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Testing the mechanical characteristics and contacting behaviour of novel manufactured and assembled sphere-tipped styli for micro-CMM probes

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Abstract. The effectiveness and versatility of the probes used on micro-co-ordinate measuring machines is currently limited by the dimensions, geometry and quality of the spherical stylus tips available. A shaft fabrication and gluing process is demonstrated to assemble a sphere-tipped stylus for tactile micro-co-ordinate measuring machine probes. The contact behaviour of the manufactured micro-styli is investigated both in a static and a vibrating mode. The ultimate strength of the glue joint is also investigated. It is concluded that the assembly of styli using the presented method is viable, however, that stylus shafts below 40 μm diameter may require new manufacturing methods.

Keywords: micro-CMM, sphere tipped stylus, assembly, gluing process, WEDG, micro-EDM

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1. Introduction

Geometrical measurement of micro-components is a constant issue for micro-manufacturing engineers. Although several optical techniques are available, some geometries, such as holes, channels and surfaces with high curvature, still need to be characterised using a tactile micro-co-ordinate measuring machine (micro-CMM). To continue to achieve accurate results while using tactile micro-CMMs, it is essential to fabricate high quality sphere-tipped micro-styli.

Using a combination of wire electro discharge grinding (WEDG) [1] and one-pulse electro discharge (OPED) technology [2], sphere-tipped micro-styli can be fabricated with spherical tip diameter of approximately 0.07 mm [3]. During the OPED process, an instant electro-discharge is focused onto the end of a stylus shaft. This process results in the formation of a spherical tip on the stylus shaft, creating a monolithic

sphere-tipped micro-stylus. However, the instant electro-discharge energy shock can result in a spherical tip with a high sphericity error, in the order of 500 nm to 800 nm [2]. To address this, a hybrid WEDG and gluing process was developed to assemble the stylus tips. The manufacturing and positioning capability of the WEDG machine are combined to achieve high accuracy assembly. Following assembly, it is essential that the glue strength is determined to ensure the manufactured styli are suitable for use with existing micro-CMM probes. This paper describes the results of an investigation into the glue strength of the manufactured sphere-tipped styli. The experimental process used to investigate the triggering behaviour of probes using these assembled styli in static and dynamic (vibrating) modes is also described.

2. Sphere-tipped micro-stylus assembly

Using a hybrid WEDG and gluing process, micro-styli with sphere tips of diameter approximately 0.07 mm were assembled. This process is fully described in a previous study [4]. The shaft manufacture and assembly process (glue deposition, manipulation and assembly) was carried out on a single machine. Using a CCD camera for position assistance, it was possible to assemble the sphere-tipped stylus with an accuracy of approximately 1 μm . Once manufactured, the micro-shaft is dipped into a glue reservoir and then assembled with a sphere secured in a small vacuum holder. A schematic of the manufacturing and assembly process is shown in figure 1.

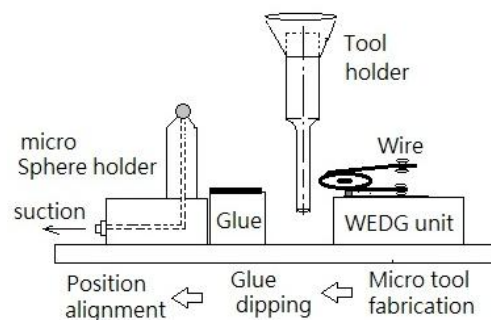


Figure 1 Sphere-tipped micro-stylus manufacturing and assembly setup [4].

High aspect ratio sphere-tipped micro-styli can be assembled using this hybrid gluing and WEDG process. This is due to the high quality of straight and long shafts that are

easily fabricated using the WEDG process. Two suitable designs for styli are shown in figure 2, along with the manufactured styli.

