Mako™ Hotend for Bambu Lab Practical Flow Rate Test

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***Abstract*— Volumetric flow rate in Fused Filament Fabrication (FFF) refers to the volume of plastic filament a hotend can extrude per unit of time. The Mako Hotend for Bambu Lab (hereafter referred to as "Mako") by Slice Engineering aims to provide makers and professionals with enhanced flow rates, reduced printing times, and increased durability. Practical volumetric flow rate tests for Mako were performed with multiple materials on the Bambu Lab X1C and P1S to give users a better understanding of the flow rate capabilities as a benchmark for their setups. A series of test prints were conducted at various speeds with Ø1.75 mm filament to measure the average volumetric flow rate possible from the hotend. Practical flow rate tests used a test print model with specific geometry designed to make viewing layers and print defects easy. Print speeds increased incrementally with height, starting from the slowest speed at the bottom and increasing by 5 mm/s every 2.5 mm. Each test print was timed and visually inspected for defects. Consumers can expect flow rate benefits up to 60% faster than the stock hotend with the caveat that these benefits will vary depending on the material, nozzle size, layer height, layer width, hotend temperature, and cooling fan speeds.**

***Index Terms*— Mako Hotend for Bambu Lab, Volumetric Flow Rate, Print Speed, Fused Filament Fabrication, Slice Engineering.**

I. Introduction

Slice Engineering aimed to provide an upgrade for the Bambu Lab X1 and P1 series of 3D printers to allow for increased print speeds to mitigate the speed gap between traditional manufacturing and fused filament fabrication (FFF) additive manufacturing. Slow print speeds hinder the user's ability to rapidly prototype designs and increase the chance for print failures to occur. To reduce print times, Slice focused on hotend flow rates. The hotend is the part of an FFF 3D printer that liquefies the polymer filament allowing it to be extruded onto a build surface. This work resulted in Mako for Bambu Lab (hereafter referred to as "Mako"), a new hotend that provides higher volumetric flow rates than stock, a rigid mechanical structure, and a swappable nozzle.

The volumetric flow rate in FFF refers to the amount of plastic a hotend can extrude during a set time. The maximum print speed achievable in FFF is related to the maximum volumetric flow rate that the hotend can deliver. However, there is no agreed-upon standard for measuring maximum volumetric flow rate limits in FFF. Without an agreed-upon method or standard, Slice determined that empirical measurements would be made by printing a specific object with a calculated volume and determining flow rates based on the print times. This method has the advantage of being easy to understand and replicate.

Printing faster than a hotend's ability to melt all the filament causes print quality issues in FFF. At such speeds, a radial temperature gradient within the filament is created due to inadequate thermal energy transfer, causing the surface of the filament to be at a greater temperature than the center. The resulting prints will have under-extrusion and diminished strength. To reduce this phenomenon, Mako incorporates an elongated melt zone and flow diffuser resulting in a more isothermal extrusion.

The primary goal of this work is to establish the practical volumetric flow rates of Mako on a Bambu Lab 3D printer to give users a better understanding of the print speeds achievable while maintaining print quality. These practical volumetric flow rates are also compared to the stock hotend's practical volumetric flow rates which were determined following the same procedures. Five materials from Bambu Lab were evaluated: polylactic acid (PLA), polyethylene terephthalate glycol (PETG), polycarbonate (PC), acrylonitrile butadiene styrene (ABS), and thermoplastic polyurethane (TPU). These materials were chosen to represent the wide range of 3D printing filaments available for Bambu Lab 3D printers.

II. Procedure

A. Test Method

Testing methods were derived from previous flow rate tests conducted with the Mosquito Magnum+® and Mosquito® Prime™. Adjustments were made to accommodate use cases that more commonly occur with a Bambu Lab 3D printer. A series of test prints were conducted at various speeds to measure the practical average volumetric flow rate. All tests implemented the same object with a specific single-walled continuous geometry to make printing defects easily visible. The printed object employed long straightaways to ensure the extrusion speed was not affected by accelerations or decelerations for as long as possible. The print speeds increased gradually, starting with the slowest speed at the bottom of the object and increasing the speed by 5 mm/s for every 2.5 mm of height. Each test print was visually inspected for defects, especially skipping and under-extrusion. The initial print speed was primarily based on the researcher's prior experience, as no empirical benchmark exists. The outcome of the initial test determined the subsequent initial print speeds until the failure condition occurred after 5 mm of height was extruded. The failure modes section of the procedure details the various failure conditions.

