In-process measurement on a machine tool – fact or fiction?

Using on-machine probing to drive process capability

Marc Saunders
General Manager
UK Sales
FACT!

• At Renishaw’s factory at Stonehouse, in-process measurement is indispensable
  – 70 CNC machines
  – 300,000+ parts per month
  – 78 direct staff (over 3 shifts)
  – Machines run unattended for up to 36 hours
  – 2000 automated batch changeovers
Agenda

• Goals of in-process inspection
• Productive Process Pyramid™
• Machine performance optimisation
• Calibration of 5-axis machine behaviour
• Impact of in-cycle process control
• The importance of temperature
• On-machine verification
Goals of in-process inspection

• The goal should **NOT** be simply to replace CMM inspection with on-machine inspection
  – This may be a consequence, but it is not the target

• The goal should be to **improve the productivity and capability of the machining process** by:
  – Monitoring and reacting to machine behaviour to prevent thermal effects impacting on the machining process
  – Automating manual setting tasks and removing manual intervention
  – Where necessary, adapting machining cutter paths to accommodate variations in surface form and position
  – Providing automated, repeatable & reproducible feedback to the process to compensate for inherent variation like tool wear
  – Reacting to unexpected events in a controlled, logical manner
  – Verifying the machining process before the part is moved

• Every measurement should have a purpose…
  – To control a process variable to reduce non-conformance
<table>
<thead>
<tr>
<th>Agenda</th>
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<tbody>
<tr>
<td>• Goals of in-process inspection</td>
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Productive Process Pyramid™

- Providing a controlled, automated process

- Verify process & monitor outcomes
  - Finish machine & check tool
  - Measure part & adjust tool wear offsets
  - Correct for thermal drift / growth
  - Rough / semi-finish & check tools
  - Calibrate & assess tools
  - Find part location & set work co-ordinate / rotation
  - Establish reference points for thermal tracking
  - Measure axis datums and rotary centre-lines
  - Calibrate probe to ensure accurate on-machine measurement
  - Check (and optimise) machine condition

- Verification
  - Adaptive machining
  - Process set-up
  - Machine behaviour
  - Machine structure
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Six steps to improved machine capability

- Determine the accuracy you need
- Establish baseline: current performance
- Identify and rank error sources
- Eliminate or calibrate errors
- Establish new baseline
- Regular health checks
### Process capability toolbox

**What tools will you need for steps 🌼 to 🌹?**

1. **QC10 ballbar**
   - As called for in ASME B5.54 and ISO 230

2. **Laser calibration system**
   - Either purchase or use a calibration service

3. **Precision machine levels**
   - To help fix any identified problems
The machine performance measurement cycle

- Fix / calibrate, baseline, monitor
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Example 5-axis machine configuration

- Y-axis
- X-axis
- Z-axis
- C-axis
- A-axis
Error sources - alignment

C-axis coupling
Alignment
X-Z plane

Table alignment
X-Z plane

Table alignment
Y-Z plane

Trunion alignment
Z axis

C-axis coupling
alignment
Y-Z plane

Trunion alignment
Y axis
Error sources - position

- C-axis centre X-axis
- A-axis pivot Z-axis
- C-axis centre Y-axis
- A-axis pivot Y-axis
- Table to A-axis pivot
### Impact of A-axis pivot point position error

- 5-axis VMC
- Pivot point not where assumed in the CNC
- Y-axis errors up to 80 µm

<table>
<thead>
<tr>
<th>Angle (A-axis)</th>
<th>X error (µm)</th>
<th>Y error (µm)</th>
<th>Z error (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30</td>
<td>-1.2</td>
<td>15.3</td>
<td>-15.0</td>
</tr>
<tr>
<td>-20</td>
<td>1.5</td>
<td>9.0</td>
<td>-11.0</td>
</tr>
<tr>
<td>-10</td>
<td>3.0</td>
<td>3.5</td>
<td>-5.0</td>
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<tr>
<td>0</td>
<td>3.0</td>
<td>0.5</td>
<td>-2.0</td>
</tr>
<tr>
<td>10</td>
<td>3.0</td>
<td>-6.0</td>
<td>1.5</td>
</tr>
<tr>
<td>20</td>
<td>5.3</td>
<td>-14.8</td>
<td>3.5</td>
</tr>
<tr>
<td>30</td>
<td>1.8</td>
<td>-22.5</td>
<td>6.0</td>
</tr>
<tr>
<td>40</td>
<td>3.2</td>
<td>-30.5</td>
<td>7.5</td>
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<tr>
<td>50</td>
<td>4.0</td>
<td>-41.3</td>
<td>7.5</td>
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<td>60</td>
<td>6.0</td>
<td>-51.7</td>
<td>6.0</td>
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<td>70</td>
<td>11.5</td>
<td>-61.2</td>
<td>3.0</td>
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<tr>
<td>80</td>
<td>11.3</td>
<td>-70.8</td>
<td>-2.0</td>
</tr>
<tr>
<td>90</td>
<td>10.7</td>
<td>-80.2</td>
<td>-9.0</td>
</tr>
</tbody>
</table>
Compensation for machine behaviour