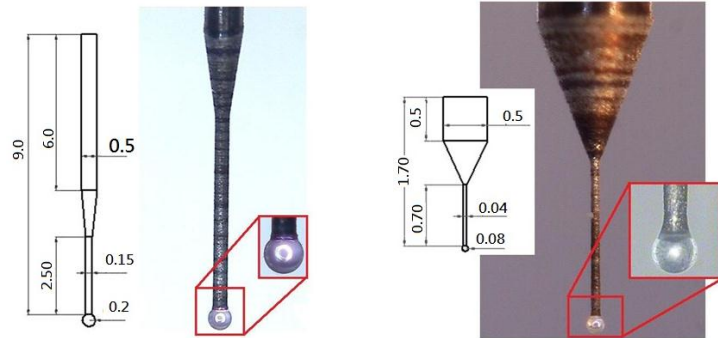


Figure 2 Assembled micro-styli. Working aspect ratios are 12.5 (left) and 8.75 (right). All dimensions are in millimetres.

3. Mechanical properties of the manufactured micro-styli

3.1. Contact behaviour

An important parameter of micro-CMM probes is the contact force they impart on the measurement surface during probing. Although the stylus itself has some effect on this parameter, the probing system, especially its stiffness and mode of operation, is the major contributor. Therefore, only an indication of the effects apparent when probing at the micro-scale can be investigated using just the stylus, such as the effect of the surface interaction forces. The true probing force cannot be determined without installing the stylus onto a micro-CMM probe for testing.

When probing at the micrometre scale with a micro-CMM probe, the surface interaction forces have the effect of causing the probe to snap-in to the measurement surface on approach and/or to stick to the measurement surface after probing, causing snap-back [5]. To address this effect, the stylus tip should be vibrated. This technique is used in several newly developed micro-CMM probes [6] [7]. An experiment was designed to investigate the different contacting behaviours of the stylus tips during static and dynamic operation. A schematic of the experimental setup is shown in figure 3.

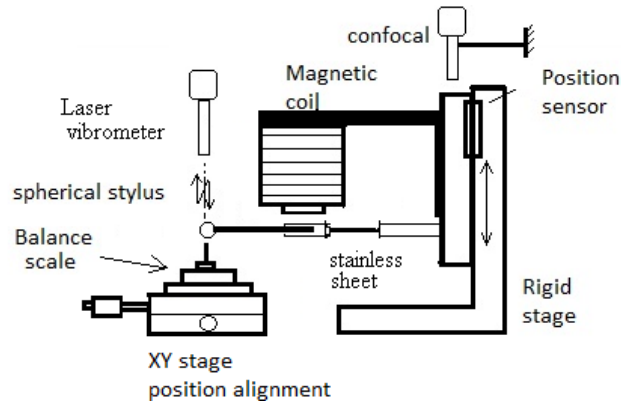


Figure 3 Schematic of the dynamic contact force testing for the stylus

By using the magnetic coil as a vibration generator, and optimizing the drive current and the length and thickness of the stainless steel flexure, the vibration frequency and amplitude of the test stylus could be adjusted. The dynamic behaviour of the test stylus was recorded using a laser Doppler vibrometer. This low cost setup can result in the test stylus vibrating at a frequency of 170 Hz and an amplitude of 1 μm . This resulting vibration amplitude is similar to that of existing vibrating micro-CMM probes; however the vibration frequency is significantly lower. A precision mass balance was used as a force sensor, and a precision manipulation stage was used to move the stylus into contact during testing. The experimental setup exhibits some hysteresis due to the slow reaction time of the precision mass balance and the backlash on the screw-drive of the manipulation stage. To correct for this, the manipulation stage was operated at a slow travel speed and a chromatic confocal distance sensor, the CHRcodile E system from Precitec Optronik GmbH, was used to determine the true motion.

The contact behaviour of the stylus and the test measurement surface in static and dynamic mode was tested. The same setup was used in each case, as the stiffness of the steel flexure was determined to be very high in comparison with the stylus shaft, by at least three orders of magnitude. A set of representative results are shown in figure 4. It can be seen that, during static testing, the test stylus remained stuck to the measurement surface for approximately 1.5 μs post contact. This resulted in up to 1 μN of sticking force, which is usually attributed to the surface interaction forces [8]. During dynamic testing, with vibration characteristics as previously described, the same stylus exhibited no appreciable sticking to the surface while retracting.

