

REPORT

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Manufacture and testing of a
micro-stylus suitable for tactile
probing in dimensional
metrology

Alan Wilson, Richard Leach

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Manufacture and testing of a micro-stylus suitable for tactile probing in dimensional metrology

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Abstract

This report presents work carried out during the initial phase of an on-going National Measurement System project aimed at developing a new micro-probe system capable of making dimensional measurements on components with micro-scale features. The report describes the design, manufacture and testing of one constituent element of the micro-probe system - the micro-stylus component.

Two techniques were investigated for the manufacture of suitable micro-styli - wire electro-discharge machining and one-pulse electro-discharge manufacturing. Several prototype styli were produced using each technique and the quality of the manufactured components assessed visually with a Scanning Electron Microscope. In order to assess the functional performance of the styli a number of the manufactured components were incorporated into contact probe sensor elements compatible for use with a high accuracy co-ordinate measuring machine. One of these hybrid probes was used to perform a series of measurements on a set of reference artefacts, and the resulting measurement data analysed to evaluate the suitability of the micro-stylus for use in contact probing applications.

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Approved on behalf of the Managing Director, NPL
by Martyn Sené, Director of Operations

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1 Introduction

1.1 Background

Recent advances in modern manufacturing techniques have meant that it is now possible to manufacture small and complex components to extremely high accuracies. Also, developments in the design and construction of modern machining systems have led to a significant enhancement in the capabilities of these systems [1]. The Kern Pyramid Nano CNC machining centre for example [2] has a quoted manufacturing precision of 1 μm and has been specifically designed for applications that require the highest manufacturing accuracy and surface quality.

A further development has been the adaptation and application of a range of techniques, originally developed in the semiconductor manufacturing industry, to manufacture small, three dimensional (3D) components. These techniques are varied and numerous, and include processes such as x-ray photolithography, wet and dry etching, focussed ion beam machining and fabrication, and laser micromachining [3], [4], [5].

One area to significantly benefit from the developments mentioned above has been micro-electro-mechanical system (MEMS) technology. MEMS devices are created through the integration of mechanical elements, sensors, actuators and electronics on a common substrate through microfabrication technology [6], [7], [8], [9]. While the electronics are fabricated using conventional semiconductor manufacturing processes the micro-mechanical components are fabricated using compatible micromachining techniques [10]. Although most commonly silicon based, MEMS devices are increasingly being manufactured using polymers, glass, and even metals such as nickel and aluminium.

One recently introduced micromachining technique of particular interest to the MEMS community is deep reactive ion etching (DRIE) [11], [12]. DRIE is an etch process used to create high aspect ratio (HAR) features in a variety of materials. Examples of HAR features are the long, deep, narrow grooves and holes found in applications such as micro-fluidic channels and miniature fuel injection nozzles. These features typically have widths of 25 μm to 50 μm , with depths of up to 500 μm .

The introduction and implementation of the above techniques has meant that it is now possible to produce precision, complex 3D structures on a micrometre scale. With the continued trend towards product miniaturisation, it is inevitable that micromachining and microfabrication technology will become increasingly important for the fabrication of constituent micro-parts used in these miniaturised devices.

1.2 Measurement systems for micro-scale dimensional applications

The improvements in manufacturing capabilities have required a corresponding improvement in the measuring techniques used to confirm the quality and accuracy of the manufactured components [13]. This is especially true for MEMS devices where the 3D nature and diversity of features typically encountered make a full inspection very difficult [14]. MEMS devices can also be comprised of structures with a wide range of shapes and dimensions making inspection using a single instrument difficult. Also, because of their small size, MEMS devices are susceptible to contamination or damage through mishandling, and this makes inspection in a production environment difficult if not impossible.

Small-scale features have conventionally been measured using optical systems such as measuring or video microscopes. For example, the Hawk 200 three-axis measuring microscope produced by Vision Engineering has a quoted measurement uncertainty of approximately $2\text{ }\mu\text{m}$ [15]. Measuring microscopes can be fitted with a range of objective lenses to provide variable magnification, and most modern systems are equipped with PC-based measurement software. However, these systems can be relatively inaccurate in the z (vertical) direction, and cannot measure features such as vertical walls. Importantly, they are incapable of measuring characteristics such as the form of the sidewalls of the micro-fluidic channels and miniature nozzles mentioned in Section 1.1, characteristics which are critical to the performance of these types of features.

In many cases the most reliable way to measure the size, form and position of 3D components is using a ball ended, contact touch-probe measurement system such as a coordinate measuring machine (CMM). Modern CMMs, such as the Zeiss F25 [16] pictured in Figure 1, utilise precision kinematics and novel probe technology, and are extremely accurate and versatile. The F25 has been designed specifically for the measurement of micro-system components and has a volumetric measurement accuracy of approximately 250 nm with a probing resolution of 7.5 nm [17]. The touch sensor technology used by the probing system employed on the F25 has also meant that the probing force of the CMM has been reduced to 0.5 mN (compared to approximately 100 mN for a conventional CMM).

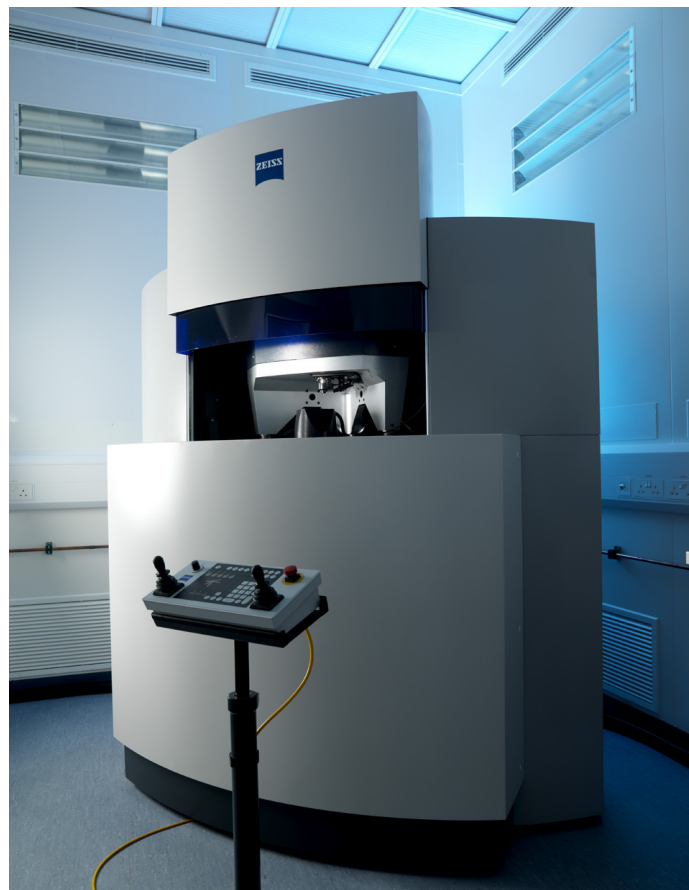


Figure 1: The Zeiss F25 high-accuracy co-ordinate measuring machine at NPL.

Currently, the smallest probe available for use with the F25 has a ball-ended stylus with a diameter of 125 μm . This means that internal features smaller than this such as holes or channels cannot be measured on this CMM. Although there are other commercially available probing systems with smaller probe dimensions, these systems have larger measurement uncertainties than those achievable with the F25. The Werth Fiber Probe WFP 3D [18] for example has a spherical glass tip with a minimum diameter of 12.5 μm . However, the Fiber Probe, used in conjunction with a Werth Video-Check HA CMM [19], has a measurement accuracy of approximately 1.5 μm , significantly higher than that of the F25.

The continual drive for product miniaturisation will lead to the development of new technologies to meet the opportunities and challenges posed by micro-scale manufacturing. In tandem with this, limitations in the capability of existing commercially available measurement equipment will drive the development of a range of new measurement systems and techniques capable of confirming the quality and accuracy of the manufactured micro-scale components.

1.3 Development of a novel micro-probing system

The introduction of the high-precision manufacturing equipment and novel manufacturing techniques discussed above has led to the demand for a measurement system capable of accurately measuring, in three dimensions, the range and variety of micro-scale components produced. As part of the National Measurement System (NMS) Engineering Measurement Programme 2005 to 2008, the National Physical Laboratory (NPL) initiated a project with the aim of creating a high-accuracy, micro-scale measurement facility for use by industry. Further aims were the development of UK capability in micro-probe technology and the enhancement of current CMM measurement capability within NPL. Because of the complexity of the project the development work is continuing into the 2008 to 2011 Programme. The project objectives can be summarised as:

- To develop a micro-scale ‘high aspect ratio structure’ measurement capability
- To develop UK capability in miniature probing

A preliminary design study carried out at the project formulation stage indicated that a system based on contact probing was the best choice for measurement of the diversity of geometric features and dimensional characteristics liable to be encountered on a typical micro-component. It was further decided that a probe geometry based upon a design previously investigated by NPL [20] offered a practical and realistic means of achieving the project objectives. This probe design comprises a three-legged, horizontal flexure element supporting a vertical, ball-ended probe stylus.

Since the features typically found on a MEMS device are micro-scale it will therefore be necessary that the new probe be itself micro-scale. One of the objectives of the initial stage of the project was to identify appropriate fabrication techniques capable of producing micro-styli suitable for integration into the final micro-probe design.

The development of a bespoke motion system for translation of the micro-probe component in three axes is not within the scope of the project. However, it is ultimately intended that the micro-probe will be interfaced to a high accuracy CMM. To further enhance the versatility of the measurement facility being developed at NPL it is envisaged that the contact probe will be one of a set of integrated probe elements (e.g. contact, optical and laser based) that can operate either individually or in combination.

1.4 Summary of this report

The work reported here is part of an ongoing NMS funded project aimed at developing a novel micro-probe system capable of performing measurements on complex 3D micro-structures. This report covers one aspect of the project: the design, manufacture and validation of the micro-stylus element.

After defining the design parameters for the stylus element, a number of prototype styli were manufactured using two different manufacturing techniques. A summary of the design requirements of the micro-probe project is given in Section 2, including those for the micro-stylus element.

The different manufacturing techniques used to produce the prototype styli are discussed in Section 3. Also included in this section are a series of images of the manufactured styli and an assessment of how suitable each manufacturing process was at producing styli of an appropriate quality for use as contact probing elements.

To assess the quality and functionality of the manufactured components a number of the styli were sent to Zeiss in Germany who incorporated them into the micro-CMM probe elements used on their F25 CMM. The assembled probes were then returned to NPL for further evaluation on the NPL F25. Section 4 includes several images of the assembled probe elements, while the measurement data obtained in the evaluation of the probes is reported in Section 5.

Finally, a summary of the work undertaken is given in Section 6, which includes comments on the suitability of the manufacturing techniques used for the production of the micro-styli elements.

2 Target specification for the NPL micro-probe system

2.1 Design requirements for the NPL micro-probe

Some of the limitations of optical probing systems have been noted previously. These systems generally have limited accuracy in the vertical (z) direction. In addition they are sensitive to characteristics such as surface texture and reflectivity, and can produce erroneous measurement data when measuring sharp edges. Most importantly, optical systems are unsuitable for measuring into high aspect ratio channels and holes. For these types of features the only practical measurement solution is by contact probing. The aim of the project will, therefore, be to develop a tactile probing system capable of measuring 3D, high aspect ratio features on micro-scale components.

In the majority of contact probing systems a ball-ended stylus is used to contact the surface under test. The use of a ball tip ensures that the test surface is contacted at a single point. It was envisioned that the probing system being developed in this project will use a ball-ended stylus with the diameter of the ball tip and the length of the stylus shank appropriate for the measurement of micro-scale holes and channels.

