: Cura, Slic3r and Simplify3D. All are different in their appearance and additional functions like support generation, but fundamental function is the same – slice 3D model into lines and layers and generate gcode. Simplify3D is used in this project. Main work window of Simplify3D slicer is shown in figure 7.



**Fig 7.** Main work window of Simplify3D

In the upper left section currently imported 3D models are listed. Just below that in the lower left section different processes are listed. Simplify3D allows slicing multiple different 3D models if build platform has enough space. Each 3D model can have different set of printing settings like retraction, wall thickness, etc. These different sets of settings are saved as beforementioned processes which can be assigned to different 3D models. Below processes section there is “Edit process settings” which opens settings window. All 3D printing settings are set there like: layer

height, retraction distance, wall thickness, speed, temperature, etc. Also advanced features like: ooze control behavior and thin wall behavior. 3D model itself is displayed in central area of the main program's window in orange color. Grey surface below it and bounding box represents build platform's area and volume of 3D printer. On the right side of the window there is vertical toolbar with 3D model movement, rotation and display settings. The last button in the toolbar allows generating automatic supports, or setting them by hand for greater control. The lowest button on the left of main window is "Prepare to Print!" which slices the model and takes to sliced model preview window (fig 8).



**Fig 8.** Sliced model preview window

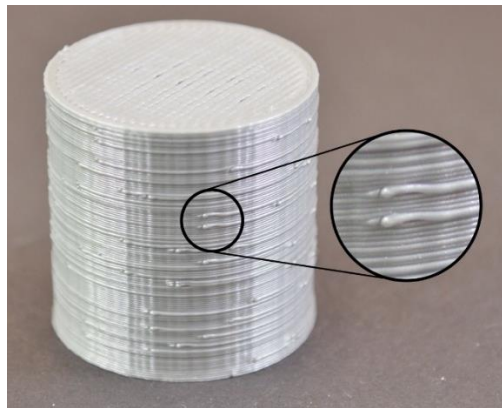
Here sliced 3D model is displayed and different layers can be seen by moving slider left and right located at the bottom of the window. Inside the 3D model rectilinear infill pattern is visible. Different colored lines represent different printing speeds. However, acceleration and jerk are not considered here, only maximum speed. In this case outer walls have lower set maximum speed to improve surface quality of the part. Thin red lines show print head's movement when plastic is not being extruded. This is useful, because areas where print head is crossing outside wall of the model might suggest places where blobs or strings of plastic might appear. In the upper left build statistics are displayed: build time, length of plastic filament and plastic weight. Again, acceleration and jerk are not considered, which means that projected printing time is only approximate. On the bottom left it is possible to choose whether to save generated gcode to SD card or to print directly from the computer using USB cable.

Another important aspect for 3D printers is their firmware. Firmware is piece of programming that runs on 3D printer's mainboard. It processes gcode and sends corresponding commands to stepper motor drivers, heaters, display, etc. The most popular open source firmware available for 3D printers is Marlin. It supports Delta, Cartesian, Scara and Core/H-Bot kinematics. Marlin version 1.1.9 is the latest version and features advanced features like Linear advance for pressure-based extrusion and S-curve acceleration [13]. Marlin is used in printers during this project. Newest

version of Marlin firmware has introduced a feature called Marlin Linear Advance. The purpose of this feature is to increase dimensional accuracy of 3D printed parts by compensating for non-linear extrusion. In practice, it is powerful tool that allows higher printing speeds with improved dimensional accuracy. However, in the experiments this feature is disabled, because it dynamically changes acceleration while printing. Linear advance feature is very computationally intensive and today's most common 8bit controllers can't cope. If controller is unable to carry out the instructions, acceleration is reduced to prevent skipped steps. It impossible to conduct experiments using it, because controlling acceleration is critical. In the near future however, 32bit mainboards might become mainstream and computational limits would be lifted. This would allow use of advanced features like Linear advance and S-Curve accelerations in conjunction with high maximum speed and high acceleration.

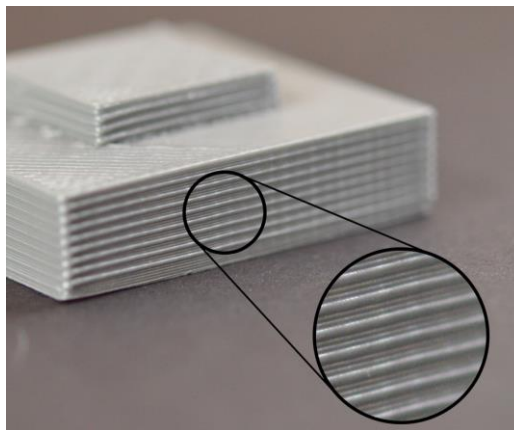
## 2. Identifying a problem

There are many different kinds of surface imperfections that can be caused by multiple different factors. Reasons of reduced quality are quite a few. Some can be related to slicer software settings, like heater temperature, fan speeds, retraction length etc. Other can be related to 3D printer's hardware, like frame rigidity and gantry's alignment, belt tensioning, stepper motor torque to name a few. Even bad plastic filament itself can introduce surface imperfections. A few examples of surface imperfections are shown in figures 1 to 4.



**Fig 9.** Blobs [14]

Blobs (Fig 9) are usually caused by incorrect retraction settings, which can be fixed in slicer software.



**Fig 10.** Lines [14]

Lines (Fig 10) are usually an indication of not perfectly straight Z axis threaded rod, which is hardware related issue.



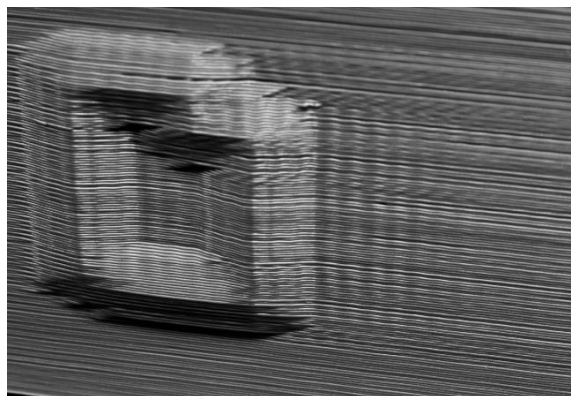
**Fig 11.** Layer separation and splitting [14]

Layer separation (Fig 11) might be caused by too thick layer height or too low environmental temperature. Disabling cooling fan can sometimes resolve this issue.



**Fig 12.** Warping [14]

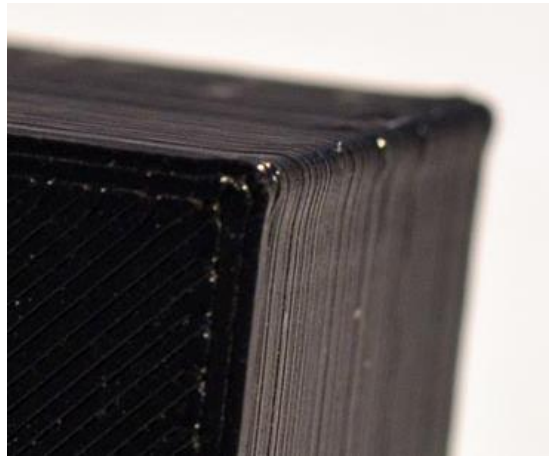
Warping (Fig 12) most often happens when heated build platform is not used or its temperature is set too low. Additionally, not perfectly clean build platform might prevent parts from sticking. After configuring printer's settings, it is possible to completely eliminate most of these imperfections without affecting print speed and accuracy significantly. However, surface ringing (Fig 13) and corner swell (Fig 14) are considered to be a direct consequence of increased or reduced speed, acceleration and jerk settings.



**Fig 13.** Surface ringing (ghosting) [11]

Surface ringing appears when print head has to make a sharp turn, but is unable to do instantly and overshoots. At the moment of direction change oscillations are introduced and continue along the

surface as vertical lines. Eventually they diminish as oscillations dissipate due to friction. Ringing could be more severe if printer's frame is not rigid enough or belts are not tensioned properly. It is thought that ringing occurs when print head is moving too fast, therefore reducing default printing speed is often a recommended solution [11].



**Fig 14.** Corner swell [15]

Corner swell also appears when print head is making a sharp turn. However, this time it is moving too slowly. Residual pressure inside the nozzle causes over-extrusion as print head is stopping for a direction change and results in a bulge at the corner of 3D printed part. Dimensional accuracy can be drastically reduced and parts that require tight tolerances might no longer fit together. Jerk setting is often considered to be the main factor here [2]

The problem of reduced dimensional accuracy and surface quality when increasing speed is more relevant than ever, because more and more parts are manufactured using FDM 3D printing technology for everyday use. Parts can take anywhere from several hours to several days to manufacture, depending on their size 3D printing settings. Long 3D prints cause increased power consumption. A medium sized 3D printer, can cost 0,03 € per hour to run in Lithuania [21]. That might not be much for a person who has one printer and uses it only sometimes. However, for a business which has a dozen of printers that run upwards of 20 hours a day, the cost can add up to thousands of Euros per year just on power alone. Reducing power usage would make 3D printing process more efficient. In addition, reduced printing time can allow more manufactured parts in a given time frame. For users this would mean shorter turnaround time.

Increasing printing speed is one of the primary ways to reduce printing time, however surface ringing and corner swell are two main problems that arise when speed is changed. These problems reduce dimensional accuracy and visual appearance of the parts. Such parts may become unusable for high-precision applications where parts have to fit together. Or surface quality might not be visually appealing for aesthetic purposes. Therefore, finding exact correlation between increased speed and change in accuracy and surface quality is the focus of this research.



### 3. Developing a hypothesis

There are a few surface imperfections that could manifest as direct or indirect consequence of increased speed and reduce dimensional accuracy. Direct effect of increased speed is overshoot at corners and consequently surface ringing. Since extruder and build platform have mass, when moving at speed they have momentum, therefore stopping them requires energy. The amount of which can be reduced by: a) reducing moving mass; b) reducing moving speed. Mass is more difficult to control on assembled printer, therefore in this research speed is the factor to be analyzed.

Indirect effects of increased speed are reduced relative output of the extruder and non-linear extrusion. When speed is increased flow rate also increases and causes under-extrusion. High maximum speed also means large changes in flow rate which manifest as non-linear behavior of extruder and can cause changes in print line width causing surface imperfections and corner swell.

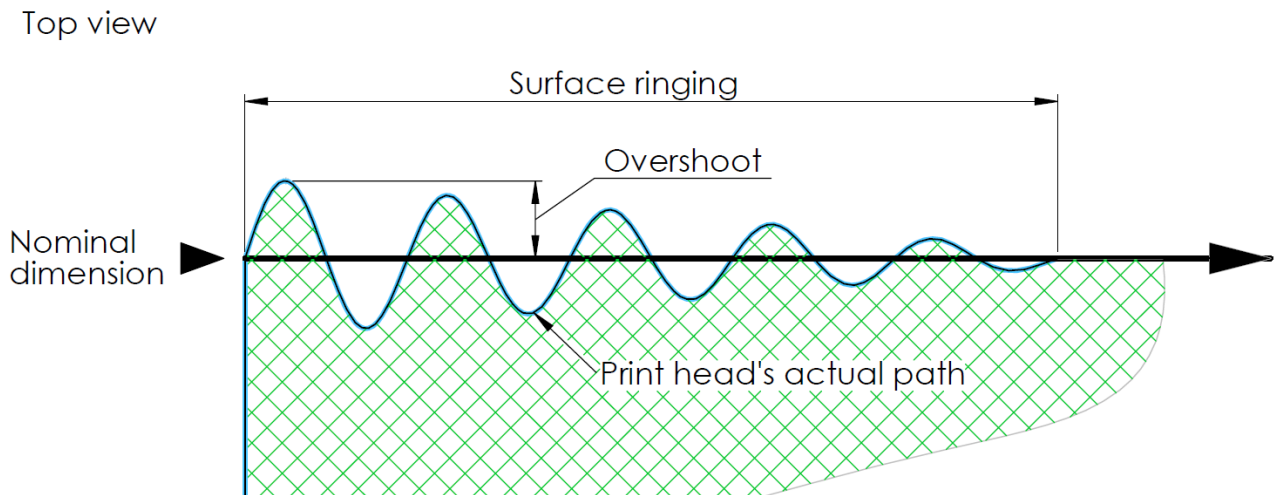
#### 3.1. Surface ringing

It is a fact that increased mass and speed increases momentum of an object. Increased momentum requires more force to stop an object, or change its direction. In FDM 3D printers, those objects can be: Print head and its gantry or build platform which are moving in X and Y axes. So, increasing speed of these parts would increase momentum and since no 3D printer's structure and drive mechanism are perfectly rigid, there would be an overshoot when changing direction causing surface ringing artifact. Example of this effect is shown in figure 15.



