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Additive Manufacturing

Variability of Additive Manufacturing Process

Contents

Introduction

While additive manufacturing (AM) has historically been used for rapid prototyping, the field has greatly advanced, drawing AM into manufacturing and production of end-use products. For use as a manufacturing solution, an AM process must produce repeatable results for material properties and geometric dimensions. An understanding of the degree to which AM processes are repeatable is a critical factor when defining items such as design allowables, quality control procedures, acceptable scrap rates and the general applicability as a method of production.

While there have been several studies examining the dimensional accuracy of AM processes, none have studied multiple technologies with a focus on precision. In addition, there are very few studies that examined the variability of mechanical properties from AM processes, and most of those analyses have been for metal AM solutions.

This study examined AM processes for both mechanical and dimensional variability to determine manufacturing readiness of polymer solutions. The study was designed to standardize the performance characterization to allow direct comparison between processes despite differences in materials and build methods. To achieve this, the testing strategy supported detection of variances across a build platform, between builds, between machines and between build orientations. For conciseness, this report limits the discussion to cumulative and machine-to-machine variances.

Variability
& Accuracy

AM processes' variability—both for mechanical properties and geometric dimensions—and dimensional accuracy, were examined and analyzed to evaluate readiness for use in production. Variability may be expressed as precision, which is different than accuracy (Figure 1).

Ideally, an AM process would be both accurate and precise when used to manufacture products. However, a precise (low variability) but inaccurate process is preferred over one that is imprecise but accurate.

Simply stated, precision leads to predictable and repeatable results that are necessary for control of a manufacturing process and confidence in the output quality. Accordingly, AM processes must demonstrate low variability to be adopted as a mainstream manufacturing method.

In this study, variability is quantified through coefficient of variation (COV) and standard deviation (SD).

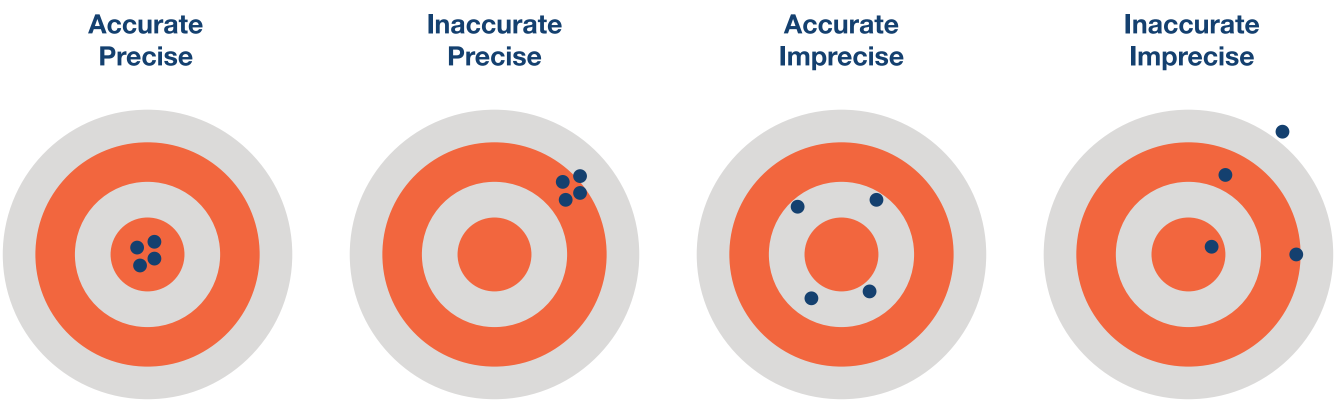

Figure 1: Accuracy vs. precision illustration.

AM Processes

There are many AM processes and a staggering number of combinations of materials and machines. To choose six AM processes and six materials for this study, the selection criteria included popularity (how commonly they are used in industrial applications) and supplier claims of manufacturing readiness. Table 1 lists the AM processes, machines and materials analyzed in this study.

AM Process	AM Class	Machine	Material	Manufacturer
FDM (Fused Deposition Modeling)	Material Extrusion	Fortus 900mc Aircraft Interiors Configuration	Certified ULTEM 9085	Stratasys
MJF (Multi Jet Fusion)	Powder Bed Fusion	HP 4200	High Reusability PA 12	HP
SLA (Stereolithography)	Vat Photopolymerization	SLA 7000	Somos Watershed XC	3D Systems /DSM
SLS (Selective Laser Sintering)	Powder Bed Fusion	Sinterstation 2500 Plus HS	PA 2201	3D Systems /EOS
CLIP (Continuous Liquid Interface Production)	Vat Photopolymerization	M1	RPU 70	Carbon
FFF (Fused Filament Fabrication)	Material Extrusion	Mark X	Onyx	Markforged

Table 1: Tested AM processes, machines and materials.

Variability: Mechanical Properties

For material properties, accuracy is the measure of how close the values are to a target, which may originate from data sheets or prior testing. Precision is the measure of the range, or dispersion, of values, independent of the accuracy. For this investigation, accuracy and the relative difference between AM materials were not evaluated. Rather, the variability (precision), as a measure of the capability to repeatedly produce a property value, was the study's focus. Since standard deviation (SD) cannot be used as a comparative measure when base values differ significantly, this analysis relies on the coefficient of variation (COV) as an indicator of the confidence that an intended result can be achieved repeatedly.

A low COV indicates high predictability, which then heightens the confidence level in repeatedly hitting a material property specification. If, for example, an AM process has a low COV but is inaccurate, part designs can be modified to accommodate the offset or processing parameters may be adjusted to obtain the desired result. Therefore, as with any process, a low COV is necessary for manufacturing to ensure consistent properties from build-to-build and machine-to-machine.

This study evaluated the COV for tensile strength, tensile modulus and elongation at break (EAB). For detailed analysis, the COVs were measured from test coupons built in both horizontal (XY) and vertical (ZX) orientations. Additionally, the COVs were investigated for consistency across two AM machines. For additional details on the testing methodology, see Appendix.

Overall

Figure 2 presents the COVs for tensile strength, tensile module and EAB by process and by test coupon orientation. It shows that FDM, MJF and SLA had low COVs for strength and modulus, with all being below 4.01%, and only slight differences between build orientations. With the exception of MJF's EAB in the XY orientation, FDM, MJF and SLA had low to moderate COVs for EAB, ranging from 4.96% to 14.12%. Typically, EAB testing results produce more variability than those for tensile strength and tensile modulus, independent of the manufacturing process, so these results are within expectations.

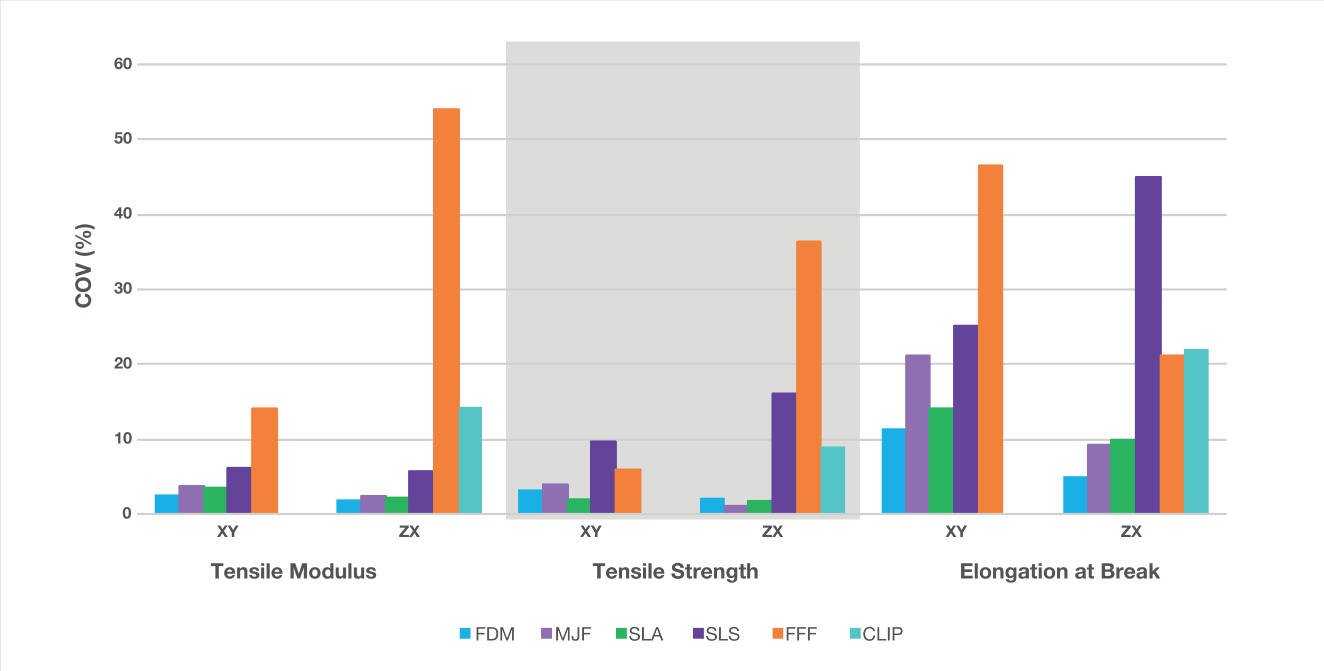

Figure 2: Coefficient of variation (COV) for mechanical properties.

Assuming that the desired mechanical properties can be obtained from the available materials, the low COVs indicate that FDM, MJF and SLA are the best suited for production applications. Higher COVs for SLS, CLIP and FFF would lead to less predictability, which is undesirable for production.

FFF had high variability, with the largest COVs in all but one case—SLS was higher for tensile strength in the XY orientation. Figure 2 also shows very large deviations for FFF between the COVs for the two orientations.

However, this fact should be disregarded since the ZX orientation is not well supported, and not recommended, for FFF due to an inability to stabilize thin, tall structures. Because of this, only half of the FFF ZX samples were constructed after discovering the vendor's orientation recommendation.

As seen in Figure 2, CLIP and SLS had COV values better than FFF in all but one instance, but they had worse values than FDM, MJF and SLA. Note that due to CLIP's build area, coupons in the XY orientation could not be built.

