White paper

HP 3D HR PA 11, HP 3D HR PA 12 GB, and HP 3D HR PP enabled by BASF for the HP Jet Fusion 5200 Series 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 whitepaper is to provide information on the dimensional capabilities that can be achieved with the HP Jet Fusion 5200 Series 3D Printing Solution with HP 3D High Reusability (HR) PA 11 HP 3D High Reusability (HR) PA 12 Glass Beads (GB), and HP 3D High Reusability (HR) PP enabled by BASF.

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 in the HP Jet Fusion 5200 Series 3D Printing Solution, according to process capability index,
- A detailed explanation of the conditions under which these values were obtained,
- Additional information on the concept of process capability and dimensional tolerancing, and a glossary of key terms used.

**HP Jet Fusion 5200 Series 3D Printing Solutions dimensional capability performance**

**Test job**

The dimensional capability performance of the HP Jet Fusion 5200 Series 3D Printing Solution with HP 3D HR PA 11, HP 3D HR PA 12 Glass Beads, and HP 3D HR PP enabled by BASF were characterized using the **HP dimensional capability characterization job** (Figure 1), which contained 122 diagnostic parts distributed throughout the printable volume. The job included three different types of diagnostic parts and a total of 1524 dimensions.

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1. HP Jet Fusion 3D Printing Solutions using HP 3D High Reusability PA 11 provide up to 70% powder reusability ratio, producing functional parts batch after batch. For testing, material is aged in real printing conditions and powder is tracked by generations (worst case for reusability). Parts are then made from each generation and tested for mechanical properties and accuracies.

2. HP Jet Fusion 3D Printing Solutions using HP 3D High Reusability PA 12 Glass Beads provide up to 70% powder reusability ratio, producing functional parts batch after batch. For testing, material is aged in real printing conditions and powder is tracked by generations (worst case for reusability). Parts are then made from each generation and tested for mechanical properties and accuracy.

3. HP Jet Fusion 3D Printing Solutions using HP 3D High Reusability PP enabled by BASF provide up to 90% powder reusability ratio, producing functional parts batch after batch. For testing, material is aged in real printing conditions and powder is tracked by generations (worst case for reusability). Parts are then made from each generation and tested for mechanical properties and accuracy.
Performance results for HP 3D HR PA 11

Testing was performed for HP 3D HR PA 11 with a 30% refresh ratio using the PA 11 Balanced print profile, natural cooling, and measured after bead-blasting with glass beads at 5-6 bars.

Table 1 shows the dimensional tolerances obtained during the characterization for a target process capability of $\text{Cpk} = 1.33$ (4 sigma).

<table>
<thead>
<tr>
<th>Tolerances for $\text{Cpk} = 1.33^{\text{i,ii,iii}}$ (in mm)</th>
<th>Nominal dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 – 30 mm</td>
</tr>
<tr>
<td></td>
<td>XY</td>
</tr>
<tr>
<td>With the default setting for HP Jet Fusion 5200 Series 3D Printing Solutions</td>
<td>$\pm 0.30$</td>
</tr>
</tbody>
</table>

i. Based on internal testing and measured using the HP dimensional capability characterization job. Results may vary with other jobs and geometries.

ii. Using HP 3D HR PA 11 material, 30% refresh ratio, Balanced print profile, natural cooling, and measured after bead-blasting with glass beads at 5-6 bars.

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

Table 1. Dimensional capabilities for HP 3D HR PA 11. Target process capability of $\text{Cpk}=1.33$.

Table 2 shows the dimensional tolerances if the process capability target is set to $\text{Cpk} = 1.00$ (3 sigma).

<table>
<thead>
<tr>
<th>Tolerances for $\text{Cpk} = 1.00^{\text{i,ii,iii}}$ (in mm)</th>
<th>Nominal dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 – 30 mm</td>
</tr>
<tr>
<td></td>
<td>XY</td>
</tr>
<tr>
<td>With the default setting for HP Jet Fusion 5200 Series 3D Printing Solutions</td>
<td>$\pm 0.26$</td>
</tr>
</tbody>
</table>

i. Based on internal testing and measured using the HP dimensional capability characterization job. Results may vary with other jobs and geometries.

ii. Using HP 3D HR PA 11 material, 30% refresh ratio, Balanced print profile, natural cooling, and measured after bead-blasting with 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 HP 3D HR PA 11. Target process capability of $\text{Cpk}=1.00$. 
Performance results for HP 3D HR PA 12 Glass Beads

Testing was performed for HP 3D HR PA 12 Glass Beads with a 30% refresh ratio using the PA 12 Glass Beads Balanced print profile, natural cooling, and measured after bead-blasting with glass beads at 5-6 bars.

Table 3 shows the dimensional tolerances obtained during the characterization for a target process capability of \( C_{pk} = 1.33 \) (4 sigma).

