EUROMET #406

Comparison measurements

of the diameter of small ring gauges

Final-Report

by

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Content

1 Introduction

In a number of industrial branches, knowledge of the diameter of small holes is decisive for the quality of the products to be manufactured (e.g. drawing dies for the wire industry, spinning nozzles for the textile industry, injection nozzles for the automobile industry). In addition, the requirements specified in ISO 9000 for the metrological traceability must be complied with.

An inquiry made in 1998 among industrial firms and national institutes revealed that only the firm of Conoptica (NO) manufactures commercial measuring instruments for the determination of hole diameters smaller than 1 mm. Some national institutes have set up measuring systems in their laboratories, some of which have been modified to allow diameters of small holes to be measured. These measuring systems use the most different methods of measurement which have not yet been well-proven, and there was an interest in comparing them in an international comparison.

Six European national metrology institutes agreed to participate in the EUROMET #406 comparison measurements of the diameter of ring gauges. The Physikalisch-Technische Bundesanstalt (PTB), Germany, was the pilot laboratory. The comparison started in June 1999 with the circulation of five ring gauges. Two of them are shown in Figure 1. The pattern chosen for the comparison was the round robin type, with a first and a final calibration by the pilot laboratory.

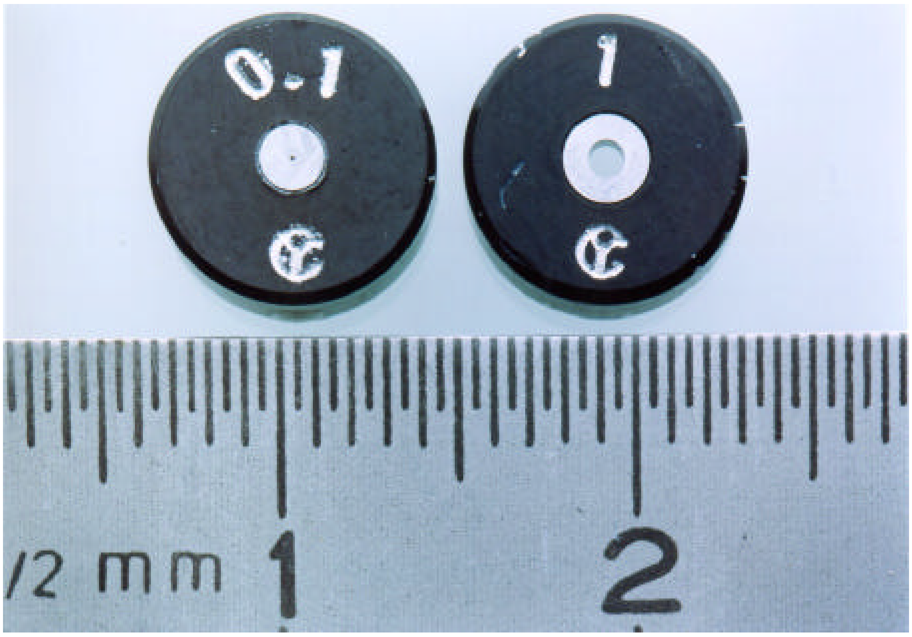

Figure 1: Ring gauges 1 mm and 0,1 mm of the comparison measurements
The ring gauges are made of tungsten carbide and enclosed with a aluminium ring for better handling.

2 Participants

Laboratory Code	Country Code	Contact person, Laboratory	Phone, Fax, email
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Justervesenet/ Conoptica	NO	Helge Karlsson National Standards Laboratory Justervesent Feitveien 99 20007 Kjeller Norway	Tel. +47 64 84 84 84 helge.karlsson@justervesenet.dep. telemax.no
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3 Time schedule

The original time schedule had foreseen about one month for each laboratory for the calibration including the transportation. The following table shows the effective measurement date for each laboratory.

Laboraty	**County**	**Date of measurement**
PTB	Germany	June 1999
NPL	United Kingdom	July 1999
OFMET	Switzerland	August 1999
Justerversenet	Norway	September 1999
IMGC	Italy	October 1999
SP	Sweden	November 1999
PTB	Germany	December 1999

4 Guidelines for realization of measurements

1. Measurement objects

5 rings of tungsten carbide with different diameter (mark): 1 mm (d10/1_B), 0,5 mm (d5/05_B), 0,3 mm (d3/03_B), 0,2 mm (d2/02_B), 0,1 mm (d1/01_A).

2. Reference temperature

Correction of the diameter measured with respect to the reference temperature of 20 °C. The linear expansion coefficient for correction is $5{,}5 \cdot 10^{-6}$ K^{-1}.

3. Measurement positions

Diameter measurement at the position 0° - 180° and different heigths *z* (cf. Table 1 and Figure 2). Definition of the positions: 0° at side of symbol and position 180° at side of diameter value. Definition of *z*-heigths: zero at height of upper plane surface.

ring	d10	d5	d3	d2	*d1*
height (z)	0,375 mm	0,35 mm	0,20 mm	0,25 mm	0,25 mm

Table 1: Measurement heights on the ring gauges

4. Description of measurement principle and device used for measurements like:

Mechanical or optical principle used.

Method of trace back of diameter measurements to length standards.

Adjustment of rings in relation to cylinder surface or cylinder end face (A – see sketch).

Consideration of form deviations like:

Repeated repositioning of rings with new adjustment,

Measurement of form deviations (roundness, straightness, parallelism),

Variation of measurement position (e.g. angle ± 5° and height ± 0,1 mm).

Cleaning procedure.

Environment conditions.

5. Uncertainty of measurements

The determination of the uncertainty has to be carried out in conformity with the ISO-guide „Guide to the expression of uncertainty in measurement“ (GUM). The error budget should be in tabular form with a complete list of the considered influence quantities.

6. Form measurements

Roundness, straightness and parallelism measurements may be carried out if possible. Please plot the results with a scale of 0,5 µm/cm.

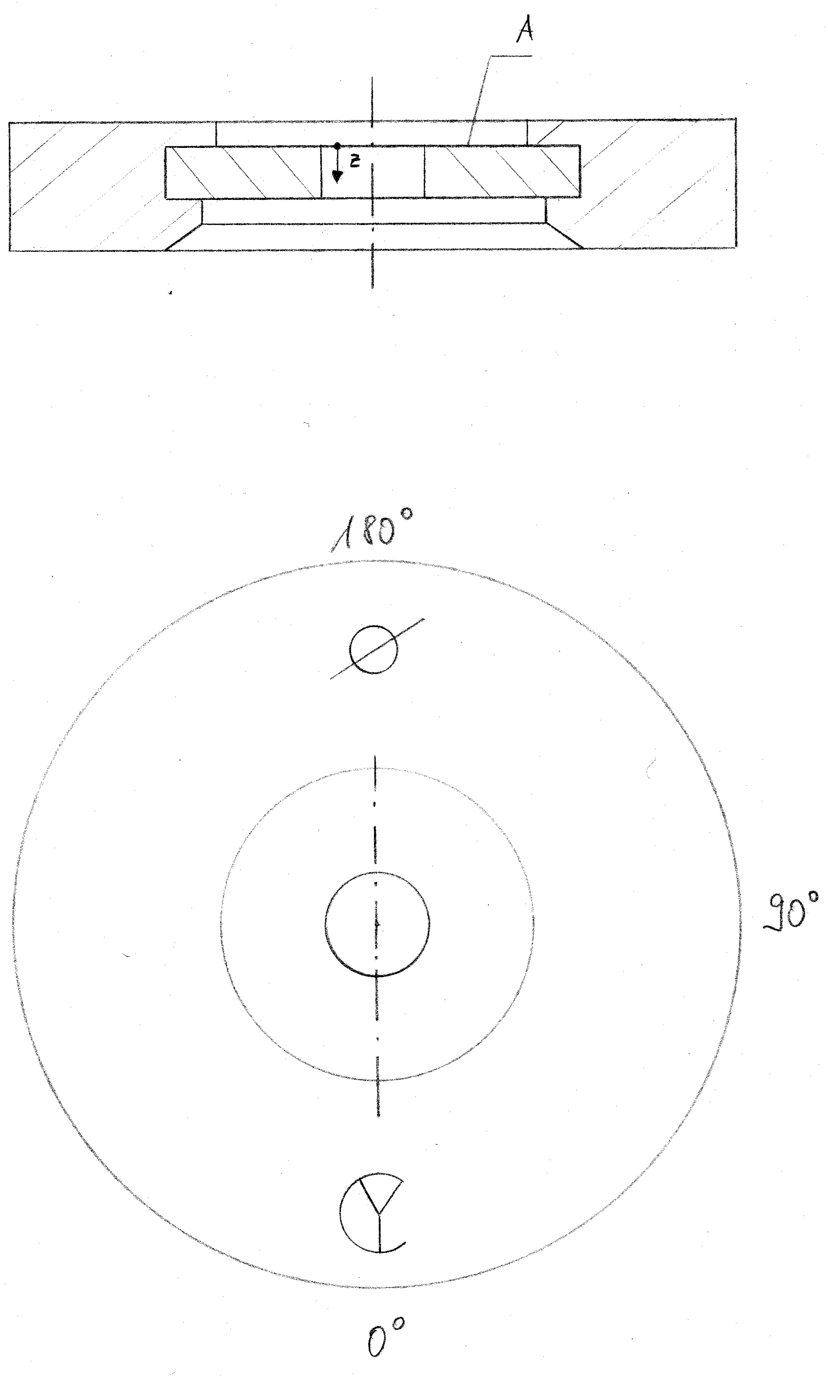


Figure 2: Definition of the position and orientation of measurement

5 Measurement methods and instruments used by the participants

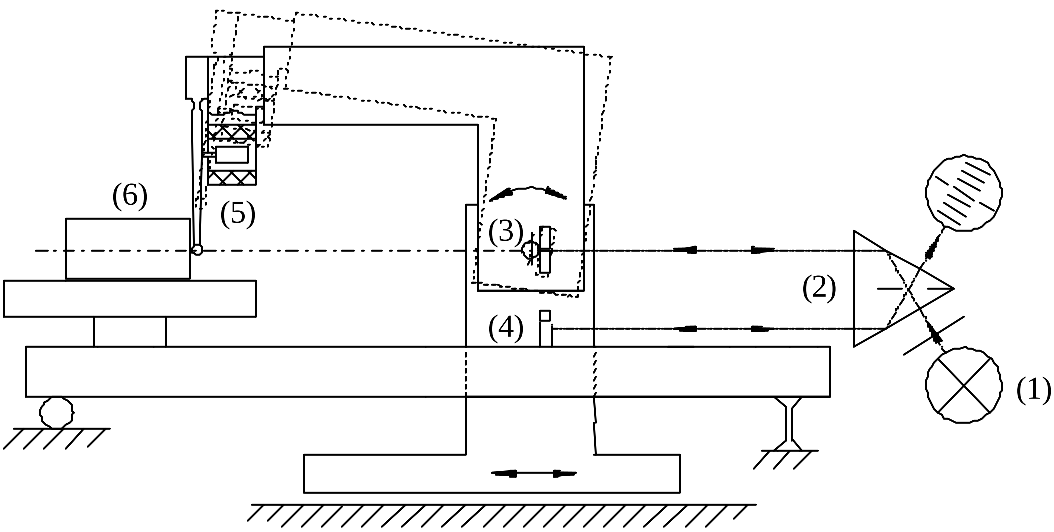
5.1 Physikalisch-Technische Bundesanstalt (PTB), Germany

Two different devices were used for the measurements:

- Ring gauges 1,0 mm and 0,5 mm: length comparator of PTB (section I), symbol LC
- All ring gauges: coordinate measuring machine of Werth with fibre probe (section II), symbol CMM

I. Length comparator with Cd spectral lamp (ring gauges 1,0 mm and 0,5 mm)

For diameter calibration, a length comparator of PTB [1] was used as shown in the diagrammatic sketch in the next figure. The length standard of the comparator is a 114 Cd spectral lamp (1) with a relative uncertainty of the wavelength of $3 \cdot 10^{-8}$.



Principle of PTB comparator used for calibration of the diameter of ring gauges 1,0 mm and 0,5 mm
1 Cd spectral lamp and filter, 2 Kösters prism, 3 measurement reflector, 4 reference reflector, 5 probe, 6 object to be measured

Description of measurement

- The measurements were carried out in a temperature-stabilized room (20 °C ± 0,1 K).
- The diameter of the contacting sphere used for calibration was 0,3 mm.
- The diameter of the probe sphere was determined using a calibrated parallel gauge block.
- The ring gauges were adjusted in relation to their cylinder axis.
- The measurement height was adjusted in relation to the upper edge of the internal cylinder determined with the contacting sphere.
- The ring gauges were cleaned with alcohol and dried with compressed air.

Uncertainty budget for measurement results obtained with the length comparator

Input quantity	Uncertainty contribution /µm	
Ring gauge	1_B	05_B
Nominal diameter /mm	1	0,5
Dater of measurements	06 99	06 99
Length measurement	0,005	0,005
Probing system	0,005	0,005
Temperature influence	assumed to be negligible	
Repeatability [1]	0,06	0,07
Adjustment of rings [2]	0,01	0,01
Cresting	0,015	0,02
Elastic deformation	assumed to be negligible	
Diameter of probe sphere [3]	0,025	0,025
Standard uncertainty	0,07	0,08
Expanded uncertainty	0,14	0,16

[1] Includes the influence of form deviations by repeated mounting of the ring measured. [2] This contribution is mainly influenced by the adjustment of the rings with a Moore No. 3. [3] Diameter of the probe sphere determined using a calibrated parallel gauge block.

II. Coordinate Measuring Machine (all ring gauges)

A commercial CMM (Werth-Videocheck) with fibre probe was used for the diameter calibration [2, 3]. (For measurements carried out in June and December, different CMMs of the same type were used.) The length measurements with the CMM were traced back with the aid of the 1 mm ring gauge, calibrated with the PTB comparator. The differences between the calibrated values and the values measured with the CMM were used for correction of the probe sphere diameter.

Description of measurement

- The measurements were carried out in a temperature-stabilized room (20 °C ± 1 K).
- The diameters of the contacting spheres were about 0,06 mm.
- The diameter of the contacting spheres was determined using the 1 mm ring gauge calibrated by PTB (cf. section 5.1 I).
- The ring gauges were adjusted in relation to their upper (engraved) front face.
- The measurement height was adjusted in relation to the edge determined with the contacting sphere.
- The diameters measured were corrected for the angle measured between cylinder axis and front face (cf. results of form measurements in section 8.1).

- The measurement position was varied as specified in the guidelines. The measurement value reported for the diameter is the mean of the diameters measured in these positions.
- The rings were cleaned by different methods:

  June: Different cleaning methods, either ultrasonic bath with alcohol or CO_2 dry ice cleaning. As a result of the cleaning methods used, the adhesive forces between probe and ring gauges were relatively strong.

  December: All ring gauges were cleaned with acetone in an ultrasonic bath and dried with nitrogen. After this, the ring gauges were packed under clean-room conditions until they were used for the measurements. As a result of the cleaning method used, the adhesive forces between probe and ring gauges were negligible.

Uncertainty budget for CMM measurement results

Error! Not a valid link. [1] Includes the influence of form deviations due to variation of the orientation and height of measurements as well as the variation of the diameter of the contacting sphere used. [2] This contribution is mainly influenced by the uncertainty of the correction of the diameter for the angle measured between cylinder axis and front face. [3] No influence because the diameter of probe sphere was determined using this ring. Its diameter was calibrated with the length comparator of PTB (cf. section 5.1 I).

III. Results of PTB measurements

Date	Ring	1,0_B	1,0_B	05_B	03_B	02_B	01_A
device		LC	CMM	CMM	CMM	CMM	CMM
June 99	*D* /µm	999,3	1000,0	499,7	298,6	199,2	101,1
	U /µm	0,15	0,6	0,9	0,9	0,9	3,0
December 99	*D* /µm	499,9	1000,0	500,3	299,1	200,5	101,1
	U /µm	0,15	0,6	0,9	0,9	0,9	1,0

Results of PTB measurements, mean values and expanded uncertainties for k = 2 (95%)

LC length comparator, CMM coordinate measuring machine

References

[1] Lüdicke F, Rademacher H-J: Bestimmung von Maß und Form an Zylindern und Kugeln. *PTB-Mitteilungen 99 (1989), pp. 429 – 433*

[2] Schwenke H, Weiskirch C, Kunzmann H: Opto-taktiler Sensor für die 2D- und 3D-Messung kleiner Strukturen auf Koordinatenmeßgeräten. *Technisches Messen 12/99*

[3] Ji G, Schwenke H, Trapet E: Ein opto-taktiler Sensor zur Messung kleiner Strukturen auf KMG. *Quality Engineering, pp. 40-43, Aug 1998*

5.2 National Physical Laboratory (NPL), United Kingdom

The measurements reported here were made with a travelling microscope where the position of the stage is monitored with a laser interferometer. The microscope uses reflected illumination and the settings are made visually with the aid of a TV camera and monitor. Supplementary measurements were made with an image shearing microscope which was calibrated with the aid of an interferometrically measured graticule. This microscope was used primarily to aid in the interpretation of the images of the edges. From comparative measurements it was noted that an offset of +3 micrometres should be applied to the measurements obtained from the travelling microscope. The diameters of the pinholes were measured close to the top surface.

