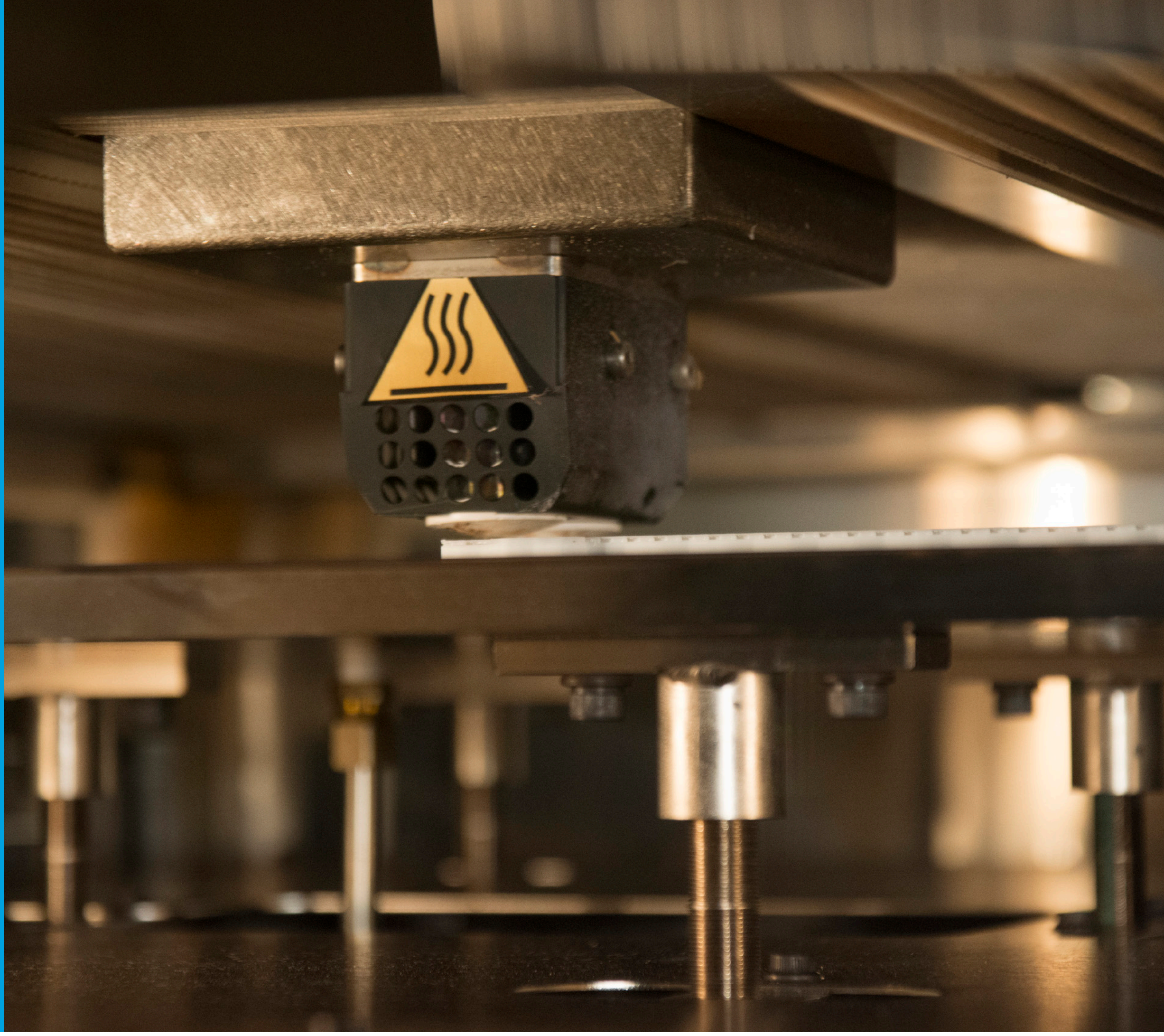

A Characterization of the Repeatability and Performance of Stratasys Fused Deposition Modeling (FDM) Systems

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ABSTRACT

Additive Manufacturing, using FDM® technology, has provided an innovative method for creating manufacturing aids, tools, and production parts for a wide variety of industries. Substantial investments, both from a supplier and end user perspective, have been directed towards producing and utilizing these solutions for wide-scale use and diverse applications. In order for any additive manufacturing technology to be thoroughly integrated into a manufacturing workflow, it is essential that the solution combining hardware, software, and material deliver a robust and predictable performance. In particular, the repeatability of the solution to deliver consistent intra- and inter-machine results over time is of paramount interest. This paper characterizes the performance of printed parts, through mechanical property analysis, dimensional repeatability, and various other metrics of print quality, on the Stratasys F370™, Fortus 450mc™, and F900™ systems using multiple materials. The data presented indicates excellent intra-system control of mechanical properties (XZ in-plane) with less than 5% coefficient of variation across each system type, using the entire system build volume and over several months of testing. Similarly, inter-system comparisons show excellent system-to-system consistency, generally within the 5% coefficient of variation for all materials and conditions tested. Properties in the z-axis (ZX) (upright) indicate the expected limitations of layer by layer processing by FDM, increasing variability in mechanical properties to generally less than 10% variance for all materials and conditions tested. Dimensional precision of printed geometry was shown to lie within 2% variation for all systems, materials, and geometries evaluated. Additionally, across the 1200 builds over the 16 systems, three materials, and various geometries used, the FDM systems performed with better than a 92% success rate for first time job completion. The data presented provides a user of these solutions confidence in printed part performance within a system, across multiple systems, and over time.

INTRODUCTION

Additive Manufacturing (AM) is a proven approach for simplifying, reducing costs, and accelerating time to market for products from design to delivery. The essence of AM is simplification. By building parts additively, many of the processes needed to set up and create specific parts from computer designs are eliminated, for example tooling and molds, thereby reducing time and costs to produce the needed parts. With these advantages, AM technologies are now widely being integrated into manufacturing operations in many industries. Adoption is, however, limited by the performance capabilities of any given technology and the extent by which it can be trusted to deliver consistent, dependable, and repeatable performance. To this end, manufacturers seek to fully characterize the performance of their equipment, software, and material so that uncertainty and risk is removed.

Fused Deposition Modeling (FDM) is one such AM technology that is finding swift adoption by manufacturers. As a material extrusion technology, FDM is advantageous for its simple workflow and outstanding range of permissible materials, enabling the highest levels of mechanical performance. The process is inherently simple. Thermoplastic materials are melted and extruded into 'beads' along a toolpath defined by the part geometry, in a layer-by-layer fashion. The motion of the extrusion head and the gantry is coupled to the extrusion of plastic so as to keep as close as possible to the ideal part geometry. At the macroscale, the geometry is replicated superbly, yet at the microscale, one begins to understand the questions that arise by the new technology when comparing it to conventional methods like machining or injection molding. An FDM part has a unique structure, more akin to lamellar composites than to bulk plastic. It becomes clear when observing the construction of the part, that how the part is constructed matters. For example, the strength of the material in the direction of the bead will be stronger than perpendicular to the bead. In the direction of the bead, the material is melted, extruded, and cooled together, making a largely homogeneous extrudate. Whereas in the direction perpendicular to the bead, the strength is defined by interlayer bonding of two different beads, heated and cooled at different times. It is important to recognize that while these technology details make the FDM process different than conventional processes, it is in no way an obstruction. Machining and molding have unique challenges themselves with issues like stress cracking, burring, and knit lines, all of which are overcome by careful characterization and understanding. AM processes are different, but not an obscurity that cannot be learned.

Rigorous characterization of FDM printed parts is therefore a prerequisite for building confidence in the technology. In this paper, three high-performance FDM systems from Stratasys are evaluated across many configurations of printing, multiple materials, multiple machines, and over time. The goal of the study was to generate a large, statistically significant dataset that would represent a user's expected outcome for any of these systems operating in good working order. By such thorough characterization, a user will understand the normally expected variation for these systems, and therefore significantly reduce uncertainty and risk to incorporating the process into manufacturing operations. For this study the Stratasys F370, Fortus 450mc, and F900 systems were chosen. Table 1 outlines the basic system capabilities and functions for these hardware solutions, demonstrating that these products cover a significant range of capabilities from part size, material compatibility and performance.

As will be described in depth herein, the repeatability and performance of these systems were tested through a serious of rigorous evaluations. The systems were run for weeks under continuous use to simulate a production operation. Mechanical properties were determined from the printing and testing of thousands of coupons in various orientations and locations on the platen, enabling statistically relevant determination of variation. Each system was studied for its intra-system variation, and then multiple systems of the same model were compared to evaluate inter-system variation. The precision and consistency of the systems was compared by repeatability check parts, as was the ability for the systems to print parts without warping, curling, or the presence of print quality errors. The amassed data illustrates what a user can confidently expect to achieve when using these systems in their environment.

Table 1 - System Capabilities and Functions

	F370	Fortus 450mc	F900
Build Size	14 x 10 x 14 in. (35 x 25 x 35 cm)	16 x 14 x 16 in. (41 x 35 x 41 cm)	36 x 24 x 36 in. (91 x 61 x 91 cm)
System Accuracy (X-Y) [1]	± 0.200 mm (± 0.008 in.) or ± 0.002 mm/mm (± 0.002 in./in.), whichever is greater	± 0.127 mm (± 0.005 in.) or ± 0.0015 mm/mm (± 0.0015 in./in.), whichever is greater	± 0.089 mm (± 0.0035 in.) or ± 0.0015 mm/mm (± 0.0015 in./in.), whichever is greater
Thermal	Extruder ≤300° C Chamber ≤110° C, active convection	Extruder ≤435° C Chamber ≤220° C, active convection	Extruder ≤435° C Chamber ≤225° C, active convection
Materials	PLA, FDM® TPU 92A, ABS-M30™, ASA, PC-ABS, ABS-ESD7™, Diran™ 410MF07, ABS- CF10	ASA, ABS-M30, ABS-M30i, ABS-ESD7, Antero™ 800NA, Antero™ 840CN03, PC-ABS, PC-ISO™, PC, ULTEM™ 9085 resin, ULTEM™ 1010, FDM® Nylon 12, FDM® Nylon 12CF	ASA, ABS-M30, ABS-M30i, ABS-ESD7, Antero 800NA, Antero 840CN03, PC-ABS, PC-ISO, PC, ULTEM™ 9085 resin, ULTEM™ 1010, PPSF, FDM Nylon 12, FDM® Nylon 6, FDM Nylon 12CF
Support Material	Dual extrusion, breakaway and soluble	Dual extrusion, breakaway and soluble	Dual extrusion, breakaway and soluble
Slice Height Options	0.005, 0.007, 0.01, 0.013 in. (0.13, 0.18, 0.25, 0.33 mm)	0.005, 0.007, 0.01, 0.013 in. (0.13, 0.18, 0.25, 0.33 mm)	0.005, 0.007, 0.01, 0.013, 0.02 in. (0.13, 0.18, 0.25, 0.33, 0.50 mm)
Material Environment	Pre-dried, vacuum sealed, and desiccant packed spools. Sealed material bay.	Pre-dried, vacuum sealed, and desiccant packed sealed metal canisters, plus onboard dry-air (-70 °C dewpoint)	Pre-dried, vacuum sealed, and desiccant packed sealed metal canisters, plus onboard dry-air (-70 °C dewpoint)

[1] Accuracy is geometry and material dependent. Achievable accuracy specification derived from statistical data at 95% dimensional yield.

EXPERIMENTAL

This study consisted of over 1200 builds across 16 systems printing three different materials and numerous part geometries. Table 2 presents an overview of systems and materials used. A minimum of four systems were used for each system type (F370, Fortus 450mc, F900). ASA was printed on all three machine types, whereas FDM Nylon 12 Carbon Fiber (Nylon 12CF), and ULTEM™ 9085 resin are only available for the higher temperature-capable Fortus 450mc and F900 systems. The builds on each machine were completed over a consecutive three week duration of continual system use. For one material, ASA, an additional week of builds was collected on all systems after turning these systems over to other users and projects for a three week period. The systems were not restricted or controlled during this three week period, allowing users to change material types. When collecting the final week of builds, no extra work was performed prior to completing the builds, other than a routine material change back to ASA for this study. All parts were built in 0.010 inch layer thickness due to its common use and availability for all materials. Table 2 includes the tip size that was used for each material.

Table 2 - Systems and Materials

Material (Tip Size)	Machine Type	Number of Machines Tested	Print Duration
ASA (T14/T16)[1]	F370	4	3 consecutive weeks plus 1 additional week after 3 weeks of use for other projects
	Fortus 450mc	4	
	F900	5	
Nylon 12CF (T20C)	F370	N/A[2]	N/A
	Fortus 450mc	4	3 consecutive weeks
	F900	4	
ULTEM™ 9085 resin (T16)	F370	N/A[2]	3 consecutive weeks
	Fortus 450mc	4	
	F900	4	

[1] T14 is the tip size for the F370, whereas the other systems utilize the T16 tip for 0.010 in. layers for ASA.
[2] Nylon 12CF and ULTEM™ 9085 resin are not available on the F370 due to system temperature constraints.

FDM Systems

For this study, the systems that were used were all located within an applications development laboratory at Stratasys headquarters in Eden Prairie, MN. The systems in this lab are utilized for a wide variety of projects, and systems are routinely operated with a variety of materials and slice heights. All printers were up to date on preventative maintenance and in good operational condition. The systems vary in age from being produced in the past year to ones that are over 10 years old. This allows for a realistic representation of systems with different ages that are found in the field. The printers used in this study were in an indoor space that houses over 20 systems in multiple rooms. The ambient air temperatures typically ranging from 65-70° F. The environment is temperature controlled by air conditioning, but humidity is not precisely controlled and can vary during different seasons. This experiment was running primarily in the summer, which tends to see higher humidity in the lab than other seasons. Relative humidity and room temperature were not recorded during the experiment.

Table 3 lists the systems that were used for this study, the details on those systems, and which materials were printed on each. Each system name begins with the first two numbers of the system type (i.e., 37 for a F370) and then the third digit is unique to be able to differentiate the systems from each other. The manufacture date identifies the age of each system. The systems range in age from a Fortus 900mc that was produced in 2010, and subsequently upgraded to an F900, to an F370 that was produced in 2019. Based on differences in age and utilization of the machine, the machines have a variety of operational hours on them. The build odometer reading listed in Table 3 contains the number of days that each system has built parts after conclusion of the build sequences for this project. As expected, the older systems typically have spent more time building parts than those that are newer.