	Tensile Modulus		Tensile Strength		Elongation at Break	
Process	XY	ZX	XY	ZX	XY	ZX
FDM	**2.51%**	**1.84%**	**3.37%**	**2.13%**	**11.54%**	**4.96%**
MJF	**3.75%**	**2.46%**	**4.01%**	**1.05%**	**21.05%**	**9.15%**
SLA	**3.55%**	**2.21%**	**1.99%**	**1.82%**	**14.12%**	**9.97%**
SLS	**6.07%**	**5.77%**	**9.60%**	**16.09%**	**25.18%**	**44.88%**
CLIP		**14.34%**		**9.02%**		**22.09%**
FFF	**14.08%**	**54.06%**	**5.95%**	**36.42%**	**46.62%**	**21.06%**

Table 2: COV values for mechanical properties.

Table 2, which is generally ordered by best to worst COVs, presents the values used for Figure 2. FDM had the lowest COVs for tensile modulus (1.84% and 2.51%) and EAB (4.96% and 11.54%) in both coupon orientations. For tensile strength, FDM had good COVs (2.13% and 3.37%), which were within 1.38 percentage points (PP) of the best results.

MJF's COVs for tensile strength and tensile modulus ranged from 1.05% to 4.01%. SLA had similar results with COVs ranging from 1.82% to 3.55%. Excluding MJF's COV for EAB in the XY orientation (21.05%), both MJF and SLA had good COVs, ranging from 9.15% to 14.12%, for elongation.

For tensile strength and tensile modulus, SLS's and CLIP's COVs ranged between 5.77% and 16.09%. While CLIP had a lower COV for tensile strength (9.02%), SLS had much better tensile modulus values (5.77% to 6.07%). Both processes also had high to very high EAB COVs, ranging from 22.09% to 44.88%.

FFF performed well with tensile strength in the XY orientation (5.95%), but it had poor consistency in all other measures with COVs ranging from 14.08% to 54.06%.

While standard deviation (SD), mean values and data ranges are not suitable for comparison, as described previously, these results are shown in Figures 3, 4 and 5 to provide a visual representation of the individual tests results that contributed to the COV values. Plotting each measured value provides visual representation of the dispersion of results. For example, FDM's tensile strength (XY) and MJF's EAB (XY) were influenced by a few outlying values.

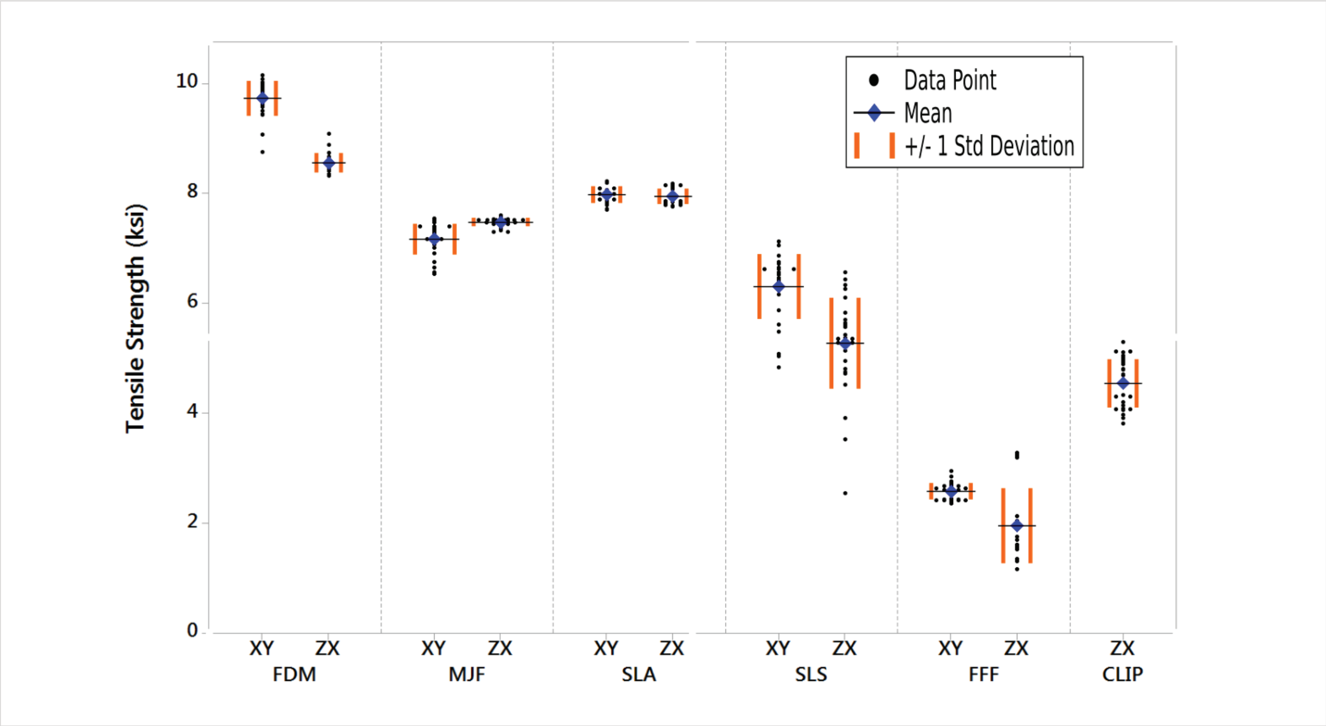

Figure 3: Tensile strength test values.

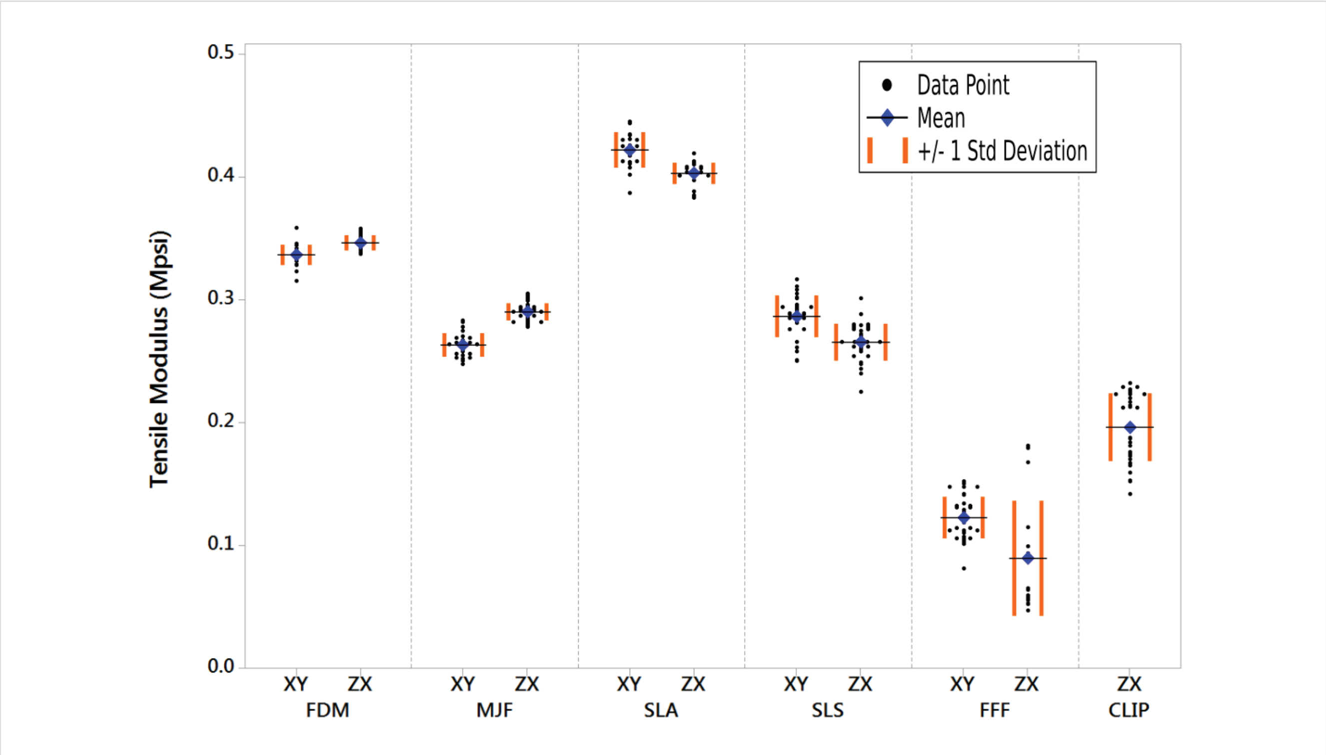

Figure 4: Tensile modulus test values.

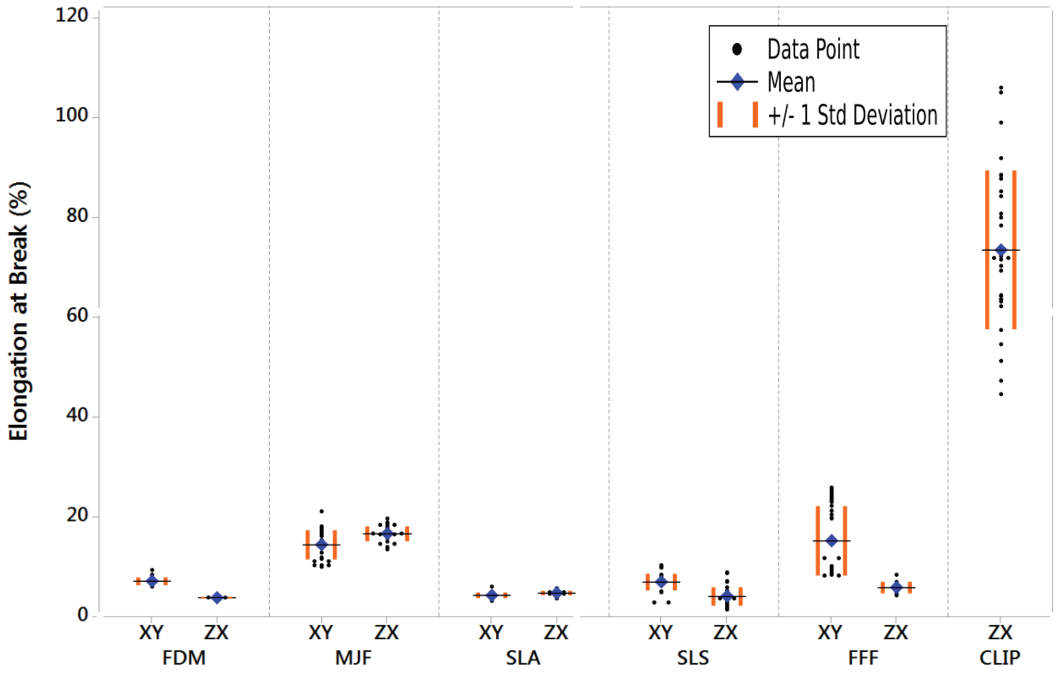

Figure 5: EAB test values

Machine to Machine

Historically, AM processes have demonstrated build-to-build and machine-to-machine variances. To determine the influence of machine-to-machine variances on COV, Figures 6, 7 and 8 show the percentage point differences between the two machines used to build the tensile test coupons for each process. A small range is desirable since it indicates repeatability in outputting parts with little variation in mechanical properties across multiple machines.