**Fig 15.** Part with no surface ringing on the left and part with ringing on the right [16]

How ringing artifact occurs is show in figure 16.



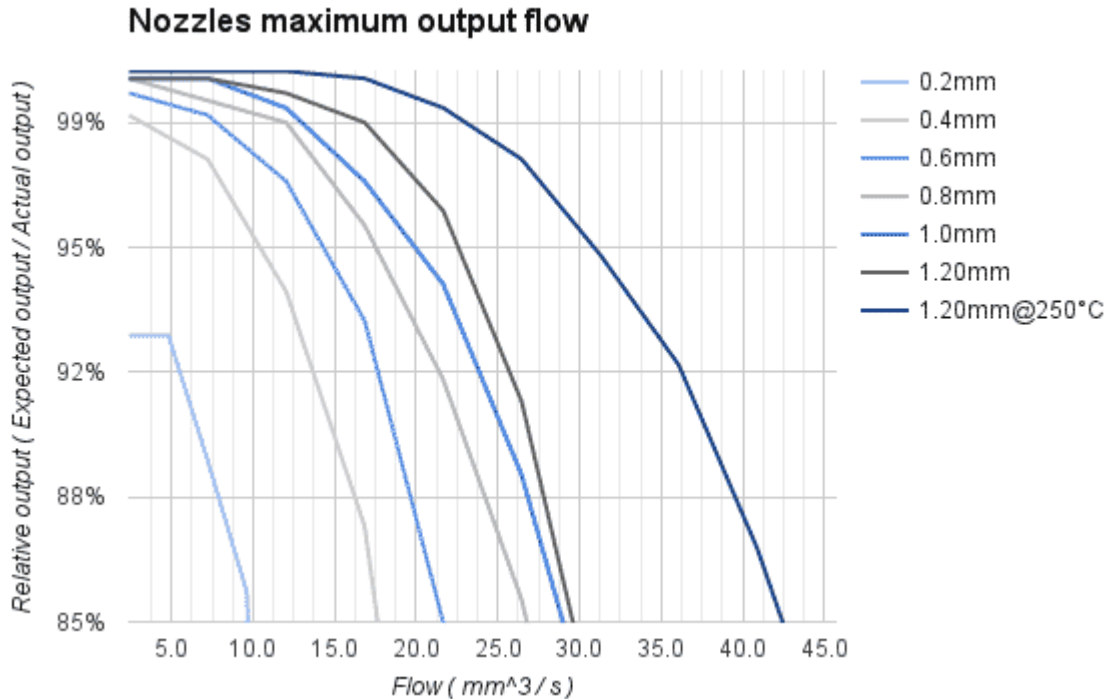
**Fig 16.** Surface ringing scheme

Here, thick blue line represents actual path of the print head as if we are looking at it from the top. Black line represents theoretical path that should've been. Green hatch represents internal volume of 3D printed part. Print head travels straight and after it makes a sharp turn to the right starts to oscillate resulting in waves on the surface of the printed part. It is expected that amount of overshoot is large enough to be measurable.

Surface ringing will be analyzed in the experiments by measuring specimens printed at different speed settings. However, it is important to keep in mind that all mechanical systems are subject to vibrations. Especially 3D printers that do abrupt and frequent direction changes. It is easily possible to introduce resonant frequencies in the frame or drive system causing some randomness in the process. For this reason it is possible that results obtained in these experiments might not be 100 % representative of real world situations.

### **3.2. Relative output of the extruder**

Next important factor when it comes to printing fast is extruder's ability to push required amount of plastic into the nozzle. Datasheets of some extruders show, that more plastic is forced through the nozzle, lower the relative output becomes [3]. In other words, faster print speeds, cause higher flow rate, making extruder unable to keep up and extrude less plastic than it is expected. For example, nozzle output flow graph for PLA plastic at 210°C with different nozzle sizes for DyzEnd-X extruder is shown in figure 17.



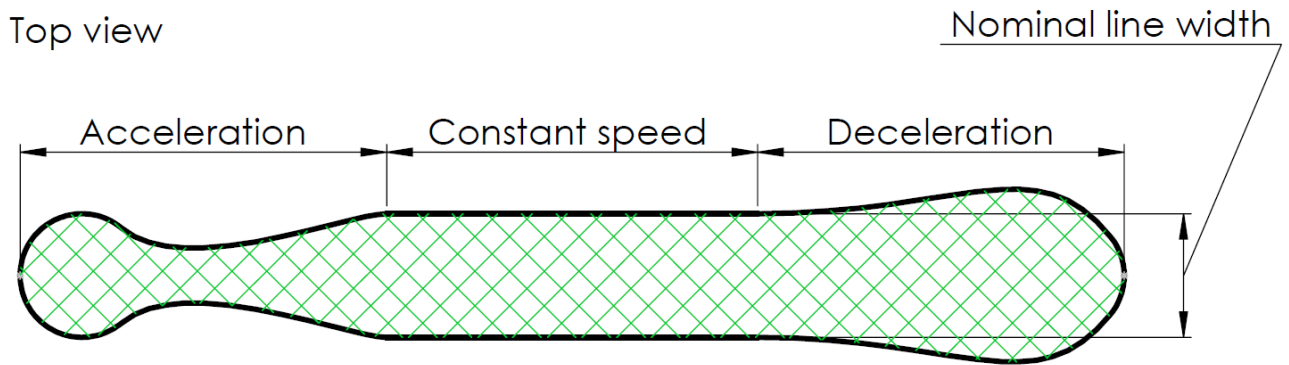
**Fig 17.** Nozzle flow/output graph for DyzEnd-X extruder [3]

With 0,4mm nozzle, when flow is 15mm<sup>3</sup>/s, relative output is only about 90%. Similar relation between flow and relative output is different on various extruders. However, most manufacturers don't provide such information.

In theory, it is possible to compensate for under-extrusion by increasing extrusion multiplier. However, this would only help when nozzle is moving at maximum speed, but nozzle is not moving at maximum speed all the time, it decelerates and sometimes completely stops when changing direction or layers. Therefore, increasing the multiplier would result in over extrusion at corners, which would make dimensional accuracy even worse.

### 3.3. Non-linear extrusion

Normally, extruder's axis is in linear proportion to x, y and z movement axes. This means that movement axes and extruder axis start moving, accelerate, move, decelerate and stop linearly. However, extruder is not a linear system, because plastic does not stop flowing immediately when extruder stops and does not start flowing immediately when extruder starts pushing [17]. Basic principle is shown in figure 18.



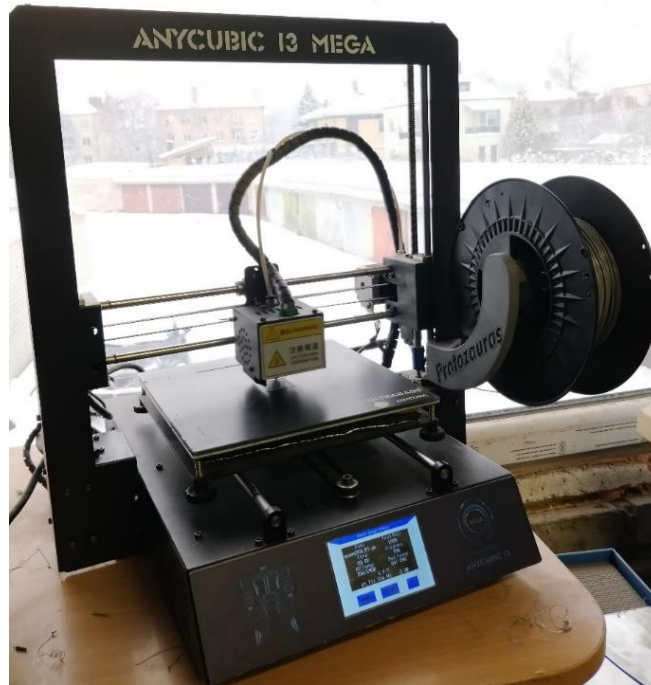
**Fig 18.** Basic scheme of non-linear extrusion

In theory, when accelerating, extruder starts pushing plastic into the nozzle, but in reality plastic starts flowing only after some pressure has built up in the nozzle, resulting in under extrusion in the beginning. When nozzle decelerates, extruder decelerates at the same rate, but pressure in the nozzle lags behind and pushes too much plastic, causing blob or over extrusion at the deceleration zone. When nozzle stops moving at the corner or when changing layer, extruder stops at the same time, but there is still some pressure inside the nozzle, so plastic continues flowing for some time causing corner swell.

Higher speeds and large differences in pressure could amplify issues mentioned in this and previous chapter. 3D printing is quite complicated process and factors that have an impact on quality get amplified when increasing speed. There can be many more aspects that are less obvious and are hard to predict when increasing speed. To test described effects of increased speed several experiments are conducted and separated to three chapters. Firstly, effects of increased maximum speed are analyzed on two different 3D printers. Printed specimens are measured to see how and how much dimensions change when increasing maximum speed. Secondly, relative output of the extruder is analyzed on one of the printers to see how much exactly increasing speed and flow rate reduces output. Last set of experiments is also done on one printer to analyze acceleration and jerk and their impact on overshoot and surface ringing.

#### 4. Equipment overview

Experiments are done on two different printers. First one used in the experiments is Anycubic i3 Mega 3D printer (Fig 19). The most important features of this printer are that it is XZ-type printer and uses bowden type extrusion.



**Fig 19.** Anycubic i3 Mega 3D printer

Technical specifications of Anycubic i3 Mega are listed in table 2.

**Table 1.** Technical specifications of Anycubic i3 Mega 3D printer [18]

Specification	Value
Technology	FDM (Fused Deposition Modeling)
Print volume (xyz)	210 x 210 x 205 mm
Frame type	Open structure
Nozzle diameter	0,4 mm
Layer resolution	0,3 – 0,05 mm
Extrusion type	Bowden
Number of nozzles	Single
Max extruder temperature	275 °C
Build platform	Heated up to 100°C
Max print speed	80 mm/s
Max travel speed	150 mm/s
Bed leveling	Manual
Display	LCD touch screen
Connectivity	SD card, USB cable
Print recovery	Yes
Filament sensor	Yes

Another printer used in the experiments is Anycubic 4Max 3D printer (Fig 20). It is XY-type printer with direct extruder. It also has more rigid frame with an enclosure which helps with certain filaments.



**Fig 20.** Anycubic 4 Max 3D printer

Technical specifications of Anycubic 4Max are listed in table 2.

**Table 2.** Technical specifications of Anycubic 4 Max 3D printer [19]

Specification	Value
Technology	FDM (Fused Deposition Modeling)
Print volume (xyz)	210 x 210 x 300 mm
Frame type	Closed structure
Nozzle diameter	0,4 mm
Layer resolution	0,1 – 0,4 mm
Extrusion type	Direct
Number of nozzles	Single
Max extruder temperature	250 °C
Build platform	Heated up to 110°C
Max print speed	60 mm/s
Max travel speed	150 mm/s
Bed leveling	Manual
Display	LCD with control knob
Connectivity	SD card, USB cable
Print recovery	Yes
Filament sensor	Yes

To measure the specimen's dimensional accuracy, Mahr Micromar 40A (25 - 50) Micrometer was used (fig. 17).