The print tests were sliced using Simplify3D slicer software and saved as factory files, each corresponding to the material, diameter, and temperature of the hotend. Within each factory file, four processes exist for each of the four print speeds experienced during the print. Process changes occurred at every 2.5 mm interval within the 10 mm tall test print geometry shown in Fig. 1. Processes differ only by the print speed at each start-stop height within a single factory file. Process print speeds and start and stop heights are indicated in Table I. Simplify3D calculated the filament length after slicing, and this value was used in the flow rate calculations. The sliced object was exported as g-code and uploaded to the printers. Additionally, a camera recorded each print to measure the print time for calculations. The total filament length and print time excluded the first layer to avoid skewing the final results, as the first layer typically requires a slower print speed for better bed adhesion.

TABLE I
PRINT SPEEDS AND START-STOP HEIGHTS

Process	Programmed Print Speed (mm/s)	Start-Stop Heights (mm)
Speed-1	***B***	First Layer Height → 2.5
Speed-2	***B+5***	2.5 → 5
Speed-3	***B+10***	5 → 7.5
Speed-4	***B+15***	7.5 → 10

1) Process Group ***Material_Print Temperature_Nozzle Diameter*** was printed to find a baseline programmed speed ***B*** that initiates flow-rate-driven abnormalities (e.g., gaps in the object, extrusion motor skipping steps, severely diminished precision) approximately mid-height (~5 mm).
    a. Iteratively increasing or decreasing baseline speed by increments of 5 mm/s gives sufficient resolution to discover a reasonably accurate value for ***B***.
    b. Repeatability was confirmed by printing the Process Group twice using the same ***B*** value.
2) The filament diameter d and length l in millimeters and print time t in seconds were measured and used to print the Process Group with the value ***B*** found in step 1. Print time starts recording at the start of the second layer.
3) The average volumetric flow rate for the tested equipment and print settings equals the flow rate Q for the Process Group printed.

$$Q = \frac{\pi d^2 l}{4t} \tag{1}$$

4) The term practical average volumetric flow rate is applied to test outcomes where defects exist but only in the last two processes of the test print.

B. Equipment

Table II lists the equipment and materials used in testing. The equipment was chosen specifically so that the hotend was most likely to be the limiting factor. Bambu Lab's materials were chosen as they represent common materials that are easily accessible to Bambu Lab users worldwide. The filament was dried per Bambu Lab's specifications before testing commenced.

TABLE II
EQUIPMENT USED FOR TESTING

3D Printers	Bambu Lab X1C and P1S
Hotend	Mako Hotend for Bambu Lab
Extruder	Stock Bambu Lab Extruder
Nozzles	Ø0.4, 0.6, 0.8 mm orifice - GammaMaster FIN
Filament	Ø1.75 mm Bambu Lab PLA Basic Ø1.75 mm Bambu Lab PETG HF Ø1.75 mm Bambu Lab PC Ø1.75 mm Bambu Lab ABS Ø1.75 mm Bambu Lab TPU 95A HF
Filament Dryer	Breville Smart Oven Air Fryer Pro
Ambient Temperature	20 – 24 °C
Object	Flow Rate Testing Model 0.4mm Nozzle.3mf Flow Rate Testing Model 0.6mm Nozzle.3mf Flow Rate Testing Model 0.8mm Nozzle.3mf
Slicer	Simplify3D v5.1.2
Slicer File	***Material_Print Temperature_Nozzle Diameter*** PLA_220_0.4.factory PLA_220_0.6.factory PLA_220_0.8.factory PETG-HF_245_0.4.factory PETG-HF_245_0.6.factory PETG-HF_245_0.8.factory PC_280_0.4.factory PC_280_0.6.factory PC_280_0.8.factory ABS_270_0.4.factory ABS_270_0.6.factory ABS_270_0.8.factory TPU-HF_230_0.4.factory TPU-HF_230_0.6.factory TPU-HF_230_0.8.factory

