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White paper

At the sharp end – a guide to CMM stylus selection

When deciding the best way to measure a component on a co-ordinate measuring machine (CMM), many choices are made by default because they have been carefully thought through many times before. The accuracy specification of the CMM, the best type of sensor to use (touch or scanning) and the optimum probing method are often taken for granted and not questioned. However, this foundation for good metrology can be undermined by an inappropriate or ill-considered choice of stylus, with the result that measurement accuracy can be compromised.

When assessing how accurate a CMM measurement needs to be, it is common practice to use a ratio of CMM uncertainty to feature tolerance of at least 5:1 (10:1 is ideal, but can prove to be too expensive to be practical in many cases). This ratio provides a safety margin that ensures the results have a relatively small uncertainty compared to the expected range of variation of the component. As long as a 5:1 ratio can be maintained on the tightest tolerance, this should be the end of the accuracy argument.

Unfortunately something as innocuous as changing the stylus on a probe can have a surprisingly large influence on the real accuracy that may be achieved, causing appreciable variation in the measurement results. It is not enough to rely on the CMM's annual calibration to check this accuracy as this will only confirm the result with the stylus being used for the test (usually a very short one). This is likely to be the best-case accuracy. To get a fuller understanding of the likely precision of a wider range of measurements, we need an appreciation of how the stylus contributes to measurement uncertainty.

Stylus specification and configuration can affect the precision of measurement results

This paper will look at four main aspects of stylus choice that affect overall CMM accuracy:

1. Stylus ball sphericity (roundness)
2. Stylus bending
3. Thermal stability
4. Stylus tip material selection (scanning applications)

1. Stylus ball sphericity (roundness)

The measuring tips of most styli feature a ball, most commonly made of synthetic ruby. Any error in the sphericity (roundness) of these tips will be a factor in the CMM's measurement uncertainty, and it is easy to lose as much as 10% of a CMM's accuracy in this way.

Spherical ruby stylus tips

Ruby balls are manufactured to various levels of precision defined by their 'grade', which is related to the maximum deviation of the ball from a perfect sphere. The two most common ball specifications used are grade 5 and grade 10 (the lower the grade the better the ball). 'Downgrading' from a grade 5 to a grade 10 ball saves a little in terms of the cost of the stylus, but may be enough to threaten the 5:1 ratio. The concern is that the ball grade is impossible to detect visually and is not obviously evident in measurement results, making it difficult to calculate if this is significant. One solution is to specify grade 5 balls as standard: they cost a little more, but this is a minor cost when compared with the potential of scrapping a good part, or worse, passing a non-conforming one. Perversely, the more accurate the CMM, the more significant the effect of ball grade is. On the highest specification CMMs, as much as 10% of accuracy can be lost in this way. Let's look at an example…

A typical probing error according to ISO 10360-2 (MPE_P), established using a stylus with a grade 5 ball:

- **MPE_P = 1.70 µm**

This figure is determined by measuring 25 discrete points that are each evaluated as 25 separate radii. The range of radii variation is the MPE_P value. Stylus ball roundness contributes to this directly, and so swapping from a grade 5 to a grade 10 ball increases this value by 0.12 µm and degrades the probing error by 7% in this instance:

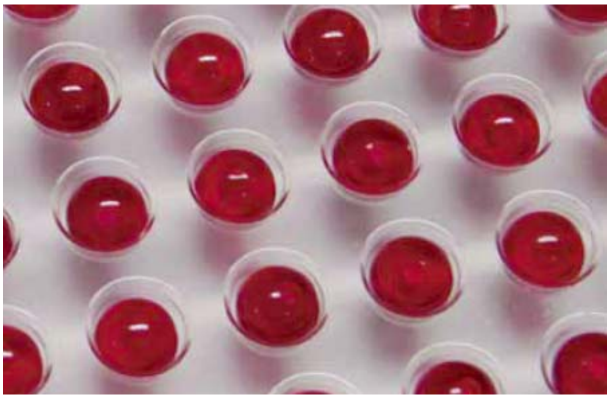
- **MPE_P = 1.82 µm**

Note that stylus ball roundness also impacts on MPE_{THP}, which uses four scanning paths across a sphere to evaluation scanning probe performance.