Table 3 - History of FDM Machines

System Type	Machine Name	Manufacture Date[1]	Build Odometer[3] (Days)	Machine Notes	Materials Printed on System
F370	371	Dec-2018	78		ASA
	372	Dec-2019	73		ASA
	374	Mar-2017	291		ASA
	375	Mar-2017	262		ASA
Fortus 450mc	451	Sep-2014	2270	Gen1 with High Performance Upgrade	ASA, ULTEM™ 9085 resin
	452	Oct-2014	2195	Gen1 with High Performance Upgrade, Composite material hardware upgrade	ASA, Nylon 12CF, ULTEM™ 9085 resin
	453	Sep-2014	2220	Gen1 with High Performance Upgrade, Composite material hardware upgrade	ASA, Nylon 12CF, ULTEM™ 9085 resin
	454	Sep-2014	2259	Gen1 with High Performance Upgrade, Composite material hardware upgrade	ASA, Nylon 12CF
	455	Dec-2015	895	Gen2	ULTEM™ 9085 resin
	456	Mar-2018	39	Gen2, Composite material hardware upgrade	Nylon 12CF
F900	901	Mar-2010	1806	900mc Gen I, Fortus 900mc PLUS upgrade	ASA, ULTEM™ 9085 resin
	902	Aug-2015	134 (since Feb -2020)[2]	900mc Gen II, F900 system upgrade	ASA, Nylon 12CF, ULTEM™ 9085 resin
	903	Aug-2011	1195 (since Apr-2013) [2]	900mc Gen I, Fortus 900mc PLUS upgrade	ASA, ULTEM™ 9085 resin
	905	Apr-2012	1296	900mc Gen I, F900 system upgrade	Nylon 12CF
	906	Jul-2018	255	F900 Gen III	ASA, Nylon 12CF, ULTEM™ 9085 resin
	909	Apr-2018	324	F900 Gen III	Nylon 12CF

[1] The first manufacture date is documented by the first entry in the machine log.
[2] The system computer or hard drive was replaced, thus a full history of the machine was not available.
[3] Days on the build odometer are the number of days (24-hour periods) of accumulative system use.

Part Geometries

Due to the nature of FDM as a material extrusion process, the part orientation matters as it impacts the mechanical properties of the part, as well as the surface finish, build time, and material usage. When describing the orientation of a part per the ASTM F2921 standard, one generally describes the first axis by the axis of the longest dimension of the part, followed by the axis of the second longest dimension of the part. The axes are typically labeled such that 'Z' represents the vertical axis and 'X' and 'Y' represent the axes of the build plane. For this experiment, the axes for listing part orientation are as shown in Figure 1.

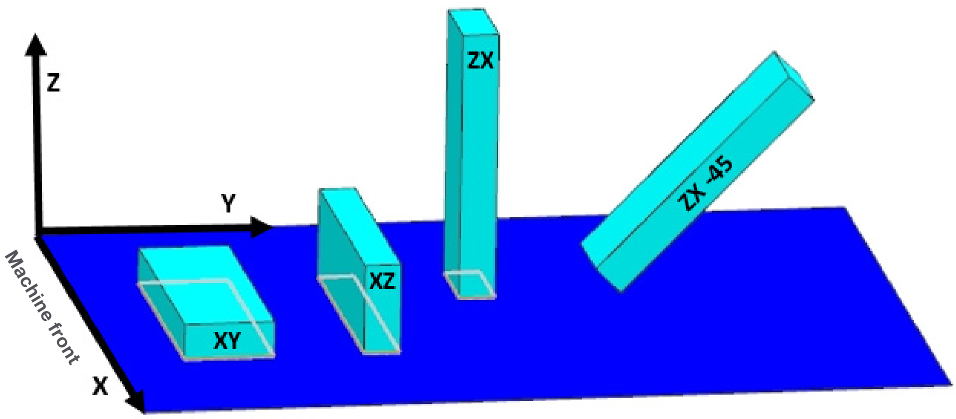
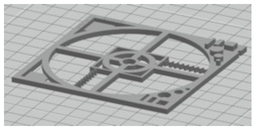
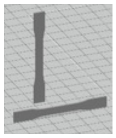
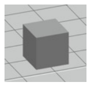
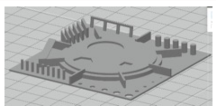
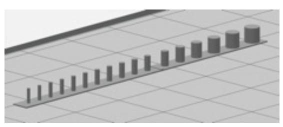
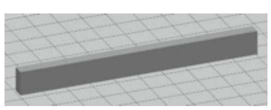
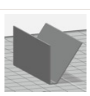
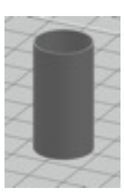


Figure 1 - Coupon build orientations according to ASTM F2921.

Many part geometries were used for this study and are described in Table 1. All part CMB files were prepared in Insight 14.4 Build 952. Each part geometry was imported into the software in STL file format and the toolpaths were generated for each the seven machine-material combinations. All files were prepared for a slice height of 0.010 inch using the tips listed in Table 2. Default ('green flag') system settings were used for all parts, except for mechanical coupons in the ZX (upright) orientation. For these parts, stabilizer walls were added. Some differences in default parameters occur across system type, even for the same material, as settings are derived from optimizing part quality of a material independently on different systems. The best overall settings for a material are not necessarily the same across systems. For example, for ASA the default part interior style is 'solid' for the Fortus 450mc and F900, whereas it is 'sparse-high density' for the F370. The difference in interior style results in a smaller raster width of 0.018 inch on F370, compared to 0.020 inch on Fortus 450mc and F900 systems. By using default parameters the experimental plan removed any risk of unintended and unexpected print quality issues. After each part was sliced, supports generated, and the toolpaths generated, CMB files were saved and submitted to each machine using Control Center™ software.

Table 4 - Part Geometries		
Part Name	**Image**	**Description**
9 Inch Check Part		A 9x9 inch square part oriented in the XY plane with predominantly flat geometry and minimal support material that can be printed on all three systems in any material. Part dimensions can be measured by automated programing on a coordinate measuring machine (CMM) and compared to CAD dimensions.
Mechanical Coupons		Coupons for mechanical tensile testing in the format of ASTM D638 Type 1 specimens. Coupons are built in two orientations, XZ (on edge) and ZX (upright). Stabilizer walls were added to ZX (upright) coupons during printing. The printed coupons are tested for tensile strength, stiffness, and elongation at break.
Density Cube		Solid printed 1x1x1 inch cubes. Density cubes provide simple and fast measurement of the consistency of material deposition by measuring the mass of the printed cubes.
QA Part		The Quality Assurance (QA) part can be visually inspected as a rapid diagnostic for any part flaws that might indicate a suboptimal performance of the system. It is built in the XY orientation with minimal support material.
Shovel Grip	Image not available (A handle like that on a shovel used for yard work. The shovel handle is roughly 6 inches in height and 4 inches across.)	Prototype part example used for visual inspection of print quality in a sloping and supported geometry. The part is approximately 6 inches tall and 4 inches wide as printed. Parts were printed upright in the ZX (upright) or ZY (upright alternate) orientations.
Connector	Image not available (A small connector, less than 1.5 inches in any dimension, like what would be used for connecting wires to an array.)	Prototype part example used for visual inspection of print quality in a fine feature geometry. The part is less than 1.5 inches in the longest dimension. Parts were printed upright in the ZX (upright) or ZY (upright alternate) orientations.
Pin Array		The pin array is used to visually inspect the minimum feature resolution afforded by the current print conditions. The part is visually inspected to determine what size pin that the machine-material configuration can print. The part is printed in either the XZ (on edge) or YZ (on edge alternate) orientation, with the flat portion of the part on the build platen.
Pin Plate	Image not available (A flat plate, roughly 8 inches square, with several hundred small pins, roughly 0.75 inch tall and 0.10 inch in diameter, in a grid array with pins roughly 0.25 inch from each other.)	The pin plate allows for an aggressive test of continuous short tool path print sequences. The approximate 8x8 inches square geometry includes several hundred small pins, roughly 0.75 inch tall and 0.10 inch diameter, in a grid array with pins positioned roughly 0.25 inch from each other. After printing the pin plate, the plate is removed and the number of strings between the pins can be counted. The pin plate is built in the XY orientation.
12 Inch Z Tower		The 12-inch Z Tower can be used to test dimensional precision in the vertical direction. The part contains touch points every 2 inches in vertical rise. The part was built in the ZX (upright) orientation.
Curl Bar		A 10 inches long, solid bar used to provide an indication of residual stresses in a material during printing. After printing, the part can be measured for curl by the maximum deviation from a reference flat surface. The curl bars were printed in the XZ (on edge) and YZ (on edge alternate) orientations.
Angled Wall		The angled wall geometry enables qualitative evaluation of potential part warpage from thermal effects. The part was printed in the YZ (on edge alternate) orientation.
Hollow cylinder		The hollow cylinder (3 inches high and 1.58 inches in diameter) part is used to evaluate extrusion control in seams. The part is a hollow cylinder printed with only 2-contours as the structure of the cylinder. The position of the seams on each layer are vertically aligned for the entire part height. Measuring the part thickness at the seam, and comparing to another location, indicates the consistency of the seam. The part is printed such that the base is flat on the XY plane.

Build Sequence

To allow for consistency of builds between printers, a build sequence was established that defined the order for all of the parts to be built. Table 5 shows the build sequence for the systems that built ASA parts. Table 6 contains the build sequence used for parts built in both Nylon 12CF and ULTEM™ 9085 resin. The build sequences were designed to keep the systems running in a near continuous fashion over many days, with one or two jobs run on each machine per day. The start of the sequence was initiated on each system independently, with various systems running in parallel. Jobs were set up so that each system could run a complete build during the day that was between four to eight hours long, and a longer build overnight to maximize the utilization of the system. Machines remained idle over weekends after the last overnight job completed until the next job was initiated on Monday morning. As a benefit of its large build platen, the XZ (on edge) and ZX (upright) mechanical coupon builds were combined into one job for the F900 system to reduce the number of operator actions.

The build sequence for ASA parts included deliberate break periods in the sequence. After 3 weeks of the sequence, the machines were released for unrestricted use on other projects. Each system was used in varying ways, including material changes. Figure 2 summarizes how each of the eight systems printing ASA parts were used during this 3 week break period. These additional sources of variation were purposefully introduced to simulate environments where these systems experience multiple use conditions. On day 43 in the sequence, jobs were restarted in the ASA sequence for an additional week of builds. At day 48 an additional one- or two-week break was taken, again with machines released for use on other projects. The build sequence was restarted after day 57 (or day 64) to complete a final series of sample parts in ASA. Not all parts collected during the print sequence were used for analysis, but the entire collection of parts were used to evaluate metrics for the success rate of jobs and parts.

Table 5 - Build Sequence for Printing Parts in ASA

Day	Build	Parts Produced
1	1	9-Inch Check Part
2	2	15 Mechanical Coupons – XZ (on edge) orientation[2]
2	3	20 Mechanical Coupons – ZX (upright) and 4 Density Cubes[2]
3	4	9-Inch Check Part
3	5	Visual Inspection Parts – QA Part, Shovel Grip, Connector & Pin Array
4	6	15 Mechanical Coupons – XZ (on edge) orientation[2]
4	7	20 Mechanical Coupons – ZX (upright) and 4 Density Cubes[2]
5	8	9-Inch Check Part
5	9	Visual Inspection Parts – QA Part, Shovel Grip, Connector & Pin Array
8	10	15 Mechanical Coupons – XZ (on edge) orientation[2]
8	11	20 Mechanical Coupons – ZX (upright) and 4 Density Cubes[2]
9	12	9-Inch Check Part
9	13	Visual Inspection Parts – QA Part, Shovel Grip, Connector & Pin Array
10	14	15 Mechanical Coupons – XZ (on edge) orientation[2]
10	15	20 Mechanical Coupons – ZX (upright) and 4 Density Cubes[2]
11	16	9-Inch Check Part
11	17	Visual Inspection Parts – QA Part, Shovel Grip, Connector & Pin Array
12	18	15 Mechanical Coupons – XZ (on edge) orientation[2]
12	19	20 Mechanical Coupons – ZX (upright) and 4 Density Cubes[2]
15	20	9-Inch Check Part
15	21	Visual Inspection Parts – QA Part, Shovel Grip, Connector & Pin Array
16	22	15 Mechanical Coupons – XZ (on edge) orientation[2]
16	23	20 Mechanical Coupons – ZX (upright) and 4 Density Cubes[2]
17	24	9-Inch Check Part
17	25	Visual Inspection Parts – QA Part, Shovel Grip, Connector & Pin Array
18	26	15 Mechanical Coupons – XZ (on edge) orientation[2]
18	27	20 Mechanical Coupons – ZX (upright) and 4 Density Cubes[2]
19	28	9-Inch Check Part
19	29	Visual Inspection Parts – QA Part, Shovel Grip, Connector & Pin Array
22-42		3 week break in sequence - machine released for use on other projects
43	30	15 Mechanical Coupons – XZ (on edge) orientation[2]
43	31	20 Mechanical Coupons – ZX (upright) and 4 Density Cubes[2]
44	32	9-Inch Check Part
44	33	Visual Inspection Parts – QA Part, Shovel Grip, Connector & Pin Array
45	34	15 Mechanical Coupons – XZ (on edge) orientation[2]
45	35	20 Mechanical Coupons – ZX (upright) and 4 Density Cubes[2]
46	36	9-Inch Check Part
47	37	15 Mechanical Coupons – XZ (on edge) orientation[2]
47	38	20 Mechanical Coupons – ZX (upright) and 4 Density Cubes[2]
48- 56+		1 to 2 week break in sequence[3] - machine released for use on other projects
57+	39	Pin Plate
58+	40	12-Inch Z Tower
59+	41	12-Inch Z Tower
60+	42	12-Inch Z Tower
61+	43	Curl Bars, Angled Wall, & Hollow Cylinder

[1] This build sequence was used for all printers that built parts in ASA, except for 906. Parts in ASA printed on 906 followed the Nylon 12CF and ULTEM™ 9085 resin build sequence, listed in Table 6.
[2] Mechanical coupon builds for XZ (on edge) and ZX (upright) orientation were combined into one job for F900s.
[3] The final break period varied between different systems over a one to two week range.

