5-Axis Test-Piece – Influence of Machining Position

Michael Gebhardt, Wolfgang Knapp, Konrad Wegener
Institute of Machine Tools and Manufacturing (IWF), Swiss Federal Institute of Technology (ETH), Zurich, Switzerland

Abstract
Square pyramid and conical test-pieces have been machined. Disadvantages of square pyramid in respect to conical test-piece have been shown. Following the proposal of Bossoni [1], ISO presents a test-piece for simultaneous, 5-axis movement in ISO/DIS 10791-7 [4] without specifying the exact position and orientation of the test-piece.

Therefore in this paper, test-pieces milled at four different positions on a 5-axis machining center are analyzed and the results are compared with kinematic simulations. It is shown by simulation and machining, that the accuracy of the test-pieces depends not only on the geometric characteristics of the machine tool, but also on the position and orientation of the test-piece.

Keywords: 5-axis machining, 5-axis test-piece, Simulation of axes movement

1 INTRODUCTION
With rising demands for 5-axis machine tools in industry, special test procedures for 5-axis kinematics become more and more important. A common way to prove accuracy and performance of machine tools are standardized test-pieces, which are used especially for acceptance tests and for periodic re-verification. With ISO/DIS 10791:2012, ISO is preparing an international standard describing test conditions for machining centers. Since 1998, part 7 considers two types of test-pieces: One positioning and contouring test-piece and a face milling test-piece. The maximum number of axes that need to move simultaneously to cut the test-pieces is two [1][2].

As described in [3], the first profile cone frustum cutting test to verify the accuracy of five simultaneously moved axes (three linear and two rotary) was developed by The Aerospace Industries Association of America, Inc. (AIA) in a National Aerospace Standard (NAS) about 40 years ago. This was meant to be manufactured with cone axis vertical on a machining center with an universal head.

2 TEST-PIECES FOR 5-AXIS MACHINE TOOLS
Important features for a test-piece for acceptance tests of 5-axis machining are [1]:

- easy and fast to manufacture
- easy and fast to measure
- easy to evaluate measuring results
- Set up in a way that it has to be manufactured using 5 simultaneously moved axes, even on different types of 5-axis machining centers
- Give comparable and quantitative results
- Show the influence of the machine tool used and not of the tool and/or the tool set-up
- Show the influence of errors relevant for the analyzed manufacturing strategy (e.g. end milling or face milling) with sufficient sensitivity

Due to these requirements, as an alternative to the conical test-piece, a truncated square pyramid test-piece was considered in ISO/CD 10791-7 [5] (Figure 3).
At IWF, several tests were completed to compare both test-pieces. Three relevant disadvantages of the truncated square pyramid test-piece are:

- Not constant process force
- Coordinate measuring machine (CMM) necessary for evaluation of the test-piece
- No additional information to conical test-piece

The manufacturing of the pyramid test-piece was programmed according to ISO/CD 10791-7 [5], so that there is a constant offset between the tool center point (TCP) and the lower edge of the test-piece. Figure 5 visualizes, that the contact length of the tool is not constant. This results in a not constant process force. Because of this and the reasons listed above, in the current version of the standard ISO/DIS 10791-7:2012-02-14 [3], only the conical test-piece is contained.

Originally, it was also assumed that the truncated square pyramid test-piece can be milled easily with just two axes in motion, which might not be detected on a smooth finished surface. This could be disproved, because the tool path can be reconstructed optically after milling. Figure 4 shows explicitly the toolmarks, which can be assigned to a 5-axis motion.

3 SIMULATION OF AXES MOTION

In [6] a simulation of axes motion for milling a conical test-piece on a 5-axis machining center was presented. Now, similar simulations were carried out for four different locations in the workspace. These positions and the nomenclature are shown in Figure 2.

Position BM (Bottom, Middle) appears to be the position which requires the shortest range of axes motion. Position BO (Bottom, Outside) shows changes of the offset to C-axis, position TM (Top, Middle) shows changes of the offset to the B-axis. Position TO (Top, Outside) shows the combination of both offsets.

![Figure 5: Not constant process force because of variable contact length](image)

![Figure 4: Truncated square pyramid test piece](image)

![Figure 3: Truncated square pyramid test-piece [5]](image)

![Figure 6: Simulated axes motion for location top outside, TO, for constant tool feed](image)
Simulation results in Figure 6 show axes movements for the position TO over radial cone angle $\varphi$. At a radial angle of 0° and 180°, axes X, Z and B have reversal points. At a radial angle of 120°, axes X and Y have reversal points. Due to the geometry of the test-piece (cone angle 45°, inclination angle 30°), the B-axis moves from -75° to -15°. The C-axis travels 360°. Due to constant contouring speed, the velocity of C-axis is not constant.

Table 1 summarizes the travel ranges for axes X, Y and Z for every simulated position for the conical test-piece. The axis of rotation B and C are not included, because axes travels are constantly 60° (B-axes) and 360° (C-axes). Because of the fact, that the milling set-up (fixture with test-piece mounted on the table) is symmetric to the Y-direction, Y-axis motion depends only on the radial offset of the test-piece location relative to the C-axis. As expected, position BM shows the smallest range of the movements. Furthermore, at this position the machine tool accomplishes just a 4-axis movement as no Z-axis motion is needed. In total, position BO (combination of radial and axial offset) shows largest axes movements.

Table 1: Axis movement ranges for different locations of the conical test-piece

<table>
<thead>
<tr>
<th>Position / Inclination angle</th>
<th>Total X-axis travel [mm]</th>
<th>Total Y-axis travel [mm]</th>
<th>Total Z-axis travel [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM / -30°</td>
<td>8</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>BO / -30°</td>
<td>210</td>
<td>360</td>
<td>196</td>
</tr>
<tr>
<td>TM / -30°</td>
<td>212</td>
<td>40</td>
<td>212</td>
</tr>
<tr>
<td>TO / -30°</td>
<td>84</td>
<td>360</td>
<td>16</td>
</tr>
<tr>
<td>TO / 30°</td>
<td>410</td>
<td>280</td>
<td>410</td>
</tr>
</tbody>
</table>

In addition to the axes motion ranges, the characteristics of axes movements strongly differs between the different positions. As an example Figure 7 shows X-axis motion for the four positions.

Figure 7: Comparison of X-Axis movement for 4 different locations (inclination angle: -30°)

Compared to the simulation presented in [7], the position of the piece is the same, but its inclination angle is -30° instead of 30°. This results in a totally different tool path shown in Figure 7 and also in different axes travels see Table 1, last line.

4 MACHINING OF TEST-PIECES

Test-pieces were milled in four different positions (according to Figure 2) corresponding to the simulations presented in section 3. At every position, four test-pieces were milled: Two in conventional and two in climb direction.
4.1 PREPARATION FOR TEST-PIECE MACHINING

To machine test-pieces in different locations, a fixture was designed (Figure 9). The fixture is variable in height (tubes of different lengths can be used) and can be mounted all along the slots of machine table, so different radial offsets can be realized.

A reference edge on top of the fixture enables automated touching with a probe on the machine tool to identify the workpiece coordinate system. The construction out of tubes enables both: a lightweight assembly and a high bending stiffness together. The bending of the fixture during movement was calculated via FEM and was verified with measurements. Measurements were carried out using capacitive sensors mounted on carbon tubes. Displacements within 1.5 µm on top of the fixture could be identified due to gravity at B equal 90°. The bending of the fixture due to process forces is estimated to be in the same magnitude as the influence due to gravity. Process forces affect the cone in radial direction (when assumed as constant), therefor they have only an influence on the diameter of the test-piece, but not on its circular form (except in the area of start / stop). Gravity has to be taken in account, because it depends on B-axis angular position.

4.2 TEST-PIECE MACHINING

NC programming and milling simulation was done in ESPRIT® (Simulation: Figure 10).

Following machining sequence was realized:

1. Face milling of upper surface (Figure 1: red plane)
2. Milling of groove in upper surface
3. Flank milling of cylinder (Figure 1: green area)
4. Flank milling of cone shape (Figure 1: yellow area)

Every step is divided in a roughing and a finishing part.

Table 2: Finishing parameters for milling operations

<table>
<thead>
<tr>
<th>Operation</th>
<th>Cutting tool diameter [mm]</th>
<th>Cutting speed $v_c$ [m/min]</th>
<th>Feed rate $v_f$ [mm/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Face)</td>
<td>20</td>
<td>350</td>
<td>585</td>
</tr>
<tr>
<td>2 (Groove)</td>
<td>6</td>
<td>188</td>
<td>1137</td>
</tr>
<tr>
<td>3 (Cylinder)</td>
<td>20</td>
<td>300</td>
<td>716</td>
</tr>
<tr>
<td>4 (Cone)</td>
<td>20</td>
<td>300</td>
<td>716</td>
</tr>
</tbody>
</table>

Figure 11 shows flank milling of cone of test-piece.

5 INTERPRETATION OF MILLED TEST-PIECES

The roundness of the test-pieces was measured on a Taylor Hobson Talyrond 265 roundness measuring instrument.

Correlations between roundness plots and orientation of test-pieces are shown in Figure 12, where start points for the operations milling cylinder and milling cone are illustrated.

Circular form error of cylinders and circular form error of cones of all test-pieces were measured according to ISO/DIS 10791: 2012-02-14 with an offset of 2 mm to the upper and lower edges of the cone. Figure 13 gives an example for a measurement at position TO (Measured object: cone, climb direction, measured 2 mm below the upper edge), corresponding with axis movement simulation in Figure 6.