**Fig 21.** Micrometer used to take measurements: Mahr Micromar 40A

To do visual analysis of surface quality of 3D printed parts, Canon MG2400 is used to scan specimens



**Fig 22.** Canon MG2400 printer/scanner

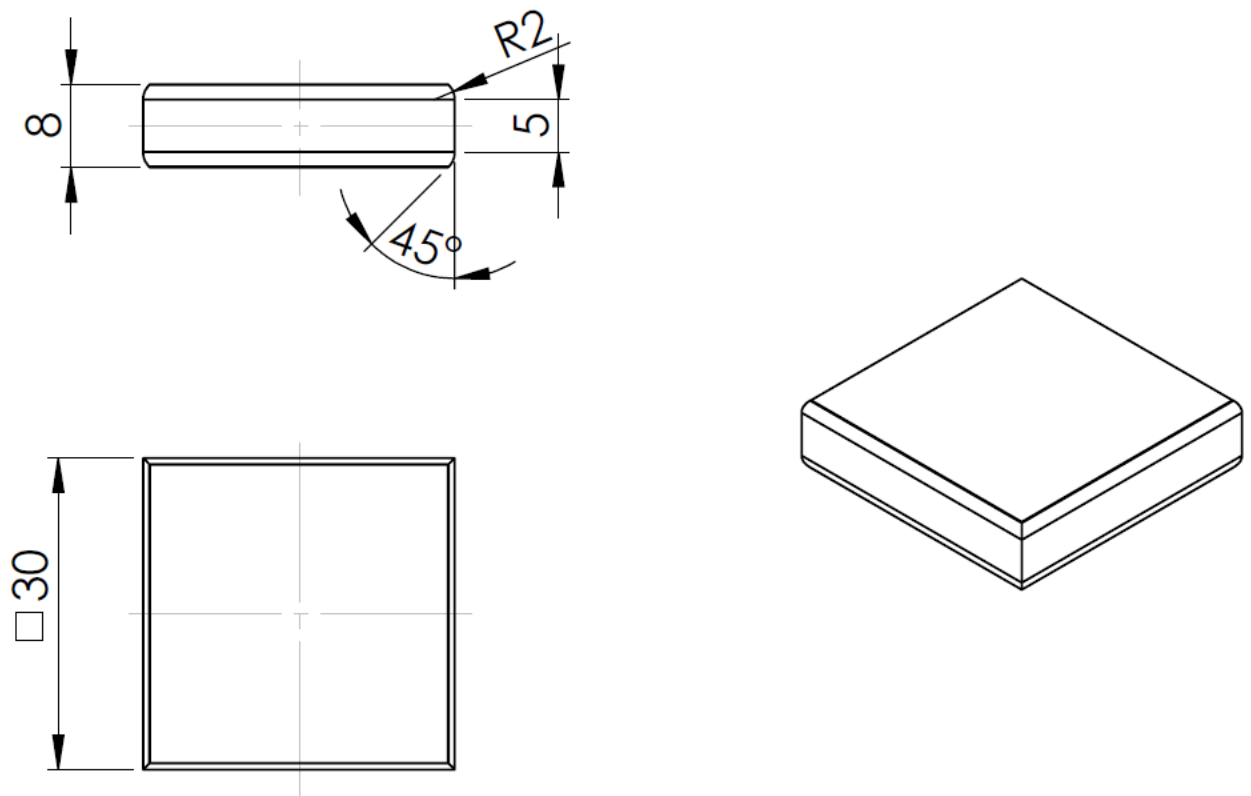
Now that all of the equipment is listed, it will be proceeded with the experiments.

## 5. Analyzing the impact of maximum speed

The following experiment is designed to test the effects of increased maximum speed on dimensional accuracy and surface quality of FDM 3D printed parts.

### 5.1. Designing the experiment

In motion characteristics section it has been determined, that maximum speed is often considered to be main specification that reduces 3D printed part's quality. Therefore, a specimen has been designed to test that assumption. Specimen has been drawn using Solidworks 2018 3D modeling software. Drawing of the specimen is shown in figure 23.



**Fig 23.** Drawing of designed test specimen

Important consideration when designing specimen was long enough edges to ensure print head accelerates to its maximum speed. Also, sharp corners to induce surface ringing. Typically, first layer is wider than nominal dimension to ensure proper adhesion. To compensate for this top and bottom have been made narrower. Since micrometer to be used for measurements has measuring surface diameter of 5mm, height of flat area on the specimen also was made 5mm. 3D model was saved in slt format, imported to slicer program to generate gcode with correct settings for 3D printers to use. Simplify3D software was used to set printing parameters and slice 3D model. Custom fixed settings that have been set constant during testing are listed in table 3.

**Table 3.** Custom fixed printing settings

Setting	Value
Nozzle diameter	0,4mm
Extrusion multiplier	1,00



Extrusion Width	0,4 mm
Top/Bottom solid layers	1 mm equivalent
Side outlines	3 (1,2 mm equivalent)
Retraction	Disabled
First layer speed	25 %
Choose start point closest to specific location	X: 999mm; Y: 999mm
Infill	10 %
Outline Overlap	30 %
Supports	No
Bed temperature	65°C
Cooling fan speed	100% from layer 2
All Underspeed	100%
Adjust printing speed for layers below 15,0 sec	Disabled
Allowed parameter overlap	30%

Initial testing at higher speeds showed that plastic was not melting fast enough when pushed through the nozzle, clogging up and causing prints to fail completely. For this reason, printing temperature has been increased regularly with increased speed. When printing with regular hot ends (with teflon inserts), it is not recommended to print at higher temperature than 240 °C, because teflon tube inside the hot-end will start to degrade and emit noxious gasses.

Experiment has been split into two parts to get results from two different printers using different set of speed settings. First test is done on i3 Mega and second test is done on 4Max 3D printers. Settings for first test specimens are shown in table 4.

**Table 4.** Print settings of first experiment on maximum speed (Anycubic i3 Mega)

Number	Printing speed ( $v_{max}$ )	Nozzle temperature	Layer height	X axis acceleration	Y axis acceleration
1	25 mm/s	200 °C	0,2 mm	3000 mm/s <sup>2</sup>	2000 mm/s <sup>2</sup>
2	50 mm/s	210 °C			
3	100 mm/s	220 °C			
4	150 mm/s	230 °C			
5	200 mm/s	240 °C			

Settings for second test specimens are shown in table 5.

**Table 5.** Print settings of second experiment on maximum speed (Anycubic 4MAX)

Number	Printing speed ( $v_{max}$ )	Nozzle temperature	Layer height	X axis acceleration	Y axis acceleration
1	50 mm/s	200 °C	0,1 mm	3000 mm/s <sup>2</sup>	3000 mm/s <sup>2</sup>
2	100 mm/s	210 °C			
3	200 mm/s	220 °C			
4	300 mm/s	230 °C			
5	400 mm/s	230 °C			

Before printing, several other variables had to be considered first:

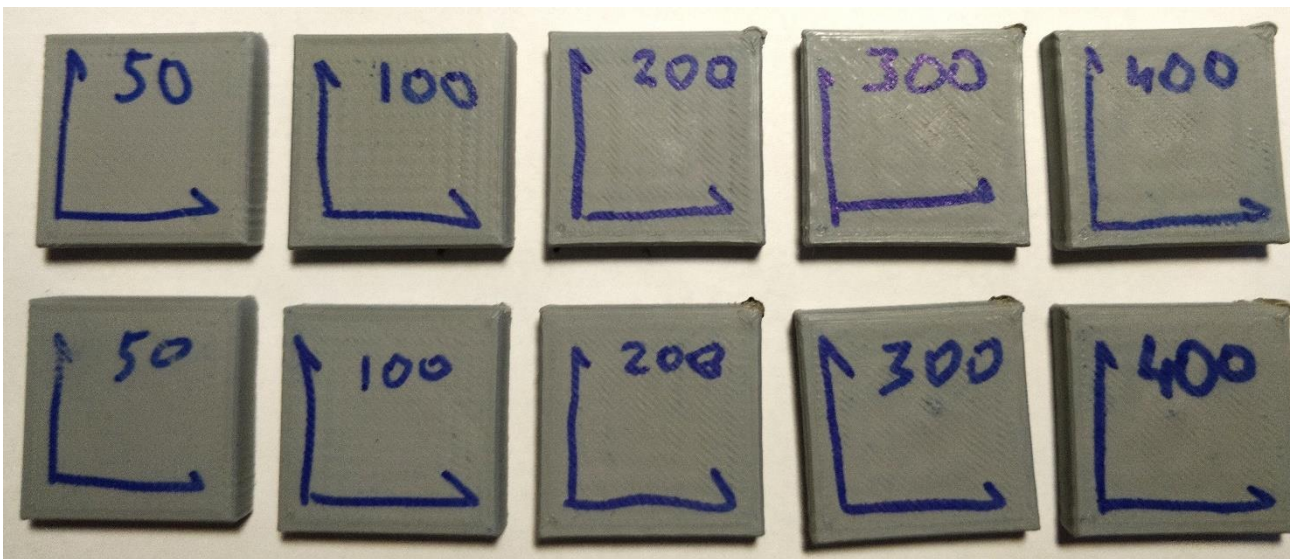
- Regular gray PLA plastic was used for specimens;
- All specimens have been printed from a single roll of filament;
- Environment temperature was 17°C during entire testing;
- Gluestick was sometimes used on heated bed to ensure good first layer adhesion.

After all gcode files have been saved in to SD cards and put to 3D printers, it was continued with printing and measuring the specimens. Specimens for first experiment that have been printed on Anycubic i3 Mega are shown in figure 24. Five specimens, each printed at different speed ( $v_{max}$ ).



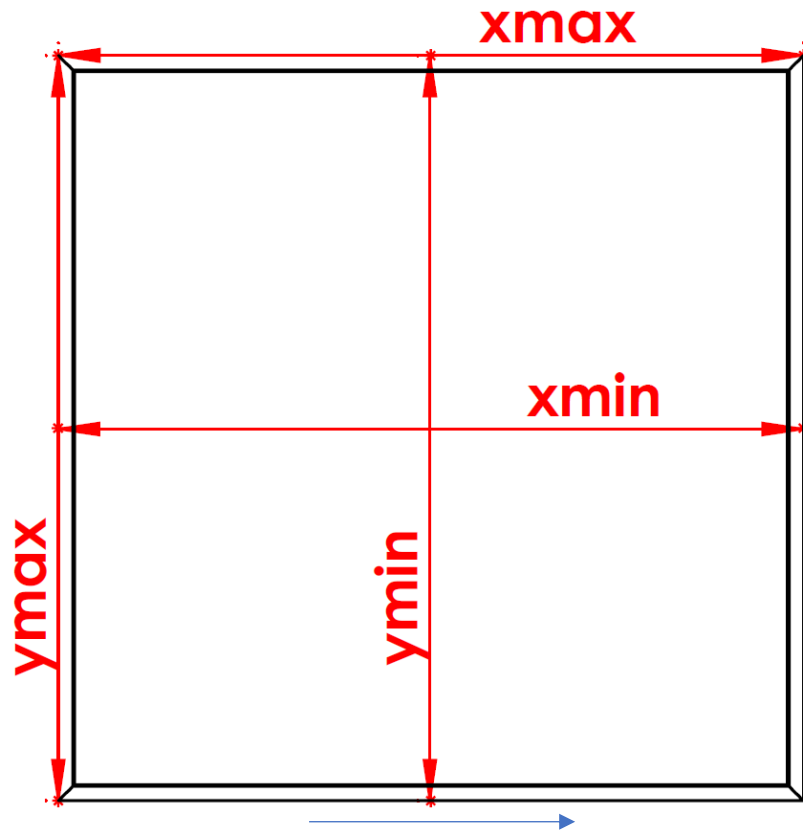
**Fig 24.** Specimens printed on Anycubic i3 Mega for first experiment

For second experiment, specimens have been printed on Anycubic 4Max printer. Two sets of identical specimens have been printed (fig. 25). Total of 10 specimens. Average dimension of each speed pair was used for analysis.



**Fig 25.** Specimens printed on Anycubic 4 Max for second experiment

Next, they have been measured. Four dimensions of each specimen have been taken. Measured dimensions are shown in figure 26.



