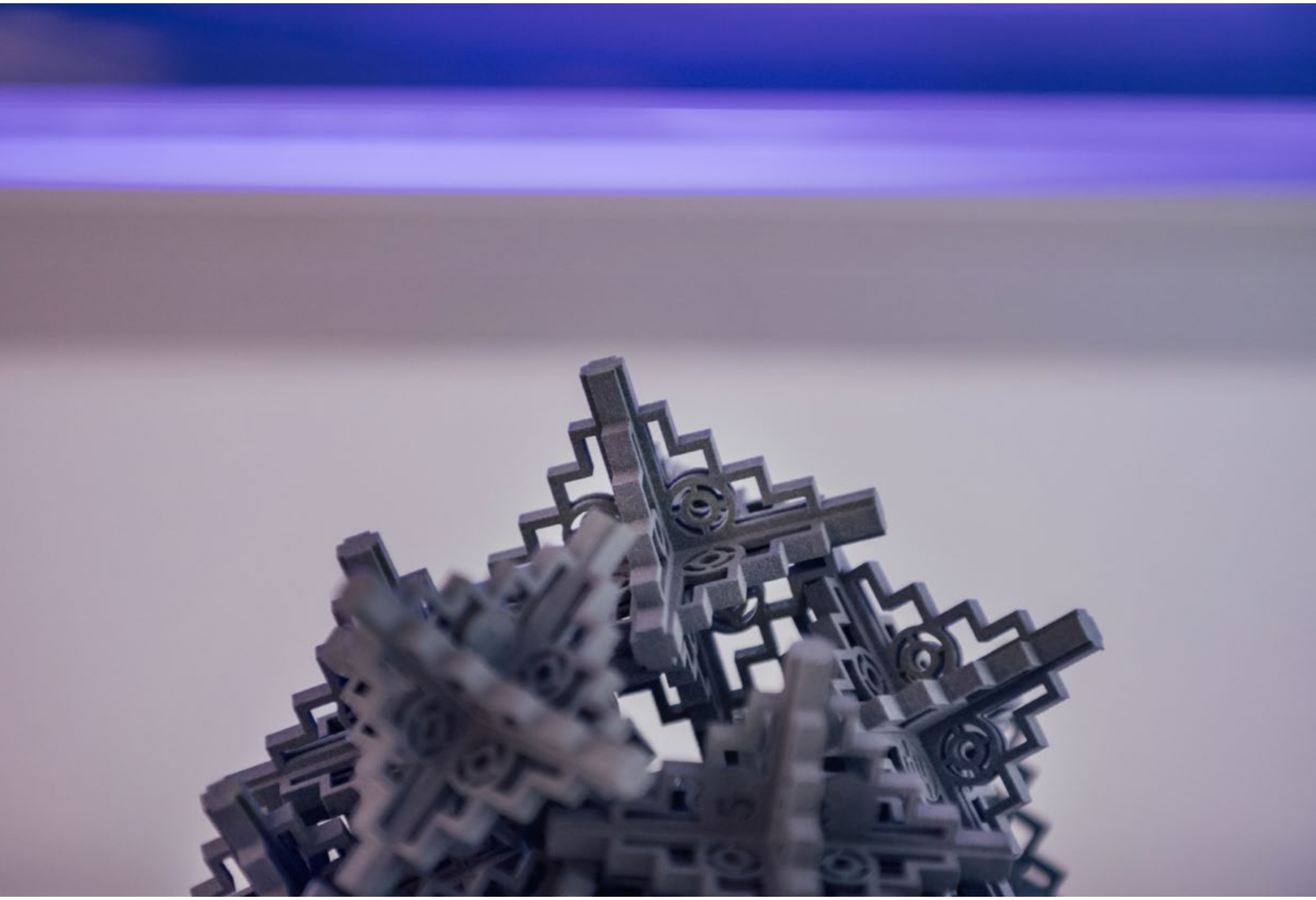
White paper

ESTANE® 3D TPU M95A for the HP Jet Fusion 4200 3D Printing Solution

Dimensional Capability



Introduction

At HP, we are committed to providing part designers and part manufacturers with the technical information and resources needed to enable them to unlock the full potential of 3D printing and prepare them for the future era of digital manufacturing.

