Publishable Summary for 17IND05 MicroProbes
Multifunctional ultrafast micro-probes for on-the-machine measurements

Overview

Traceable measurements of surface form and property are essential for controlling the use of or assessing the condition of machined parts and tools in high precision mechanical manufacturing machines especially when these components are subject to wear and surface contamination. Therefore, this project will develop new tactile microprobes for reliable and ultrafast, on-the-machine (i.e. in-line) topographical micro-form and roughness measurements that are 30 times faster than conventional methods and fast methods using contact resonance and force-distance curves to measure adhesion, stiffness, friction, coating thickness and to detect contaminants through adhesion contrast.

Need

Quality control for manufacturing machines is predominantly carried out off-line, and thus requires the workpiece to be dismounted, measured off-line, and then re-mounted. This is both time consuming and expensive and therefore on-the-machine, in-situ characterisation is urgently needed. Other challenging constraints for the measurement and quality control of machined parts include the size of the small micro-structures to be measured against the strong vibrations of the workpiece, contamination by oil and lubricants and large temperature variations. Fast optical sensors are not adequate for measuring such contaminated surfaces and large measurement artefacts can result.

Another measurement option is the use of tactile small coordinate measuring sensors i.e. microprobes. However, tactile microprobes are currently not small enough or fast enough for use in the quality control of manufacturing machines. Current, silicon microprobes with 5 mm long cantilevers with integrated silicon tips for roughness measurements in injection nozzles fulfil several requirements like high scanning speed and low probing force, but suffer from strong tip wear, reduced vertical measurement range and a lack of damping. Manufactured parts in industry are also becoming smaller and smaller (micro-metre size), leading to higher requirements concerning the uncertainty of topography and micro-form measurements (where an uncertainty of < 50 nm is required). However, precise measurements are only possible, if the influence of the probing tip shape on the measured profile can be appropriately corrected for.

Further to roughness and topography measurements there is a need in industry to simultaneously measure the mechanical properties of workpieces. Examples of surface layers needing to be measured simultaneously on-the-machine include rubber, polyurethane and wear protection coatings on printing rolls. In addition to the workpiece, a wide variety of tools on micro-finishing machines as well as on roll grinding machines and wear testers also need to be measured on-line.

Objectives

The project is focussed on the traceable measurement and characterisation of multifunctional ultrafast microprobes for integration into manufacturing machines. The specific objectives are

1. To develop methods for i) obtaining wear resistant probing tips and to characterize the tips on-the-machine with an uncertainty ≤ 50 nm), ii) the development of the morphological filtering of the tip influence on measurements, iii) setting probing force and scanning speed of microprobes and iv) to develop prototype microprobes with integrated actor, preamplifier and damping for fast measurement of topographic micro-form, structure, roughness and enhanced surface properties like elasticity, adhesion, contamination and thickness of coatings.
2. To develop new large deflection (> 200 µm) and high speed (> 10 mm/s) microprobes for simultaneous measurement of micro-form, roughness, elasticity, adhesion, contamination and thickness of coating

layers under industrial conditions. This should include the development of i) pre-deflected cantilevers, ii) actively damped or material-damped cantilevers with thin-film piezoelectric or electro-thermal actuators and iii) thin-film piezoelectric actuator exciting higher-order bending modes suitable for fast CR measurements.

