



Dimensional tolerancing

Design for HP MJF: Union joints design

Introduction

HP Multi Jet Fusion technology allows for the designing and printing of parts that can be assembled between them or to other manufactured parts, such as metal parts, to create final products and functional assemblies. The parts can be joined by union joints such as self-tapping screws, threaded inserts, or snap-fits.

It is important to consider tolerances at an early stage of the product development process and to design every part involved in a final product or functional assembly taking into account the permissible range of variation in dimensions to ensure that it fits suitably and works according to the design intent.

Depending on how the parts must interact to create a final product or achieve the assembly’s functional needs, the required tolerances will be tighter or wider, which will require the most capable manufacturing process to produce the part with suitable accuracy.

International Tolerance (IT) Grades

Designing a part often involves the use of the International Tolerance Grades defined in ISO 286/ANSI B4.2-1978, which provide a standardized reference for typical manufacturing process capability in terms of tolerance accuracy for a given dimension.

The most common manufacturing processes have an associated IT Grade that specifies their capability to provide accurate parts, as shown in the image below:

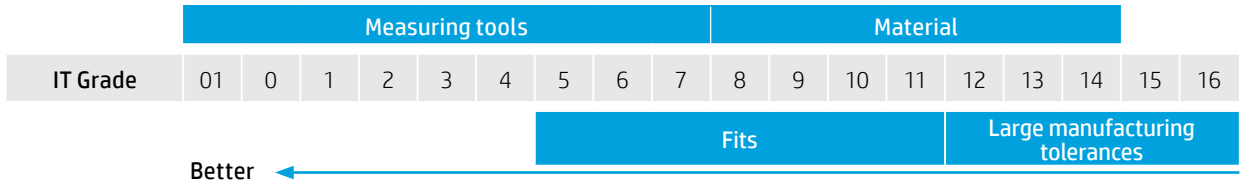


Figure 1: International Tolerance (IT) Grades

Each IT Grade establishes the allowable tolerance limits for a given dimension. As shown in the following table, a smaller IT Grade provides tighter tolerances:

Standard tolerance grades	Values of standard tolerance (mm)								Nominal size (mm)
	from: 1 to: 3	3 to: 6	6 to: 10	10 to: 18	18 to: 30	30 to: 50	50 to: 80	80 to: 120	
1	0.0015	0.0015	0.0015	0.0015	0.0015	0.002	0.002	0.003	Measuring tools
2	0.002	0.002	0.002	0.002	0.002	0.003	0.003	0.004	
3	0.003	0.003	0.003	0.003	0.004	0.004	0.005	0.006	
4	0.004	0.004	0.004	0.005	0.006	0.007	0.008	0.010	
5	0.005	0.005	0.006	0.008	0.009	0.011	0.013	0.015	Engineering fits, bearings, machining processes (grinding, turning)
6	0.007	0.008	0.009	0.011	0.013	0.016	0.019	0.022	
7	0.009	0.012	0.015	0.018	0.021	0.025	0.030	0.035	
8	0.014	0.018	0.022	0.027	0.033	0.039	0.046	0.054	
9	0.025	0.030	0.036	0.043	0.052	0.062	0.074	0.087	
10	0.040	0.048	0.058	0.070	0.084	0.100	0.120	0.140	
11	0.060	0.075	0.090	0.110	0.130	0.160	0.190	0.220	
12	0.090	0.120	0.150	0.180	0.210	0.250	0.300	0.350	Large manufacturing, die casting, stamping, sand casting
13	0.140	0.180	0.220	0.270	0.330	0.390	0.460	0.540	
14	0.250	0.300	0.360	0.430	0.520	0.620	0.740	0.870	
15	0.400	0.480	0.580	0.700	0.840	1.000	1.200	1.400	
16	0.600	0.750	0.900	1.100	1.300	1.600	1.900	2.200	
17	0.900	1.200	1.500	1.800	2.100	2.500	3.000	3.500	
18	1.400	1.800	2.200	2.700	3.300	3.900	4.600	5.400	

Table 1: Standard tolerance grades

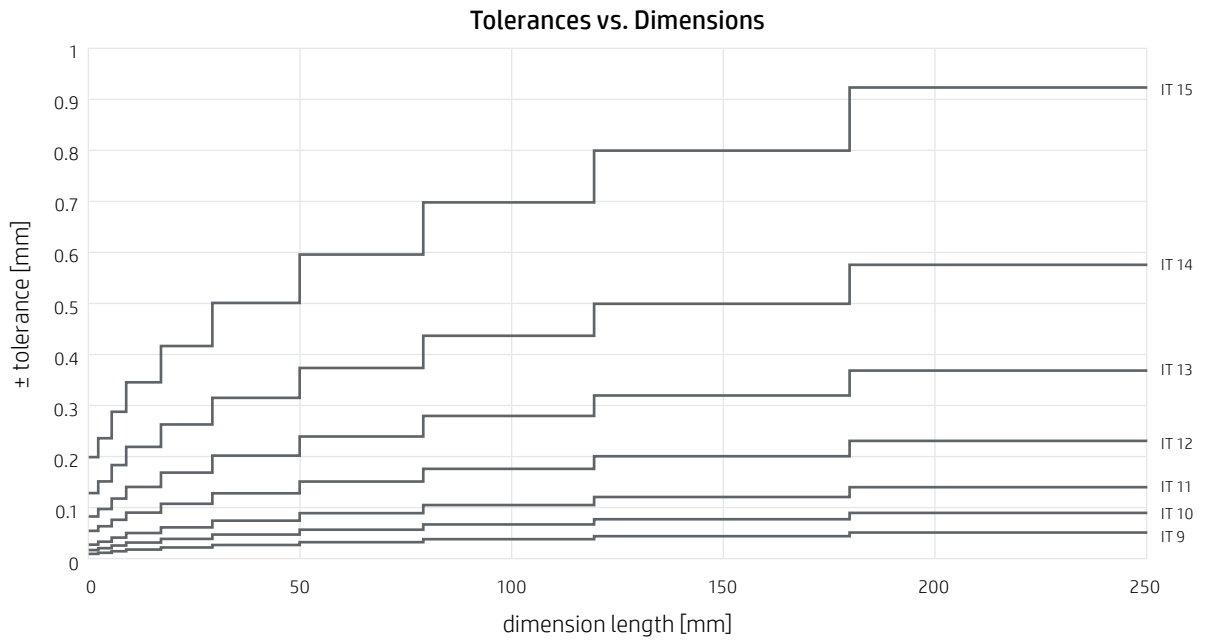


Figure 2: Graph of International Tolerance (IT) Grades

Process capability

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**.

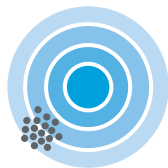
Repeatability is how close multiple measurements are to each other (also called precision).

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

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

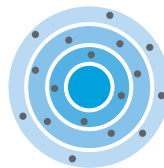
- How **repeatable** it is compared to the width of the specification limits, measured by the C_p
- How **accurate** it is, measured by the **bias**

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



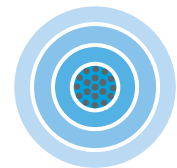
Repeatable, but not accurate

Good C_p (low variability) but high bias



Accurate, but not repeatable

Good bias (low) but high variability



Both, repeatable and accurate

Low bias and good C_p so C_{pk} is good

Figure 3: 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. 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 C_{pk} is considered good:

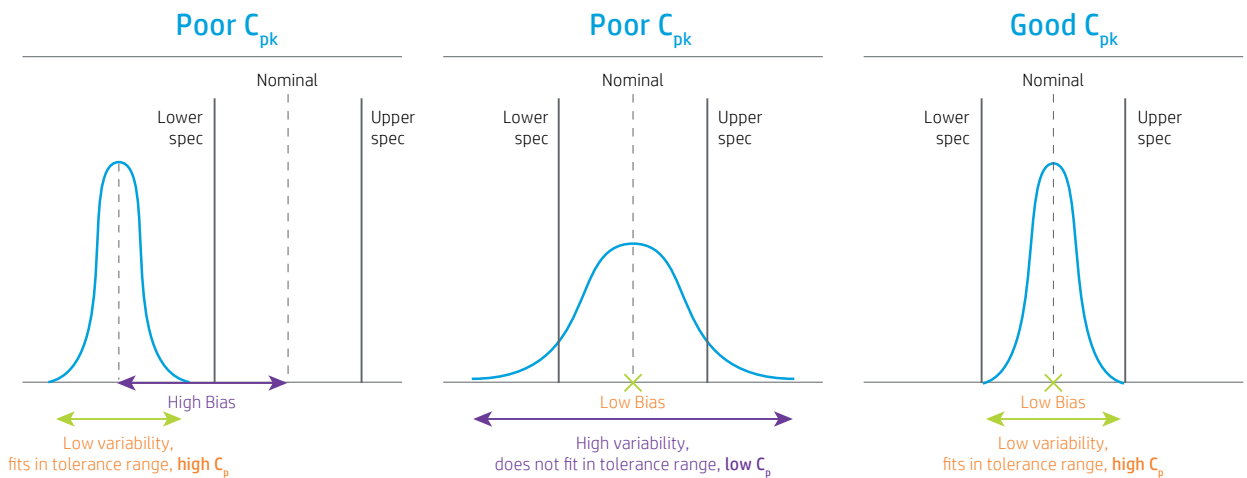


Figure 4: Process capability C_{pk} scenarios

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 1.0 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 2: 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, 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 (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 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 multipart complex mechanisms.

HP 3D Process Control

The HP Jet Fusion 5200 Series 3D Printing Solution has an in-printer feature that provides the capability to apply dimensional profiles. This feature helps streamline the workflow and provide an enhanced experience while helping to achieve manufacturing-level accuracy and repeatability.

By default, the solution comes with a general dimensional profile. Using HP 3D Process Control software, hardware-specific dimensional profiles can be generated and managed to achieve optimized dimensional capability and ensure uniform results across a fleet of printers.

For more information on HP 3D Process Control, please visit: hp.com/go/3Dsoftware5200.

Dimensional Capability Performance

The dimensional capability performance of the HP Jet Fusion 4200 3D Printing Solution and the HP Jet Fusion 5200 Series 3D Printing Solution with HP 3D HR PA 12 have been characterized in the white papers [HP 3D HR PA 12 for the HP Jet Fusion 4200 3D Printing Solution – Dimensional Capability](#) and [HP 3D HR PA 12 for the HP Jet Fusion 5200 Series 3D Printing Solution – Dimensional Capability](#), respectively. The dimensional capability of the HP Jet Fusion 500 Series 3D Printer can be found in the [HP 3D HR CB PA 12 for HP Jet Fusion 500 Series 3D Printers – Dimensional Capability](#) white paper.