The aim of this white paper is to provide you with information on the dimensional capabilities that can be achieved with the HP Jet Fusion 4200 3D Printing Solution with ESTANE® 3D TPU M95A.[1]

In this white paper, you will find:

- Tolerances in XY and Z for nominal dimensions ranging from 0 mm to 80 mm that can be achieved with the HP Jet Fusion 4200 3D Printing Solution, according to a process capability index,
- A detailed explanation of the test conditions under which these values were obtained, and
- Additional information on the concept of process capability and dimensional tolerancing, and a glossary of key terms used.

HP Jet Fusion 4200 3D Printing Solution dimensional capability performance

Test job

The dimensional capability performance of ESTANE® 3D TPU M95A with the HP Jet Fusion 4200 3D Printing Solution was characterized using a test job, half bucket part property test build (Figure 1), to evaluate part properties and material performance. Parts were selected for mechanical, dimensional, and look-and-feel qualitative evaluation.

The printable volume was packed at 6.89% and had a total of 134 parts with a minimum part spacing of 6 mm.

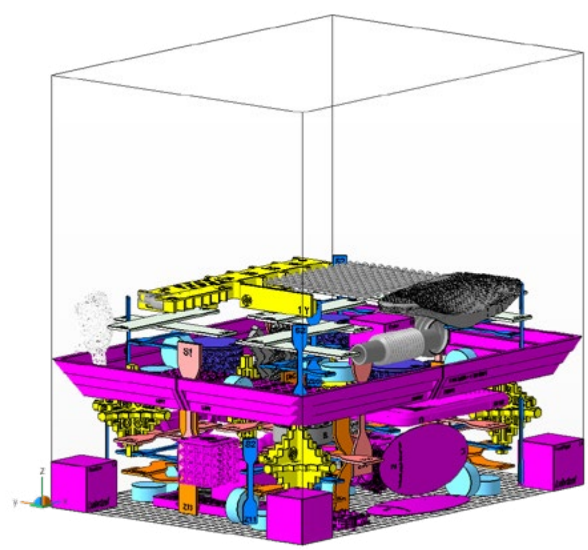


Figure 1. Half bucket part property test build. Parts are color coded by mechanical (orange/blue), dimensional (orange), and look and feel (purple/grey).

1. Available for the HP Jet Fusion 4200 3D Printing Solution.

Test job description	Half bucket part property test build
Total parts	134
Time to print	12 hours
Time to cool (Auto Cool & Reclaim)	22 hours
Packing density	6.89%

Table 1. Description of the half bucket part property test build

Several dimensional parts were included to examine the dimensional integrity across print volume positions and dimensional ranges (Figure 2). Dimensions were evaluated and optimized primarily using the snow star part.

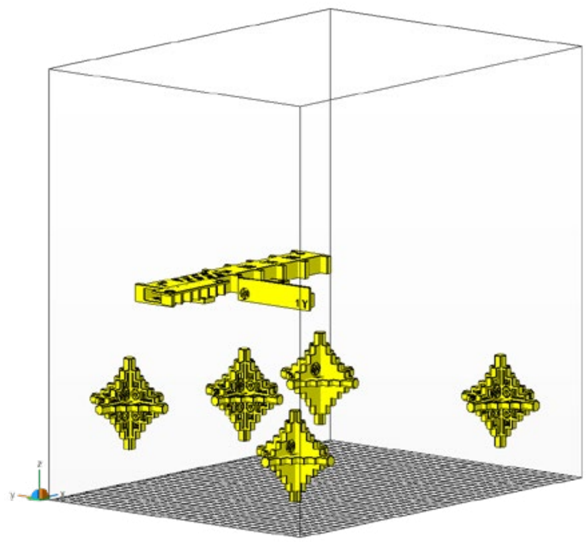


Figure 2. Dimensional test parts in half bucket part property test build. Mechanical and look and feel parts are hidden to highlight location of dimensional parts.