In these charts, the range boxes' upper limits are the highest COV from the two machines. The lower limit represents the COV for the other machine.

For example, FDM's combined COV for tensile strength (XY) was 3.37%. Figure 6 shows that the COVs for the FDM machines were 1.63% and 4.23%, which is a small 2.6 percentage point (PP) difference.

Tensile strength is shown in Figure 6. It reveals that FDM, MJF, SLA and CLIP had both a low overall COV and a low variance between the machines. Collectively, the differences between Machine 1 and Machine 2 are small, ranging from 0.37 to 2.60 PP. Therefore, these processes should be expected to produce consistent results across multiple machines.

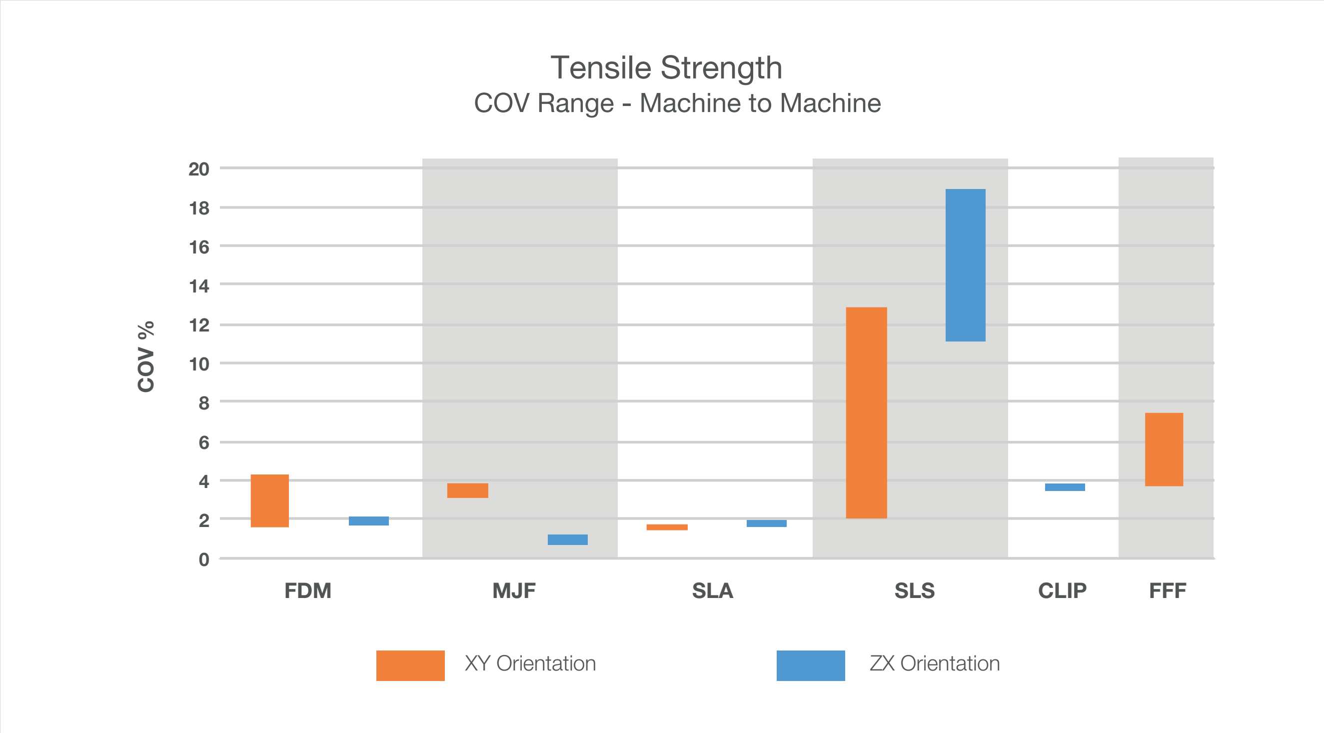

Figure 6: Tensile strength —COV range between machines.

FFF, in the XY orientation, had slightly larger machine-to-machine variance with a 3.84 PP difference. Since no test coupons were made on a second machine, due to the previously described issue with building in the ZX orientation, FFF had no comparative results for that orientation. SLS yielded the highest machine-to-machine variances, with 10.83 PP and 7.8 PP for XY and ZX, respectively. Interestingly, SLS Machine 1 had a very low COV for XY coupons while Machine 2 had a low COV for ZX samples.

Figure 7 plots the COV range boxes for tensile modulus. The results for FDM, MJF and SLA were very similar to those for tensile strength. SLS, CLIP and FFF, on the other hand, showed pronounced differences. SLS proved to be more consistent for tensile modulus with COV ranges of 5.03 PP (XY) and 2.28 (ZX). Both CLIP and FFF had greater variances when compared to tensile strengths. CLIP had a difference of 5.77 PP, and FFF had a difference of 10.55 PP.

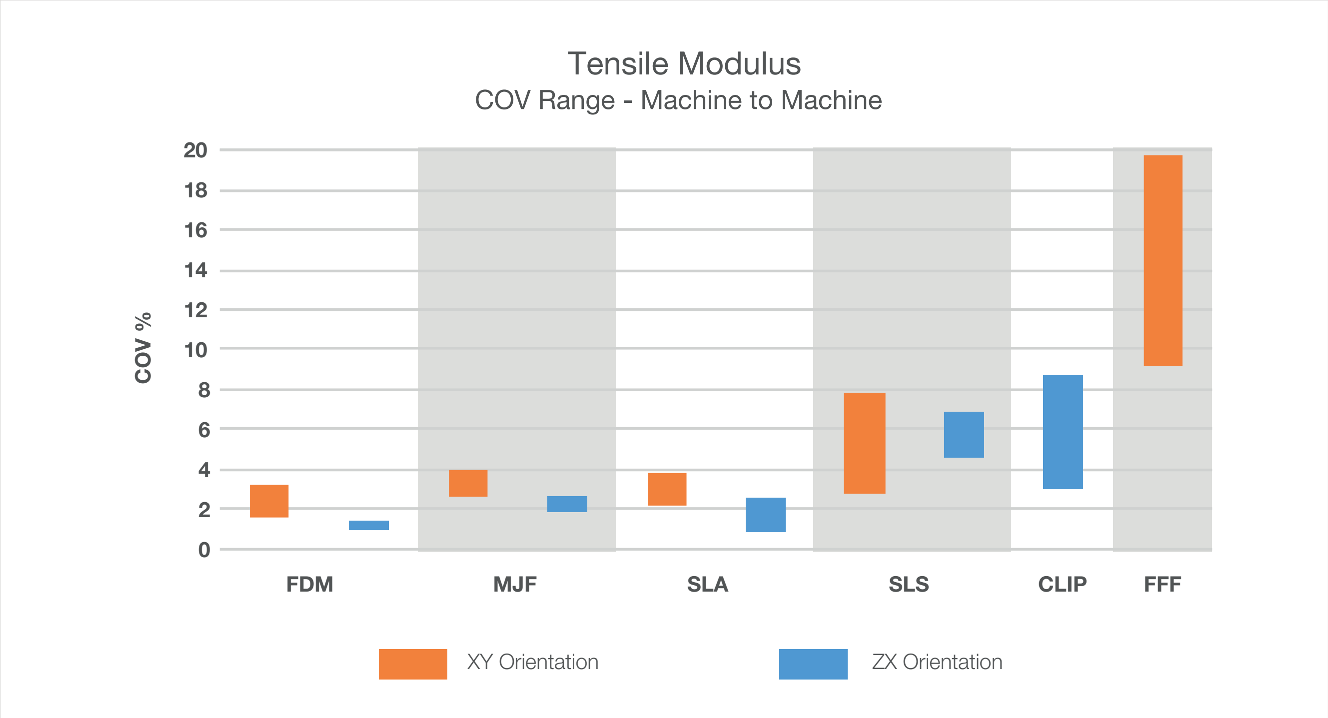

Figure 7: Tensile modulus — COV range between machines.