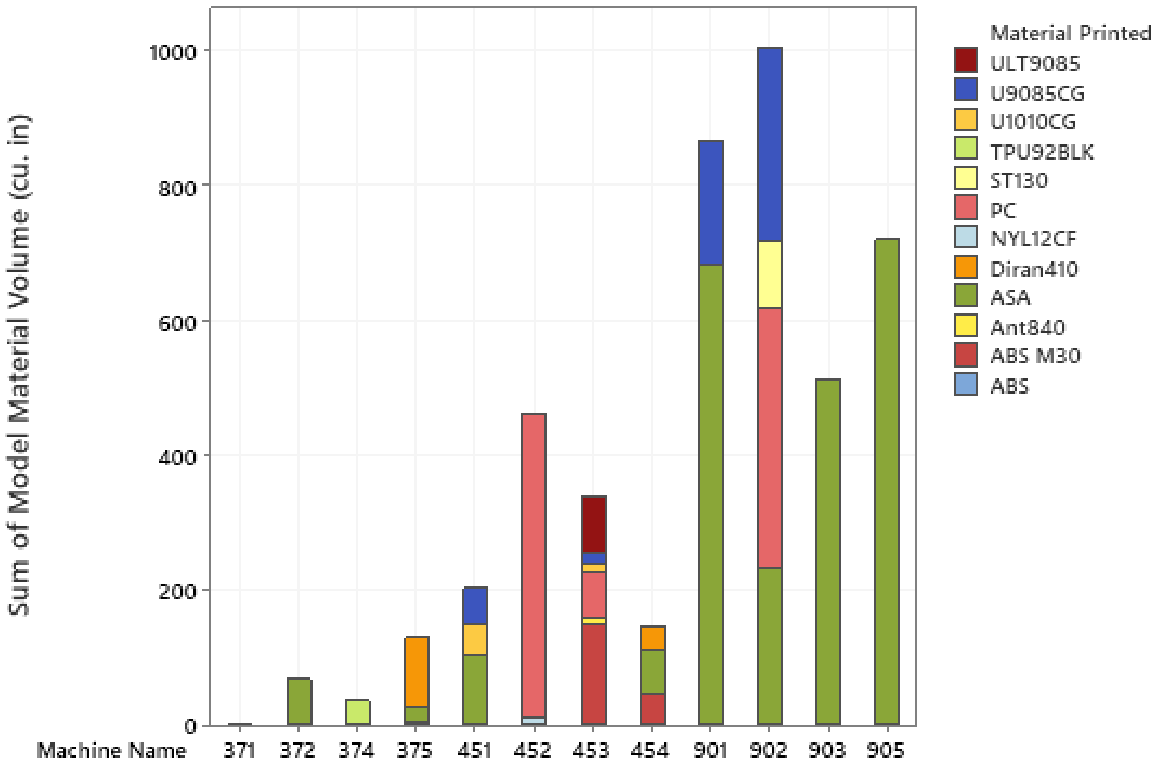


Figure 2 - Volume of model material built (bar chart - left axis)) on each system during the 3 week break in the build sequence of printing ASA parts.

The build sequence for parts made from Nylon 12CF and ULTEM™ 9085 resin on Fortus 450mc and F900 systems is listed in Table 6. The sequence followed a three-week period of builds similar to ASA, but did not extend past the third week. Some substitutions were made in the parts that replaced visual inspection parts with alternate geometries such as Z towers and curl bars. Similar to the sequence in ASA on the F900, XZ (on edge) and ZX (upright) coupons were combined into one job file, taking advantage of the large F900 size to reduce the number of operator actions.

Table 6 - Build Sequence for Printing with Nylon 12CF and ULTEM™ 9085 Resin Materials

Day	Build	Parts Produced
1	1	9-Inch Check Part
2	2	15 Mechanical Coupons – XZ (on edge) orientation[1]
2	3	15 Mechanical Coupons – ZX (upright) and 4 Density Cubes[1]
3	4	9-Inch Check Part
3	5	12-Inch Z Tower
4	6	15 Mechanical Coupons – XZ (on edge) orientation[1]
4	7	15 Mechanical Coupons – ZX (upright) and 4 Density Cubes[1]
5	8	9-Inch Check Part
5	9	Pin Plate
8	10	15 Mechanical Coupons – XZ (on edge) orientation[1]
8	11	15 Mechanical Coupons – ZX (upright) and 4 Density Cubes[1]
9	12	9-Inch Check Part
9	13	12-Inch Z Tower
10	14	15 Mechanical Coupons – XZ (on edge) orientation[1]
10	15	15 Mechanical Coupons – ZX (upright) and 4 Density Cubes[1]
11	16	9-Inch Check Part
11	17	Visual Inspection Parts – QA Part, Shovel Grip, Connector & Pin Array
12	18	15 Mechanical Coupons – XZ (on edge) orientation[1]
12	19	15 Mechanical Coupons – ZX (upright) and 4 Density Cubes[1]
15	20	9-Inch Check Part
15	21	Curl Bars, Angled Wall, & Hollow Cylinder
16	22	15 Mechanical Coupons – XZ (on edge) orientation[1]
16	23	15 Mechanical Coupons – ZX (upright) and 4 Density Cubes[1]
17	24	9-Inch Check Part
17	25	12-Inch Z Tower
18	26	15 Mechanical Coupons – XZ (on edge) orientation[1]
18	27	15 Mechanical Coupons – ZX (upright) and 4 Density Cubes[1]
19	28	9-Inch Check Part
19	29	Visual Inspection Parts – QA Part, Shovel Grip, Connector & Pin Array

[1] Mechanical coupon builds for XZ (on edge) and ZX (upright) orientation were combined into one job for F900s.

Build trays were arranged in Control Center 14.4 build 952. Working through one machine-material combination at a time, the part CMBs were imported into Control Center and arranged to minimize the motion of the heads between parts. For mechanical coupons, an equal number of coupons was placed in each corner and the center of the platen. The coupon order was arranged to prevent the head from passing over a coupon additional times per layer. Control Center defaults were used to define use of a sacrificial tower. CMB files were saved for each machine and material combination, with the one file submitted to each respective machine type. Figure 3 displays examples of build tray arrangements used for printing mechanical coupons on an F370 and F900.

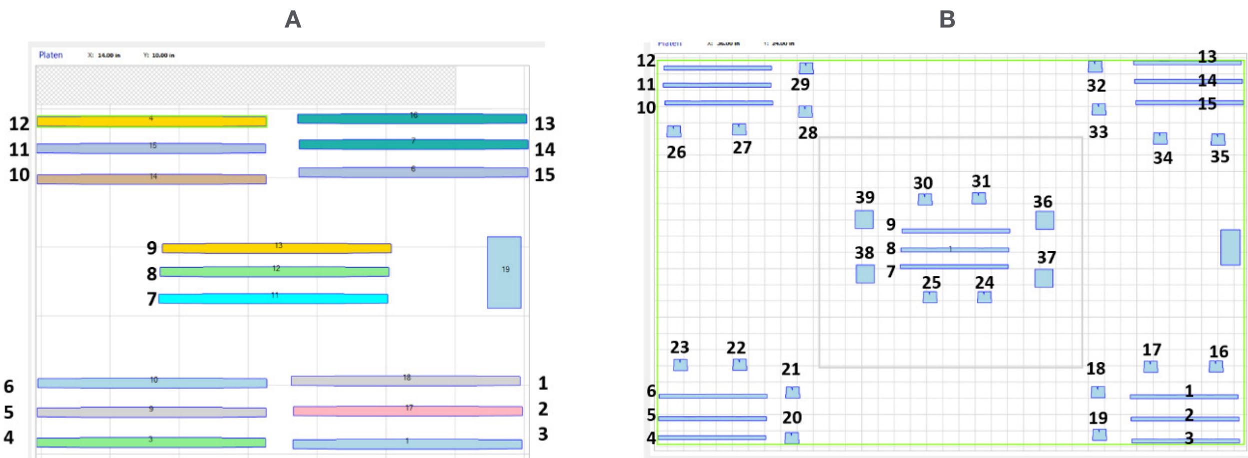


Figure 3 - Examples of build tray arrangement for printing mechanical coupons. A) Arrangement of 15 XZ (on edge) coupons on an F370 system, including a standard purge tower. B) Arrangement of a build on an F900 system including 15 XZ (on edge) coupons, 20 ZX (upright) coupons, four density cubes, and a single purge tower. Numbering superimposed on the diagram indicate the order that the parts were built. Note figures A and B are not to the same scale.

Build Process

To build the parts, each machine underwent a material change as needed to get the machine to the correct material and tip combination. Machine oven temperatures were stabilized prior to the tip-to-tip calibration on the system. Once the machine was calibrated, the build sequence printing began using standard operator procedures such as inserting the build sheet or build tray and starting the build.

A large quantity of material was consumed during the course of this study. Table 7 lists the reported volume of material that was consumed (from machine logs) and the calculated minimum number of material canisters and spools required. The F370 utilized spools each containing 60 cubic inches of ASA, whereas 92-cubic-inch canisters were used on Fortus 450mc and F900 systems for all materials. During the execution of the work, systems were running simultaneously, so the actual number of canisters and spools used was larger than the calculated minimum indicated in Table 7. Tracking of individual ASA spools and canisters was not performed. For Nylon 12CF, material usage included 48 individual canisters from seven unique production lots. For ULTEM™ 9085 resin, 54 canisters were used from 11 unique production lots. All material was new or recently opened canisters that had been stored with the canister sealed per standard product recommendations. Within the materials of each type, canisters were selected randomly for loading onto machines, and operators followed standard best practices for preparing material for printing. For jobs producing coupons for mechanical testing and dimensional accuracy check parts, it was verified prior to starting the job that sufficient material was available to complete the build without changeover of material.

Table 7 - Volume of Material Consumed

	Volume of material consumed (in^3)			Minimum number of material canisters/spools[1] consumed		
Model Material (Support material)	F370	450mc	F900	F370	450mc	F900
ASA (QSR / SR-30)[2]	2572 464	2781 305	3485 373	43 8	30 3	38 4
Nylon 12CF (SR-110 Support)	N/A[3]	1924 101	1911 90	N/A[3]	21 1	21 1
ULTEM™ 9085 resin (ULTEM™ Support)	N/A[3]	1829 107	2115 107	N/A[3]	20 1	23 1

[1] F370 utilized spools with 60 in^3 of material, whereas the Fortus 450mc and F900 utilized canisters that contain 92 in^3 of material.
[2] QSR is the support material for ASA on the F370, whereas the Fortus 450mc and F900 utilize SR-30 for ASA support material.
[3] Nylon 12CF and ULTEM™ 9085 resin are not able to be printed on the F370.

Canisters of ULTEM™ 9085 resin were tested for moisture per ASTM D7191 prior to mechanical coupon builds to ensure that the moisture content was below the 0.04% by mass. Best practices have shown that ULTEM™ 9085 resin mechanicals are sensitive to moisture content above 0.04% by mass. If the moisture content exceeded this limit, the canister was dried in a vacuum oven at 70 ºC until moisture content was less than 0.04%. Canisters and spools of ASA and Nylon 12CF were used as received.

All build errors were recorded and classified. Unsuccessful builds included builds that failed to finish, fallen parts, or machine issues. Unsuccessful builds were repeated after any machine issues were resolved. Any build pauses during mechanical or dimensional parts were deemed unacceptable and required that the job be rebuilt. If a pause occurred during a visual part due to a minor issue such as a failed auto changeover, it could be resumed if the machine had only been paused for a short duration and no impact to part quality was visually observed.

After a build was completed, parts were removed from the build sheets while they were still warm. ULTEM™ 9085 resin is paired with a breakaway support, so all supports were removed manually while warm. ASA and Nylon 12CF are paired with soluble support materials. Supports were removed by dissolution in a recirculation tank filled with a solution of WaterWorks™ at recommended processing temperatures. Nylon 12CF parts are recommended to be placed in the WaterWorks tank for at least four hours to rehydrate the material and increase the part strength. All Nylon 12CF parts that were measured, tested, or visually inspected were placed in the WaterWorks tank until the support was dissolved and it had been in the solution for at least 4 hours. All parts placed in the tank were rinsed and soaked in water to remove the WaterWorks solution and then air dried beneath circulating fans.

Dimensional Measurements

To check machine repeatability for dimensional precision, the 9-inch check part was used on all systems. For the 9-inch check part in ASA, four of the parts from each system were selected for measurement to capture effects over time and the use of multiple systems. Parts were selected from builds 4, 16, 28, and 36 (see Table 5 for the build sequence) as these builds were spread out within the three-week build and the one-week of follow-up. For ULTEM™ 9085 resin and Nylon 12CF, two copies of the 9-inch check part were selected for measurement. The selected parts were from builds 4 and 28 on each system (see Table 6 for the build sequences). The Nylon 12CF parts were processed in WaterWorks overnight to dissolve support, then soaked in water and dried in ambient air prior to being measured.

Specific dimensions on the test parts were measured by automated programming of a Mitutoyo Quick Vision Apex coordinate measuring machine (CMM) by a combination of touch probe and optical inspection. The automated program measured 43 dimensions on each part, ranging from 0.14 inch (3.52 mm) to 9.0 inches (228.60 mm). For the largest dimensions measured at around 9 inches, the accuracy of the CMM in x and y coordinates was specified as better than 0.000086 inch by machine specification.

Measurement of Mechanical Coupons

With thousands of mechanical coupons built throughout the build sequences for all systems and materials, it was not practical to test every coupon due to cost and timeline. In total, 1,400 mechanical coupons were tested for this study. Table 8 lists the builds that were selected for analysis of mechanical coupons. Builds were selected across the duration of the build sequence to capture variation over time. Coupons were selected to evaluate variation in mechanical performance intra-platen, inter-system, and over-time in both the XZ (on edge) and ZX (upright) orientations. For each machine and material combination, five coupon locations were tested for each of the listed builds. For example, a total of 30 XZ (on edge) coupons and 30 ZX (upright) coupons were tested on each machine printing ASA. To characterize intra-platen variation, coupons were selected from each of the five build locations shown in Figure 3 from different jobs in the build sequences on each system. The data from the four corners and the center of the platen represent the spread that occurs across the platen by including data from the points that are furthest apart. Note that the separation distances are different for F370, Fortus 450, and F900 due to the differences in platen size.

Table 8 - Mechanical Coupons Selected for Testing

Material	Machine Type	Coupon Orientation	Build IDs Tested
ASA	F370, Fortus 450mc, F900	XZ (on edge)	2, 10, 18, 26, 30, 37
	F370, Fortus 450mc	ZX (upright)	3, 11, 19, 27, 31, 38
	F900		2, 10, 18, 26, 30, 37
Nylon 12CF	Fortus 450mc, F900	XZ (on edge)	2, 10, 18, 26
	Fortus 450mc, F900	ZX (upright)	3, 11, 19, 27
ULTEM™ 9085 resin	Fortus 450mc, F900	XZ (on edge)	2, 10, 18, 26
	Fortus 450mc	ZX (upright)	3, 11, 19, 27
	F900		2, 10, 18, 26

Coupons were tested over the span of approximately three months. All coupons were conditioned prior to testing, and conditioning varied by the material type. Coupons printed in ASA were tested at room temperature and ambient humidity. Coupons printed in Nylon 12CF were tested within 72 hours from removing support material. Re-hydrating Nylon 12 and Nylon 12CF parts for a minimum of four hours (usually during support removal) is recommended to maximize the mechanical properties and dimensional accuracy of the parts. Printed coupons in ULTEM™ 9085 resin were conditioned for 24 hours minimum (72 hours maximum) at 250 °F in an oven. The coupons were placed in a fixture that allowed them to be evenly spaced and positioned on edge. After the parts were conditioned, the fixture and coupons were placed in a desiccator container, the container sealed, and allowed the coupons to cool. The coupons were then removed three at a time for testing.