The snow star part has measurable dimensions ranging from 8-80 mm in X, Y, and Z (Figure 3). This is the primary dimensional range for tuning performance. The snow star is symmetrical in each axis, in order to equally evaluate X, Y, and Z dimensional accuracy. In general, dimensions do not vary substantially between generations. Each of these parts has different critical dimensions that are measured in each print. For example, some of the critical dimensions collected for a specific part included in one of the jobs are shown in Figure 3.

	Name	Nominal/mm
1	Height-1	8
2	Height-2	18
3	Height-3	30
4	Height-4	45
5	Height-5	60
6	Height-6	80

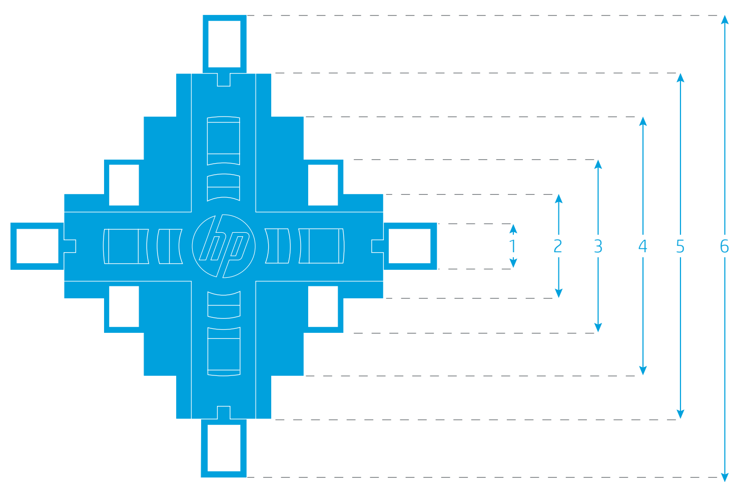


Figure 3. Dimensional fiducial nominal dimensions of the snow star part

Performance results for ESTANE® 3D TPU M95A

Tests were based on a single print volume configuration; therefore, the results may vary as part design and print volume configuration change. All testing was performed with a new-to-recycled powder mix ratio of 20:80.

Table 2 shows the dimensional tolerances that were obtained during the characterization for a target process capability of C_{pk} = 1.33 (4 sigma).

Tolerances for C_{pk} = 1.33[i ii iii] (in mm)	Nominal dimension					
	0 – 30 mm		30 – 50 mm		50 – 80 mm	
	XY	Z	XY	Z	XY	Z
With the default setting for the HP Jet Fusion 4200 3D Printing Solution	±0.54	±0.68	±0.51	±0.95	± 0.56	± 1.19

i. Based on internal testing and measured using the Half Bucket Part Property Test Build job. Results may vary with other jobs and geometries.

ii. Using ESTANE® 3D TPU M95A material, 20% refresh ratio, Balanced print profile, natural cooling, and measured after bead-blasting with 40–60 mesh (250-425 µm) glass beads at 5-6 bars.

iii. Following all HP-recommended printer setup and adjustment processes and printheads aligned using semi-automatic procedure.

Table 2. Dimensional capabilities for ESTANE® 3D TPU M95A. Target process capability of C_{pk} = 1.33.

Where the process capability target is set to C_{pk} = 1.00 (3 sigma), the dimensional tolerances are specified in Table 3.

Tolerances for C_{pk} = 1.33[i ii iii] (in mm)	Nominal dimension					
	0 – 30 mm		30 – 50 mm		50 – 80 mm	
	XY	Z	XY	Z	XY	Z
With the default setting for the HP Jet Fusion 4200 3D Printing Solution	±0.45	±0.57	±0.43	±0.78	± 0.49	± 0.96

i. Based on internal testing and measured using the Half Bucket Part Property Test Build job. Results may vary with other jobs and geometries.

ii. Using ESTANE® 3D TPU M95A material, 20% refresh ratio, Balanced print profile, natural cooling, and measured after bead-blasting with 40–60 mesh (250-425 µm) glass beads at 5-6 bars.

iii. Following all HP-recommended printer setup and adjustment processes and printheads aligned using semi-automatic procedure.