3. To develop validated Contact Resonance (CR) and Force-Distance Curves (FDC) methods for the fast measurement of enhanced surface properties with microprobes on-the machine. The main aim for developing the CR method is the fast detection (< 10 s) of property contrasts on the surface of machined parts on-the-machine, including i) the development of a theoretical model, ii) the determination of the measurement range and resolution, iii) the determination of the lateral resolution, iv) the measurement of the thickness (10 nm – 1 µm) of soft coatings on hard substrates v) fast measurement of the stiffness and characterisation of the elastic modulus of machined parts on-the-machine and vi) the production of a Good Practice Guide. Aims of the FDC method are i) to detect liquid contamination layers from lubricants through adhesion contrast and extend the range of measurable thicknesses to 10 nm – 500 nm, ii) measurement of the stiffness and of the elastic modulus in the range 100 MPa – 3 GPa, iii) measurement of the thickness (1 - 200 nm) of soft coatings on hard substrates, iv) comparison of FDC results with CR results for a better understanding of the CR method, v) adhesion and friction measurements on the surface of machined parts, vi) to implement the method on-the-machine, vii) to improve the measurement speed and viii) to produce a Good Practice Guide.
4. To develop the integration of microprobes into manufacturing machines, roll grinding machines and wear measuring machines and to develop measuring methods resistant against ambient influences. For the manufacturing machine, this will include i) the development of a new high-speed feed-unit, ii) the development of a probe-machine interface, iii) the development a high-speed data acquisition system and iv) the improvement of resistance against ambient influences. For the roll grinding machines, this will include i) the development of mechatronics to drive the microprobe into contact with the roll, ii) the development of a measurement strategy for roughness measurements, iii) measurements of microprobes with and without damping in comparison to reference probes and iv) the production of a Good Practice Guide. For the wear measuring machines, this will include i) the integration of the microprobes into a pin-on-disc tribometer, ii) the relative wear measurement by an additional reference microprobe, iii) the integration of the microprobes into a reciprocating tribometer and vi) the integration of an additional traverse unit to enable measurement of wear damage during in-situ measurements of wear and v) the production of a Good Practice Guide.
5. To facilitate the take up of the developed technology and measurement infrastructure, in particular the methods for traceable microprobe measurements on-the-machine by the measurement supply chain.

Progress beyond the state of the art

The use of dimensional metrology on manufacturing machines is currently hindered by strong vibrations, contamination of workpieces and the high measurement speed requirements of the sensors. Existing piezoresistive silicon microprobes can be used for standard roughness measurements at high speeds up to 15 mm/s, but the wear of the silicon tips is so strong, that approximate only 1,000 measurements in the roughness range below Ra = 2 µm can be performed until the probe must be exchanged. In addition to the quick tip wear, these microprobes suffer from exhibiting no damping, a reduced measurement range of approximately 70 µm and contain no integrated actuator or preamplifier. First prototypes of the new microprobes developed by this project now contain wear resistant diamond tips, exhibit an improved damping, an extended measurement range of ± 100 µm, and can be operated either in roughness mode or in contact resonance mode using an integrated actuator and a preamplifier on the printed circuit board (PCB).

The project for the first time brought piezoresistive silicon microprobes onto three different types of machines for ultrafast roughness, topography and micro-form measurements aiming at measurement speeds up to 15 mm/s and vertical measurement ranges up to ± 200 µm. Preparations are underway for microprobe measurements on microfinishing machines, on wear testers and on roll grinding machines.

In order to obtain the small uncertainties in roughness measurements required (i.e. uncertainty for Ra = 3 %) the project will develop a microprobe unit (microprofiler) with integrated feed-unit for traverse speeds up to 15 mm/s. The biggest challenge when developing this, will be to measure roughness under strong vibration levels, high contamination levels and strong temperature variations.

To reduce wear of the integrated silicon tips new diamond tips have been developed and mounted to microprobes [1]. For precise topography and micro-form measurements, the influence of the probing tip shape on the measured profiles needs to be corrected for. Thus, robust methods for measuring the probe tip shape on-the-machine will be developed. One method developed uses the tip imaging at sharp silicon edges using newly developed tip testing standards with rectangular grooves [1]. The project developed an algorithms for the evaluation of profile measurements and will develop algorithms for morphological filtering of the profiles for the tip shape.