It was not intended to develop a bespoke motion system to translate the new probe system within the designated measurement volume. Therefore, one key requirement of this project is that the probe system be compatible with an existing motion system, for example a commercially available CMM such as the Zeiss F25. The assembled probe system should, therefore, be a 'stand-alone' component with dimensions, mass and packaging compatible with the chosen host CMM.

A further design consideration was the time required to measure a component. The system should be capable of making accurate measurements of a wide range of geometric features within reasonable timescales. This requirement means that the probe system should ideally be able to operate in both single-point and scanning modes.

Although the aim is to develop a contact probing system, it is imagined that the probe will be one element of a multi-sensor probing system to ensure maximum capability and flexibility of the micro-scale measurement facility. The design of the new probe should, therefore, be compatible with other probe technologies such as optical and laser based non-contact measurement systems.

The design requirements for the new micro-probe system can be summarised as:

- 3D high accuracy, tactile probe/probing system.
- Capable of measuring small scale, HAR features.
- Operate in single-point and scanning mode.
- 'Stand alone' probe compatible with commercial CMMs.
- Capable of integration into a multi-sensor configuration.

2.2 Development of the prototype NPL micro-probe

During the formulation stage of this project it was decided the objectives could be met by using a probe design based upon a prototype, contacting probe that had been previously developed at NPL [20]. The configuration of this prototype probe is based upon a triskelion (three-legged) arrangement of flexures supporting a miniature stylus. The performance of this arrangement has been investigated by several authors [21], [22] and was found to be a suitable geometry for use in contact probing applications.

A conceptual design review held after project initiation indicated that two features of the original triskelion micro-probe had to be altered - the dimensions of the flexure element and the mechanism by which deflection of the probe tip is detected.

2.2.1 *Dimensions of the flexure element*

The operating principle of the triskelion probe is that contact of the probe tip with a test surface is detected by a deflection of the supporting flexure element. Therefore the dimensions of the flexure element, primarily the dimensions of the flexure legs, need to be of a similar scale to those of the probe stylus to avoid the stylus bending in preference to the flexure (making the legs of an extremely flexible material would lead to them bending under the weight of the stylus). Specifically, in the case of the new micro-probe, the combined stiffness of the three-legged flexure needs to be less than the stiffness of the micro-stylus. If the micro-stylus has a diameter of a few tens of micrometres and a length of a few hundred micrometres it follows that the legs of the flexure will need to be very thin and flexible, probably only a few micrometres thick, to achieve the necessary stiffness for this element.

2.2.2 *Deflection of the flexure element*

In the original triskelion micro-probe design an optical lever system was used to monitor probe tip deflection. The central island of the flexure structure was polished, and the focussed beam from a laser diode was reflected off this surface and onto a quadrant photodetector. When the probe tip came into contact with a test surface the flexure was deflected, and this deflection was detected by a translation of the reflected spot across the photodetector (the original detection system employed two optical levers, one to detect the tilt of the flexure and one to detect its vertical displacement).

The implementation of this type of detection system in the new micro-probe is not possible, primarily because of the incompatibility of this arrangement with a standard CMM probe head. However, the requirement that the flexure legs be thin and flexible also places restrictions on the type of sensor mechanism compatible with the flexure design.

It was decided that the most practical means of detecting deflections of the flexure was by the use of micro-scale piezo-electric (PZT) strain sensing elements incorporated into the flexure legs. Therefore, an additional feature included in the design was the incorporation of PZT actuating elements on the flexure legs. The addition of actuators would also allow the micro-probe to operate in a 'tapping' mode similar to an AFM tip [23]. The planar nature of the flexure element, and the requirement of integrated sensing and actuating elements, allows the possibility of the flexure being manufactured using one or more of the micro-fabrication techniques discussed in Section 1.1.

Full details of the design of the micro-flexure element will be given in a subsequent publication, whilst the remainder of this document will primarily be related to the design and manufacture of the micro-stylus element.

2.3 Design requirements of the micro-stylus element

The specification of the ball-tipped micro-stylus was determined by four main criteria:

- The dimensions and geometry of the features it will be required to measure.
- The physical properties of the materials used to construct the stylus.
- The dimensions and stiffness of the micro-probe flexure element.
- The limitations of the manufacturing process used to make the stylus to the requisite dimensions.

Examples of the types of features that the micro-probe will be required to measure are the high aspect ratio micro-fluidic channels and micro-injection nozzles described in Section 1.1. The diameter of a typical injection nozzle is 40 μm to 80 μm , while the depth of micro-fluidic channels created using deep reactive-ion etching can be up to 500 μm . The tip of the micro-stylus will ideally have a diameter of less than 40 μm , with a shank length exceeding 750 μm .

The stylus should be made from a very stiff, low density, low mass material to avoid the shank bending when the probe comes into contact with a test surface. Additionally, the stylus material will need to be chosen to be compatible with the mechanical properties and dimensions of the flexure element to ensure that the flexure deflects in preference to the stylus.

The ball tip should be hard and durable, with good sphericity and surface finish. Also, the stylus should be designed such that it can be securely attached to the flexure element.

The target design specification of the micro-stylus element can be summarised as:

- Tactile probe, ball tip diameter: ideal – 5 μm , realistic – 50 μm .
- Sphericity of ball tip: ~ 50 nm.
- Stylus (shank) length: 0.75 mm to 1 mm.
- Mass ~ 1 g.
- Stylus compatible with triskelion flexure element.
- Probing force: ≤ 1 μN , isotropic.

These target dimensions are extremely demanding, and are probably at the limits of what can be produced using conventional engineering processes. It was therefore decided to investigate the feasibility of producing the micro-stylus element using microfabrication technology. The initial micro-styli produced were considered prototype elements and were made primarily to assess the capability of the manufacturing process employed. These techniques are described in detail in Section 3.

2.4 Summary of micro-stylus design requirements

A conceptual design has been produced for the micro-probe system including some target dimensional parameters for the micro-stylus element. The principle features of the micro-stylus are a ball tip with a diameter of approximately 50 μm , and a stylus shank length of approximately 1 mm. The dimensional requirements of the micro-stylus make this element compatible with microfabrication technology. The aim of this stage of the project was to identify a suitable manufacturing technique capable of producing micro-styli with dimensions close to those defined in the design specification.

3 Manufacture of the micro-styli elements

3.1 Micro-styli requirements

One of the most important components in a contact probing system is the probe stylus. A typical CMM stylus is shown in Figure 2. The stylus can be considered to be composed of three constituent parts - the stub, the shank and the tip.

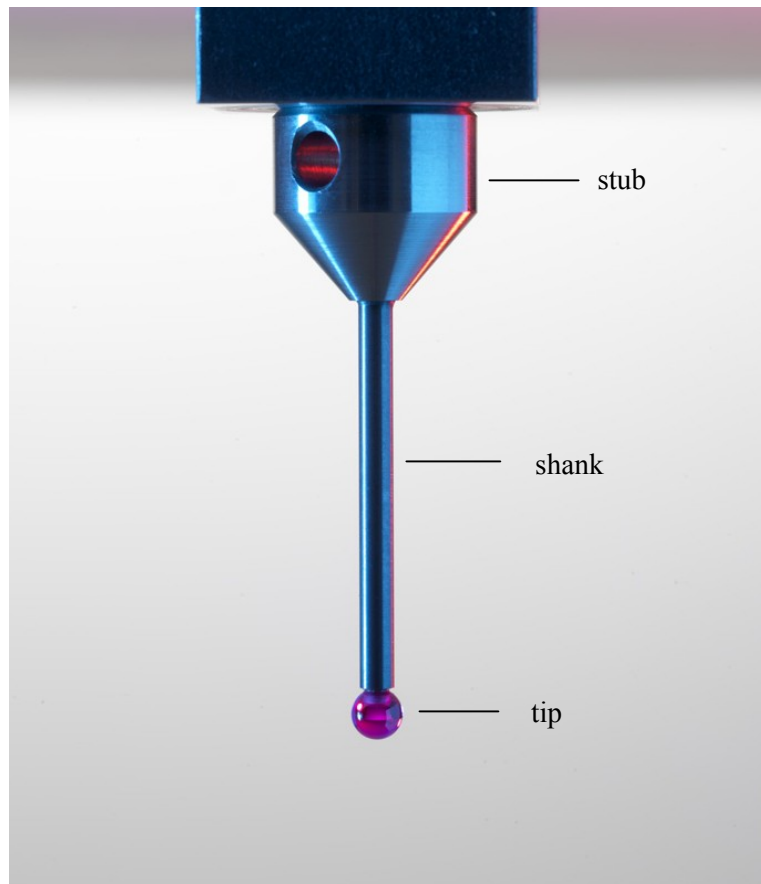


Figure 2: Image of a typical CMM stylus with a 5 mm diameter ball tip.

3.1.1 *The stylus stub*

The stylus stub is the region that attaches to the probe head. The stub is generally cylindrical and is the thickest part of the stylus. In a conventional CMM the upper end of the stub is threaded with an M4 thread and the stub body has a Tommy bar hole to allow the stub to be tightened to the probe head mating surface.

Because the required dimensions of the NPL micro-stylus are extremely small and the stylus is extremely delicate, it is not possible to produce a thread on the stylus stub. It will, therefore, be necessary to develop an alternative method of aligning and securely attaching the micro-stylus to the flexure element.

3.1.2 *The stylus shank*

The stylus shank is the region between the stub and the tip. It is most commonly cylindrical in shape, with a diameter smaller than that of the probe tip to avoid unwanted contacts with the surface being measured (referred to as probe shanking). In a conventional CMM stylus the shank is generally made from non-magnetic stainless steel, tungsten carbide or even a ceramic, to maintain rigidity over a range of styli lengths. The shank length effectively determines the depth of the features the stylus can be used to probe.

3.1.3 *The stylus tip*

The stylus tip is the region of the probe that actually contacts the surface under test during measurement. In the majority of cases a spherical tip is used, although stylus tips can also be cylindrical or disc shaped to satisfy specific measurement requirements. A spherical tip, usually a ruby ball, is used to ensure single point contact with the test surface. The balls have very good sphericity and are extremely hard, so wear is minimised. In addition, ruby is a low-density material and its use minimises the tip mass eliminating false triggers caused by machine motion or vibration. The ball tip is glued onto the stylus shank, typically located in a small spherical recess machined into the end of the shank. The ball should ideally be located symmetrically on the shank axis, again to avoid probe shanking.

The sphericity of the probe ball should be such that any spherical form error in the ball is not translated into a measurement error in the co-ordinates reported by the host CMM. Grade 5 ruby balls (0.13 μm sphericity) are commonly used, with some manufacturers also offering Grade 3 (0.08 μm sphericity) balls for high-accuracy applications.

Although companies such as Saphirwerk Industrieprodukte AG (SWIP) can provide high quality ruby spheres with diameters as small as 0.12 mm, it has proven very difficult to consistently produce spheres smaller than this with the sphericity required for use in high accuracy, contact probing applications. It is also difficult to determine or verify the form error of very small spheres using conventional metrological techniques.

3.2 Design of the initial NPL micro-styli

The target specifications for the micro-probe system given in Section 2 place severe restrictions on the maximum dimensions of the constituent elements, in particular for the micro-stylus. The dimensional requirements of this element make it impossible to obtain commercially, either as a complete stylus or even as a series of constituent parts. To overcome this limitation, the styli reported here are *produced as single elements*, rather than as a ball attached to a separate shank.