Table 3. Dimensional capabilities for ESTANE® 3D TPU M95A. Target process capability of C_{pk} = 1.00.

Appendix 1: Understanding process capabilities

Process capability determines whether a process meets a specification. The process capability index or process capability ratio or C_{pk} is a statistical measure of process capability. It quantifies the ability of a process to produce output within specification limits.

When talking about a dimensional specification, the C_{pk} measures the statistical probability that a certain process produces a dimension within its tolerance range. The higher the C_{pk} value the better, meaning that more measurements will be within its tolerance range.

For a process to be capable, it needs to be both **repeatable and accurate**.

Repeatability is how close multiple measurements are to each other (also called precision).

Accuracy is how close a measurement value is to the specified nominal.

The capability of a process is then a function of two parameters:

- How **repeatable** it is compared to the width of the specification limits, measured by the $\mathbf{C_p}$
- How **accurate** it is, measured by the **bias**

$$Capability = C_{pk} = C_p * (1-2*bias)$$

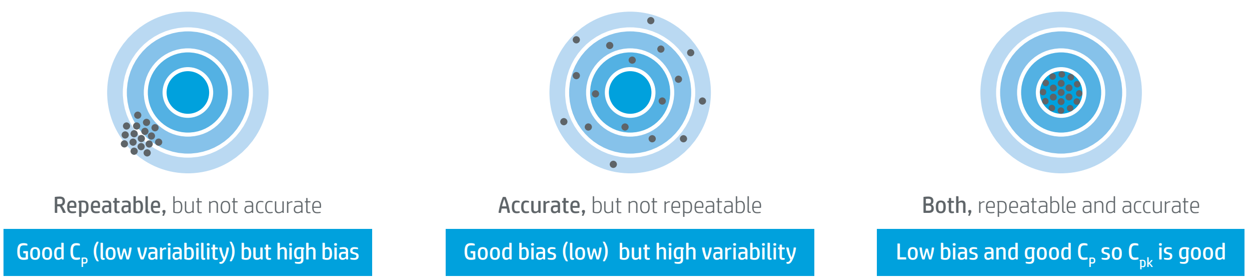


Figure 6. Relationship between bias and variability

This concept only holds meaning for processes that are in a state of statistical control with an output that is approximately normally distributed.

Both conditions happen when dealing with the dimensional quality control of HP MJF–produced parts where the output is the dimensional value of the different geometrical features of a part.

Dimensional quality control processes define an upper specification limit (USL) and lower specification limit (LSL), also called the "tolerance range" of the process. The target of the process is the center of this range, typically the nominal dimension value.

The objective to have a well-controlled dimensional process is to have its normal distributed population of measurements:

- With a variability (calculated as standard deviation) that "fits" in the tolerance range. $\mathbf{C_p}$ measures how well the variability fits within the tolerance range.
- With a mean (average) as close as possible to the target. The deviation is measured by the **bias**.

Only if both conditions are met, process capability measured by $\mathbf{C_{pk}}$ is considered good:

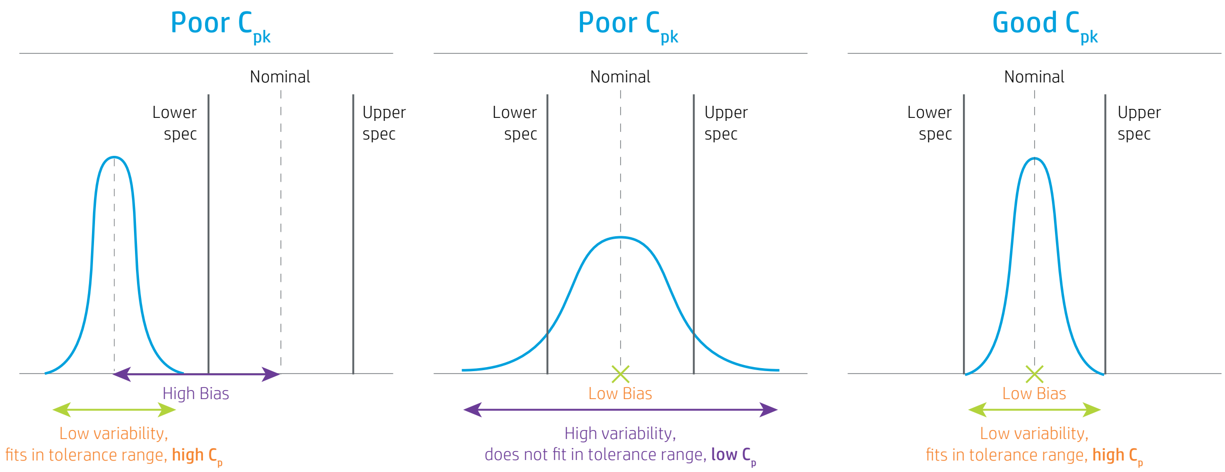


Figure 7. Process capability C_{pk} scenarios

The mathematical calculation of these parameters is as follows:

$$C_p = \frac{\text{Specification width}}{\text{Process width}} = \frac{(USL - LSL)}{6\sigma}$$

Standard deviation estimates the sigma and quantifies the variability and dispersion of the process.

C_p should always be greater than 1.00 for the variability to fit within the tolerance range.

$$C_{pk} = \min\left[\frac{[USL - \mu]}{3 \cdot \sigma}, \frac{[\mu - LSL]}{3 \cdot \sigma}\right]$$

The statistical mean estimates the mu (μ).

Therefore:

- C_{pk} "measures" the distance of the mean to the closer specification limit, which could be the upper or the lower limit.
- C_{pk} takes into account how centered the process is ($C_{pk} \leq C_p$).
- For a perfectly centered process, $C_p = C_{pk}$.
- If $C_p > C_{pk}$, it is possible to increase the C_{pk} by readjusting the mean of the process.

The following table displays the relevant C_{pk} values and their correlation with process yields:

	C_{pk}	Sigma level	Dimensions within specs (%)	Dimensions out of specs (units per million)	Part yield for a part with 10 dimensions (%)	
100% inspection	0.33	1	68.27	317,300	2.20	
	0.67	2	95.45	45,500	62.77	
Statistical process control	1.00	3	99.73	2,700	97.33	
	1.33	4	99.9937	63	99.94	Desired
	1.50	5	99.99966	3.4	100	
	1.67	6	99.99997	0.6	100	

Table 4. C_{pk} and process yield correlation

For a part to be considered good, all the specified dimensions need to be within tolerances. Therefore, the part yield is a metric that can be calculated as the statistical sum of the single dimension success rate. In the previous table, an example for a part with 10 dimensions is shown in the right column.

For **C_{pk} values below 1.00,** the yield is such that the best quality control method is **100% inspection**, and the general fabrication process is to over-produce and send only the parts that meet the tolerance requirements. This is costly but it is a reasonable process, especially for low-volume production.

For **C_{pk} values above 1.00** (3 sigma), the dimensional success rate and the yield begin to approach each other, and **statistical process control** starts to become a viable option. This means that after the process has demonstrated that it is statistically and consistently achieving C_{pk} above 1.00 for all dimensions, one could move to auditing random parts per each lot of parts.

Generally, a **C_{pk} of 1.33 (4 sigma) is desired** to ensure enough of a margin for statistical process control, especially when dealing with multi-part complex mechanisms.

Appendix 2: Dimensional requirements & IT grades

The International Tolerance grades (IT grades) defined in ISO 286/ANSI B4.2-1978 provide standardized tolerance ranges. The smaller the IT grade, the smaller the tolerance range, meaning better dimensional performance (less variability).

Each IT grade has a tolerance range that varies depending on the nominal value of the dimension. The larger the specified dimension, the larger the tolerance range for accuracy.