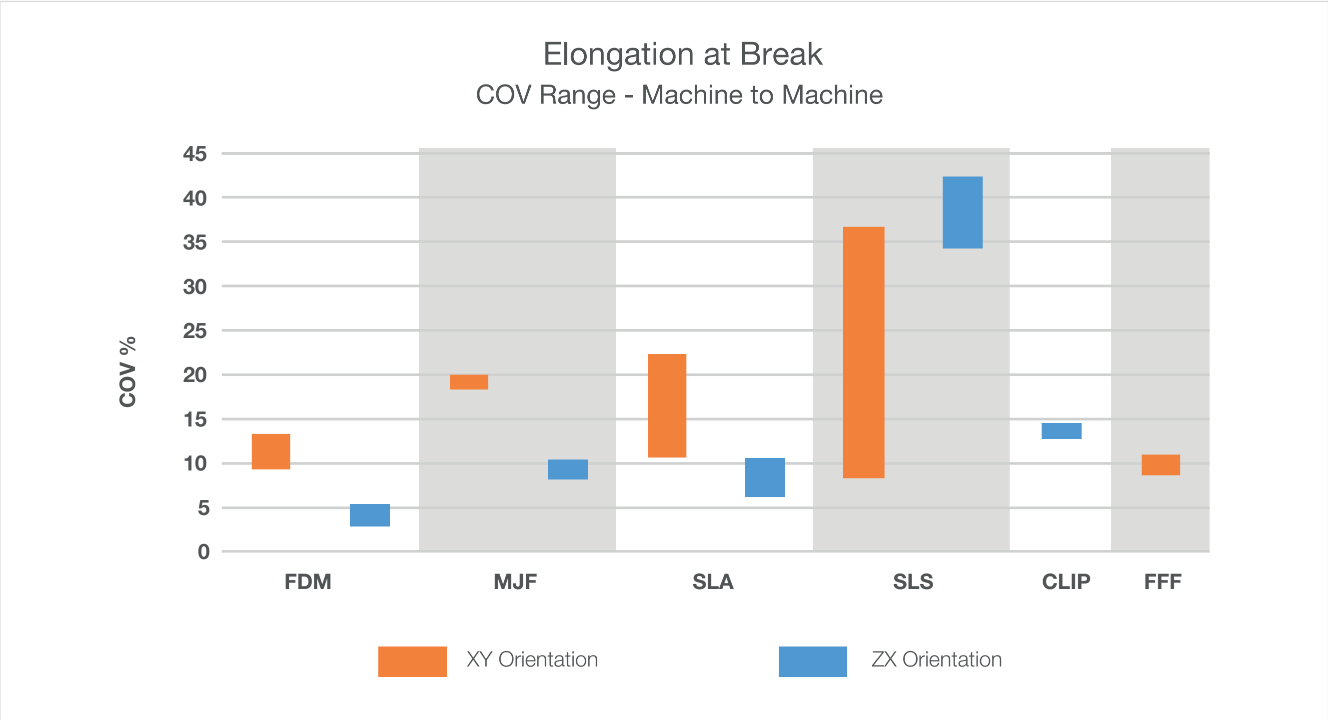

Figure 8: EAB —COV range between machines.

The last machine-to-machine comparison is for EAB, which is shown in Figure 8. FDM, MJF, CLIP and FFF all had small variances between machines with values ranging from 1.57 PP to 4.07 PP. While the ZX value for SLA was also good, the XY difference between machines grew to 11.96 PP. SLS's XY difference was the largest of any machine-to-machine variance for all properties with a 28.60 PP difference.

Variability: Dimensional Measurements

In the context of accuracy versus precision, dimensional measurements can use mean (average) measurement values as a comparative gauge of accuracy. Unlike mechanical properties, the results of dimensional inspection are directly comparable since there is a common target, the nominal dimension specified in the design. And since the target is common, standard deviation (SD) comparison is a suitable gauge of precision. Ideally, for high confidence in the quality of the AM process' output, the mean for the deviation from the nominal dimension and the SD should be very low.

This study evaluated dimensional variances of five AM processes using six instances of a check part for each process. To understand any contribution to variance from machine-to-machine discrepancies, three of the check parts were constructed on Machine 1 and the balance on Machine 2.

All data presented in the following tables and charts are based on the deviation from the nominal dimension. The threshold for allowable tolerances has been set to the greater of +/- 0.0035 in. or 0.0015 in./in., which is the most stringent target documented by equipment and service suppliers of these technologies. For additional details on the testing methodology, see Appendix.

Note that CLIP has been excluded from the dimensional accuracy and precision analysis. To achieve the study's goal of evaluating dimensional accuracy across the extents of the build area, the check part's size exceeded the build area of the CLIP machine. Also note that FFF required post-build heating to remove warpage that impeded check part measurement.

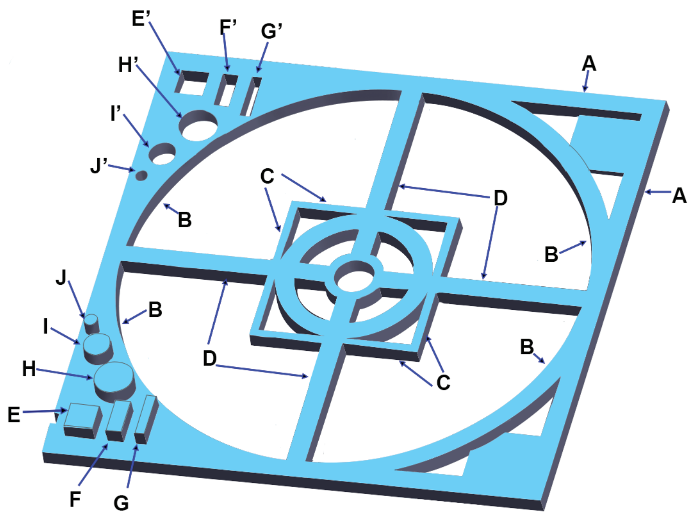

Figure 9: Check part features that were used for dimensional study.

Check Part

The selected check part, as shown in Figure 9, is 9 in. X 9 in. It includes a variety of positive features, such as bosses and ribs, and negative features, such as holes and slots. The analysis considered 19 features that were inspected through 43 measurements.

To understand any influence of feature type or size, the following information is segmented into three categories: large features; small, positive features; and small, negative features. The large features, labeled A, B C, and D in Figure 9, were measured in multiple locations along both the X and Y axes. By combining six to eight measurements for each feature, the resulting mean value and SD provide an indication of overall accuracy and precision, independent of axis. Note that for features C and D, the dimensional analysis considered the wall thickness, not the overall size.

The small features were mirrored and reversed to understand any difference between positive and negative feature accuracy while minimizing the effect of position within the AM machine. The small, positive features are located on the lower left of the check part. These are labeled in Figure 9 as E, F, G, H, I and J. To indicate the axes of measurement, each label for a rectangular feature has an 'x' or 'y' appended. The small, negative features are mirrored on the centerline of the check part (X axis) and located on the upper left. These features use the same labeling convention as that for the small positive features with the addition of a prime symbol (').

Note that due to impediments to the CMM inspection routine, three measurements were omitted, H, G'x and G'y.

Overall Results

In testing, reliance upon meeting tolerance specifications may be misleading since it only considers accuracy. To characterize predictability, variability (SD) must also be considered. For example, an AM process with high precision but low accuracy can use adjustments to either the design or build parameters in order to achieve tolerance specifications with confidence. Conversely, an accurate but imprecise AM process may not achieve the same level of repeatable performance.

The accuracy vs. precision matter becomes clear from the test results shown in Figures 10, 11 and 12. SLS and FFF were the AM processes with most features (12 each) falling within tolerance. However, both proved to be imprecise with a mix of SDs that ranged from very good to very poor. Conversely, SLA was inaccurate, with only two features being in tolerance, but it was precise, with six of the lowest SDs. MJF proved to be both inaccurate and imprecise. Meanwhile, FDM had the best combination of accuracy and precision with 11 in-tolerance features and 14 of the lowest SDs.

The results for large features are shown in Figure 10 and Table 3. Figure 10, and all subsequent charts, plots the mean value of the deviation from the nominal dimension with a circle marker and +/- 1 SD with error bars. Additionally, the red lines indicate the tolerance band for the respective features

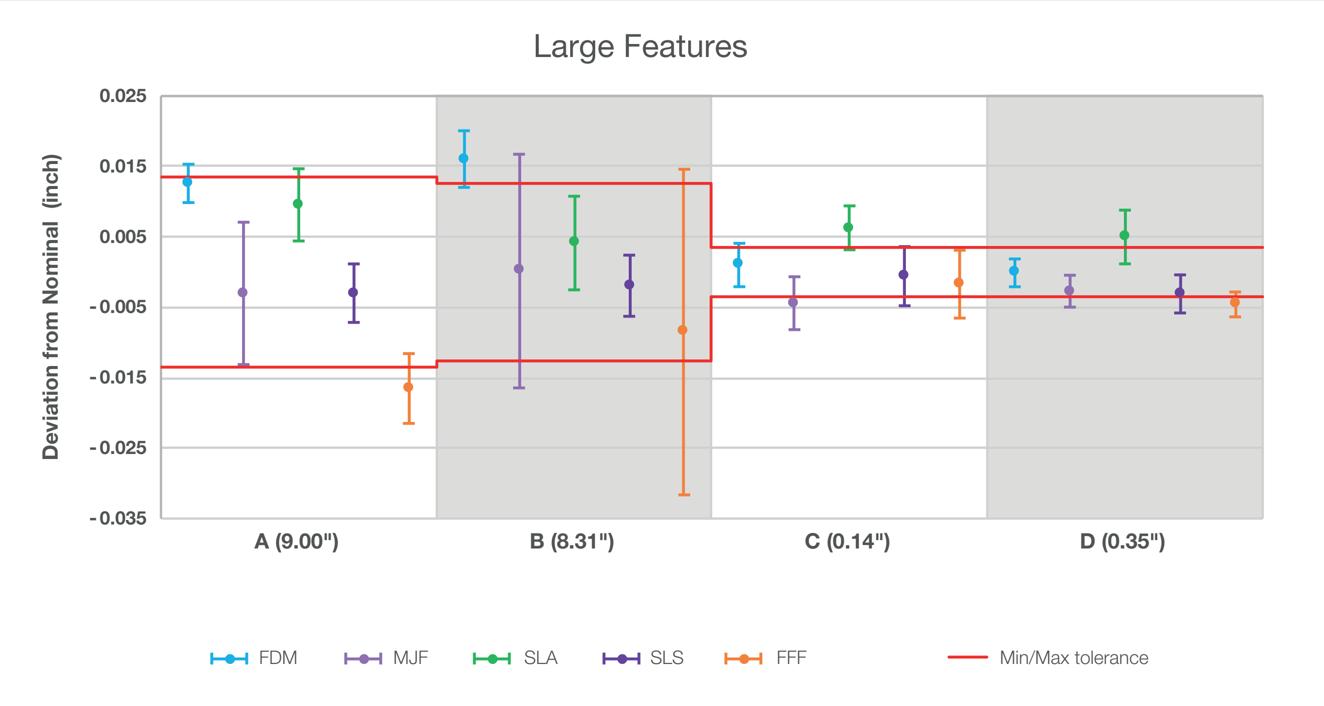

Figure 10: Dimensional accuracy and precision for large features.

