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Calibration of a Master Gear

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I.N.RI.M. TECHNICAL REPORT

Abstract

This technical report describes the calibration of a master gear provided by Newcastle University. The calibration has been performed with the coordinate measuring machine CMM/ST001 at INRIM, with the master gear mounted on the workpiece table (no rotary table) and a star configuration of the stylus system.
The present work is related to the deliverable 2.1.9 of Drive Train Poject (ENG56).

Questo rapporto tecnico descive la taratura di un Master Gear fornito dall'università di Newcastle. La taratura è stata condotta con la macchina a coordinate CMM/ST001 dell'INRIM nella configurazione con il Master Gear montato sulla tavola (non rotante) e con un tastatore a stella.
Questo lavoro si colloca all'interno del Progetto DriveTrian (ENG56) come deliverable 2.1.9.

1. Measurand, measurement procedure and conditions

1.1 Measurands

The measurands are the profile parameters ($f_{H\alpha}$, $f_{f\alpha}$, F_{α}) and lead parameters ($f_{H\beta}$, $f_{f\beta}$, F_{β}) of the left and right flanks of teeth 1, 9, 17 and 25, the pitch parameters (f_p, F_p) and the runout (F_r) [1, 2].

The nominal parameters of the gear are summarised in the following table.

Diameter d	Facewidth b	Teeth z	Helix angle β	Normal Module m_n	Pressure angle α_n	Base diameter d_b
390.048 mm	100 mm	32	35° RH	10 mm	20°	356.994

The profile parameters are evaluated in the range (377 – 407) mm of the length or roll. The lead parameters are evaluated along the facewidth with exclusion of 10 mm on each side (i.e. in the range (10 – 90) mm of the axial coordinate, while the full facewidth scans (0 – 100) mm).
The diameter of the theoretical sphere used to evaluate the runout is 18 mm.

1.2 Procedure

The calibration is performed with the coordinate measuring machine CMM/ST001, with the master gear mounted on the workpiece table (no rotary table) and a star configuration of the stylus system.

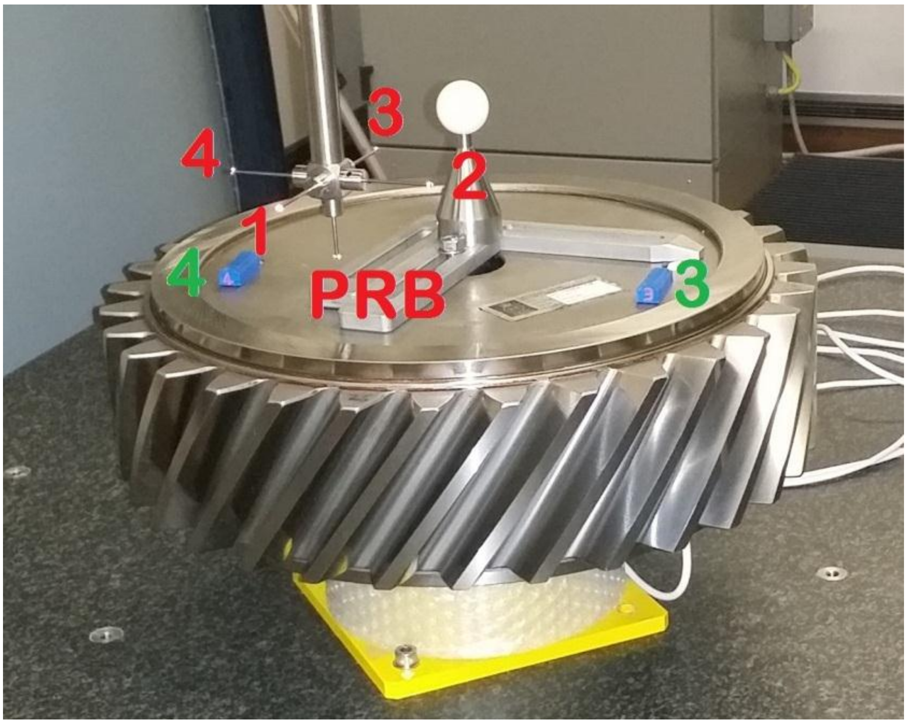


Figure 1: Mounting arrangement.

1,2,3,4: probe tips used to scan the gear surfaces (the vertical one is for alignment only).
3,4: thermometers.

The calibration is done in two steps with different measurands: a preliminary calibration (hereafter referred to as precalibration) and the actual calibration.