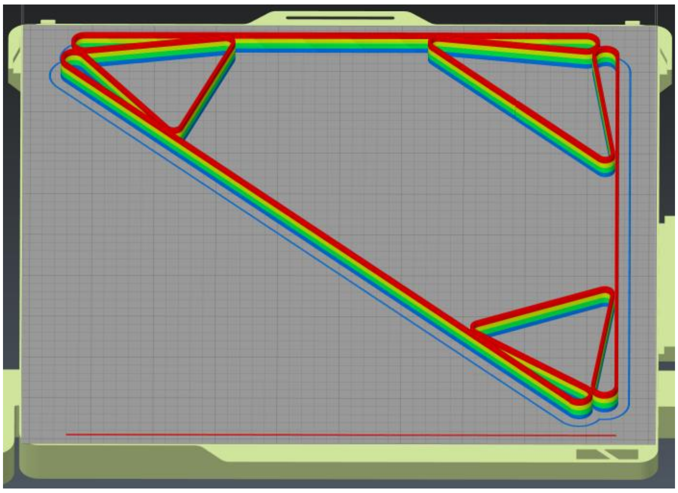

Fig. 1. Flow rate test model with process locations shown

C. Print Settings

The print settings were chosen to represent typical settings Bambu Lab users may use while stressing both the heat capacity of the hotend and its ability to effectively deliver heat to the filament while minimizing the impact of kinematics. The layer height was set to 50% of the nozzle diameter, and the layer width was set to 125% of the nozzle diameter. Table III outlines these values for the three nozzle sizes.

Hotend temperatures and cooling fan speeds were set to the manufacturer's recommended values, as found in the Bambu Studio presets. Table IV lists these values for each of the five materials being tested. Accelerations were set to 20,000 mm/s^2 for the X and Y axes. The bottom and top layers were set to zero solid layers. The print started at one end of the object, and a skirt was enabled to remove preheated material in the hot block.

TABLE III
EXTRUDER AND LAYER SETTINGS

Nozzle Size (mm)	Layer Height (mm)	Layer Width (mm)	Vase Mode
0.4	0.20	0.50	Enabled
0.6	0.30	0.75	
0.8	0.40	1.00	

TABLE IV
TEMPERATURE AND COOLING SETTINGS

Material	Hotend Temp. (°C)	Bed Temp. (°C)	Extruder Part Cooling Fan Speed (%)	Auxiliary Part Cooling Fan Speed (%)
PLA	220	55	100	50
PETG-HF	245	70	40	0
PC	280	100	20	0
ABS	270	90	40	0
TPU-HF	230	35	100	50

D. *Failure Modes*

One of the challenges of establishing average volumetric flow rates was determining what failure looks like. Minimal published material discusses what levels of flow rate abnormalities might be acceptable for 3D printing. Two different failure conditions were established for testing: under-extrusion or skipping from the extruder and a lack of heating power from the heater. The flow rate that caused under extrusion at the 5 mm height point was defined as the practical average flow rate. Detection of under-extrusion was purely observational. For the second failure condition, the flow rate that caused the hotend to run out of heating power was noted, and the next lowest ***B*** value that successfully finished printing was tested for the full 10 mm height. The flow rate for this test was recorded as the practical average flow rate. Figure 2 shows the error message that occurs when the hotend temperature was lower than the set point for a predetermined amount of time.

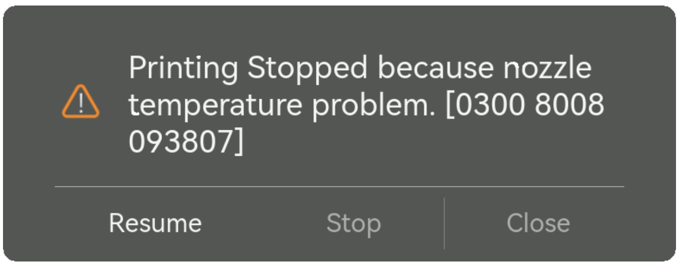

Fig. 2. Error message caused by a prolonged drop in the hotend temperature

III. RESULTS

The practical average volumetric flow rates achieved by Mako are displayed in Table V. Figures 3-17 show the test prints and their respective failure points. A print speed of 500 mm/s was determined to be a firmware speed limitation, so the ABS 0.4 mm nozzle result used 500 mm/s for each of the four processes.