Several applications for microprobes exist where not only workpiece topography is needed, but where information about the mechanical properties of the measured material underneath the tip is also necessary. This applies to all kind of wear protective layers, including the layer thickness. The project for the first time applied two methods simultaneously to topography measurements made with microprobes [2]. The first method is fast contact-resonance (CR) measurements, well-known from Atomic Force Microscopy (AFM) metrology for the measurement of Young's modulus (used to describe tensile elasticity), simultaneously with topography measurements. The project went beyond the state of the art by developing a new type of actuator integrated into the microprobes for CR measurements. This new actuator allows the selective excitation of higher eigen frequencies (i.e. the frequency at which a system tends to oscillate in the absence of any driving or damping force) and thus will suppress noise and improve performance. The second method will be force-distance curve (FDC) measurement. The project will go beyond the state of the art by developing methods for the detection of lubricant layers on workpieces and the measurement of their thickness in a large range between 10 nm and 500 nm [3]. Moreover, new test methods are being developed with both CR and FDC for the detection of contrasts due to different elastic moduli of sample components and/or to different thicknesses of coating layers [4].

Tribology includes the study of friction, lubrication, and wear of interacting surfaces. Current, real-time measurement of small wear volumes on tribological test systems use post-test static stylus profilometry or real time non-contact optical measurement. The project will go beyond this by the application of fast microprobe measurements in real time on tribological test systems.

Results

The microprobes used in this project consist of a slender silicon cantilever with an integrated silicon tip at the end and integrated piezoresistive elements at the fixing point of the cantilever wired to a Wheatstone Bridge for deflection sensing [1]. The project plans to enlarge the measuring range by predeflection, to integrate a damping layer and an actuator and to integrate new electrodes for the actuation of higher order bending modes for contact resonance (CR) measurements as well as improving the wear resistance of the probing tip. In order to use these microprobes in manufacturing and measuring machines it is very important to amplify the output signal of the Wheatstone bridge as near to the bridge as possible to reduce coupling-in of noise contributions. This was realized by integrating the first preamplifier on the printed circuit board (PCB) that is used to hold and electrically contact the microprobe. Moreover, for CR measurements the integration of the phase-locked loop (PLL) into the PCB was realized [5].

Development of prototype microprobe PCBs and optimisation of probing tips

- Five different microprobe holder PCBs were developed to meet the industrial requirements concerning small size and low cost. Three holders for the measurement of roughness, one of which is very compact and two holders for the measurement of contact resonance, have been developed. For the first time long piezoresistive microprobes can be applied on three different commercially available AFMs and on manufacturing machines.
- To improve the wear resistance of the silicon tips, diamond tips were designed and fabricated. Diamond tips were manually glued to microprobes and measurements of the tip shape were done by tapping mode AFM, scanning electron microscopy tomography and using a new tip testing standard with rectangular grooves of different width. Currently methods to detect tip flight at and during high speed scanning are developed.

Future in-line applications with rolls of paper-making machines, micro-finished workpieces (contaminated with oil and wear particles) and randomly moving and vibrating workpieces require the development of novel probes with improved functionality. The project will provide improved microprobes and develop new tactile microprobes with a vertical measurement range of ± 200 µm for safe detection of all features, a critical damping (D = 0.5), integrated self-actuation and improved CR capabilities.

Development of new large-deflection, high-speed, low tip-wear microprobes for industrial measurement conditions

- Specifications of a microprobe holder PCB were collected for a data sheet. Two versions are available, one optimized for roughness and one for contact resonance measurements.
- Transport boxes for the safe delivery of prototype PCBs to the partners were designed, fabricated, and tested.
- Laser-bending for extending the measurement range of the microprobes towards ± 200 µm was investigated. Unexpected oxidation of the microprobe cantilever was observed. Bimorph bending using a deposited layer showed better results, enabling both predeflection and damping simultaneously.
- For operation in resonance a chip piezoactuator was attached to the cantilever. Microprobe redesign was done towards integrated thermal actuator elements on the cantilever for improved higher-mode resonance excitation or active damping.
- A setup for CR measurements was designed and fabricated based on different phase locked loop (PLL) circuits for continuous frequency tracking. Furthermore, a physical-based model including calibration routines of CR with microprobes was created and preliminarily verified. CR frequencies measured with thin PEDOT films showed a linear dependence on the layer thickness using the second out-of-plane bending mode of the cantilever.
- Soft nanoimprint resist layers on silicon were found to be suitable as preliminary references for comparison of CR with AFM-based force-distance curve (FDC) measurements. A microprobe holder/adapter PCB (including transport box) for operation in a Cypher AFM was developed and delivered.