An investigation was made to determine if micro-fabrication techniques are capable of producing styli with the required dimensions and manufacturing quality. After a review of potential manufacturing facilities and technologies, two processes were chosen for further investigation: 1) one-pulse electro-discharge fabrication performed at the National Taipei University of Technology (NTUT), Taiwan; and 2) wire electro-discharge machining performed at Cardiff University, UK. In both cases, the styli were micro-machined as single elements.

Both Cardiff University and NTUT were asked to manufacture a batch of trial micro-styli to a specification produced by NPL. Although the initial styli were considered to be prototype components primarily for use in assessing the suitability of each manufacturing process, and to identify the optimum manufacturing settings and conditions, the target dimensions were chosen

to be similar to the final stylus design criteria to allow the elements to be tested at a subsequent stage for characteristics such as mechanical integrity.

A schematic drawing showing the target dimensions of the prototype styli is shown in Figure 3. Each manufacturer chose the material used to manufacture the styli, which were tungsten carbide in the case of Cardiff University and tungsten in the case of NTUT.

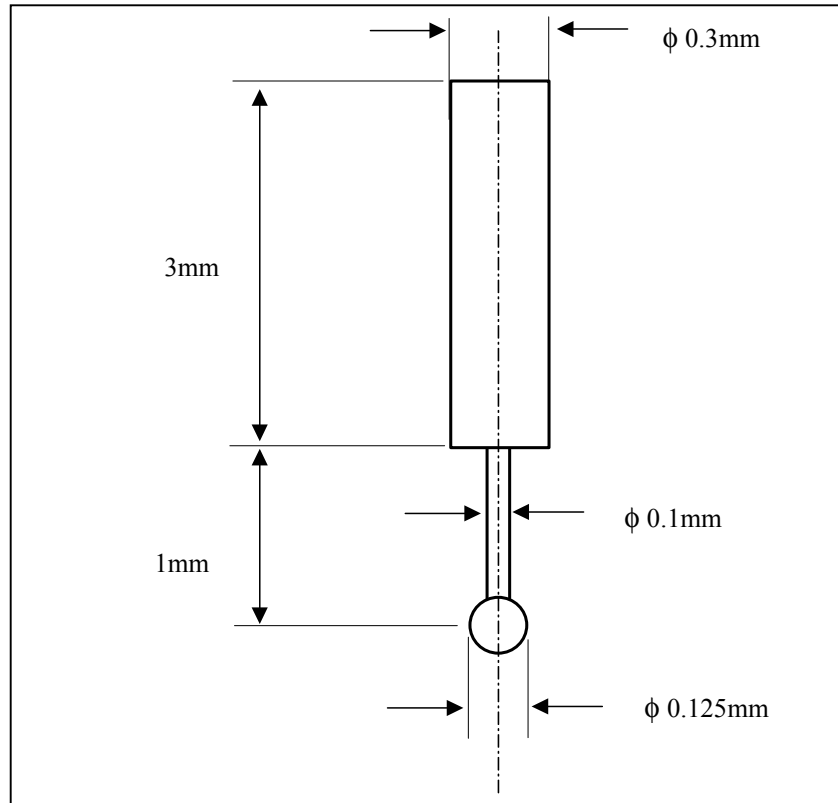


Figure 3: Target dimensions of the prototype micro-styli.

In the case of the tip diameter, the specified dimension of 125 μm is clearly much larger than the figure of 50 μm given in the target specification in Section 2.3. However, since neither of the techniques investigated had been previously used to manufacture components with these small dimensional requirements, the diameter was increased to give both manufacturers a more realistic chance of success at this initial stage.

Because the preliminary micro-styli were primarily being manufactured to assess the suitability of the manufacturing process, no specific dimensional tolerances were defined for the manufactured components.

3.3 Wire electro-discharge machining at Cardiff University

3.3.1 Wire electro-discharge grinding

Wire electro-discharge machining (WEDM) is a cutting operation that utilises a computer numerically controlled (CNC) wire electrode to “burn” through a raw block or stack of material, producing an accurate cut and clean finish [24]. The electro discharge process utilises the

thermal energy generated by the current that flows during spark discharge between the cutting or tool electrode and the workpiece (which acts as a second electrode) to remove unwanted material and generate the desired surface. Both the wire electrode and workpiece are submerged in de-ionised water or hydrocarbon oil, which acts as a dielectric layer between the two electrodes. When the gap between the two electrodes is reduced below a certain distance the dielectric breaks down allowing current to flow between the electrodes, with a secondary effect being the removal of material from both tool and workpiece. The liquid dielectric is continuously renewed to remove material debris and to assist temperature stabilisation during the EDM process.

The technique can be applied to the manufacture of micro-components (commonly referred to as micro-WEDM) by carefully varying the electrode orientation during machining. Mounting the workpiece on a rotary spindle can further enhance the process when manufacturing cylindrical components, a technique known as wire electro-discharge grinding (WEDG).

3.3.2 *Prototype styli produced using the WEDG process*

The Manufacturing Engineering Centre at Cardiff University produced a set of prototype styli using WEDG manufacturing. Since the dimensions and geometry of the required components were non-standard, a preliminary stylus was produced to investigate the suitability of this manufacturing technique. A set of scanning electron microscope (SEM) images of the preliminary stylus were taken by Cardiff and sent to NPL for evaluation. Figures 4(a) and (b) are SEM images of this stylus.

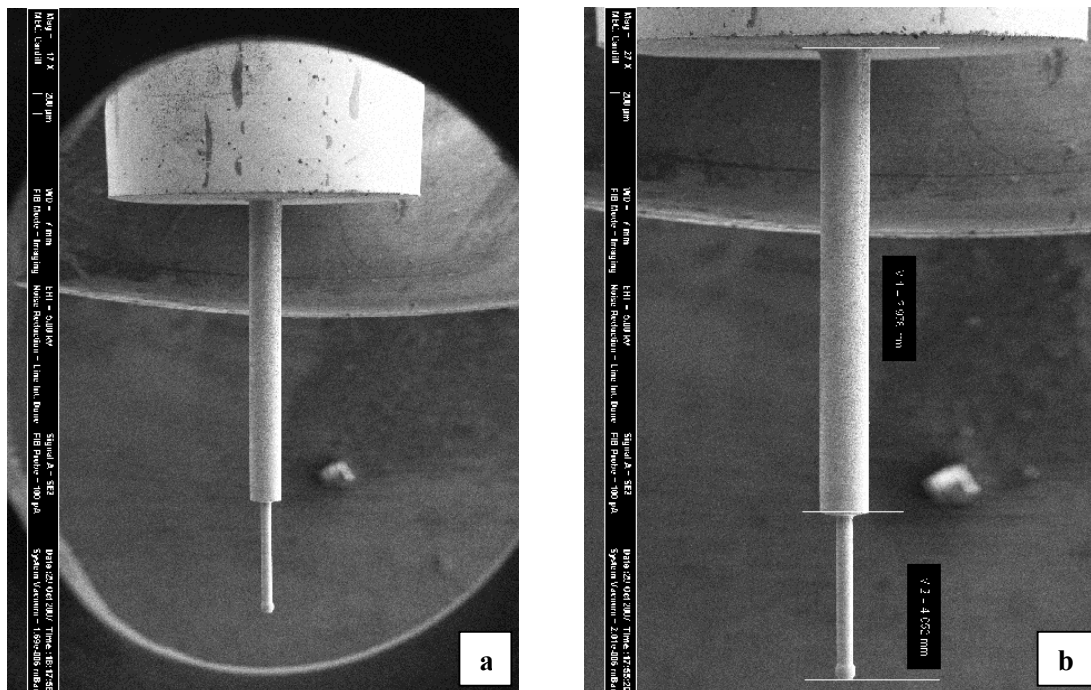


Figure 4: SEM images of a micro-stylus manufactured using WEDG, (a) image of stylus, (b) magnified image of stylus.

The stylus was made from tungsten carbide and its target dimensions are specified in Figure 3. The measured dimensions are reasonably close to the target values, with the stylus shank having a length of 1.07 mm and the stylus tip having a diameter of approximately 126 µm. However,

the sphericity of the tip is relatively poor, with the pole of the tip being quite flattened. This can be explained by insufficient control of the machining process when producing this region. The manufacture of a high quality spherical shape using this process is difficult and requires close control of the rate of travel of the 'cutting' electrode and the rate of erosion of the workpiece.

A potentially greater problem was the relatively rough finish of the stylus tip. The lack of sphericity of the tip can be seen in Figure 5(a), while the poor surface finish can be seen in Figure 5(b). Poor form of the stylus tip would lead to poor probing repeatability if this stylus were to be used in a tactile probing system.

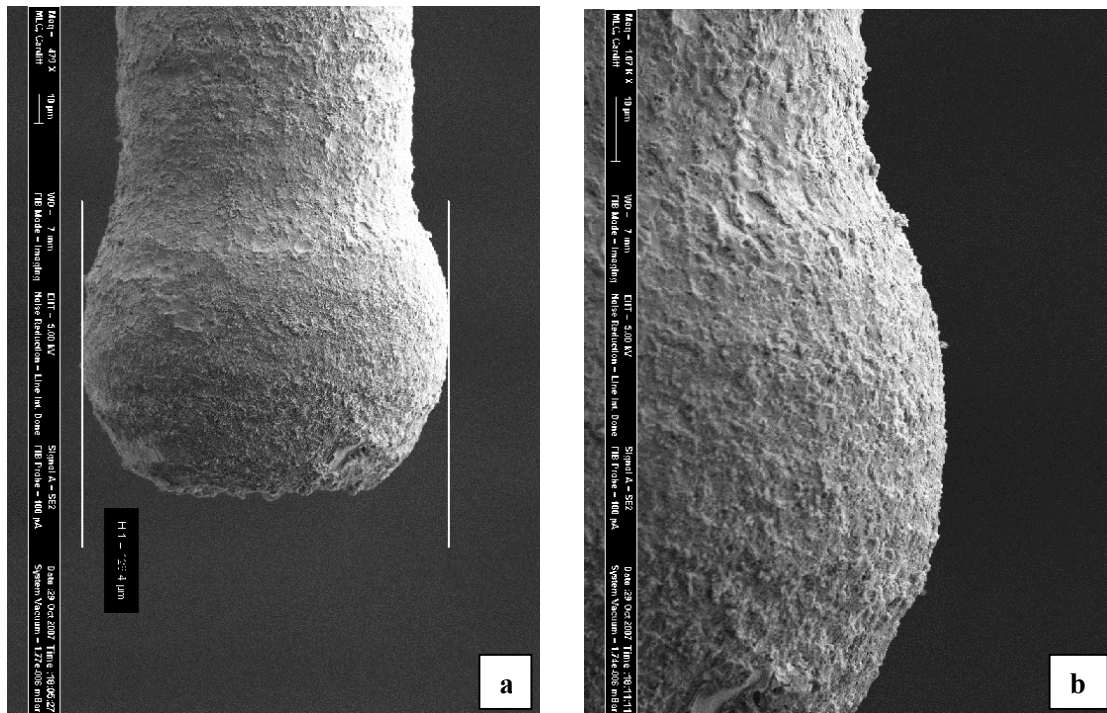


Figure 5: SEM images of a micro-stylus tip manufactured using WEDG, (a) image of stylus tip, (b) magnified image of stylus tip.

A further two styli were manufactured by Cardiff University using the WEDG process. The experience gained in the manufacture of the preliminary styli was employed in an attempt to improve the control of the machining process and, therefore, improve the quality of the manufactured components.

Figures 6 (a) and (b) show SEM images of the first of the two new styli. The diameter of the stylus tip was measured to be approximately 125 μm while the length of the shank region was close to the target dimension of 1 mm.