### Table 3. Dimensional capabilities for HP 3D HR PA 12 Glass Beads. Target process capability of \( C_{pk} = 1.33 \).

<table>
<thead>
<tr>
<th>Nominal dimension</th>
<th>0 – 30 mm</th>
<th>30 – 50 mm</th>
<th>50 – 80 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>XY</td>
<td>±0.31</td>
<td>±0.43</td>
<td>±0.71</td>
</tr>
<tr>
<td>Z</td>
<td>±0.35</td>
<td>±0.39</td>
<td>±1.16</td>
</tr>
</tbody>
</table>

- Based on internal testing and measured using the HP dimensional capability characterization job. Results may vary with other jobs and geometries.
- Using HP 3D HR PA 12 Glass Beads material, 30% refresh ratio, PA12 Glass Beads Balanced print profile, natural cooling, and measured after bead-blasting with glass beads at 5-6 bars.
- Following all HP recommended printer setup and adjustment processes and printheads aligned using semi-automatic procedure.

Table 4 shows the dimensional tolerances if the process capability target is set to \( C_{pk} = 1.00 \) (3 sigma).

### Table 4. Dimensional capabilities for HP 3D HR PA 12 Glass Beads. Target process capability of \( C_{pk} = 1.00 \).

<table>
<thead>
<tr>
<th>Nominal dimension</th>
<th>0 – 30 mm</th>
<th>30 – 50 mm</th>
<th>50 – 80 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>XY</td>
<td>±0.27</td>
<td>±0.30</td>
<td>±0.56</td>
</tr>
<tr>
<td>Z</td>
<td>±0.33</td>
<td>±0.32</td>
<td>±0.89</td>
</tr>
</tbody>
</table>

- Based on internal testing and measured using the HP dimensional capability characterization job. Results may vary with other jobs and geometries.
- Using HP 3D HR PA 12 Glass Beads material, 30% refresh ratio, PA12 Glass Beads Balanced print profile, natural cooling, and measured after bead-blasting with glass beads at 5-6 bars.
- Following all HP recommended printer setup and adjustment processes and printheads aligned using semi-automatic procedure.
Performance results for HP 3D HR PP enabled by BASF

Table 5 shows the dimensional tolerances obtained during the characterization for a target process capability of $C_{pk} = 1.33$ (4 sigma).

<table>
<thead>
<tr>
<th>Tolerances for $C_{pk} = 1.33$</th>
<th>Nominal dimension</th>
<th>0 – 30 mm</th>
<th>30 – 50 mm</th>
<th>50 – 80 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>XY</td>
<td>Z</td>
<td>XY</td>
<td>Z</td>
<td>XY</td>
</tr>
<tr>
<td>With the default setting for HP Jet Fusion 5200 Series 3D Printing Solutions</td>
<td>±0.45</td>
<td>±0.90</td>
<td>±0.50</td>
<td>±1.30</td>
</tr>
</tbody>
</table>

i. Based on internal testing and measured using the HP dimensional capability characterization job. Results may vary with other jobs and geometries.

ii. Using HP 3D HR PP enabled by BASF material, 20% refresh ratio, Balanced print profile, natural cooling, and measured after bead-blasting with glass beads 70-110 µm at 5-6 bars.

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

Table 5. Dimensional capabilities for HP 3D HR PP enabled by BASF. Target process capability of $C_{pk} = 1.33$.

Table 6 shows the dimensional tolerances if the process capability target is set to $C_{pk} = 1.00$ (3 sigma).

<table>
<thead>
<tr>
<th>Tolerances for $C_{pk} = 1.00$</th>
<th>Nominal dimension</th>
<th>0 – 30 mm</th>
<th>30 – 50 mm</th>
<th>50 – 80 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>XY</td>
<td>Z</td>
<td>XY</td>
<td>Z</td>
<td>XY</td>
</tr>
<tr>
<td>With the default setting for HP Jet Fusion 5200 Series 3D Printing Solutions</td>
<td>±0.35</td>
<td>±0.70</td>
<td>±0.40</td>
<td>±1.00</td>
</tr>
</tbody>
</table>

i. Based on internal testing and measured using the HP dimensional capability characterization job. Results may vary with other jobs and geometries.

ii. Using HP 3D HR PP enabled by BASF material, 20% refresh ratio, Balanced print profile, natural cooling, and measured after bead-blasting with glass beads 70-110 µm at 5-6 bars.

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

Table 6. Dimensional capabilities for HP 3D HR PP enabled by BASF. 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 ($C_{pk}$) 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 the 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

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

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:

![Process capability scenarios](image)

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 ($\mu$).

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.
Table 7 displays the relevant $C_{pk}$ values and their correlation with process yields.

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

Table 7. $C_{pk}$ 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 Table 5, 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 a costly but 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, random parts could be audited for 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.

### Table 8. Standard international tolerance grades

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

Figure 4. 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 shown in Table 9.

<table>
<thead>
<tr>
<th>IT Grade</th>
<th>01</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fits</td>
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</tbody>
</table>

Table 9. 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 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.