- **Alignment errors** do not change quickly, except in the event of a machine crash
  - Check alignments and adjust if unacceptable
  - Establish baseline and re-check when machine is re-calibrated and after a severe crash

- **Position errors** are affected by ambient temperature and heat generated during the machining process
  - These positions can be established using a calibration process and then tracked using in-process checks in the machining program to improve the process capability
  - The position of rotary axis centre-lines should be checked prior to performing precision finishing processes
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## Case study: impact of in-cycle process control

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Machine:</strong></td>
<td>Mori Seiki SL153Y</td>
</tr>
<tr>
<td><strong>Part:</strong></td>
<td>Angle encoder ring</td>
</tr>
<tr>
<td><strong>Feature:</strong></td>
<td>Finish bore 95.00/95.04mm</td>
</tr>
<tr>
<td><strong>Problem:</strong></td>
<td>Unacceptable level of process variation resulting in scrap &amp; rework</td>
</tr>
</tbody>
</table>
Case study: tests performed

• **Baseline**
  – Run 23 parts straight off without process adjustment to establish inherent variation

• **CMM process control**
  – Measure part at end of process and adjust finishing process on next part

• **In-process gauging**
  – Control roughing and finishing processes in-cycle, adapting finishing cut based on semi-finished size with 75% offset correction
Capability with no process control

**Process Data**
- LSL: 95
- Target: *
- USL: 95.04
- Sample Mean: 95.0103
- Sample N: 23
- StDev(Within): 0.0106786
- StDev(Overall): 0.0087827

**Observed Performance**
- PPM < LSL: 130434.78
- PPM > USL: 0.00
- PPM Total: 130434.78

**Exp. Within Performance**
- PPM < LSL: 167284.03
- PPM > USL: 2710.77
- PPM Total: 169994.81

**Exp. Overall Performance**
- PPM < LSL: 120346.86
- PPM > USL: 360.91
- PPM Total: 120707.78

**Potential (Within) Capability**
- Cp: 0.62
- CPL: 0.32
- CPU: 0.93
- Cpk: 0.32

**Overall Capability**
- Pp: 0.76
- PPL: 0.39
- PPU: 1.13
- Ppk: 0.39
- Cpm: *

**Cpk** = 0.32
**Ppk** = 0.39
Scrap / rework = 12.1%
Capability with ‘CMM process control’

Process Data

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LSL</td>
<td>94.803</td>
</tr>
<tr>
<td>Target</td>
<td>*</td>
</tr>
<tr>
<td>USL</td>
<td>94.843</td>
</tr>
<tr>
<td>Sample Mean</td>
<td>94.828</td>
</tr>
<tr>
<td>Sample N</td>
<td>48</td>
</tr>
<tr>
<td>StDev(Within)</td>
<td>0.00618681</td>
</tr>
<tr>
<td>StDev(Overall)</td>
<td>0.00584352</td>
</tr>
</tbody>
</table>

Process Data Summary

- **Cp**: 1.08
- **CPL**: 1.34
- **CPU**: 0.81
- **Cpk**: 0.81
- **Pp**: 1.14
- **PPL**: 1.42
- **PPU**: 0.86
- **Ppk**: 0.86
- **Cpm**: *

Potential (Within) Capability

- PPM < LSL: 0.00
- PPM > USL: 0.00
- PPM Total: 0.00

Observed Performance

- PPM < LSL: 94.803
- PPM > USL: 94.843
- PPM Total: 94.828
- Sample N: 48
- StDev(Within): 0.00618681
- StDev(Overall): 0.00584352

Exp. Within Performance

- PPM < LSL: 27.40
- PPM > USL: 7523.48
- PPM Total: 7550.88

Exp. Overall Performance

- PPM < LSL: 9.73
- PPM > USL: 5025.43
- PPM Total: 5035.15

PPM Total: 7550.88

Cpk = 0.81
Ppk = 0.86
Scrap / rework = 0.5%
Capability with in-cycle process control

**Process Data**
- LSL: 95
- Target: 95.04
- USL: 95.036
- Sample Mean: 95.0221
- Sample N: 48
- StDev(Within): 0.00358382
- StDev(Overall): 0.0038922

**Process Capability**
- Cp = 1.86
- CPL = 2.06
- CPU = 1.66
- Cpk = 1.66
- Pp = 1.71
- PPL = 1.89
- PPU = 1.53
- Ppk = 1.53
- Cpm = *

