Testing of the relationship between Nozzle Size, Layer Height, Print Speed and Material Consistency for Clay Extrusion 3D Printing

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Introduction

As with many technical processes there are a number of variables that go into successful clay extrusion 3D printing. Concentrating on print quality, these tests focus on the relationship between nozzle size, layer height, print speed, and material consistency . For convenience and the time individual prints take, the tests were kept to a small cup size scale using a standard shape of 8 cm height. While the specifics of these tests are relevant to this scale of 3D print it is hoped that the general conclusions and patterns of results will be relevant across all scales of clay extrusion 3D printing.

Previous tests have shown (see Clay Print Tests) that the physical properties of the material used, particularly the plasticity of the clay, has a significant influence on the print quality. To help concentrate on the specific objectives of this series of tests the variables of the material were standerdised to a single clay body. A stoneware clay was selected (Sio2, PRAI 13 310 200) that was known to show good extrusion printing qualities in the printer being used.

Note: All images have been produced at high quality to enable zooming to see detail. (Ctrl+mouse wheel)

Benchmark Print

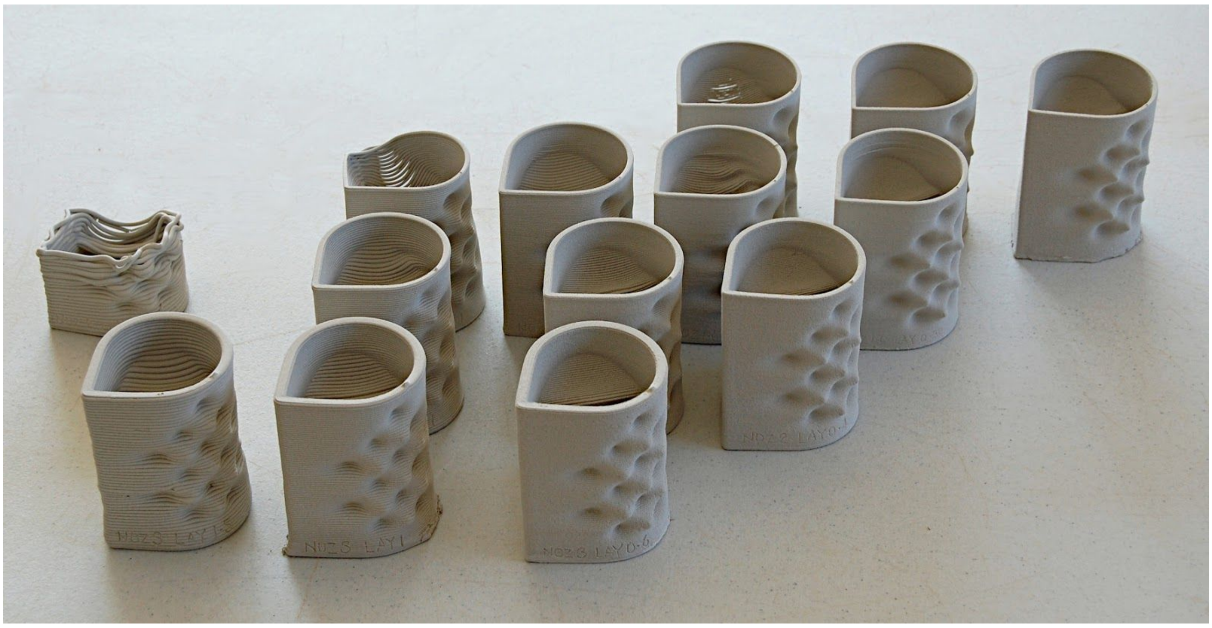
To set a benchmark for comparing print tests against, an initial sample of the shape was printed. From past experience a 1.6 mm nozzle was used with a 0.5mm slice height, print speed of 30mm per second and clay of a medium consistency. (See clay test for measurements of consistency) A double wall or shell was printed as this is known to offer stability to the print. It must be noted that all other tests were performed with a single wall or shell. The objective here was to prove that the sample shape could be printed crisply and without deformation, that was the case.

Benchmark print using a 1.6mm nozzle, layer height 0.5mm, medium consistency clay and double wall or shell.

Nozzle to Layer Height Tests

The first objective was to undertake a series of tests to see if an ideal ratio could be found between nozzle size and layer height for successful prints. The print speed and material consistency were kept constant. Clay of a medium consistency was used at a print speed of 25mm per second.