Notes:

- Grade 5 ball sphericity = 0.13 µm
- Grade 10 ball sphericity = 0.25 µm

For the most demanding applications, Renishaw offers a range of styli employing grade 3 balls, which feature a sphericity of just 0.08 µm.

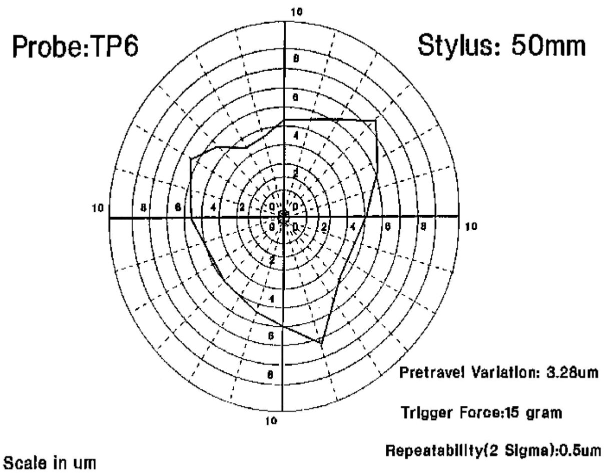


2. Stylus bending

When using touch-trigger probes such as the industry-standard TP20, it is common practice to swap between stylus modules to take advantage of different styli, each optimised for a measurement task. The reason one long stylus isn't used for all features is that there is an accuracy penalty that increases with longer stylus lengths. It is good practice to keep stylus as short and as stiff as possible – but why?

Although the stylus is not directly responsible for this particular error, it does magnify it with stylus length. The error originates from the variable force required to trigger the probe in different directions. Most probes do not trigger the instant contact is made between the stylus and the component; they require a force to be built up to overcome the spring-loading within the sensor mechanism. This force elastically deforms the stylus. This bending allows the probe to move a short distance relative to the part after physical contact is made and prior to the trigger being generated. This movement is known as *pre-travel*.

The triangular kinematic arrangement of most probes results in differing forces being required to generate a trigger. In the stiffer directions the probe will resist triggering until more stylus bending has occurred. This also means the CMM will travel further, so the pre-travel will vary with the approach angle (see diagram below). This *pre-travel variation* is further complicated when compound approach angles are used (X, Y and Z-axes).



Angle of approach vs. pre-travel required to trigger a TP6 touch trigger probe.

To minimise this effect all styli are calibrated on a reference sphere of known size before they are used. In an ideal world this process would map the errors at every combination of stylus and approach angle. In practice, a sample of angles is often taken to save time, some averaging takes place, and a small proportion of the error can remain.

It is difficult to calculate the effect of this on measurement uncertainty without carrying out empirical tests. The key fact to note is that any residual pre-travel variation errors will be magnified by the flexibility of the stylus that is selected. This emphasises the importance of materials choice in stylus design, weighing up the flexural rigidity of the stem against other characteristics such as its weight and cost. Whilst steel is suitable for many shorter styli, featuring a Young's modulus E = 210 kN/mm^2, the stiffest material commonly used in is *tungsten carbide* (E = 620 kN/mm^2), but this is also dense and is therefore rarely used on long styli. In these instances, carbon fibre provides an excellent combination of stiffness (E ≥ 450 kN/mm^2) and light weight. Meanwhile, ceramic stems (E = 300 – 400 kN/mm^2) are often used in machine tool probing applications where their light weight and thermal stability are valued.

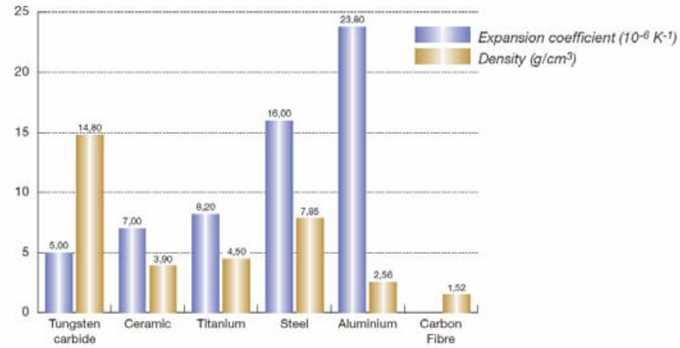
Long styli and extensions are often made from carbon fibre for optimum stiffness and weight