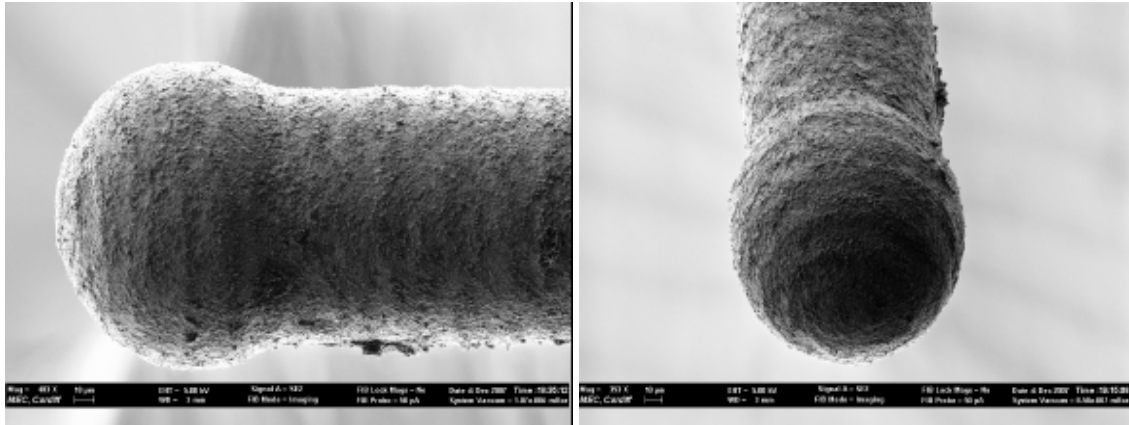


Figure 6: SEM images of second micro-stylus manufactured using WEDG, (a) magnified image of stylus tip, (b) close-up image of tip pole.

The sphericity of this tip is again relatively poor, although in this case, the pole of the tip is quite rounded. In addition, a series of bands can be seen along the length of the stylus. It was thought that these were ‘machining’ bands, analogous to lathe machining marks. The surface finish of this tip was also observed to be poor.

Figures 7 (a) and (b) show SEM images of the second of the new styli. The diameter of this stylus tip was measured to be approximately 60 μm , which is significantly less than the target diameter, and indicates a lack of control of the machining process.

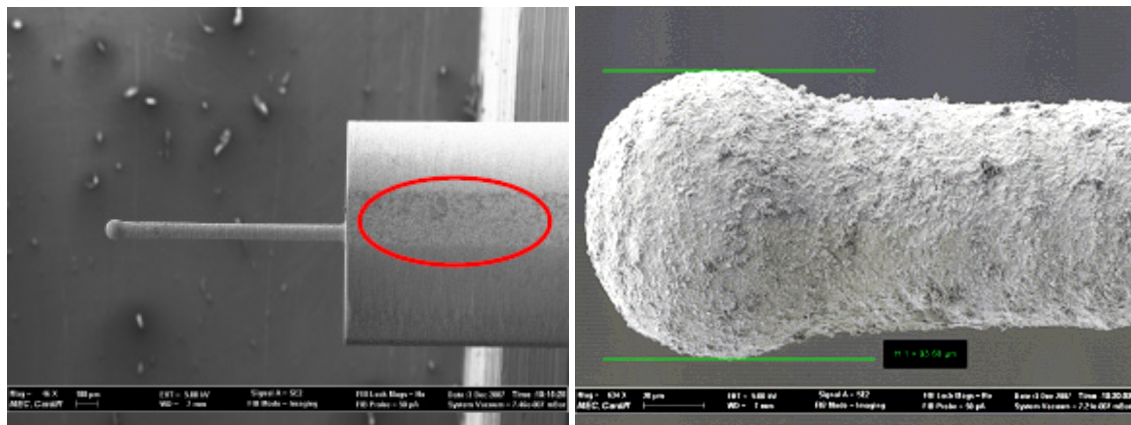


Figure 7: SEM images of third micro-stylus manufactured using WEDG, (a) image of stylus shank and tip, (b) close-up image of stylus tip.

3.3.3 Summary of WEDG manufacturing technique

Although the manufacture of micro-styli using the WEDG process has been shown to be possible, the quality of the first styli produced using this technique were relatively poor. The dimensions of the manufactured styli were close to the target values but the surface finish of the shank and tip was, in each case, poor. In addition, the sphericity of the manufactured tips was of insufficient quality for use in contact probing applications. Further experimentation with material feed and cut rates is required to confirm the suitability of this technique for the production of the micro-styli required for the NPL micro-probe.

3.4 One-pulse electro-discharge manufacturing at the NTUT

3.4.1 *One-pulse electro-discharge manufacturing at the National Taipei University of Technology*

The second technique investigated for the manufacture of micro-styli uses a combination of WEDG technology and one-pulse electro-discharge (OPED) machining. A thin rod of tungsten or tungsten carbide, typically 20 μm to 30 μm in diameter, is produced using WEDG. The tip of the rod is then subjected to a single, high-energy electro-discharge pulse that melts the material. The melted material then rapidly solidifies into a spherical shape due to surface tension.

The Department of Mechanical Engineering at NTUT have been investigating this approach to manufacture micro-spherical probes [25] and the department agreed to produce a set of styli for NPL. The initial styli were made from tungsten with target dimensions the same as those specified in Figure 3.

3.4.2 *Production of initial batch of styli*

To assess the suitability of the technique an initial batch of seven styli (numbered 1 to 7) were manufactured using the OPED process. A series of images of the styli were taken by NTUT and these were despatched to NPL along with the styli for evaluation. A set of the styli images are shown and discussed below.

Stylus 1

Figure 8 is a series of images of Stylus 1. The stylus was mounted on a rotation stage to allow assessment of the quality of the shank and ball tip.

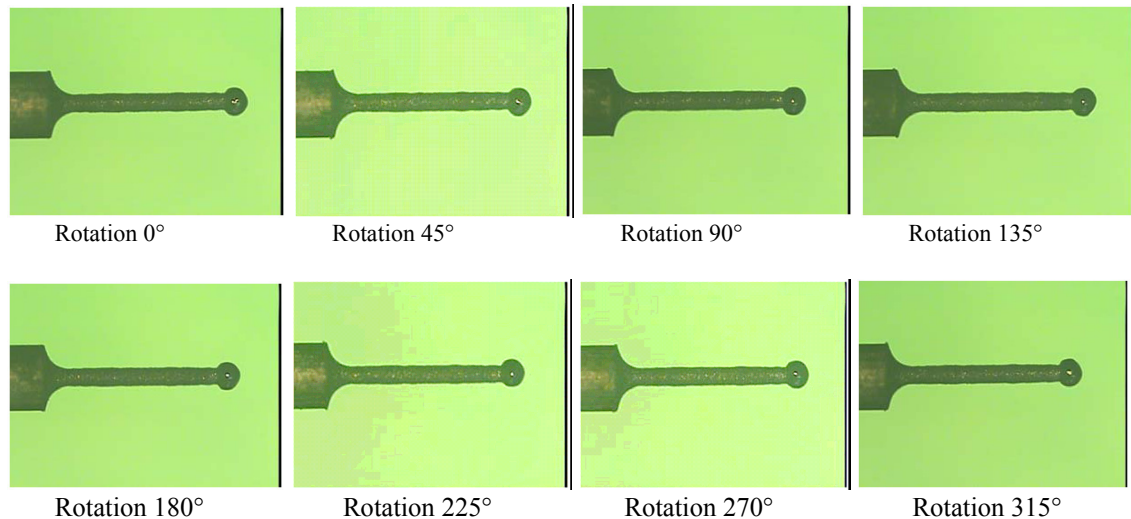


Figure 8: Stylus 1 produced by OPED. Images show stylus being rotated about the probe shank axis.

The images show that the probe tip is reasonably spherical and is fairly well centred on the axis of the stylus. It can be assumed that the surface of the ball tip is quite smooth, as indicated by

the reflection of the camera illumination. However, the sphericity of the ball tip would not be adequate for use in high accuracy co-ordinate metrology applications.

Figures 9 and 10 are images of a further two styli from the first batch produced using the OPED process. Again, the images indicate that the styli are reasonably good, but are of insufficient quality for use in high accuracy, 3D-contact probing applications.

Stylus 2

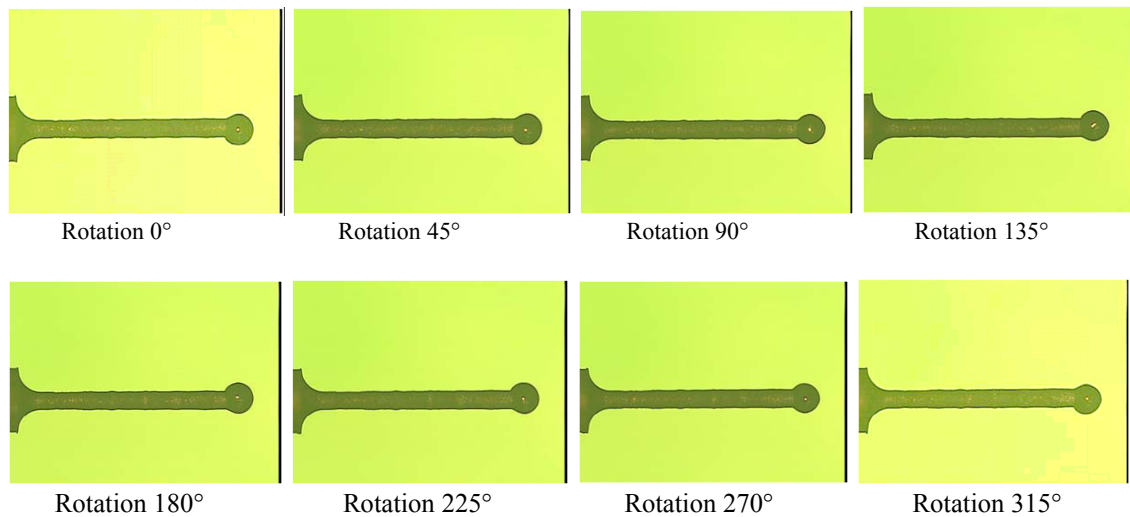


Figure 9: Stylus 2 produced by OPED. Images show stylus being rotated about the probe shank axis.

Stylus 4

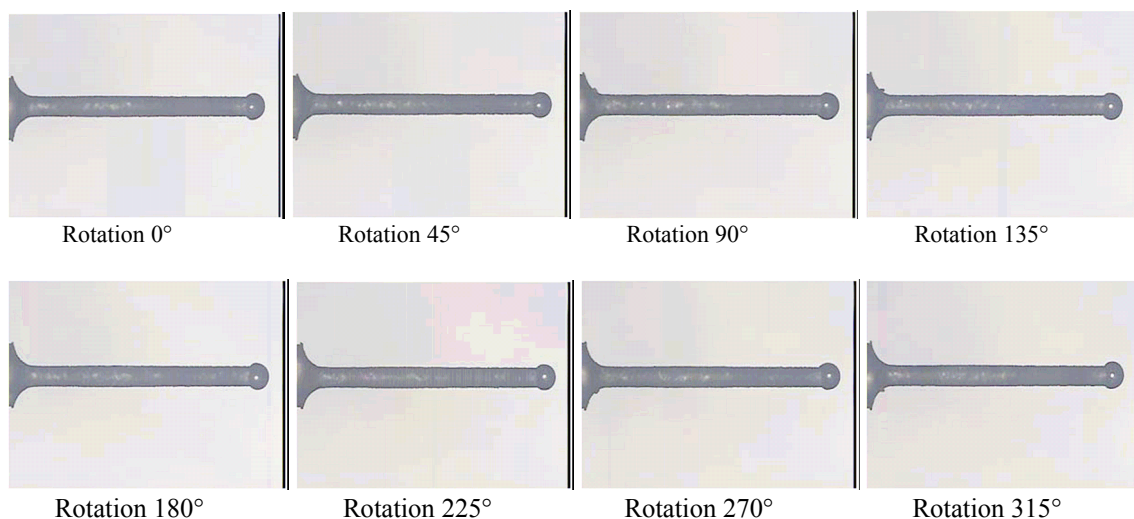


Figure 10: Stylus 4 produced by OPED. Images show stylus being rotated about the probe shank axis.