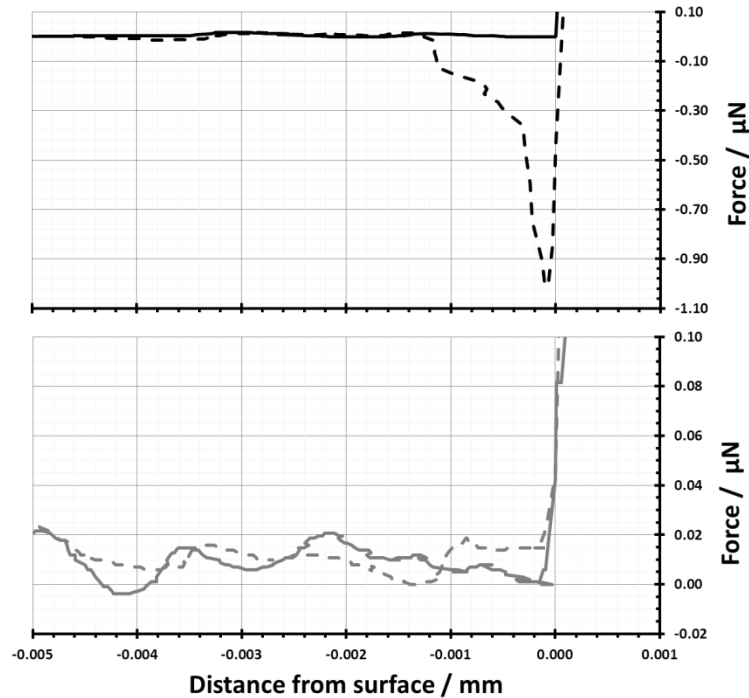


Figure 4 The change in retract behaviour between static probing (top) and dynamic probing (bottom). The solid lines indicate approach, and the dashed lines indicate retract.

3.2. Glue strength

The main use for these sphere-tipped micro-styli is as the contacting part of tactile micro-CMM probes [9]. For this application, knowledge of the stiffness of the stylus is required so that accurate determination of the transfer of mechanical contact to the sensing part of the CMM probe can be known. Also, the ultimate gluing strength should be determined to ensure there is no risk of stylus breaking during use. The gluing force of a glass spherical stylus tip has been previously measured to be in the order of 12 mN [4]. When testing a stylus of a similar design to that shown in figure 2 (left) but with a shaft diameter of 65 µm, a glue strength of 22 mN ± 1 mN ($k = 1$) was measured. A second stylus with a shaft diameter of 28 µm exhibited a glue strength of 5 mN ± 1 mN ($k = 1$), with an ultimate yield strength of the stylus shaft of 17 mN ± 1 mN ($k = 1$). Combined with the previously reported results for a 40 µm diameter of 12 mN, it is suggested that there is a first order linear relationship between the diameter of the stylus shaft and the glue strength of the assembled

spherical tip. Due to the bespoke nature of these styli, the repeatability of the assembly process could not be determined. The experimental setup to complete these glue strength experiments was similar to that shown in figure 3, but with the test stylus held rigidly, rather than with a steel flexure.

3.3 Glue strength – dynamic mode and comparative measurements

It was also possible to test the glue strength of the assembled stylus during dynamic operation. When operating in a dynamic mode, with a vibration amplitude of $1.2\ \mu\text{m}$ and a vibration frequency of 161 Hz, a stylus with a shaft diameter of $40\ \mu\text{m}$ showed a glue strength of 10 mN. This is in line with the previous results from the static glue tests.

A set of tests were also completed on styli manufactured using the previously described hybrid WEDG/OPED process. These monolithic styli exhibit very high strengths; a stylus with a shaft diameter of $40\ \mu\text{m}$ showed an ultimate tensile strength of over 50 mN. The difference between the breaking modes of the assembled styli and the monolithic styli is shown in figure 5.

