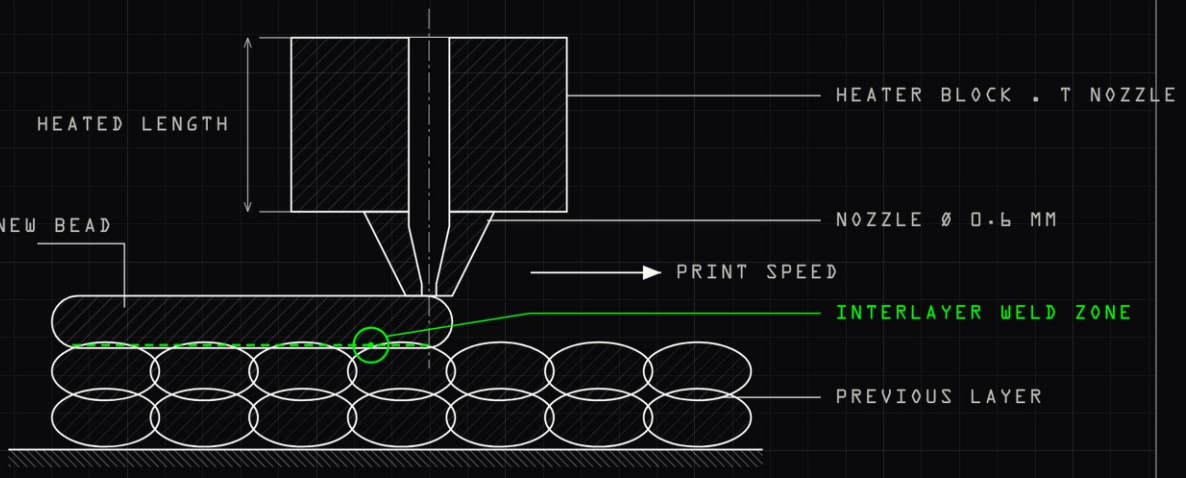
FIBERTHREE

DETAIL B . INTERLAYER WELD



WHITE PAPER . WP009

INTERLAYER ADHESION IN BUILD DIRECTION

How nozzle temperature, print speed and hotend determine strength in z. With a test series on F3 PA Pure Pro.

DOCUMENT

WP009

FIBERTHREE WHITE PAPER

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00 . EXECUTIVE SUMMARY

An FFF part is weakest in the build direction (z), because each new layer is only welded onto the already cooled layer beneath it. How well this weld succeeds decides the strength of many functional parts.

In a test series with 360 upright-printed tensile specimens of F3 PA Pure Pro, three variables were varied: nozzle temperature, print speed and the length of the heater block. Temperature proved to be the most important lever, speed the second. The length of the heater block had no measurable effect on the achievable strength. The best combination reached 33.1 MPa in z, the least favourable only 1.0 MPa.

AT A GLANCE

- **The build direction is the weak point:** each layer is only welded onto the cooled layer beneath it.
- **Temperature is the strongest lever:** about 6 MPa more strength per 10 K; at 285 °C F3 PA Pure Pro reached up to 33.1 MPa in z.
- **Speed costs strength:** about 1.8 MPa per 10 mm/s, considerably more at low temperature.
- **A long heater block** makes the strength more uniform but does not raise the maximum.

Recommendation: Print z-loaded parts of F3 PA Pure Pro at 275 to 285 °C and 20 to 30 mm/s without part cooling fan, and avoid tension in z by design.

33.1 MPa	≈ 6 MPa	360
Tensile strength in z, best combination, 285 °C, 30 mm/s	more strength per 10 K nozzle temperature	Tensile specimens of F3 PA Pure Pro

01 BACKGROUND

Filament manufacturers usually state strength for flat-printed specimens. In the build direction it is considerably lower, for all plastics and on all printers. For designers, however, this value is often the decisive one, because hardly any part can be oriented so that no tension acts across the layer boundaries anywhere.

The literature on FFF strength is extensive but concentrates on geometric parameters such as orientation in the build space, raster angle, layer height and infill. Thermal variables such as nozzle temperature and print speed are studied considerably less often, and the design of the printer, such as the length of the heated zone, hardly at all.

This paper summarises a study that closes exactly this gap for polyamide. It was carried out as a student research project at TU Darmstadt, Institute of Printing Science and Technology, with support from Fiberthree [1]. We place the results in the context of the literature and derive recommendations for printing.

This paper is part of our white paper series (overview in WP001). WP004 shows how to avoid z loads by design; WP002 and WP003 cover drying and annealing, which also affect interlayer adhesion.

FIG. 1: SCHEMATIC
DETAIL B . INTERLAYER WELD

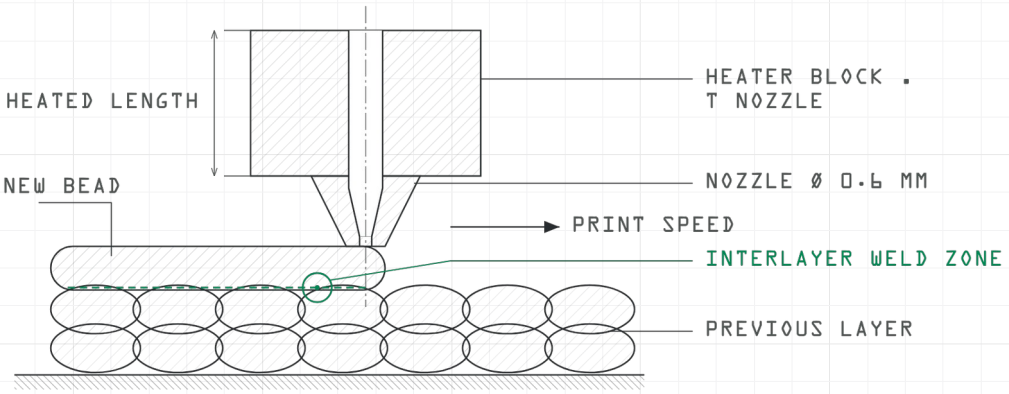


FIG. 1 New bead welded onto the previous layer, weld zone between the layers, schematic, not to scale.

02 WHY Z IS WEAKER

Two plastic parts only weld when enough heat, enough time and sufficient pressure come together at the joint. Only then can the molecular chains of both sides interpenetrate and entangle [2]. In injection moulding or hot-plate welding, all three variables can be set specifically.

In FFF printing the conditions are less favourable. The new bead is deposited almost without pressure. Its mass flow is very small, so it cools quickly and stays hot only briefly. The layer beneath has already cooled and is only remelted by the heat of the new bead. Within a layer the neighbouring bead is often still warm; between layers the bond is weakest.

The only control variable is therefore the heat that the melt brings from the nozzle, and the residual heat of the layer beneath. Both depend on nozzle temperature, print speed, cooling and the design of the hotend.

Too much heat is harmful as well, however: if the melt stays too hot for too long, the molecular chains can degrade and gases form. Strength then drops again [11].

03 STATE OF RESEARCH

Three review papers together evaluate about 250 studies, partly overlapping, on the strength of FFF parts [3, 4, 5]. Raster angle, layer height and orientation in the build space are studied most often. Where orientation was studied, it had the greatest effect on tensile strength [4]. Extrusion temperature and print speed appear in only two to eight of the evaluated papers each; heating power, nozzle length or filament diameter in none.

The existing studies on thermal variables show a consistent picture:

- **Orientation in the build space:** upright-printed PLA specimens fail between the layers, brittle and with the lowest properties. Flat and on-edge specimens break through the beads and are considerably stronger [6].
- **Nozzle temperature:** in ABS, the interlayer fracture resistance increased by 38 % when the nozzle temperature was raised from 220 to 240 °C. About 15 % is due to better adhesion, 23 % to a larger contact area between the beads [7]. The thickness of the weld zone also grows with temperature [8].
- **Residual heat of the layer beneath:** temperature, fan, speed and layer time can be reduced to two variables, the temperature of the previous layer and the volume of material actually extruded. If both are increased, the interlayer strength approaches that of the bulk material [9].
- **Layer height and nozzle:** in PLA, the strength across the layers changed by a factor of about 3.5 from the smallest to the largest layer height. A larger nozzle at the same layer height increased it [10]. In ABS, the fracture resistance dropped to about a third at a layer height of 0.3 mm [7].
- **Heat transfer in the hotend:** heat transfer in the heated zone limits how fast printing can be. Only about half the expected value was measured, partly because of deposits in the melt zone [11]. Faster printers therefore need more effective heating of the filament [12].
- **Printer:** the same parameters have different effects on different printers. Optimal settings therefore cannot be transferred from one machine to another without testing [13, 3].