The measurement uncertainties come from a variety of sources; they are listed below in descending order of importance:

1 - Uncertainty in the position of the true edge within the image of the edge (±3 µm)

2 - Edge raggedness (±1µm)

3 - Difficulty in ensuring the measurement of a diameter and not that of a chord. (this is particularly difficult with the larger diameter pinholes. (±1 µm)

4 - Calibration uncertainty in the magnification of supplementary microscopes used in the image interpretation. (±0.2 µm)

5 - Measurement repeatability (operator repeatability and interferometer noise) (±0.5 µm)

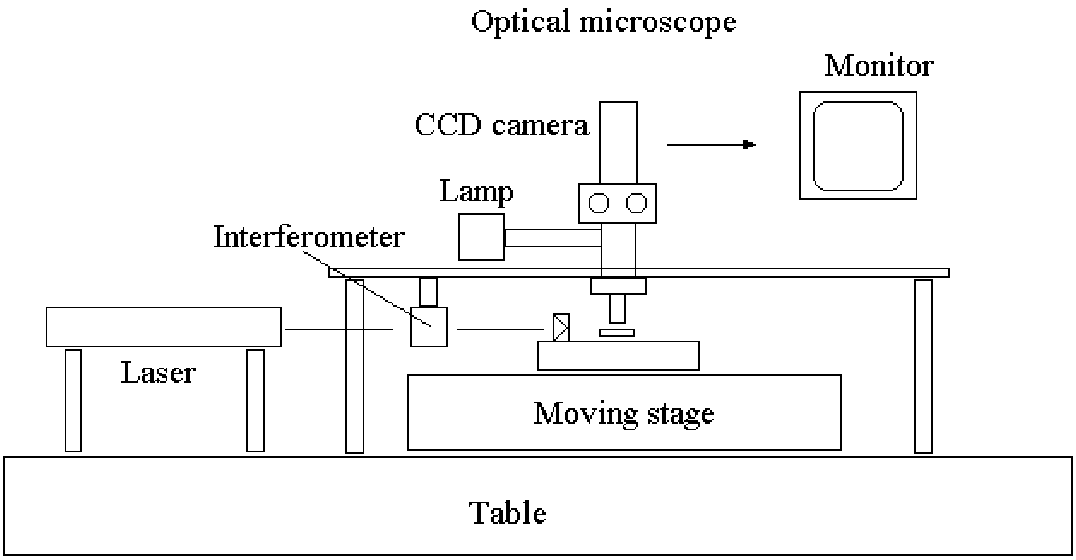
These expanded uncertainties have not been calculated in a rigorous way as required by ISO, and we are not confident that they are sufficiently independent so as to be able to add them in quadrature; we think that our best total uncertainty is close to ±5 µm.

In the case of the 100 µm pinhole, the additional microscope used gave us the slightly better confidence limit of ±3 µm.

The table below presents our final measurements. These supersede the many confusing measurements I had sent you before.

0.1 mm		0.2 mm		0.3 mm		0.5 mm		1.0 mm	
X	Y	X	Y	X	Y	X	Y	X	Y
129.0	119.3	213.4	211.0	319.5	317.6	523.5	525.7	1034.1	1034.5
± 3		± 5		± 5		± 5		± 5	

It was also noted that measurements made using transmitted illumination (and hence more representative of the diameters deeper inside the bore of the hole) were approximately 5.5 µm smaller than those obtained with reflected illumination (reported in the above table)



NPL measurement device

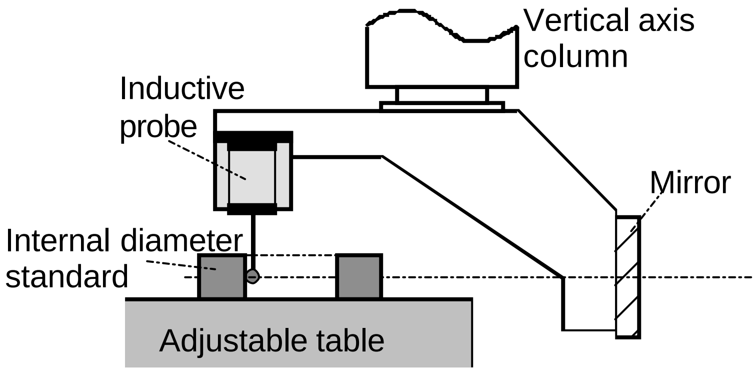
5.3 Swiss Federal Office of Metrology (OFMET), Switzerland

Measurement principle

Length measurement machine SIP/EAM-LMM5, according to:

R. Thalmann, *A new high precision length measuring machine*, 9-IPES/UME 4, Braunschweig, 26 - 30 May 1997.

Measurement head:



Measurement system: Plane mirror interferometer

Stylus: - 3 ruby spheres (Ø 0.5 mm, 0.3 mm, 0.2 mm) with tungsten carbide stylus;
- ground „spherical“ tungsten carbide probe of Ø 0.12 mm with unknown roundness deviation.
Diameter of probing sphere determined with the help of a calibrated gauge block.

Adjustment: With respect to cylinder generating line, probed with the measurement probe (as good as this was possible...)

Form deviations : Each ring was measured at three different heights. The following diameter variations were observed:

Ring	**diameter variation with height**
d10	210 nm / 0.1 mm
d5	390 nm/ 0.1 mm
d3	300 nm/ 0.1 mm
d2	240 nm/ 0.1 mm

For the realization of the nominal measurement height, an uncertainty of 30 µm has been assumed. Roundness deviations were considered to be much smaller than the influence of the diameter variations with height: Each standard was also measured in directions ± 5° from the nominal direction, the variations were, however, considerably smaller (in the same order of magnitude than the repeatability of measurement in a given direction).

Cleaning procedure : Using benzine and Q-Tips (or at least parts of Q-Tips).

Measurement results

Note: The measurement results obtained with the smaller than the largest possible probe diameters are given for information only! Measurement uncertainties are given with a coverage factor $k = 2$.

Ring	meas. height	measured diameter	probe Ø used
d10	-0.375 mm	(0.99956 ± 0.00010) mm	0.5 mm
d10	-0.375 mm	0.99956 mm	0.3 mm
d10	-0.375 mm	0.99957 mm	0.2 mm
d5	-0.35 mm	(0.50021 ± 0.00012) mm	0.3 mm
d5	-0.35 mm	0.50022 mm	0.2 mm
d3	-0.20 mm	(0.29975 ± 0.00012) mm	0.2 mm
d3	-0.20 mm	0.29977 mm	0.12 mm
d2	-0.25 mm	(0.19990 ± 0.00020) mm	0.12 mm

Uncertainty of measurement

In the following table, only the major contributions to the combined unceratinty are given. All length dependent terms (such as laser wavelength, refractive index, temperature effects or cosine error) become negligible for the small dimensions and are therefore omitted.

Description of the contribution	**Std. uncertainties / nm**			
	d10	**d5**	**d3**	**d2**
Repeatability (average of 6 measurements)	10	13	18	18
Searching point of max. diameter (lateral alignment of ring w.r.t. measurement axis	20	25	25	40
diameter variation with height: uncertainty of nominal measurement height	35	45	45	45
stability of the probe constant (essentially sphere diameter including difference between left and right zero deflection of probe)	20	20	20	40
roundness deviation of probe (??)	-	-	-	50
uncertainty of gauge block length at height used for determination of probe constant (not necessary central length of gauge block)	10	15	15	30
Combined standard uncertainty u_c	**47**	**59**	**60**	**95**

5.4 National Standards Laboratory (Justervesenet), Norway

Description of measurement principle used

- The measurement instrument is the Conoptica Profiler 1000 (CP 1000) from Conoptica, Klaebu, Norway. This instrument was developed for measuring the inner geometry of wire drawing dies. It covers the diameter range from 20 micrometers to 7 millimeters. See www.conoptica.no.
- The measured diameter is the one visible when looking through the hole when the observation direction coincides with the hole cylinder axis. The hole cylinder axis is determined by tilting the ring gauge in small angular steps around two axis that are normal to the hole cylinder orientation, whereby the distance across the opening is recorded as function of the tilt angle.
- The calibration object is a photomask. There is one dot that corresponds each of the ring gauges.
- Optical. Object automatically tilted around two axes normal to the hole cylinder axis to bring the illumination/observation directions in coincidence with the cylinder axis. Hole depth and image projections analyzed from video images.
- Optical enhancement of edge positions.
- Dimensions measured relative to “Dot and line comparison chart”, Calibration mark 3087, issued by Physikalisch-Teknische Bundesanstalt. The dots (“holes”) of the calibration object, which correspond to the ring gauge dimensions, were measured immediately before and after measurement of each Cary ring gauge. Ten measurements were carried out of both ring gauges and calibration object.
- The measurements were corrected for light diffraction caused by the straight cylindrical shape of the ring gauges, were the calibration object has zero z-depth.
- Cleaning procedure: acetone bath in an ultra sound device for five minutes.
- All measurements were carried out in a closed compartment without air turbulence, with an environmental temperature of 21ºC. The expansion relative to 20ºC is negligible in this context.
- The diameter and ovality were measured at the depth were the projected diameter, in the prescribed orientation, has its minimum.

Uncertainty of measurements

We expect that the expanded uncertainty draws its main contribution from the following quantities:

The expanded uncertainties of the diameters of the calibration object 3087, as reported by PTB (U_{ptb})

The expanded uncertainty of the correction for light diffraction (U_{diff})

The expanded uncertainty related to the repeatability of the measurement system (U_{ms})

$$U = \sqrt{U_{ptb}^{\;2} + U_{diff}^{\;2} + U_{ms}^{\;2}}$$

Uncertainties are calculated with coverage factor K=2, or two times the standard uncertainty.

Ring	d10	d5	d3	d2	d1
U_{ptb}	0,3µm	0,1µm	0,1µm	0,1µm	0,06µm
U_{diff}	0,5µm	0,4µm	0,4µm	0,4µm	1,0µm
U_{ms}	0,15µm	0,15µm	0,15µm	0,15µm	0,15µm
U	0,6µm	0,4µm	0,4µm	0,4µm	1,0µm

For the d1 ring gauge the uncertainty of the correction for light diffraction, U_{diff}, is high. The reason for this is lack of information about the actual depth profile for this object. The measurements show that it is more trumpet-shaped than the other rings. See the attached *Drawing Die Measurement Report* samples. The portion called *Bearing length* in these reports indicates which part of the cylinder is used for calculating the diffraction shift.

Measurement results

Diameter measurements at 0º - 180º

Ring	d10	d5	d3	d2	d1
Diameter	999,3±0,6µm	499,6±0,4µm	300,2±0,4µm	200,4±0,4µm	100,9±1.0µm

Form measurements

The ovality of the hole was calculated as the difference between the two main axes of a best-fit ellipse approximation. These measurements were carried out by utilising the software package for measuring wire drawing dies. The object is tilted and the position of the hole edges is recorded as function of the tilt angle. From this data the actual shape of the hole is computed.

The depth of the ring gauge cylinder was measured between two points were the depth profile tangent angle exceeds approximately 5º for the d1 ring, approximately 10º for the other four rings. Due to a mistake this depth was measured at orientation 90º - 270º, at right angles to the diameter measurement orientation.

Ring	d10	d5	d3	d2	d1
Ovality	0,4µm	0,2µm	2,5µm	1,0µm	1,4µm
Depth 90º	736µm	524µm	454µm	517µm	382µm
Depth 270º	679µm	512µm	423µm	498µm	396µm

5.5 *Istituto di Metrologia G. Colonnetti (IMGC), Italy*

Abstract

This report details the IMGC measurements made on five tungsten carbide small ring gauges circulated among the European laboratories participating in the EUROMET Project 406 piloted by PTB.

Introduction

The inner diameter of 5 ring gauges was measured at IMGC, within the frame of a EUROMET comparison of diameter measurements piloted by PTB and involving six National Measurement Institutes.

Circulated standards

The five tungsten carbide rings circulated for this exercise were:

Diameter/mm	Identification
1	d10/1_B
0.5	d5/05_B
0.3	d3/03_B
0.2	d2/02_B
0.1	d1/01_A

The linear expansion coefficient was given in the Measurement Guidelines by the pilot laboratory as: $5.5 \cdot 10^{-6}$ K^{-1}.

Diameters had to be measured along the direction 0° - 180° taken along the direction identified by the trade mark and the nominal value engraved on the upper surface of the ring gauge.

Before starting the measurements, nothing was noted by visual inspection, but with an optical microscope indentations (presumably made by a spherical probe) were noted on the following rings:

d10/1_B: spherical indentation at 0°
d5/05_B: spherical indentation at 0°

Measuring instruments

The measuring apparatus is that one which is normally used for calibrating larger rings and plugs. It is based on a Moore Measuring Machine, modified at IMGC, equipped with a laser interferometer and a LVDT probe. This latter has been used only for d10 ring, for smaller rings it was replaced by a microscope with a CCD-camera.

Tab. 1. Instrument identification.

Instrument	Manufacturer	Model	Ser. No.
Universal Measuring Machine	Moore	n. 3	M245
Laser interferometer	HP	5518	3626A03700
LVDT probe (tip ball dia. = XX)	Cary	I DIM	6283
Calibrated gauge block	Cary	LUX 00	15/9081
Microscope (objective 50×)	Nikon	OPTIPHOT 100S	628562
CCD camera	REGIS	T1RS4NL	30AGAF00192
Stage micrometer	Leitz	-	060_643.008

Measurement procedure

By IMGC, this exercise is considered a pilot study on the subject of small ring calibration (this range being out of the IMGC calibration services) rather than a formal comparison.

The measurement procedure is basically the same, independent of mechanical or optical probe. The probe is used to determine the start and the end point for the interferometric displacement measurement. The mechanical probe diameter is determined with a calibrated gauge block, whereas the optical probe width is determined with a calibrated stage micrometer (object micrometer).

Traceability is given by the gauge block (or by the stage micrometer, for the optical probe) and the wavelength of the laser interferometer.

In this exercise, mechanical measurements were made only on d10 at the required depth of 0.375 mm. The other ring gauges were measured only with the optical probe, then only at about the top surface (no attempt was made to correct either for the depth specified in the Guidelines or for the bevel effect).

Mechanical probe

The equipment configuration from bottom up was: Moore carriage, tilt table, small rotary table, mounting cylinder (stainless steel height adapter up to Abbe condition in vertical).

Probe (ruby) ball diameter: 0.5 mm, overall length: 15 mm, stem (thicker) length: 2 mm, stem diameter: 1 mm. Probe measuring force: 2 mN.

The applied procedure is the following:

1. The ring is set (glued) on the mounting cylinder, and the selected measuring direction is (visually) aligned with the displacement axis and the measuring (laser) axis. The ring holder is roughly aligned

with the Y and Z Moore axis.

2. The probe diameter is calibrated with a 10 mm gauge block.
3. Three complete measurements of the ring diameter are made.
4. Step 3 is iterated two other times by repositioning the probe at the same (nominal) depth.
5. Steps 2, 3 and 4 are repeated two other times.
6. A total of three sets of 9 measurements each is then obtained.

With the automatic control of the Moore machine, no manual handling of the ring is required to reset the equipment between each set of measurements.
The same procedure was applied when the ring was measured along the optional direction (90°-270°).

Optical probe

The optical probe has been developed for the calibration of line standards, i.e. bi-dimensional artefacts with a high definition of the measured edge. In the case of a ring gauge (3D artefact measured as if it were 2D artefact!), the poor definition of its circular edge (and of its z-location, as well) is an additional severe problem.

A rectangular window is created via software in order to simulate the behaviour of a mechanical probe. The "contact" reading is obtained from a digital image processing system (assembled at IMGC with boards manufactured by Imaging Technology) of the CCD-camera output of the Nikon microscope.

The window width corresponds to the ball tip diameter for bi-directional measurements, whereas the window height determines the number of pixel rows activated (integration amplitude). By displacing the artefact (relative displacement between artefact and CCD camera), the window "penetrates" in the measurement area and defines the artefact edge position by measuring its distance from the window side (left or right).

The inverse of window sensitivity (about 0.32 µm/pixel, with a magnification of 50X) is determined on both window sides against the displacements (between 2 µm and 12 µm) measured with the laser interferometer.

In addition, the window width is calibrated against a reference stage micrometer (from the left edge of the first line to the right edge of the fourth line, at a distance of about 320 µm) calibrated in terms of both line separation and linewidth.

With this optical probe, the measurement procedure and data processing are exactly the same used with the mechanical probe, except for the probe calibration which is made against the stage micrometer.

For each ring, three measurement series were made, each consisting of 15 runs.

Results

Measurement dates: from 14/10/1999 to 4/11/1999.

The temperature in the measuring volume is (20 ± 0.1) °C.

In a few cases (see Tab. 2.), additional measurements were made along the optional 90°-270° direction.

For ring d10, the optical measurement along the 0°-180° direction was not made because of an indentation at 0° (a similar indentation was detected in the same position also for ring d5, estimated depth: ~ 9-10 µm; estimated width: ~ 40 µm).

Tab. 2. Measurement results.

Ring	**Method**	**Direction**	**Diameter/mm**
d10/1_Bb	mechanical	0-180	0.999 65
	mechanical	90-270	0.999 50
	optical	90-270	1.031 33
d5/05_B	optical	0-180	0.527 04
	optical	90-270	0.516 93
d3/03_B	optical	0-180	0.316 08
d2/02_B	optical	0-180	0.210 68
d1/01_A	optical	0-180	0.118 09
	optical	90-270	0.130 75

The large difference (of about 32 µm on d10 ring) between the optical and the mechanical measurement, is due to the different definition of the ring edge between mechanical method (contact surface) and optical method (average position between maximum and minimum intensity signal).

In particular, with these ring gauges, this difference is even larger because of the effect of the bevelled edge. As a consequence all optical method diameters are larger than contact measured diameters. In order to evaluate the relevant correction, a specific study should be necessary, but has not yet been made. On this occasion, the results are reported as obtained.

Uncertainty evaluation

The sources of uncertainty are summarised in Tab. 7.

Tab. 3. Uncertainty sources (u/µm)

Source of uncertainty	Mechanical	Optical	Optical
Ring diameter/mm	*1*	*1; 0.5; 0.3; 0.2*	*0.1*
Repeatability	0.008	0.07	0.07
Reproducibility (repositioning)	0.058	0.28	0.97
Probe calibration	0.023	0.11	0.11
Air wavelength	0.002	0.001	0.001
Ring alignment	0.012	0.12	0.12
Deformation	0.002		
Ring temperature correction	0.001	0.001	0.001
Form deviation	0.029	0.79	0.79
U (k = 1)/µm	0.070	0.85	1.26
U (k = 2)/µm	**0.14**	**1.7**	**2.3**

In this evaluation, the uncertainty related to the difference between the mechanical and optical measurements was not taken into account. In other words, the optical measurand is considered different from the mechanical measurand because of edge identification problems and because of the different height of the measurement plane (optical measurements at the top ring surface).