The dimensions of the first set of OPED styli were also determined using a measuring microscope. The dimensions of Styli 3 and 4 are shown in Table 1 below.

Dimension	Target	Stylus 3	Stylus 4
Stub length/mm	3.0	3.021	3.155
Stub diameter/mm	0.3	0.3	0.3
Shank length/mm	1.0	1.071	1.136
Shank diameter/mm	0.1	0.089	0.092
Diameter 0°/mm	-	0.153	0.121
Diameter 45°/mm	-	0.150	0.117
Diameter 90°/mm	-	0.149	0.121
Diameter 135°/mm	-	0.151	0.122
Diameter 180°/mm	-	0.153	0.121
Diameter 225°/mm	-	0.151	0.117
Diameter 270°/mm	-	0.148	0.122
Diameter 315°/mm	-	0.150	0.124
Mean diameter/mm	0.125	0.151	0.121
Std dev ball dia/mm	0.0005	0.0018	0.0024

Table 1: Dimensions of styli 3 and 4 produced by the OPED manufacturing process.

The measured dimensions indicate that the manufacturing process was reasonably controllable, with the actual dimensions being close to the target dimensions. However, the measurements of the ball tip diameter show that the tip is quite aspherical with standard deviation values of 1.8 μm and 2.4 μm . This compares with the target value of 0.5 μm in the mean diameter.

In discussions about the manufactured styli, NTUT explained that the diameter of the tips requested by NPL was larger than ideal for this manufacturing process and that smaller tips were likely to have a better sphericity. The styli reported in [25] had diameters around 50 μm . A smaller tip diameter is achieved by reducing the diameter of the rod produced by WEDG machining prior to applying the discharge pulse.

3.4.3 *Summary of OPED manufacturing technique*

The combination of the WEDG and OPED manufacturing processes proved capable of producing micro-styli of the correct dimensions and of reasonable quality. Visual inspection indicated that the probe tips were much smoother than those produced by WEDG alone. Although the spherical forms of the tips produced were relatively poor, it was thought that this could be improved upon by producing a smaller tip diameter.

Because the smooth ball tip produced using the WEDG/OPED process was more suitable for use as a contact stylus than those produced by WEDG alone, a second set of styli were ordered from the NTUT for further experiment and evaluation.

3.5 Design of the second set of micro-styli produced by OPED

It was decided to investigate whether it was possible to attach one of the new batch of micro-styli produced by the OPED process to the silicon wafer membranes produced by Zeiss for use with their F25 micro-CMM probes. Since NPL has an F25 CMM, incorporation of one of the micro-styli into a probe element compatible with the F25 provided a possible means of testing the mechanical integrity of the styli.

The geometry of the stylus was changed to make it compatible with the silicon membrane. Figure 11 shows the new geometry and the target dimensions of the modified stylus. The most obvious changes are an increase in the dimensions of the probe stub and the addition of a locating bush on the end of the stub. The bush locates, and is glued, into a mating hole in the silicon membrane of the Zeiss probe. The target diameter of the probe tip was reduced to 60 μm to assess whether the sphericity of the tip could be improved.

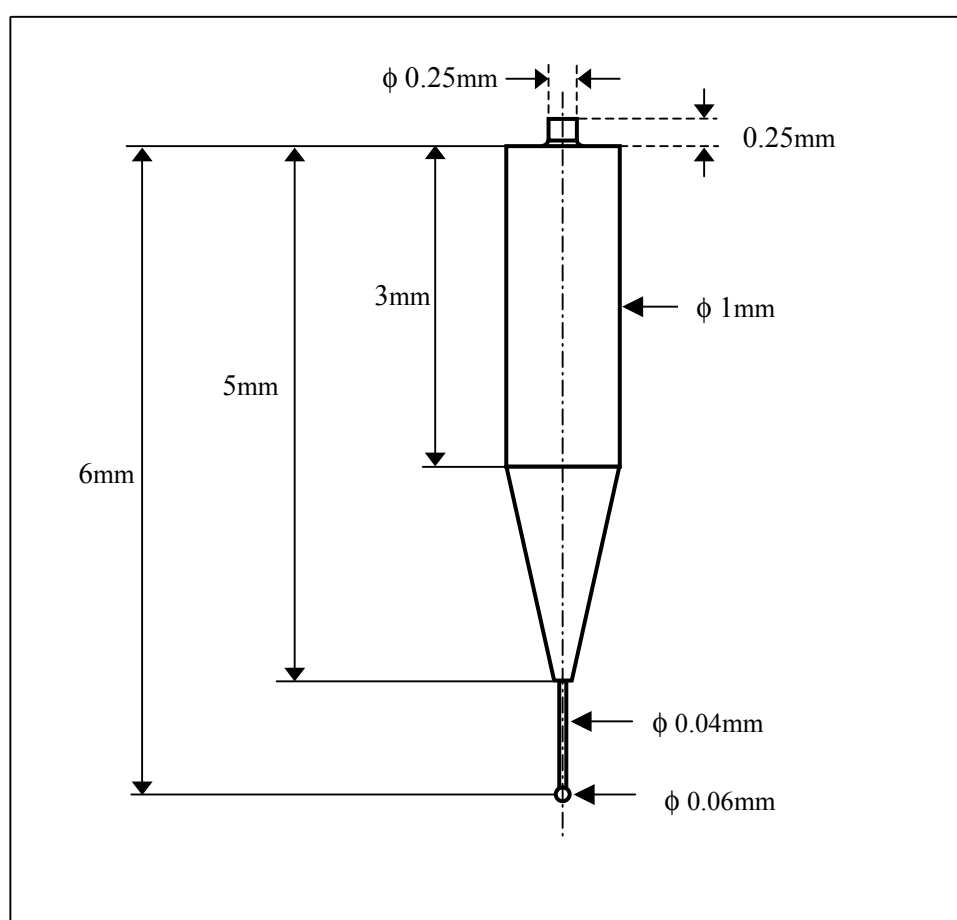


Figure 11: Sketch showing the modified dimensions of the OPED micro-stylus.

A total of four modified styli were successfully produced by NTUT and were despatched to NPL for further evaluation (see Section 5). In this case, no images of the styli were provided so it was not possible to assess the quality of the manufactured components at this stage.

3.6 Micro-styli manufacturing techniques: summary

Two micro-manufacturing techniques, WEDG and a combination of WEDG and OPED, were investigated with respect to their suitability for the production of the micro-stylus elements required for the NPL micro-probe.

Cardiff University produced a set of micro-styli using WEDG manufacturing. Although the dimensions of the manufactured styli were close to the target values, the sphericity and surface finish of the styli tips were poor. Although it may be possible to produce styli of an appropriate quality using this technique, further investigation of the machining process is required.

NTUT produced a set of micro-styli using a combination of WEDG and OPED manufacturing. The dimensions of the manufactured styli were again close to the target value, but in this case the surface finish of the stylus tip was significantly better. Although the sphericity of the manufactured tips was not of a suitable quality for use in contact probing applications, it was thought that the tip sphericity could be improved by reducing the target dimension of the tip diameter. A further set of modified styli was produced by NTUT for incorporation into probe elements compatible with a commercial micro-CMM.

4 The NPL/Zeiss micro-probes

4.1 Assembly of NPL/Zeiss micro-probes

The second set of styli produced by NTUT to the modified design requirements were sent to Carl Zeiss, in Germany, for assembly onto the silicon chip membranes used in the F25 SSP (small scanning probe) contact probes. The probes used on the F25 are designed to operate with a probing force of 500 μN and this makes the CMM an idea platform for testing the extremely small (and, therefore, delicate) micro-styli. An additional advantage of the F25 is the presence of the visualisation camera on the probe head to prevent damaging the micro-stylus when nearing a test surface.

The ability to attach the styli onto a co-ordinate measurement system at this stage is highly desirable since it allows the styli to be assessed, both in terms of their structural integrity and with regard to their suitability for use as CMM probe elements. A total of four probes were assembled and assessed at Zeiss, the probes being identified as NPL-1 to NPL-4.

4.2 Assessment of the NPL/Zeiss micro-probes at Zeiss

A series of images of the assembled probes were taken at Zeiss using a measuring microscope to check features such as the sphericity and dimensions of the ball tip and the stylus shank. In addition to a visual inspection, Zeiss performed some preliminary functional (probe qualification) tests on the four assembled probes using one of their F25 CMMs. However, only two of the probes proved to function correctly (NPL-1 and NPL-4) and these probes were sent to NPL for further functional testing on the NPL F25 CMM. Figure 12 is an image of one of the delivered micro-probes.

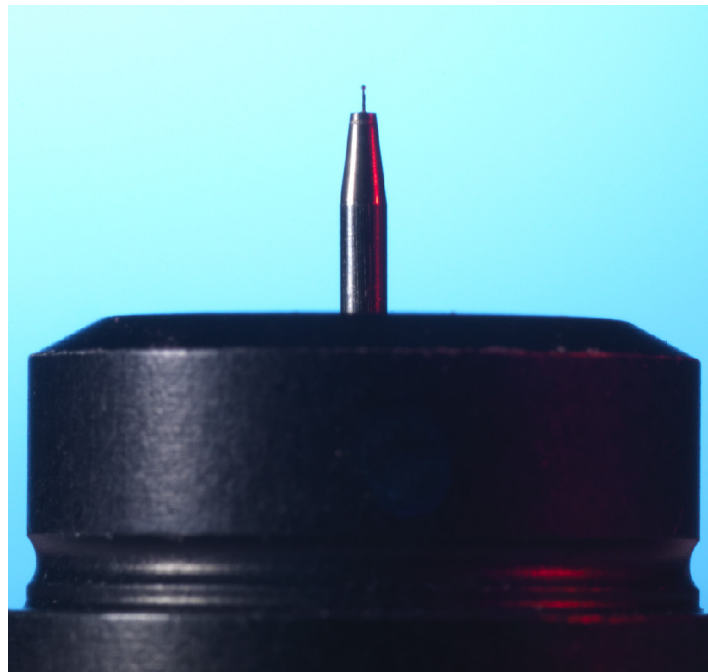


Figure 12: Image of an assembled NPL/Zeiss micro-probe.

Micro-probe NPL-1

Figures 12, 13 and 14 are a series of images provided by Zeiss of micro-probe NPL-1 showing the measured dimensions of the constituent regions.

