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Design and evaluation of non-planar material extrusion on a 3-axis printer

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Abstract

The use of material extrusion (MEX) has increased rapidly due to the affordability of 3D printers. This has led to a growing demand for improved print quality, high fidelity, strength, or fast print times. In this study, a non-planar approach for better surface quality is investigated. The hardware of a 3-axis MEX printer was developed together with testing new software for non-planar slicing. The aim was to identify the most influential parameter combinations using design of experiments. A novel method for measuring surface quality was presented together with future research work.

Keywords: non-planar material extrusion, additive manufacturing, design of experiments, nozzle design, 3D printing

1. Introduction

Non-planar material extrusion (MEX) has gained attention in recent years (Mitropoulou, 2022) (Ahlers, 2019). This involves the use of additional axes of motion in 3D printers to create non-planar layers, resulting in improved strength, surface finish and a reduced need for support material (Chakraborty, 2008). Kalmanovich (1997) began producing curved, laminated objects. The layers are bonded together as non-planar surfaces, which provide additional strength and reduce construction time. Diegel (2011) investigated curved plastic parts with conductive electronic tracks and components printed as an integral part of the plastic component and developed an algorithm to generate the curved paths. Huang and Singamneni (2015) developed the adaptive curved layer slicing based on the three-plane intersection method for curved layer offsetting and consideration of facet angles together with the residual heights for adaptive slicing. Tests confirmed better mechanical properties of curved samples. Zhao (2023) studied a combination of ray-based slicing and helical path planning for nonuniform path spacing between the adjacent paths in the same curved layer. The proposed slicing method can be used for revolving thin-wall parts based on a rotary 3D printer. While traditional MEX technology has been widely used, exploring the non-planar approach offers numerous advantages. However, there are still uncertainties and limitations associated with non-planar MEX, making it a significant area of research and development.

The purpose of this study is to investigate a promising software solution for non-planar MEX that enables the generation of machine code for consumer-grade printers. The Slic3r plugin for non-planar MEX by Daniel Ahlers made it possible to generate non-planar g-code for any geometry entered into the slicer (Ahlers, 2019). This is an advance over the previous approach to generating non-planar g-code, which was more manual, requiring the user to specify planar and non-planar regions and use MATLAB scripts. Additionally, this research aims to enhance understanding of hardware modifications required to optimize the utilization of non-planar MEX features. By conducting practical experiments, data on the effects of printer parameters on the surface quality will be gathered. Moreover, the study will explore feasible nozzle design modifications to improve the performance of existing printers in non-planar MEX. By investigating the technical aspects of printer design and mechanics, feasible modifications aiming to enhance performance will be identified. These findings will contribute to the development of practical recommendations for manufacturers and users interested in adopting non-planar MEX technology.

Design for AM is a must if we want to apply AM in a cost-effective way and take advantage of specific manufacturing opportunities (Diegel, 2022). Design for AM must be applied already in the conceptual phase of design (Tavčar, Nordin, 2021). Applying non-planar MEX to an existing printer has some limitations and the design constraints must be considered to maximize the benefits of non-planar MEX. A review of the existing literature on non-planar MEX will be conducted to provide a theoretical framework for understanding the benefits, limitations and potential applications of this technology. This analysis will provide valuable insight into the current state of non-planar MEX and identify areas that require further development and improvement. The design of experiments methodology will be used to systematically vary the printer settings and measure the resulting outcomes. This approach will provide valuable insights into the optimal printer design and configurations to achieve the desired results in non-planar MEX.

Non-planar material extrusion offers significant potential for the additive manufacturing industry by providing improved strength, surface finish, and reduced reliance on support material. However, the current state of non-planar MEX is characterized by uncertainties and limitations, making it a crucial area for research and development.

2. Material Extrusion - MEX

Material extrusion (MEX) or fused deposition modelling (FDM) is a widely used manufacturing method in which a filament of a material, such as plastic is extruded from a nozzle to build up a model layer by layer to create a final 3D object. According to Godec et al., a generic term for FDM is material extrusion (Godec, 2022). For a material to be suitable for the MEX process, it needs to have sufficient viscosity to be extruded through the nozzle and possess properties that allow it to solidify after deposition.

The expiry of MEX patents around 14 years ago gave manufacturers the opportunity to produce machines using this technology. As a result, prices dropped significantly, making MEX printers and printer kits more accessible to hobbyists (Filemon, 2016). The growing user base of MEX has led to rapid advances in both software and hardware. Enthusiasts have driven the development of faster devices and a better understanding of the factors that influence the appearance and characteristics of the final printed product.

A relatively new focus in MEX is exploring the potential of printing non-horizontal layers, with the aim of better utilizing the movement capabilities of different MEX printers. This emerging development is the main focus of this research, which aims to investigate and optimize the development and operation of machines that can print in non-horizontal orientation.

Non-planar MEX, also known as Curved Material Extrusion (CMEX), involves the generation of g-code commands that enable movements beyond strictly horizontal layers in 3D printing. This approach offers the advantage of more accurate surface reproduction by minimizing staircase effects. Figure 1B illustrates the non-planar movements in g-code. The inaccuracy resulting from the approximation of the layers is evident in Figure 1 (left), where individual layers are visible, while Figure 1 (right) shows a smoother surface achieved by non-planar printing. Non-planar MEX printing also offers advantages such as higher strength, higher resolution and a reduced need for support material (Nayyeri, Zareinia, & Bougherara, 2022). In this article, the effects on the performance and applications of non-planar MEX are explored.

CMEX can go beyond the traditional Cartesian system. MEX machines with 4 axes and more have been explored for CMEX purposes. They offer advantages such as improved clearance to avoid collisions with previously extruded material and better adhesion to the previous layer. In a study by Mitropoulou, Bernhard and Dillenburger (2022), a 6-axis robotic arm was used for non-planar printing, which showed improved handling of branched models. The results emphasized the ability to handle more complex models, eliminate the need for support material, and achieve esthetically pleasing prints with layer lines that match the shape of the model (Mitropoulou, Bernhard, & Dillenburger, 2020).

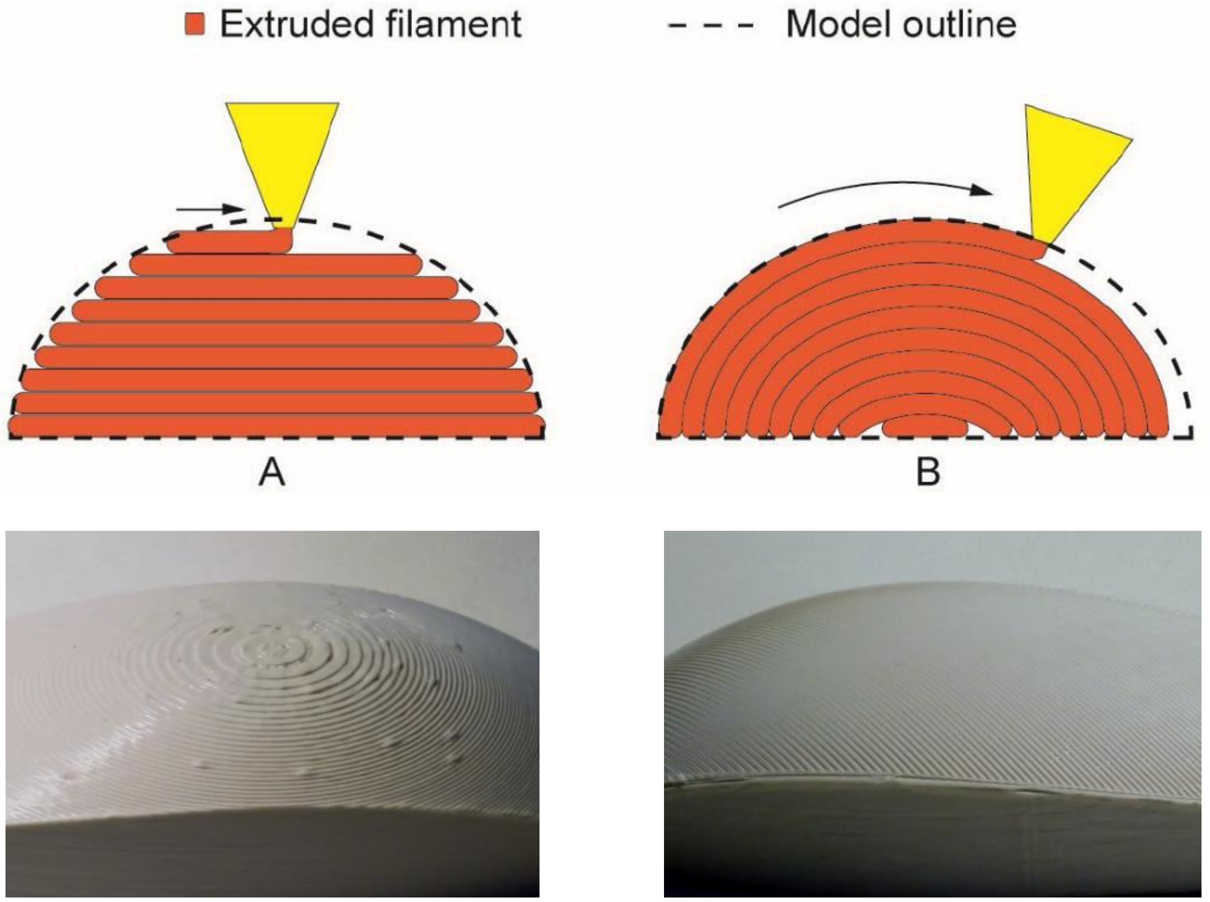


Figure 1. **Schematic representation of the difference between conventional slicing (A) and non-planar slicing (B) during printing**

Planar and non-planar layers can be combined using a modified slicer software (Ahlers, 2019). The software selectively applies non-planar layers to improve the top surface of the print. This approach is suitable for 3-axis printers with limited clearance. User-defined clearance settings can be input to avoid collisions or restrict non-planar printing within the printer limitations. This method provides a practical solution to achieve higher surface quality while optimizing the use of non-planar capabilities.

3. Nozzle design for CMEX

The design of the nozzle plays a crucial role in the success of a 3D printing process, especially when creating non-planar surfaces. As noted by Nayyeri, Zareinia, & Bougherara (2022), a limitation of fixed-angle nozzles is the risk of gouging already printed material. One approach to improve the clearance around the hot end of the printer is to extend the length of the nozzle. In this way, the new nozzle design enables the creation of larger non-planar surfaces with a larger angle (Figure 2). This concept was implemented by making a longer version of the E3D nozzle with an exposed length of 10 mm, which is 5 mm longer than the standard E3D nozzle on the Prusa MK3s+ test printer (Rowley, 2017). This extended length provides more space for the plastic material to flow freely, reducing the likelihood of unwanted contact with the hot end of the printer.

Another design change to the nozzle was to reduce the tip area (Figure 2). This was achieved by adding a secondary angle to the tip of the nozzle, reducing the flat area at the tip from 1 mm to 0.6 mm in diameter (Rowley, 2017). The smaller the flat area of the nozzle, the smaller the detail that can be printed on the top surface.

The geometry of the nozzle has a direct impact on the flow behaviour of the plastic material during the 3D printing process. The aforementioned changes in nozzle design, including the extended length and reduced tip area, are intended to optimize the flow of the plastic material. It is important to note that the flow behaviour of the plastic material depends not only on the nozzle design but also on various printer settings.

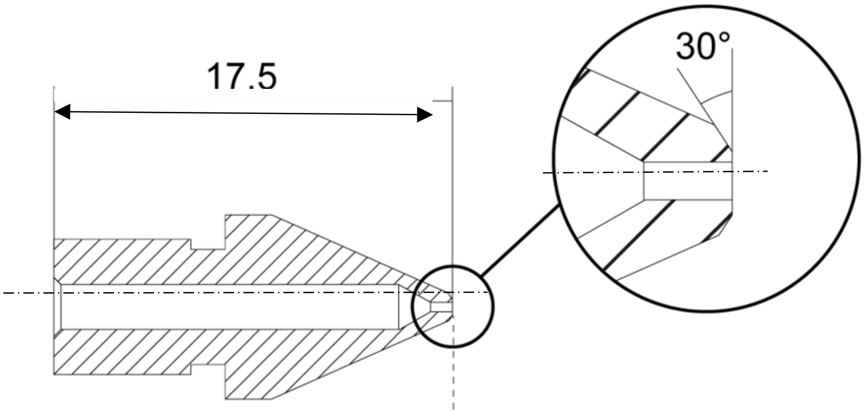


Figure 2. The cross section of the nozzles with an added tip angle of 30 degrees

To ensure a fair comparison between the different nozzle designs, certain printer settings were calibrated and adjusted accordingly. The retraction, which is the amount of plastic that is retracted into the hot end after a finished line, was adjusted to minimize excess plastic due to leakage (Prusa3D, 2022). The flow rate multiplier, which controls the amount of plastic extruded, was calibrated by measuring the individual wall thickness of a hollow mold (Prusa3D, 2022). The linear feed rate, a factor used to correct for the different pressure build-up, was also adjusted based on the nozzle used (Prusa3D, 2022). The nozzles used in the analysis were machined on a manual metal lathe from brass hexagonal material. The specific sequence of operations for the machining process was planned to ensure the accurate manufacture of the nozzles.

To summarize, the design of the nozzle in CMEX plays a crucial role in achieving high-quality 3D prints, especially when it comes to non-planar surfaces. The changes made to the nozzle design, including the extended length and reduced tip area, are aimed at improving the clearance around the hot end and optimizing the flow behaviour of the plastic. However, it is important to consider the calibration of the different printer settings to ensure accurate comparisons between different nozzle designs. The machining process of the nozzles should also be carefully planned and monitored to ensure their precise manufacture.

4. Method

The research process includes the following steps:

- Making of the nozzle with new design parameters
- Development of the test to evaluate the surface quality
- Identification of the most influential parameters through Design of Experiments (DoE)
- Evaluation of the results and plan for future research

Design of Experiments (DoE) is an efficient method to gain better, reproducible, and robust knowledge about a system that cannot be modeled well numerically. DoE enables easy comparison of parameters, as well as the ability to test multiple factors simultaneously to minimize the number of runs required. The method overcomes the limitations of analyzing a single factor at a time (Bradley, Douglas, 2019). It helps to explore a larger part of the experimental design space and see how the factors interact. The most important step in the DoE is the selection of the process parameters and the determination of the low and high values, as shown in Table 1. The samples were prepared according to the experimental design plan (Table 1) and evaluated in the next step according to the target function – visual quality, speed or strength.

In order to achieve the goal of obtaining comparable results for the test models in the DoE experiment, a model for surface defects was created (NIST, 2012). This model aimed to identify areas of the parts that were affected by defects. The construction of this model was based on the experience gained from using the slicer software and the resulting parts. The test artifact used to investigate the impact of the DOE study parameters was selected based on a simple, quick-to-print part that would have a large number of stair steps when printed with conventional MEX. The part consists of multiple surfaces, some of which are flat and slightly angled, while others are curved surfaces that reach 45° slope at the tips in extreme cases.

Four main categories of surface defects were found during the identification process. These categories are as follows:

1. Ridging: This refers to the accumulation of material between the filament paths when printing at more acute angles.
2. Over extrusion: This is an accumulation of plastic in certain areas due to either nozzle interference with previously extruded plastic or incorrect flow from the nozzle.
3. Visible previous layers: In this case, a previously printed layer can be seen on the top surface, appearing as lines normal to the top printed surface extrusions.
4. Surface trueness: This refers to the dividing lines between different areas of the print and how visible they are.

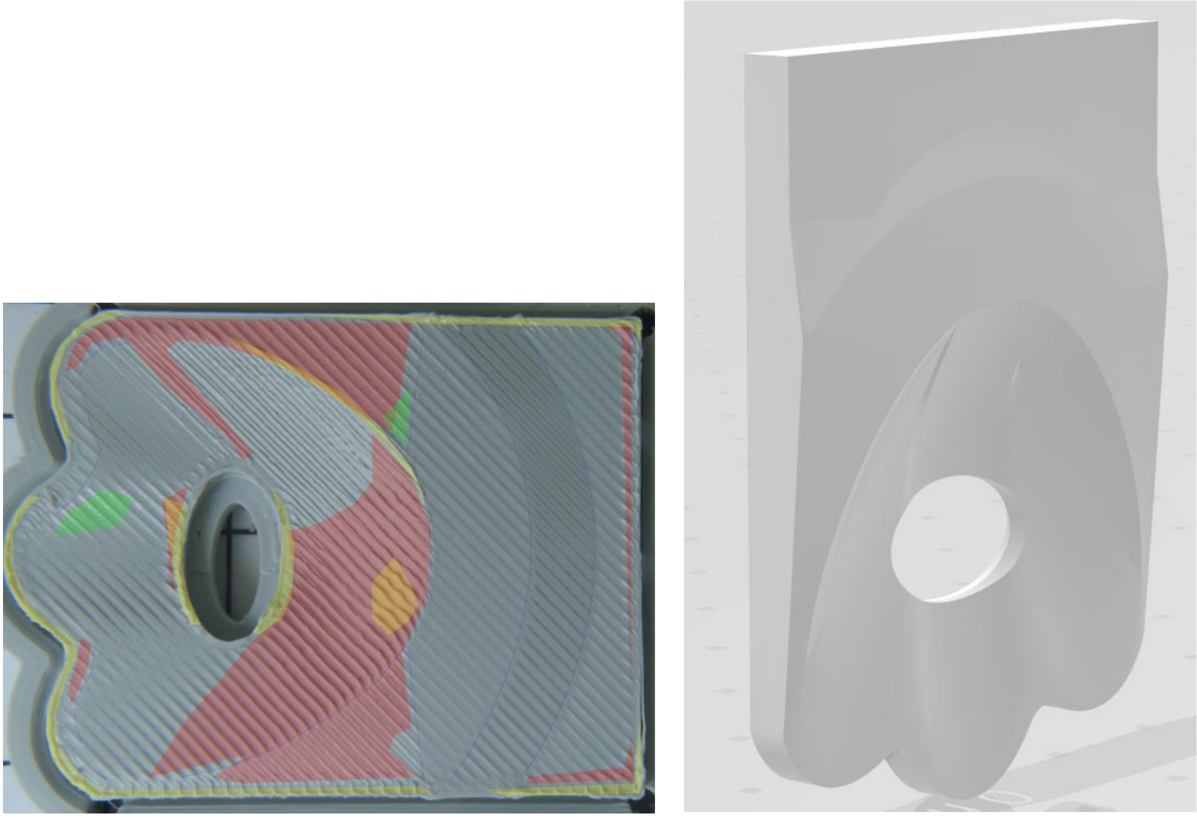


Figure 3. A test sample; the areas of a test print with defects were calculated against the overall surface (left); an isometric view of the test sample (right)

For the goal function of the experiment, these different defects were summarized to acquire a percentage value of total defect for each of the samples analyzed. The objective of the tests was to find the parameters that showed the greatest effect in minimizing the total surface defect percentage.

To ensure uniform and consistent results, a standardized approach was taken when taking the photographss for analysis. This was done to minimize variations in surface area and perimeter length, as these factors would impact the comparison of values from the 3D model.

A permanently mounted light source and fixture were used to ensure repeatable placement of samples in a photo box. A Panasonic DMC-GX1 camera was positioned in another fixture at a fixed distance from the sample, allowing a photograph to be taken with the subject positioned on a grid of known dimensions (Figure 3). This grid was used to facilitate the use of lens correction tools in the image editing software (e.g. Photoshop 2023) and the alignment of the sample. The areas of the sample in Figure 3 were classified as follows: Red – ridging, Yellow - over extrusion, Green - visible previous layers, and Blue lines - surface trueness.

The same standardized process was applied to all sample photos to ensure proper placement and low distortion for the subsequent steps. The measurement of surface defects was then performed using Adobe Illustrator V27.11. In this software, the areas of surface defects were observed and noted as a percentage of the total area and perimeter. These measurements served as the goal parameter to minimize. To measure surface trueness, the built-in perimeter measurement tool in Adobe Illustrator was used. Additionally, a plugin for the calculation of area in Adobe Illustrator, developed by Buchanan (2018), was utilized.

A 2D approach was used to analyze how large the area of the test samples affected by printing errors was and how accurately the different features of the 3D model were printed. It allows comparison of parts and requires only simple tools. Its use was deemed appropriate as all parts to be compared were from the same original 3D model and image capture was done under controlled lighting conditions. For a general approach, a 3D scanning approach might be more suitable as it is not dependent on the factors mentioned above.

5. Results and discussion

The results of the experimental study conducted to investigate the effects of the process parameters on the 3-axis C process are presented in this section. The design of experiments (DoE) methodology was employed to systematically explore the interactions between various parameters and their effects on the process and the final product.

Table 1. The five selected process variables and their respective values for low (1) and high (2)

Process variable	A -Tip angle (°)	B- Layer height(mm)	C- Acceleration (mm/s^2)	D- Fill angle (°)	E- Temperature(°C)
Low Value - 1	0	0,1	400	0	190
High Value – 2	30	0,3	2000	45	220

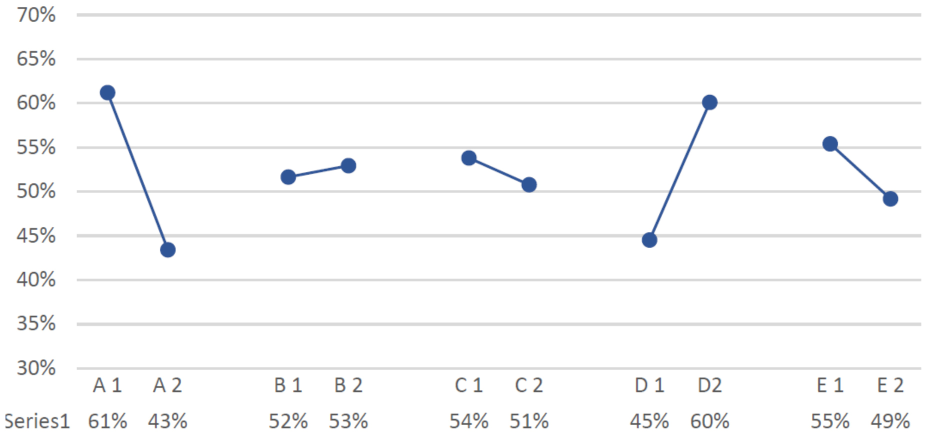
Prior to conducting the main experiment, smaller 2-factor factorial tests were performed to observe the impact of different printing parameters on the process (Antony, 2014). This initial exploration helped in identifying the critical process variables to be studied. As the CMEX technology and software used were relatively new, the factors derived for the design of experiments were based on these preliminary tests.

The process variables selected for the main experiment were determined based on both practical experience from previous trials and information from the relevant literature. Table 1 summarizes of the process variables, along with their identification letters and low-high level values. The first process variable, A - tip angle, was selected based on the theory proposed by Ahlers (2019). According to this theory, the optimal nozzle for 3-axis CMEX should have a flat surface diameter of the tip that is as close to the orifice diameter as possible. Hence, the tip angle was introduced as a secondary angle at the tip, resulting in a flat tip area diameter of 0.6 mm compared to the other nozzles with a diameter of 1 mm (Figure 1).

The second process variable, B - layer height, was chosen considering the interference of the nozzle with the extruded filament during the curves. Previous studies have found that layer height can significantly affect surface finish during surface printing (Ali, Chowdary, & Maharaj, 2014).

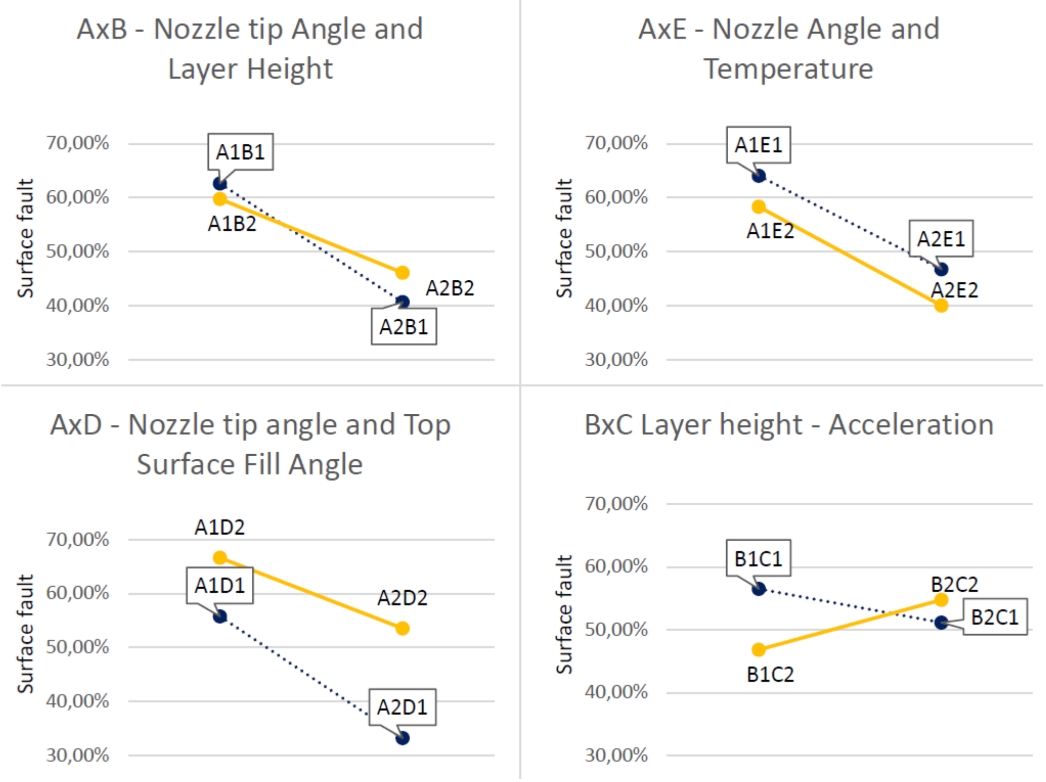
Other process variables, such as C - acceleration, D - fill angle, and E - temperature, were selected based on the preliminary 2-factor analysis. These variables were considered important factors to be investigated in order to gain a comprehensive understanding of their effects on the process and the final product.

Table 2. The mean effects of the main factors on surface quality - goal function of the test parts; the graph shows that the nozzle tip angle (A), surface fill angle (D), and temperature (E) had the greatest impact



To determine the optimal levels for each process variable, a DoE method with 32 samples and a full factorial design was used. The experiment consisted of multiple trials, with each trial representing a combination of different levels of the process variables. The resulting surface finish depending on the number of surface defects as a function of the plane top area of the test prints.

The results of the experiment showed significant interactions between the process variables and their effects on the responses. For example, it was found that increasing the tip angle (A) improve the visual surface quality, while a decreasing the layer height (B) has no significant impact on the surface (Figures 4 and 5).


AxB - Nozzle tip Angle and Layer Height

AxE - Nozzle Angle and Temperature

AxD - Nozzle tip angle and Top Surface Fill Angle

BxC Layer height - Acceleration

Figure 4. Visualization of the high impact interactions; descriptions of the samples, one example: A1B1 - parameter A at level 1, parameter B at level 1. A2B1 - parameter A at level 2

Similarly, the acceleration (C) was shown to have a minor impact on surface quality during testing. The surface fill angle (D) also played a crucial role in the process, smaller angel is better. The temperature (E) was found to have some effect on surface quality, indicating that the higher temperature value of 220°C improved surface quality.

The results obtained from the DoE provided a more comprehensive understanding of the individual and interactive effects of the process variables on the 3-axis CMEX process. This knowledge can be used to optimize the process parameters and achieve better overall quality and performance. In this section, we present the results of our experiments on the nozzle tip design and its impact on surface defects in the 3-axis CMEX. We conducted a series of tests, varying key parameters including the nozzle tip shape, surface fill angle and the nozzle temperature. In addition, we analyzed the interactions between these parameters to understand their combined effect on surface defects.

The dominant main factor that showed the largest impact on surface defects was the shape of the nozzle tip. In particular, a tip angle of 30° had the greatest influence on minimizing surface defects. This results shows that nozzle design plays a crucial role in achieving high-quality prints in 3-axis CMEX. Among all the main parameters and interactions, the shape of the nozzle tip proved to be the most important factor.

It was found that the filling angle of the surface is the second most important factor in minimizing surface defects when it is set to 0°. This parameter is more closely related to the geometry of the individual models to be printed. Our results demonstrate that changing the surface fill angle can have a notable impact on surface defects, particularly in non-planar prints.

Furthermore, the interaction between the fill angle and nozzle tip showed a positive correlation with the 30° tip and a fill angle of 0°. This suggests that optimizing both the fill angle and nozzle design can result in improved surface quality. However, further investigation is required to determine the extent of this impact.