The mechanical coupons were tested on a Zwick 30kN Allround Tisch static material testing machine with a 10kN load cell. Apart from conditioning, testing followed the ASTM D638 test procedures. Test speed was 0.2 in./min. A jig was used to mark in ink the gage section of the coupon and where the bottom of the coupon should align within the grips to ensure consistent testing of the coupon. For each specimen tested, strain (%), standard force (N), and both crosshead and extensometer travel (mm) were recorded.

For each specimen that was tested, a photo was taken of the broken pieces after testing was complete. The location of the break was identified for each coupon according to Figure 4. The gage section is the constant diameter portion of the specimen where ideally all specimens break. This region is appropriately covered by the span of the extensometer. To evaluate elongation correctly, the break must occur between the extensometer arms, therefore only specimens that break inside the gage region should be included in the dataset for elongation at break. The 'narrowed section' of the specimen has the same cross-sectional area as the gage length, but falls outside of the arms of the extensometer. The section identified as 'in radius' denotes a break in the area where the cross-sectional area is changing and the section identified as 'grips' denotes a break at the outer edge of the coupon where the testing machine's grips are engaged with the coupon. Any visual defect on the coupon, such as a blob of additional material, was circled in ink prior to testing. The location of the break was identified as 'at defect' if the coupon broke at that location. Data from coupons that broke at the grips, in the radius, at a defect location, or that had testing error (e.g., extensometer slip) were not included within the analysis of the data. For evaluation of strength, all data from break locations in gage or in the narrowed section were included. Only data from coupons that broke in the gage was reported for elongation at break, as only those coupons had the break within the span of the extensometer.

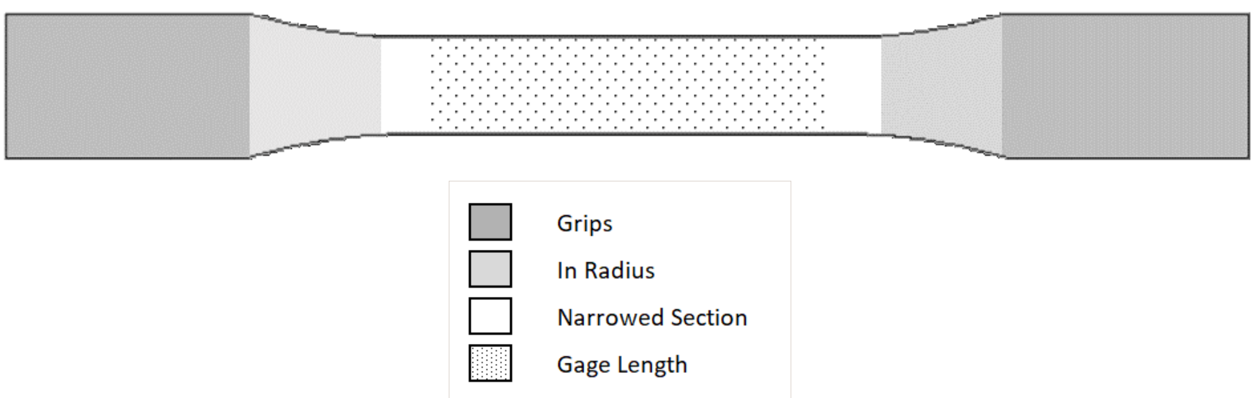


Figure 4 - Break locations of D638 coupons.

RESULTS AND DISCUSSION

Dimensional Precision

Dimensional precision in a manufacturing process is critical to hitting part tolerances. Making dimensionally consistent parts time-after-time enables high part yield. To demonstrate the dimensional precision of the FDM process on the F370, Fortus 450mc, and F900 models, the 9-inch check part from Table 4 was printed in ASA. The check part was printed four times on each machine, once per week for three consecutive weeks and then one final time several weeks later. Four separate machines were used for each model totaling 16 check parts per model.

On each check part, specific feature dimensions were measured by an automated program of a Mitutoyo Quick Vision Apex coordinate measuring machine (CMM) utilizing a combination of touch probe and optical inspection. For 9-inch and smaller features, dimensional measurement accuracy of the CMM was listed as better than 0.000086 inch. As such, measurement error will be assumed insignificant for the remainder of the analysis.

By looking at individual features on the check part, it is possible to quantify the dimensional precision over time and between machines. One feature (AA1), a thin rectangular bar section with a nominal width of 0.140 inch, is examined for illustration. Results in Figure 5 are plotted as a deviation from the nominal CAD dimension (measured width – nominal width [0.140 inch]).

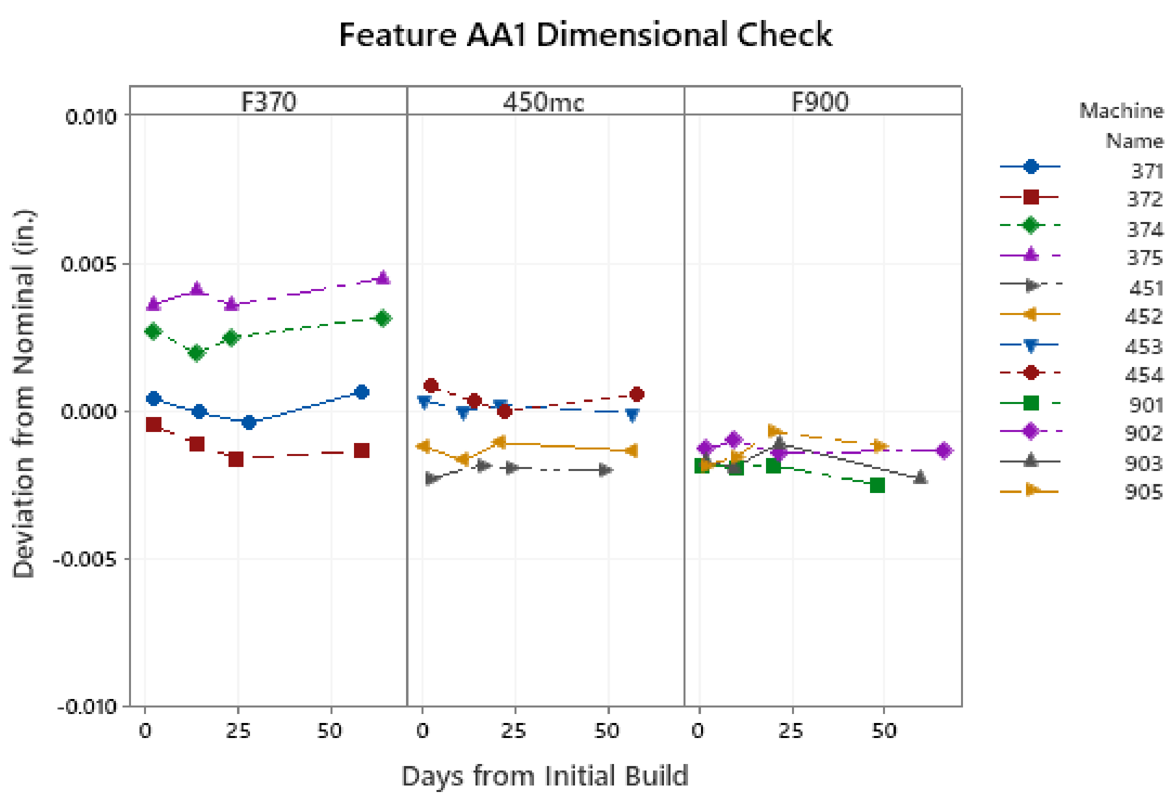


Figure 5 - Measured width for 0.140-inch wide rectangular bar feature (AA1).

The flatness of each of the connected lines represents the consistency of each machine over time. The clustering of lines represents the machine-to-machine variability, which is tightest on the F900. The overall spread between measurements can be assessed by looking at the standard deviation of the measurements for this feature. To quantify the impact of machine-to-machine variation, ANOVA was used. ANOVA shows that machine-to-machine variation was significant for the F370 ($F = 93.29$, $p = 0.000$, $\alpha = 0.05$) and Fortus 450mc ($F = 78.25$, $p = 0.000$, $\alpha = 0.05$), but was not significant for the F900 ($F = 3.31$, $p = 0.057$, $\alpha = 0.05$). This agrees with the graphical analysis in Figure 5.

Table 9 - Standard Deviation for Feature AA1 Measured Width

Model	Standard Deviation Feature AA1 (inches)
F370	0.0021
Fortus 450mc	0.0011
F900	0.0005

Continuing this analysis to the broader set of feature measurements from the 9-inch check part, the average standard deviations are presented in Table 10. The calculations are split between features equal to or smaller than 2 inches (31 features) and those larger than 8 inches (12 features). Note, there are no features between 2-8 inches on the 9-inch check part. This reflects the standard accuracy regimes for FDM.

Table 10 - Summary of Dimensional Variability within Measured Features by FDM Product Model

Model	Average Standard Deviation for Features 2 Inches and Under (inches)	Average Standard Deviation for Features Over 8 Inches
F370	0.0012	0.0119
Fortus 450mc	0.0009	0.0141
F900	0.0009	0.0032

Summaries of the collected measurements are plotted here for each machine by feature. Note, AA1 is in the upper left panel of each of the small feature summary charts. Consistent with the example illustrated earlier, FDM produces consistent results over time with little variation between machines.

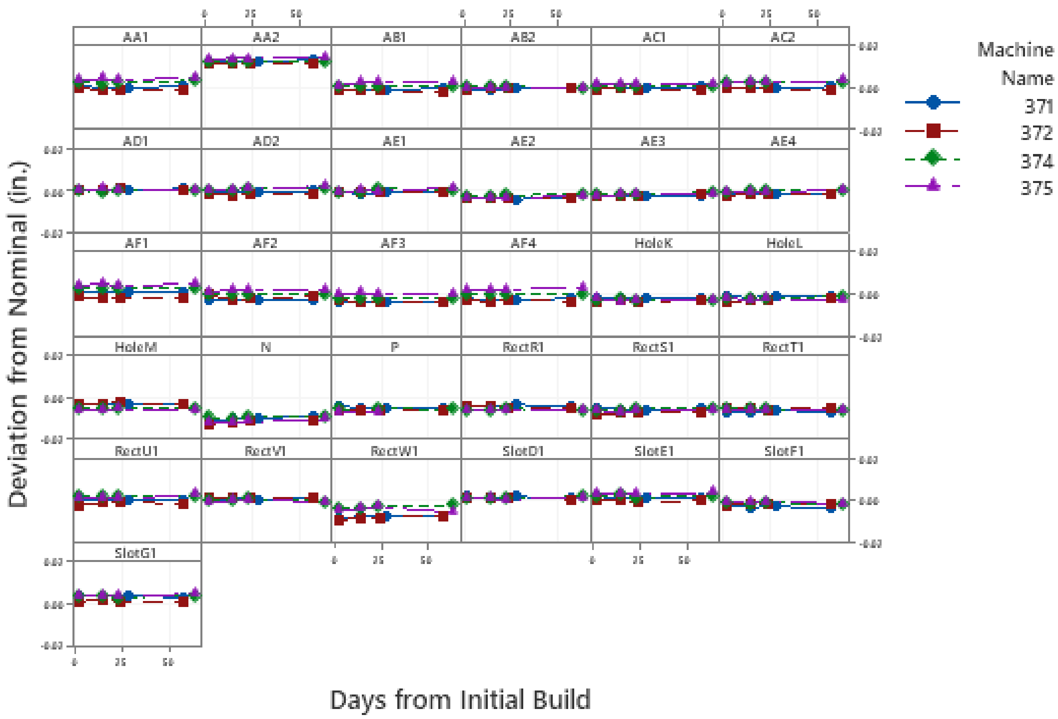


Figure 6 - Small (<2 inch) features for ASA 9-inch check part on F370.

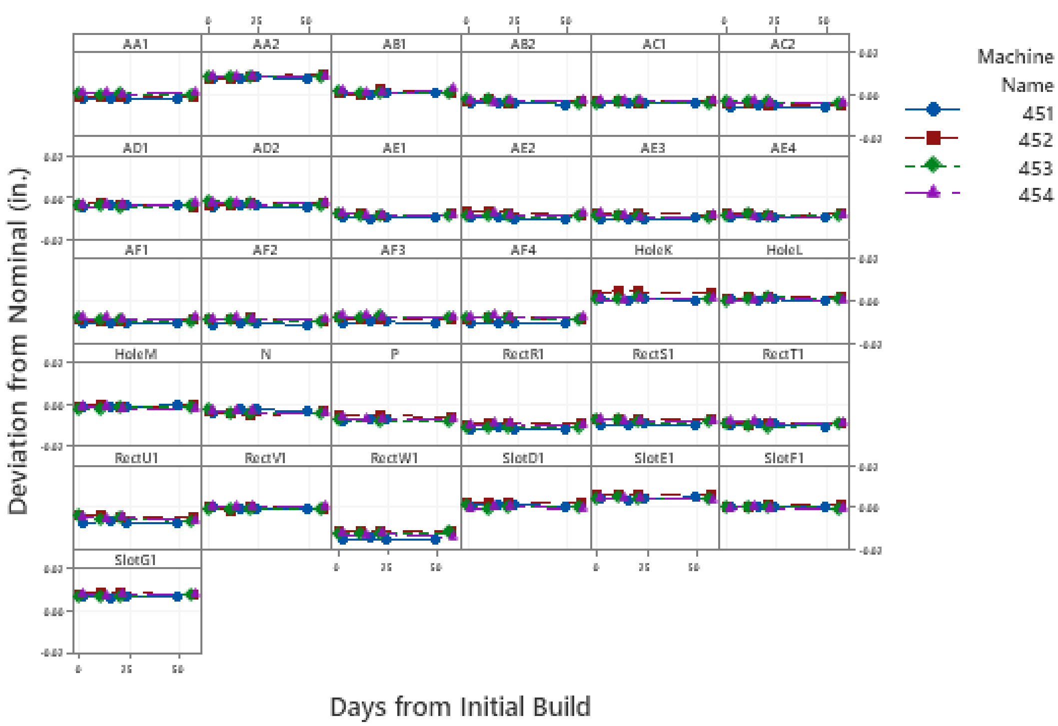


Figure 7 - Small (<2 inch) features for ASA 9-inch check part on Fortus 450mc.