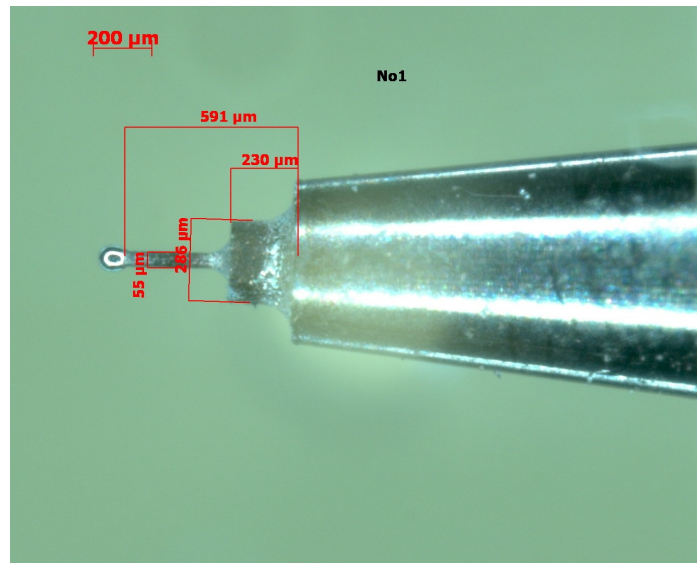


Figure 13: Measuring microscope image of NPL/Zeiss microprobe NPL-1 showing the probe tip, shank, and stub regions.

Of particular note in Figure 13 are the values for the length 361 μm and diameter 55 μm of the probe shank. In Figure 13 the stylus appears fairly well centred on the probe stub. However, Figure 14 shows the probe rotated by 90° and it is apparent that, viewed from this orientation, the shank is actually misaligned from the axis of the stub.

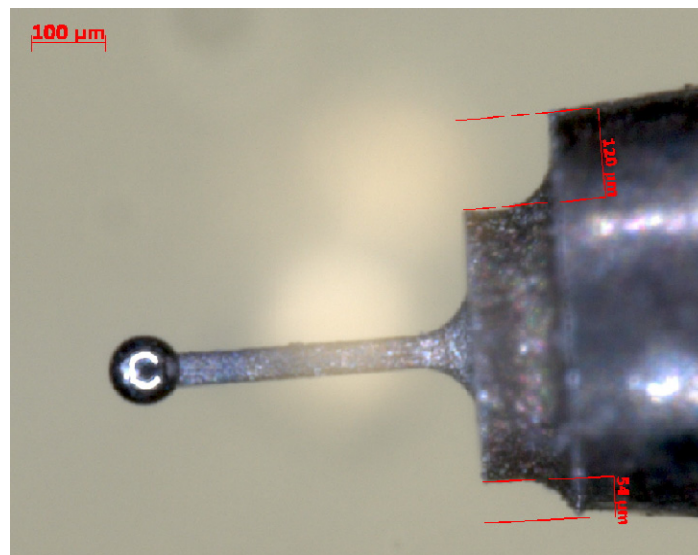


Figure 14: Measuring microscope image of NPL/Zeiss microprobe NPL-1 showing the misalignment of the shank and stub axes.

Figure 15 is an image of the stylus tip. The diameter of the tip was measured as 97 μm and the tip looks reasonably spherical. In addition, the tip surface looks smooth, as indicated by the

strong reflection of the microscope illumination source. However, the centre of the ball tip is not aligned with the axis of the shank.

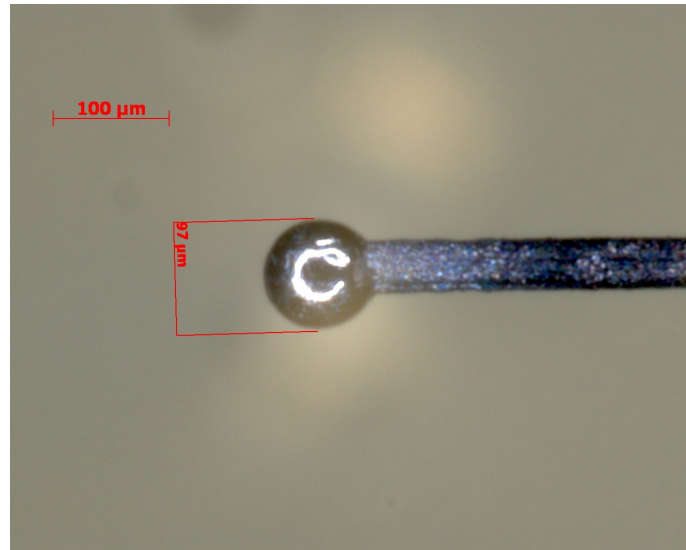


Figure 15: Measuring microscope image of NPL/Zeiss microprobe NPL-1 showing the probe tip.

Micro-probe NPL-4

Figures 16 and 17 show images of micro-probe NPL-4. It is apparent from Figure 16 that the shank region is less well defined in this probe, with the shank apparently tapering upwards towards the stub region. Again, the stylus appears misaligned with respect to the axis of the probe stub.

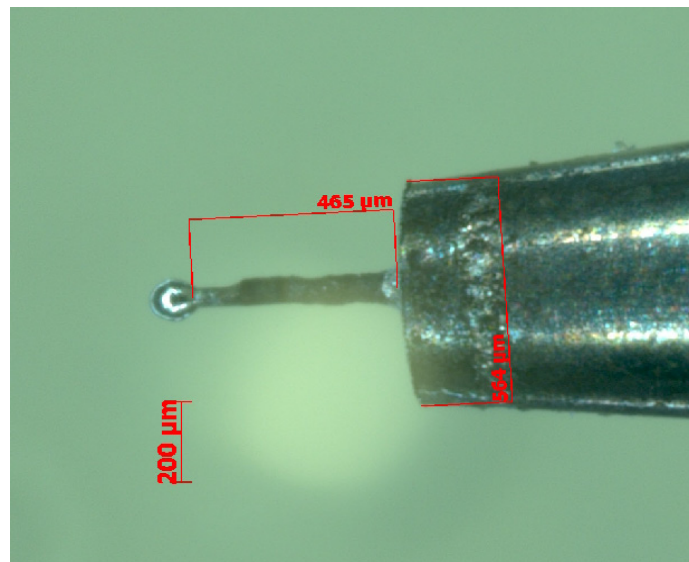


Figure 16: Measuring microscope image of NPL/Zeiss microprobe NPL-4 showing the probe tip, shank, and stub regions.



Figure 17: Measuring microscope image of NPL/Zeiss microprobe NPL-4 showing the probe tip.

Figure 17 is an image of the stylus tip. The diameter of the tip was measured as 98 µm but in this case the tip does not look spherical, appearing slightly compressed in the direction of the shank axis. However, the probe tip surface again looks reasonably smooth.

The lack of cylindricity of the probe shank is very apparent in this image, with what appears to be a step in the shank a short distance from the tip. In operation this non-uniformity of the shank cylinder is undesirable because of the potential of contacting the shank rather than the probe tip during probing, especially if, for example, measuring down a hole.

It was not possible to make a quantitative assessment of the spherical form of the stylus tip from the images shown above. Zeiss did not supply images of micro-probes NPL-2 and NPL-3 because, as noted previously, these probes did not pass a preliminary functionality test (subsequent communication with Zeiss indicated that this was due to the poor sphericity of the ball tips).

4.3 The NPL/Zeiss micro-probe: summary

The four micro-styli manufactured by NTUT using the WEDG/OPED manufacturing technique were sent to Zeiss and were successfully assembled onto the SSP membranes used by the F25 CMM. Only two of the four assembled probes were found to function correctly when tested at Zeiss and these probes were despatched to NPL for further testing and evaluation.

Zeiss also provided a series of calibrated (dimensioned) images of the functioning probes showing the dimensions of the constituent regions of each stylus. From the images it was also possible to make qualitative assessments of some of the important characteristics of the styli such as the tip smoothness and shank alignment. The successful incorporation of the styli into the SSP mounts meant that the styli could be fitted to the F25 at NPL for testing.

5 Testing of the NPL/Zeiss micro-probe

5.1 The NPL/Zeiss micro-probe on the F25 CMM

Micro-probe NPL-1 was fitted to the NPL F25 for testing and evaluation. The NPL/Zeiss micro-probe locating insert is identical to that of a conventional F25 SSP and is installed in the same manner. After installation, the mass of the micro-probe was counterbalanced using the F25 test software AutoOffset programme.

The probe amplification factors were entered and stored in the F25 BossFactor.ini file. There are three amplification factors, one for each axis x , y and z , relating to the probing deflection parameters for a particular probe. The amplification factors are unique to each probe and are determined by Zeiss at the probe manufacturing stage. The amplification factors are noted below, along with the amplification factors of a typical SSP probe for comparison.

<u>NPL/Zeiss</u>		<u>F25 SSP</u>
Ser No.	NPL-1	6201519100-000
Chip	W024C046	W029C007
X	0.06966	0.048514
Y	0.077555	0.048126
Z	-0.007127	-0.005621

The probe output values to the machine controller were recorded from the Mini-Commander CMM Controller display window and are noted below:

X	70.975794	Y	-62.499287	Z	-46.803261	probing point		
mx	1.000	my	1.000	mz	1.000	selected force		
MX	-.001	MY	-.001	MZ	.012	actual force		
A	-.01715	B	-.00309	C	-.04581	D	-.09451	output

The output signals in the Controller display window were observed to be 'live' and similar to those produced by a conventional F25 SSP probe, indicating that micro-probe NPL-1 was functioning correctly.

5.2 Qualification of the NPL/Zeiss micro-probe

Before performing measurements on a test artefact it was necessary to qualify the probe. Probe qualification provides a means by which the probe ball's centre co-ordinates and diameter are determined. This information is required by the CMM during measurement of a component in order to determine the co-ordinates of a probed point. Probe qualification is achieved by probing a high quality sphere (normally referred to as a reference or qualification sphere) of a known diameter and sphericity. The F25 has a built-in routine within the machine's Calypso™ operating software that performs the qualification operation.

In normal operation of the F25 a reference sphere of diameter 6.35 mm is used for probe qualification. However, because of the short shank length of the NPL/Zeiss micro-probe, a much smaller reference sphere had to be used. An unused CMM probe, with a ball tip diameter of 1 mm, was used as the reference sphere. Figure 18 shows the micro-probe positioned above the much larger 1 mm diameter sphere.

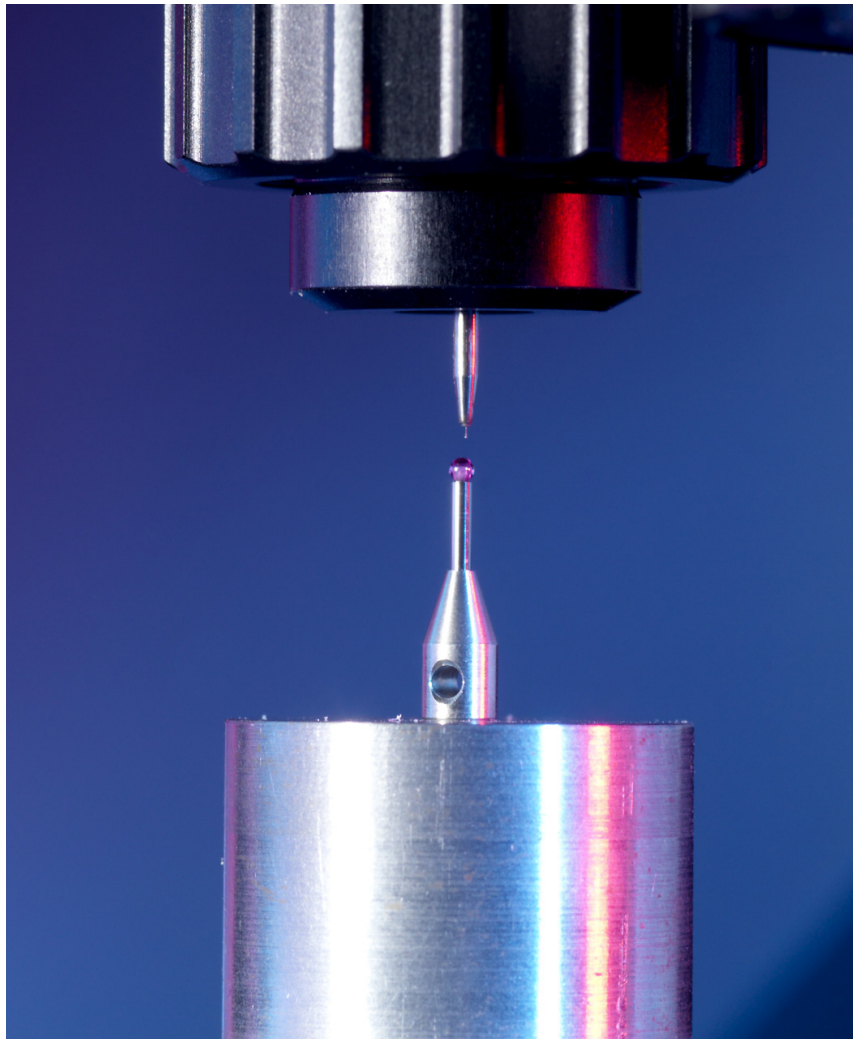


Figure 18: NPL/Zeiss micro-probe positioned above the 1 mm diameter sphere used to qualify the probe.