Figure 10 shows that FDM was the most precise with SD's ranging from 0.0020 in. to 0.0040 in. While the wall thickness measurements (C and D) were accurate, the largest features' (A and B) dimensions approached or exceeded the upper tolerance limit. With three in-tolerance measurements, MJF was accurate for the largest features yet imprecise with SDs ranging from 0.0023 in. to 0.0166 in. SLS was the most accurate with mean values ranging from -0.0006 in. to -0.0031 in. while having reasonable precision (0.0027 in. to 0.0043 in.). For SLA, the results were mixed. SLA's features C and D were inaccurate but reasonably precise (0.0031 in. and 0.0038 in.), yet features A and B were accurate but less precise (0.0051 in. and 0.0066 in.). FFF proved to be somewhat accurate, but its precision was the most varied, ranging from 0.0018 in. to 0.0231 in.

	FDM		SLS		SLA		MJF		FFF	
	Mean (in.)	SD (in.)	Mean (in.)	SD (in.)	Mean (in.)	SD (in.)	Mean (in.)	SD (in.)	Mean (in.)	SD (in.)
A (9.00")	0.0126	0.0027	-0.0030	0.0042	0.0095	0.0051	-0.0030	0.0101	-0.0165	0.0050
B (8.31")	0.0160	0.0040	-0.0019	0.0043	0.0041	0.0066	0.0001	0.0166	-0.0085	0.0231
C (0.14")	0.0010	0.0031	-0.0006	0.0042	0.0063	0.0031	-0.0044	0.0038	-0.0017	0.0048
D (0.35")	-0.0001	0.0020	-0.0031	0.0027	0.0050	0.0038	-0.0027	0.0023	-0.0046	0.0018

Table 3: Large features - dimensional accuracy (mean deviation from nominal) and precision (standard deviation) values.

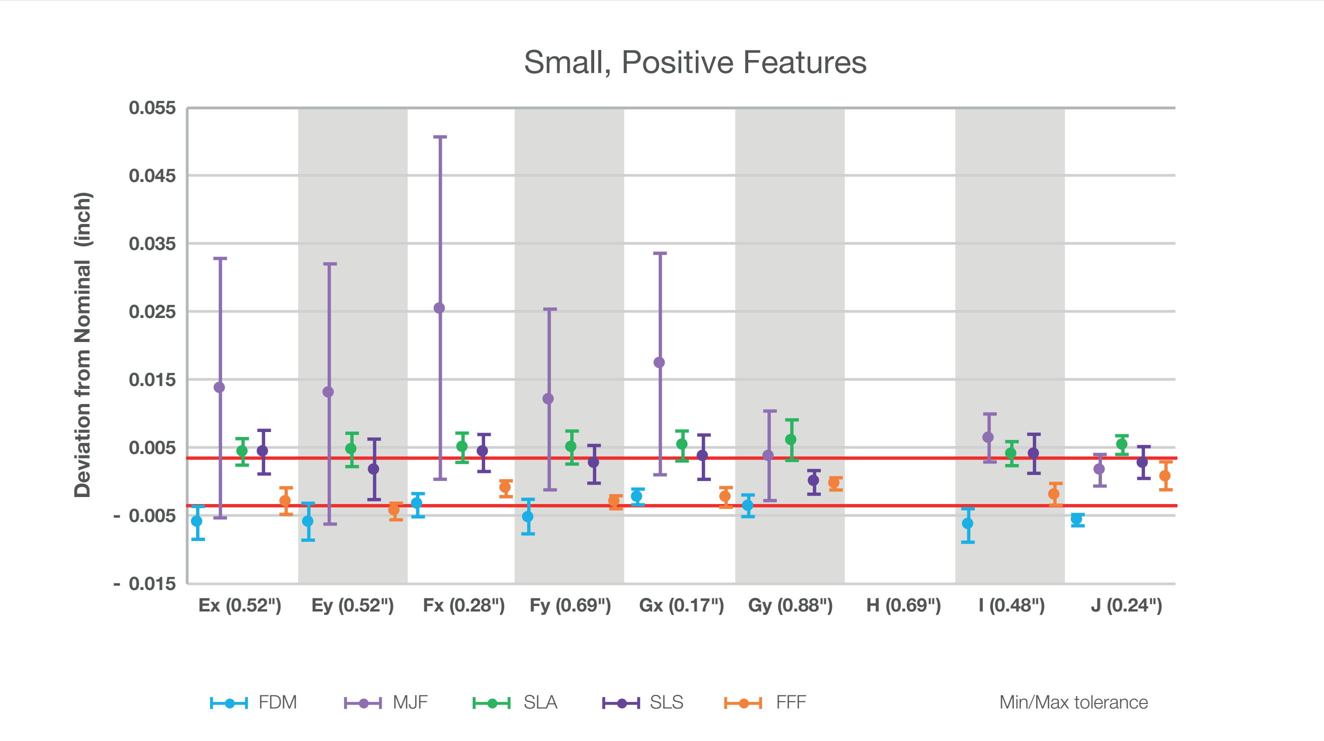

Figure 11: Dimensional accuracy and precision for small, positive features.

	FDM		SLS		SLA		MJF		FFF	
	Mean (in.)	SD (in.)	Mean (in.)	SD (in.)	Mean (in.)	SD (in.)	Mean (in.)	SD (in.)	Mean (in.)	SD (in.)
Ex (0.52")	-0.0060	0.0024	0.0044	0.0032	0.0044	0.0019	0.0138	0.0191	-0.0028	0.0020
Ey (0.52")	-0.0059	0.0027	0.0018	0.0044	0.0047	0.0025	0.0129	0.0191	-0.0044	0.0012
Fx (0.28")	-0.0034	0.0017	0.0042	0.0027	0.0050	0.0022	0.0256	0.0252	-0.0010	0.0012
Fy (0.69")	-0.0051	0.0025	0.0026	0.0028	0.0051	0.0024	0.0121	0.0133	-0.0030	0.0010
Gx (0.17")	-0.0022	0.0012	0.0036	0.0033	0.0053	0.0022	0.0173	0.0163	-0.0023	0.0014
Gy (0.88")	-0.0035	0.0016	-0.0001	0.0017	0.0061	0.0030	0.0038	0.0066	-0.0003	0.0009
H (0.69")										
I (0.48")	-0.0064	0.0025	0.0041	0.0029	0.0042	0.0018	0.0065	0.0035	-0.0018	0.0016
J (0.24")	-0.0056	0.0008	0.0028	0.0023	0.0054	0.0014	0.0017	0.0023	0.0009	0.0021

Table 4: Small, positive features - dimensional accuracy (mean deviation from nominal) and precision (standard deviation) values.

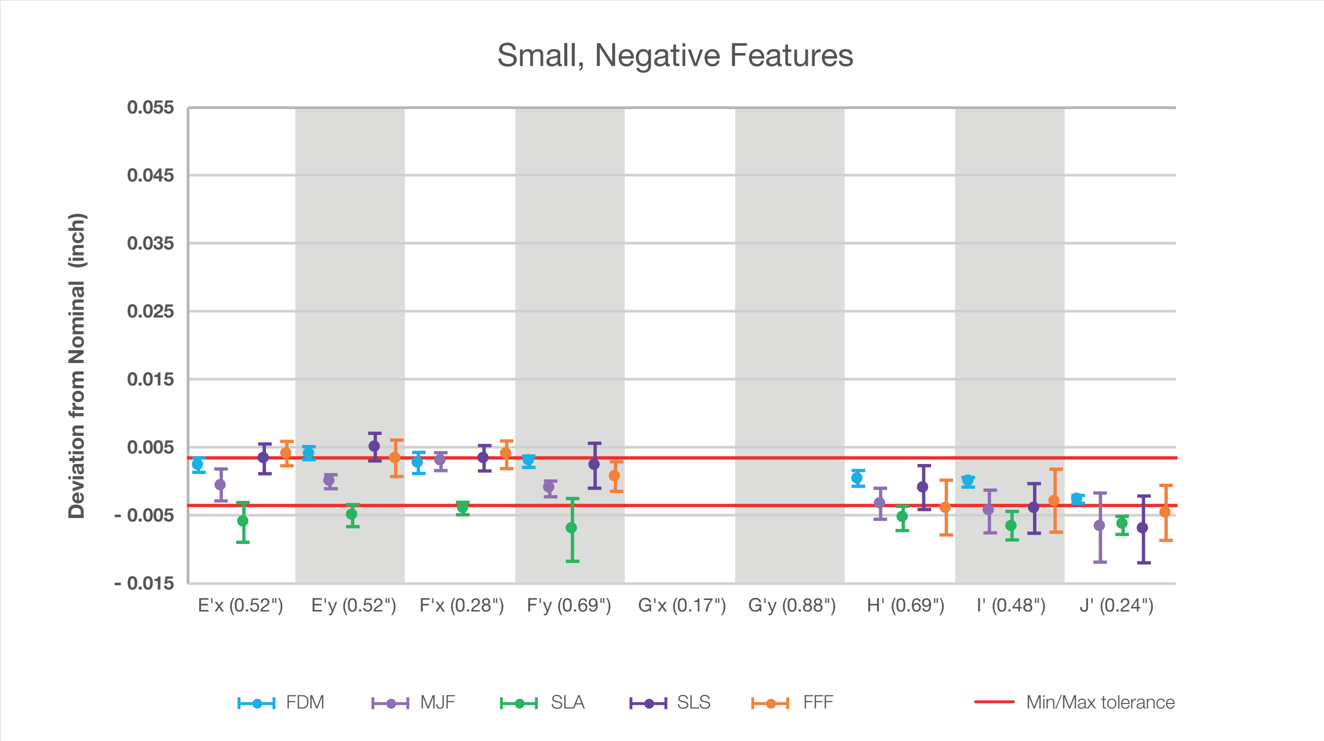

Figure 12: Dimensional accuracy and precision for small, negative features.

The results for small, positive features are shown in Figure 11 and Table 4. FFF had the best results with seven features being within tolerance. However, SLA, SLS and FDM accuracy was fair to good with all measurements being within or very near the specified tolerance band. MJF proved to be very inaccurate (0.0017 in. to 0.0256 in.) and very imprecise (0.0023 in. to 0.0252 in.). For precision, SLA, FFF and FDM were comparable with SDs ranging from 0.0008 in. to 0.0027 in.

