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

Overview

Traceable micro-measurements of surface form and property are essential in high precision manufacturing industries where the precision control of tools and components and the quality of the finished piece relies on the surface properties achieved. Tool wear and surface contamination are two of the main contributors to a poor surface finish. This project has developed new tactile microprobes for reliable in-line topographical micro-form and roughness measurements that are 20 times faster than conventional methods and methods to measure mechanical surface properties. Users are now able to measure adhesion, stiffness, friction, coating thickness and to detect contaminants through adhesion contrast using contact resonance and force-distance curves.

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 leading to measurement deviations up to 100 %.

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. Currently, 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 was focussed on the traceable measurement and characterisation of multifunctional ultrafast microprobes for integration into manufacturing machines. The specific objectives were

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 e.g., manufacturers of machines, standards developing organisations and end-users e.g., high precision mechanical engineering, printing and wear measuring industries. This includes i) direct impact industrial case studies [D8], ii) knowledge transfer, iii) training and iv) uptake and exploitation activities.

Progress beyond the state of the art

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

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).

Integration of fast microprobes into processing machines

This 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. First microprobe measurements have been successfully made on a wear tester and on a roll grinding machine [12, 16, 17]. Preparations are underway for microprobe measurements on a microfinishing machine.

In order to obtain the small uncertainties in roughness measurements required (i.e,. uncertainty for Ra = 3 %) the project has developed a microprobe unit (MicroProfiler) with integrated feed-unit for traverse speeds up to

8 mm/s. The biggest challenge when developing this, was to measure roughness under strong vibration levels, high contamination levels and strong temperature variations.

Development of prototype microprobe PCBs and optimisation of probing tips

To reduce wear of the integrated silicon tips new diamond tips have been developed and mounted to microprobes [1,2]. A mode analysis was made to determine the reduction of resonance frequency and thus bandwidth of microprobes with tips of different length and thus different weight [2]. Experimental results confirmed the reduction of bandwidth and thus, possible scanning speed, of microprobes with diamond tips compared to microprobes with silicon tips [13].

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 were 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 algorithm for the evaluation of profile measurements and an algorithm for morphological filtering of the profiles for the tip shape.

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

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 [10]. 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 [9]. 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 [4]. The second method will be force-distance curve (FDC) measurement. The project went 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. 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 [10, 14].

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 went 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 up to 5 mm long slender silicon cantilevers with an integrated silicon tip at the end and integrated piezoresistive elements for deflection sensing [1]. The project enlarged the measuring range by pre-deflection, integrated a damping layer and an actuator and integrated new electrodes for the actuation of higher order bending modes for contact resonance (CR) measurements and improved the wear resistance of the probing tip.

Development of prototype microprobe PCBs and optimisation of probing tips

- Several 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 [3, 7], have been developed. Microprobes with electrothermal [8] and piezoelectric actuator designed for high-order CR, layouts and MEMS process parameters (tested only with electrothermal actuator [9]) are available. For the first time long piezoresistive microprobes can be applied on three different commercially available AFMs [10] including one inside a scanning electron microscope [11]. Adapters were developed for roll-grinding machines with overload protection [16] and for wear measuring machines also with overload protection. One MicroProfiler system is available which includes an integrated feed-unit for scanning speeds up to 8 mm/s for measurements in manufacturing machines [1].
- To improve the wear resistance of the silicon tips and for measuring structures that are hidden in recessed areas in workpieces, pencil shaped diamond tips with 2 µm radius, 90° conical opening angle and different heights of 0.2 mm, 1 mm and 2 mm [1] were developed by Breitmeier. These are available upon request.
- For the measurement of the tip shape on-the-machine a new tip testing standard with rectangular grooves of different width [1,13] and a Good Practice Guide were developed.

- Methods to detect tip flight during high-speed scanning were developed [13] showing that microprobes with integrated silicon tip can be used up to 10 mm/s scanning speed without tip flight and oscillations. For the heavier diamond tips the maximum scanning speed reduces to 5 mm/s [13]. To improve the dynamic properties of microprobes for fast roughness measurements, a dynamic model, describing their resonant response was developed [13]. An FEM mode analyses was performed for the 5 mm long, undamped microprobes with added diamond tips of varying length for fast roughness measurements [2,4].
- The source code of a mathematical morphology-based algorithm was developed for reconstruction of the actual surface profile from a measured profile using the known tip shape (https://gitlab.com/cmi6014/tip-imaging).
- Since microprobes with silicon tips currently offer the highest scanning speeds possible with microprobes (10 mm/s) it was investigated how these microprobes wear. It was found, that dependent on the probing force, the scanning speed and on the load conditions (sharp edges and steep walls) wear and a successive breaking of the tips occurs [18].
- A Good Practice Guide was developed which helps end-users of microprobes to set the maximum probing force and the maximum scanning speed of their microprobing system for reliable topography and roughness measurements without tip flight and scratching.

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

- Two microprobe holder PCBs are available, one optimized for roughness and one for contact resonance measurements [10]. Passive damping of a CAN50-2-5 using droplet dispensing [15] of a mixture of epoxy glue, isopropanol and glycerol was investigated [6, 8], but further research is necessary to make passively damped microprobes commercially available.
- Transport boxes for the safe delivery of prototype PCBs with mounted microprobes were designed, fabricated, and tested [10].
- Bimorph bending depositing a layer for extending the measurement range of the microprobes towards ± 200 µm was used, enabling both pre-deflection and damping simultaneously.
- Microprobe redesign was done towards integrated thermal actuator elements on the cantilever for improved higher-mode resonance excitation [9] and the investigation of active damping.
- A setup for CR measurements was designed and fabricated based on different phase locked loop (PLL) circuits for continuous frequency tracking [5]. Furthermore, a physical-based model including calibration routines of CR with microprobes was created and 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 [5].
- 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.

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 have been developed and compared to determine the suitability of both methods for the measurement of surface properties of an object on-the-machine.

- A new semi-empirical CR model, based on approximations of the equations describing the cantilever-sample system, was developed and applied to measurements on polymer films. Thereby, CR measurements were compared with FDC measurements [14].
- An exhaustive analysis of force-distance curves on nine different lubricants has been performed [10]. The influence of lubricant surface tension, contact angle, and viscosity on the shape of the curves was analyzed. The main features of force–distance curves on different lubricants have been characterized and the underlying phenomena could be explained.
- A commonly used method to analyse CR data requires the determination of the relative position of the tip, the calculation of the normalized contact stiffness, and the use of a calibration sample for the calculation of the elastic modulus of the sample. This project developed an alternative procedure, based on approximations of the equations describing the system. This allowed determination of the elastic modulus of the sample as a parameter of the fit of the CR frequency as a function of the load [14]. Unfortunately, it demonstrated that CR measurements are not appropriate for polymer samples. Major drawbacks are the

bad resolution for moduli lower than ca. 10 GPa and the lack of a comprehensive physical model accounting for many factors affecting the dynamic response of a cantilever in contact with a sample.

- A special holder with integrated preamplifier was developed for a state-of-the-art AFM in order to make topography, force-distance and contact resonance measurements and topography measurements comparable to conventional AFM cantilevers [10]. During these measurements it was found that the tip shape was not stable due to wear. Further measurements with a new microprobe with glued diamond tip need to be done in future.
- A Good Practice Guide on the "Measurement of liquid lubricant layer thickness using the Force-Distance Curve method" was published.
- A Good Practice Guide on the "Measurement of the thickness of coating layers using the Contact Resonance technique with fast microprobes" was published.
- Force-volume measurements yielding the adhesion of polymer films, were performed with microprobes [10].
- Gwyddion AFM evaluation software has been extended with force-distance curve processing capabilities, released in version 2.60 in November 21.

Integration of fast microprobes into processing machines

The main objective of the project was to develop methods for integrating ultrafast measuring microprobes directly onto measuring machines for three different applications: 1) 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).

- ultrafast roughness measurements of the workpiece or machined part on micro-finishing machines: Bmt developed a piezoresistive MicroProfiler with 5 mm long microprobes and an integrated feed unit for scanning speeds up to 8 mm/s. To integrate the MicroProfiler into a roundtable microfinishing machine *MicroStar 28* Thielenhaus Technologies developed an adapter and a machine-probe interface. Measurements were made to evaluate the performance of the developed adapter and to measure the vibration amplitudes and frequencies of the microfinishing machine with two rotating spindles and also the influence of oil on the workpiece surface was investigated.
- topography measurements with microprobes on roll grinding machines: a very compact microprobe holder PCB was designed and fabricated for microprobe measurements on rolls [16]. A microprobe measurement sensor with test set-up has been designed, built and characterized [17]. The printed circuit board is based on a previous design [7]. Using the test setup, measurements were performed characterizing the sensitivity, noise and linearity at scanning speeds up to 1.7 mm/s. Integration of the microprobe sensor into a roll measuring machine was done and the ability of the microprobe sensor to measure surface roughness was verified. Although not perfect, the initial results are acceptable and promising. However, further development and testing will be needed before the presented industrial application becomes commercially available [12].
- The introduction of fast microprobes into tribological testing systems has also been demonstrated through their introduction into four different test systems (a scratch testing system, a pin-on disc test system, a reciprocating tribometer and a microtribometer). It was found that excellent results were obtained from the in-situ measurements giving high resolution profiles of the wear damage that had been developed during tribological tests. The quality of the measurements and their sensitivity was good and compared well quantitatively with conventional post-test measurements. The quality of the quantitative information that is provided together with the opportunity to acquire real time in situ results during tests make the use of fast microprobes a useful tool that should be introduced more widely into wear measuring systems. One drawback of the microprobes is that they are very fragile, so great care is needed to ensure that they are handled carefully. To help to protect the microprobes a simple overload protector was designed and fabricated. This overload protector was practically tested when a sample slipped in a tribological test bringing the microprobe head down sharply onto the opposing sample. The overload protector did its job preventing damage to the microprobe.

Impact

The consortium organised two stakeholder meetings/workshops. The first took place at the Euspen international conference on June 3, 2019 in Bilbao. Among the 23 participants, nine were from industry (Bruker, Micro Epsilon, Sub Micron Tooling BV, Bestec GmbH, Carl Zeiss SMT GmbH, Zygo Corprporation, Egile mechanics) and fourteen from universities and research institutes from ten different countries all over the world

(USA, China, Japan, United Kingdom, Spain, Netherlands, France, Italy, Czech Republic and Germany). The project was well received and the stakeholders' provided suggestions on how to more closely align the work of the project to their needs.

The second meeting was on-line and held on June 23, 2021 for the presentation of project results to 20 stakeholders drawn from the same audience as the previous meeting. At this meeting there was a lively discussion of topics relating to tip wear of fast silicon tips, improving CR metrology using spherical diamond tips, measurement errors due to cantilever oscillation and increasing damping.

In addition, the consortium has held discussions with industry to find out the metrological requirements of end-users. One 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. A follow up project is planned to address this issue.

A further request came from an instrument manufacturer who looked for traceability of his AFM based indentation modulus measurement device for applications in breast cancer detection. Again a follow up project is planned to address this request.

The project has held five training courses for the consortium on i) how to use the microprobes without feed-units for topography and CR measurements, ii) on the determination of 2d tip form on the machine, iii) on how to determine noise and drift of microprobes, iv) on the improvement of the project and v) on measuring mechanical properties of polymers with AFM. These courses have enabled industrial project partners to develop new microprobe adapters and to apply microprobe for topography and mechanical property measurements, to exactly determine the 2d tip radius, to determine the metrological properties of microprobes and for the first time to apply long microprobes on a commercially available AFM and compare the microprobe performance with that of one of the best AFM instruments available on the market [10]. Two master theses have been published and nineteen presentations have been made at conferences.

Impact on industrial and other user communities

This project worked to support industrial users of tactile surface texture metrology by developing new fast tactile microprobes for integration into their manufacturing machines however there remained a significant challenge to convince stakeholders of this new technology. The project vigorously promoted the benefits of piezoresistive microprobes that create a faster and cheap tactile measurement system with two functionalities: topography and mechanical surface parameters to end users in high precision mechanical engineering used in transportation, power generation, paper production 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.* New microprobes with integrated electrothermal actuator, diamond tips, different microprobe holders and complete microprofilers with integrated feed-unit developed in this project allow industry to integrate the microprobes onto micro-finishing machines, high-tech roll measuring and control systems, tribometers and dimensional surface measuring machines. GETec Microscopy GmbH and nano analytic GmbH [11] have built small adapter boards with which the microprobes can be used on their fast-measuring machines. This will allow industries developing structures, where only the long slender microprobes can enter in, to measure topography and mechanical parameters of their products. The PCBs developed in this project can be used by researchers to measure topography and mechanical parameters on manufacturing machines. 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 2d tip form of microprobe tips has been successfully tested and a Good Practice Guide was developed. The Good Practice Guide describes 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.
- *A new method for the determination of the maximum scanning speed at a given probing force.* A Good Practice Guide on the setting of probing force dependent on the hardness of the material to be measured and the maximum scanning speed to avoid tip-flight was developed. Developers of 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 and probing forces 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 long-term TUBS and PTB can supply the calibration and reference standards.

Impact on the metrology and scientific communities

The project benefited from a variety of partners, such as NMIs, academic organisations, and industry as well as collaborators from microfinishing, rolls and tribology. The project has facilitated joint working between companies, NMIs and the scientific community in developing microprobe PCBs for different applications. The project has also facilitated the training of the next generation of metrologists through the five training courses mentioned above. The project has had direct impact on the scientific community through the significant use of project's outputs by the scientific research community as indicated by the high number of scientific publications.

Impact on relevant standards

The project concentrated 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 steps have been made to standardize the measurement of probing forces and the estimation of plastic deformation during tactile measurements. Interactions with the German DIN standardization committee NAFuO 027, the technical committee 03-03 on the influence of probing force and scanning speed on plastic deformation of soft layers on hard substrates led to the presentation to ISO TC 213 WG 16 of the fast piezoresistive microprobes culminating in a first draft of a new work item proposal in 2019. The committee received the draft with interest and started an intensive discussion about the transfer, e.g. into the surface roughness standard ISO 25178.

During the project, several new measurement methods based on the application of piezoresistive microprobes have been developed and these have been promoted to 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) and on ceramic coatings (ISO TC 206 WG10 Ceramic Coatings).

The project developed Good Practice Guide "Calibration of tip radius of fast microprobes on-the-machine" was presented by the partners to VDI/VDE GMA 3.41 subcommittee, as this organisation specialises in guideline development.

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

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This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	1 June 2018, 36 months + 6 months = 42 months	
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Internal Funded Partners: 1 PTB, Germany 2 BAM, Germany 3 CMI, Czech Republic 4 NPL, United Kingdom 5 VTT, Finland	External Funded Partners: 6 bmt, Germany 7 GET, Austria 8 NA, Germany 9 RRI, Finland 10 TT, Germany 11 TUBS, Germany	Unfunded Partners: 12 PT, United Kingdom
RMG: -		