5.6 Swedish National Testing and Research Institute (SP)

Measurement objects

5 rings of tungsten carbide with different diameter (mark): 1 mm (d10/1_B), 0,5 mm (d5/05_B), 0,3 mm (d3/03_B), 0,2 mm (d2/02_B), 0,1 mm (d1/01_A).

Laboratory

These measurements were made by

The Swedish National Testing and Research Institute (SP)

Length section, Borås, Sweden.

Operators: SO, RJ

Reporting officer: Mikael Frennberg

Reference conditions

Cleaning procedure:

The rings were cleaned in an ultrasonic bath with petrol and dried with compressed air.

Environment conditions:

The laboratory has a temperature of 20 ± 0,2 C°

Measurement results

Diameter measurement at the position 0° - 180° and at the edges of the holes:

ring	d10	d5	d3	d2	*d1*
height (z = 0)	0,9974 mm	0,4967 mm	0,2981 mm	0,1982 mm	0,1018 mm
height (z = max)	0,9974 mm	0,4977 mm	0,2989 mm	0,1971 mm	0,1031 mm
mean value[1]	0,9974 mm	0,4972 mm	0,2985 mm	0,1977 mm	0,1024 mm
repeat diff z = 0	0,9 µm	0,02 µm	0,5 µm	0,5 µm	0,8 µm
repeat diff z = max	0,6 µm	0,8 µm	1,0 µm	0 µm	0,8 µm

Description of measurement principle and device used for measurements:

The measurements were made with an optical microscope (Zeiss ZKM 250) with a movable X-Y table with built in glass-scales and digital read-out system. The readout has been calibrated with a laser interferometer (HP 5528A) which is traceble to our national standards.
The rings were placed in the horisontal position on the table under the microscope.

The measurements were performed at the edge of the holes on both sides. Z = 0 refers to side A according to the sketch in the guidelines. Z = max refers to the other side. The rings were turned upside down for this measurement.
The measured diameter in X-direction was found by taking the middle position in the Y-coordinate. Five repeated measurements were made in each position.

[1] According to an information of Mr. Källberg (SP), the mean values are used for calculation.

Repeated repositioning of rings with new adjustment were made once for each ring (and side). Thus a total of ten measurements on each side was made. The difference between the mean values of the first and second set of measurements is reported as repeat difference in the table above.

Consideration of form deviations:

Measurement of form deviations: The only consideration was the measurements from both ends (to reveal conical shape). Real form measurements were not made.

Uncertainty of measurements

Uncertainty component	**Type (A/B)**	**Size (k = 1)**
Repeatability	A	0,7 µm
Temperature (0,5 °C)	B	0,006 µm
Instrument calibration	B	0,4 µm
Measurement procedure (edge detection)	B	1,7 µm
Combined std uncertainty		1,9 µm
Expanded (k = 2)		3,8 µm

6 Results of comparison measurements

6.1 Survey of measurement methods used

The measurement principles used can be divided into four groups as follows:

A mechanical contacting measurement

B optical measurement with respect to the projection of the inner diameter

C optical measurement with respect to the position of the edges on upper side

D optical measurement with respect to the position of the edges on both sides

6.2 Summary of measurement results

The measurement results and the uncertainties given by the participants are summarized in Table 2 and represented for each ring gauge in Figure 3 to Figure 7.

Rings	Participants	PTB 1 LC	PTB 2 CMM	NPL	OFMET	Juster-vesenet	IMGC	SP	PTB 3 CMM
	Method	A	A	C	A	B	C	D	A
1 mm	*D in µm*	999,3	1000,0	1034,1	999,56	999,3	999,65[A]	997,4	1000,0
	U in µm	0,15	0,6	5	0,10	0,6	0,14	3,8	0,6
0,5 mm	*D in µm*	499,9	499,7	523,5	500,21	499,6	527,04	497,2	500,3
	U in µm	0,15	0,9	5	0,12	0,4	1,7	3,8	0,9
0,3 mm	*D in µm*	—	298,6	319,5	299,75	300,2	316,08	298,5	299,1
	U in µm	—	0,9	5	0,12	0,4	1,7	3,8	0,9
0,2 mm	*D in µm*	—	199,2	213,4	199,90	200,4	210,68	197,7	200,5
	U in µm	—	0,9	5	0,20	0,4	1,7	3,8	0,9
0,1 mm	*D in µm*	—	101,1	129,0	—	100,9	118,09	102,4	101,1
	U in µm	—	3,0	3	—	1,0	2,3	3,8	1,0

Table 2**:** Results of diameter measurements

D diameters and *U* expanded uncertainties (95%) given; for methods cf. section 6.1

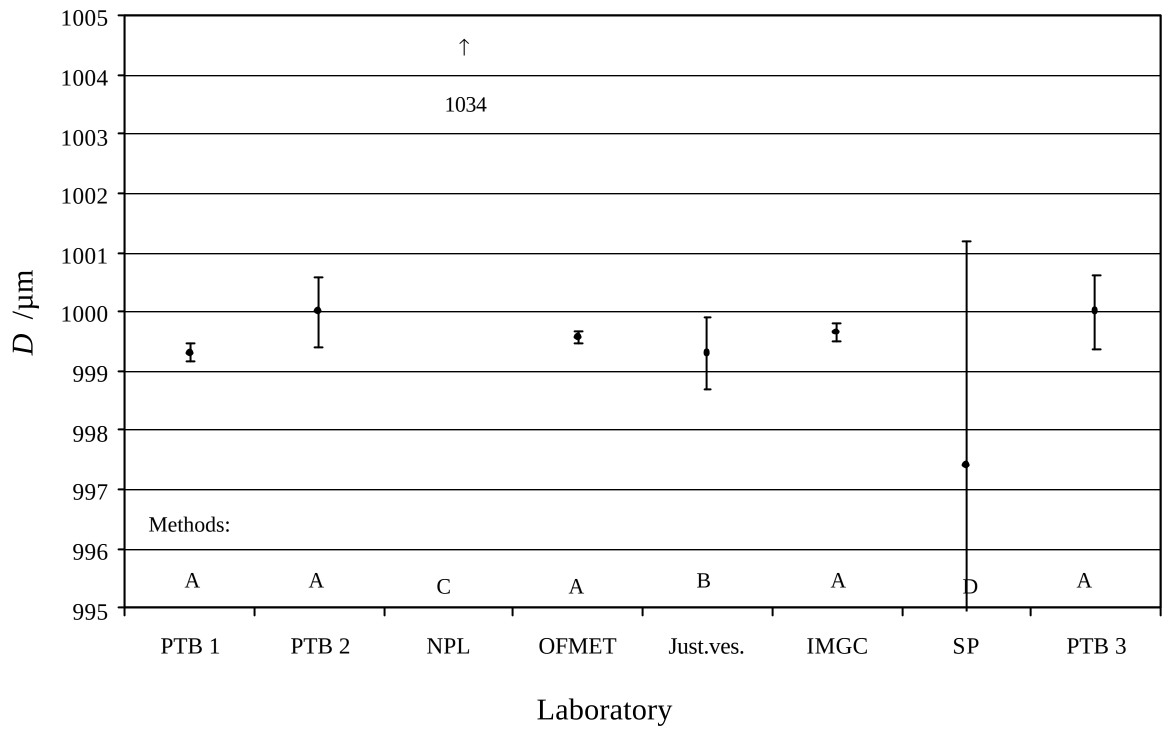


Figure 3: Ring gauge 1 mm, diameter and expanded uncertainties (95%)

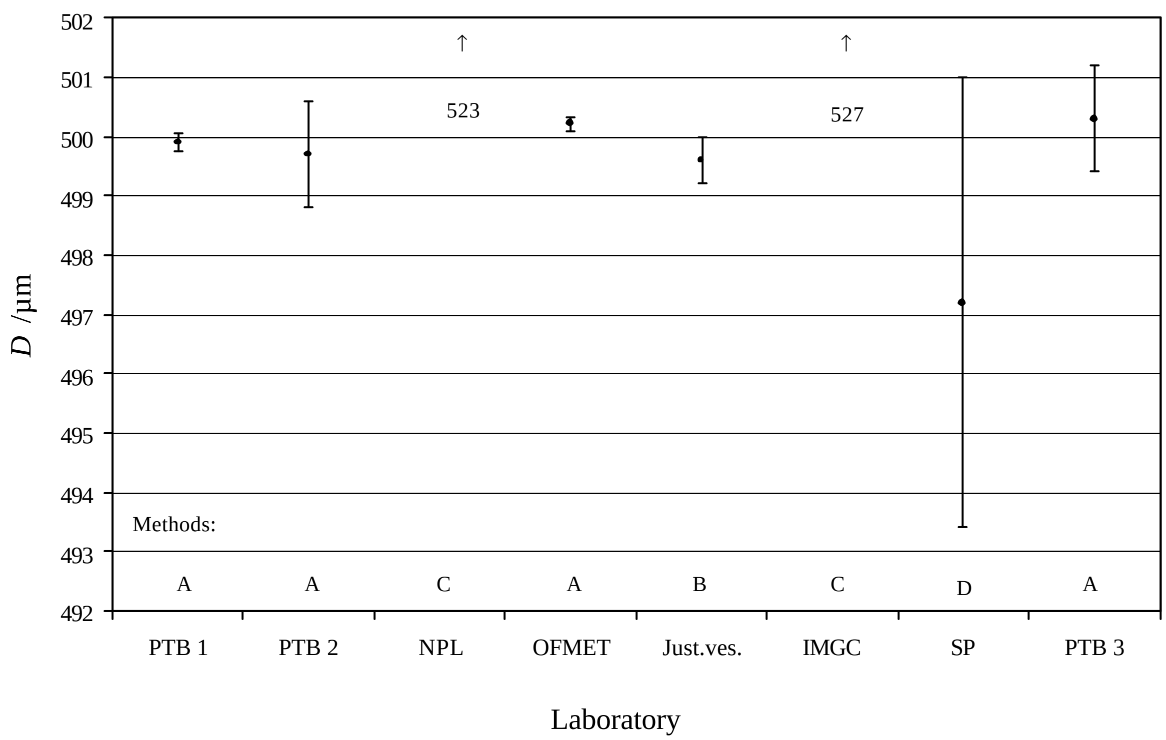


Figure 4: Ring gauge 0,5 mm, diameter and expanded uncertainties (95%)

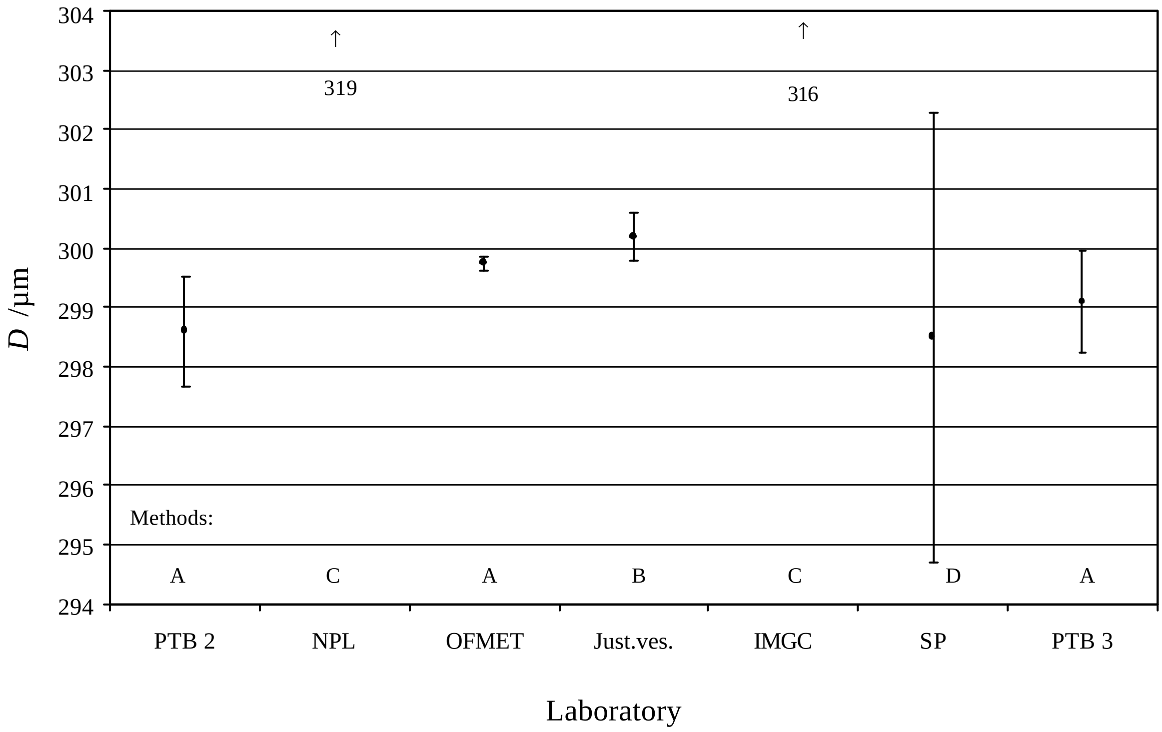


Figure 5: Ring gauge 0,3 mm, diameter and expanded uncertainties (95%)

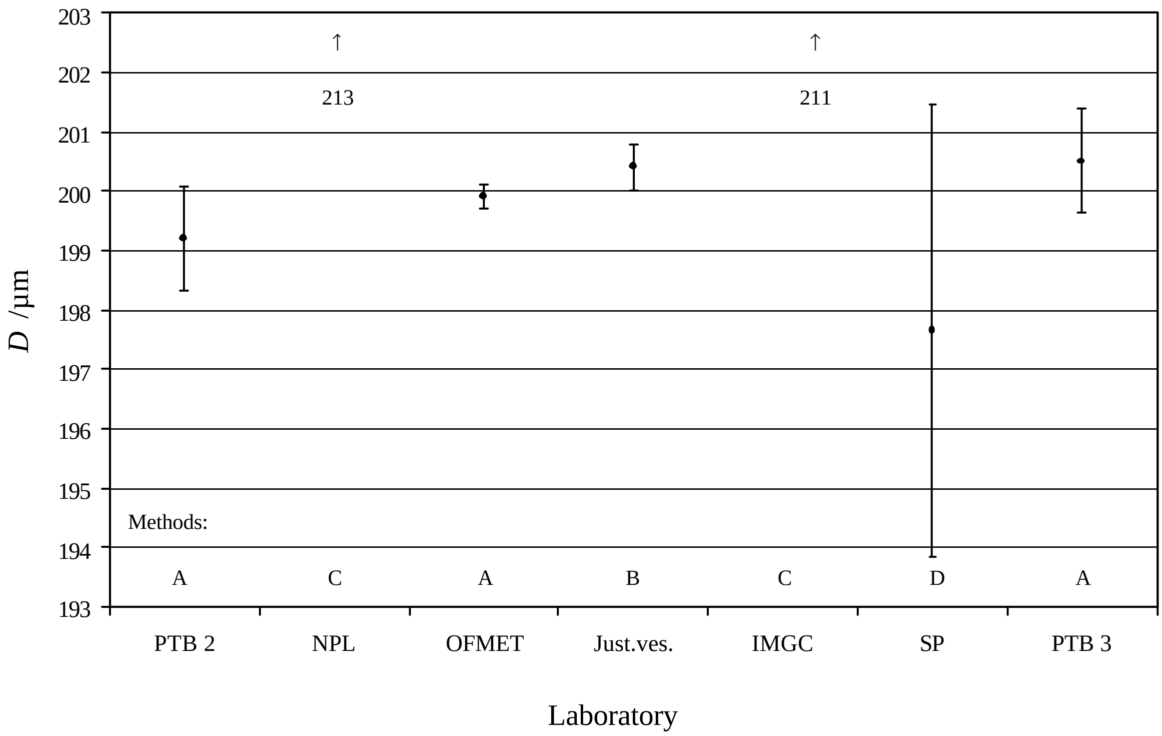


Figure 6: Ring gauge 0,2 mm, diameter and expanded uncertainties (95%)

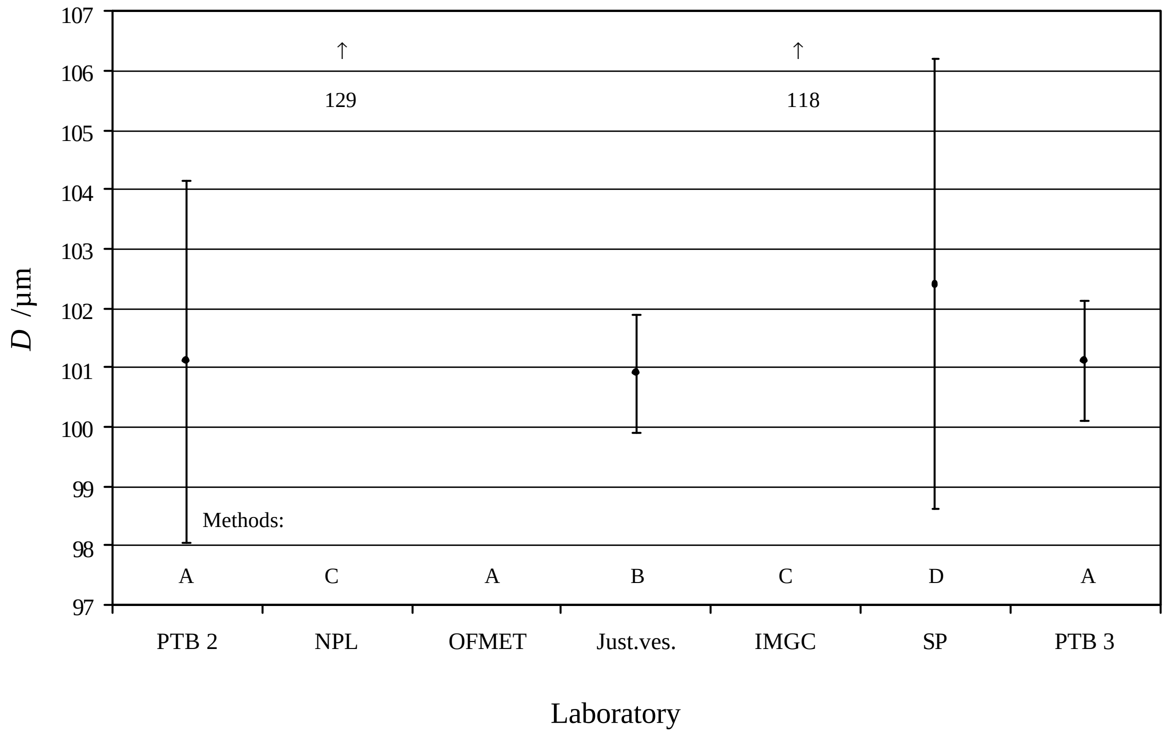


Figure 7: Ring gauge 0,1 mm, diameter and expanded uncertainties (95%)

7 Determination of reference values

7.1 General remarks

7.1.1 Prerequisites for the comparability of measurement results

To guarantee the internal consistency of comparison measurements, some basic prerequisites must be complied with to make a comparison of the results possible. These prerequisites can be formulated as follows:

1. The participants must measure the same measurand.
2. The measurand must be stable, or drifts must be appropriately taken into account.
3. Well-defined measurement instructions must be available.
4. The influence of the characteristics of the object to be compared on the uncertainty of the measurand must be relatively small.