Development of methods for the measurement of surface properties on-the-machine

Two different techniques, namely FDC and CR, for the measurement of surface properties of an object on-the-machine will be developed and compared to determine the suitability of both methods for the measurement of surface properties of an object on-the-machine.

- Several different polymers have been tested as reference samples for comparison between FDC and CR measurements. Three series of polymer films with different thicknesses (mr-NIL210-2µm, not irradiated and irradiated, and mr-UVCur06, not irradiated) have been found as suitable artefacts; the elastic modulus of these samples has been measured quantitatively through force–distance curves. Further polymer samples (PnBMA, PMMA, PS) have been prepared and tested as reference samples for comparison between force-distance curves and contact resonance measurements.
- A hardware update of the AFM has been installed, enabling contact-resonance measurements. This new operating mode has been extensively tested on polymer samples. Comparative measurements with this additional mode and with force-distance curves are currently being performed on PnBMA, PMMA, and PS.
- An exhaustive analysis of force-distance curves on nine different lubricants has been performed and submitted for publication.

Development of measuring methods resistant against ambient influences

The main objective of the project is to develop methods for integrating ultrafast measuring microprobes directly onto measuring machines for three different applications; 1) ultrafast roughness measurements of the workpiece or machined part on micro-finishing machines, 2) topography measurements with microprobes on roll grinding machines and 3) wear measurements on objects using microprobes on wear measuring machines (i.e. tribological test systems).

- The mechanical design of the mounting device for the integration of a microprofiler prototype into the flat finishing machine “MicroStar” has been completed.
- All available microprobe holders were too large to be integrated into a roll grinding system. Thus, a very compact holder PCB was designed and fabricated. Microprobes have been glued and bonded to the new holder. Multipurpose storage and transport cases have been designed and 3D printed. They can also be used for soldering and as installation aids. First tests with a working microprobe with suitable mechatronics

have started. The integration of microprobes into roll grinding machines is in progress.

- In the field of tribological testing, a macroscale scratch test system with appropriate actuator systems has been prepared to enable integration of a microprobe measurement system. A microprobe PCB optimized for roughness measurements was set up and is now ready to be integrated into the scratch test system. Within a collaboration with Southampton University it it planned to integrate a microprobe into a commercially available Plint Tribology in situ profile system.

Impact

The consortium organised the first stakeholder meeting/workshop which took place at the Euspen international conference on the 3rd of June 2019 in Bilbao. Among the 23 participants, nine came from industry (Bruker, Micro Epsilon, Sub Micron Tooling BV, Bestec GmbH, Carl Zeiss SMT GmbH, Zygo Corproration, Egile mechanics) and fourteen from universities and research institutes from ten different countries all over the world (USA, China, Japan, GB, Spain, NL, F, IT, CS, D). The project was well received and the stakeholders provided suggestions on how to more closely align the work of the project to their needs. One main suggestion was to extend the capability of the multifunctional microprobe towards the sensitivity for torsion measurements and the other was to address the problem of strong temperature changes on processing machines, which can lead to strong signal changes of the sensors.

In addition, the consortium has already planned the first industrial visits to collaborators and stakeholders in the fields of microfinishing, roll grinding and tribology to identify specific industrial needs and opportunities to adopt the outputs of this project. A recent request from audio industry focusses on the measurement of the complex modulus of elasticity for polymer materials for frequencies up to 20 kHz. This modulus is necessary for the modelling and simulation of the dynamic behaviour of devices.

The project has held two training courses for the consortium on how to use the microprobes without feed-units for topography and CR measurements in March 2019 and on the determination of 2d tip form on the machine in January 2020. Two research papers have been published in high impact peer-reviewed journals and a further one has been submitted. Eight conference papers have also been published.