04 TESTING IN BUILD DIRECTION

ISO 527 applies to tensile testing of plastics. For additively manufactured specimens, the guideline VDI 3405 recommends printing type 1A specimens upright [1]. In practice this revealed two problems:

- **Stability:** type 1A stands on only 40 mm² of footprint. In preliminary tests, at least one of six specimens detached from the print bed and fell over in each of four runs.
- **Short beads:** in the 10 × 4 mm measuring section, the nozzle hardly reaches the set speed. Two specimens whose print times should have differed by 30 % by calculation differed by only 14 %.

A dedicated specimen was therefore designed for the study. It is at most 100 mm high, has 55 mm wide clamping shoulders, a transition radius of 22.1 mm and a depth of 4.8 mm, an integer multiple of the 0.6 mm bead width. The edges are rounded so that the print head does not ring.

The beads are thus 3.5 times as long as with type 1A, and the footprint grew to 227 mm². In validation no specimen fell over, and the specimen clearly reflected the effect of print speed.

In practice this means: when testing the z strength of a material or a print setting, use specimens with long, closed beads and a wide footprint. Comparisons are only meaningful within the same specimen geometry.

05 TEST SERIES

The material studied was F3 PA Pure Pro, a polyamide 6 without colour masterbatch. DSC measurement according to ISO 11357 gave a glass transition at 72.7 °C and a melting peak at 236.1 °C; from about 255 °C the material is completely molten [1]. This set the lower limit of the test series.

Three variables were varied:

VARIABLE	LEVELS	VALUES
Heater block	3	V6 (11.5 mm), Volcano (20 mm), SuperVolcano (50 mm)
Nozzle temperature	4	255, 265, 275 and 285 °C
Print speed	5	20, 30, 40, 50 and 60 mm/s

TAB. 1 Variables of the test series.

This gave 60 combinations with six specimens each, a total of 360 tensile specimens, 480 print hours and almost 11 kg of material.

Printing was done on three identical printers with direct-drive extruder, copper heater block, titanium heat break and hardened 0.6 mm steel nozzle, which differed only in the hotend. The other settings were the same for all specimens: bead width 0.6 mm, layer height 0.25 mm, part cooling fan off, the whole specimen made of walls without top and bottom layers. The filament was dried for 24 hours before printing and processed from dry boxes.

The specimens were conditioned for at least one week at 20 °C and 50 % relative humidity and tested at TU Berlin on a Zwick/Roell Z050 universal testing machine.

06 RESULTS

As expected, strength increased the hotter and slower the specimens were printed. In the best case, all three hotends reached comparable values of around 30 MPa:

FIG. 2: RESULTS

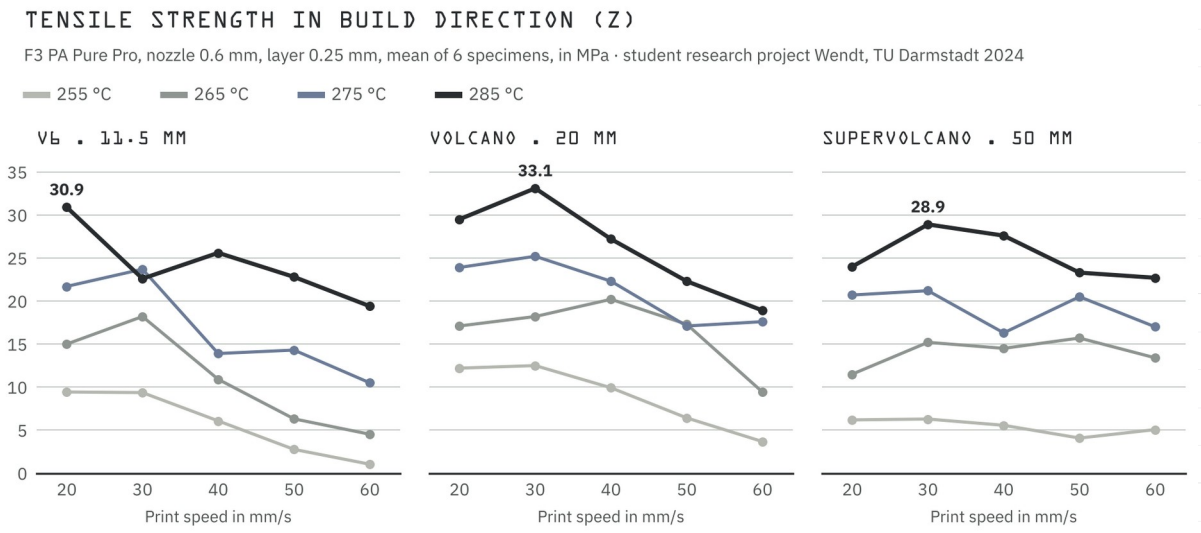


FIG. 2 Tensile strength of F3 PA Pure Pro in z by print speed, nozzle temperature and hotend [1].

HOTEND . TEMPERATURE	20 MM/S	30 MM/S	40 MM/S	50 MM/S	60 MM/S
V6 · 255 °C	9.4	9.4	6.1	2.8	1.0
V6 · 265 °C	15.0	18.2	10.9	6.3	4.5
V6 · 275 °C	21.7	23.7	13.9	14.3	10.5
V6 · 285 °C	30.9	22.6	25.6	22.8	19.4
Volcano · 255 °C	12.2	12.5	9.9	6.4	3.7
Volcano · 265 °C	17.1	18.2	20.2	17.3	9.4
Volcano · 275 °C	23.9	25.2	22.3	17.1	17.6
Volcano · 285 °C	29.5	33.1	27.2	22.3	18.9
SuperVolcano · 255 °C	6.2	6.3	5.6	4.1	5.1

HOTEND . TEMPERATURE	20 MM/S	30 MM/S	40 MM/S	50 MM/S	60 MM/S
SuperVolcano · 265 °C	11.5	15.2	14.5	15.7	13.4
SuperVolcano · 275 °C	20.7	21.2	16.3	20.5	17.0
SuperVolcano · 285 °C	24.0	28.9	27.6	23.3	22.7

TAB. 2 Tensile strength in z in MPa, mean of up to six specimens [1].

TEMPERATURE IS THE STRONGEST LEVER

Across all 60 combinations, nozzle temperature alone explains three quarters of the differences in strength. A regression model with all three variables describes 85 % of the measured values [1]:

- **Nozzle temperature:** about 6 MPa more strength per 10 K, highly significant.
- **Print speed:** about 1.8 MPa less per 10 mm/s faster, highly significant.
- **Heater block length:** no statistically significant effect.

At low temperature, strength drops particularly sharply with increasing speed. With the V6, the specimens printed at 255 °C still reached a third of the strength of those printed at 285 °C at 20 mm/s, but only a twentieth at 60 mm/s. Nine specimens from these ranges broke already when removed from the print bed, during storage or during preparation for testing, seven of them from the V6 and two from the Volcano.

THE HEATER BLOCK DETERMINES STABILITY, NOT THE MAXIMUM

The length of the heater block did not raise the best achievable strength. The longest hotend, the SuperVolcano, was even below the Volcano at 28.9 MPa versus 33.1 MPa. At 285 °C and 20 mm/s, at 24.0 MPa, it possibly already showed first signs of thermal degradation, because the material stays longer in the hot zone.

Length did, however, clearly affect uniformity: the longer the heater block, the less strength was lost at higher speed. At 275 °C, strength dropped from the slowest to the fastest level by just over 51 % with the V6, by about 26 % with the Volcano and by 18 % with the SuperVolcano.

CLASSIFICATION

For F3 PA Pure Pro printed flat, DLR measured 67.5 MPa along the bead and 61.3 MPa across it [17]. The best z values of this test series are about half of that. The comparison is only an indication, because

printer, specimen and laboratory were different. It does, however, show the order of magnitude achievable in the build direction with a well-tuned process, and how far below it an unfavourable setting can be.

The type of specimen also plays a role. On upright-printed specimens, the transitions between the layers form fine notches on the surface where stress concentrates and fracture begins. A tensile specimen milled out of a printed plate does not have these surface notches and is therefore likely to reach somewhat higher values. The values of this test series are thus on the safe side; they correspond, however, to what a printed part with an unmachined surface actually withstands.

07 PRINTING RECOMMENDATIONS

For parts loaded in the build direction, we derive the following rules from the test series and the literature:

01 **Clarify orientation first:** avoid tension across layer boundaries by design and orient the part along the load path (WP004). Process parameters improve z strength but do not replace good orientation.

02 **Temperature at the top of the window:** print F3 PA Pure Pro at 275 to 285 °C. Higher temperatures only with testing, because strength can drop again with too much heat.

03 **Couple speed to temperature:** with a 0.6 mm nozzle and 0.25 mm layers, the best values were at 20 to 30 mm/s. Printing faster means considerably lower z strength, especially with a short heater block.

04 **Long heater block for uniform quality:** a Volcano or longer hotend makes strength less sensitive to speed changes, for example between outer wall and infill. It is not needed for peak strength.

05 **Small layer height relative to the nozzle:** a flat layer on a wide bead increases the contact area between the layers [7, 10].

06 **Keep the layer beneath warm:** part cooling fan off or minimal for polyamide, and do not lengthen the time per layer unnecessarily so that the previous layer is still warm [9].

07 **Print dry:** moist polyamide foams and forms pores in the weld zone (WP002).

08 **Check the result:** compare the mass of a part with the target value from volume and density. Too low a mass indicates under-extrusion inside that cannot be seen from outside [14]. For critical parts, print a specimen upright with the same setting and test it.

The current trend towards ever faster printers should therefore be viewed critically for engineering plastics. Polyamide in particular needs high temperatures and sufficient time for the layers to weld.

08 LIMITS OF THE STUDY

The results initially apply to one material, a 0.6 mm nozzle, a layer height of 0.25 mm and printers of one design. The set values were used for nozzle temperature and speed. The actual melt temperature and the power consumption of the heater cartridges were not measured. All specimens were printed upright and tested with an unmachined surface; the notch effect of the layers is therefore included in the values.

The regression model describes the measured values well but cannot simply be transferred to other materials or printers. A general model would have to include further materials with their properties such as thermal conductivity, heat capacity and enthalpy of fusion, as well as 2.85 mm filament and temperatures above 285 °C.

For the fibre-reinforced grades, DLR values in z are available: F3 PA-CF Pro reached 21 to 29 MPa depending on the printer (WP004). A comparable parameter study for them is still pending.

09 CONCLUSION

Strength in the build direction is not a fixed material property but a result of the process. For F3 PA Pure Pro it ranged from 1 to 33 MPa depending on the settings. What matters is a high nozzle temperature and a moderate speed; a long heater block ensures uniform quality. When printing z-loaded parts, first get the orientation right, then set the process up for welding rather than speed.

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ABOUT FIBERTHREE

Fiberthree develops and produces technical filaments for FFF printing in Darmstadt, with polyamide at the heart of the portfolio. Building on our background as an engineering office, we also offer engineering, training and contract manufacturing on more than 30 printers, from first sample to small series.

WHITE PAPER SERIES

All white papers are available at www.fiberthree.com. We update the series regularly; the latest version applies.

NO.	TOPIC	HELPS WITH
WP001	Plastics for the FFF Process: Material Overview and Process Comparison	Choosing material and process
WP002	Effect of Moisture on Polymers in the FFF Process	Drying filament and keeping it dry
WP003	Annealing and Post-Processing of FFF Parts	Annealing, conditioning, finishing
WP004	Design for Manufacturing in the FFF Process	Designing parts for FFF
WP005	Heat-Setting Threaded Inserts in FFF Parts	Detachable screw connections
WP006	Nozzle Selection for Filled Filaments	Nozzle material and diameter
WP007	Print Bed and Adhesion	First-layer adhesion
WP008	Electrostatic Dissipative (ESD) Parts in FFF Printing	Printing and testing ESD parts
WP009	**Interlayer Adhesion in the Build Direction: Nozzle Temperature, Print Speed and Hotend (this paper)**	**Strength in the z direction**

TAB. 3 Overview of the Fiberthree white papers.

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