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Design considerations for the development of stylus systems for micro-CMMs

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Abstract

Products are routinely being manufactured with dimensions below 50 µm and, therefore, demand has increased for micro-co-ordinate measuring machines (micro-CMMs) to have stylus systems with tip diameters of 10 µm or less. However, it is a challenging task to scale down styli from the smallest commercially-available dimensions (of the order of 100 µm) to a diameter of 10 µm or less. Many issues that are not relevant at the macro-scale, will be significant at the micro- and nano-scale. In this paper, a set of design rules, developed for the manufacture of stylus systems with diameters of the order of 10 µm, will be introduced. The critical issues of geometry, material properties, resultant probing forces and probing speeds are discussed. A brief discussion of some preliminary modelling, conducted to verify the presented design rules and the developed practical designs for new stylus systems, is also included. The results of the preliminary modelling will add to the knowledge required for the development of suitable stylus systems.

Keywords: micro-CMMs, micro-CMM styli, design rules

1. Introduction

Over the last decade the main focus for micro-CMM research and development activities has been associated with the CMM probing systems [1][2][3]. The detection mechanism of micro-CMM probes plays a major part in probing error and uncertainty in micro-CMM measurements. However, in recent years, with complex miniature products being manufactured in increasing volume, research in the field of micro-CMMs has focused on shrinking the dimensions of the stylus system itself. Demand for dimensional metrology of miniature products, with feature dimensions below 50 µm, is increasing, and currently available stylus systems for micro-CMMs are becoming unsuitable. It is a challenging task to shrink the tip diameters of stylus systems to 10 µm and below, as there is a lack of established development methods able to address the known scaling issues. Therefore, new stylus design rules are needed, which compile the relevant existing knowledge of behaviour at the micro-scale. In this paper, a set of design rules and design considerations for the development of a sub-10 µm stylus system will be introduced. A preliminary analytical model of a test stylus designed using these rules will be presented.

2. Summary of design rules

This section summarises the critical issues that lead to new design considerations for the development of stylus systems, with tip diameters below 10 µm. These issues are all interlinked, but some attempt has been made to categorise them to allow for better descriptions of their effects. The suggested categories of issues affecting the design of micro-CMM styli are: geometrical considerations, resultant probing forces, probing speeds (coupled with effective mass and stylus stiffness), surface quality of the stylus tip, and material selection.

A detailed study has revealed many rules that should be considered. However, this paper presents only a selection of the final design rules developed throughout the course of this investigation. Twenty-five individual rules have been identified, based on the issues summarised in this paper. All of the developed design rules are being compiled as part of a separate report, to be published at a later date.

2.1. Geometrical consideration

As defined in ISO 10360-1 [4], a stylus for contacting CMMs is a mechanical device that comprises a stylus tip and a stylus shaft. Therefore, the dimensions and geometry of the stylus shaft and stylus tip should be disscused together.

One universal rule that must be followed for designing a stylus system is that the stylus tip diameter should be small enough to measure and access the features to be measured. Also, the stylus tip diameter should be larger than the stylus shaft diameter. There is increasing demand for high aspect ratio stylus systems, as well as for stylus systems with smaller tip diameters. Therefore, any designed stylus system has to have an aspect ratio higher than the aspect ratio of the surface features intended for measurement.

The relationship between the length of the stylus shaft, its diameter and the diameter of the stylus tip can be expressed by equation (1). Equation (1) is derived from the combination of Hertz's theory with acceptable probing forces [2], elastic deformation of a stylus shaft [5] and the limits for allowable stylus deflection.

$$d_{tip} = \frac{d_{shaft}^{4} \pm \sqrt{d_{shaft}^{8} - 4\left(\frac{224\,\sigma^{3}\,l^{3}}{\pi\,E\,E^{*2}}\right) d_{shaft}^{5}}}{2\left(\frac{224\,\sigma^{3}\,l^{3}}{\pi\,E\,E^{*2}}\right)}. \qquad (1)$$

In equation (1), d_{tip} and d_{shaft} are the diameters of the stylus tip and shaft, l is the length of the stylus shaft, E^{*} is the reduced Young's modulus (between the materials of the stylus tip and measured surface) and E and σ are the Young's modulus and yield strength of the stylus shaft material respectively. For adequate mathematical precision, this equation is applicable for stylus aspect ratios below 36.