**Fig 26.** Measured dimensions. Blue arrow shows movement direction of print head

It is expected that specimens will have dimensions above nominal at the corners due to corner swell. Also, it is also expected for specimens to have different values in x and y axes due to different masses moving in each direction. To see by how much, two measurements of each axis are taken:  $x_{max}$ ,  $x_{min}$ ,  $y_{max}$  and  $y_{min}$ . To calculate dimensional inaccuracy the following calculations are done:

$$\Delta l_x = x_{max} - x_{min} \quad [1]$$

$$\Delta l_y = y_{max} - y_{min} \quad [2]$$

Here  $\Delta l$  is total error on that axis,  $x_{min}$  and  $y_{min}$  are minimum dimensions measured at the center of the specimen.  $x_{max}$  and  $y_{max}$  are maximum dimensions measured at the corners of the specimen.

After printing and measuring the specimens, all data has been stored in the spreadsheet for analysis. Data analysis is split into two parts. Firstly, dimensional measurements will be analyzed. After that, some visual comparison of the specimens.

## 5.2. Analysis of maximum speed impact on dimensional accuracy

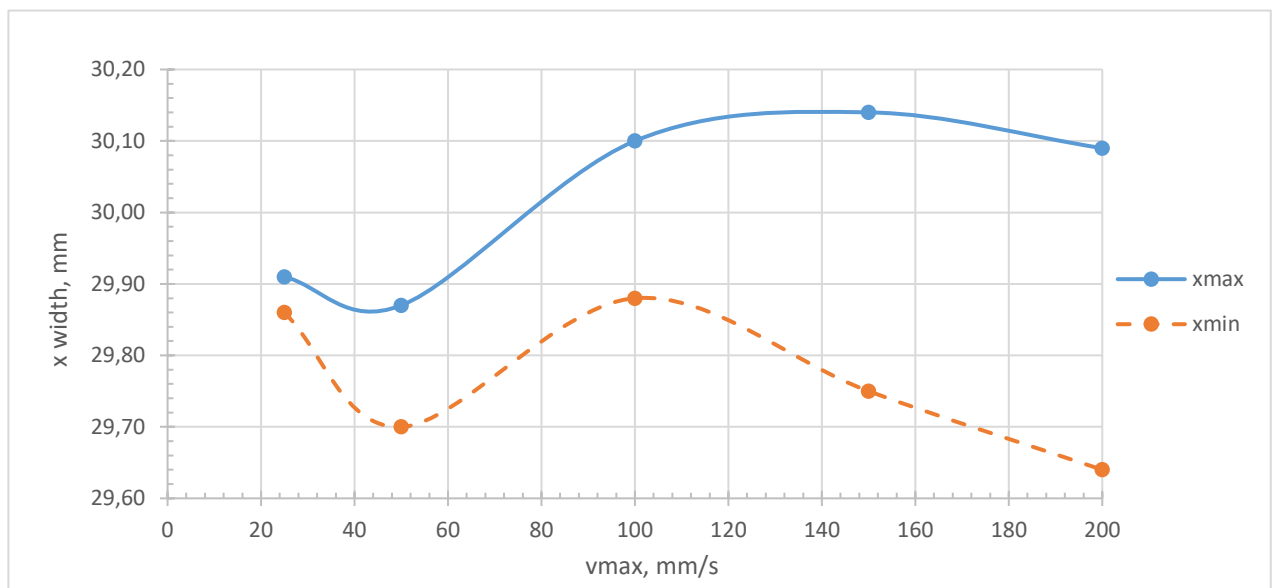
In this part the effect of increased speed on dimensional accuracy will be analyzed. Two separate tests have been conducted on two different printers. Firstly, results of Anycubic i3 Mega will be analyzed.

On this printer one set of five specimens at different speed have been printed. Speed has been incrementally changed from 25 mm/s to 200 mm/s. Final results of first five specimens is provided in table 6.

**Table 6.** Results of first experiment on maximum speed (Anycubic i3 Mega)

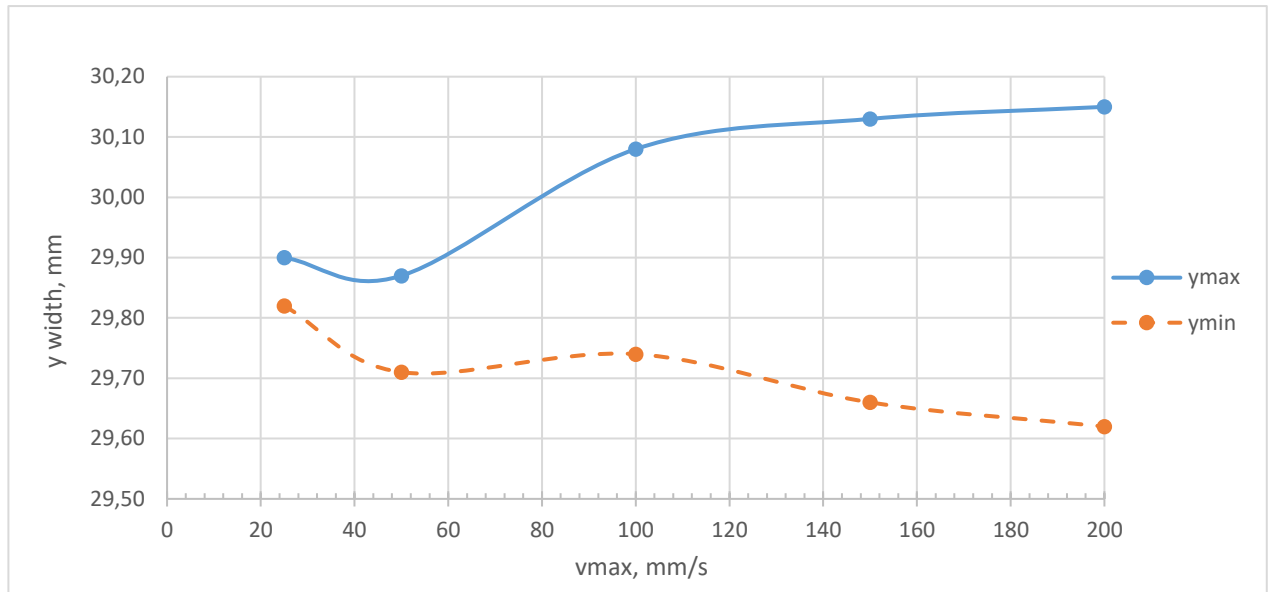
Nozzle temp (°C)	Speed, $v_{max}$ (mm/s)	$x_{max}$	$x_{min}$	$\Delta x$	$y_{max}$	$y_{min}$	$\Delta y$	Average $\Delta xy$
200	25	29.91	29.86	0.05	29.90	29.82	0.08	0.06
210	50	29.87	29.70	0.17	29.87	29.71	0.16	0.17
220	100	30.10	29.88	0.22	30.08	29.74	0.34	0.28
230	150	30.14	29.75	0.39	30.13	29.66	0.47	0.43
240	200	30.09	29.64	0.45	30.15	29.62	0.53	0.49

From the table it can be seen what temperatures have been used for what speed. Also, all of the dimensional measurements. Data shows that specimen width at the corners tends to increase when increasing the speed and tends to decrease at the middle of the prints. This behavior is present in both x and y axes. Last column (average  $\Delta xy$ ) clearly shows that increasing speed increases the difference between smallest and largest dimension along the side of the print. Average  $\Delta l$  is average of x and y axes. Below are some graphs to visualize the results.



**Fig 27.** Specimen width in x axis

Figure 19 shows how specimen width in x axis changes when increasing the speed. Blue solid line represents width when measured at the corners and orange dashed line represents width when measured in the middle. Lines are not completely straight, likely due to inconsistent nature of 3D printed parts. However, it is clearly visible that gap between minimal and maximum is increasing. This gap represents total  $\Delta x$  in the table.



**Fig 28.** Specimen width in y axis

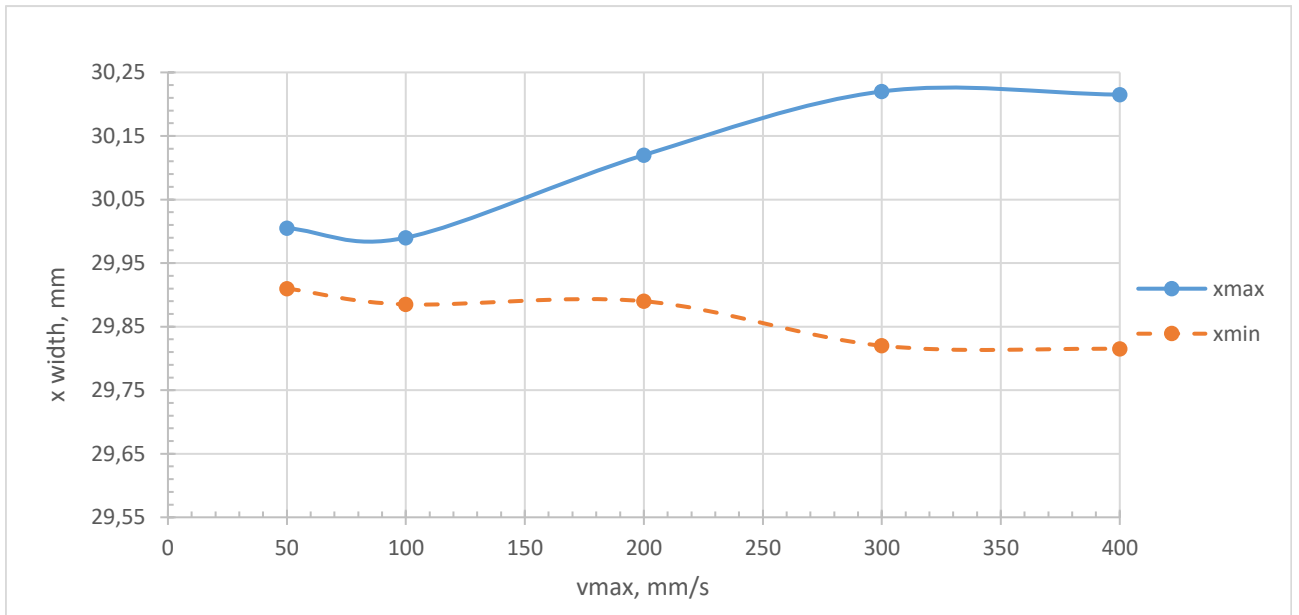
From figure 28 it can be seen how specimen width in y axis changes when increasing the speed. Results are similar to x axis's results. However, gap between the lines ( $\Delta y$ ) is increasing more with increased speed when compared to x axis ( $\Delta x$ ). Anycubic i3 Mega printer moves build platform in y axis, this could be an indication that increased mass is affecting dimensional accuracy. Next, results of Anycubic 4Max will be analyzed.

From previous test it has been determined that printing at 0,2 mm layer height at high speeds causes too much plastic flow, requiring high temperature. During second experiment layer height has been reduced to 0,1 mm to reduce flow rate and allow reaching higher maximum speeds before requiring unreasonably high nozzle temperatures. This increases printing time, but allows reaching higher speeds and has added benefit of increased resolution in z axis. This time speed has been incrementally changed from 50 mm/s to 400 mm/s. Final results of second test is provided in table 7.