Impact on industrial and other user communities

The project will support industry to integrate new tactile microprobes into their manufacturing machines however there is a signigicant challenge to convince stakeholders of this new technology. The first step is to get the end users interested in project from the work. The benefit for the end users is that they will have a fast tactile measurement system with two functionalities: topography and mechanical surface parameters. Thus, a large variety of potential users is conceivable in high precision mechanical engineering, printing and surface foil industries, transportation, power generation, residential, passenger cars, trucks and buses, paper machines and the mining industries. Specific examples include:

- *The development of new microprobe devices and prototypes for simultaneous roughness and modulus mapping measurements on-the-machine.* Different microprobe holders were developed to bring the microprobes onto micro-finishing machines, high-tech roll measuring and control systems, tribometers and dimensional surface measuring machines. GETec and NA have built small adapter boards with which the microprobes can be used on their measuring machines. This will allow industries developing structurres, where only the long slender microprobes can enter in, to measure topography and mechanical parameters of their products. TUBS developed a special printed circuit board (PCB) with an integrated piezoelectric actuator for CR measurements. A further PCB is available especially optimized for fast roughness measurements with onboard amplifier and Wheatstone Bridge voltage supply. Both PCBs can be used by researchers to measure topography or mechanical parameters on manufacturing machines. Moreover, new plastic transport boxes have been developed which allow the safe transport of the sensors and even the sending of the probes by mail. All these devices are available on request.

- *A new method for the tip form measurement on-the-machine.* A new method to measure the 3d tip form of very sharp tips with radii down to 10 nm has been successfully tested. The method uses a new tip testing standard with very sharp edges (5 nm radius) and rectangular grooves. By rotating the tip testing standard also 3d tip form can be measured. A Good Practice Guide is currently under preparation.

- *A new method for the determination of the maximum scanning speed at a given probing force.* Developers of optical and tactile surface profile and roughness measuring instruments, microfinish machine manufacturers, roll measuring machine manufacturers, tribology measurement instrument manufacturers and similar organisations will benefit from these results.

- *Two new measurement methods: CR and FDC.* Two companies showed interest in these new methods. One is interested in dynamic FDC measurements for the dynamic measurement of the elastic properties of polymer materials, which is needed for the optimization of materials in acoustic products. The second company is interested in the traceability of the measured tip form of AFM tips which are used for the early detection of cancer using AFM stiffness measurements.
- *The development of new reference materials and calibration standards.* Beneficiaries will be organisations interested in modulus mapping and those providing the microprobing systems. In the short-term BAM can supply the calibration and reference standards.

Impact on the metrology and scientific communities

PTB will submit a Calibration Measurement Capability (CMC) entry to the BIPM Key Comparison Database according to the measurement of roughness on micro-form elements with silicon microprobes on the Profilscanner of PTB.

Further to this, the project benefits from a variety of partners, such as NMIs, academic organisations, and industry as well as collaborators. The project already facilitated joint working between companies, NMIs and the scientific community in developing microprobe PCBs for different applications. All these devices are available on request for users. The project also facilitated the training of the next generation of metrologists.

The project will produce an online training guide on the ‘Calibration of piezoresistive microprobes on-the-machine‘ as well as a Good Practice Guide for tip radii calibration on-the-machine. The Good Practice Guide will describe the project’s newly developed calibration methods, conditions under which they are to be operated, procedures to be followed, target uncertainties and the best working practices and will be published on the project website for end-users.

Impact on relevant standards

The project concentrates on the standardisation of the metrology for piezoresistive long microprobes, i.e. (i) tip form measurements on-the-machine, (ii) permitted probing forces in dependence of material elasticity, hardness and scanning speed, (iii) elastic modulus measurement using CR and (vi) thickness of lubricant films using FDC. First measures were taken to standardize the measurement of probing forces and the estimation of plastic deformation during tactile measurements. Within the German DIN standardization committee NAFuO 027, the technical committee 03-03 Production equipment for microsystems prepared and translated the parts 2 and 3 of the German standard DIN 32567 on the influence of probing force and scanning speed on plastic deformation of soft layers on hard substrates in order to present them to ISO TC 213 WG 16. A first draft of this new work item proposal was presented to ISO TC 213 WG 16 in 2019.