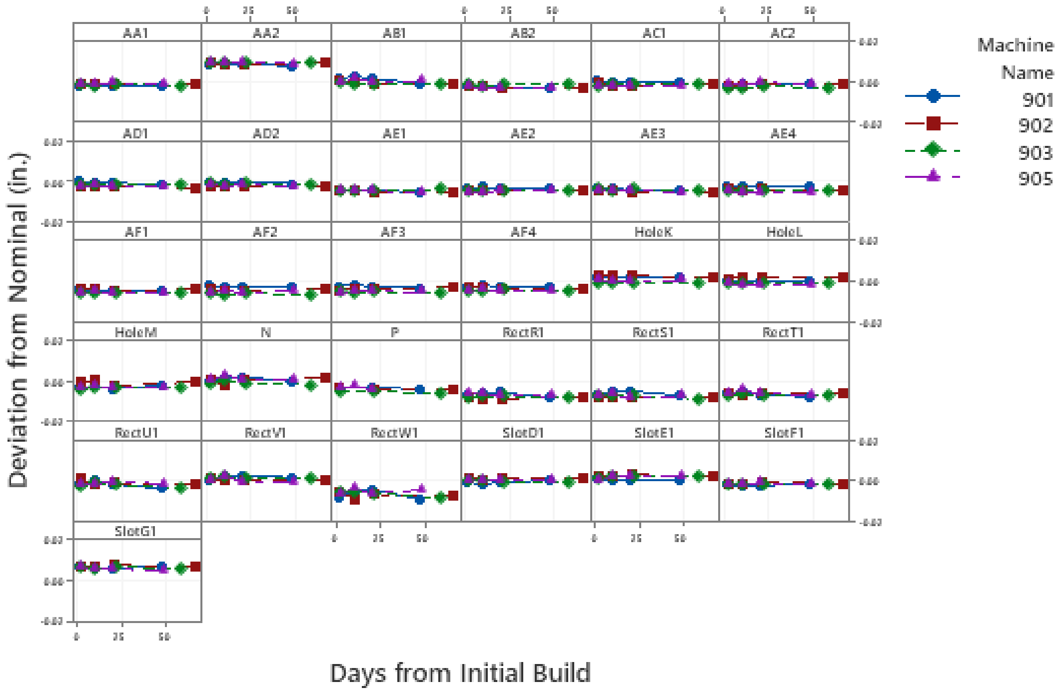


Figure 8 - Small (<2 inch) Features for ASA 9-inch check part on F900.

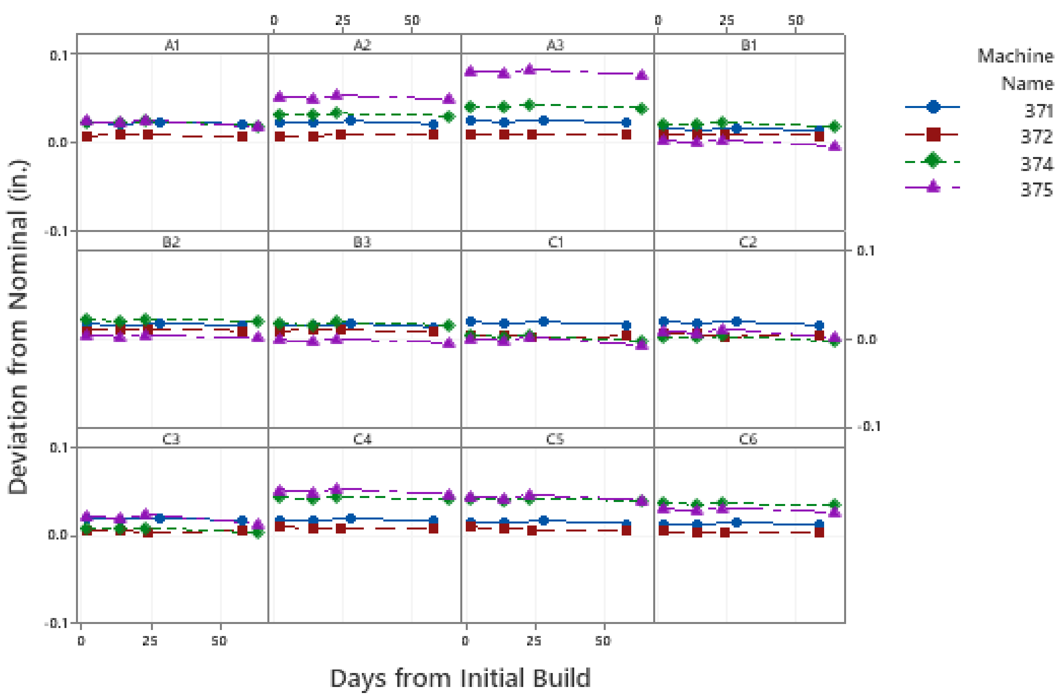


Figure 9 - Large (>8 inch) features for ASA 9-inch check part on F370.

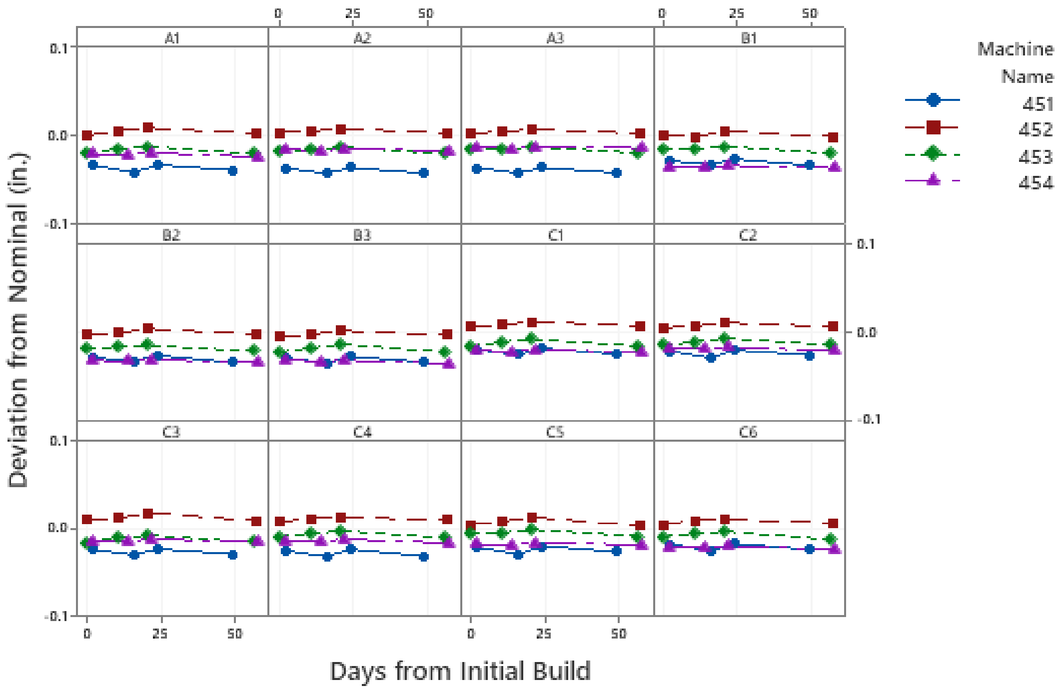


Figure 10 - Large (>8 inch) Features for ASA 9-inch check part on Fortus 450mc.

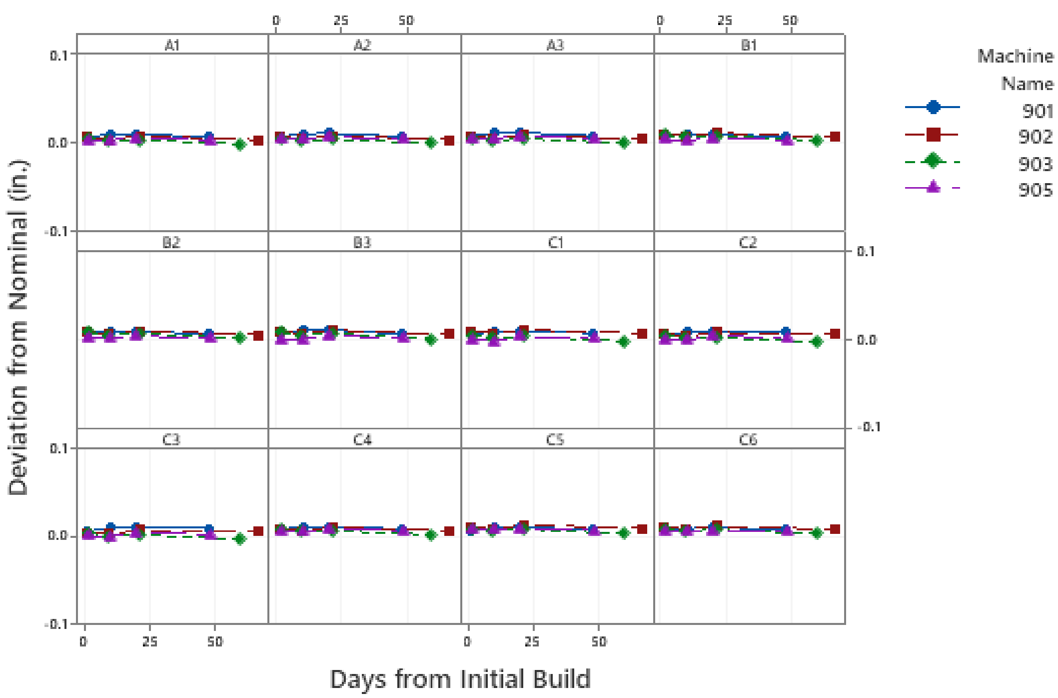


Figure 11 - Large (>8 inch) Features for ASA 9-inch check part on F900.

Capability analysis assesses the ability of a manufacturing process to produce parts within tolerance. As an example, the same feature as above will be analyzed from the F900. Tolerances are specific to part requirements. In absence of defined part requirements, a common industry tolerance of +/-0.005 inch is used here as a proxy for engineering requirements for this feature.

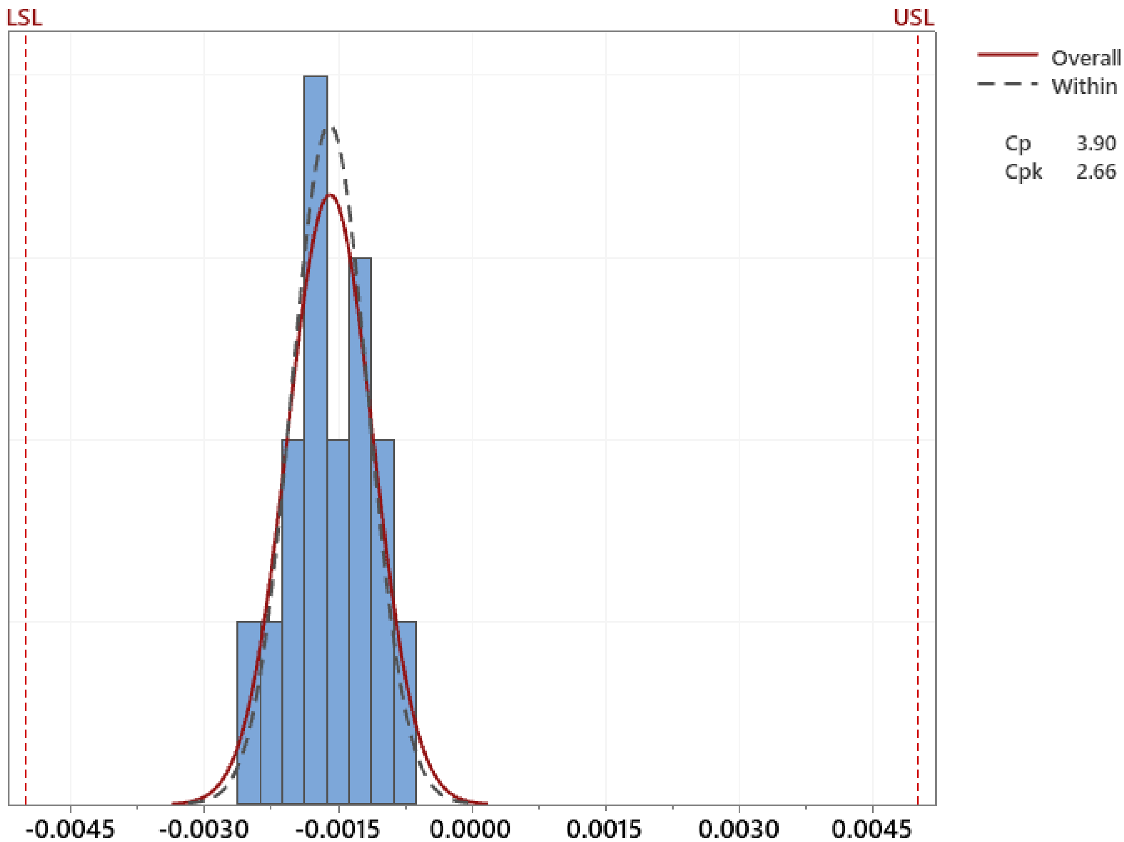


Figure 12 - Capability analysis for 0.140-inch wide rectangular bar feature on ASA 9-inch check part with tolerance +/-0.005 inches.

The capability analysis yields a Cp value of 3.66 and a CpK value of 2.9. The Cp is the ratio of the spread of the data at 6σ to the tolerance range. It shows that the data easily can fit within the specifications. CpK accounts for the centeredness of the data and is lower because the mean of the data is not equal to the nominal target of 0.140. The Cp value exceeds 1.67 and thus the process is controllable. The CpK value exceeds 1.67, so the process is also controlled.

For some features in the analysis, the geometry is not as centered as the example shown above. For example a rectangular boss feature with nominal measurement of 0.520 inch in width, has a mean deviation from the nominal target outside the tolerance band, but is still precise enough to be controllable.

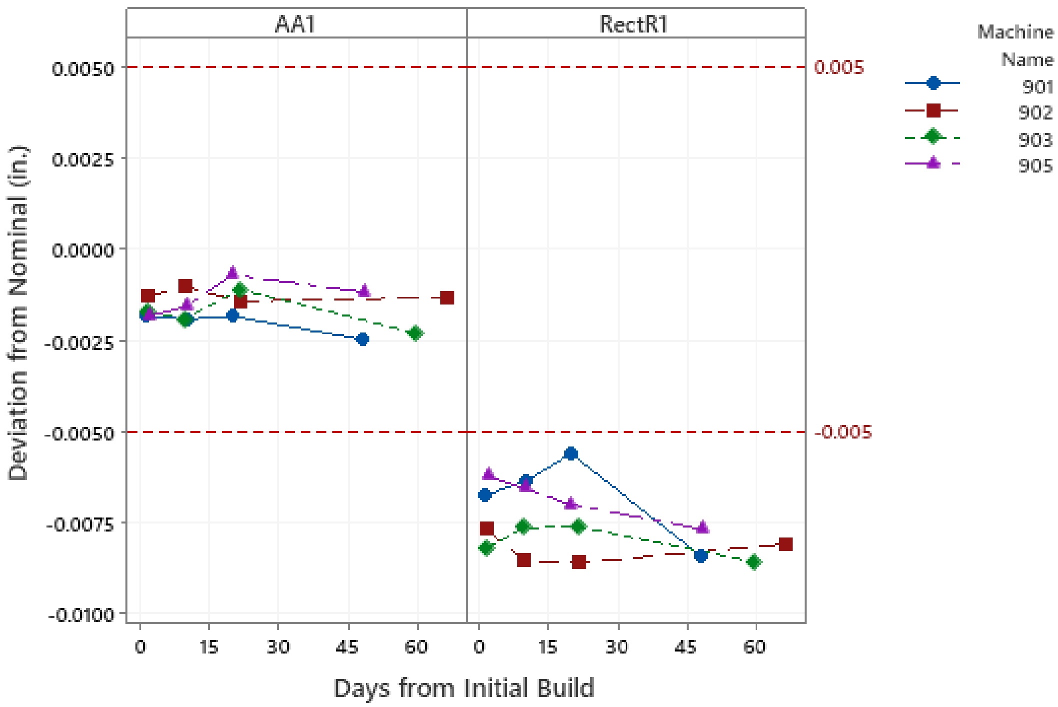


Figure 13 - Comparison of a feature within tolerance (AA1) and a feature outside of tolerance (RectR1).