**Table 7.** Second test results (dimensions are in millimeters)

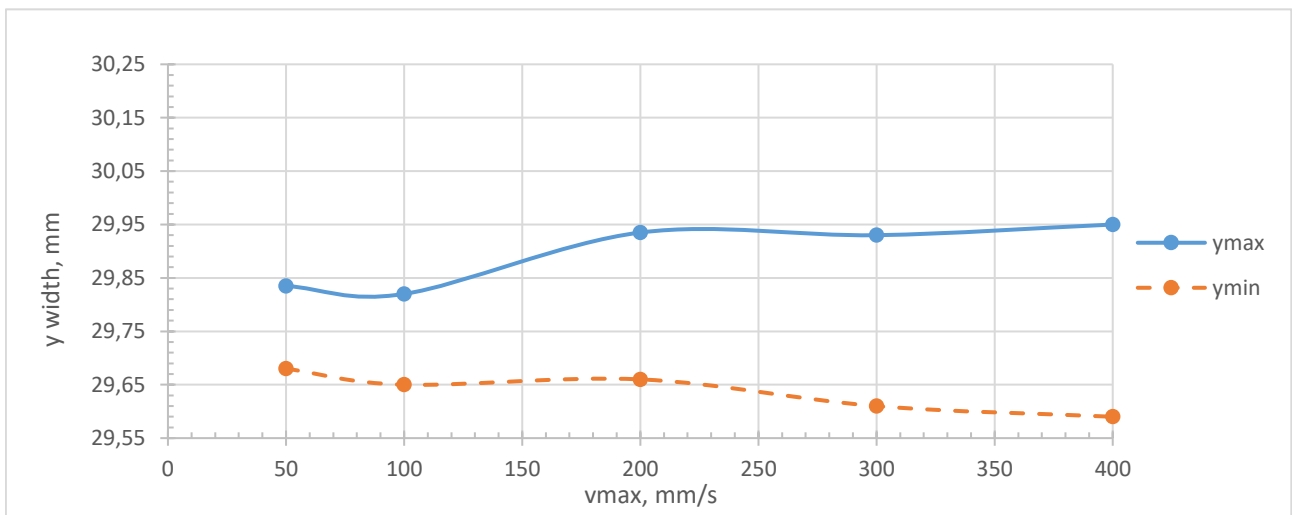
Nozzle temp (°C)	Speed, $v_{max}$ (mm/s)	$x_{max}$	$x_{min}$	$\Delta x$	$y_{max}$	$y_{min}$	$\Delta y$	average $\Delta xy$
200	50	30.01	29.91	0.09	29.84	29.68	0.16	0.13
210	100	29.99	29.89	0.11	29.82	29.65	0.17	0.14
220	200	30.12	29.89	0.23	29.94	29.66	0.28	0.25
230	300	30.22	29.82	0.40	29.93	29.61	0.32	0.36
230	400	30.22	29.82	0.40	29.95	29.59	0.36	0.38

Data in Table 7 shows what temperatures have been used for what speed. Also, all of the dimensional measurements. In general, results are very similar to the first test. Total  $\Delta xy$  seems to be similar to the first test, however speed is two times higher. It is clear that second printer is much better at maintaining dimensional accuracy at increased speeds. It is most likely due to reduced flow rate which is a consequence of reduced layer height. Below are some graphs to visualize the results.



**Fig 29.** Specimen width in x axis

From figure 29 it can be seen how specimen width in x axis changes when increasing the speed.



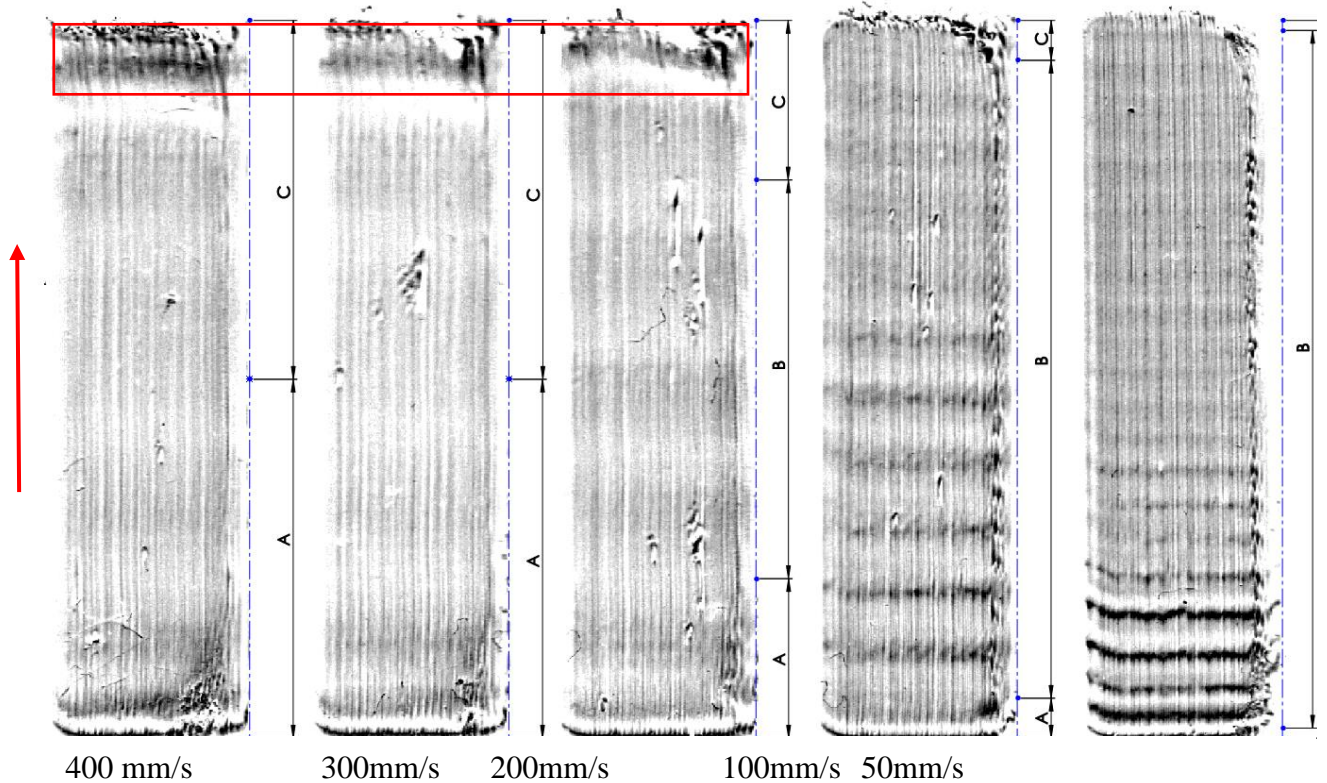
**Fig 30.** Specimen width in y axis

Figure 30 shows how specimen width in y axis changes when increasing the speed. Graphs are similar to the previous test. This time however, difference between  $\Delta x$  and  $\Delta y$  is not so significant. It is likely because Anycubic 4Max has similar moving mass in x and y axes, due to XY-type construction that it has. In general, x axis tends to be longer than y axis. This is probably due to poor axis calibration of the printer and is not related to speed. Lastly,  $\Delta xy$  of both axes seems to be almost identical when printing at 300mm/s and 400mm/s. This is because of acceleration preventing printer from reaching  $v_{max}$ . This will be further analyzed in the next section.

Both printers show similar behavior that could have been expected. When increasing speed, specimen width is increasing at the corners, due to surface ringing and, probably, some corner swell caused by non-linear extruder behavior. Width is decreasing in the middle, most likely due to under extrusion caused by relative extruder output being lower.

### 5.3. Analysis of maximum speed impact on surface quality

In this section 3D printed specimen's surface will be analyzed from scanned images. In figure 31 five specimens are scanned and placed side by side for easy comparison. Here specimens are placed on their side, so layer lines are going vertically.



**Fig 31.** Printed specimens side view. Red arrow shows movement direction of print head. Letters on the side show: A – acceleration zone; B – maximum speed zone ( $v_{max}$ ); C – deceleration zone.

From the scans, surface ringing is present on all specimens as horizontal waves that start at the bottom and fade as they go to the top. Most striking difference is frequency of oscillations. Clearly, increased speed reduces frequency of the waves. It appears that lower speed did not remove surface ringing, only increased frequency.

When looking at figure 31, it can be seen that specimens above 100mm/s have a noticeable horizontal bulge at the end of print head's travel, just before the corner, marked with red rectangle. At this point oscillations should've settled like on 100 mm/s and 50 mm/s specimens. This bulge is likely caused by non-linear extrusion effect, which was described in the hypothesis chapter.

300 mm/s and 400 mm/s specimens appear to be the same. Knowing that acceleration is  $3000 \text{ mm/s}^2$ , it can be calculated how long it takes to reach  $v_{max}$  at each speed using formula [3].

$$t = \frac{a}{v_{max}} \quad [3]$$

Here  $a$  is acceleration ( $\text{mm/s}^2$ ) and  $v_{max}$  – maximum printing speed set in slicer software. Using formula [4], it can be calculated the distance that is needed to reach  $v_{max}$ .

$$l = \frac{1}{2}at^2 \quad [4]$$

Knowing that specimen length is 30 mm, distance required for acceleration and deceleration can be subtracted and the distance that nozzle travels at top speed ( $v_{max}$ ) is gotten. After doing calculation for each specimen these three sections have been represented in the figure 31 as A, B and C. When printing speed is 300 mm/s, nozzle travels 0 mm distance at  $v_{max}$ . This means that on this specimen with set acceleration maximum possible speed is 300 mm/s. Setting anything faster would make no difference because there is not enough distance to accelerate. This explains why 300 mm/s and 400 mm/s specimens look the same and have same dimensional accuracy in Anycubic 4Max test.

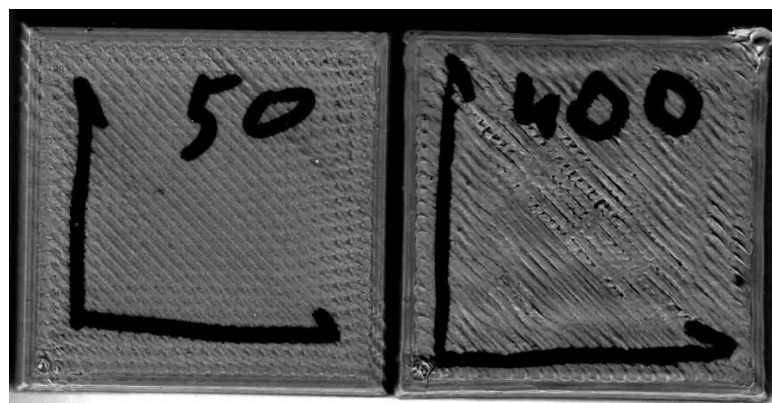
Since increasing speed requires more distance to reach it, acceleration has bigger and bigger impact on printing time. This suggests that after a certain  $v_{max}$ , printing time should not change if acceleration is kept the same. This is proven in table 8.

**Table 8.** Time to print specimens

Speed, mm/s	theoretical time (minutes)	real time (minutes:seconds)
50	30	31:58
100	15	18:17
200	8	12:10
300	6	11:55
400	5	11:45

Here, theoretical time is time provided in the slicer software and real time is actual measured time. Slicer software has no information about printer's acceleration setting therefore it does not consider them when calculating printing time. It is obvious, because when doubling speed, print time is roughly halved. However, from measured time it can be seen that there are diminishing returns when it comes to setting higher speed. This is important to consider since it highly depends on specific part. If it has a lot of long straight edges, then more time will be saved. If part is small or has a lot of small details, then setting speed high will make no difference.

Another visual aspect that can be mentioned is under extrusion that is visible at the top layer of the prints (fig 32).



**Fig 32.** Number on specimen shows speed at which it was printed

In figure 32 it can be clearly seen that increasing speed from 50 mm/s to 400 mm/s results in visible gaps between top layer lines. This is most likely the result of previously described relative output of the extruder. It is also very likely the cause of below nominal dimensions on the sides of the specimens.



## 6. Analyzing relative output of the extruder

In the previous experiment, it has been determined that output of the extruder has large impact on dimensional accuracy. Therefore, in this chapter analysis of the extruder's relative output will be done. Anycubic i3 Mega will be used in this experiment

All extruders will have reduced relative output when flow rate is increased. Every printer will have different amount of reduction in output. Amount of which can depend on everything from quality of the filament to amount of wear in the nozzle, but mainly on quality of the extruder and its construction.

The advantage of knowing exact amount of relative output gives an opportunity to choose, how much under-extrusion is acceptable and calculate maximum speed accordingly.