The dimensional parameters of the reference sphere were entered into the F25 operating software before performing the qualification routine. The nominal diameter was set as 1.000 mm, with the nominal form error set as 127 nm (corresponding to a Grade 5 ball). The dynamic response of the probe can be set at the probe qualification stage to take into account the compliance of the measurement surface. In this case, the qualification was carried out using the standard 100 % value for the probing dynamic, the default value for an inelastic surface.

The Calypso™ probe qualification routine was run several times to evaluate the quality of the micro-stylus and to determine the necessary probe data; the probe ball diameter, the probe ball form and the probe ball centre co-ordinates. The qualification routine drives the probe under computer control to contact the reference sphere at several points (and, in the case of the F25, at three probing forces) over its upper hemisphere.

The qualification routine reports the probe ball radius and probe ball form (calculated by assuming the form of the reference sphere to be perfect). These results are given in Table 2 and were calculated from fifteen data sets.

	Radius/mm	Form/mm
Mean	0.047 542	0.000 180
Std Dev	0.000 012	0.000 002
Max	0.047 562	
Min	0.047 518	
Range	0.000 044	

Table 2: Micro-probe parameters generated by the Calypso™ software probe qualification routine for micro-probe NPL-1.

The results obtained from the qualification routine indicated that the micro-stylus ball tip had a calculated mean diameter of 0.095 084 mm, with a form error of 0.000 180 mm. The diameter was larger than the target diameter of 0.060 mm and the form error is a factor of 1.4 worse than a conventional Grade 5 CMM probe stylus. The results are, however, very repeatable and indicate that the stylus is sufficiently robust to be used as a tactile probe.

5.3 Dimensional measurements using the NPL/Zeiss micro-probe

Micro-probe NPL-1 was used to make a series of measurements on two reference artefacts, a high quality sphere and a calibrated gauge block, to confirm functionality and assess performance. The reference artefacts were then re-measured by the F25 using a standard SSP probe and the measurement data was compared.

Micro-probe NPL-1

5.3.1 Reference sphere measurements

Measurements were initially made of the same 1 mm diameter probe stylus that was used in the probe qualification procedure. Although in normal CMM operation the qualification sphere should not be used to evaluate the probing error, the short length of the probe stylus meant that there were a limited number of reference artefacts suitable for measurement and, since the prototype stylus was not going to be used for metrological work, the procedure was considered acceptable.

The 1 mm ball was probed at 145 points over its upper hemisphere, with one point on the pole and the remainder evenly spaced in eight concentric rings with a vertical spacing 0.062 5 mm, which included thirty-two points on the equatorial ring. A number of characteristics of the 1 mm ball were reported including the diameter, spherical form and the standard deviation of the measurement data. The ball was also rotated about a vertical axis by 90° and re-measured. The results from these measurements are given in Table 3, with the reported values calculated from five data sets.

	initial position		rotated 90°	
	Mean/mm	Std Dev/mm	Mean/mm	Std Dev/mm
diameter	0.999 854	0.000 003	0.999 885	0.000 069
form	0.001 591	0.000 019	0.002 308	0.000 646

Table 3: Measurement of a 1 mm diameter sphere using micro-probe NPL-1.

The reported spherical form error of the 1 mm ball is relatively large. Because the nominal form error of the ball is 0.000 127 mm (and because the quality of CMM probe balls is invariably very good), any form error seen in the measurement of the sphere will most likely be caused by a lack of sphericity of the micro-stylus ball tip.

The standard deviation of the reported characteristics when measured in the initial position was reasonably low indicating that the stylus was making repeatable measurements. This indicates that the stylus is reasonably robust and is not deforming, either elastically or inelastically, through the contact probing process. The discrepancy between the measurement data in the two orientations will be discussed later in this section.

A series of measurements around the equator of the 1 mm ball were also made and the roundness is reported. The equator was measured both as a series of single points (sixty-four points), and in scan mode (approximately 1900 points) where the measuring probe tip was in continuous contact with the test surface. The sphere was again rotated by 90° and re-measured. The roundness measurements are given in Table 4, with the reported values calculated from five data sets.

	initial position		rotated 90°	
	Mean/mm	Std Dev/mm	Mean/mm	Std Dev/mm
roundness single point	0.000 732	0.000 004	0.000 713	0.000 006
roundness scan	0.000 868	0.000 005	0.000 879	0.000 008

Table 4: Single point and scan roundness measurement of a 1 mm diameter sphere using the micro-probe NPL-1.

The reported roundness is quite poor and again can be explained by the lack of sphericity of the stylus ball tip. This is clearly illustrated in Figures 19 (a) and (b), which show roundness plots of the equator of the 1 mm sphere generated by the Calypso™ operating software. Here the equator of the 1 mm sphere has been measured twice, with the sphere rotated by 90° between the two sets of measurements.

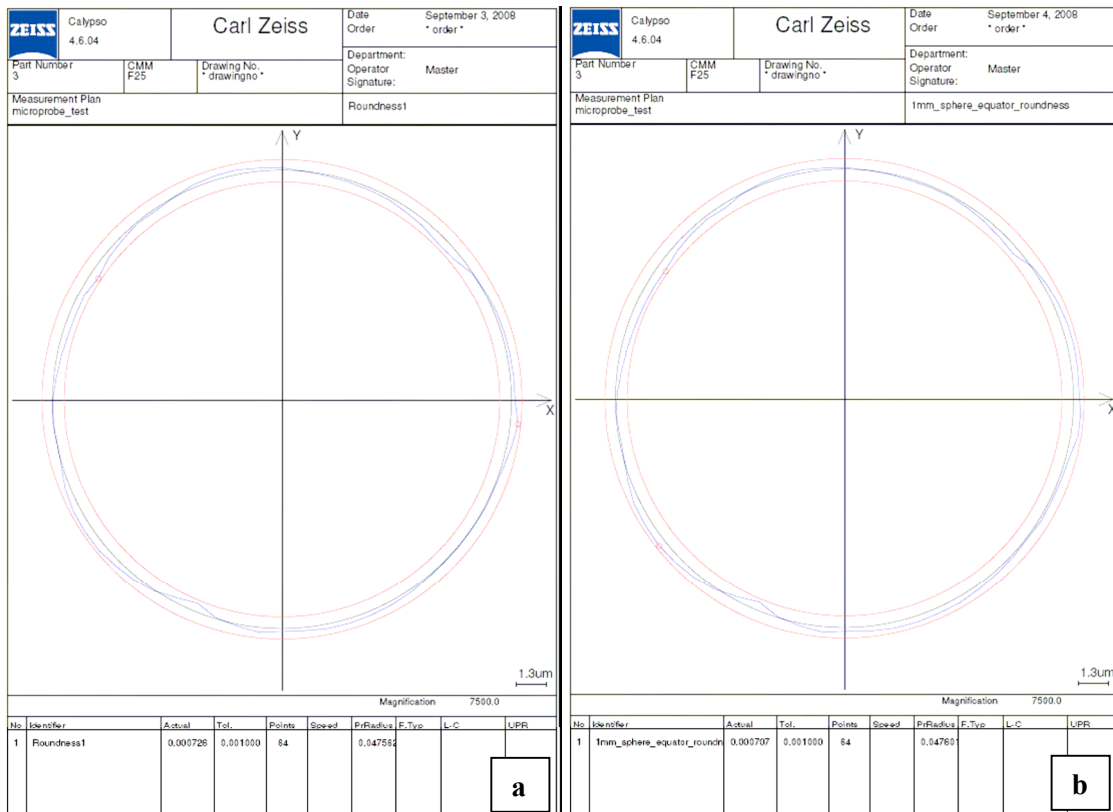


Figure 19: Roundness plots of the equator of the 1 mm sphere, (a) measured in the initial position, (b) measured after a 90° rotation.

The same features can be seen in both traces and at the same position of both plots. If the form errors were due to imperfections in the 1 mm sphere they would have been observed to rotate by 90° in Figure 19 (b). The form error is therefore caused by a lack of sphericity of the probe ball.

To confirm the above conclusions, the 1 mm ball was re-measured using a conventional F25 SSP probe. The roundness results are given in Table 5, along with the results obtained using the micro-probe NPL-1 for comparison.

	F25 SSP probe		NPL1 micro-probe	
	Mean/mm	Std Dev/mm	Mean/mm	Std Dev/mm
roundness single point	0.000 230	0.000 005	0.000 732	0.000 004
roundness scan	0.000 396	0.000 005	0.000 868	0.000 005

Table 5: Comparison of roundness measurements obtained using micro-probe NPL-1 and a conventional F25 probe.

It can be seen that the roundness results obtained using a conventional F25 SSP probe are better than those obtained using micro-probe NPL-1 confirming that the observed roundness error is due to the lack of sphericity of the micro-probe ball tip.

It would appear from the results shown in Table 5 that the roundness figure achieved using the F25 SSP probe is significantly worse in scan mode than in single point mode. Although this may be possible because the point density in scan mode is far greater than in single point mode (and there is consequently a greater chance of contacting an 'outlier' point), the magnitude of the difference observed here is still greater than would be expected. Further investigation indicated that the surface of the 1 mm sphere had become contaminated and subsequent measurements made in scan mode after the 1 mm sphere had been thoroughly cleaned produced a roundness error of 152 nm. Although this is still a little higher than the nominal form error of a Grade 5 probe ball it was thought that this was due to residual contamination on the SSP probe.

It is believed the source of the contamination was material that had been rubbed off the ball tip of the NPL/Zeiss microprobe while the probe was scanning the 1 mm sphere. Conventional CMM probe tips are generally ruby balls that are extremely hard and durable. The tungsten tip of the micro-probe is softer in comparison. It is also possible that the surface layer of the tungsten tip is even softer than the bulk material due to the physical processes that occur as the tip is coalescing into a sphere after the OPED process.

5.3.2 Gauge block measurements

A series of measurements were made of a 10 mm nominal length gauge block to assess the performance of the micro-probe when probing in a single direction. The length of the gauge block was measured to observe the probing performance in the x and y directions, and the flatness of the lapped surface was measured to observe the performance in the z direction.

(a) Length measurement

The gauge block was placed on the F25 CMM with the block calibration length direction aligned with the machine x axis. A local co-ordinate system was constructed on the gauge block, with the top of the block defined as the $z = 0$ plane. The length of the gauge block was determined by reporting the distance between corresponding pairs of points on the opposing gauge lapped faces. The distance was reported at five equally spaced, lateral positions along the faces of the gauge block at a height $z = -0.3$ mm, and with the measurements repeated five times.