7.1.2 Assessment of the comparison measurements carried out

For the measurements carried out within the scope of the EUROMET 406 comparison, the following statements can be made with respect to the prerequisites defined above:

1. Different measurands were determined: given diameter, projected diameter, distance between edges.
   a) Only three participants determined the measurand defined in the Guidelines: PTB, OFMET, IMGC on the 1 mm ring (method A).
   b) As regards the characteristics of the rings, another participant determined the defined measurand in all probability, as the projected (minimum) diameter measured and the defined diameter differ only slightly from each other: Justervesenet (method B).
   c) Three participants did not determine the defined measurand: NPL, IMGC on the rings smaller than 1 mm (method C) and SP (method D). One participant corrected the measurement results to be able to draw conclusions regarding the defined measurand: SP (method D).
2. The stability of the measurand can be taken for granted.
3. Well-defined measurement instructions were available (Guidelines).
4. The influence of the object measured on the uncertainty of measurement is considerable (form deviations, roughness, quality of the edge). The influence on the method (C) could be demonstrated (cf. section 8.2).

7.1.3 Conclusions regarding the evaluation of the results

For the evaluation of the results, the following conclusions are drawn from the assessment of the comparison measurements made in section 7.1.2:

- The reference value is calculated on the basis of the measurement results of those participants who determined the defined measurand (A) or corrected the measured value with respect to the defined measurand (D).
- In addition (with the ring characteristics known), the measured values of that participant are used where, in all probability, the measurand measured deviates only slightly from the defined measurand (B).
- Two reference values are calculated and compared in order to assess the correction procedure (D) and the coincidence of defined diameter and measured diameter (B):
  - I. The reference value from the results of the participants (A) who determined the defined measurand.
  - II. II: The reference value from the results of the participants (A, B, D) who either determined the defined measurand or made corresponding corrections, or where the measurand measured deviated only slightly from the defined measurand.

7.2 Methods for the determination of reference values

In the course of the comparison measurements, complete measurement results $X_i = x_i \pm u(x_i)$ (k = 1,..., n_i) were obtained independently for the same physical quantity Y in n laboratories, using different measuring devices and different measurement methods. The measurement results obtained are fitted on the assumption that the measurands X_i are identical with Y.

7.2.1 Weighted mean

Fitting can be carried out according to [Weis99] by weighted averaging of the input quantities. The weighted mean is determined as follows:

$$y = u^2(y)\sum_{i=1}^{n}\frac{x_i}{u^2(x_i)} \tag{1}$$

or

$$y = \sum_{i=1}^{n} g_i x_i \tag{2}$$

with

$$g_i = \frac{u^2(y)}{u^2(x_i)} \tag{3}$$

and

$$u^2(y) = \left[\sum_{i=1}^{n}\frac{1}{u^2(x_i)}\right]^{-1}. \tag{4}$$

According to eq. (4), the uncertainty of the weighted mean $u(y)$ is influenced only by the uncertainties $u(x_i)$ and not by the dispersion of the values measured.

The best estimate of the difference between measured value and reference value is $\Delta x_i = x_i - y$, and the associated standard uncertainty according to GUM is:

$$u^2(\Delta x_i) = u^2(x_i) + u^2(y) - 2u(x_i, y) \tag{5}$$

As y is calculated according to eq. (1), y and x_i are correlated and the following is valid according to [Wöge00]:

$$u(x_i, y) = u^2(y). \tag{6}$$

From this it follows for the standard uncertainty of the difference between measured value and reference value:

$$u^2(\Delta x_i) = u^2(x_i) - u^2(y) \tag{7}$$

or, for the expanded uncertainty, with the coverage factor $k = 2$

$$U(\Delta x_i) = 2\sqrt{u^2(x_i) - u^2(y)}\ . \tag{8}$$

The ratio of the deviation of a measured value from the reference value to the measurement uncertainty associated with this measured value informs about the plausibility of the uncertainty statement. According to [MRA], a possibility for checking this plausibility is the *En* value as the ratio of the deviation of a measured value from the reference value to the expanded uncertainty of this deviation according to eq. (9). If the amount of the *En* value in relation to the measured value is greater than 1, it can be assumed that too low a value has been indicated for the measurement uncertainty associated with the measured value.

$$En = \frac{\Delta x_i}{U(\Delta x_i)} \tag{9}$$

The consistency of the measured values with the model of the comparison measurements allows a statement to be made on whether the requirements for the comparability of measurement results summarized in section 7.1.1 are met. The chi-squared criterion [Weis99] serves for this purpose, whose development leads to the Birge ratio R_B with an expectation value of $R_B = 1$. According to [SAIC99], the Birge ratio can be described as the ratio of external consistency s_{ext} to internal consistency s_{int}.

$$R_B = \frac{s_{ext}}{s_{int}} \tag{10}$$

with

$$s_{int} = u(y) \tag{11}$$

and

$$s_{ext} = \sqrt{\frac{\sum_{i=1}^{n}\left[\frac{x_i - y}{u(x_i)}\right]^2}{(n-1)\sum_{i=1}^{n}\frac{1}{u^2(x_i)}}} \tag{12}$$

For a coverage factor of $k = 2$, the data of the comparison measurements are consistent with the model, provided the following is valid according to [SAIC99] for the Birge ratio determined:

$$R_B < \sqrt{1 + \sqrt{8/(n-1)}} \tag{13}$$

7.2.2 Arithmetic mean

In the special case when the standard uncertainties are not given, the reference value is determined from the arithmetic mean

$$y = \frac{1}{n}\sum_{i=1}^{n} x_i \ . \tag{14}$$

The uncertainty of the reference value is equal to the experimental standard deviation of the mean $s(\overline{x})$, i.e.

$$u(y) = s(\overline{x}) \ , \tag{15}$$

and, therefore, independent of the uncertainties $u(x_i)$ associated with the measurement results. The best estimate for the difference between measured value and reference value is $\Delta x_i = x_i - y$, and the associated standard uncertainty according to GUM is:

$$u^2(\Delta x_i) = u^2(x_i) + u^2(y) - 2u(x_i, y) \tag{16}$$

The degree of correlation between y and x_i depends on the number of participants and the uncertainty is determined by [Krys00]

$$u^2(\Delta x_i) = u^2(y) + u^2(x_i)\left[1 - \frac{2}{n}\right] . \tag{17}$$

To assess the consistency of data and model, the *En* value is determined in analogy to eq. (9).

Remark:

The result of eq. (17). is obtained approximately by using the algorithms in the Guide GUM 5.2.2

$$u^2(\Delta x_i) = u^2(x_i) + u^2(y) - 2u(x_i)u(y)r(x_i, y) \tag{18}$$

and GUM C.3.6.3

$$r(x_i, y) \approx \frac{u(x_i)}{u(y)} \cdot \frac{dy}{dx_i} \tag{19}$$

with dy change of the output quantity y by change dx_i of the input quanity x_i. The input quantities for the determination of the arithmetic mean according to eq. (14) are of the same magnitude and eq. (20) is valid.

$$dy \approx \frac{1}{n} dx_i \tag{20}$$

Inserting eq. (20) and eq. (19) into eq. (18) results in eq. (21), which is an approximation to the result given in eq. (17).

$$u^2(\Delta x_i) \approx u^2(x_i) + u^2(y) - 2u^2(x_i) \cdot \frac{1}{n} \tag{21}$$

7.3 Comparison of the reference values determined with different methods

For the arithmetic mean and the weighted mean, the reference values for the diameters of the rings were determined using the results obtained by methods (A) and (A, B, D) (cf.section 7.1.3). In addition, these reference values were determined for the results obtained by all methods used (A, B, C, D) (for symbols of methods: cf. section 6.1). The reference values D_{ref} and the expanded uncertainties of the reference values $U(D_{ref})$ according to eq. (4) and eq (15) for k = 2 are shown in Table 3.

		Reference values and expanded uncertainties in µm					
		from arithmetic mean of method			from weighted mean of method		
Ring gauge		A	**A, B, D**	A, B, C, D	A	**A, B, D**	A, B, C, D
1 mm	D_{ref}	999,70	**999,32**	1003,66	999,54	**999,53**	999,54
	$U(D_{ref})$	0,27	**0,67**	8,72	0,07	**0,07**	0,07
0,5 mm	D_{ref}	500,03	**499,49**	505,93	500,09	**500,06**	500,14
	$U(D_{ref})$	0,28	**0,94**	8,49	0,09	**0,09**	0,09
0,3 mm	D_{ref}	299,15	**299,23**	304,53	299,67	**299,76**	299,95
	$U(D_{ref})$	0,52	**0,66**	6,90	0,19	**0,11**	0,17
0,2 mm	D_{ref}	199,87	**199,53**	203,10	199,90	**199,98**	200,11
	$U(D_{ref})$	0,75	**1,05**	4,71	0,19	**0,17**	0,17
0,1 mm	D_{ref}	101,10	**101,38**	108,77	101,10	**101,05**	103,62
	$U(D_{ref})$	0,00	**0,69**	9,77	0,96	**0,68**	0,64

Table 3: Reference values D_{ref} and expanded uncertainties $U(D_{ref})$
Reference values determined from arithmetic mean and from weighted mean using the measurement results obtained by different methods (only A, A and B and D, all methods), expanded uncertainties for k = 2, bold values used for evaluation in sections 7.4 and 7.5; for methods cf. section 6.1

For both, the arithmetic mean and the weighted mean the differences between the reference values according to (A) and (A, B, D) are very small. This leads to the conclusion that the deviations of the correction for (D) and the difference between measured and defined diameter for (B) are relatively small. The arithmetic mean according to (A, B, C, D) clearly deviates from the two arithmetic means obtained by (A) and (A, B, D). This supports the decision to determine the reference values without taking the results obtained by (C) into account. The respective weighted mean, however, clearly deviates only in the case of the 0,1 mm ring, the reason for this being the comparably high measurement uncertainty of the values measured according to (C).

Figure 8 shows the differences between arithmetic mean and weighted mean for the methods in question. In addition, the expanded uncertainties of these differences are indicated as the sum of squares of the uncertainties of arithmetic mean and weighted mean (k = 2).

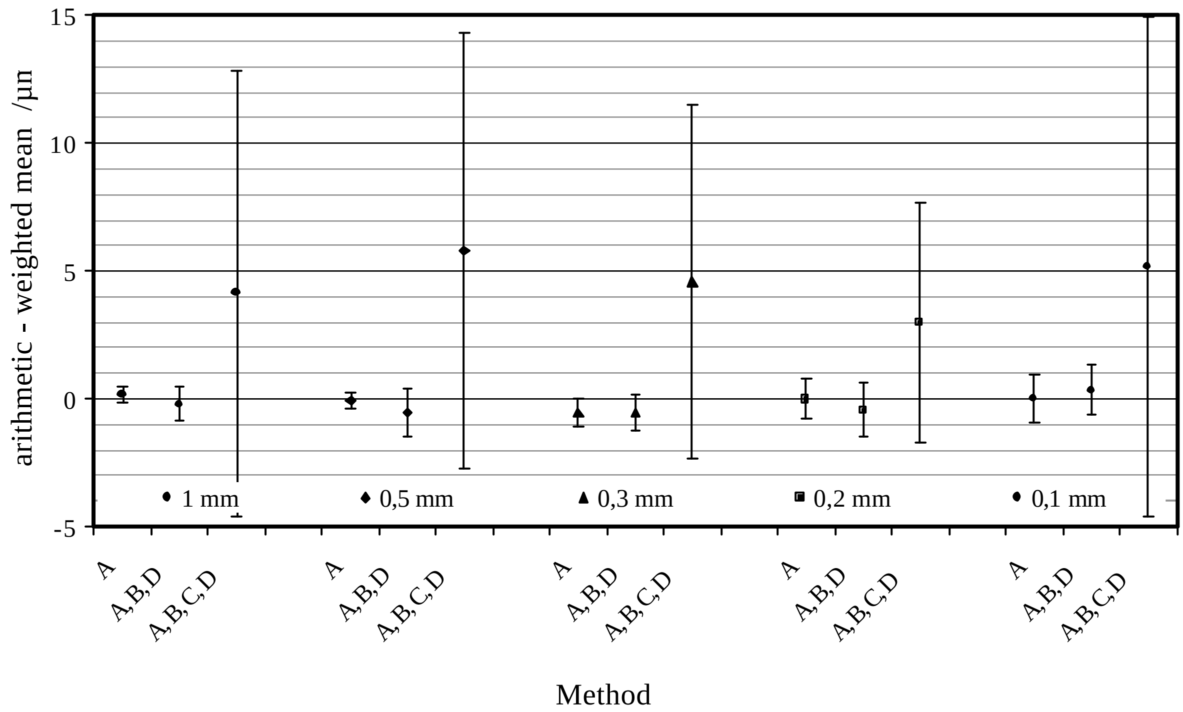


Figure 8: Deviations of the reference values from arithmetic mean and from weighted mean using the values obtained by different measurement methods (only A, A and B and D, all methods). Uncertainty of the deviations for k = 2; for methods cf. section 6.1

It can be seen that the differences between both computation methods, i.e. arithmetic mean and weighted mean, are relatively small when the results obtained by (C) are not taken into account. Basic differences between the reference values determined as the arithmetic mean and the weighted mean will, therefore, not be treated in detail. For the evaluation of the comparison measurements described in the following two sections, both the arithmetic mean (section 7.4) and the weighted mean (section 7.5) were used as reference values. Section 7.5 covers additional investigations into the consistency of data and model according to section 7.2.1.

7.4 Deviations of measurement results from the arithmetic mean

The deviations ΔD of the measurement results from the arithmetic mean acc. to eq. (14) are summarized in Table 4. The arithmetic means have been determined from the measurement results obtained with the methods (A, B, D), cf. section 7.1.3. The expanded uncertainties acc. to eq. (15) and the *En* values acc. to eq. (9) are given in addition. For symbols of methods cf. section 6.1.

Ring gauge	Participants	PTB 1	PTB 2	NPL	OFMET	Just.ves.	IMGC	SP	PTB 3
	Method	A	A	C	A	B	C	D	A
1 mm	ΔD in µm	-0,02	0,68	34,78	0,24	-0,02	0,33	-1,92	0,68
	$U(\Delta D)$ in µm	0,59	0,82		0,58	0,83	0,59	3,84	0,84
	$\|En\|$	0,03	0,83		0,42	-0,02	0,57	0,50	0,81
0,5 mm	ΔD in µm	0,42	0,22	24,02	0,73	0,12	27,56	-2,28	0,82
	$U(\Delta D)$ in µm	0,78	1,17		0,78	0,87		3,88	1,18
	$\|En\|$	0,53	0,18		0,93	0,13		-0,59	0,69
0,3 mm	ΔD in µm		-0,63	20,27	0,52	0,97	16,85	-0,73	-0,13
	$U(\Delta D)$ in µm		1,06		0,52	0,65		3,83	0,99
	$\|En\|$		0,59		0,99	**1,50**		0,19	0,13
0,2 mm	ΔD in µm		-0,33	13,87	0,37	0,87	11,15	-1,88	0,97
	$U(\Delta D)$ in µm		1,20		0,84	0,90		3,89	1,20
	$\|En\|$		0,28		0,44	0,96		0,48	0,81
0,1 mm	ΔD in µm		-0,28	27,63		-0,47	16,72	1,03	-0,28
	$U(\Delta D)$ in µm		3,08			1,11		3,83	1,12
	$\|En\|$		0,09			0,43		0,27	0,25

Table 4: Deviations ΔD of measured diameter from the arithmetic mean D_{ref} (A, B, D)
Expanded uncertainties $U(\Delta D)$ for $k = 2$ and E_n-values; for methods cf. section 6.1

In the case of two participants, the amount of the *En* values is higher than 1 (PTB 1: ring gauge 1 mm and Justervesenet: ring gauge 0,3 mm). A possible reason for this is that the participants stated too low values for the measurement uncertainties in Table 2.

For each ring gauge the deviations ΔD from the arithmetic mean (A, B, D) and the expanded uncertainties $U(\Delta D)$ are represented in Figure 9 to Figure 13. The broken lines indicate the expanded uncertainty of the reference value $U(D_{ref})$ acc. to Table 3.

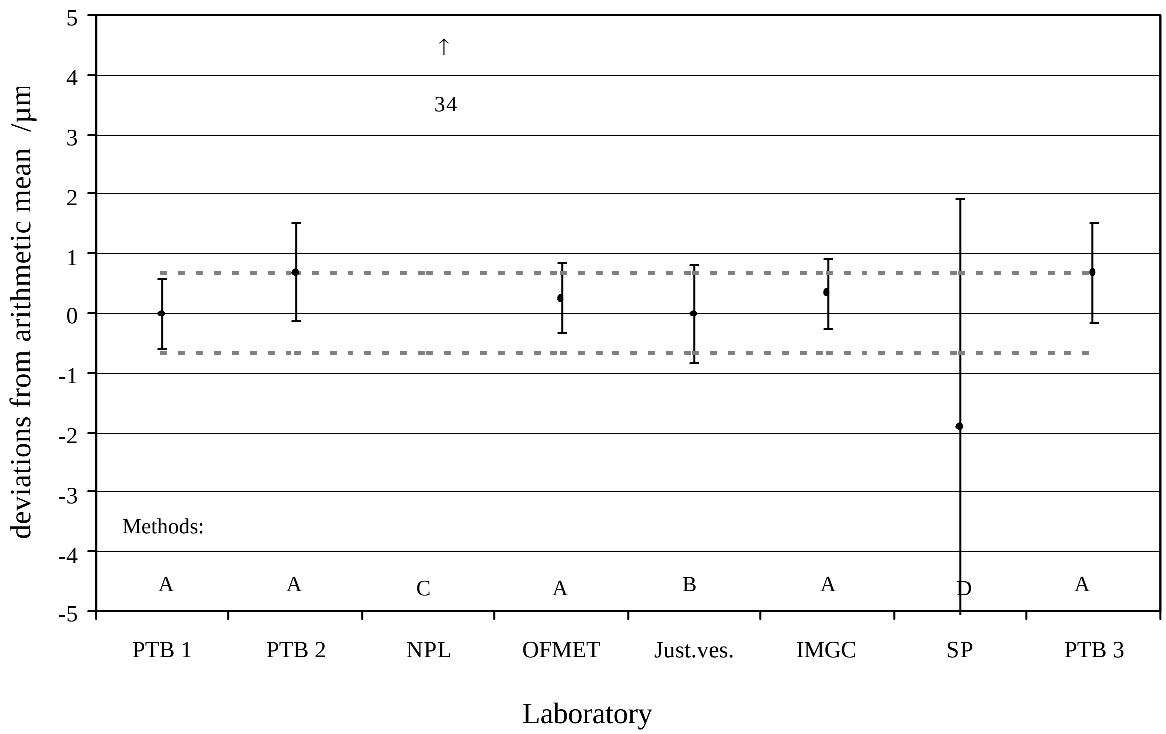


Figure 9: Ring gauge 1 mm: deviations ΔD of measured diameter from the arithmetic mean D_{ref} (A, B, D) with $U(\Delta D)$ for k = 2, broken lines $U(D_{ref})$; for methods cf. section 6.1

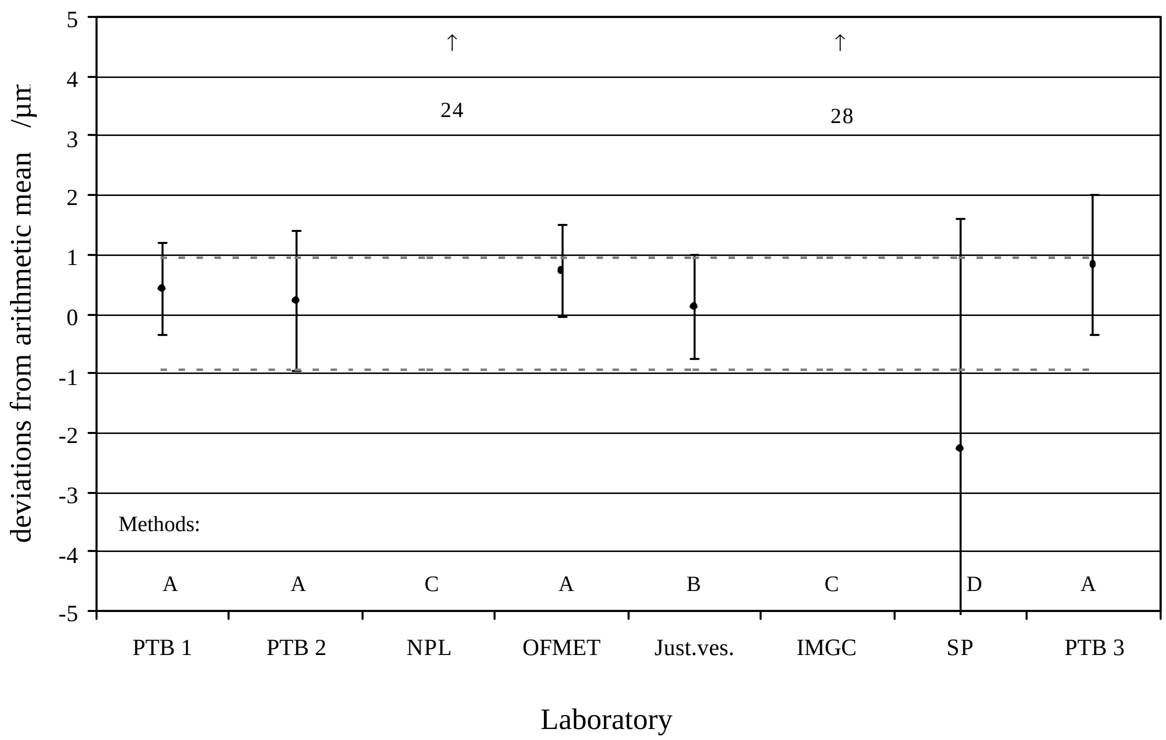


Figure 10: Ring gauge 0,5 mm: deviations ΔD of measured diameter from the arithmetic mean D_{ref} (A, B, D) with $U(\Delta D)$ for k = 2, broken lines $U(D_{ref})$; for methods cf. section 6.1

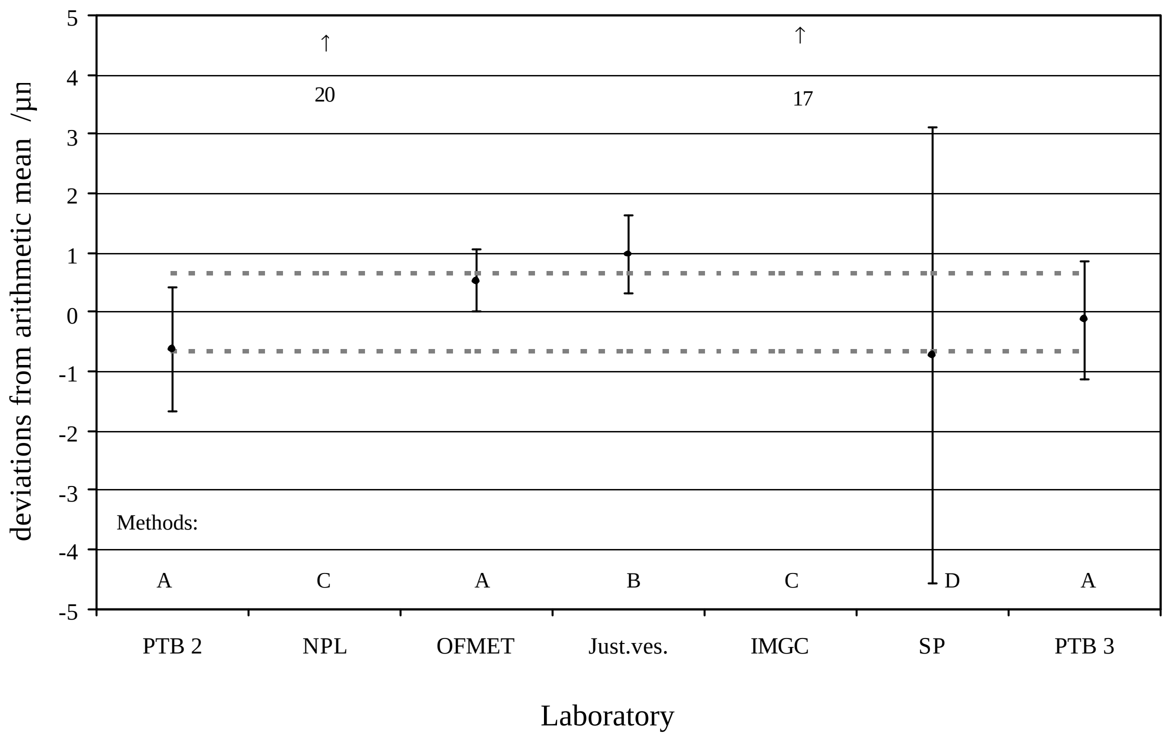


Figure 11: Ring gauge 0,3 mm: deviations ΔD of measured diameter from the arithmetic mean D_{ref} (A, B, D) with $U(\Delta D)$ for k = 2, broken lines $U(D_{ref})$; for methods cf. section 6.1

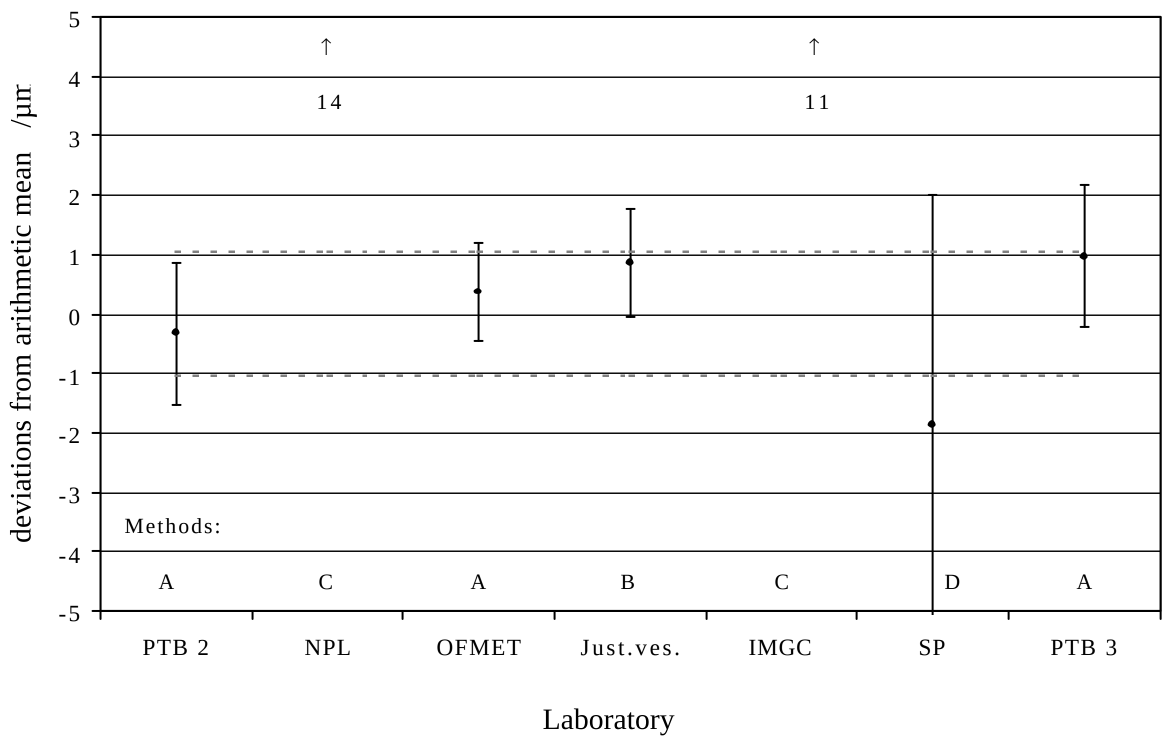


Figure 12: Ring gauge 0,2 mm: deviations ΔD of measured diameter from the arithmetic mean D_{ref} (A, B, D) with $U(\Delta D)$ for k = 2, broken lines $U(D_{ref})$; for methods cf. section 6.1

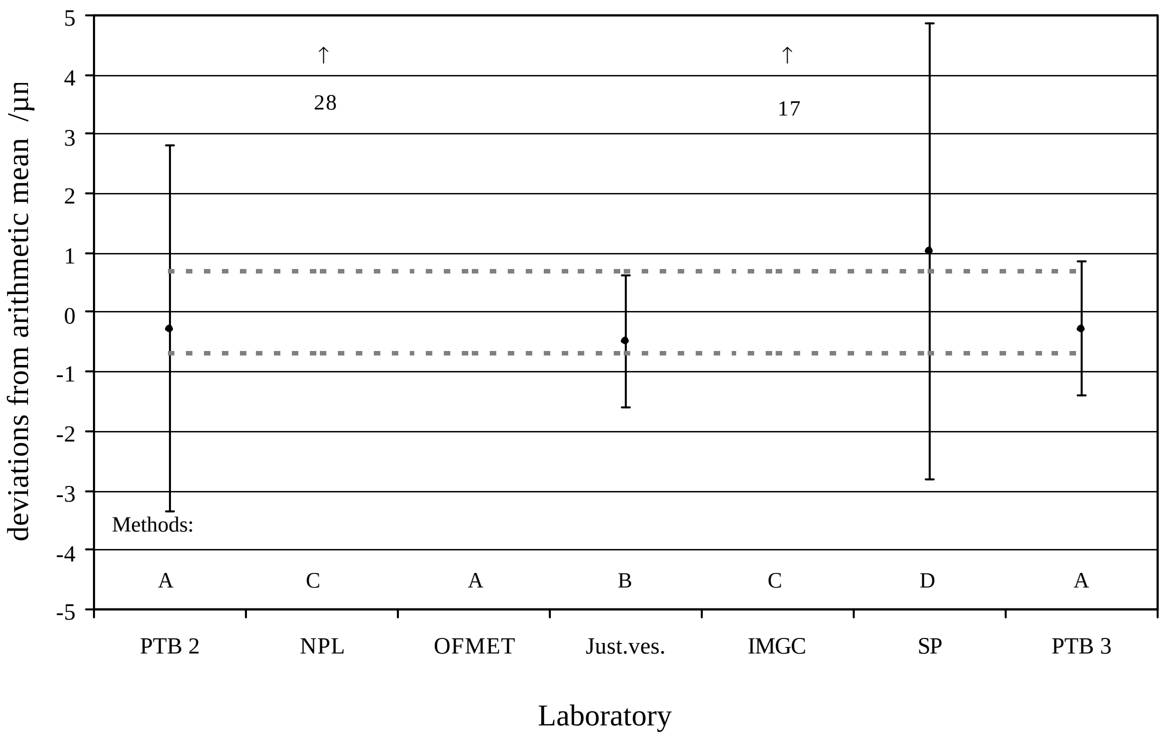


Figure 13: Ring gauge 0,1 mm: deviations ΔD of measured diameter from the arithmetic mean D_{ref} (A, B, D) with $U(\Delta D)$ for k = 2, broken lines $U(D_{ref})$; for methods cf. section 6.1

7.5 Deviations of measurement results from the weighted mean

The deviations Δ*D* of the measurement results from the weighted mean acc. to eq. (1) are summarized in Table 5. The weighted means have been determined from the measurement results obtained by methods (A, B, D), cf. section 7.1.3. The expanded uncertainties acc. to eq. (4) and the *En* values acc. to eq. (9) are given in addition. For symbols of methods cf. section 6.1.

Rings	Participants	PTB 1	PTB 2	NPL	OFMET	Just.ves.	IMGC	SP	PTB 3
	Method	A	A	C	A	B	C	D	A
1 mm	Δ*D* in µm	-0,23	0,47	34,57	0,03	-0,23	0,12	-2,13	0,47
	U(Δ*D*) in µm	0,13	0,59		0,07	0,60	0,12	3,80	0,62
	|*En*|	**1,76**	0,79		0,37	0,39	0,96	0,56	0,76
0,5 mm	Δ*D* in µm	-0,16	-0,36	23,44	0,15	-0,46	26,98	-2,86	0,24
	U(Δ*D*) in µm	0,12	0,88		0,08	0,39		3,80	0,89
	|*En*|	**1,34**	0,41		**1,89**	**1,18**		0,75	0,27
0,3 mm	Δ*D* in µm		-1,16	19,74	-0,01	0,44	16,32	-1,26	-0,66
	U(Δ*D*) in µm		0,91		0,10	0,36		3,80	0,83
	|*En*|		**1,27**		0,14	**1,21**		0,33	0,80
0,2 mm	Δ*D* in µm		-0,78	13,42	-0,08	0,42	10,70	-2,33	0,52
	U(Δ*D*) in µm		0,86		0,10	0,36		3,80	0,86
	|*En*|		0,91		0,82	**1,15**		0,61	0,60
0,1 mm	Δ*D* in µm		0,07	27,95		-0,15	17,04	1,35	0,05
	U(Δ*D*) in µm		2,96			0,73		3,74	0,75
	|*En*|		0,02			0,20		0,36	0,07

Table 5: Deviations Δ*D* of measured diameter from the weighted mean D_{ref} (A, B, D)

Expanded uncertainties *U*(Δ*D*) for $k = 2$ and *En* values, for methods cf. section 6.1

For a number of measurement results, the amount of the *En* values is greater than 1. A possible reason for this is that the participants stated too low values for the respective measurement uncertainties in Table 2.

In Table 6 the Birge ratios R_B, determined acc. to eq. (10), are given, as are the maximum values of Birge ratios $R_{B\ max}$, determined acc. to eq. (13). It can be seen that for the ring gauges 0,2 mm and 0,1 mm the Birge ratios R_B are smaller than $R_{B\ max}$. For these measurements, there is a consistency between data and model. For the ring gauges 1 mm, 0,5 mm and 0,3 mm, the Birge ratios R_B are only sligthly larger than the $R_{B\ max}$. It can therefore be said that for these measurements the consistency of data and model is approximately given.

Ring gauge	R_B	$R_{B\ max}$
1 mm	1,66	1,5
0,5 mm	1,79	1,5
0,3 mm	1,67	1,6
0,2 mm	1,49	1,6
0,1 mm	0,45	1,6

Table 6: Birge ratio for evaluation of weighted mean

For each ring gauge the deviations ΔD from the weigthed mean (A, B, D) and the expanded uncertainties $U(\Delta D)$ are represented in Figure 14 to Figure 18. The broken lines indicate the expanded uncertainty of the reference value $U(D_{ref})$ acc. to Table 3.

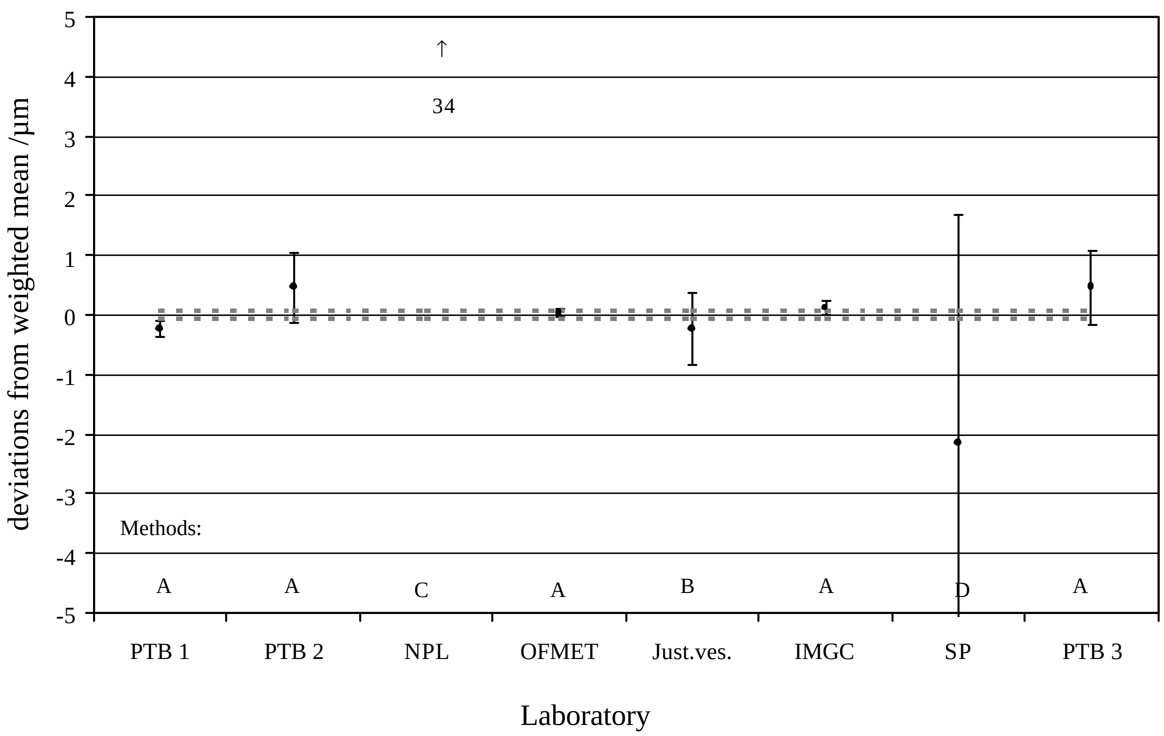


Figure 14: Ring gauge 1 mm: deviations ΔD of measured diameter from the weighted mean D_{ref} (A, B, D) with $U(\Delta D)$ for k = 2, broken lines $U(D_{ref})$; for methods cf. section 6.1

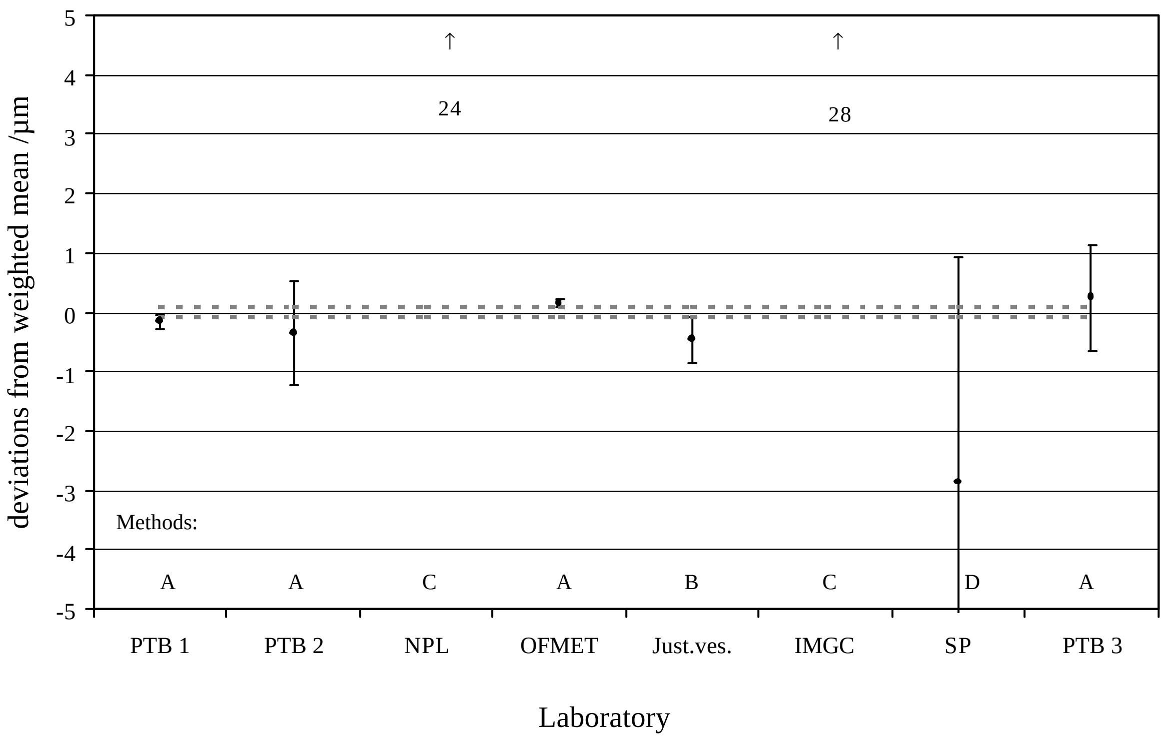


Figure 15: Ring gauge 0,5 mm: deviations Δ*D* of measured diameter from the weighted mean D_{ref} (A, B, D) with *U*(Δ*D*) for *k* = 2, broken lines $U(D_{ref})$; for methods cf. section 6.1

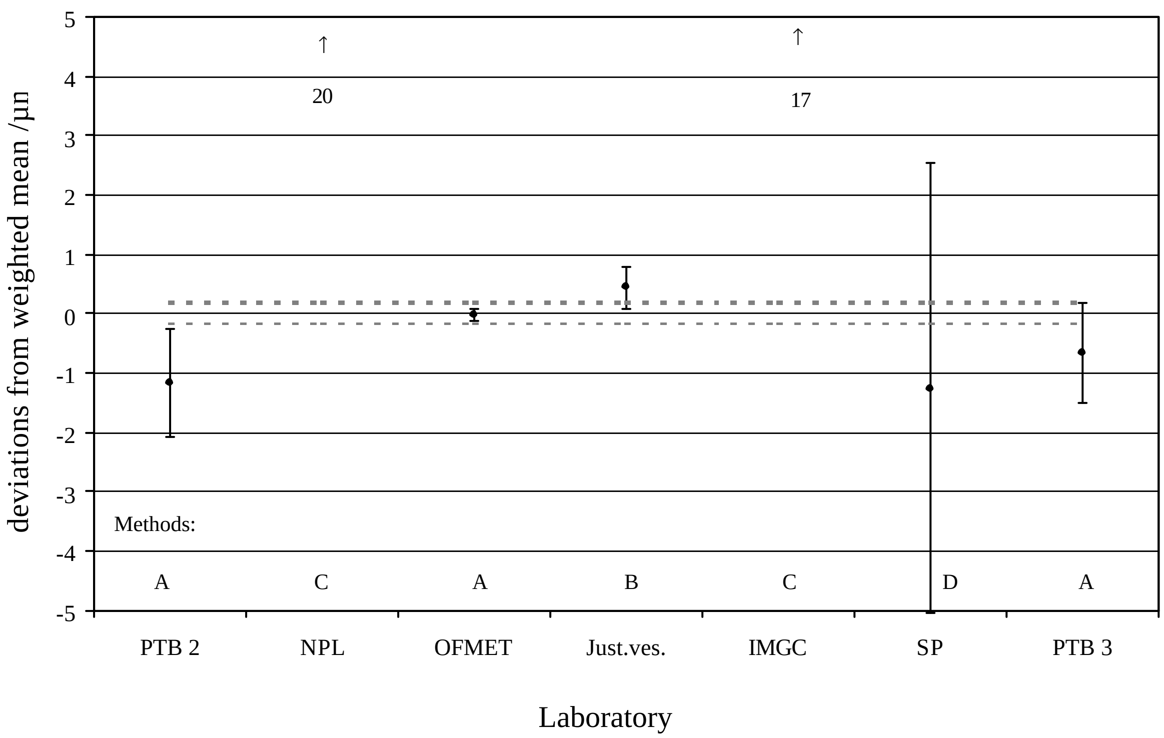


Figure 16: Ring gauge 0,3 mm: deviations Δ*D* of measured diameter from the weighted mean D_{ref} (A, B, D) with *U*(Δ*D*) for *k* = 2, broken lines $U(D_{ref})$; for methods cf. section 6.1

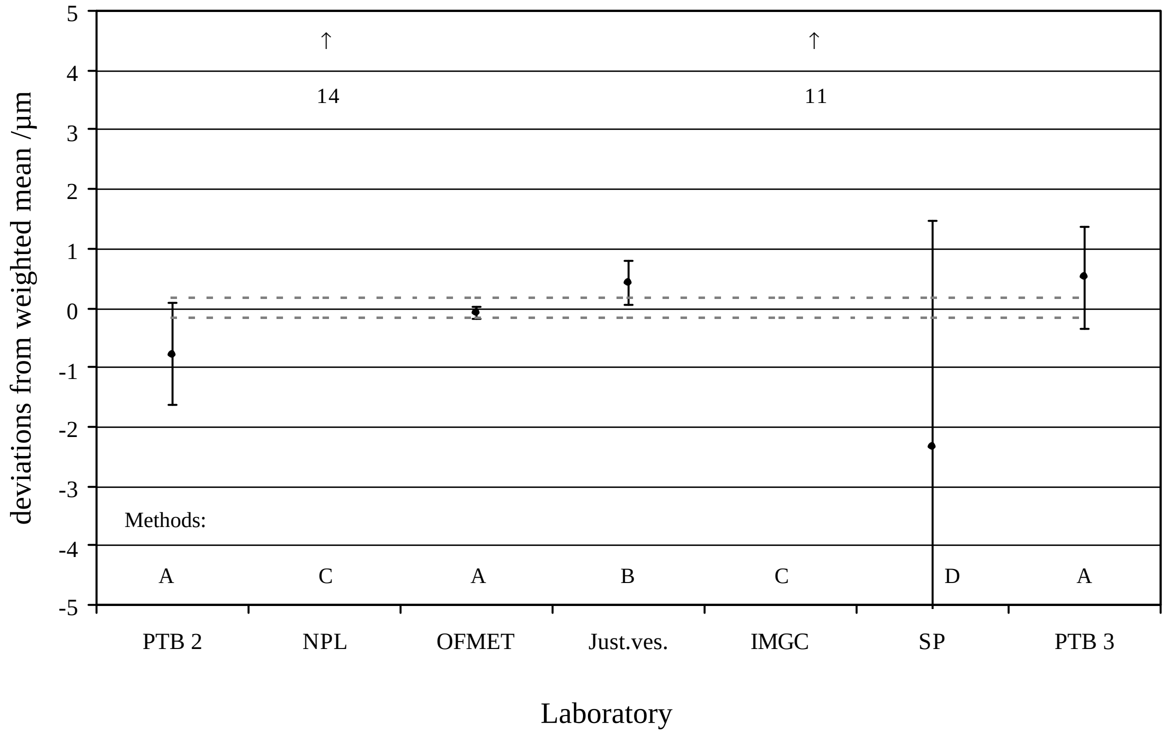


Figure 17: Ring gauge 0,2 mm: deviations ΔD of measured diameter from the weighted mean D_{ref} (A, B, D) with $U(\Delta D)$ for k = 2, broken lines $U(D_{ref})$; for methods cf. section 6.1

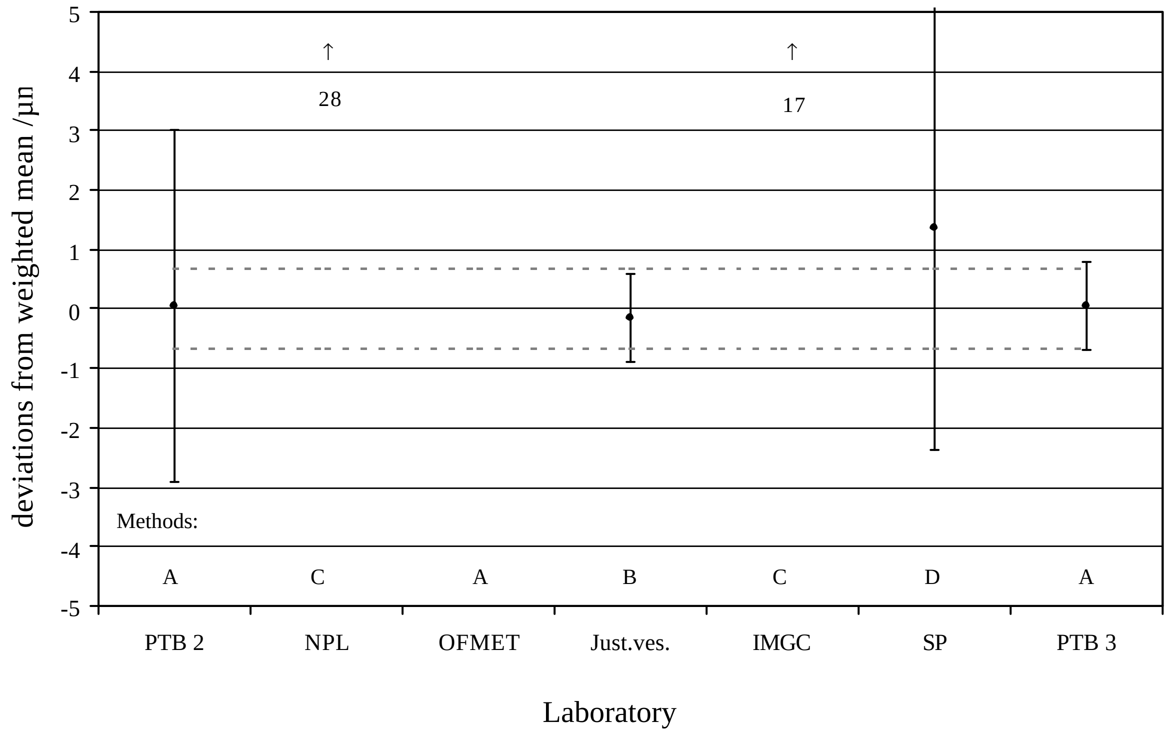


Figure 18: Ring gauge 0,1 mm: deviations ΔD of measured diameter from the weighted mean D_{ref} (A, B, D) with $U(\Delta D)$ for k = 2, broken lines $U(D_{ref})$; for methods cf. section 6.1

8 Influence of the form of the cylinder face

8.1 Influence of straightness deviations

Straightness measurements on the ring gauges were carried out by the pilot laboratory using a CMM and a fibre probe (cf. section 5.1 II). This had to be done to investigate the influence of the form of the ring gauges on the uncertainty of diameter measurements (cf. section 7.1.1, 5.).

In the following, the deviations from straightness and parallelism are shown for each ring gauge. As the ring gauges were adjusted for the CMM measurements in relation to their upper front face, the original data (grey curve) include the angle between the cylinder face and this front face. The black curves were obtained after fitting of the original data. The respective heights for diameter measurements have been marked in addition. It can clearly be seen that, especially for the smaller ring gauges, a variation of the measurement height within 0,05 mm may result the diameter measured varying by up to several tenths of a micrometer.