### 6.1. Theory and calculations

Flow rate is measured in  $\text{mm}^3/\text{s}$  and defines volume of liquid flowing through a surface per second [20]. In this case, theoretical flow rate of liquid plastic flowing through the nozzle is calculated using formula [5].

$$Q = d \cdot h \cdot v \quad [5]$$

Here  $Q$  is flow rate (in  $\text{mm}^3/\text{s}$ ),  $d$  is diameter of the nozzle (in mm),  $h$  is layer height (in mm) and  $v$  is printing speed (in mm/s). Flow rate is increased when printing speed is increased, but can be compensated for by reducing layer height. Anycubic i3 Mega 3D printer has a nozzle of 0,4 mm and for experiments 0,12 mm layer height is used.

Simplify3D software allows to specify and extrude set length of filament strand at desired speed. This way it is possible to test increasing amount of flow rate through the nozzle by extruding fixed amount of filament at increasing speeds. To do this, it is required to convert flow rate through the nozzle to length of filament strand per second.

It can be done using [6] formula.

$$f = \pi \cdot R^2 \cdot Q \quad [6]$$

Here  $f$  is length of filament per second (in mm/s),  $R$  is diameter of filament strand (mm) and  $Q$  is flow rate. 1,75 mm is currently the most popular diameter filament and is also used in the experiments.

Variables are inserted and simplified:

$$f = 2,41 \cdot Q \quad [7]$$

[7] formula allows to convert desired flow rate to length of filament strand per second. The latter variable can be used in Simplify3D to test relative output.

### 6.2. Designing the experiment

Data points to be tested have been defined and are presented in table 9.

**Table 9.** Data points to test relative output of the extruder

Flow rate through the nozzle (mm <sup>3</sup> /s)	filament strand per second (mm/s)	Equivalent speed at 0,12mm layer height (mm/s)	Equivalent speed at 0,2mm layer height (mm/s)
31.99	13.3	666.5	400
24.05	10	501	301
16.10	6.7	335,5	201
12.02	5	250,5	150
8.18	3.4	170,5	102
4.08	1.7	85	51
1.68	0.7	35	21
0.72	0.3	15	9

Before starting the experiment, 3D printer's extruder has been calibrated to extrude exactly 100 mm of filament at slowest speed of  $f = 0,3$  mm/s. So that when flow rate is  $0.72$  mm<sup>3</sup>/s relative output is 100 %.

To measure actual extruded length of filament strand, 100 mm from where filament enters the extruder's body, strand is measured and marked with digital calipers. Then in Simplify3D software 100 mm of filament has been set and extruded at increasing speeds. Each time, some length of filament would be under extruded and actual measured extruded value was less than theoretical set 100 mm.

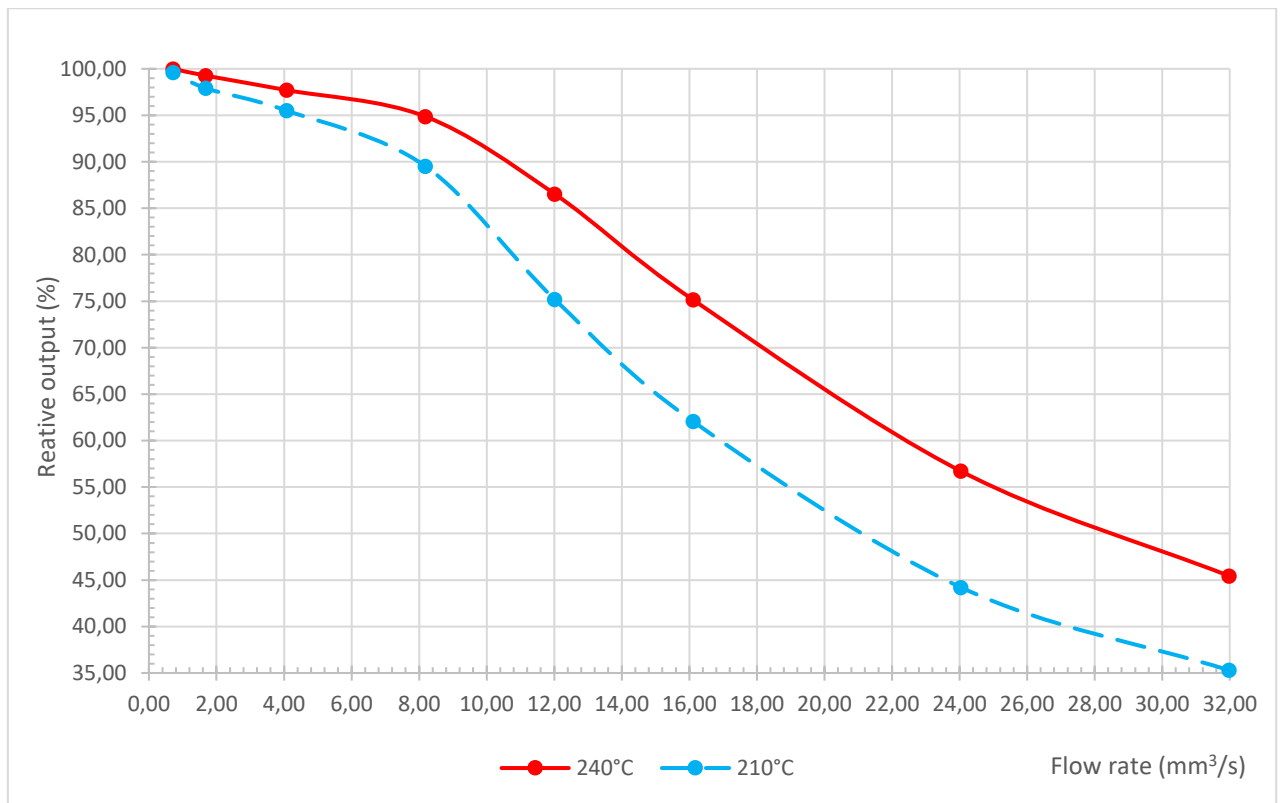
This experiment has been done at 8 flow rates defined in table 9. Four tests have been done for each data point, so 32 measurements. To determine how nozzle temperature affects relative output of the extruder. Each of these tests have been done twice - at nozzle temperature of 240 °C and 210 °C. In total, 64 measurements have been taken.

Several other notable variables:

- "Aluminum" PLA plastic was used;
- All extrusions have been made from a single roll of filament;
- Environment temperature was about 20 °C during testing;

### **6.3. Analyzing the data**

Actual extruder output at a given flowrate has been determined and results are presented in figure 33.



**Fig 33.** Relative output of Anycubic i3 Mega

In this graph, solid red line represents average results for relative output at 240 °C, and dashed blue line represents relative output at 210 °C. The results confirm that under-extrusion increases as flow rate is increased. Output graph has distinct two sections: up to ~8 mm<sup>3</sup>/s decline in output is linear and not very significant, but after that it becomes much more significant and drops rapidly. Also, it is clear that higher temperatures improve output as plastic can melt better as it flows through the nozzle at increased rate. Increasing temperature from 210°C to 240 °C improves output by 5% at flow rate of 8 mm<sup>3</sup>/s and gap increases to as much as 15% as flow rate is increased.

It was previously determined that printing speed directly impacts flow rate. And now that increasing flow rate reduces output. Knowing the exact relation allows to choose maximum speed depending on how much under-extrusion is acceptable. Exact amount will depend on what is preferable – shorter printing time or stronger parts. From figure 32 in impact of maximum speed chapter, specimen printed at 400 mm/s has visible gaps on top layer. These gaps indicate that adjacent layers are not connecting due to severe under-extrusion and result in not only in low quality surface, but also in potentially weak part since less plastic is laid down.

Currently there seems to be no way to compensate for reduced relative output. Neither in slicer software, nor 3D printer firmware. Installing more robust extruder could reduce under-extrusion.

The only way to completely avoid effects of relative output, in theory, is to print at constant speed at all times, ensuring constant flow. This, however, is unfeasible, because maximum speed would be limited to jerk setting. Meaning that prints could take 5 times longer or more, depending on other settings.

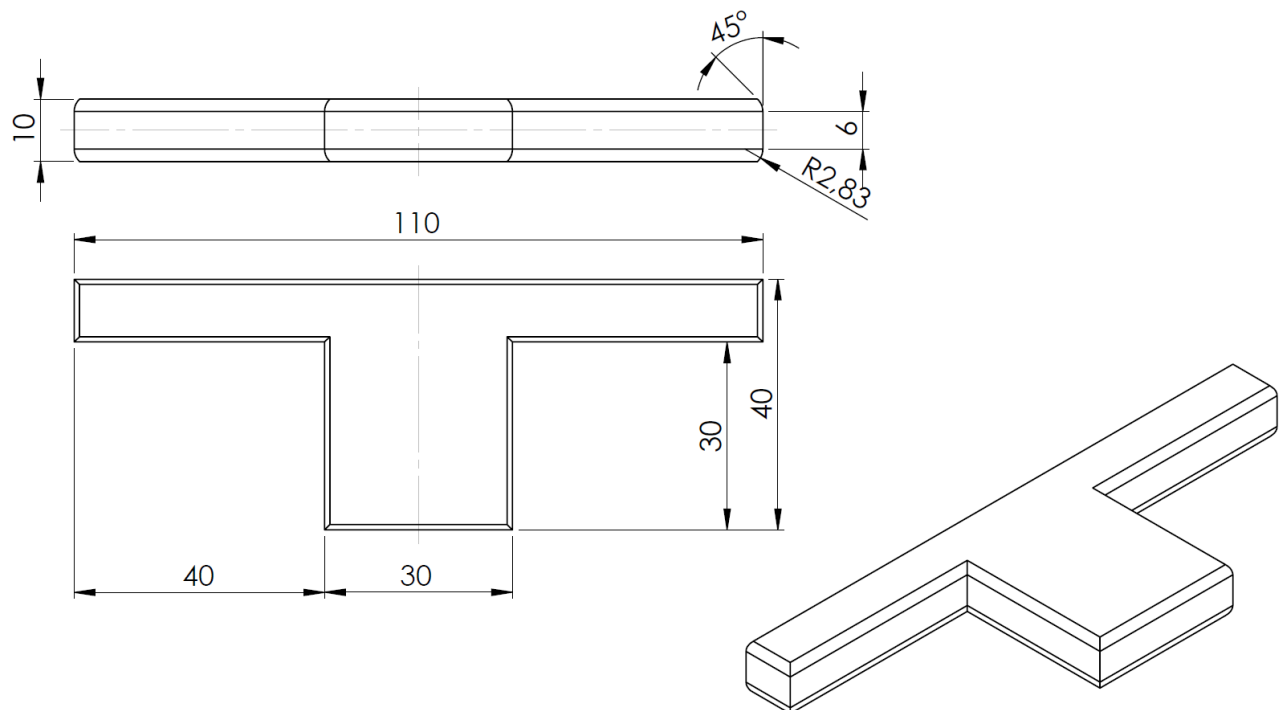
## 7. Analyzing the impact of acceleration and jerk

The following experiment is designed to test the effects of acceleration and jerk on dimensional accuracy and surface quality of FDM 3D printed parts. It has been conducted on Anycubic i3 Mega 3D printer.