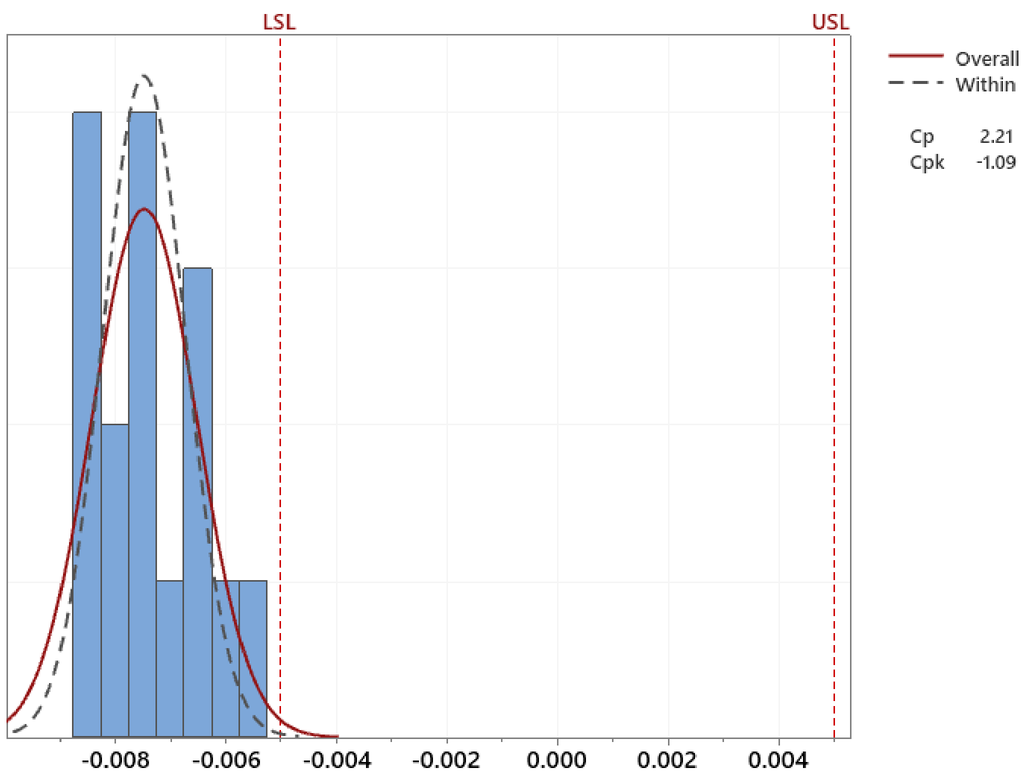


Figure 14 - Capability analysis for RectR1, a 0.520-inch wide rectangular boss feature on ASA 9-inch check part with tolerance +/-0.005 inches.

Capability analysis on feature RectR1 yields a Cp of 2.21 and a CpK of -1.69. Thus, this feature production is controllable, but the process needs improvement to be controlled. The procedure for approaching this is described next.

Centeredness within specification is what differentiates Cpk from Cp. Centeredness is a measure of accuracy. FDM accuracy is dependent on part geometry. In both Insight™ and GrabCAD Print™ software, the translation from CAD geometry to toolpathing is done using cartesian shrink factors. These factors account for the thermal contraction that occurs as the polymer cools from extrusion temperature to room temperature. These factors are experimentally tuned for each machine-material-slice height/tip combination. In the vast majority of cases, these factors work well to generate accurate parts relative to the CAD model. Some features will not be as accurate due to the neighboring geometry resulting in nonuniform cooling causing differential shrinkage. In the cases where the toolpaths generated do not result in acceptable dimensions, geometric adjustments to the base CAD model can be made to compensate. Due to tight dimensional precision of FDM, once these adjustments are made, the part can be reproducibly printed within specification. As such, a high Cp value can be adjusted to reach the desired Cpk value needed for production.

Ultimate Tensile Strength of Printed Coupons

In the course of this study, several thousand coupons were built during the build sequences used. Not all coupons were tested due to the significant size of this study. Out of the total, 1400 individual coupons were chosen for testing of mechanical properties. The tested coupons were chosen as a representative sampling of each machine's performance on each type of system at different platen locations and over time. Mechanical property evaluation largely focuses on ultimate tensile strength in XZ (on edge) and ZX (upright) orientations, however an overall summary of strength, stiffness, and elongation is included upon conclusion of this section in Table 14.

The F370, Fortus 450mc, and F900 systems are all capable of printing ASA, thereby providing a common basis of material to compare the mechanical performance achieved by three different systems that vary in build size and hardware. Nylon 12CF and ULTEM™ 9085 resin were evaluated only on Fortus 450mc and F900 systems due to availability only on that equipment.

In total, 1400 mechanical coupons were tested for this study. As described in the experimental section, each specimen was visually inspected during the test to verify that the specimen failed inside of the gage region of the coupon without the presence of a notable printing defect. A summary of the break location of all the coupons is shown in Figure 15. This chart includes all materials and system types. Of all coupons, 1334 coupons (95%) broke within the acceptable regions of the gage length and narrowed section. The data from 66 coupons (5%) was excluded from further analysis as the break locations were in the radius or grip regions of the coupon, or breakage occurred at a defect location that was noted prior to testing. Interestingly, all 66 of the coupons that were excluded were printed in the ZX (upright) orientation. Fifty-three of these coupons broke in the radius of the coupon, five in the grip region, six coupons were identified with visual defects that coincided with the break location, and two were excluded from slippage of the extensometer during testing. Although the number of specimens rejected was small, less than 5% of the tests performed, it remains best practice to remove the data so as not to affect interpretation of mechanical performance and variation.

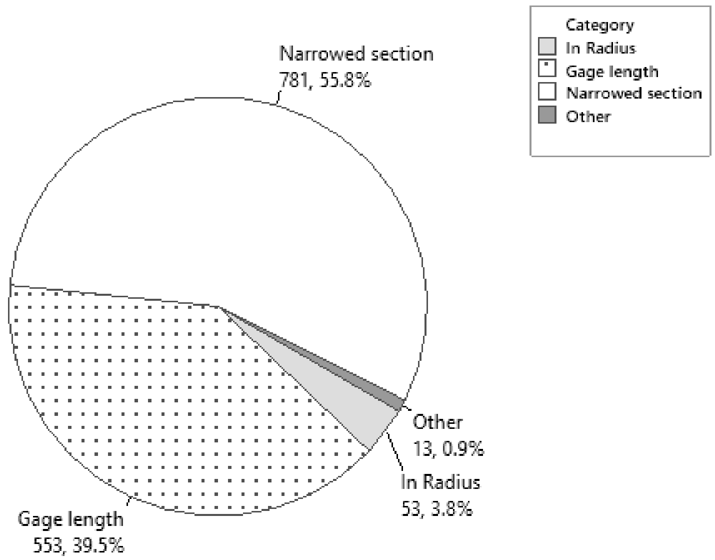


Figure 15 - Summary of coupon break locations including all materials and machines.

The break location varied by the material, machine type, and coupon orientation. Ideally, the specimens would break exclusively inside the gage length. Unfortunately, many breaks of FDM coupons fall within the narrowed section. For this data set of 1334 measurements, 55.8% of the coupons broke within the narrowed section. Although not ideal for measuring elongation since breakage occurs outside the span of the extensometer, it was concluded that since the cross section of the printed part in the narrowed section and the gage section are equivalent, that the measurement of strength was correctly calculated. Note that since the narrowed region is outside the span of the extensometer, tensile elongation was only calculated from specimens that broke in the gage region.

Mechanical Performance of ASA

ASA is a common material option for the Stratasys F370, Fortus 450mc, and F900 systems, enabling comparison of these systems on a similar material basis. In addition to hardware differences, there are differences in the default parameters used for printing ASA on each system due to independent optimization of material performance, although the material chemistry is the same. Over the duration of the build sequence, six time points were taken for analysis of mechanical coupons (see Figure 16). Note that four of the time points were taken within the first three weeks of continuous printing, and the last two time points were taken after the intentional three-week break in the build sequence. Figure 17 displays the results for average ultimate tensile strength in this material for coupons printed in the XZ (on edge) and ZX (upright) orientation for each of the three systems. Each data point represents the average of 5 coupons taken at different locations on the build plane (four corners and center). The work was repeated on four F370, four Fortus 450mc, and five F900 systems.

Overall, individual systems exhibit excellent consistency over two months of printing. No obvious differences in performance are seen before or after the intentional break period in the build sequence for which material changes and uncontrolled use of the systems were permitted. As expected by the anisotropic nature of FDM and interlayer bonding, the strength in the ZX (upright) orientation is generally less than that of the XZ (on edge) orientation. Figure 17 also provides an indication of the relative magnitude of the effects of build plate location, inter-system, and over-time variations. As seen in the plots, each source of variation is generally overlapping, and no single source emerges as a dominant contributor to mechanical strength variation.

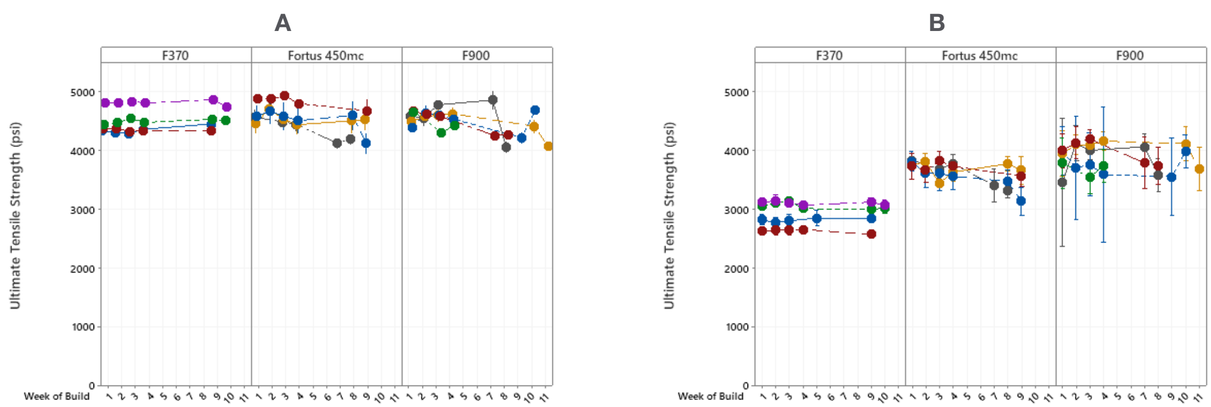


Figure 16 - Ultimate tensile strength of coupons printed in ASA on multiple F370, Fortus 450mc, and F900 systems, for A) XZ (on edge) and B) ZX (upright) orientations. Each data point represents the average of the measured ultimate tensile strength from a build including five specimens positioned across the platen at that point in time during the build sequence.

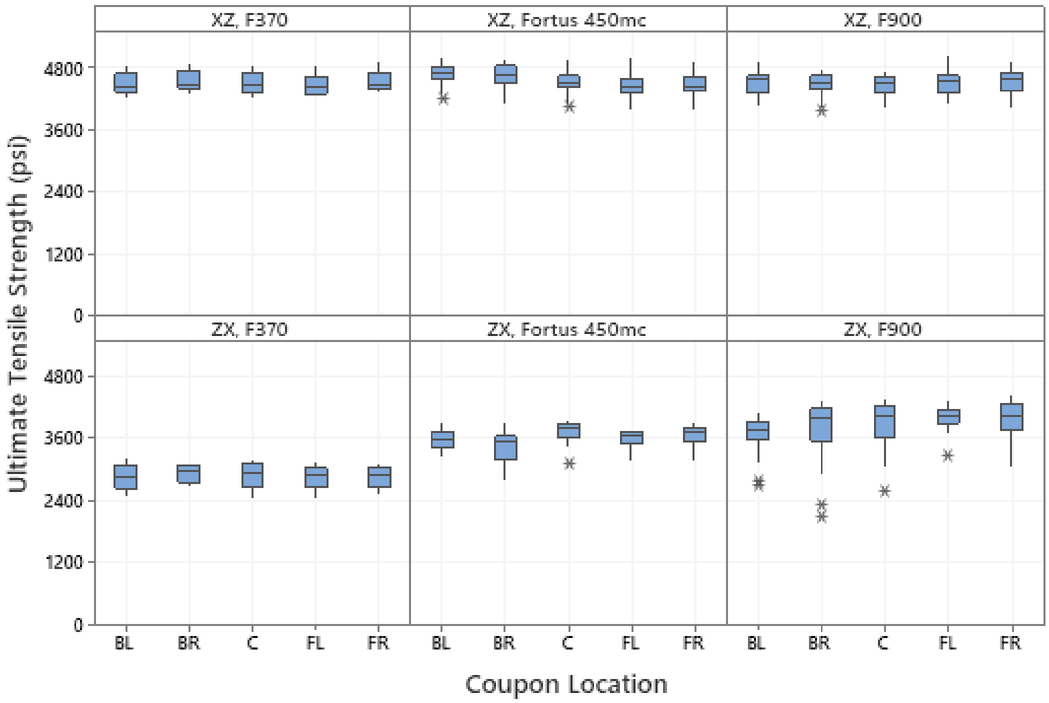


Figure 17 - Average ultimate tensile strength in ASA for coupons printed at specific locations on the build tray - back left (BL), back right (BR), center (C), front left (FL) and front right (FR). Data is presented in XZ (on edge) and ZX (upright) orientations and is averaged across multiple systems for six points in time during the build sequence.

To further explore if there were systematic variations in the results across position on the build plate due to the design of the system, for example from thermal conduction or convection inside the heated build chamber, the data was averaged over time and multiple systems per location on the tray as show in Figure 17. The position of each coupon was recorded as back left (BL), back right (BR), center (C), front left (FL) and front right (FR). The resulting data is summarized for both XZ (on edge) and ZX (upright) orientations for each system type. For the XZ (on edge) orientation, the average strength across the build plate for each system type varies within about a 100 psi range, and for ZX (upright) orientation the variation is within 500 psi, highlighting the consistency of mechanical performance across position. For F900, the trend in average strength values from back to front positions could suggest that a slight thermal profile in the large build chamber of the F900 may exist. However, the distributions in the data for all positions overlap, and no evidence is seen in the XZ (on edge) orientation, making a definitive conclusion doubtful. Since the standard deviations at each position are overlapping on all systems in both orientations, it is concluded that there are no systematic variations in mechanical performance due to part placement on the build plates for these systems.