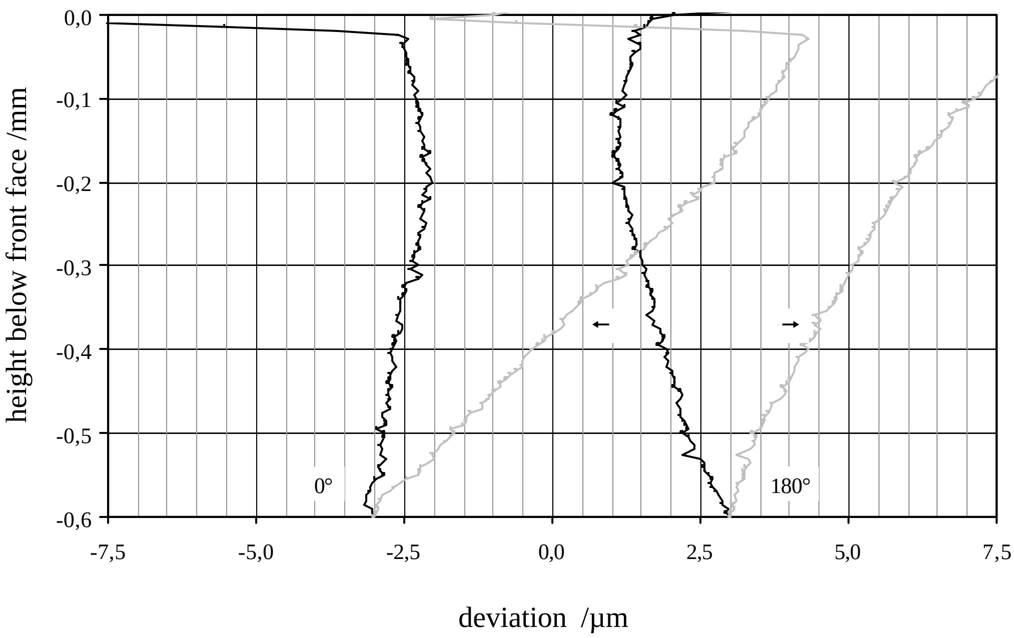


Figure 19: Ring gauge 1 mm: results of straightness measurements
Measurements carried out with a CMM and a fibre probe. grey curve: original data; black curve: obtained after fitting of the original data (angle between cylinder face and front face: about 90°-2,2°), ← →: height of diameter measurement

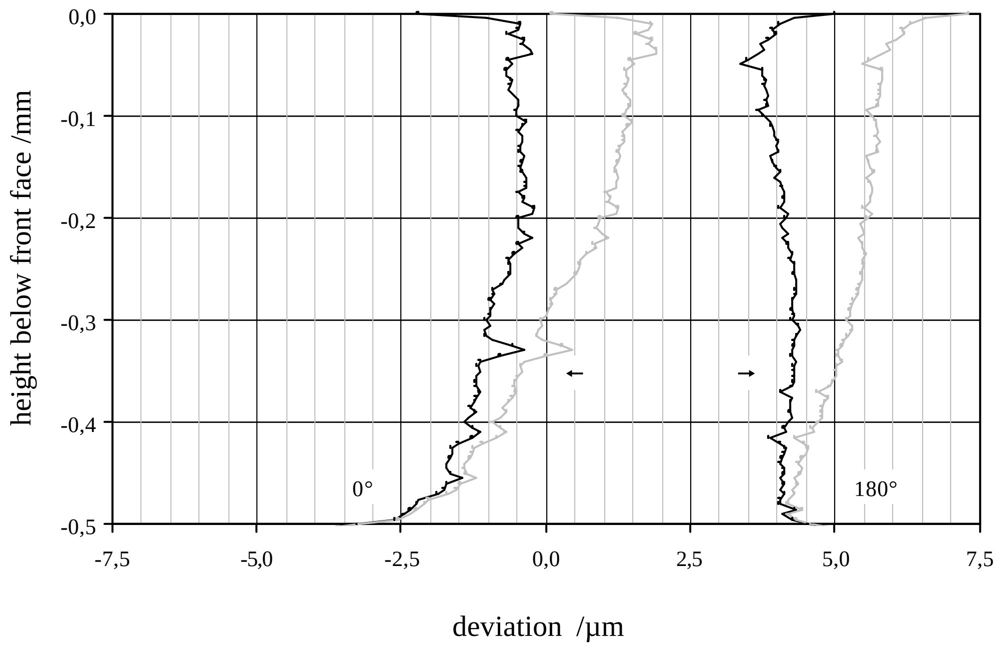


Figure 20: Ring gauge 0,5 mm: results of straightness measurements

Measurements carried out with a CMM and a fibre probe. grey curve: original data; black curve: obtained by after fitting of the original data (angle between cylinder face and front face: about 90°-1,4°), ← →: height of diameter measurement

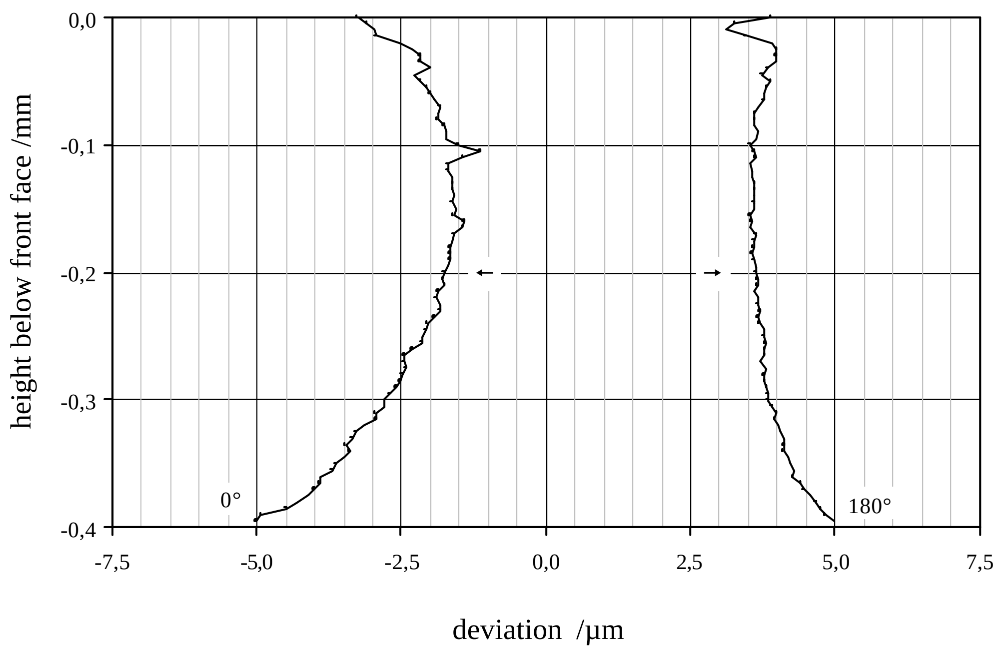


Figure 21: Ring gauge 0,3 mm: results of straightness measurements

Measurements carried out with a CMM and a fibre probe. original data,

← →: height of diameter measurement

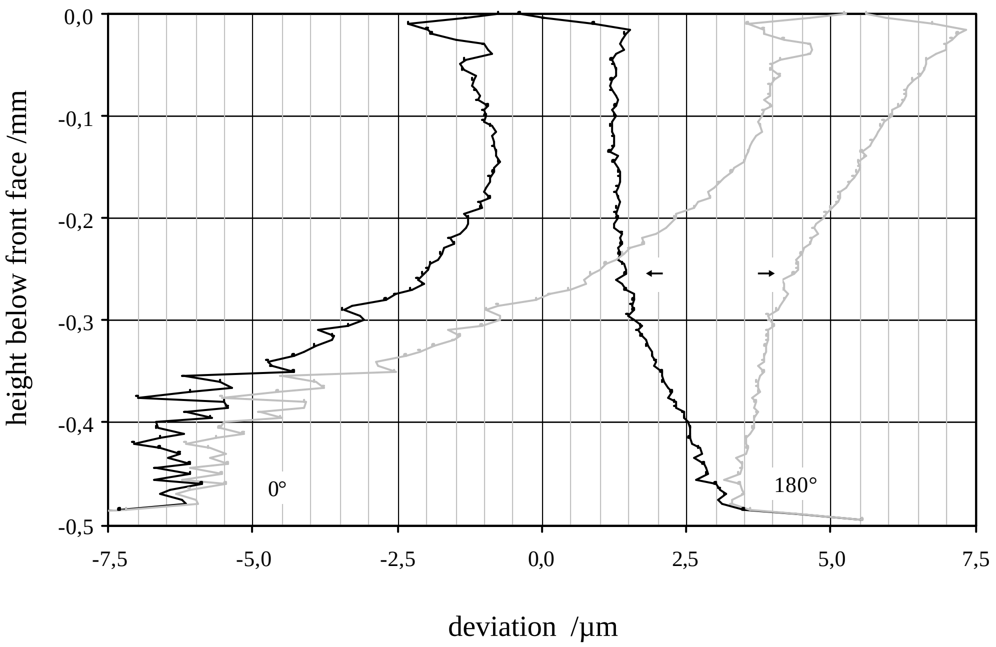


Figure 22: Ring gauge 0,2 mm: results of straightness measurements

Measurements carried out with a CMM and a fibre probe. grey curve: original data; black curve: obtained after fitting of the original data (angle between cylinder face and front face: about 90°-4,6°), ← →: height of diameter measurement

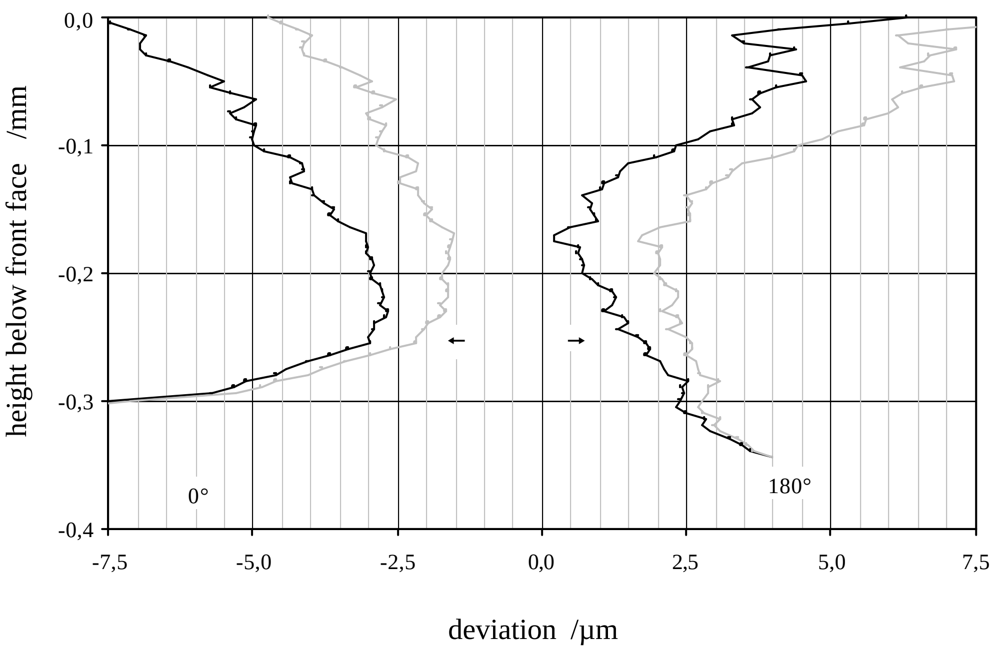


Figure 23**:** Ring gauge 0,1 mm: results of straightness measurements

Measurements carried out with a CMM and a fibre probe. grey curve: original data; black curve: obtained after fitting of the original data (angle between cylinder face and front face: about 90°-3°), ← →: height of diameter measurement

8.2 Influence of the determination of the edge of the cylinder

As shown in section 6.2 large differences were found between the measurement results obtained by method (C) and the other results. These differences are probably not caused by the measurement uncertainty but by the measurement procedures, in combination with the properties of the ring gauges. For the optical measurement with respect to the position of the edges on the upper front face (C) these edges have to be determined. If the edge is not sharp but lacerated, deviations in the determination of the edge position results in deviations of the diameters measured.

To investigate this influence, measurements were carried out at the ring 0,3 mm with the aid of a confocal laser scan microscope (Lasertec 1LM21P, objective: x80 long distance, NA 0,75, lateral resolution: 0,5 µm). First, the upper front surface of the ring was focused and the edge position was determined. Then the focus was scanned down until the edge of the cylinder face was visible.

The result of these measurements are shown in Figure 24 for the 0° side of the ring. The image field is 141 µm x 110 µm. The upper photograph shows the front face, the lower photograph the edge of the cylinder. The height difference between the two focal planes is about 6 µm. From this measurement, the lateral difference of the two different edges can be estimated to be approximately 8 µm. The lateral difference at the 180° side of the ring is in the same order. These lateral differences result in a deviation of the diameter measurements by about 16 µm in relation to the measurement at the edge of the cylinder.

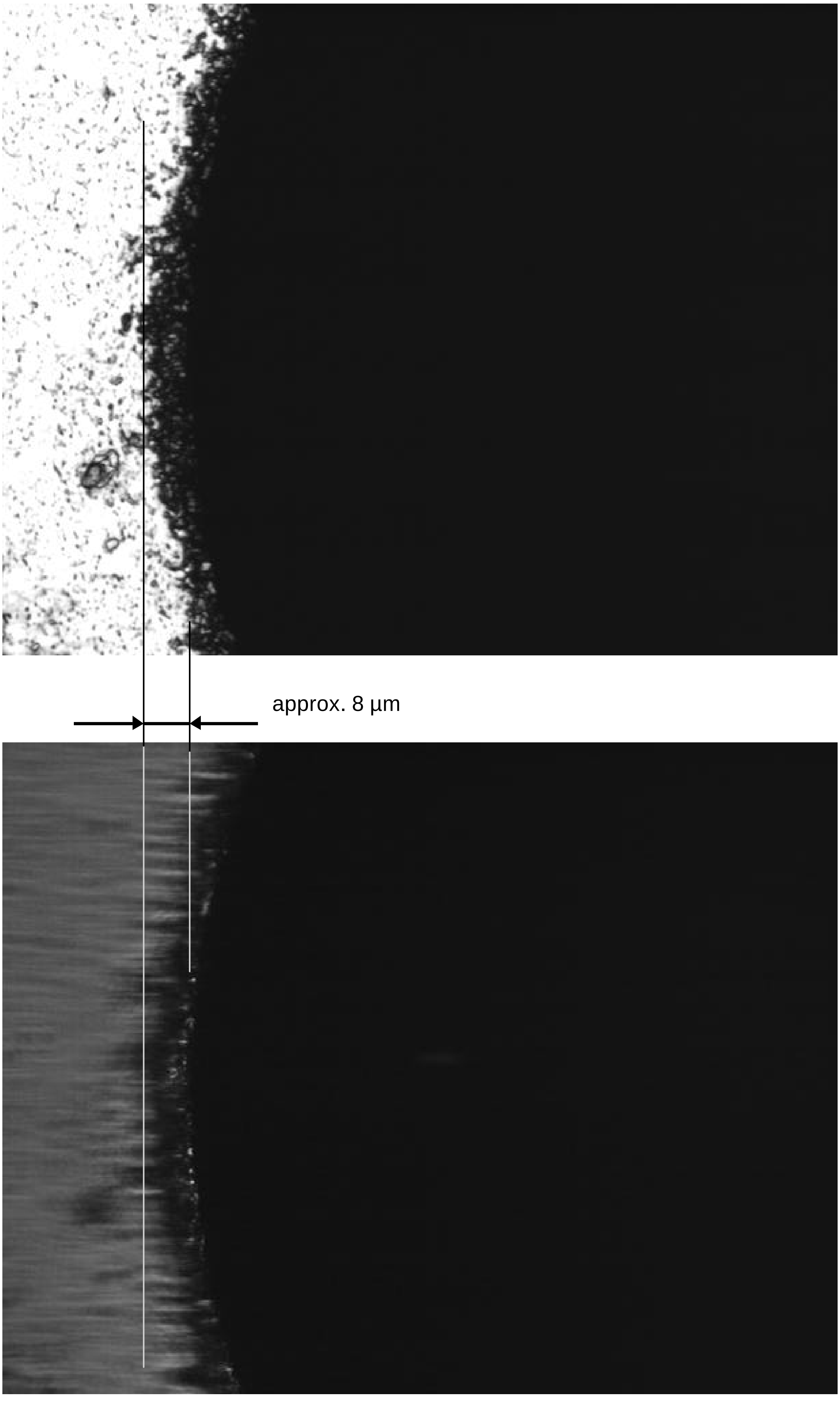


Figure 24: Influence of the quality of the edge on diameter measurements Ring gauge 0,3 mm.
Front face (upper photograph) and edge of cylinder (lower photograph), field of view: 141 µm x 110 µm

8.3 Cylinder surface

To investigate the cylinder surface, ring gauges of the same charge as the rings used for the comparison measurements are prepared for REM measurements. The rings are ground in the axial direction to be a half-pipe, fixed with epoxy and all over coated with gold (approx. 5 nm thick). Figure 25 and Figure 26 show REM measurement results obtained on a 0,1 mm ring gauge. Residues of epoxy can be seen on the cylinder surface. The right side of the photograph can be assigned to the upper face of the ring gauge. It can be seen that the cylinder form is very bad, especially from the middle to the left side. On the detailed figure, scratches can be seen which are probably due to manufacture, as well as holes and the lacerated edge. Figure 27 shows a detail obtained on a 0,2 mm ring gauge.

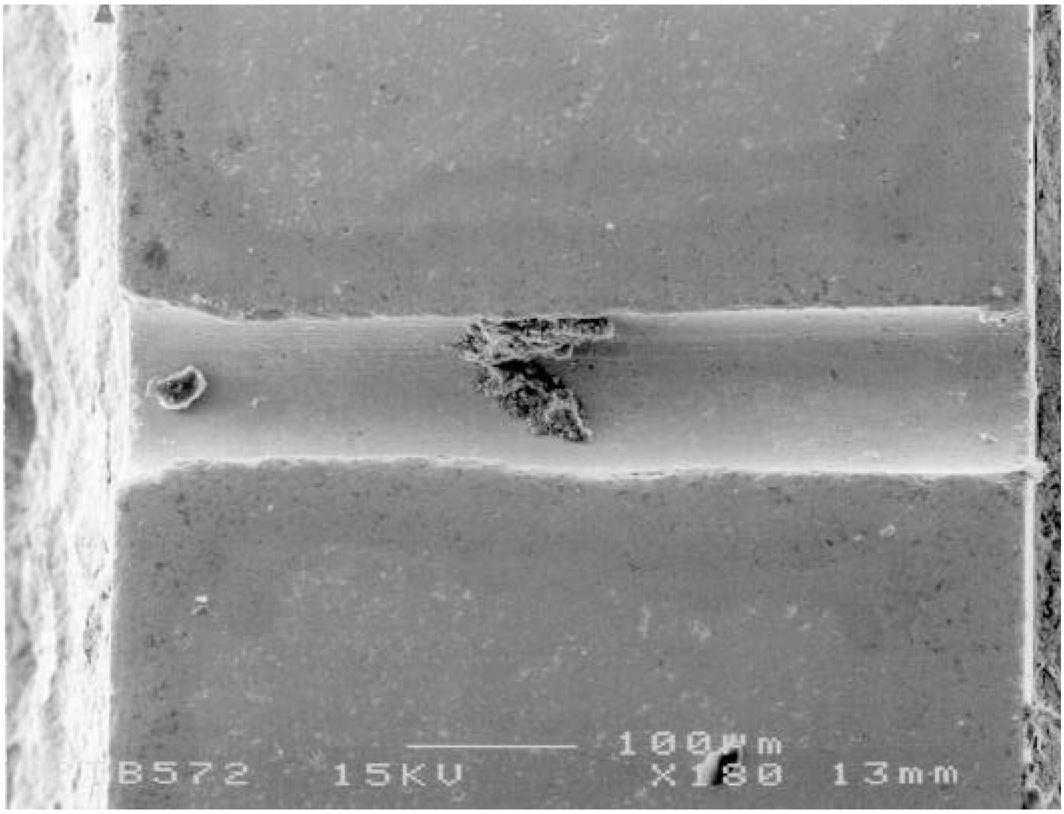


Figure 25: REM shot of a cut ring gauge (0,1 mm in diameter)

Large particles are probably residues of epoxy used for preparation.