Except for FDM, small, negative feature results (Figure 12 and Table 5) were not consistent with those for small, positive features. FDM continued to show both accuracy (-0.0026 in. to 0.0042 in.) and precision (0.0006 in. to 0.0016 in.). SLA, SLS and FFF, on the other hand, have poorer accuracy and precision. Meanwhile, MJF has generally better results for both accuracy and precision.

	FDM		SLS		SLA		MJF		FFF	
	Mean (in.)	SD (in.)	Mean (in.)	SD (in.)	Mean (in.)	SD (in.)	Mean (in.)	SD (in.)	Mean (in.)	SD (in.)
E'x (0.52")	0.0024	0.0011	0.0034	0.0022	-0.0060	0.0029	-0.0005	0.0023	0.0041	0.0018
E'y (0.52")	0.0042	0.0010	0.0051	0.0020	-0.0050	0.0016	0.0000	0.0010	0.0034	0.0027
F'x (0.28")	0.0028	0.0016	0.0034	0.0019	-0.0039	0.0009	0.0029	0.0013	0.0040	0.0020
F'y (0.69")	0.0029	0.0008	0.0023	0.0033	-0.0071	0.0046	-0.0011	0.0012	0.0008	0.0022
G'x (0.17")										
G'y (0.88")										
H' (0.69")	0.0005	0.0012	-0.0009	0.0032	-0.0054	0.0018	-0.0032	0.0023	-0.0038	0.0040
I' (0.48")	-0.0001	0.0007	-0.0039	0.0036	-0.0065	0.0021	-0.0044	0.0031	-0.0028	0.0046
J' (0.24")	-0.0026	0.0006	-0.0070	0.0049	-0.0064	0.0013	-0.0068	0.0051	-0.0046	0.0040

Table 5: Small, negative features - dimensional accuracy (mean deviation from nominal) and precision (standard deviation) values.

Machine to Machine

To determine the influence of inconsistencies between machines on accuracy and precision, Figures 13, 14 and 15 present the dimensional measurement results for Machine 1 and Machine 2. These charts use the same format as those that preceded them, but the results for each machine are presented side by side. Low variability is shown when the mean deviation from nominal dimensions and standard deviations (SD) are similar for both machines.

For large, small-positive and small-negative features, FDM proved to be the most consistent across two machines for both accuracy and precision.

For precision, the standard deviation difference did not exceed 0.0007 in. MJF, on the other hand, proved to have significant differences in both accuracy and precision. For accuracy, the average difference between machines is 0.0128 in. while the average SD difference is 0.0021 in. Additionally, for some features, such A, B, E and F, MJF lacked precision on individual machines.

In comparing machine-to-machine results for SLA, SLS and FFF, Figures 13, 14 and 15 do not show a consistent pattern across all features for either accuracy or precision.

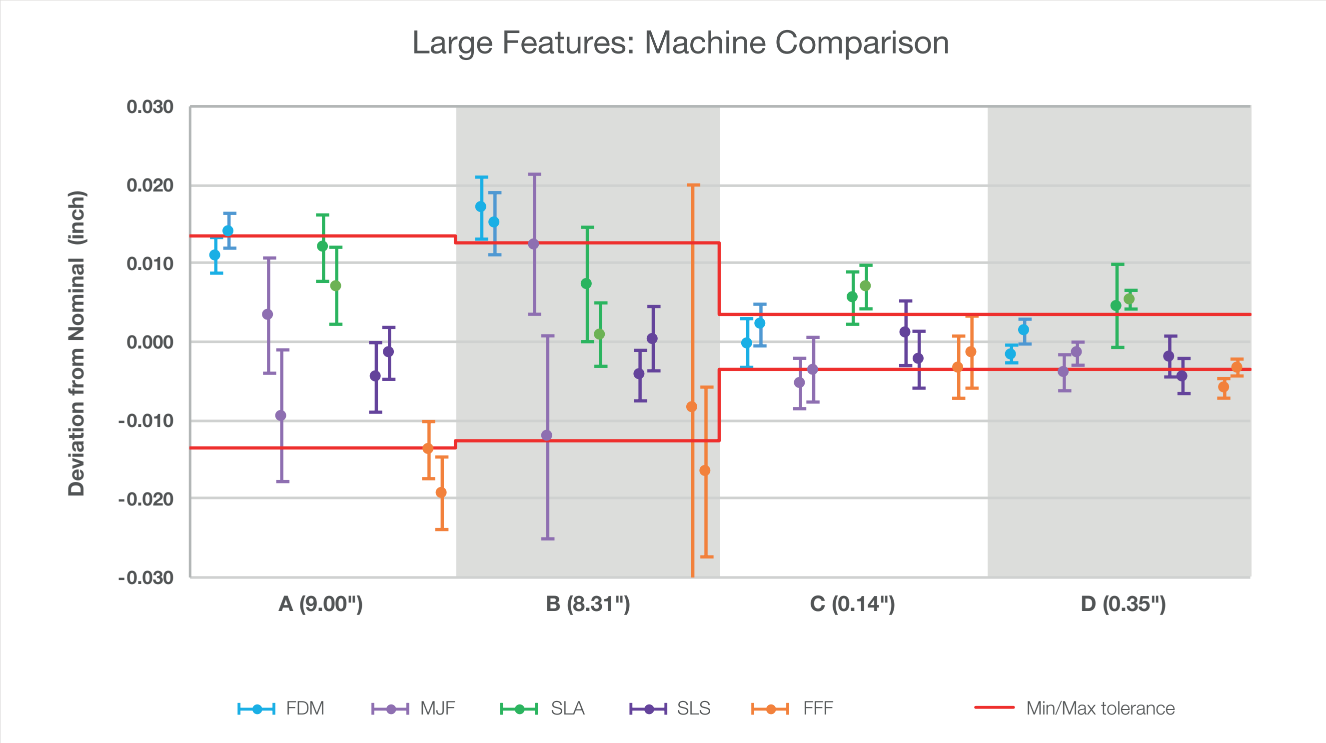

Figure 13: Dimensional accuracy and precision – machine to machine comparison for large features.

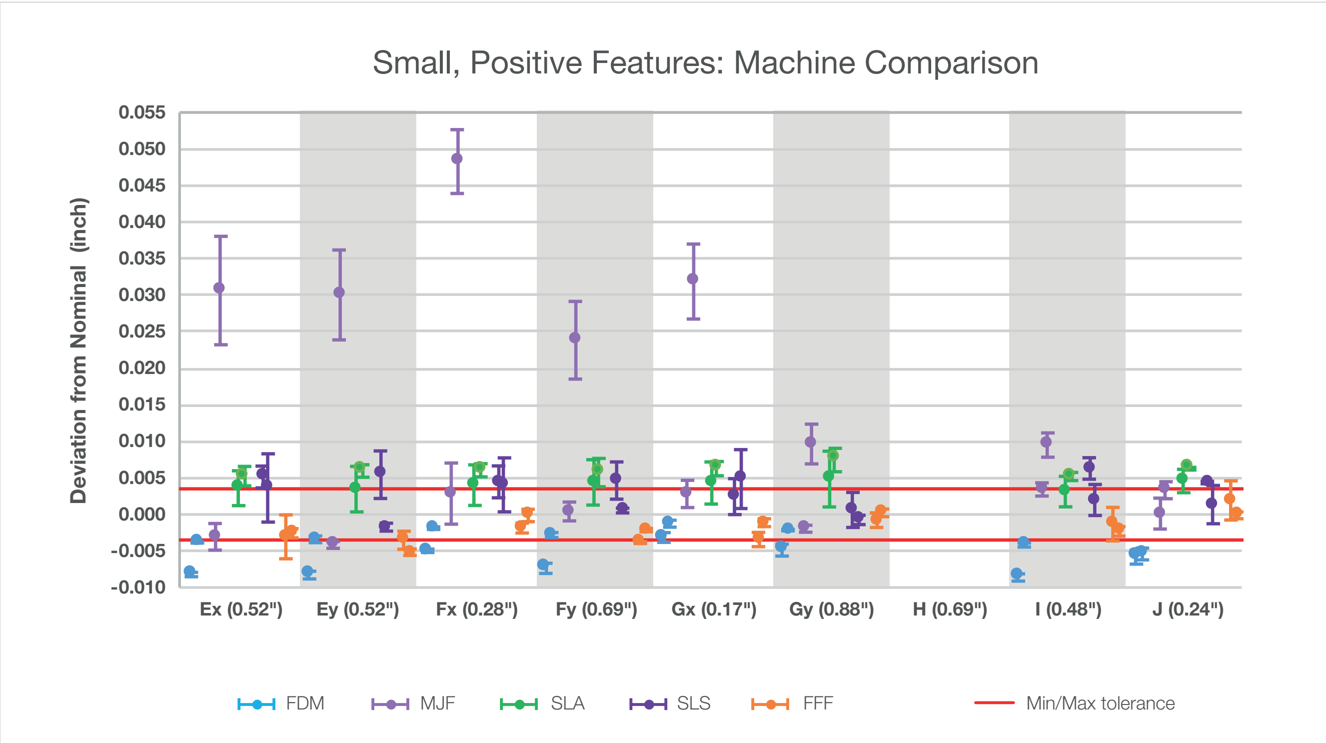

Figure 14: Dimensional accuracy and precision – machine to machine comparison for small, positive features.