Stylus stiffness is also affected by joints in stylus assemblies. As a general rule of thumb, it is best to avoid joints wherever possible as they can introduce hysteresis, although this may not be possible when using a fixed sensor to measure complex parts. In these cases, a configuration built up from a range of styli, extensions, connectors and knuckles may be needed. Once again, it is important to consider the materials chosen for each element, as this will impact on the stiffness, weight and robustness of the configuration.

Complex stylus configurations demand a thoughtful choice of materials if precision is to be maintained.

3. Thermal stability

Fluctuations in temperature can cause serious measurement errors. Choosing the right material for stylus extensions can provide greater stability under changing conditions, yielding more consistent measurement results. Materials with a low coefficient of thermal expansion are preferable, especially where long styli are being used as thermal growth is length-dependent:



Relative thermal expansion coefficients and densities of stylus stem materials

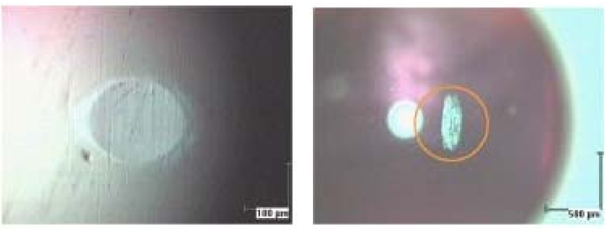
As stated previously, carbon fibre is the material most commonly used for long styli and extensions as it is stiff, light and does not change its length as temperature varies. Where metals are needed – for joints, knuckles etc. – titanium provides the best combination of strength, stability and density. Renishaw provides probe and stylus extensions that feature both these materials.

4. Stylus tip material selection

For most applications, ruby balls are the default choice for stylus tips. However, there are some circumstances where other materials provide a better alternative.

With touch-trigger measurements, the stylus tip only comes into contact with the surface for short periods and there is no relative movement. Scanning is different as the ball slides over the surface of the component, resulting in frictional wear. This prolonged contact can, in extreme circumstances, cause removal or deposition of materials on the stylus ball that affect its sphericity. These effects are magnified if one region of the ball is in constant contact with the part. Renishaw has conducted extensive research into these affects, highlighting two different wear mechanisms:

- **Abrasive wear** is caused when scanning a surface such as cast iron, where tiny particles of residue cause minute scratches on the stylus and workpiece, resulting in a small 'flat' on the stylus tip. Tough zirconia stylus tips are the optimum choice for these applications.



Abrasive wear (left) results in material being removed from the stylus tip, whereas adhesive wear (right) involves surface material being deposited on the stylus ball.

- **Adhesive wear** results when the stylus ball and the component material have an chemical affinity for one another. This may be seen when scanning aluminium parts with a ruby (aluminium oxide) ball. Material passes from the relatively soft component to the stylus, resulting in a coating of aluminium on the stylus tip, once again affecting its roundness. In this instance, silicon nitride is the best choice, as it is shows good wear resistance and is not attracted to aluminium.

5. Other factors

Further considerations when selecting a stylus include:

- Stylus thread size to suit the chosen sensor
- Stylus type – straight, star, swivel, or custom configuration
- Stylus tip type – ball, cylinder, disc, hemisphere
- Stylus tip size to minimise the impact of surface roughness on measurement accuracy

All these issues are explored in detail in Renishaw's *Precision styli* brochure (document H-1000-3304) which can be downloaded from www.renishaw.com/styli.

Conclusion

Styli are a critical contributor to any measurement, providing the crucial interface between the sensor and the component. They provide access to features around the part and must faithfully relay the location of the surface to the probe. To facilitate accurate inspection, they must be constructed from precision components that are each made from materials that match the demands of the measurement task. If selected with care, the right stylus will not add significantly to uncertainty, producing consistent and reliable results. Where part tolerances are tight, and longer styli are required, the impact of these choices on accuracy must be carefully considered.