### 7.1. Designing the experiment

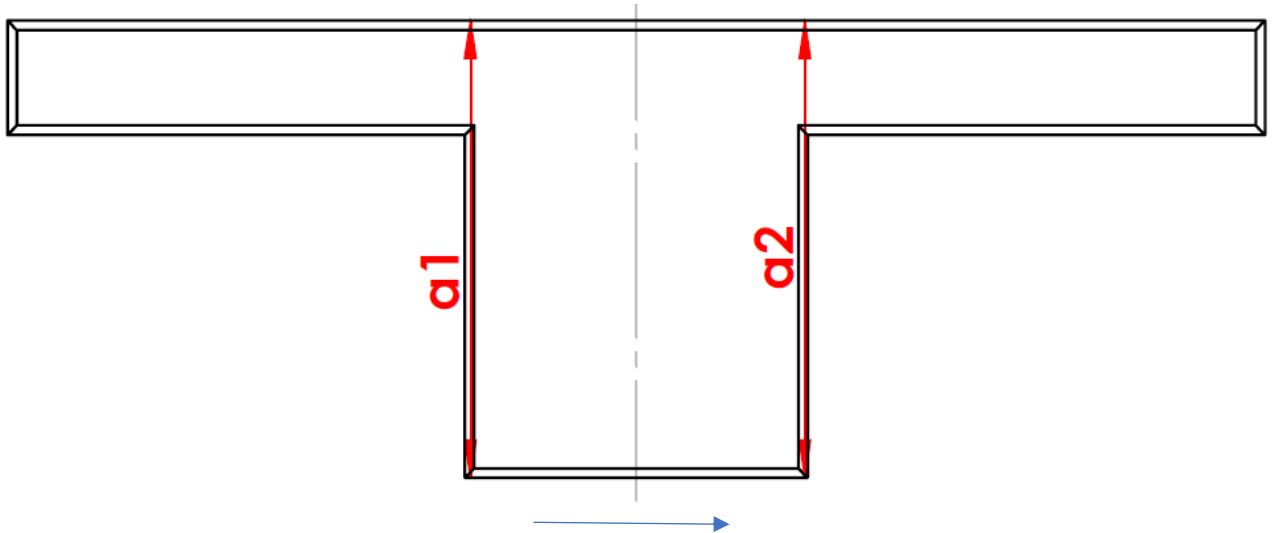
First experiment on impact of maximum speed showed that reducing speed does not eliminate surface ringing, it only changes frequency of oscillations. As stated in hypothesis chapter, jerk and acceleration are considered to be main characteristics that affect print head's overshoot when changing direction and consequently surface ringing. Therefore it is necessary to prove it by conducting the following experiment.

Specimen has been changed from previous experiment (fig 34). To improve measurement accuracy specimen has been designed to have as flat of a surface as possible on the opposite side of measured corners. This has been achieved by increasing the length of that surface ensuring that print head has reached its maximum velocity and oscillations are dissipated at the point where measurement is taken.



**Fig 34.** Drawing of the specimen

Measuring overshoot at corners is not straight forward. Increase in dimension at corners is caused not only by overshoot, but also some corner swell. It is assumed that corner swell occurs to all directions equally, however overshoot happens only at the start of printed line. Therefore, subtracting a measurement taken at the corner at the end of printed line (a2 in figure 35) from dimension taken at the corner at the start of the printed line (a1 in figure 35) would result in only overshoot amount.



**Fig 35.** Measured dimensions. Blue arrow shows movement direction of print head

Calculation is described by formula [8].

$$\Delta a = a1 - a2 \quad [8]$$

Here  $\Delta a$  is distance of overshoot at the corner and will be measured in  $\mu\text{m}$ . Dimensions  $a1$  and  $a2$  are taken from the specimen as shown in figure 35.

First part of the experiment is to determine the impact of increased jerk from 5 mm/s to 30 mm/s when acceleration is fixed at low value of  $1000 \text{ mm/s}^2$ . Main settings for first part are shown in table 10.

**Table 10.** Printer settings to test impact of jerk

Number	Printing speed ( $v_{\text{max}}$ )	Nozzle temperature	Layer height	X and Y axes acceleration	X and Y axes jerk
1	150 mm/	240 °C	0,12mm	1000 mm/s <sup>2</sup>	5 mm/s
2					20 mm/s
3					30 mm/s

Second part is to determine the impact of increased acceleration from  $1000 \text{ mm/s}^2$  to  $7500 \text{ mm/s}^2$  when jerk is fixed at low value of 5 mm/s. Main settings of second part are shown in table 11.

**Table 11.** Printer settings to test impact of acceleration

Number	Printing speed ( $v_{\text{max}}$ )	Nozzle temperature	Layer height	X and Y axes acceleration	X and Y axes jerk
1	150 mm/	240 °C	0,12mm	1000 mm/s <sup>2</sup>	5 mm/s
2				5000 mm/s <sup>2</sup>	
3				7500 mm/s <sup>2</sup>	

Part three is to determine the impact of increased both acceleration and jerk. Main settings of third part are shown in table 12.

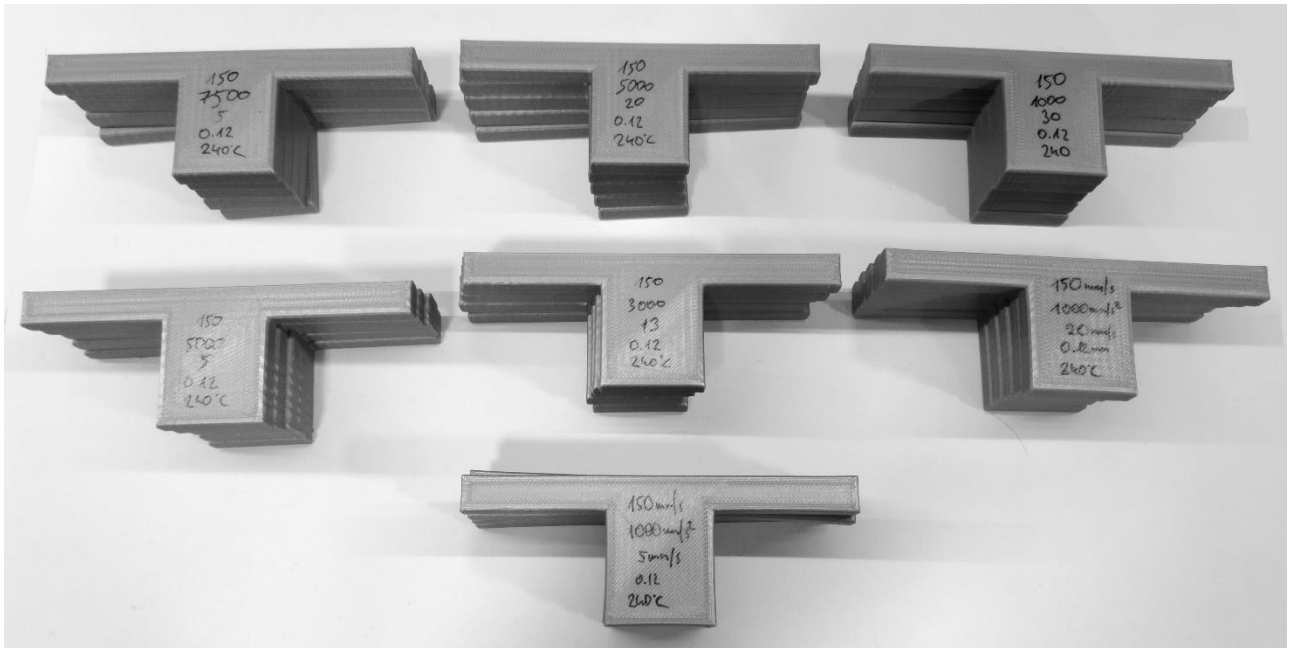
**Table 12.** Printer settings to test impact of both acceleration and jerk

Number	Printing speed ( $V_{max}$ )	Nozzle temperature	Layer height	X and Y axes acceleration	X and Y axes jerk
1	150 mm/	240 °C	0,12mm	1000 mm/s <sup>2</sup>	5 mm/s
2				3000 mm/s <sup>2</sup>	13 mm/s
3				5000 mm/s <sup>2</sup>	20 mm/s

Specimens are printed on Anycubic i3 Mega 3D printer and measurements taken on the same micrometer as in previous experiment. All other slicer settings are the same as of analysis of maximum speed. Several other notable variables:

- “Aluminum” PLA plastic was used for specimens;
- All specimens have been printed from a single roll of filament;
- Environment temperature was about 20 °C during entire testing;
- Gluestick was sometimes used on heated bed to ensure good first layer adhesion.

For each set of parameters five specimens are printed and measured. It is important to note that set 1 for each part is the same, so same set of specimens is used. That is 35 specimens in total. Printed specimens are show in figure 36.



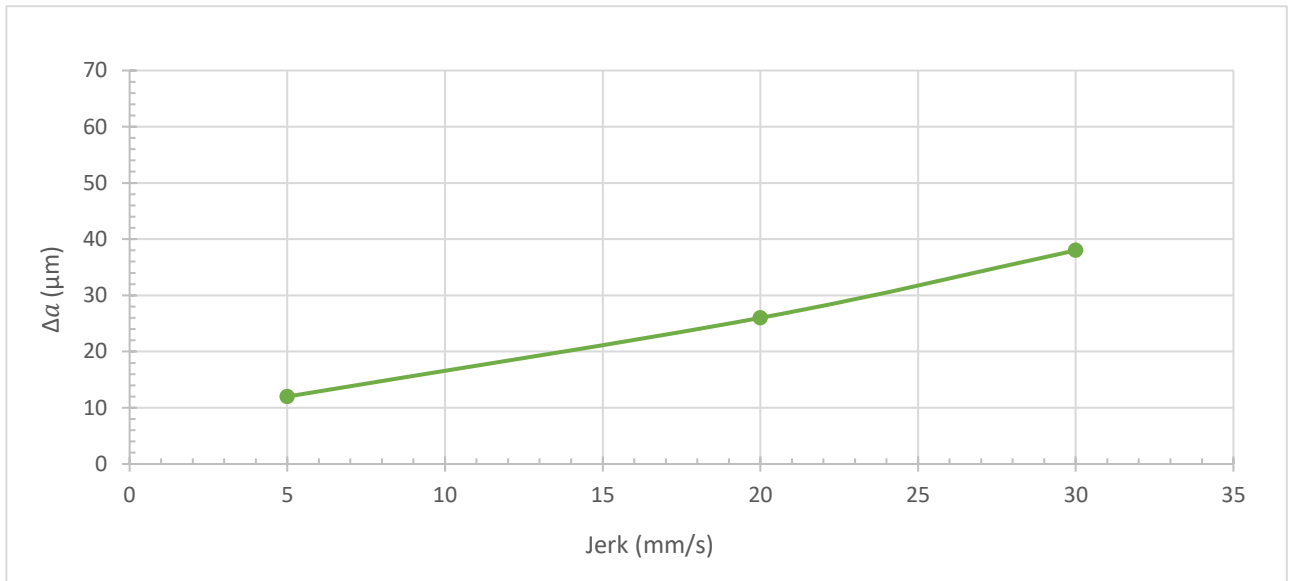
**Fig 36.** Printed specimens

Several specimens have failed to print completely or had dimensions that were much beyond average. These specimens have been replaced with new ones. Data analysis is split into two parts. Firstly, dimensional measurements will be analyzed. After that, some visual comparison of the specimens.

## 7.2. Analysis of acceleration and jerk impact on dimensional accuracy

After all 35 specimens have been printed and measured, all data has been stored in a spreadsheet for analysis. Three plots for each part of the experiment have been drawn. x axis represents jerk or

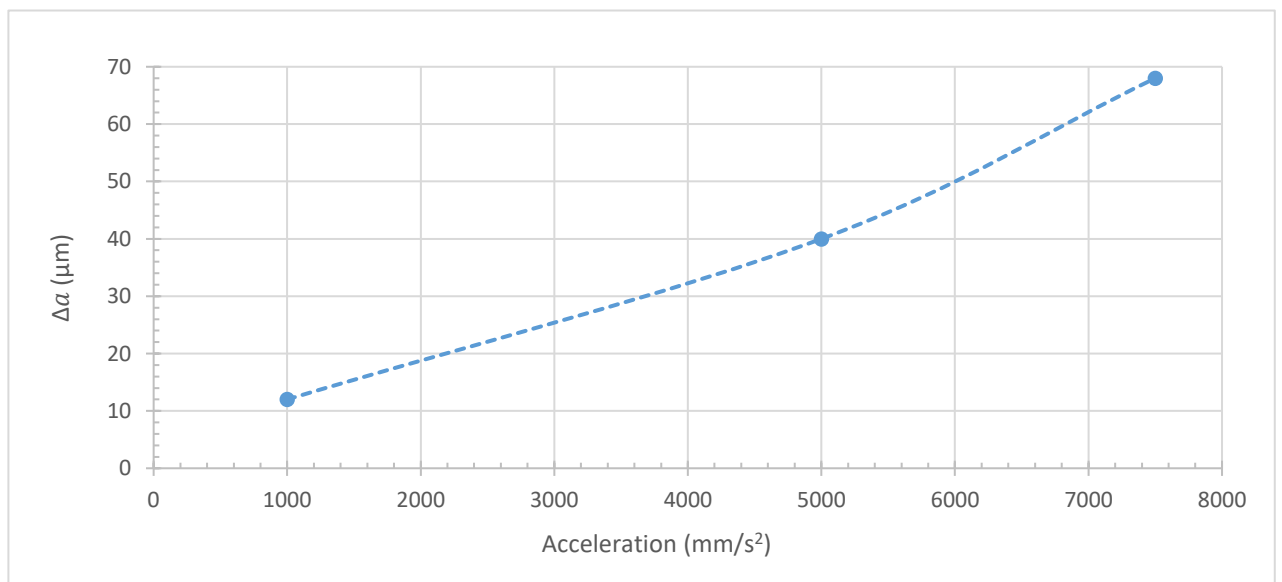
acceleration value and y axis represents amount of overshoot ( $\Delta a$ ) measured in  $\mu\text{m}$ . Figure 37 shows jerk effect on overshoot amount.