2.2. Probing force

Probing force, or contacting force, is a critical factor during contacting measurement at the micrometre scale. It is well understood that the force exerted during both discrete (single point) probing and scanning, can cause damage to the surface under test. Thus, a maximum allowable probing force can be introduced. The allowable probing force is defined as the force where the shear stress at a point somewhat below the measurement surface exceeds a critical value and plastic deformation starts locally [6][3].

Impact force and overtravel force are other well-known types of probing force. In micro-scale measurement, surface interaction forces at the probe, such as electrostatic and capillary forces, become dominant over the gravitational force [7][8]. As a result, the surface interaction forces will disturb the measurements for single probing and will increasingly cause stick-slip effects in scanning [8]. It is also noted that the stiffness of the stylus shaft, the probing speed, the effective mass, the material properties of the stylus system and the environmental humidity are all factors that influence the magnitudes of the various forces associated with contact probing. Therefore, any design rule associated with a probing force ensures that the magnitude of that force, exerted during probing, be smaller than the estimated value of the maximum allowable probing force.

2.3 Probing speed, effective mass and stylus shaft stiffness

Two conditions need to be considered in the selection of probing speed during contact probing. Firstly, the probe needs to move fast to achieve low probing uncertainties [3]. However, high probing speed can cause damage to the surface under test [9]. Therefore, secondly, to prevent plastic deformation and surface damage, the probing force needs to be limited, and hence the probing speed should be reduced [10]. From these two conditions, the maximum effective mass and stiffness at the stylus tip can be determined [8].

In contrast, the probing sensor which the stylus shaft is attached to, the length of the stylus shaft and the Young's modulus of the shaft material determines the stiffness of the stylus shaft. Therefore, it is essential that the stiffness of the stylus shaft be larger than the stiffness of the probing sensor, and that the resulting probing/stylus system act isotropically [11].

2.4 Surface quality of the stylus tip

Theoretically, the spherical stylus tip should have low surface roughness, uniform sphere diameter, small concentricity of the sphere from the stylus shaft and a good sphericity. In practice, the stylus tip sphere cannot be perfect, so the sphericity error, centric offset and roughness error should be minimised. The surface roughness and sphericity error of the stylus tip should be smaller than the surface roughness of the surface under test [1]. The spherical stylus tip and the surface under test should be free from contamination, or contamination should at least be minimised [12].

2.5 Material selection for stylus manufacture

The preceding sections demonstrate the important role of the material properties in geometrical design of the stylus, the probing forces and resulting stiffness. Therefore, it is crucial to select an appropriate material for the manufacture of the stylus system. A material with a high Young's modulus is preferable, in order to maximise stiffness. Also, a material with a low density is preferable, in order to minimise effective mass.

To minimise adhesive and abrasive wear, the material of the measurement surface must also be considered while selecting the material of the stylus tip [5].

3. Preliminary modelling

A preliminary analytical model has been constructed based on the design consideration described in section 2. An analytical solution to the model is presented in table 1, where the boundary conditions were defined as: a stylus aspect ratio of 35 and stylus tip diameter of 8 µm. A schema of the styus design output from this model is shown in figure 1.

Table 1 example analytical solution of the stylus design model

Analytical model parameter	Output
Length of the stylus shaft	0.28 mm
Maximum diameter of the stylus shaft	6.9 µm
Maximum allowable probing force	3.42 µN
Stiffness of the stylus shaft in horizontal direction	6.28 N/m
Stiffness of the stylus shaft in vertical direction	54.9 kN/m
Stylus system material	Tungsten

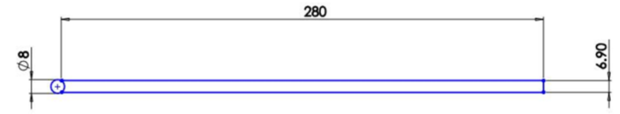

Figure 1. stylus design based on the preliminary analytical design model (µm)

4. Conclusion and future work

In conclusion, several critical issues need to be well understood if a stylus is to be designed for use with a micro-CMM probe. The main issues associated with micro-CMM probe stylus design were discussed, and a small selection of specific rules for the design of such styli was presented. A preliminary model has been developed, and an example stylus design was presented. The presented stylus design contains several challenging features for manufacture and its use as a stylus system as part of a micro-CMM probe seems unlikely using existing micro-probe and control technology.

In the next phase of the work, the set of design rules will be extended and refined, and manufacture will be realised using existing techniques. Mechanical testing of the stylus will also be conducted.

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