The area around the first contact point was omitted for evaluation of circular form error but not for figures 13 – 15.
5.1 INFLUENCE OF RADIAL OFFSET

Two explicit differences can be seen: At position \textit{BM}, peaks (signed in figure 14) are visible which do not appear at position \textit{BO}. Peaks at 90° (tagged green, dotted) repeat in every measurement. Other peaks (tagged red) repeat sporadic. This has to be checked-up in further investigations.

Additionally it can be noticed, that the amplitude of the “noise” in the roundness measurement with a radial offset to the C-axes (Position \textit{BO}) is larger as at Position \textit{BM}. A possible reason for this aspect is the influence of angular positioning of C-axis. The resolution of the C-Axis of 0.001° leads to a range of 1.2 $\mu$m at position \textit{BO} (Offset: 160 mm, influence of twice the resolution).

5.2 MONTE CARLO SIMULATIONS FOR ESTIMATION OF CIRCULAR FORM ERRORS

Two explicit differences can be seen: At position \textit{BM}, peaks (signed in figure 14) are visible which do not appear at position \textit{BO}. Peaks at 90° (tagged green, dotted) repeat in every measurement. Other peaks (tagged red) repeat sporadic. This has to be checked-up in further investigations.

Additionally it can be noticed, that the amplitude of the “noise” in the roundness measurement with a radial offset to the C-axes (Position \textit{BO}) is larger as at Position \textit{BM}. A possible reason for this aspect is the influence of angular positioning of C-axis. The resolution of the C-Axis of 0.001° leads to a range of 1.2 \(\mu\)m at position \textit{BO} (Offset: 160 mm, influence of twice the resolution).
The simulation is based on a kinematic model of the machine tool, the calculated tool path (depending on location of test-piece) and the geometric deviations specified as ranges in the acceptance test report. Figures 16 and 17 show occurrence distribution of circular form errors at position TO.

![Circular form error of cone](image)

Figure 17: Monte Carlo Simulation to estimate cone form error in position TO

Every Monte Carlo simulation was carried out with 1000 runs. Depending on the location of the test-piece, the values of form errors vary. The largest calculated form errors can be found at position TM. Table 4 gives an overview of all simulated form errors (mean values and twice the standard deviations) for cylinder and cone at each of the four simulated positions.

Table 4: Mean values and twice the standard deviations for circular form errors of all test-pieces based on Monte Carlo simulations.

<table>
<thead>
<tr>
<th>Position</th>
<th>Monte Carlo Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cylinder</td>
</tr>
<tr>
<td></td>
<td>[mm]</td>
</tr>
<tr>
<td>BM</td>
<td>0.004±0.002</td>
</tr>
<tr>
<td>BO</td>
<td>0.004±0.002</td>
</tr>
<tr>
<td>TM</td>
<td>0.005±0.002</td>
</tr>
<tr>
<td>TO</td>
<td>0.005±0.002</td>
</tr>
</tbody>
</table>

According to the simulated form deviations, Table 5 shows measured values. Comparison between simulated and measured values shows a similar magnitude for cylinder and cone shape, but measured form errors at positions BM and BO are larger than the simulated values, but within the ranges of twice the standard deviations. Machining operations were done with standard NC setting. A comparison between the measured values in Table 5 and the axis movement ranges for the different locations (Table 1) shows very nicely that large circular form errors come along with large axes movements. A comparison of climb and conventionally milled (up and down milled) workpieces shows no systematic behavior or significant difference in the circular form error.

Table 5: Mean values and twice the standard deviations for circular form errors of all test-pieces

<table>
<thead>
<tr>
<th>Position</th>
<th>Measured object</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cylinder</td>
</tr>
<tr>
<td></td>
<td>[mm]</td>
</tr>
<tr>
<td>BM</td>
<td>0.005±0.004</td>
</tr>
<tr>
<td>BO</td>
<td>0.006±0.002</td>
</tr>
<tr>
<td>TM</td>
<td>0.007±0.004</td>
</tr>
<tr>
<td>TO</td>
<td>0.007±0.004</td>
</tr>
</tbody>
</table>

6 CONCLUSIONS

A conical test-piece presented in ISO/DIS 10791-7 [4] is a smart possibility to proof accuracy and performance during simultaneous 5-axis machining. Disadvantages of a second test-piece (truncated square pyramid) are described. Using the example of a radial offset to rotary axes B and C, it could be shown that it is important to pay attention to the position and orientation of the center of the test-piece, what could be demonstrated by machining and simulations.

7 FUTURE STEPS

Occurred phenomena like repeating peaks or systematic variation of the amplitude of measurements have to be evaluated furthermore. For simulations regarding circular form error of cylinder and cone, it is planned to measure all geometric deviations of all five axis instead of the use of ranges from the acceptance test report. Information on inclination angle and center offset of test-piece shall be included in test-report, as well as travels of all machine axes which is currently not requested in [4].

ACKNOWLEDGEMENT

IWF/inspire thanks MTTRF for their generous support for this research for 5-axis machining centers and test-pieces for 5-axis machining.

REFERENCES


© 2012 The Proceedings of MTTRF 2012 Annual Meeting