Dimension (mm)		IT1	IT2	IT3	IT4	IT5	IT6	IT7	IT8	IT9	IT10	IT11	IT12	IT13	IT14	IT15
Above	Up to and including						µm		Tolerance ranges							mm
-	3	0.8	1.2	2	3	4	6	14	10	25	40	60	0.10	0.14	0.25	0.4
3	6	1	1.5	2.5	4	5	8	18	12	30	48	75	0.12	0.18	0.30	0.48
6	10	1	1.5	2.5	4	6	9	22	15	36	58	90	0.15	0.22	0.36	0.58
10	18	1.2	2	3	5	8	11	27	18	43	70	110	0.18	0.27	0.43	0.70
18	30	1.5	2.5	4	6	9	13	33	21	52	84	130	0.21	0.33	0.52	0.84
30	50	1.5	2.5	4	7	11	16	39	25	62	100	160	0.25	0.39	0.62	1.00
50	80	2	3	4	8	13	19	46	30	74	120	190	0.30	0.46	0.74	1.20
80	120	2.5	4	6	10	15	22	54	35	87	140	220	0.35	0.54	0.87	1.40
120	180	3.5	5	8	12	18	25	63	40	100	160	250	0.40	0.63	1.00	1.60
180	250	4.5	7	10	14	22	29	72	46	115	185	290	0.46	0.72	1.15	1.85
250	315	6	8	12	16	23	32	81	52	130	210	320	0.52	0.81	1.30	2.10
315	400	7	9	13	18	25	36	89	57	140	230	360	0.57	0.89	1.40	2.30
400	500	8	10	15	20	27	40	97	63	155	250	400	0.63	0.97	1.55	2.50
500	630	9	11	16	22	32	44	100	70	175	280	440	0.70	1.10	1.75	2.80

Table 5. Standard international tolerance grades

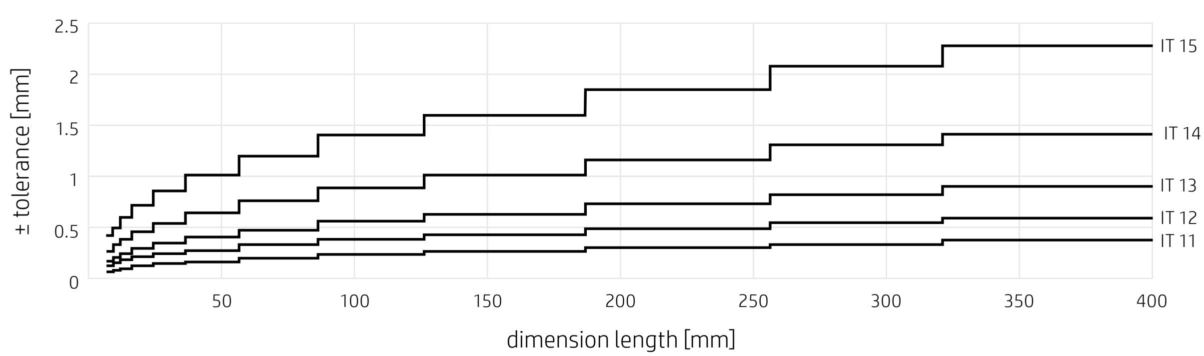


Figure 8. Tolerance range vs. dimension length

IT grades provide a standardized reference to compare typical manufacturing process capability in terms of dimensional tolerance for a given dimension, as show in the following table:

	Measuring tools									Material								
IT Grade	01	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
							Fits							Large manufacturing tolerances				

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Table 6. IT Grades for measuring tools & materials

Appendix 3: Key terms

- **Process capability:** Statistical measurement of a process's ability to produce parts within specified limits on a consistent basis.
- **International Tolerance Grade (IT Grade)**: Grade used to identify the tolerances a given industrial process can produce for a given dimension.
- **Repeatability**: Ability of a process to consistently produce the same output; in this case, the same part dimensions.
- **Bias**: Difference between the average of the population for a given dimension and the target value of that dimension.
- **C_p**: Process capability index that measures of the ability of a process to produce consistent results—the ratio between the permissible spread and the actual spread of a process. This does not take into account how well the output is centered on the target (nominal) value.
- **C_{pk}**: Process capability index that estimates what the process is capable of producing, considering that the process mean may not be centered between the specification limits. $C_{pk} < 0$ if the process mean falls outside of the specification limits.

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