**In-process adaptive control**
- Potential (Within) Capability
  - PPM < LSL: 0.00
  - PPM > USL: 0.00
  - PPM Total: 0.00
- Potential (Overall) Capability
  - PPM < LSL: 0.01
  - PPM > USL: 2.13
  - PPM Total: 2.14
- Observed Performance
  - PPM < LSL: 0.00
  - PPM > USL: 0.00
  - PPM Total: 0.00
- Expected Within Performance
  - PPM < LSL: 0.00
  - PPM > USL: 0.30
  - PPM Total: 0.30
- Expected Overall Performance
  - PPM < LSL: 0.01
  - PPM > USL: 2.13
  - PPM Total: 2.14
- Scrap / rework = 0.0002%
Case study: commentary

• Conclusions
  – applying feedback based on finished part inspection provides some benefits - it helps to control tool wear
  – in this case, there is significant part-to-part variation caused by upstream processes
  – measurements of the previous part are therefore not a good predictor of the size of the next part
  – in these circumstances - common in many aerospace processes - in-cycle gauging is by far the most effective solution
Process control software

Productivity+

- Program probing at the same time as tool path generation
  - offline programming
  - integrate metal cutting, probing and process feedback
  - logic and branching
  - executes on the CNC – no external PC

- Family of products…
  - GibbsCAM plug-in
  - Active Editor Pro
  - post processors
  - growing range of CAM plug-ins and future extensions
Productivity+™ Active Editor Pro

Rapid off-line programming and simulation of probing cycles

Selection of features to be measured from CAD model
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The impact of temperature

- **Thermal effects can dominate**

  - if the material temperature is uncertain, then the level of thermal growth may swamp the tolerance that is being targeted
  
  - ambient temperature in many shops varies from cold (perhaps 15 °C) to hot (> 30 °C)
  
  - on many large parts, temperature is a significant or dominant uncertainty

% of tolerance consumed by thermal growth (11 ppm/ °C) where temperature varies by ±5 °C

<table>
<thead>
<tr>
<th>Feature size</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>±5μm</td>
</tr>
<tr>
<td>10 mm</td>
<td>11%</td>
</tr>
<tr>
<td>25 mm</td>
<td>28%</td>
</tr>
<tr>
<td>50 mm</td>
<td>55%</td>
</tr>
<tr>
<td>100 mm</td>
<td>110%</td>
</tr>
<tr>
<td>250 mm</td>
<td>275%</td>
</tr>
<tr>
<td>500 mm</td>
<td>550%</td>
</tr>
<tr>
<td>1000 mm</td>
<td>1100%</td>
</tr>
<tr>
<td>2500 mm</td>
<td>2750%</td>
</tr>
<tr>
<td>5000 mm</td>
<td>5500%</td>
</tr>
</tbody>
</table>

Significance of thermal growth

- 0% - 10% Insignificant
- 11% - 30% Significant
- > 30% Dominant
Maintaining thermal stability

- Machine tools also generate heat as they work
  - heat flows distort machine structure
- The fastest rate of change occurs when the machine starts and stops
- Keep the machine warm
  - run warm-up cycles if machine has been idle
  - run ‘exercise cycles’ to keep the machine warm during short idle periods
- Avoid sudden temperature change
  - windows and doors

Z drift

- Fastest distortion when machine starts or stops
Renishaw’s approach

• **Controlled thermal environment…**
  – control of ambient temperature to ±2 °C
  – modern machines with through ball-screw and through tool coolant
  – coolant chiller systems
  – parts mostly < 100 mm
  – thermal growth is not a significant source of part-to-part variation in most cases

• **Yet we still use artefacts…**
  – artefacts provide TRACEABILITY
  – allows elimination of post-process measurement
The artefact control process

Machining

- On-machine measurement (controls & audits machining process)
- Hourly thermal tracking
- Correction of critical features
- Hourly artefact measurement
- Daily cleaning & visual checks
- Weekly artefact health check
- Offset updates

CMM

- (audits on-machine measurement)
- Re-calibration service using calibrated length standards
- Annual machine calibration
- Artefact sent for re-calibration
- 6-monthly artefact re-calibration

Measurement standards

- (audits CMM measurement performance)
- Artefact calibration data
- ISO 10360 certification

NPL

- National Physical Laboratory

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Verifying the process using on-machine probing

- Verification can be combined with control of finishing process
  - artefact measured first to calibrate current machine thermal condition
  - comparative measurement gives traceability and is independent of machine tool measurement accuracy
  - part measured using gauging points on surfaces - critical features only
  - thermal effects identified by artefact are compensated when updating the process variables

Video_9.6_RAMTIC_1st_part.mpg
Measurement of the first part in a batch on RAMTIC
On-machine verification software

**Renishaw OMV**

- Features are easily selected from the CAD model and the number of points & slices can be configured:
  - free form points
  - circles
  - slots
  - rectangle
  - cylinders
  - cones
  - spheres
  - lines
  - planes
On-machine verification software

Renishaw OMV

- Rapid feature selection from CAD model
- Simulation of probing cycles
- Requires PC to analyse data gathered on the machine

NEW multi-axis version

- Display points taken in multiple orientations against the CAD model
On-machine verification software

Renishaw OMV

• The inspected features can be added into comprehensive reports and the data is also graphically placed back on the CAD model: