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How to Trace Back Shaft Lead Measurement to the SI Unit System?

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Lead structures on the sealing counterfaces of rotary shaft seals are a recurring root cause of leakage and a significant source of warranty claims in the automotive and machinery sectors. FVA Guideline 975 I defines structure-based methods to measure and evaluate shaft lead, but the instruments used for these measurements cannot currently be calibrated traceably to the SI unit system. As a consequence, lead values are not comparable across suppliers and original equipment manufacturers, which complicates quality assurance and frequently leads to disputes in industrial supply chains. FVA research project 1091 aims to establish traceability through a deterministic PTB standard produced by ultra-precision diamond turning, which serves as the metrological anchor to the SI unit system. In this paper, we present the design, manufacturing, and first measurement results of a copper prototype of this standard. The prototype was fabricated to conduct feasibility studies on manufacturing, metrological characterisation, and evaluation using structure-based lead analysis methods. These results underpin the final design and the approach for traceable lead measurement.

1 Introduction

The surface topography of the sealing counterface critically governs the performance of rotary shaft seals (RSS), [1]. Lead structures on these surfaces—features deviating from the circumferential direction that arise during the grinding process—induce an axial transport of fluid in the sealing gap and, depending on their orientation, cause either leakage or lubricant starvation (Figure 1). The pumping rate associated with this effect scales with shaft speed, so the rapid proliferation of high-speed electric drives is elevating lead-induced seal failures to a common failure mode in modern drivetrains, [2].

Structure-based measurement methods developed and refined in a series of research projects [3], [4], [5], [6] have proven effective for quantifying lead on ground sealing counterfaces. These methods identify and evaluate individual grinding ridges in high-resolution optical surface-topography data and extract statistical parameters such as the median structure angle $Sd_{median,S}$. FVA Guideline 975 I [7] consolidates these findings into an industry standard that defines measurement procedures, limit values, and evaluation criteria for both micro- and macrolead. The guideline is increasingly applied in supplier–OEM quality control as the basis for sealing-counterface acceptance.

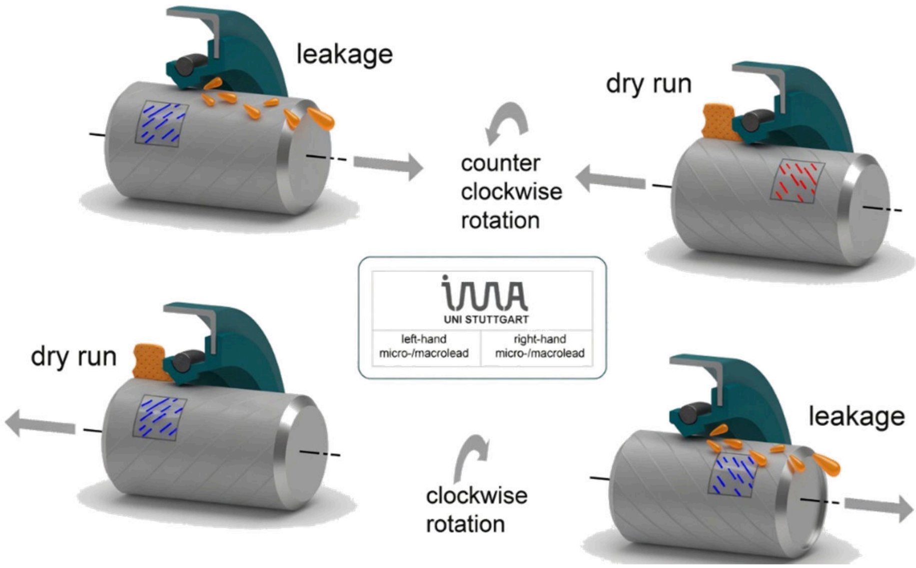

Figure 1: Shaft lead and its effects on the sealing system

Despite this progress, a critical metrological gap remains: the measurement instruments used for lead inspection in industry cannot currently be calibrated traceably to the SI unit system. Only factory calibration referenced to manufacturer-internal artefacts are available, so measurement results are not comparable across company boundaries. In practice, this regularly causes disputes between shaft suppliers and seal or system manufacturers when contested lead values must be reconciled, and it introduces unquantified uncertainty into quality-assurance processes. The lack of traceable lead standards is therefore not a purely academic concern but has direct economic consequences, in particular for small and medium-sized enterprises operating as component suppliers.

The root cause of this traceability gap lies in the stochastic nature of ground shaft surfaces. Grinding produces a surface composed of a large number of randomly distributed grinding ridges generated by geometrically undefined cutting edges, which makes an exact geometric reproduction of the surface impossible. Traceable calibration, however, requires a geometrically defined and reproducible reference structure that a calibration laboratory or national metrology institute can unambiguously characterise within a complete uncertainty budget following the Guide to the expression of uncertainty in measurement (GUM) [8]. Preliminary work at IMA has shown that a thread structure with a precisely known helix angle—generated on a conventional lathe with a single-point scratching tool driven through the kinematic gear ratio between spindle and lead screw—can be evaluated with structure-based lead measurement methods and yields results consistent with the design geometry (Figure 2). This forms the conceptual basis for a calibration chain that bridges the gap between deterministic national standards and stochastic industrial surfaces.

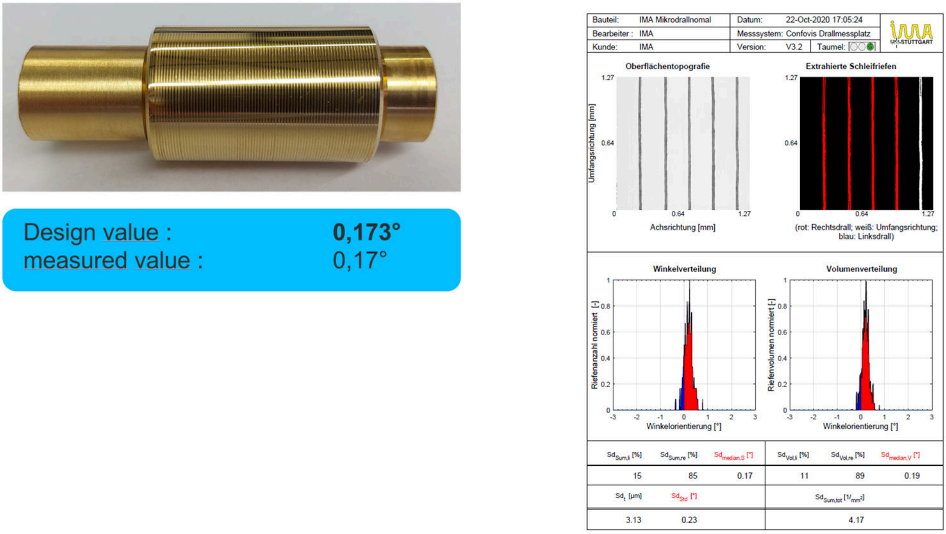

Figure 2: IMA Prototype Lead Standard and Measurement Report for Microlead Analysis

FVA research project 1091, a collaboration between the Institute for Machine Elements (IMA) at the University of Stuttgart and the German National Metrology Institute Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, closes this gap. Following the common idea of the calibration pyramid, the project establishes a two-tier calibration chain: a PTB standard with a deterministic thread geometry produced by ultra-precision diamond turning serves as the metrological anchor to the SI unit metre, while an IMA application standard with a representative ground surface transfers the traceability into industrially relevant measurement conditions (Figure 3).

This paper presents the design of the planned PTB standard, together with the manufacturing and first measurement results of a copper prototype specimen produced ahead of it. While the final Ni-P-coated standard is still in manufacture, the prototype was used to conduct feasibility studies on the manufacturing process, the tool-path planning software, the metrological characterisation using optical methods, and the evaluation with the structure-based lead analysis methods defined in FVA Guideline 975 I, thereby validating the overall approach before committing to the final standard; all measurement results reported in this paper were obtained on it. These studies support the development of the final standard and the approach for traceable lead measurement.

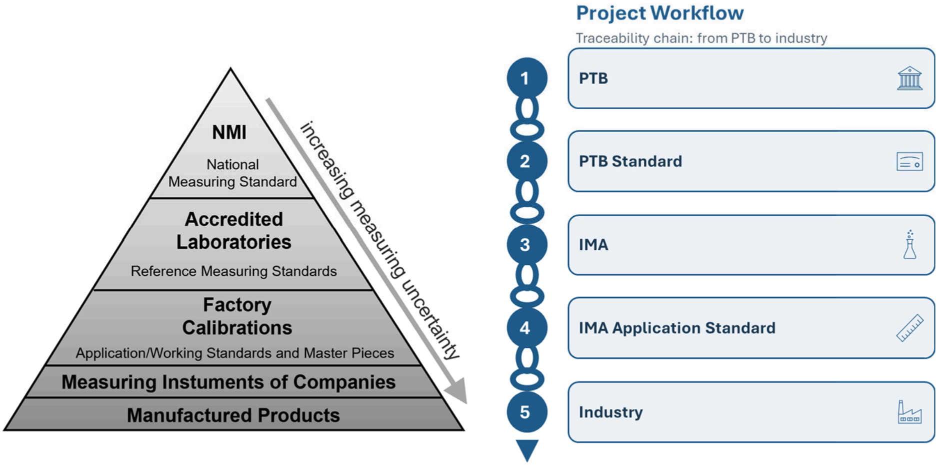

Figure 3: Calibration pyramid to visualise the traceability chain based on measuring standards

2 Materials and Methods

2.1 Manufacturing Approaches

PTB Standard and Copper Prototype Specimen

The PTB standard is designed as a cylindrical specimen featuring two separate deterministic helical thread structures, one representing microlead and one representing macrolead. The geometry was developed according to six design criteria:

- The overall dimensions must be compatible with the working envelope of the PTB ultra-precision lathe.
- The geometry is optimised for common optical instruments (confocal microscope and Alicona µCMM).
- Raised shoulder sections protect the functional surfaces from damage.
- Stepped ends allow clamping in a jaw chuck.
- Centre-bore holes enable mounting between centres if required.
- A permanent marker supports reliable localisation of measured features.

A technical drawing of the overall specimen is shown in Figure 3.

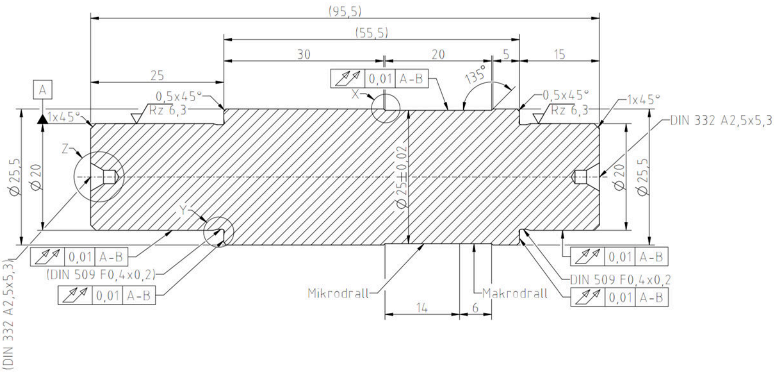

Figure 4: Cross-section geometry of the PTB standard

The final standard will be manufactured from a pre-machined stainless-steel shaft with a nickel–phosphorus (Ni-P) coating. Ni-P was selected for its excellent suitability for single-crystal diamond machining, corrosion resistance, and sufficient hardness. The helical thread structures will be generated by ultra-precision diamond turning. The designed micro- and macrolead properties will require a multi-start thread which has not been done before by ultra-precision diamond turning and constitutes a considerable manufacturing challenge. Tool trajectories are generated by purpose-developed software that predicts the resulting surface geometry and verifies compliance with the nominal structure angles prior to machining (Figure 5).

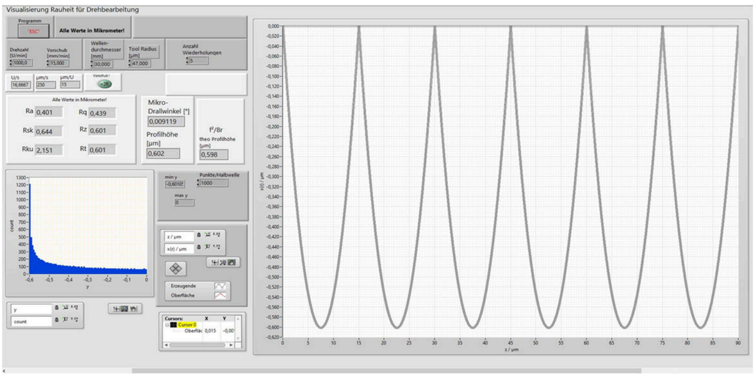

Figure 5: PTB design software and structure geometry for the copper prototype.

As a first step toward this multi-start manufacturing, the copper prototype was produced with only a single-start thread in order to trial the demanding diamond-turning process on a simpler geometry. It has a nominal diameter of 25 mm and features a single-start helical thread structure (microlead) combined with a coarser (macrolead) structure that was produced by plunge cutting without feed and runs sinusoidally in the circumferential direction. The nominal structure depths are 0.07 µm for the fine and 3.6 µm for the coarse structure, with structure widths of 4.99 µm and 50.2 µm, respectively. The lead angle of the fine structure is 0.009°; by design it results from the axial feed and the specimen diameter. Copper was selected because it is well suited to single-crystal diamond machining and sufficient for initial feasibility tests, although its hardness and long-term stability is lower than that of the final Ni-P coating.

2.2 Metrological Approaches and Measurement Strategies

PTB Approach to Measure and Analyse the Thread Structure

A first PTB measurement strategy was developed based on the copper prototype described previously in 2.1 and is intended for subsequent transfer to the final Ni-P-coated PTB standard. The deterministic geometry of the prototype provides a defined reference against which the measurement procedure can be evaluated. The strategy consists of two steps: optical acquisition of the surface, followed by a geometric evaluation that determines the width, depth, and angle of the thread structures.

The surface structures were acquired by focus-variation microscopy on an Alicona µCMM equipped with a rotary table. The challenge of optical metrology on such surfaces is the high specular reflectivity of the diamond-turned copper; nevertheless, the initial feasibility measurements showed promising results.

In preparation of the measurements, the rotary table unit has been quantified in order to minimise the influence of radial run out. The measurements were acquired with a 50× objective (NA = 0.6, Figure 6). The micro- and macrolead structures differ by almost two orders of magnitude in structure depth and width, which is why they were captured separately using different acquisition settings. The macrolead structure was measured over the full circumference at a lateral point spacing of 2.2 µm, a point density of 7×10^4 points/mm², and a vertical resolution of approximately 0.04 µm. The microlead structure was measured at a finer lateral point spacing of 1.1 µm, a point density of 2.4×10^5 points/mm², and a vertical resolution of approximately 0.01 µm. At this point density, a full-circumference acquisition would have generated a prohibitive data volume, so the surface was sampled in four circumferential segments of 30°. In both cases, the axial measurement length corresponded to a single measurement field of 0.265 mm.

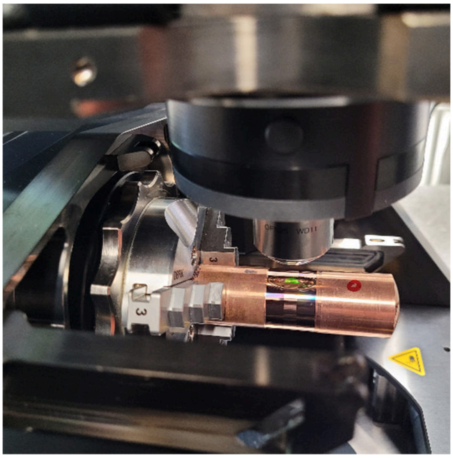

Figure 6: Measurement of the copper prototype specimen with the optical coordinate measuring machine Alicona µCMM

The measured data are evaluated by fitting a three-dimensional (3D) cylindrical form element using the object-oriented FUNKE algorithm, which has been implemented by PTB for various evaluation purposes such as three-dimensional screw-thread or involute-gear evaluation [9],[10],[11].

The starting model of the cylindrical form element was parameterised in 3D by its height and the angle that describes single points of the cylinder circumference. The initial geometry was defined by two nominal geometry parameters: the cylinder conicity and the radius of the cylinder. The residuals of the fitting result are defined as the signed deviations of the measured points from the fitted surface element and contain the lead structures. The fitted cylinder was unwrapped into a plane for mapping and interpolating the residuals onto a regular high-resolution grid with a spacing of 2,4 µm × 2,1 µm for the macrolead and 1.2 µm × 1.1 µm for the microlead. To determine the structure width *SDBmean*, a Fast Fourier Transform was applied to axial profiles extracted at each circumferential position across the surface grid. The dominant wavelength was identified from the resulting frequency spectra and averaged across all circumferential positions. In the next evaluation step, a representative peak-to-valley height was computed for each axial profile as the mean of the vertical distances between consecutive local maxima and minima; these per-profile values were then averaged over all circumferential positions to yield the structure depth *SDTmean*.

An evaluation method for the lead angle has not yet been finally defined and is still pending. For this reason, no representation is provided at this stage. The procedure will be detailed once the method has been finalized.

The metrological traceability for the Alicona µCMM will be realised through a calibrated contour standard following the applicable standards of the ISO 10360-series, thereby closing the first link of the two-tier calibration chain between the SI unit metre and the PTB standard.

Structure-Based Lead Analysis

The structure-based lead analysis comprises two complementary quantitative methods for characterising lead on ground sealing counterfaces, both defined in FVA Guideline 975 I: the structure-based microlead analysis and the structure-based macrolead analysis. Both methods operate on three-dimensional surface-topography data acquired with optical surface-measurement instruments, typically confocal laser-scanning microscopes or white-light-interferometers. In this study, measurements are performed on a Confovis confocal microscope using a 20× Olympus LEXT objective. Individual surface features are identified, geometrically localised, and characterised as discrete geometric elements. A subsequent statistical evaluation of these elements yields the structure-based lead parameters.

The structure-based microlead analysis identifies and evaluates the individual grinding ridges stochastically distributed across the sealing counterface. For each detected grinding ridge, the orientation angle relative to the shaft's circumferential direction is determined, and the angular distribution of all detected ridges is then statistically evaluated to compute the following key output parameters:

Microlead parameter	Description	Unit
Sdmedian,S	Median angle of the microlead angle distribution; values near 0° indicate a balance between left- and right-hand oriented grinding ridges and therefore a negligible net pumping effect	°
Sdt	Arithmetic mean of the microlead depths of all detected grinding ridges	µm

The structure-based macrolead analysis identifies and evaluates macro-scale lead structures superimposed on the ground surface, which can be either periodic or aperiodic. The method was developed within FVA research project 876 "3D-Makrodrall". The key output parameters are:

Macrolead parameter	Description	Unit
SDγmedian	Median of the structure angles of all detected macrolead structures; values near 0° indicate a balanced orientation and therefore a negligible net pumping effect	°
SDBmean	Mean structure width of all detected macrolead structures	µm
VarKSDB	Coefficient of variation of structure widths (SDBstd / SDBmean); lower values indicate a more periodic macrolead	–
SDTmean	Mean structure depth of all detected macrolead structures	µm

Both methods are applied to the PTB standard and later to the IMA application standard to establish the connection in the calibration chain. On the PTB standard, the lead results are compared with the thread geometry characterised at PTB in order to verify metrological agreement and to determine the measurement uncertainty of the structure-based approach for a deterministic surface. On the IMA application standard, the combined micro- and macrolead analyses characterise the as-manufactured lead under industrially representative surface conditions.

3 Results

3.1 PTB Metrological Characterisation

Figure 7 shows the form deviation of the copper prototype. The residuals are dominated by a five-fold circumferential structure, visible as horizontal sinusoidal bands. This structure has a measured depth of approximately 3.1 µm and a width of approximately 51 µm.

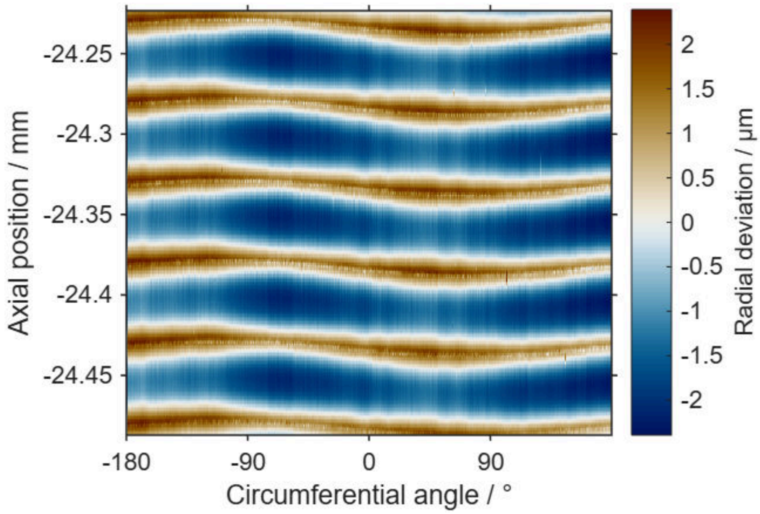

Figure 7: Form deviation of the copper prototype showing the dominant macrolead structure (five-fold circumferential pattern).

Figure 8 shows the microlead structure in the same representation. As only four circumferential segments, each 30° wide, were measured, the data between these segments are interpolated. This structure has a measured depth of approximately 0.1 µm and a width of approximately 5 µm.

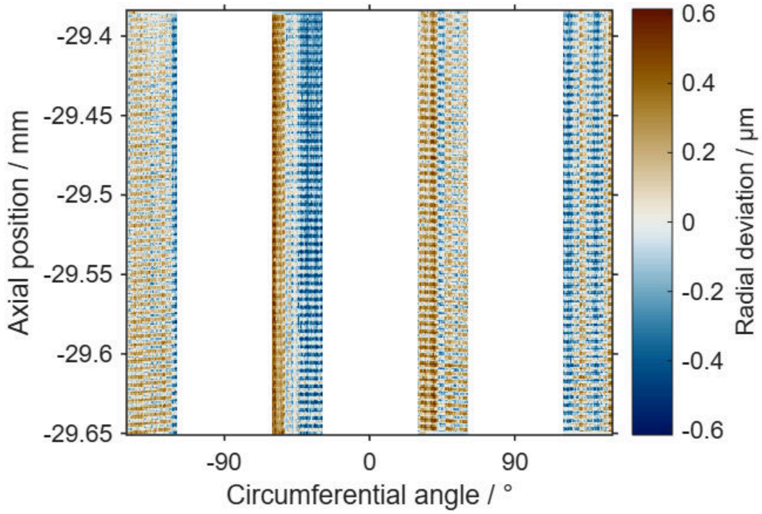

Figure 8: Microlead structure of the copper prototype (interpolated between measured segments).

The corresponding results are summarised in Table 1. The structure widths show very good agreement between the measured and nominal design values. The structure depths deviate by 14% for the macrolead and 43% for the microlead structure, which can presumably be attributed to the tools used so far in the manufacturing process. Specially designed precision tools will be procured and used for the final PTB standard. Overall, however, the results are promising and demonstrate that the process works and can be transferred to the subsequent PTB standard.

Table 1: Comparison of nominal (Section 2.1) and measured (Section 3.1) geometry of the copper prototype surface structures.

Parameter	Nominal (µm)	Measured (µm)	Deviation (%)
Macrolead Structure Depth *SDTmean*	3.6	3.1	14
Macrolead Structure Width *SDmean*	50.2	51	2
Microlead Structure Depth *Sdt*	0.07	0.1	43
Microlead Structure Width	4.99	5	0.2

3.2 Structure-Based Lead Analysis

In addition to the PTB metrological characterisation presented in Section 3.1, the copper prototype was evaluated with the structure-based lead analysis methods defined in FVA Guideline 975 I. The surface was measured on a Confovis confocal microscope with a 20× Olympus LEXT objective (Figure 9).

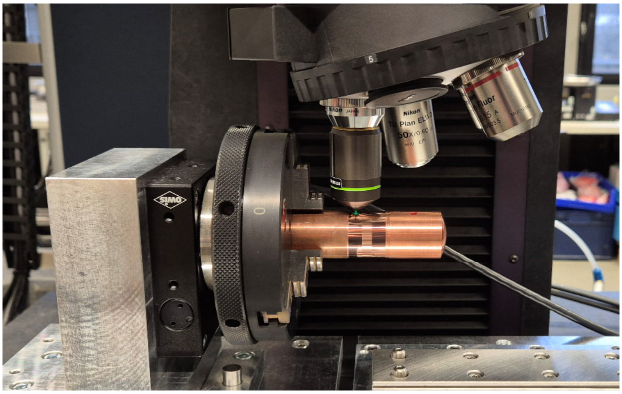

Figure 9: Measurement of the copper prototype specimen with the Confovis confocal microscope

Applying the industrial evaluation to the deterministic prototype verifies that it can be assessed with the same procedures used for real ground surfaces and allows the resulting parameters to be compared with both the nominal design geometry and the PTB direct measurement.

The structure-based microlead analysis (Figure 10, left) identifies the individual fine structures and statistically evaluates their orientation. For the copper prototype it yields a median structure angle $Sd_{median,S}$ of 0.0054° and a mean microlead depth Sd_t of about 0.06 µm. The structure-based macrolead analysis, on the other hand (Figure 10, right), characterises the macro-scale structure. It yields a median structure angle $SD\gamma_{median}$ of 0.01°, a mean structure width SDB_{mean} of 49.96 µm, and a mean structure depth SDT_{mean} of 2.23 µm.

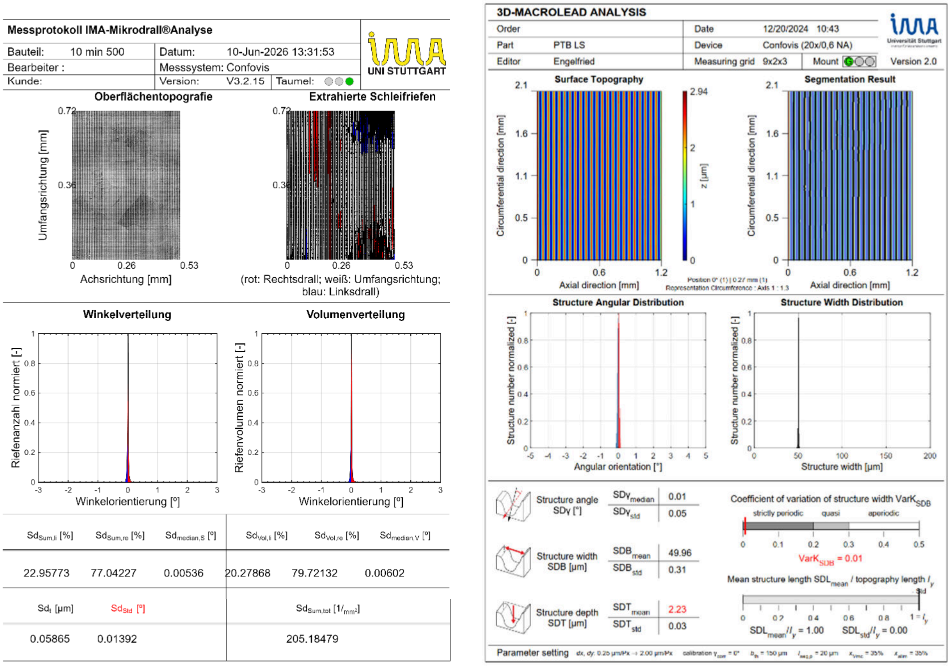

Figure 10: Structure-based lead analysis according to FVA 975 I - (microlead left, macro-lead right)

These values are summarised in Table 2, comparing the structure-based results with the nominal design values from Section 2.1.

Table 2: Comparison of nominal (Section 2.1) and structure-based (Section 3.2) geometry of the copper prototype.

Parameter	Nominal (2.1)	Structure-based (3.2)	Deviation (%)
Macrolead Structure Depth	3.6 µm	2.23 µm	38%
Macrolead Structure Width	50.2 µm	49.96 µm	0.5%
Microlead Structure Depth	0.07 µm	0.06 µm	14%
Microlead Structure Angle	0.009°	0.0054°	40%

Overall, the structure-based parameters mirror the PTB analysis from Section 3.1. The structure widths show very good agreement with the nominal design values, while the depths exhibit larger deviations. The microlead structure angle deviates by

40% (0.009° nominal vs. 0.0054° measured); however, this is attributable to the extremely small absolute values. The final PTB standard will use a much larger angle of 0.3°. Although discrepancies remain at this stage, the evaluations demonstrate that both approaches can measure the same deterministic lead structures. This confirms the feasibility of building a calibration chain and ultimately enabling the calibration of shaft lead measurements in industry.

4 Summary and Conclusion

Measurements on the copper prototype demonstrate that a deterministic lead structure with defined geometry can be manufactured by ultra-precision diamond turning and characterised using optical methods. The measured macro- and microlead parameters showed good agreement with the nominal design values.

The surface data were also evaluated using the structure-based lead analysis methods of FVA Guideline 975 I. The results were consistent with the known geometry, confirming that the prototype can be evaluated with the methods applied to industrial ground surfaces. These findings establish the feasibility of the manufacturing and evaluation approach for the PTB standard.

Overall, the fundamental approach to establishing SI-traceability for shaft lead measurement can be regarded as working. Building on the copper-prototype results, the final Ni-P-coated PTB standard is currently in production, and the development and manufacture of the IMA application standards are likewise ongoing. Once both standards are available, the two-tier calibration chain will be closed end-to-end and the associated measurement-uncertainty budgets will be determined, completing the transfer of traceability from the SI unit system through the PTB standard to industrially representative ground surfaces.

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