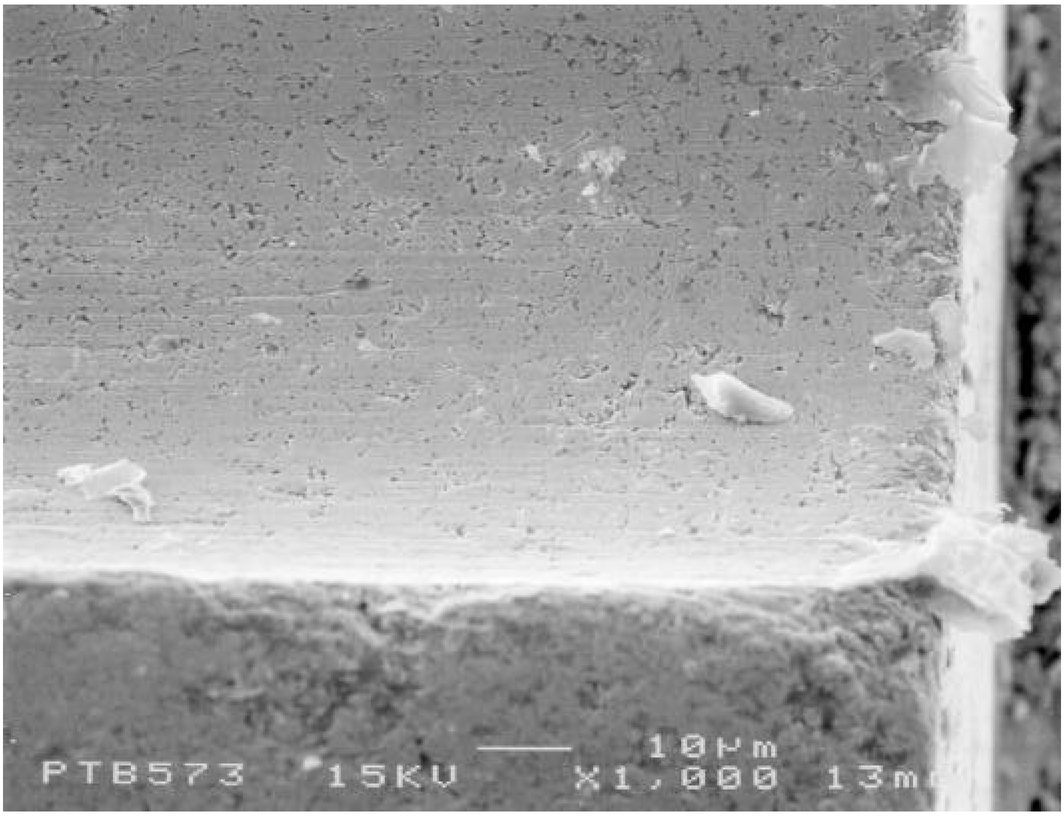


Figure 26: REM shot of a cut ring gauge (0,1 mm in diameter), detail

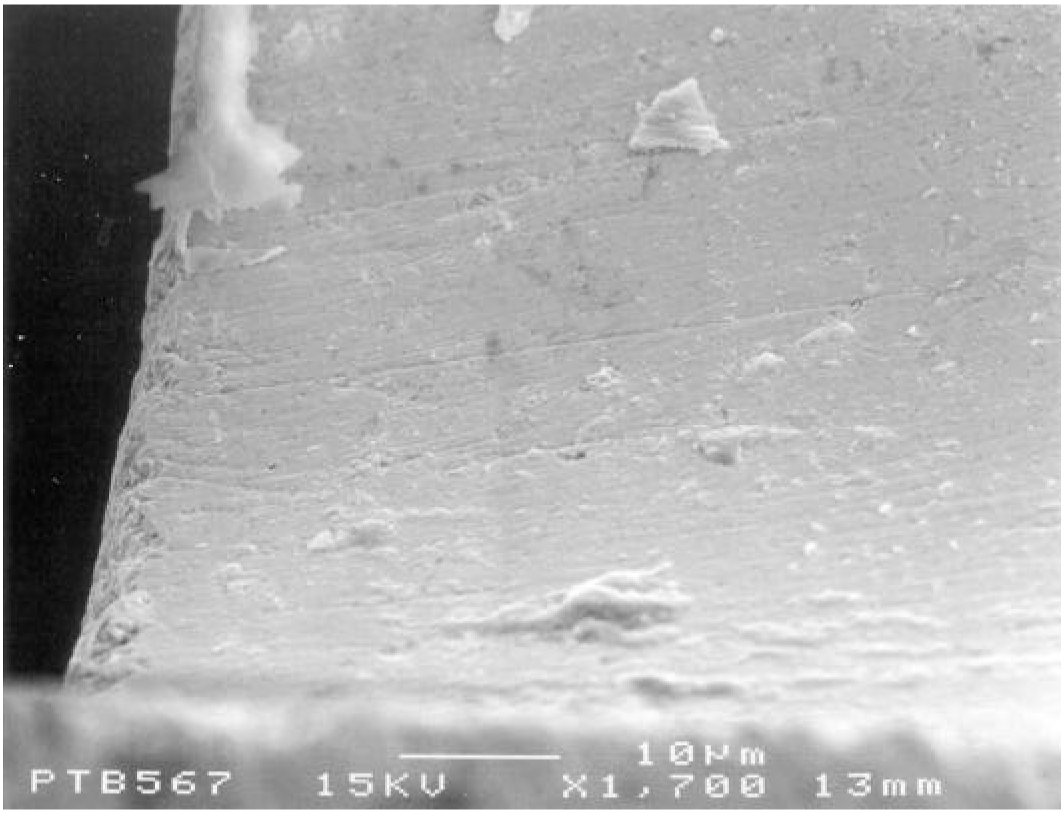


Figure 27: REM shot of a cut ring gauge (0,2 mm in diameter), detail

8.4 Artefacts for future projects

As shown in section 8.1 and section 8.2, both the deviations of cylinder form and the lacerated edges of the ring gauges used result in large uncertainty contributions and, therefore affect the comparability of the measurement methods applied. To avoid such large influences of the artefacts to be measured, both the cylinder form and the quality of the edges have to be improved for future projects. After the comparison measurements had been completed PTB obtained another type of artefact for calibration, which is used as a transfer standard for manufacturers of spinning nozzles in the textile industry. The artefact includes 5 holes of different diameter from 0,1 mm to 0,5 mm, with a depth of about 0,5 mm.

Both the cylinder form and the quality of the edges were investigated at PTB.

8.4.1 Straightness and parallelism measurements with a CMM

Straightness measurements on the artefact were carried out by the pilot laboratory using a CMM and a fibre probe (cf. section 5.1 II). As an example, the mesurement results for the hole 0,2 mm are shown in Figure 28. The deviations from straightness and parallelism are within about 1 µm and, therefore, much smaller than the deviations from straightness and parallelism measured at the ring gauge 0,2 mm (cf. Figure 22 on page 49). Furthermore it can be seen that the angle between the cylinder axis and the upper face of the artifact is nearly 90°.

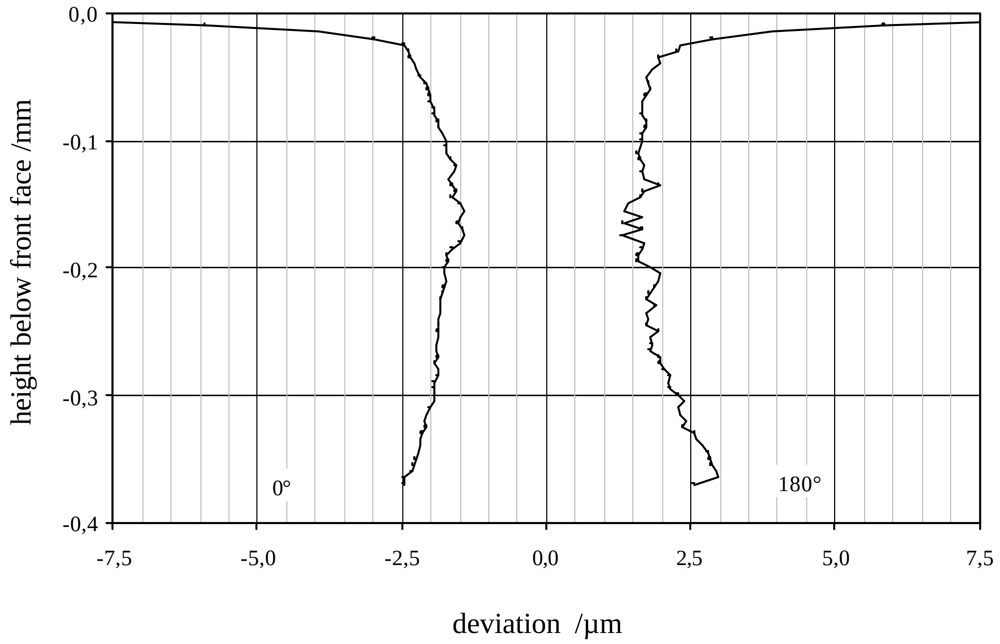


Figure 28: Artefact, hole 0,2 mm: results of straightness measurements.
Measurements carried out with a CMM and a fibre probe. original data

8.4.2 Measurements at the edges with a confocal laserscan microscope

The measurements at the edges are carried out with the aid of a confocal laser scan microscope (Lasertec 1LM21P, objective: x80 long distance, NA 0,75, lateral resolution: 0,5 µm). The result of these measurements can be seen, for example, in Figure 29 for the hole 0,1 mm. (The edges of the other holes are of the same quality.) Within the depth of focus of approx. 6 µm below the front face, no deviations from the edges were found as for the ring gauge 0,3 mm in Figure 24. This means that the edges of the holes are very sharp compared with the edges of the ring gauges used for comparison measurements, and it can be expected that this influence would be very small.

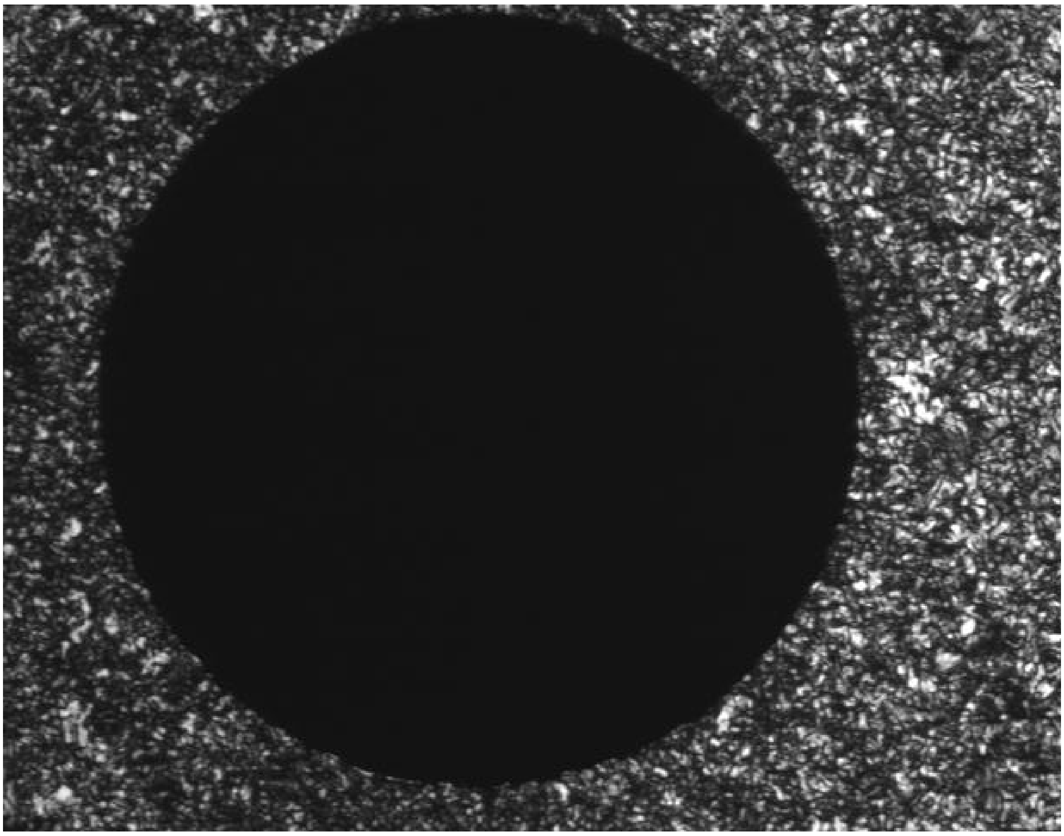


Figure 29: Hole 0,1 mm of a transfer standard for spinning nozzles
Field of view: 141 µm x 110 µm; depth of focus: approx. 6 µm

9 Summary

Goal of comparison measurements

The goal of the EUROMET #406 comparison measurements of the diameter of ring gauges was to explore and harmonize the measurement capabilities for diameter measurements on small rings with diameters of up to 1mm. Six European national metrology institutes agreed to participate in these comparison measurements. The investigations were organized by the Physikalisch-Technische Bundesanstalt (PTB), Germany. The comparison started in June 1999 with the circulation of five ring gauges. The pattern chosen for comparison was the round robin type, with a first and a final calibration by the pilot laboratory.

Ring gauges used and definition of measurements

Five ring gauges with diameters of 1 mm, 0,5 mm, 0,3 mm, 0,2 mm and 0,1 mm were used for the comparison measurements. The thickness or heights of the ring gauges were in the range from 0,3 mm to 0,6 mm. The gauges were made of tungsten carbide and, for better handling, enclosed in a aluminium ring-shaped housing. The participants had to measure the diameter in a defined orientation and at specified height distance from the engraved front face. Additional form measurements were to be carried out as far as possible.

Measurement methods used

The participants used different measurement principles as follows:

Number of participants	Method used	Symbol
2	mechanical contacting measurement	A
1	optical measurement with respect to the projection of the inner diameter	B
2	optical measurement with respect to the position of the edges on upper side	C
1	optical measurement with respect to the position of the edges on both sides	D

The defined measurands were determined only by method A. The measurement results obtained by method B correspond approximately to the defined measurands because the smallest diameters of the ring gauges are very similar to the defined measurement heights. In the case of method C, neither the defined measurands were determined nor were the measurement results corrected with respect to the defined measurands. With method D, the measurement results were corrected with respect to the defined measurands.

Evaluation of reference values

To guarantee the comparability of the measurement results, the reference values were determined only from the measurement results of methods (A, B, D). This evaluation was carried out for the arithmetic mean and the weighted mean. The differences of these reference values (A, B, D) to the reference values determined with the results of method (A) only are relatively small for both, the arithmetic mean and the weighted mean. This means, that the influence of the corrections with method (B) and (D) is small.

En values were determined to evaluate the measurement results with respect to the relation of deviation from the reference value to the associated uncertainty. To obtain an estimate of the consistency of the data and the model of the comparison measurements, the Birge ratios were determined in addition for the evaluation of the reference values from the weighted mean.

Comparison of measurement results

The uncertainties associated with the diameter measurement results differ considerably among the different participants. The lowest expanded uncertainty given is U = 0,10 µm whereas the largest uncertainy is U = 5 µm (95 %). This fact emphasizes the variety of the devices and methods used for the comparison measurements. In general, the measurement results obtained by methods (A, B, D) agree within their associated uncertainties. The results by method (C) exceed the reference values by between 10 µm and 30 µm. This is probably due to the influence of the lacerated edges of the ring gauges.

The relations of deviations from the reference values to the associated uncertainties are reasonable for most results given. In this context it may be possible that too small values of the associated uncertainties have been given for a few measurement results, especially with respect to the relatively strong influence of surface and shape of the ring gauges on the uncertainty. For the determination of the weighted mean this may result in some cases to *En* values which misrepresent the measurement capabilites of some participants. For an assessment of the comparison measurements indepent on the associated uncertainties the arithmetic mean and the corresponding *En* values was therefore given additionally. It can be assumed that the *En* values from arithmetic mean characterise the measurement capabilities of some participants better than the *En* values from weighted mean. Another newly developed type of artefact of better quality mainly in the area of the edges was presented. These artefacts may possibly prevent this influence in future projects.

Nevertheless it can be stated that the consistency of the data and model of the comparison measurements (without method C) is given. For the measurements on the ring gauges 1 mm, 0,5 mm and 0,3 mm, the evaluated Birge ratios only slightly exceed the limit, whereas the Birge ratios evaluated for the measurements on the ring gauges 0,2 mm and 0,1 mm are clearly below this limit.

Result, bottom line

The investigations described here, may be only a first step to the harmonization of calibration work in this important field. Further investgations for the development of new measurement equipment and efforts to harmonize the different, probably mainly optical methods are urgently required.

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List of tables

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