**Fig 37.** Overshoot dependency on jerk

Graph data shows that increasing jerk from 5 mm/s to 30 mm/s at acceleration of 1000 mm/s<sup>2</sup> has linear increase in overshoot from 10  $\mu\text{m}$  to 40  $\mu\text{m}$ . In this case, optimal jerk value completely depends on how much dimensional inaccuracy is acceptable.

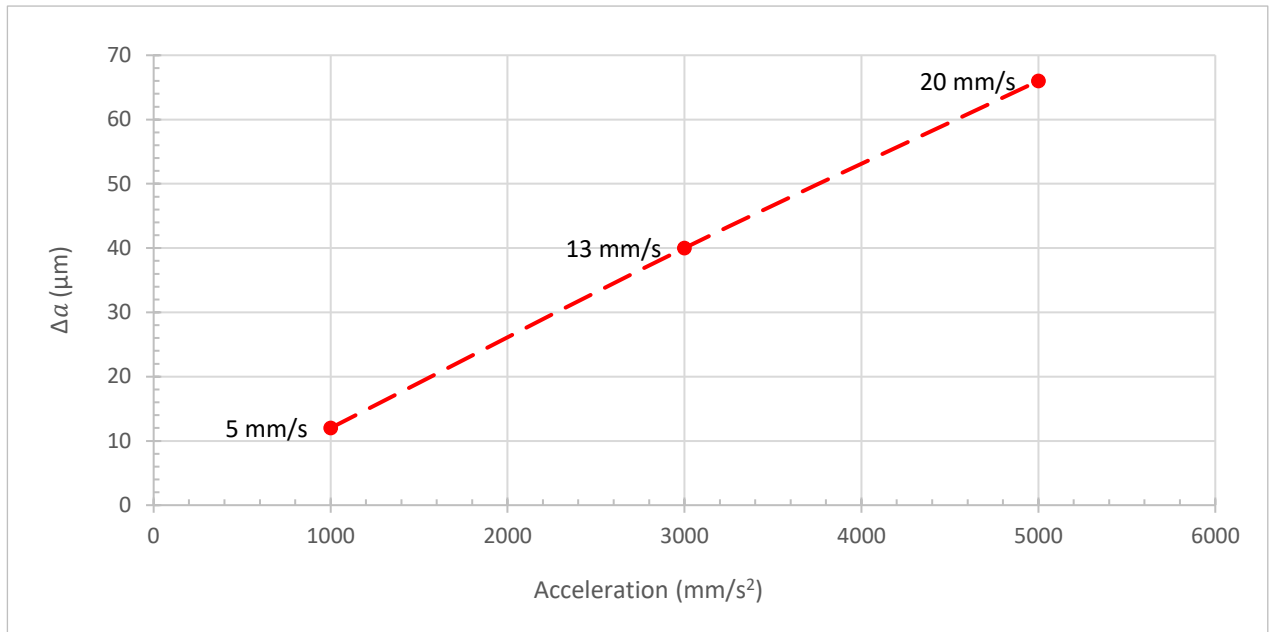
Figure 38 shows acceleration effect on overshoot amount.



**Fig 38.** Overshoot dependency on acceleration

Data shows that increasing acceleration from 1000 mm/s<sup>2</sup> to 7500 mm/s<sup>2</sup> also has linear increase in overshoot from 10  $\mu\text{m}$  to 70  $\mu\text{m}$ . Just like with jerk, optimal acceleration value depends on how much dimensional inaccuracy is acceptable.

Figure 39 shows both jerk and acceleration effect on overshoot amount. x axis shows values of acceleration and callouts next to data points on the graph represent jerk value



**Fig 39.** Overshoot dependency on acceleration and jerk

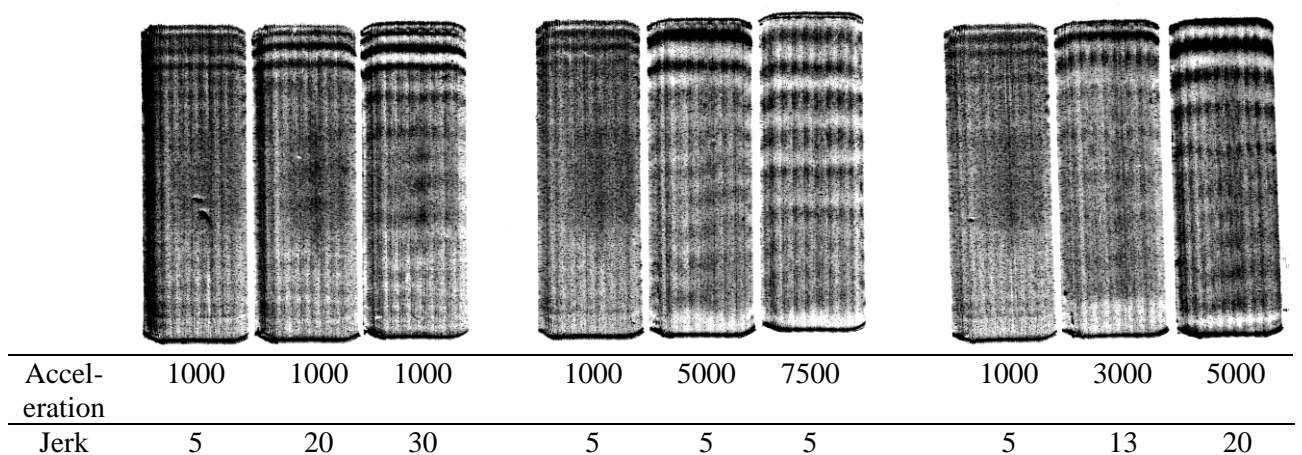
Data shows that increasing acceleration from 1000 mm/s<sup>2</sup> to 5000 mm/s<sup>2</sup> together with jerk from 5 mm/s to 20 mm/s has linear increase in overshoot from 10 μm to 70 μm. When increasing both characteristics at the same time, overshoot increase is higher than when changing them individually. It seems that increased acceleration and jerk have a cumulative effect on dimensional accuracy.

In general lower is better when it comes to acceleration and jerk impact on overshoot. It is important to keep in mind though, that lowering these parameters would significantly increase printing time.

### 7.3. Analysis of acceleration and jerk impact on surface quality

Increasing acceleration and jerk in addition to increased overshoot increases visible surface ringing.

Just like in analysis on maximum speed specimens of each set of parameters have been scanned and placed side by side for easy comparison in figure 40. Here specimens are placed on their side, so layer lines are going vertically.



**Fig 40.** Specimen's surface ringing visual comparison



From the pictures it can be seen that even very low acceleration and jerk settings result in visible surface ringing. Increasing these values also increases visible ringing amount that roughly coincides with amount of measured overshoot. There is noticeable difference in frequency of oscillations when comparing increasing jerk values versus increasing acceleration values. High jerk values probably have higher frequency because acceleration is set low and average speed is much lower. This coincides with results from maximum speed analysis.

If visual appearance is the most important, then setting acceleration low is best. Jerk also introduces visible surface ringing, but setting it low while keeping acceleration high could result in visible corner swell which might not be desirable.

## 8. Summary of results

To test impact of increased maximum printing speed specimens at five different speeds have been printed on two 3D printers. Specimens printed on Anycubic i3 Mega showed that increasing maximum speed to 200 mm/s at 0,2 mm layer height results in average dimensional error of 0,49 mm. Specimens printed on Anycubic 4Max showed that increasing maximum speed to 400 mm/s at 0,1 mm layer height results in average dimensional error of 0,38 mm. Increased maximum sprinting speed has direct and indirect impact on dimensional accuracy. Direct impact manifests as overshoot at corners and surface ringing. Indirect impact manifests through extruder when increased maximum speed causes increased flow rate. And increased flow rate results in reduced relative output and non-linear behavior of the extruder. Together these factors result in over-extrusion and increased dimension at the corners and under-extrusion and reduced dimension along the middle of the part's side walls. During visual analysis of surface quality, it has been determined that frequency of surface ringing reduces as speed increases.

Following the results of impact of maximum speed, experiment on relative output of the extruder has been carried out. Relative output of Anycubic i3 Maga has been measured at eight different flow rate values. In general, increased flow rate results in reduced output. One of the data points shows that when printing speed is increased to 200 mm/s at 0,2 mm layer height and nozzle temperature of 210 °C, relative output of the extruder is only 62 %. When extrusion temperature is increased from 210 °C to 240 °C relative output can be increased by as much as 15 %.

Lastly, to see how much increased acceleration and jerk settings affect overshoot and surface ringing of 3D printed parts, specimens at three different values each have been printed on Anycubic i3 Mega. Results show that increasing acceleration causes linear reduction dimensional accuracy with error of 70  $\mu\text{m}$  at 7500  $\text{mm/s}^2$  of acceleration. Increasing jerk also causes linear reduction dimensional accuracy with error of 40  $\mu\text{m}$  of overshoot at 30 mm/s of jerk. Increasing these values at the same time has a cumulative effect and result in error of about 70  $\mu\text{m}$  at 5000  $\text{mm/s}^2$  of acceleration 30 mm/s of jerk. Visual comparison of the specimens shows that even low acceleration and jerk settings result in some visible surface ringing.

## Conclusions

Research has been carried out on FDM 3D printing technology to find main types of FDM 3D printers, their construction types motion characteristics. Maximum speed, acceleration and jerk values have been determined to be the most important when it comes to dimensional accuracy of printed parts. After analyzing possible surface imperfections caused by increased speed, hypotheses have been developed for the experiments. After analyzing the results the following conclusions can be made:

1. Increasing maximum printing speed increases flow rate which reduces relative output and increases non-linear effect of the extruder. Both of these effects result in reduced dimensional accuracy - lower than nominal dimension along the middle of printed line and above nominal dimension at corners. Average dimensional error of 0,38 mm was measured when maximum speed was increased to 400 mm/s at 0,1 mm layer height with Anycubic 4Max 3D printer. Average dimensional error of 0,49 mm was measured when maximum speed was increased to 200 mm/s at 0,2 mm layer height with Anycubic i3 Mega 3D printer.
2. Increasing printing speed increases flow rate of the plastic which results in reduced relative output of the extruder. At extrusion temperature of 210 °C, layer height of 0,2 mm and equivalent printing speed of 200 mm/s relative output only 62 %. Relative output is increased by as much as 15 % when printing temperature is increased from 210 °C to 240 °C.
3. Reduction in dimensional accuracy at corners is linear to increased acceleration or jerk characteristics. Dimensional error at acceleration of 7500 mm/s<sup>2</sup> is 70 μm. Dimensional error at jerk of 30 mm/s is 40 μ. Increasing these values at the same time has a cumulative effect - at 5000 mm/s<sup>2</sup> of acceleration 30 mm/s of jerk error is about 70 μm
4. Visual analysis of surface quality was conducted by comparing scanned specimens. Results show that frequency of surface ringing increases when maximum speed is increased. In addition, even low acceleration and jerk settings result in some visible surface ringing.

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