The gauge block was then rotated by 90° such that it was aligned with the y axis of the F25 and the measurement procedure describe above repeated.

The short length of the probe shank (from Figure 13, approximately 0.37 mm) meant that it was not possible to probe any lower in the z direction. However, it also meant that it was not possible to compare the measurement data obtained with the calibrated length of the gauge block since the specification dimensions of the chamfer on the edge of a gauge block is approximately 0.5 mm. The pairs of points probed at $z = -0.3$ mm were therefore liable to be in the chamfer region of the gauge block. It was possible to check the measurement data for repeatability and, therefore, make some assessment of the quality of the micro-probe.

The reported length measurements with the gauge block in both alignment orientations are given in Table 6. The Table shows both the individual measurements in each of the five lateral positions and the mean and standard deviations of the five, recorded data sets.

Alignment with x-axis	Mean length/mm		Alignment with y-axis	Mean length/mm
Position 1	9.998 950		Position 1	9.998 709
Position 2	9.998 942		Position 2	9.998 686
Position 3	9.998 912		Position 3	9.998 701
Position 4	9.998 900		Position 4	9.998 713
Position 5	9.998 890		Position 5	9.998 704
Mean	9.998 919		Mean	9.998 702
Std Dev	0.000 026		Std Dev	0.000 010

Table 6: Measurement of a 10 mm nominal length gauge block using micro-probe NPL-1.

The reported length data is close to the calibrated gauge block length (9.999 823 mm) given that the micro-probe is most likely contacting in the chamfer region at the edge of the block. There is also a fairly close agreement (approximately 200 nm) between measured dimensions in x and y alignment directions. The low standard deviations of the measurement data in both orientations indicates that the performance of the micro-probe is very repeatable and again shows that the micro-stylus is suitable for tactile probing, having no apparent elastic or inelastic deformation of the probe.

(b) Flatness measurement

The lapped surface of the gauge block was probed over a rectangular pattern of 200 points and the measured flatness is reported. The measurement was repeated five times and the results recorded. The same area of the gauge block surface was then re-measured using a conventional F25 SSP probe and the data again recorded. The mean values of the recorded flatness measurements are given in Table 7.

	Flatness	
	Mean/mm	Std Dev/mm
NPL/Zeiss microprobe	0.000 145	0.000 007
Standard F25 probe	0.000 159	0.000 007

Table 7: Measured flatness of the lapped surface of a gauge block using micro-probe NPL-1 and a conventional F25 probe.

The flatness values measured with both probes are in good agreement but the magnitudes are larger than would be expected for the lapped face of a Grade K gauge block (flatness < 50 nm). The flatness of the gauge block had also been measured using the micro-probe in scan mode and

it was thought that the surface of the gauge block had possibly become contaminated by debris being removed from the tip of the micro-probe during the scan. Subsequent cleaning and re-measurement of the gauge block using the F25 SSP probe gave a reported flatness value of $0.052\text{ }\mu\text{m}$.

Figures 20 (a) and (b) show Calypso™ generated flatness plots obtained with each probe and illustrates the good agreement obtained between the probes when measuring flatness.

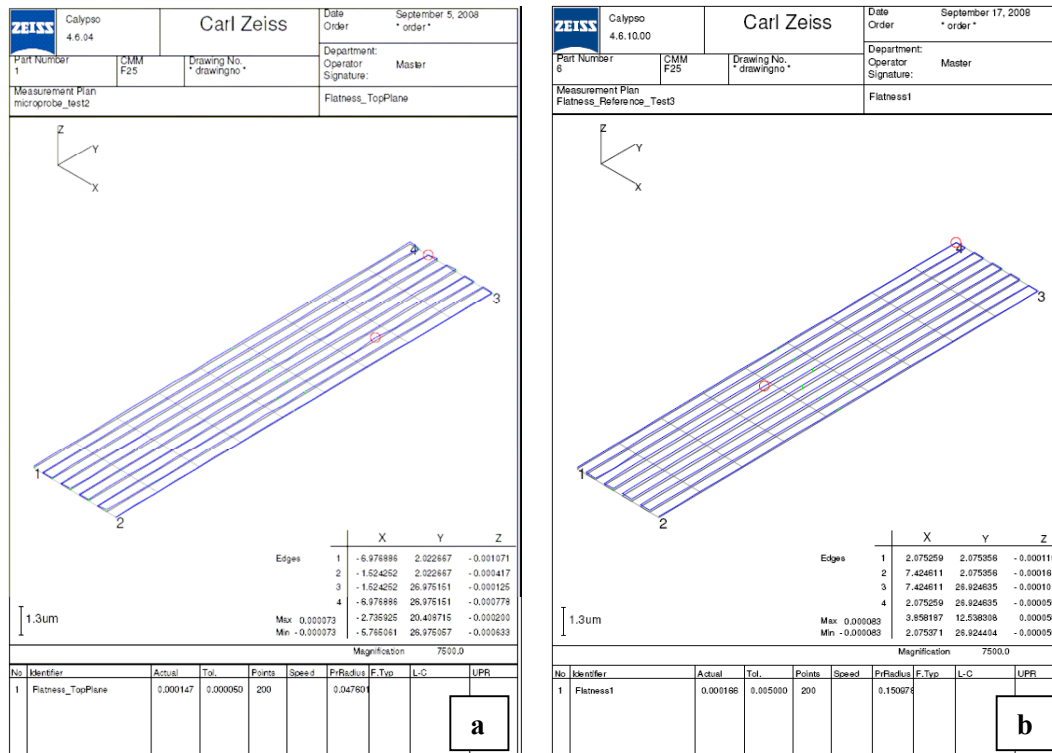


Figure 20: Flatness plots of a rectangular array of points probed on the face of a gauge block. Measurement data recorded using (a) micro-probe NPL-1 and (b) a conventional F25 probe.

Micro-probe NPL-4

Micro-probe NPL-4 was fitted to the F25 with the aim of repeating the test and evaluation measurements described above. Although the output signals in the Controller display window were observed to be ‘live’ and similar to those produced by a conventional F25 SSP probe, indicating that the micro-probe was producing appropriate electrical output signals, it was not possible to complete the Calypso™ qualification procedure on this micro-probe. The qualification routine failed to terminate properly and generated an error message.

The qualification routine produces such an error message when the calculated sphericity of the probe tip is outside predetermined parameters. This error message is commonly observed if either the probe ball tip or the reference sphere is contaminated. It was not possible to clean the micro-probe tip, but the 1 mm reference sphere was removed from the CMM and thoroughly cleaned. However, further attempts to run the Calypso™ qualification routine also proved unsuccessful.

It was thought that the observed failure was due to the inherent lack of sphericity of the tip of NPL-4. The measuring microscope image of probe NPL-4 shown in Figure 17 suggests that the sphericity of the ball tip is indeed relatively poor.

5.4 NPL/Zeiss micro-probe tests: summary

A number of micro-styli manufactured by NTUT using the OPED process were incorporated into the SSP components used on the Zeiss F25 CMM. Although four of these modified SSP components were assembled, only one of the probes proved to function correctly.

The modified probe was fitted to the NPL F25 and a series of measurements were performed on a set of reference artefacts to assess the functionality of the stylus element. The output of these tests was generally positive, with the probe performing reasonably well as a contact probe. The stylus proved capable of withstanding contact probing events, and the measurement data obtained seemed to indicate that the stylus was sufficiently robust to generate reliable contact probing data.

The principle limitation of the stylus investigated here, with regard to its suitability for use in contact measuring applications, was the poor sphericity of the stylus tip, made apparent by the quality of the data obtained from the reference artefact measurements. A further limitation is the low hardness of the stylus material, which in use, may lead to excessive wearing of the tip and potential contamination of the component under test. However, the OPED technique has been shown to be capable of producing micro-styli elements on a scale similar to those that will be required by the NPL micro-probe system.

6 Conclusions

Two micro-fabrication techniques have been investigated to assess their suitability for use in the manufacture of micro-styli elements. The manufacturing processes were used to produce sets of ball-ended micro-styli suitable for use in contact probing applications. The techniques used to produce the micro-styli were WEDG, and a combination of WEDG and OPED. Because of the specialised nature of these processes, manufacturing was carried out at two external research organisations to a specification produced by NPL. The target dimensions of the styli were chosen such that the manufactured styli were suitable for use in miniature, co-ordinate measurement applications.

A set of styli was produced by Cardiff University using WEDG manufacturing. The technique was shown to be capable of producing styli of the required dimensions. However, the quality of the initial batch of ball tips was inadequate for use in high-accuracy contact probing applications. When viewed using an SEM the surface of the tip appeared rough with obvious machining marks, and the shape of the tip was not spherical. Further investigation of this technique is required before its suitability for the manufacture of micro-styli can be confirmed.

A set of styli were produced by NTUT using a combination of WEDG and OPED. This technique was also shown to be capable of producing styli of the required dimensions. Visual inspection using a measuring microscope again indicated that the sphericity of the ball tips was relatively poor. However, in this case the surface finish of the tips appeared much smoother.

In order to assess the mechanical performance of the micro-styli elements a second set of styli were manufactured using WEDG/OPED. The geometry and dimensions of the second batch was modified to allow the styli to be configured as SSP probes used by the Zeiss F25 CMM. One of these hybrid probes was evaluated on the F25 at NPL by performing a series of measurements on a set of reference artefacts. The probe proved to be mechanically sound, although the measurement data obtained confirmed that the sphericity of the ball tip was relatively poor.

The spherical form of the tip tested was not of a sufficient quality to be used in high accuracy metrological applications. However, it may be possible to improve the tip sphericity by reducing the diameter of the ball tip (and, by necessity, the diameter of the precursor stylus shank). Since the formation of the tip by surface tension effects should take place at a quicker rate if the amount of molten material is reduced, it is reasonable to expect that the shape of the tip will be more spherical the quicker it solidifies.

Although it would have been possible to ask the NTUT to manufacture smaller styli, it would not have been possible to evaluate these styli on the F25 CMM. The probe technology employed by the F25 uses a bridge array of micro-strain gauges deposited on a patterned silicon wafer structure, with contact of the probe ball tip during probing being indicated by a change in the output of one or more of the strain gauges. Although the magnitude of the default probing force of the F25 is low in comparison to a conventional CMM, of the order of 0.5 mN compared to 50 mN, even this low value would have been likely to cause a smaller stylus shank to bend or potentially break during probing (the magnitude of the probing force is effectively defined by the stiffness of the patterned silicon wafer structure). Evaluation of a stylus with smaller dimensions will only be possible if the probing force experienced by the stylus during the probing process is reduced. It is not possible to reduce the probing force on the F25 whilst still maintaining the metrological integrity of the machine. To fully exploit the potential metrological applications of the micro-styli described here it will be necessary to develop a

compatible micro-flexure element which, when combined with a micro-stylus, will form a micro-probing system.

As noted in Section 2.1.3, the quality of the ball tip on the end of the stylus is one of the most important aspects of a contact probing system. Any irregularity in the form of the ball tip will lead directly to a measurement uncertainty in the probing system unless the form error can be accurately mapped and compensated for. It will be necessary to confirm the quality of the ball tip used on the micro-probe system by measuring the spherical form of the tip. A number of measurement techniques are currently being evaluated to perform this task.

The work reported here indicates that the manufacture of micro-styli elements is possible through the use of micro-fabrication manufacturing techniques. However, the processes reported in this document require further refinement and careful investigation to ensure that the components produced are of a suitable quality to allow them to be used in high-accuracy co-ordinate measurement applications.

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