The collection of data collected for each machine was averaged to evaluate the variation found per system, including across build plate position and time in the build sequence, and is presented in Table 11. Additionally, an overall average of the strength data was calculated for all of the data measurements with respect to multiple machines. Inherently, these averages also include the uncontrolled variations due to differences in system age, material lot, testing, and other factors that were not expressly controlled. The significant size of this study provides confidence that these results are typical of those to be observed from any of the systems under typical operating conditions. The data reinforces the generally accepted conclusion that variation from FDM processes is more significant in ZX (upright) orientation than in the XZ (on edge) due to interlayer bonding, as is evident by the greater COV. In addition to reduced strength in the Z axis, the variation in strength measurement increases. For the F370 systems, the individual machine variation is very low, with COVs less that 2-3%. For this specific machine type, the machine-to-machine variation is larger than the variation within a single machine. For the Fortus 450mc and F900 systems, with their significantly larger build volumes, the machine to machine variation is approximately the same magnitude as the measured intra-machine variation.

Table 11 - Average Ultimate Tensile Strength for ASA

System Type	Machine ID	XZ (on edge) Orientation		ZX (upright) Orientation	
		Average Ultimate Tensile Strength (psi)	Coefficient of Variation (COV)	Average Ultimate Tensile Strength (psi)	Coefficient of Variation (COV)
F370	371	4365	1.8%	2826	2.9%
	372	4346	1.6%	2621	2.8%
	374	4496	1.1%	3061	2.6%
	375	4812	1.1%	3105	1.8%
	Overall Average:	4505	4.4%	2903	7.2%
Fortus 450mc	451	4384	4.4%	3653	6.0%
	452	4530	3.3%	3677	4.5%
	453	4511	5.3%	3542	7.6%
	454	4807	4.0%	3702	4.7%
	Overall Average:	4558	5.5%	3643	6.0%
F900	901	4601	6.3%	3831	13.7%
	902	4462	4.6%	4045	6.2%
	903	4511	3.8%	3882	10.2%
	905	4495	3.9%	4010	7.7%
	906	4425	3.6%	3687	9.9%
	Overall Average:	4504	4.8%	3915	9.8%

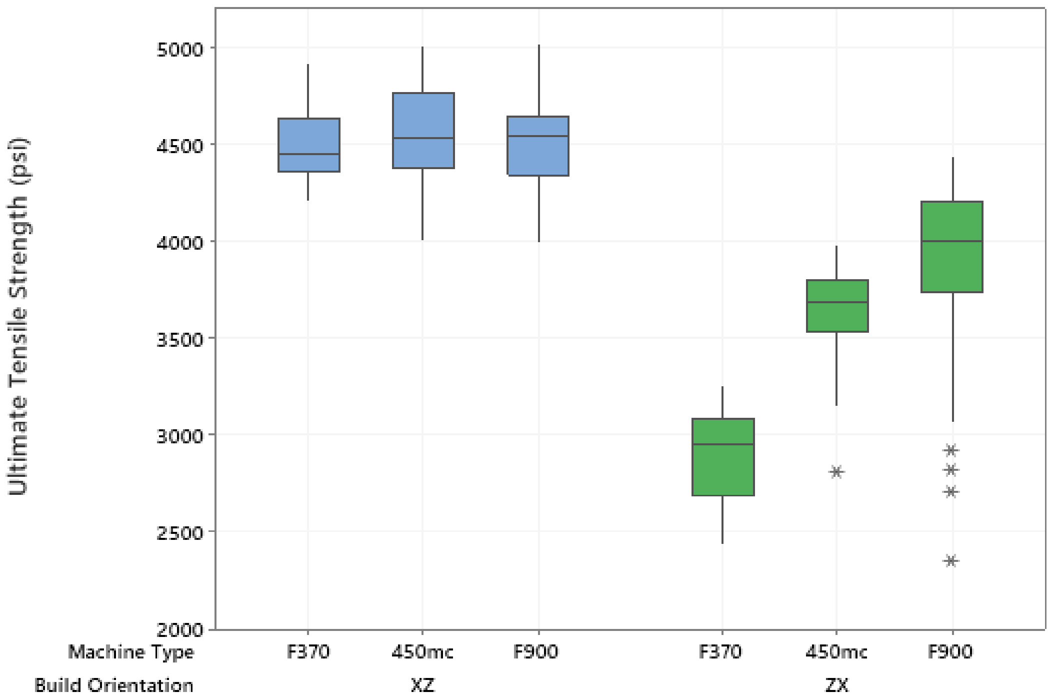


Figure 18 - Overall average ultimate tensile strength in ASA for coupons printed on F370, Fortus 450mc, and F900 systems in XZ (on edge) and ZX (upright) orientation.

Figure 18 plots the overall average strength results for each orientation and system type. All three machine types perform similarly for strength of ASA coupons in the XZ (on edge) orientation, with overlapping standard deviations. In this orientation, each machine type achieves the same result over its full build area and over the duration of the continuous build sequence on multiple machines. Results in the ZX (upright) orientation indicate performance differences between system architecture. All three systems demonstrate an anticipated anisotropy due to interlayer bonding, however the ASA specimens printed on the Fortus 450mc and F900 have superior strength in the ZX (upright) orientation over those printed on the F370. For the coupons printed on the F370, the strength in the ZX (upright) orientation is 64% of the strength of the XZ (on edge) orientation, whereas on the Fortus 450mc and F900 systems it increases to 80% and 87%, respectively. These differences originate from different optimizations of material printing parameters and the performance of the hardware in managing the interface temperature between layers during printing, which is known to affect the strength of interlayer bonding. As noted previously, the F370 default parameters use a value of 0.018 inch for raster width, but the Fortus 450mc and F900 systems use 0.020 inch as the default. These small differences in bead width will affect the contact area and fill density of material and can affect interlayer bond strength. The oven and extruder both affect the local temperature of the plastic during printing. When material printing parameters are determined for a specific system, the temperature of the oven and the extruder are varied to optimize general part performance. One aspect of the optimization is mechanical strength, but other aspects also are important, such as adhesion with support material or the build plate, the ability to bridge over unsupported geometries, print speed, bead diameter control, and numerous other considerations that contribute to part aesthetics, quality, or success rate in printing. Ultimately, the parameters even for the same material can differ across systems, and in this case, the optimization of ASA material resulted in a lesser value of ultimate tensile strength in the ZX (upright) orientation. It is important to note that although affected by anisotropy, the overall COV values for strength are low, indicating very good reproducibility and consistency of mechanical strength across many sources of variation.

Mechanical Performance of Nylon 12CF and ULTEM™ 9085 resin

Nylon 12CF and ULTEM™ 9085 resin materials require high temperature extrusion and build environments for optimal printing and therefore are only available on the Fortus 450mc and F900 systems. Furthermore, as a carbon fiber reinforced material, Nylon 12CF requires additional hardware upgrades to prevent premature wear on components due to the abrasive nature of carbon fiber. Figure 14 presents the results for ultimate tensile strength of Nylon 12CF in the XZ (on edge) and ZX (upright) orientations for four Fortus 450mc and four F900 systems over four time points of the build sequence, approximately one month in duration. For each point in time, the data averages the results across five locations on the build plate. Figure 15 illustrates the complementary data for ULTEM™ 9085 resin.

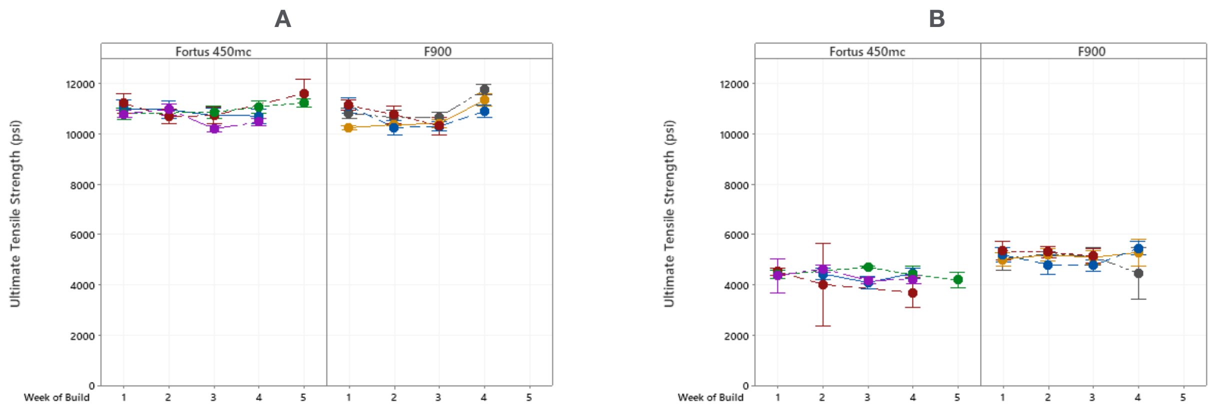


Figure 19 - Ultimate tensile strength of coupons printed in Nylon 12CF on four Fortus 450mc and F900 systems, for A) XZ (on edge) and B) ZX (upright) orientations. Each data point represents the average of the measured ultimate tensile strength from a build including five specimens positioned across the platen at that point in time during the build sequence.

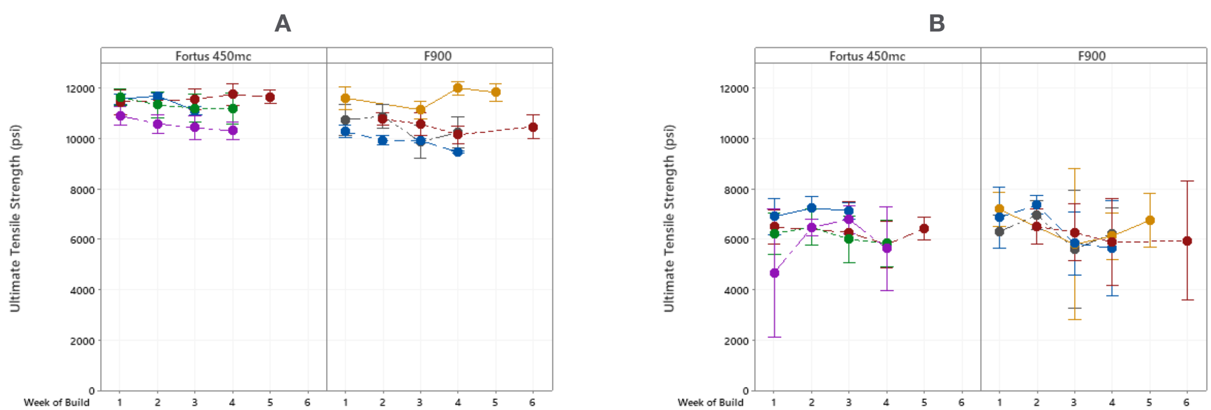


Figure 20 - Ultimate tensile strength of coupons printed in ULTEM™ 9085 resin on four Fortus 450mc and F900 systems, for A) XZ (on edge) and B) ZX (upright) orientations. Each data point represents the average of the measured ultimate tensile strength from a build including five specimens positioned across the platen at that point in time during the build sequence.

Note: Data depicted illustrates ULTEM™ 9085 resin performance with a T16 tip. Using a T16A tip will result in higher mechanical performance with a lower COV. T16A was only available on the F900 at the time of publication and it is not examined in this report.

The figures illustrate the relative effects of machine-to-machine variation and repeatability over time. Generally, strength varies within a range of less than 1000 psi for any individual machine, but between machines the difference can be as much as 2000 psi in some cases of the extremes. Both materials exhibit nearly equivalent strength in the XZ (on edge) orientation despite very different chemical compositions. The polyetherimide polymer base of ULTEM™ 9085 resin is intrinsically stronger than that of the nylon polymer base of Nylon 12CF, however the alignment of carbon fiber in the XZ (on edge) orientation leads to greater strength than the base material, and in this case equivalent to ULTEM™ 9085 resin. In the ZX (upright) orientation, the differences between polymer chemistry are seen, with ULTEM™ 9085 resin being stronger than Nylon 12CF.

The data collected for each point in time was subsequently assessed by position on the build plate, as shown in Figure 21 for both Nylon 12CF and ULTEM™ 9085 resin. ULTEM™ 9085 resin demonstrated a larger standard deviation in strength than Nylon 12CF across position of the build plate. For both materials, the average results per position on the build plate did not indicate a significant trend, as each position had overlapping distributions in the results.

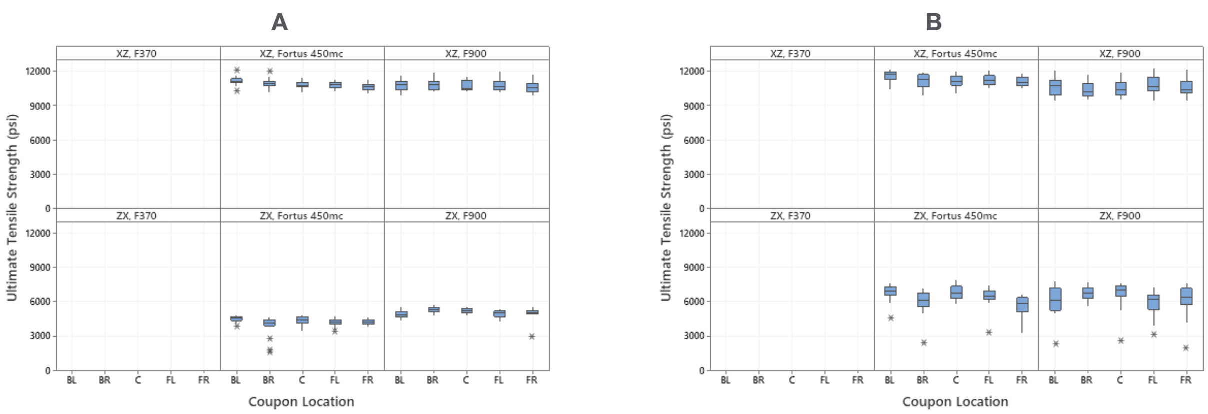


Figure 21 - Average ultimate tensile strength in Nylon 12CF and ULTEM™ 9085 resin for coupons printed at specific locations on the build tray - back left (BL), back right (BR), center (C), front left (FL) and front right (FR). Data is presented in XZ (on edge) and ZX (upright) orientations and is averaged across multiple systems for six points in time during the build sequence. A) Nylon 12CF and B) ULTEM™ 9085 resin.