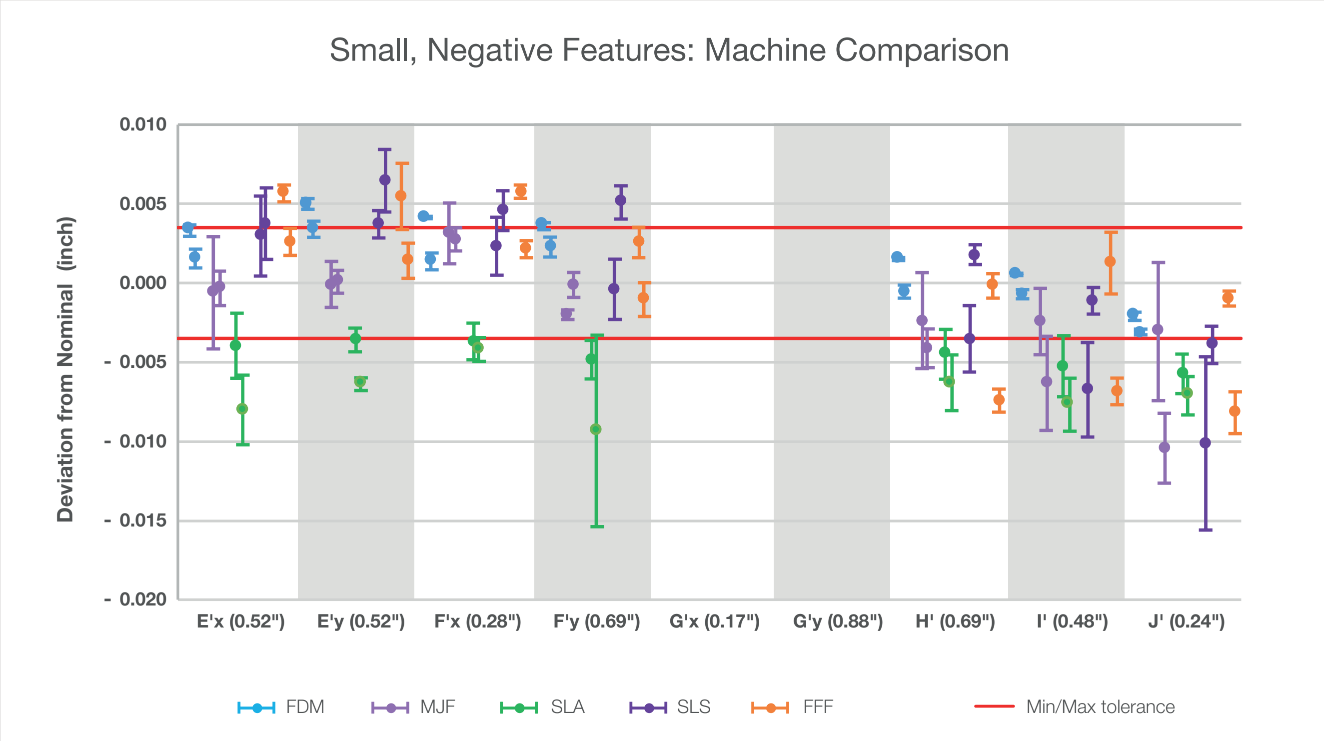

Figure 15: Dimensional accuracy and precision – machine to machine comparison for small, negative features.

Conclusion

Considering all mechanical properties, FDM and SLA had the lowest variabilities with tensile strength and tensile modulus COVs below 3.55% and EAB variances below 14.12%. MJF performed well in all areas except EAB in the XY orientation. SLS, CLIP and FFF faired poorer with significantly higher variations and a lack of consistency in the COV values for the three properties between build orientations.

When evaluated for property variability between machines, FDM and MJF were the most consistent. However, SLA and CLIP each showed good machine-to-machine consistency for two of the three properties. In contrast, SLS and FFF both showed high variability between the mechanical properties delivered from each machine.

The analysis of dimensional accuracy and variance showed FDM to have the best results across large, small-negative and small-positive features. SLA proved to have low variances but was less accurate. The opposite was true for SLS, which was accurate but imprecise. FFF results were mixed with accuracy and precision varying by feature type. In the dimensional component of this study, MJF was found to be both inaccurate and imprecise.

In the comparison of machine-to-machine results, FDM also was found to be the most consistent with respect to both accuracy and precision. Meanwhile, MJF had the highest discrepancies between machines. SLA, SLS and FFF had a mix of good and poor variance in the machine comparison.

This study found that for mechanical properties, considering both overall results and machine-to-machine variances, FDM and MJF had the best precision. For dimensional accuracy and variance, both overall and machine-to-machine, FDM had the best results. Therefore, this study shows that for variance in mechanical properties and geometric dimensions, FDM is the front-runner for manufacturing readiness.

Appendix: Test Methods

Tensile test coupon and check part construction for the six AM processes are described below.

FDM

The test used the Stratasys Fortus 900mc Aircraft Interiors Configuration with Certified ULTEM 9085™ material. Build parameters were set to the Aircraft Interiors Certification settings. Following the builds, supports were manually removed.

Note that material property testing used three discrete batches of Certified ULTEM 9085 to include variances in materials in the overall variability analysis. This was a requirement of the National Institute of Aviation Research (NIAR), under which FDM was tested for the purpose of determining variation and providing a materials dataset. Also note that per NIAR testing standards, 24 tensile test coupons were constructed for XY and ZX orientations.

MJF

An HP 4200 printer, using the mechanical grade settings for build parameters, produced the test parts in HP's High Reusability PA 12 material (partially recycled). After removal from the machine, all test parts were media blasted to remove excess powder.

Note that five coupons were excluded from the mechanical properties testing because of "jaw breaks" in the tensile testing machine.

SLA

All test parts were produced in a 3D Systems SLA 7000 using Somos Watershed XC material using the standard build style suggested by DSM (the material manufacturer). Following the builds, test parts were cleaned of excess resin and post-cured for 30 minutes.

Note that the SLA 7000 is a legacy printer. However, it was selected for its ability to run Watershed XC, a widely used material. Additionally, the source of the parts confirmed that any differences between the SLA 7000 and the contemporary ProJet 7000 would have minor, if any, effect on the test results.

Due to procedural errors, mechanical properties testing used 18 test coupons for the XY orientation and 21 for the ZX orientation rather than the 30 each prescribed in the test plan. However, upon review, the COV results were consistent across the tested coupons, thus making the procedural error negligible.

SLS

The test used 3D Systems' Sinterstation 2500 Plus HS machine with EOS PA2201 material (partially recycled). The build parameters used were those for the 42-Watt setting. Test parts received a media blast, after the build, to remove excess powder.

Note that three coupons were excluded from the mechanical properties testing because of "jaw breaks" in the tensile testing machine. Also note that the Sinterstation 2500 Plus HS is a legacy machine, but the source of the parts confirmed any difference from contemporary machines would have minor, if any, effect on the test results.

FFF

Markforged's Onyx thermoplastic material was used for all test parts, which were constructed in a Markforged Mark X printer (which has since been rebranded as X7). The build parameters include a 100-micron slice and triangular infill with default settings. Following the builds, support structures were manually removed.

Note that of the planned 30 test coupons for the vertical (ZX) orientation only fifteen were made. The vertical build orientation for a tall, thin part is unsupported, and after review of the fifteen samples, the production of the balance was cancelled.

Also note that the check parts had significant warpage (curl) that prevented measurement. To resolve this, the check parts were heated to 100 °C and then fixtured to remove the warpage. Following this procedure, the flatness of the check parts was within 0.050 in.

CLIP

Carbon's M1 printer, with its RPU 70 material, was used to create the test parts. After building, all parts were cleaned in an agitated alcohol bath for three to five minutes and allowed to dry for one hour. The parts were then thermally post-cured for four hours at 120 °C.

Note that due to the size of the build area, tensile coupons in the horizontal orientation (XY) and the check part were not compatible with the M1.

Test Methods: Mechanical Properties

Mechanical properties, including tensile strength, tensile modulus and elongation at break (EAB) were tested by a third-party laboratory according to ASTM D638 testing standards. The coupons (tensile bars) were ASTM D638 Type I with a thickness of 0.130 in.

FDM testing was performed in an America Makes program and conducted by RP+M (Avon Lake, Ohio). The testing methodology and procedures followed the National Institute of Aviation Research's (NIAR) National Center for Advanced Materials and Process (NCAMP) procedures. All testing for the other AM processes was performed by Element Materials Technology (Duarte, Calif.).

For each AM process (see Figure 16), 60 coupons were requested. Thirty of these were constructed in a horizontal orientation (flat), which is referred to as 'XY'. The balance was constructed in a vertical orientation (upright) and are labeled 'ZX'. To evaluate variation between machines, half (15) of the XY and ZX coupons were built on one machine, and the balance were built on a second machine. Each build contained five coupons, which yielded 12 builds across two machines. The layout for each build was one coupon in the center and one each in the four corners. This layout plan was designed to capture any variation within the AM machines' build areas.

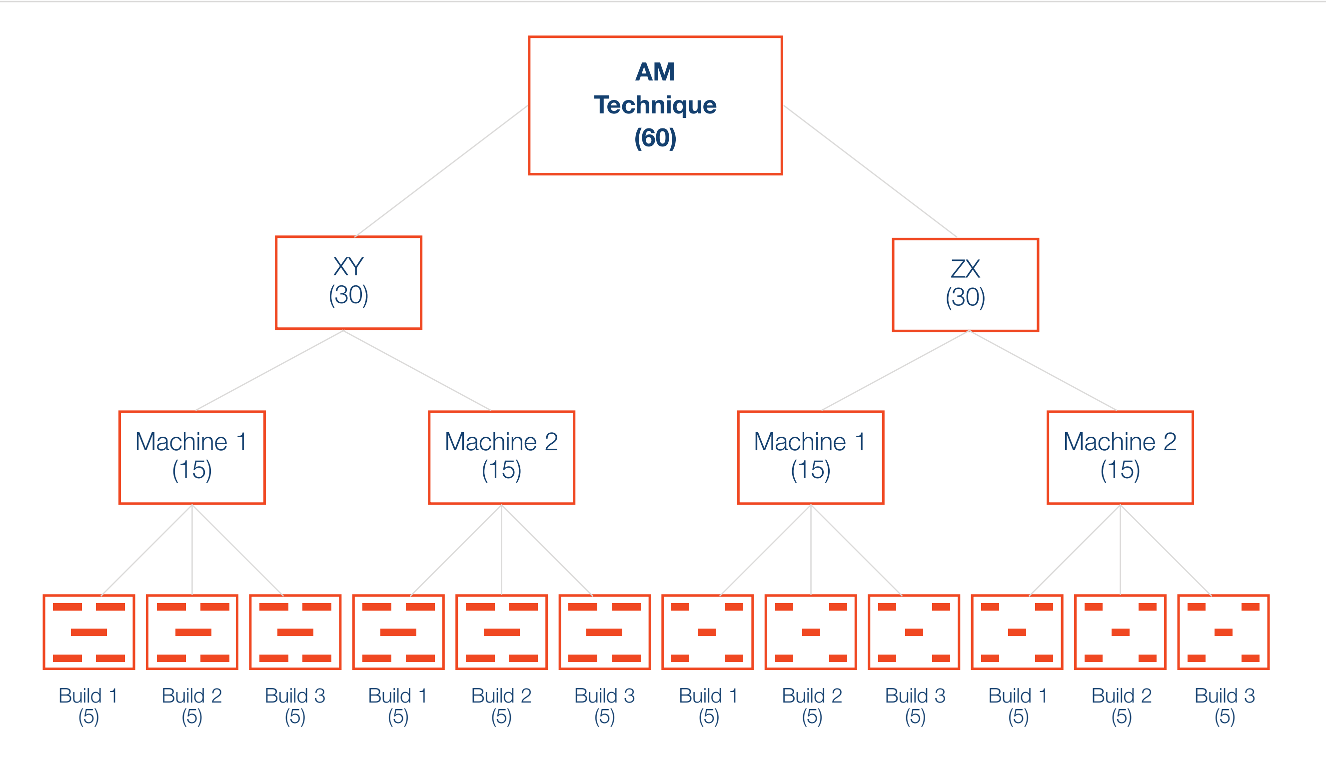

Figure 16: Tensile test coupon build plan.