The temperature of the nozzle also showed a certain influence on surface defects in our tests. However, it is important to point out that our experiments were limited in exploring this parameter, and additional tests are needed to establish the full extent of its impact. In particular, we found that a high nozzle temperature of 220°C resulted in the fourth largest improvement in minimizing surface defects. This results suggests that controlling the nozzle temperature can potentially contribute to enhancing print quality. In conclusion, our experiments highlight the significance of nozzle design in 3-axis CMEX. The shape of the nozzle tip was identified as the most influential factor in minimizing surface defects, particularly at a tip angle of 30°. In addition, optimizing the surface fill angle and considering the interaction with the nozzle tip can contribute to improved surface quality. Although the temperature of the nozzle showed some impact, further tests are necessary to fully understand its influence.

5.1. CMEX printing tips and design guidelines for 3-axis MEX printers

The following is a summary and practical tips for CMEX printing and printer design. The conclusions are based in part on research by the authors of this paper and in part on review by other researchers.

Hardware: The usual hardware equipment for a consumer 3-axis printer is generally not suitable for CMEX, which may be due to the fact that CMEX is not a common application for a 3-axis printer. As a result, special care must be taken to ensure that the part being printed does not strike the printhead itself. To identify potential problems of this nature, you should measure the distance around the extrusion nozzle and compare it to the model you are printing. A standard 3-axis MEX printer can easily print angled, rounded surfaces with good results if the proper precautions are taken.

Software: There is currently no slicer that can slice CMEX G-code without plug-ins. However, advanced user may be interested in the work of (Ahlers, 2019), which has resulted in a plug-in for the slicer program "Slic3r" that allows a user to use their own models for CMEX. However, to evaluate the technology of CMEX, there are a variety of pre-sliced G-code files available online, which can then be adapted to the G-code of the printer used. This can be a good way to test this technology and see some of its benefits.

Design: The main problem with using CMEX on a 3-axis printer is that in normal printing, where the printer extrudes the filament horizontally layer by layer, creates a more or less uniform force that pushes the melted filament onto the previous layer. In CMEX printing, the force changes while the nozzle remains horizontal, resulting in over- or under-extrusion depending on the printing angle. A general rule for achieving good surface quality is to minimize the angle of a surface in relation to the horizontal plane. This is also where great progress can be made in eliminating stair-step artifacts on rounded surfaces of parts where esthetic quality is important.

6. Conclusions

The aim of this research was to modify a consumer 3D printer to incorporate CMEX technology and evaluate its performance through a series of experiments. However, modifying the hardware posed a challenge to the planned timeline, as testing the CMEX parameters and other hardware prototypes required the printer to already have a higher level of non-planar printing capability. To overcome the time constraints, the researchers chose an approach that combined previous work with their experience with the planar MEX. By leveraging existing knowledge and insights, they were able to create a reasonable design space for the nozzle that allowed for a viable prototyping process that required few iterations. This approach also involved the use of data from external sources, which proved valuable in synthesizing and interpreting information.

Although the decision to employ a full fractional design was made with the intention of collecting comprehensive data and exploring parameter interactions, in hindsight, a more thorough consideration of this choice would have been beneficial. Conducting a fractional factorial design with more measurements in a smaller population could have facilitated easier validation or negation of the significance of the results obtained.

For future research, the investigation of nozzle geometry has emerged as a crucial factor that should be explored further. While the nozzle design remained relatively conservative in this study, exploring other geometries holds the potential for improved performance of the CMEX technology. Furthermore, if the surface defect measurement system is to be used in future studies, it would be worthwhile looking at ways to speed up the process. One possible solution could be the implementation of 3D scanning, which would reduce human error and allow for more accurate and faster surface quality measurements. The experimental design used in this study provided intriguing results, but further analysis could uncover additional insights. In particular, performing a three-stage analysis for certain process parameters, such as nozzle design, could provide a better understanding of how their effects evolve or mitigate. Such an in-depth analysis has the potential to open up new opportunities and ways to improve CMEX technology.

In conclusion, in this research, a consumer 3D printer was modified to incorporate CMEX technology and its performance was evaluated through experimentation. The results highlight the importance of effective hardware modification, the value of combining previous work with personal experience, and the benefits of considering alternative experimental designs. Future investigations into nozzle geometry, the possible use of 3D scanning and more advanced analysis techniques may contribute to further advances in CMEX technology.

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