During the project, several new measurement methods based on the application of piezoresistive microprobes will be developed. The project visited standardisation committees concentrating on areal surface metrology (ISO TC 213 WG 16 Areal and profile surface texture), on mechanical parameter measurements (ISO TC 164 Mechanical testing of metals), on wear measurements (ASTM G02 Wear and Erosion), on ceramic coatings (ISO TC 206 WG10 Ceramic Coatings) and presented first project results and the objectives.

The draft Good Practice Guide “Measurement of tip form using a new Tip Testing Standard with rectangular grooves and sharp edges” developed in the project was transferred by the partners to VDI/VDE GMA 3.41 subcommittee, as this organisation specialises on guideline development. The guidelines will then be transferred to ISO for establishing a corresponding NWIP or integrated into existing standards such as ISO 25178 or VDI/VDE 2629.

Longer-term economic, social and environmental impacts

The direct environmental impact of the project comes from the reduction in manufacturing waste on micro-finishing machines, which can be achieved through the new microprobes that this project will enable. The optimisation of product quality will lead to an increase in manufactured part quality and at the same time decrease associated costs.

Reduction of waste in manufacturing has a direct economic benefit, as does a reduction in the amount of raw materials used; which can both be obtained by zero defect quality. The improved measurement capabilities and more rapid manufacturing developed by this project will support an improvement in industrial quality control and hence allow more rapid innovation, cheaper prototyping, and an overall reduction in time to market. Based on this, the machine tool industry (exports reached a record level of 19 billion euros in 2016), the printing machine industry, surface foil industry and the wear testing machine industry will be able to strengthen their position on the world market.

List of publications

1. Brand, U., Xu, M., Doering, L., Langfahl-Klabes, J., Behle, H., Bütefisch, S., Ahbe, T., Peiner, E., Völlmeke, S., Frank, T., Mickan, T., Kiselev, I., Hauptmannl, M., Drexel, M. *Long Slender Piezo-Resistive Silicon Microprobes for Fast Measurements of Roughness and Mechanical Properties inside Micro-Holes with Diameters below 100 µm*, Sensors 2019, 19(6), 1410, 2019, https://doi.org/10.3390/s19061410.
2. Fahrbach, M.; Peiner, E. P2.10 Entwicklung eines taktilen Mikrotaster-Messsystems für Hochgeschwindigkeitsmessung von Form, Rauheit und mechanischen Eigenschaften. In Proceedings of the Proceedings; 2019; pp. 720–725, https://doi.org/10.5162/sensoren2019/P2.10
3. Friedrich, S.; Cappella, B. Study of Micro-and Nanoscale Wetting Properties of Lubricants Using AFM Force–Distance Curves. Tribol. Lett. 2020, 68, 36, https://doi.org/10.1007/s11249-020-1275-3
4. Fahrbach, M., Krieg, L., Voss, T., Bertke, M., Xu, J., Peiner, E. Optimizing a Cantilever Measurement System towards High Speed, Nonreactive Contact-Resonance-Profilometry, Proceedings 2018, 2(13), 889, 2018, https://doi.org/10.3390/proceedings2130889 .
5. Fahrbach, M.; Friedrich, S.; Cappella, B.; Peiner, E. Calibrating a high-speed contact-resonance profilometer. *J Sens Sens Syst* **2019** under review.

Project start date and duration:	1 June 2018 for 36 months	
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Project website address: https://www.ptb.de/empir2018/microprobes/home/		
Internal Funded Partners:	External Funded Partners:	Unfunded Partners:
1 PTB, Germany	6 bmt, Germany	12 PT, United Kingdom
2 BAM, Germany	7 GET, Austria	
3 CMI, Czech Republic	8 NA, Germany	
4 NPL, United Kingdom	9 RRI, Finland	
5 VTT, Finland	10 TT, Germany	
	11 TUBS, Germany	
RMG: -		