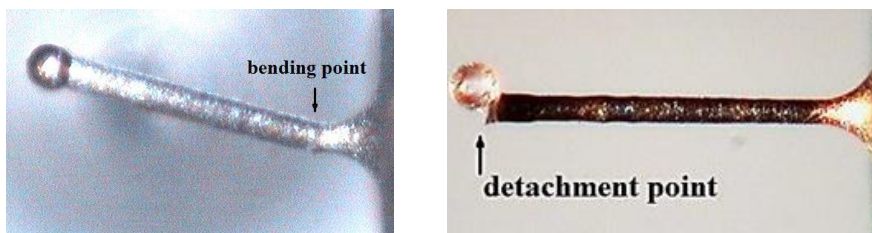


Figure 5 Breaking of a WEDG/OPED monolithic (left) and a micro-assembled stylus (right)

However, with smaller shaft diameters becoming more prevalent, to accommodate smaller diameter sphere tips, WEDG technology becomes inappropriate for stylus shaft manufacture. This is due to the variability of the manufactured surface, which is not smooth, but instead is badly damaged and pitted. These rough features can act as initiation points for cracking, resulting in significantly weaker styli. For example, one tested stylus, manufactured using the hybrid WEDG/OPED process, with a shaft diameter of $40\ \mu\text{m}$, showed an ultimate tensile strength of only 6 mN, with the elastic limit being reached around 5 mN.

This issue of WEDG manufacture for small diameter shafts (below $50\ \mu\text{m}$) could be addressed through the use of electro-chemical machining (ECM). The surface

roughness of a probe shaft manufactured using the ECM process is much lower than that formed by WEDG, which could result in stronger styli with diameters smaller than 40 μm . A trial micro-stylus with a tip diameter of 8 μm has been manufactured to demonstrate the capability of a hybrid ECM and OPED process. This stylus is shown in figure 6.

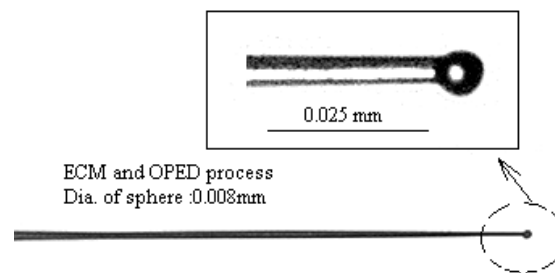


Figure 6 A micro-stylus manufactured using a hybrid ECM and OPED process. The stylus tip has a diameter of 8 μm

3.4 Lifetime investigation

To investigate the suitability of the assembled styli to perform as styli for micro-CMM probes, a short lifetime investigation was completed. An assembled probe, shaft diameter 40 μm , was contacted, in dynamic mode, to a force of 2 mN. This was repeated ninety times over 4.5 hours. During this time, no appreciable change in contact response was detected beyond that expected for the temperature fluctuations in the laboratory (estimated to have an effect of ± 200 nN over the time of the experiment).

4. Conclusion

Styli of various diameters, manufactured by this new assembly method, have been tested for glue strength. The strengths of the glue joints range from 5 mN to 22 mN, and have a first order linear relationship to the diameter of the stylus shaft. The glue strength results of the assembled styli have been compared to similar strength (the elastic limit) for monolithic styli and found to be significantly lower. This disparity is due to the inclusion of a glue joint in the assembled styli.

The strengths of the monolithic styli can be around 50 mN for styli diameters above 40 μm . The strength of the styli shafts manufactured using WEDG once the shaft diameter is below 40 μm is significantly lower. This is due to the high surface roughness produced during the WEDG process, whose features act as initiation points

for cracking. It is suggested that the ECM process may be useful for the production of stylus shafts below 30 μm diameter. Styli shafts produced using ECM have lower surface roughness than those produced by WEDG, which reduces the chance of surface features acting as initiation points for cracking.

A low cost setup was designed and built to operate the test styli in a dynamic (or vibrating) mode. Through the use of a precision mass balance, the contact behaviour of the assembled styli was investigated. During static testing, the effect of the surface interaction forces resulted in the stylus sticking to the measurement surface with a force of approximately 1 μN . During dynamic testing, the same stylus exhibited no appreciable sticking to the surface while retracting. It is therefore concluded that dynamic operation is essential for micro-CMM probe operation at the micro-scale.

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