Because of the huge variation in the character of clays, to talk of ideals in clay printing is dangerous. So it would be better to say the objective was to find the general sweet spot for the proportion of the diameter of the print nozzle and the sliced height of each print layer. Four nozzles sizes were tested, (1mm, 1.6mm, 2 mm, 3 mm) with the overall pattern of proportion being important rather than individual tests.



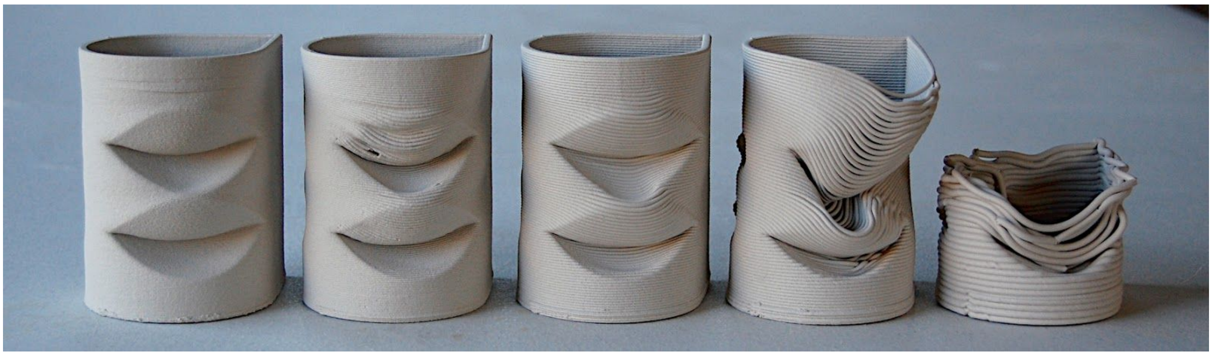
Overview of tests - nozzle size decreasing from front to back and layer height decreasing left to right.

Nozzle size - (left to right) 3 mm, 2 mm, 1.6 mm and 1 mm.

Procedure

To begin with an initial set of tests was undertaken to establish the most likely proportions for further testing. A test of 1:1 (nozzle diameter:layer height in measurement) proved to break down quite soon after reaching the textured area and overhang in the test shape - extreme right in the photo below. Using a 2 mm nozzle with a 2 mm layer height, the printed layer sunk below the printhead nozzle height and the connection between print and printhead was lost.

Next a 1.6 mm nozzle with a 1 mm layer height was tested, offering a ratio close to a 3:2 proportion - second from right in the photo below. While this printed better than the 1:1, the layers were not adequately packed together to cope with the overhang. This proportion printed fine in the vertical and coped adequately without distortion or delayering in the textured area, but collapsed very early in the 45° angle.



Tests determining nozzle to layer height proportions worth considering. Left to right - 5:1, 3:1, 2:1, 3:2, 1:1.

Proportions of 2:1, 3:1 and 5:1 all proved to print successfully so a test was designed using these three proportions across the four nozzle sizes.

The tests, as laid out in the illustrations below, are designed first to compare the crispness or sharpness of a printed corner for each of the four nozzle sizes. Each nozzle size is tested making use of the three nozzle, layer proportion ratios. Secondly, designed into the test form is an area of low relief pattern so as to be able to compare how nozzle and layer height affects the print quality of such a repeat pattern. Thirdly, there are two 45° angled indentations to the form, to be able to observe how well the different settings cope with the problem of clay slumping on an overhang during printing. Bearing in mind that the two walled benchmark test printed showing no sign of slumping.

All tests were printed on a small Delta type printer (CERAMBOT) and as said using clay of the same medium consistency and at the same print speed of 25 mm per second. Compressed air was used to deliver the clay to the printhead, with more air pressure required to feed adequate clay flow for the larger nozzle diameters. The printhead screw speed, having previously been configured in the slicing software (Cura) will have automatically changed with each new gcode file that was prepared. Each test was printed with a three layered base.

Note: All photographs have been embedded in this document at high quality so as to be able to be zoomed for detailed observation.

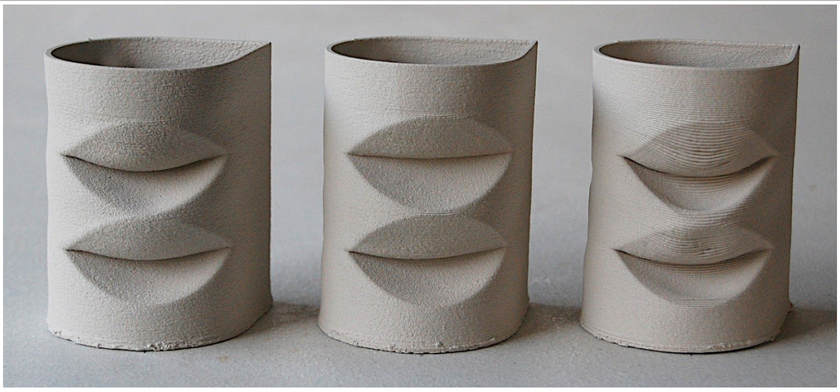
Vertical Edge Test

Nozzle : Layer	1:5	1:3	1:2
Nozzle 1 mm			
Layer height	0.2 mm	0.33 mm	0.5 mm
Nozzle 1.6 mm			
Layer height	0.32 mm	0.53 mm	0.8 mm
Nozzle 2 mm			
Layer height	0.4 mm	0.6 mm	1 mm
Nozzle 3 mm			
Layer height	0.6 mm	1 mm	1.5 mm

Low relief Pattern Test

Nozzle : Layer	1:5	1:3	1:2
Nozzle 1 mm			
Layer height	0.2 mm	0.33 mm	0.5 mm
Nozzle 1.6 mm			
Layer height	0.32 mm	0.53 mm	0.8 mm
Nozzle 2 mm			
Layer height	0.4 mm	0.6 mm	1 mm
Nozzle 3 mm			
Layer height	0.6 mm	1 mm	1.5 mm

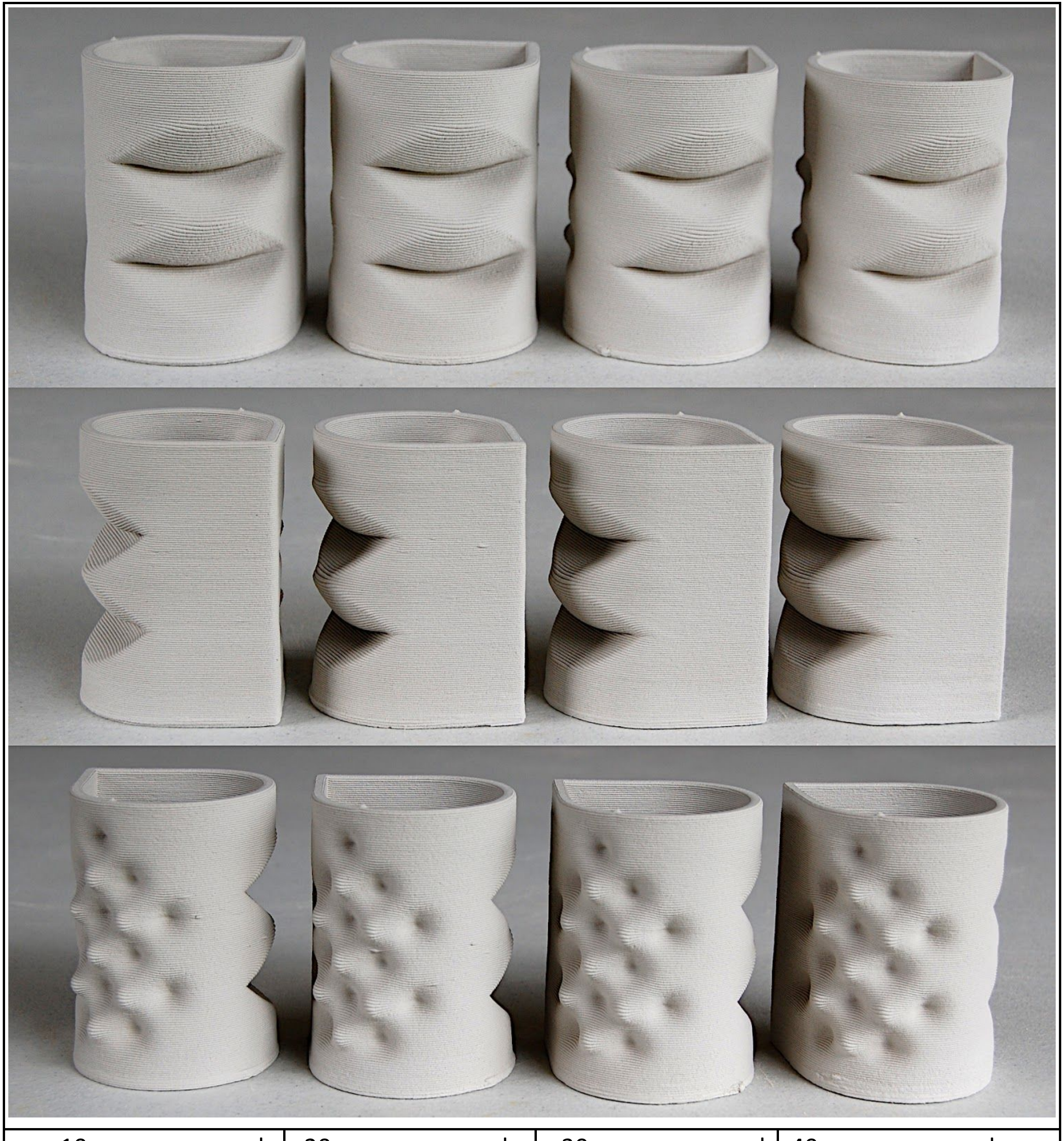
Overhang Test

Nozzle : Layer	1:5	1:3	1:2
Nozzle 1 mm			
Layer height	0.2 mm	0.33 mm	0.5 mm
Nozzle 1.6 mm			
Layer height	0.32 mm	0.53 mm	0.8 mm
Nozzle 2 mm			
Layer height	0.4 mm	0.6 mm	1 mm
Nozzle 3 mm			
Layer height	0.6 mm	1 mm	1.5 mm

Speed Test

The purpose of this test was to determine whether the print speed has any significant outcome to the final result. For this test a 2 mm nozzle was used throughout, as was a clay of medium consistency and a layer height of 0.6 mm. A three layer base was again included in each print.

It must be noted that the printer used is stable and smooth at both low speed and higher speeds so there were no inaccuracies due to mechanical limitations. Further, for the purposes of a fair test it was ensured that the clay delivery was generous at all speeds and there were no shortcomings due to material feed. A large difference in print time, from 42 minutes to 12 minutes was designed into the test to ensure greatest comparison.



10 mm per second	20 mm per second	30 mm per second	40 mm per second
42 minute print	22 minute print	15 minute print	12 minute print

Stiff to Hard Clay Test

With clay extrusion printing there is a logic that the stiffer the consistency of clay used the more stable the print should be. Stiffer, or the harder the clay is, the more the print should stand up and not distort or collapse.

Two tests were designed to test this speculation. The first again makes use of the test shape as used above and prints were made using a 2 mm nozzle with a layer height of 0.6 mm and a print speed of 25 mm per second. The second group of tests makes use of a flared shape with a 45° angle to it and a base of 4 cm, a height of 6 cm and a rim diameter of 16 cm. These tests were made with a 3 mm nozzle and a layer height of 0.6 mm and printed at 25 mm per second.

Medium printing consistency, as used for above tests	Hard printing consistency	Soft pottery wheel throwing consistency	Hard pottery wheel throwing consistency

For these tests four samples of clay were prepared from a medium to hard consistency. As a rough visual guide, the clay of a medium printing consistency makes a soft ball in the hands and the clay sticks and soon builds up on the hands as handled. A ball of hard printing clay is still soft to the touch but if your hands are clean can be handled with only a small amount of clay sticking to the hands. Handling of soft pottery wheel throwing clay, little sticks to the hands and a ball is reasonably resistant to handling. Hard throwing clay, your hands remain clean and some force is required to knock up a ball.

	Medium Printing consistency	Hard Printing consistency	Soft Pottery Wheel Throwing consistency	Hard Pottery Wheel Throwing consistency
Drop Spike - this tool represents the distance a 38 cm (235gm) sharpened steel rod penetrates into the clay sample when dropped from a constant height of 9 cm.	30 mm	26 mm	22 mm	17 mm
The pressure used during printing. For the hardest clay a mechanical ram clay delivery was used.	2.5 Bar	4 Bar	6 Bar	Mechanical ram clay delivery used.

Clay Stiffness Test - hardest clay to the left softest to the right.

For the flared shape test the objective was to run the test until the print broke down. To ensure the test was printable a benchmark was again set - right in photo. This was once more printed with a double wall using the medium printing clay, a 1.6 mm nozzle, layer height 0.5 and at 30mm per second. Also the hard printing clay (Hard Pottery Wheel Throwing consistency) was not tested.

In the illustration the ‘Soft Pottery Wheel Throwing’ consistency clay test is to the left. Followed by the ‘Hard Printing’ consistency clay, second left. The two right hand tests are the same ‘Medium Printing’ clay. The extreme right hand sample is the benchmark. The second to right, as with the first two tests are single shells prints using the 3 mm nozzle.

Conclusions

There is no desire to see these tests as providing hard and fast rules but to be a documentation in time that offers a reference enabling informed judgments and decisions to be based on. With the variability of clay and the complexity of the technology used, the aim was to offer some insight into the general pattern of the processes involved rather than the specifics.

Nozzle to layer height proportion

The decision of what nozzle size to layer height proportion to use when extrusion printing will always be an individual choice based on personal preference and the type of work or job being done. What this research has shown is that there are workable parameters between a proportion of 1:2 up to 1:5 layer height to nozzle diameter.

From the nozzles tested it appears 1:3 is a good starting point. A further observation is that as the nozzle gets larger the ratio proportion moves towards the smaller end of the ratio scale. For example a ratio of 1:2 produces a clean print with a 1mm nozzle while a 1:5 ratio might be preferable with a 3mm nozzle.

On the vertical edge test it stands to reason that the finer or smaller the nozzle the sharper or crisper a corner will be - a corner can only be as sharp as the diameter of the clay extrusion. The layer height appears to have little significant effect on the edge quality.

Layer height did show to have more significance in the low relief pattern test. All printed adequately so choice will come down to personal preference with the larger proportion being strongly layered and smaller proportions becoming granular in texture as layers become compacted together. This becomes more pronounced as the nozzle size gets smaller.

The 45° degree indentation test did not have as marked differences as expected. There is certainly a balance to be had where the contour stepping happens on a 45° slope. Too much flattening that happens with a fine proportion setting will distort the print while too great a contour step with a large ratio proportion results in the layer breaking apart. Possibly for this reason the mid range of 1:3 often proved to print with the least distortion.

An observation made while printing, that is obvious but worth bearing in mind, is that the larger the nozzle the more stable the print. While the proportion of the height to width of the extrusion was being kept constant for each nozzle size, as the wall got wider with each nozzle size, the print looked more stable during the print. That said, while the printed wall looked very delicate and wavy or unstable during printing of the 1mm nozzle the prints turned out fine.

Print speed

While the speed test outcomes do not look very interesting the test was very revealing for this very reason. To watch a printer print at 40 mm per second, taking 12 minutes to print the sample shape including a three layered base. Then to watch the same shape being printed at 10 mm per second and taking 42 minutes and there then being very little difference between the two prints is quite striking.

It would appear that as long as the equipment can stand up to it, printing speed is not that important in the outcome of print quality. Obviously this is assuming that you have a fully balanced system where clay delivery and mechanical smoothness can take the speed.

Stiff to Hard Clay

The two tests designed to examine the effect of progressively stiffer clay consistency being used on printed samples were both most informative and in different ways.

On the upright sample shaped, it showed that there is very little difference to print quality between a soft and hard clay consistency. The repeat pattern printed very similarly across all four tests. There are variable flow rate layering issues on the test using the hardest clay but these are due to the equipment and not the clay. Because of how stiff the clay was, a mechanical ram was used to feed the clay to the printer for this test and the variation in surface quality was due to not controlling the ram speed well. It was expected that the harder clay would show less distortion on the 45° degree indentation but as can be seen in the photographs there is little difference across all four test samples. The stiffer clay stood up no better than the clay of medium consistency.

The photographic documentation of the flared sample shape tests tells its own story. The harder the clay the less the flare will build. Contrary to expectation the stiff clay does not stand up in this shape better than a medium softer clay. It would appear the stiffness of the extrusion collapses the wall underneath. On a vertical build this would not be a problem but with any shape that goes off the vertical it would appear that there is no advantage in using stiffer clay. It must be pointed out that as has been shown from other tests (see Formulating and Testing a Clay Body for Extrusion 3D Printing) that overly soft clay will also not work.

Optimising any system is often by small degrees and this series of tests has gone some way to offering insights into where clay extrusion printing can be nudged. The information on nozzle, layer ratio probably only confirms what practitioners have arrived at through trial and error. People will print at whatever speed they and their equipment are comfortable with but it is reassuring that whatever speed that is there is no great advantage in changing it. The lack of any discernible advantage of using stiff clay, except for vertical printing, possible has the most relevance. Using stiff or hard clay requires more robust equipment and if there is no advantage to be gained then there is not the requirement to explore the increased engineering challenge.

Telling is that the best result obtained where those of the benchmark tests that were arrived at through gradually attained experience, using standard but well configured equipment and careful technique.