TABLE V
PRACTICAL AVERAGE VOLUMETRIC FLOW RATE DATA

Material	Nozzle Size (mm)	Baseline Print Speed ***B*** (mm/s)	Print Time *t* (s)	Filament Length *l* (mm)	Flow Rate *Q* (mm^3/s)
PLA	0.4	310	542	5703	**25**
	0.6	195	507	8514	**40**
	0.8	95	685	11527	**41**
PETG-HF	0.4	405	476	5703	**29**
	0.6	185	524	8514	**39**
	0.8	90	776	11527	**36**
PC	0.4	470	447	5703	**31**
	0.6	125	755	8514	**27**
	0.8	65	1068	11527	**26**
ABS	0.4	500*	433	5703	**32**
	0.6	210	494	8514	**42**
	0.8	80	870	11527	**32**
TPU-HF	0.4	290	578	5703	**24**
	0.6	210	479	8514	**43**
	0.8	110	644	11527	**43**

*Maximum speed achievable due to firmware limitation

A. *Mako Ø1.75 PLA 220 °C*

1) *0.4 mm Nozzle:* A baseline print speed *B* of 310 mm/s, filament diameter *d* of 1.75 mm, filament length consumed *l* of 5703 mm, and print time *t* of 542 s yielded a flow rate *Q* of 25 mm^3/s. The under-extrusion failure mode was observed.

Fig. 3. Ø1.75 PLA at 220 °C with a 0.4 mm nozzle

2) *0.6 mm Nozzle:* A baseline print speed *B* of 195 mm/s, filament diameter *d* of 1.75 mm, filament length consumed *l* of 8514 mm, and print time *t* of 507 s yielded a flow rate *Q* of 40 mm^3/s. The under-extrusion failure mode was observed.

Fig. 4. Ø1.75 PLA at 220 °C with a 0.6 mm nozzle

3) *0.8 mm Nozzle:* A baseline print speed B of 95 mm/s, filament diameter d of 1.75 mm, filament length consumed l of 11527 mm, and print time t of 685 s yielded a flow rate Q of 41 mm^3/s. The under-extrusion failure mode was observed.

Fig. 5. Ø1.75 PLA at 220 °C with a 0.8 mm nozzle

B. *Mako Ø1.75 PETG-HF 230 °C*

1) *0.4 mm Nozzle:* A baseline print speed B of 405 mm/s, filament diameter d of 1.75 mm, filament length consumed l of 5703 mm, and print time t of 476 s yielded a flow rate Q of 29 mm^3/s. The under-extrusion failure mode was observed.

Fig. 6. Ø1.75 PETG-HF at 245 °C with a 0.4 mm nozzle

2) *0.6 mm Nozzle:* A baseline print speed B of 185 mm/s, filament diameter d of 1.75 mm, filament length consumed l of 8514 mm, and print time t of 524 s yielded a flow rate Q of 39 mm^3/s. The under-extrusion failure mode was observed.

Fig. 7. Ø1.75 PETG-HF at 245 °C with a 0.6 mm nozzle

3) *0.8 mm Nozzle:* A baseline print speed B of 90 mm/s, filament diameter d of 1.75 mm, filament length consumed l of 11527 mm, and print time t of 776 s yielded a flow rate Q of 36 mm^3/s. The lack of heating power failure mode was observed.

Fig. 8. Ø1.75 PETG-HF at 245 °C with a 0.8 mm nozzle

C. *Mako Ø1.75 PC 280 °C*

1) *0.4 mm Nozzle:* A baseline print speed B of 470 mm/s, filament diameter d of 1.75 mm, filament length consumed l of 5703 mm, and print time t of 447 s yielded a flow rate Q of 31 mm^3/s. The lack of heating power failure mode was observed.

Fig. 9. Ø1.75 PC at 280 °C with a 0.4 mm nozzle

2) *0.6 mm Nozzle:* A baseline print speed B of 125 mm/s, filament diameter d of 1.75 mm, filament length consumed l of 8514 mm, and print time t of 755 s yielded a flow rate Q of 27 mm^3/s. The lack of heating power failure mode was observed.

Fig. 10. Ø1.75 PC at 280 °C with a 0.6 mm nozzle

3) *0.8 mm Nozzle:* A baseline print speed B of 65 mm/s, filament diameter d of 1.75 mm, filament length consumed l of 11527 mm, and print time t of 1068 s yielded a flow rate Q of 26 mm^3/s. The lack of heating power failure mode was observed.

Fig. 11. Ø1.75 PC at 280 °C with a 0.8 mm nozzle

D. *Mako Ø1.75 ABS 270 °C*

1) *0.4 mm Nozzle:* A baseline print speed B of 500 mm/s, filament diameter d of 1.75 mm, filament length consumed l of 5703 mm, and print time t of 433 s yielded a flow rate Q of 32 mm^3/s. No failure was observed due to reaching the firmware printing speed limit of 500 mm/s.

Fig. 12. Ø1.75 ABS at 270 °C with a 0.4 mm nozzle

2) *0.6 mm Nozzle:* A baseline print speed B of 210 mm/s, filament diameter d of 1.75 mm, filament length consumed l of 8514 mm, and print time t of 494 s yielded a flow rate Q of 42 mm^3/s. The lack of heating power failure mode was observed.

Fig. 13. Ø1.75 ABS at 270 °C with a 0.6 mm nozzle

3) *0.8 mm Nozzle:* A baseline print speed *B* of 80 mm/s, filament diameter *d* of 1.75 mm, filament length consumed *l* of 11527 mm, and print time *t* of 870 s yielded a flow rate *Q* of 32 mm^3/s. The lack of heating power failure mode was observed.

Fig. 14. Ø1.75 ABS at 270 °C with a 0.8 mm nozzle

E. Mako Ø1.75 TPU-HF 230 °C

1) *0.4 mm Nozzle:* A baseline print speed *B* of 290 mm/s, filament diameter *d* of 1.75 mm, filament length consumed *l* of 5703 mm, and print time *t* of 578 s yielded a flow rate *Q* of 24 mm^3/s. The under-extrusion failure mode was observed.

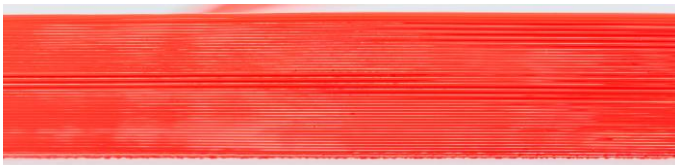

Fig. 15. Ø1.75 TPU-HF at 230 °C with a 0.4 mm nozzle

2) *0.6 mm Nozzle:* A baseline print speed *B* of 210 mm/s, filament diameter *d* of 1.75 mm, filament length consumed *l* of 8514 mm, and print time *t* of 479 s yielded a flow rate *Q* of 43 mm^3/s. The under-extrusion failure mode was observed.

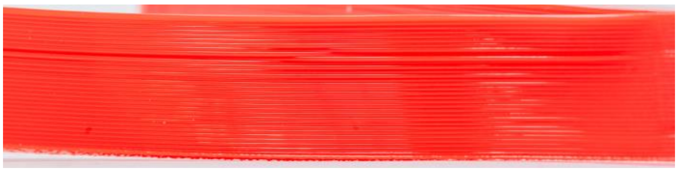

Fig. 16. Ø1.75 TPU-HF at 230 °C with a 0.6 mm nozzle

3) *0.8 mm Nozzle:* A baseline print speed *B* of 110 mm/s, filament diameter *d* of 1.75 mm, filament length consumed *l* of 11527 mm, and print time *t* of 644 s yielded a flow rate *Q* of 43 mm^3/s. The lack of heating power failure mode was observed.

Fig. 17. Ø1.75 TPU-HF at 230 °C with a 0.8 mm nozzle

IV. Discussion

A. Practical Average Flow Rate

Slice Engineering looked for a way to shorten print times for Bambu Lab 3D printers and did this by producing a hotend with higher volumetric flow rates, and thus higher print speeds. The research completed was designed to demonstrate both the suitability of the targeted test method and to identify practical average volumetric flow rates for the Mako Hotend for Bambu Lab. These flow rates are compared to the stock Bambu Lab hotend's flow rates in Table VI where it is shown that for four out of five materials, Mako achieved faster flow rates.

The materials with lower printing temperatures, PLA, PETG-HF, and TPU-HF, typically exhibited the under-extrusion failure condition which resulted in higher flow rates than the other two materials. These results tested how much material could be pushed through Mako at any one point in time until the force required to push the filament exceeded the extruder's abilities. The other two materials, ABS and PC, both exhibited the heater power failure and thus had lower practical average volumetric flow rates. It is likely that these materials could be tested with lower printing temperatures and may achieve higher practical average volumetric flow rates. In addition, a more powerful heater could increase the flow rates as well by making the hotend the limiting factor instead of the heater. The stock Bambu Lab hotend has a smaller thermal mass when compared to Mako, so less heating power is required to maintain a stable printing temperature. This explains why the PC results show better flow rates for the stock hotend over Mako.

Table VI
Practical Average Volumetric Flow Rate Comparison

Material	Nozzle Size (mm)	Mako Flow Rate *Q* (mm^3/s)	Bambu Lab Flow Rate *Q* (mm^3/s)	Flow Rate Percent Increase from Bambu to Mako (%)
PLA	0.4	25	25	0
	0.6	40	26	54
	0.8	41	29	41
PETG-HF	0.4	29	23	26
	0.6	39	24	63
	0.8	36	35	3
PC	0.4	31	32	-3
	0.6	27	40	-33
	0.8	26	41	-37
ABS	0.4	32	25	28
	0.6	42	29	45
	0.8	32	29	10
TPU-HF	0.4	24	22	9
	0.6	43	26	65
	0.8	43	27	59

B. Flow Rate Benefits for a Typical Print

Fig. 18 depicts the difference in printing time between Mako and the stock hotend with Mako finishing the print 38% faster. This test was run to show the effect using a higher flow rate capable hotend can have on a typical 3D print while maintaining the same level of quality.

Both prints used a 0.3 mm layer height, 0.62 mm layer width, and 100% infill. They also had their outer wall speeds limited to 100 mm/s to ensure the printing quality was acceptable. The internal wall and infill speeds were set to the maximum value of 500 mm/s and the volumetric flow rate was limited to 23 mm^3/s and 45 mm^3/s for the stock hotend and Mako, respectively.

Fig. 18. Printing comparison between Mako and the stock hotend for a rocket model. The print used a 0.6 mm nozzle and Bambu Lab's PLA Basic filament.

C. Procedural Comments

A fundamental assumption for this study is the volume of the test print. The filament length calculated in Simplify3D is a theoretical length. No attempt was made to empirically establish the degree to which any test print achieved this length. Using the computed filament length from a slicer is a typical practice in FFF to estimate the price per part, the part mass, and the remaining filament for more prints.

The test methodology was designed to identify scenarios where flow abnormalities would begin in the third process of a four-process test series. The assumption is that if the first two processes do not produce defects and the second two do produce defects, the first two processes are at speeds below the practical average volumetric flow rate, and the second two are above it. The practical average volumetric flow rate was assumed to be the average of all four process speeds. The average speed for the process group is the preferred expression of the practical average volumetric flow rate rather than the speed for the process group at which defects began to occur. There are two reasons for this. First, the speed that produced defects is, in theory, above the practical, and second, print speeds vary even within a single process through accelerations and decelerations necessitated by object geometry.

D. Limitations

Flow rate testing has many variables that could limit the flow rate for any test condition. One significant limitation is the subjectivity inherent in the observation of under-extrusion related failure. For instance, the gaps caused by under-extrusion are smaller when testing a 0.4 mm nozzle to the point that they can be missed. In addition, the variation between the heater power from each heater, temperature sensor tolerances, and the thermal grease application can all affect the achievable flow rate.

The testing was conducted with two different printer setups, which may not represent other printer setups or be statistically significant. Additionally, only one material color was tested for each material type. There are concerns that different color pigments can affect the melt flow index of thermoplastic polymers.

During testing, Slice Engineering was not able to tune the closed-loop feedback of the heater and hotend temperature sensor, so Mako's thermal characteristics had to be similar to the stock hotend. It is possible that some of the heater power failures may not have occurred if the feedback loop was better optimized for Mako leading to more consistent control of the hotend temperature.

V. Conclusion

This research hopes to inform Mako users of the expected practical average volumetric flow rate for the common materials PLA, PETG-HF, PC, ABS, and TPU-HF. Mako can deliver flow rates of over 40 mm^3/s for low melting temperature polymers such as PLA and TPU-HF. High melting temperature polymers may be able to experience similar flow rate benefits with optimized settings or more heating power. These benchmark measurements inform users of the expected performance and hotend capabilities for using Mako with their Bambu Lab X1C, X1E, P1S, or P1P.