Table 12 and Table 13 tabulate the average ultimate tensile strength and the COV in each orientation for Nylon 12CF and ULTEM™ 9085 resin, respectively. The effects of anisotropy can be seen by comparing XZ (on edge) and ZX (upright) orientations. For Nylon 12CF, which lacks fiber reinforcement across layers, the strength in the ZX (upright) orientation is about 45% of the XZ (on edge) strength. For ULTEM™ 9085 resin, it is about 60% due to the stronger polymer composition. As expected for material extrusion processes, the COV for the strength of XZ (on edge) coupons is lower than for the ZX (upright) orientations. Individual machines frequently demonstrate lower COV than the overall COV for the data, suggesting machine-to-machine variation is a more dominating influence on variability, however in some cases, the COV on a single machine can be larger than the COV for the full set of data. It is therefore anticipated that the data represents the full expected range of variation that a user would experience on these systems with these materials under normal operating conditions. Consistency in strength is very good for the XZ (on edge) orientation in both materials, demonstrated by COV values less than 7%, and in most cases less than 5%. For the ZX (upright) orientation, the COV is larger, remaining less than 12%, over all of the factors included in this expansive study.

Table 12 - Average Ultimate Tensile Strength for Nylon 12CF

System Type	Machine ID	XZ (on edge) Orientation		ZX (upright) Orientation	
		Average Ultimate Tensile Strength (psi)	Coefficient of Variation (COV)	Average Ultimate Tensile Strength (psi)	Coefficient of Variation (COV)
Fortus 450mc	452	10851	2.5%	4357	6.7%
	453	11060	4.4%	4296	9.5%
	454	10955	2.2%	4434	5.9%
	456	10609	3.1%	4392	5.7%
	Overall Average:	10879	3.5%	4373	6.9%
F900	902	10972	4.5%	4959	10.8%
	905	10589	4.4%	5142	5.5%
	906	10640	4.1%	5052	7.3%
	909	10744	4.3%	5271	5.6%
	Overall Average:	10736	4.5%	5106	7.7%

Table 13 - Average Ultimate Tensile Strength for ULTEM™ 9085 Resin

System Type	Machine ID	XZ (on edge) Orientation		ZX (upright) Orientation	
		Average Ultimate Tensile Strength (psi)	Coefficient of Variation (COV)	Average Ultimate Tensile Strength (psi)	Coefficient of Variation (COV)
Fortus 450mc	451	11364	2.9%	7071	6.3%
	452	11601	2.8%	6327	9.6%
	453	11342	3.7%	6132	11.1%
	455	10555	3.5%	6371	12.3%
	Overall Average:	11215	4.7%	6467	11.1%
F900	901	10432	5.8%	6458	10.3%
	902	11644	3.7%	6933	10.2%
	903	9894	3.2%	6726	12.3%
	906	10491	3.5%	6479	11.5%
	Overall Average:	10915	6.7%	6548	11.2%

Summary of Mechanical Performance

A summary of the ultimate tensile strength, tensile modulus, and elongation at break for each machine and material is shown in Table 14 along with data from product datasheets. In most cases, values from data sheets agree with those collected in this study within the experimental error demonstrated by COV values. The anisotropic nature of FDM is evident in all materials and systems in which the XZ (on edge) orientation is stronger than the ZX (upright) orientation. Generally, modulus (stiffness) is less affected by orientation with the exception of Nylon 12CF due to fiber alignment. All materials exhibit low elongation, as is typical for material extrusion processes.

Table 14 - Summary of Mechanical Performance for All Systems and Materials

Material	Machine	XZ (on edge)						ZX (upright)					
		Ult. Tensile Strength (psi)		Tensile Modulus (psi)		Elongation at Break (%)[1]		Ult. Tensile Strength (psi)		Tensile Modulus (psi)		Elongation at Break (%)[1]	
		Average	COV	Average	COV	Average	COV	Average	COV	Average	COV	Average	COV
ASA	F370	4505	4.4%	247000	5.3%	6.5%	11.2%	2903	7.2%	197000	6.9%	1.8%	9.4%
	450mc	4558	5.5%	235000	11.6%	6.3%	21.5%	3643	6.0%	243000	7.6%	1.9%	11.5%
	F900	4504	4.8%	246000	7.4%	6.0%	15.3%	3915	9.8%	262000	8.2%	1.7%	24.5%
	Datasheet (F900)	4750		311000		9.0%		4300		298000		3.0%	
Nylon 12CF	450mc	10879	3.5%	1225000	16.6%	3.3%	5.3%	4373	6.9%	406000	22.4%	1.8%	14.2%
	F900	10736	4.5%	1227000	13.6%	3.2%	3.4%	5106	7.7%	488000	17.6%	1.8%	19.4%
	Datasheet (F900)	9190		1370000		1.9%		4170		434000		1.2%	
ULTEM™ 9085 resin	450mc	11215	4.7%	340000	6.9%	5.8%	8.4%	6467	11.1%	299000	5.1%	2.5%	13.0%
	F900	10615	7.3%	333000	4.9%	5.4%	8.8%	6639	11.2%	330000	6.2%	2.3%	16.9%
	Datasheet (F900)	9950		348000		5.8%		6100		309000		2.2%	

[1] For elongation at break, only data from coupons that broke within the gage length are included.
[2] Typical product testing for data sheets includes one set of ten specimens evaluated once per three different F900 systems, for a total of 30 measurements.

Material Throughput and Printing Speed

Productivity of equipment is an important consideration for manufacturing operations because the average cost of a part generally decreases as throughput increases. In order to compare the relative productivity of the Stratasys F370, Fortus 450mc, and F900 systems, the log files were reviewed for printing identical parts during the build sequences. Two different parts were evaluated; the 9-inch check part and the 12-inch Z tower. For each part, only one copy of the part was built in the printer at a time. Table 15 and Table 16 compare the average build duration, amount of model and support material consumption, and the resulting average material throughput for each machine-material combination when printing these parts. The average material consumption is calculated from the total volume of model and support material printed.

As seen in the tables for both parts, the F370 takes more time to build the same part than the Fortus 450mc and the F900 in ASA. Due to hardware differences that include the extruder and the gantry, the Fortus 450mc and F900 systems are faster printing ASA than the F370. In ASA and ULTEM™ 9085 resin materials, both the Fortus 450mc and the F900 produce these two parts with a similar build duration. For Nylon 12CF, the F900 demonstrates an advantage in speed over the Fortus 450mc.

Although the geometry is the same across the different machine-material combinations, the material consumption is different for each of the test cases. The Fortus 450mc and the F900 demonstrate nearly identical material consumption when printing either of these parts in any of the three materials. The F370 consistently uses less model material and a larger amount of support material compared to the other systems. Overall these differences are due to multiple factors in process to optimize material print parameters of the material on each system. For example, the F370 uses 10 layers of support material by default before initiating the first layer of the model material in order to fully planarize the build surface over the removable plastic build tray. The Fortus 450mc and F900 systems generally use fewer layers of material prior to building a model. Similarly, the use of purge towers on the F370 is a default practice, whereas on the Fortus 450mc and F900 systems a printed purge tower is generally not used but nozzle purge steps over a purge station are used on each head swap. The volume of material spent on purging is determined empirically for different materials. The differences in purge volume is likely the dominant factor that results in a different volume of material expended per system in these cases. However, other factors of defining the material extrusion such as fill style, support style, and bead width can also affect material consumed.

Table 15 - Build Duration, Material Consumption, and Average Material Throughput for Printing the 9-Inch Check Part

Material	Machine	Ave. Build Duration (min.)	Model Material Volume (in^3)	Support Material Volume (in^3)	Average Material Throughput (in^3/hr)
ASA	F370	298	8.0	3.4	2.3
	Fortus 450mc	220	9.4	1.2	2.9
	F900	222	9.5	1.2	2.9
Nylon 12CF	Fortus 450mc	282	10.1	0.9	2.3
	F900	241	10.1	0.9	2.7
ULTEM™ 9085 resin	Fortus 450mc	263	11.1	0.8	2.7
	F900	262	10.7	0.8	2.6

Table 16 - Build Duration, Material Consumption, and Average Material Throughput for Printing the 12-Inch Z Tower

Material	Machine	Ave. Build Duration (min.)	Model Material Volume (in^3)	Support Material Volume (in^3)	Average Material Throughput (in^3/hr)
ASA	F370	443	10.6	4.0	2.0
	Fortus 450mc	376	12.6	2.3	2.4
	F900	382	12.6	2.1	2.3
Nylon 12CF	Fortus 450mc	411	13.6	0.7	2.1
	F900	355	13.8	0.7	2.4
ULTEM™ 9085 resin	Fortus 450mc	361	14.0	0.6	2.4
	F900	352	13.4	0.6	2.4

Reliability of Job Starts and Part Yield

The sum off all machine time spent during the build sequences used in this work totaled 1,385 days for all systems and materials. For each system, the totals were 318 days on the F370, 541 days on the Fortus 450mc, and 525 days on the F900. More materials were utilized on the Fortus 450mc and F900 systems, increasing overall printing time, but these machines also have higher throughput compared to the F370 and therefore the increased time was less than a multiple of the F370 build time.

During the build sequences, some issues occurred that affected the completion of the programmed jobs. The most severe issues included replacement of an electronics board responsible for oven temperature control on an F900 and replacement of a vacuum generator used for securing build sheets on a Fortus 450mc. Neither of these issues resulted in critical failure of the system, but the issues did affect the start of jobs on a system due to temperature stability for running ULTEM™ 9085 resin and securing build sheets. Each of the three systems recorded one instance of a job pause that was recovered in each case. There were a few instances of fallen parts during builds, all from ZX (upright) coupons, in which the printer continued to print 'in air.' Other minor issues included a single occurrence of a canister with cross-wound filament, two instances of clogged tips, and a single failed auto changeover. The variety of machine issues, and their relative frequency of occurrence, was representative of the kinds of errors that users experience, as learned from customer feedback by the authors.

Table 17 tallies the number of jobs starts and rebuilt jobs, and calculates a job yield for each system type. The number of jobs starts includes all jobs that were started on the system during the build sequence. The number of rebuilt jobs is the number of jobs that were rebuilt due to machine errors, part quality issues, or due to human error, such as the job being out of order with the defined build sequence. The job yield was calculated as the percentage of jobs that passed on the first attempt of the build out of the total number of builds. There were no instances in which a rebuilt job could not be completed successfully. The three systems demonstrated very good job yield values over the several hundred days of print time experienced during this work.

Table 17 - Number of Job Starts, Rebuilt Jobs, and Job Yield

System Type	F370	Fortus 450mc	F900
Number of Systems	4	6	6
Materials	ASA	ASA, Nylon 12CF, ULTEM™ 9085 resin	ASA, Nylon 12CF, ULTEM™ 9085 resin
Total Number of Job Starts	181	452	380
Rebuilt Jobs	9	52	21
Job Yield	95%	88%	94%

The reliability of these systems to produce parts can additionally be viewed on the basis of part yield. Part yield is the percentage of 'good' parts out of the total number of parts attempted on the system. The total number of parts included the count of parts from rebuilt jobs if required. Good parts were defined as parts that successfully built during a job per the intention of the job, without any obvious failure or quality issue. If a job had an unrecoverable error, any part that was not completely built through all layers of its design was counted as a failure. It was therefore possible that parts with fewer layers in the Z axis than other parts of the build could remain counted as good, should an error have occurred late in a job. Parts from a job that were rebuilt due to operator error, such as jobs being built in the wrong order, did not count towards the number of failed parts since the equipment did not produce the error. Using this logic, the part yield for each of the systems is shown in Table 18. The reported part yields are 99%, 93%, and 92% for the F370, Fortus 450mc, and F900, respectively, demonstrating very high completion of printed parts on these systems.

Table 18 - Calculated Part Yield

System Type	F370	Fortus 450mc	F900
Total Parts	1586	3984	4844
Failed Parts	10	279	381
Good Parts	1576	3705	4463
Part Yield	99%	93%	92%

CONCLUSION

In this work, printed parts from the F370, Fortus 450mc, and F900 FDM systems have been characterized under variables of key concern to manufacturers implementing an additive manufacturing process into their operations. In particular, the repeatability of a process is often far more valuable to a manufacturer than the absolute magnitude of a result. Equipment and processes must be trusted to deliver the same results, every time with confidence. It was the intention of this work to test these three systems under conditions that represented those that a typical user would experience for operations in a factory environment. The study blended multiple variables together to arrive at results that should confidently represent the variations seen by any customer under expected use conditions. The build sequences used in this work incorporated long durations of continuous use, multiple systems of varying age and history, occupying the full build area of the printer, and working with different types of materials across multiple material lots. The sum of all of these variables allows a user the confidence to set expectations on printed part performance.

For the investigation of dimensional repeatability, the use of ASA on all three systems allowed for a comparison that was, in part, independent of a material contribution. The data demonstrated the F900 performed with the least variations, which lends significant benefit to users working with the full build volume of the machine. The Fortus 450mc and F370 systems also perform extremely well. Target dimensions are achieved with high precision over time and other variables, without requiring repeated calibrations. The effect of the material contribution on accuracy to the CAD design is a well-known challenge in material extrusion technology. Comparison of the three materials demonstrated the benefits of low thermal expansion materials, such as the reinforced Nylon 12CF, to hold tolerances with less variation. Overall, it becomes the precision of the system and material combination that will define the repeatability of printed part dimensions. All three systems demonstrated consistency and repeatability that would enable a designer to make small adjustments to the CAD design to correct for any material influences that might affect part accuracy to the design for a specific geometry. In the future, a more ideal situation will be material model-based corrections that could predictively adjust geometry during the print preparation step of the workflow. Until then, the precision of these machines offers users consistency and well-understood expectations.

The evaluation of mechanical strength in printed coupons similarly included a very large sample size with emphasis on different types of variations that a user might encounter in a factory floor environment. One of the most important findings is the low COV calculated from the overall average data. In the XZ (on edge) orientation, all material and system combinations demonstrated a COV in the range of 3.5 to 7.3%, with most of the results being less than 5% COV. As expected for material extrusion processes, there was greater variation in ZX (upright) orientation, with COV of all material and system combinations in the range of 6.0% to 11.2%. The evaluation from printed ASA draws the conclusion that all three systems produce equivalent strength parts in the XZ (on edge) orientation, but there are differences in the vertical ZX (upright) orientation. In that orientation, the Fortus 450mc and F900 systems are able to print stronger parts in ASA. The performance of the Fortus 450mc and F900 was very similar on the basis of strength in all three materials. And furthermore, part position on the build plate was not found to be dominant factor on strength for any of the systems.

Overall, the F370, Fortus 450mc, and F900 were proven by dimensional precision and mechanical strength to generate very consistent results. Success rates for producing parts were greater than 92% for all of these systems over very long build sequences and a large number of variations explored. Compared to each other, it is clear that while all three systems perform well, the Fortus 450mc and F900 systems offer advantages in build size, strength in the ZX (upright) orientation, and high-performance material selections like Nylon 12CF and ULTEM™ 9085 resin. With respect to the performance against the broader number of options for material extrusion printers, there are no standards of comparison today. Although direct comparisons were not readily available or equivalent to include in this work, previous studies have shown a significantly better performance out of Stratasys FDM systems. We believe the results and methods used in this report go well beyond the rigor of previous studies and should be viewed by users as the most robust benchmark for comparison.

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