Variability was evaluated through the coefficient of variation (COV). It is a measure of the relative variability that accommodates comparison when the mechanical properties of the AM materials vary significantly. The COV calculation (below) is the ratio of the standard deviation to the mean (average).

$$\text{Coefficient of Variation} = \frac{\text{Standard Deviation}}{\text{Mean}} \times 100$$

Test Methods: Dimensional Measurements

The dimensional inspection was performed with a Mitutoyo QV 606 CMM using a touch probe, which is calibrated annually, and a pre-programmed inspection routine. The inspection routine included 43 separate measurements on 19 features.

For each AM process, six check parts were produced in six builds (Figure 17). The builds were split, three each, over two machines. In each build, the check part was located at the center of the build platform and oriented in the XY plane.

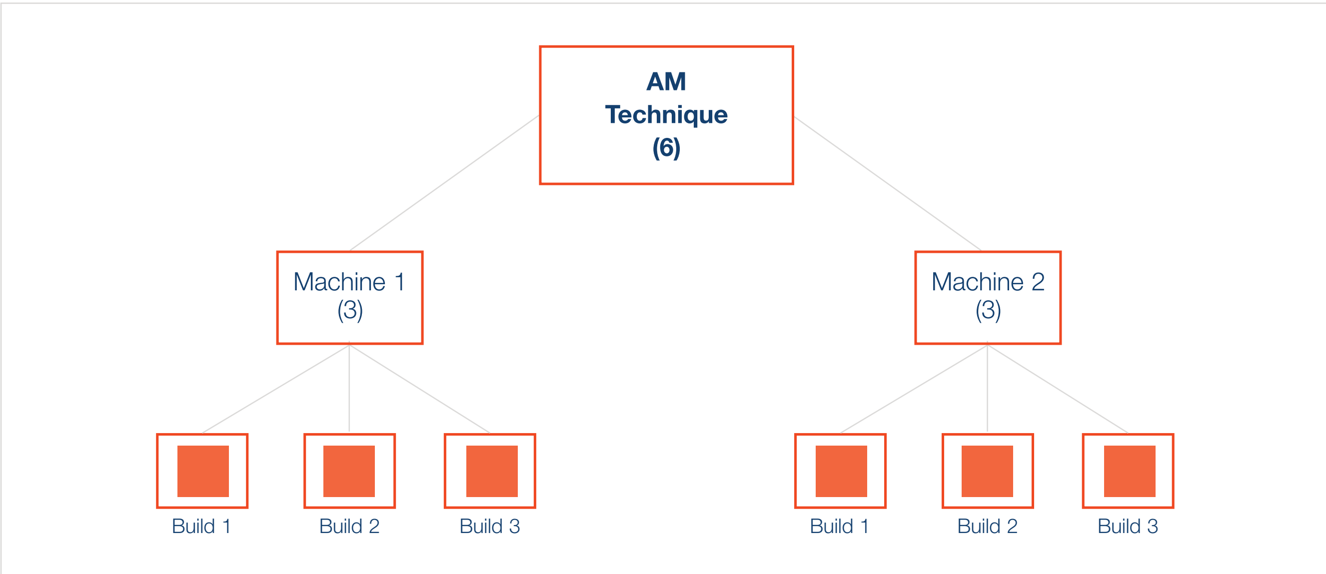

Figure 17: Dimensional check part test plan.

The intent of the study was to evaluate dimensional accuracy and precision across the extents of the processes' build areas. Therefore, testing used a check part measuring 9 in. x 9 in. (Figure 18). Due to the significantly smaller build area of the CLIP M1 machine, versus others in this study, this study design element prevented dimensional inspection for CLIP.

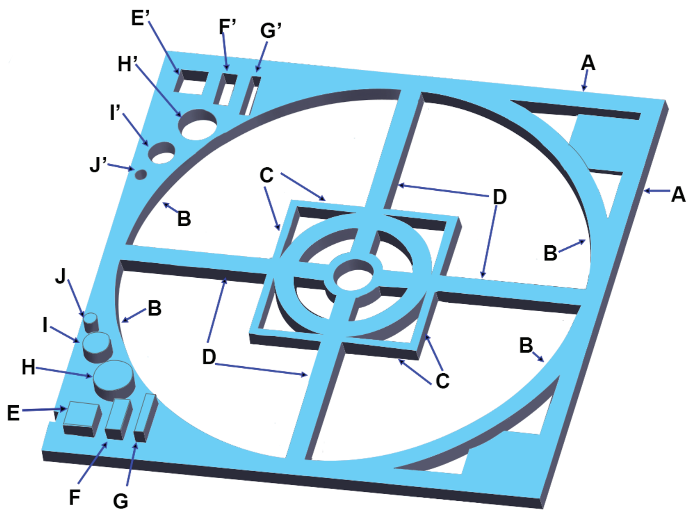

Figure 18 : Check part features used for dimensional accuracy and precision.

Large features		Small, positive features		Small, negative features	
Nominal (in.)		Nominal (in.)		Nominal (in.)	
A	9.00	Ex (0.52")	0.52	E'x (0.52")	0.52
B	8.31	Ey (0.52")	0.52	E'y (0.52")	0.52
C	0.14	Fx (0.28")	0.28	F'x (0.28")	0.28
D	0.35	Fy (0.69")	0.69	F'y (0.69")	0.69
		Gx (0.17")	0.17	G'x (0.17")	0.17
		Gy (0.88")	0.88	G'y (0.88")	0.88
		H (0.69")	0.69	H' (0.69")	0.69
		I (0.48")	0.48	I' (0.48")	0.48
		J (0.24")	0.24	J' (0.24")	0.24

Table 6: Check part features' nominal dimensions.

The check part has three categories of features' for inspection: large; small, positive; and small, negative. The large features, labeled A, B, C, and D in Figure 18, were measured in multiple locations along both the X and Y axes. Note that for features C and D, the dimensional analysis considers the wall thickness, not the overall size. Figures 19 and 20 show the location of each of these measurements.

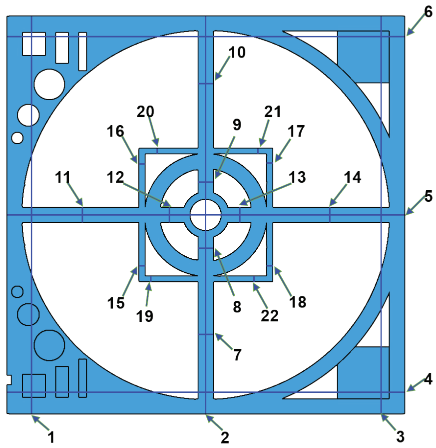

Figure 19: Measurement locations for features A, C and D.

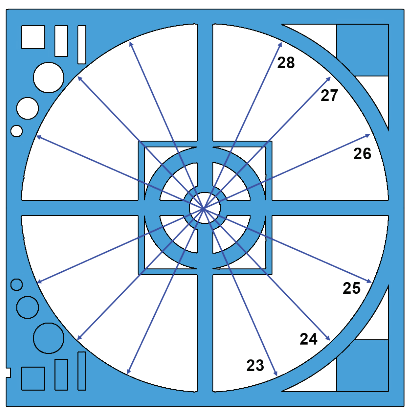

Figure 20: Measurement locations for feature B.

The small features are mirrored along the centerline (X axis) of the check part, and they are reversed to have identical features that are both positive (cylindrical bosses and rectangular standoffs) and negative (holes, slots and cutouts). The small, positive features are located on the lower left of the check part. These are labeled in Figure 18 as E, F, G, H, I and J. To indicate the axes of measurement, each label has an 'x' or 'y' appended to the labels for rectangular features.

The small, negative features are located on the upper left. These features use the same labeling convention as that for the positive features with the addition of a prime symbol (').

The locations of the measurements for small features are shown in Figures 21.

Note that due to impediments to the CMM inspection routine, three measurements were omitted, H, G'x and G'y. Feature H, a cylindrical boss, was eliminated after discovery of a CMM programming error that caused the touch probe to contact feature F. Feature G' was too narrow for the CMM touch probe to enter.

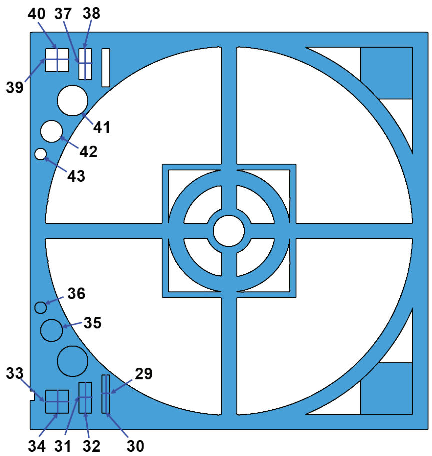

Figure 21: Measurement locations for small positive and negative features.