- Precalibration. Two radial and an axial features of the master gear are calibrated by comparison with calibrated gauge blocks (see figure 2):

- Two orthogonal point-to-point external diameters of the upper shoulder, l_x and l_y, aligned to the CMM *x* and *y* axes, respectively; they are calibrated by comparison with the calibrated 400 mm gauge block CEJ s/n 750004.
- The average of two point-to-point distances of the upper to the lover shoulders, l_{z1} and l_{z2}, in the axial direction, in two point pairs opposite to the gear axis[1]; each distance is calibrated by comparison with the calibrated 100 mm gauge block CARY 100 s/n 40077.

- Actual calibration. All measurands of the master gear are measured while the precalibrated features are remeasured. The (*x*,*y*,*z*) coordinates of all sampled points are multiplied by three global scale factors, respectively and independently for each axis, equal to the ratios of the pre-calibrated values to the currently measured ones. This way the actual values of the precalibrated features are brought back to their traceable precalibrated values; as the same scale factors are applied to all sampled points, the traceability is extended to all measurands.

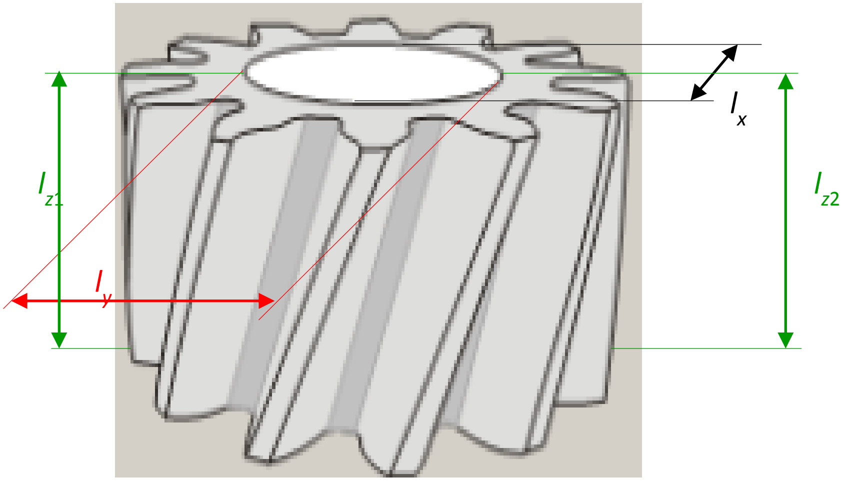


Figure 2: Features of the master gear precalibrated at step 1, to introduce traceability.

To minimise the effects of the CMM geometry errors, the calibrated gauge blocks used at step 1 are aligned parallel and fixtured as close as possible to the features under precalibration. This way the effects of the CMM geometry errors are second order and neglected.

The deviation of the mean temperatures of the gear and of the calibrated gauge blocks from the standard reference temperature (20 °C [3]) is relevant to the precalibration and is compensated for. On the contrary, it is not to the actual calibration as the scale factors applied to all sampled points already include and compensate for thermal expansion effects.

1.3 Environmental conditions

The gear and gauge blocks temperatures varied during the measurement in the range (19.84 - 20.26) °C. The value of the thermal expansion coefficient (CTE) of the gear was assumed at $(11.5 \pm 2.5) \times 10^{-6}$ K^{-1}.

[1] The average is taken for sake of symmetry, as the gear seat makes the central portion of the gear unavailable.

2. Measurement results and associated uncertainties

2.1 Results

The calibration values and their uncertainties are reported in the two tables below.

Flank	Left				Right				Uncertainty
Tooth	25	17	9	1	1	9	17	25	*U*
$f_{H\alpha}$	2.85	4.44	2.30	0.87	6.97	7.54	6.56	7.89	1.0
F_{α}	3.71	4.75	3.05	2.57	7.49	8.07	6.72	7.99	1.0
$f_{f\alpha}$	1.55	1.57	1.56	2.47	2.23	2.54	1.97	2.05	1.0
$f_{H\beta}$	-2.87	-5.78	-2.83	2.47	2.76	-4.79	-7.71	-4.47	1.0
F_{β}	4.37	6.84	3.70	4.02	2.83	5.54	8.29	5.27	1.0
$f_{f\beta}$	2.02	1.15	1.56	4.13	1.25	1.63	0.93	1.20	1.0
All values in micrometres (apart from the tooth numbering)									

Flank	Left	Right	Uncertainty *U*
f_p	5.23	4.13	0.6
F_p	12.40	23.27	2.7
F_r	26.27		1.9
All values in micrometres			

The graphical report of a measurement repetition is given in the attachment.

2.2 Uncertainty

The uncertainty of measurement is summarised in the following tables.

Precalibration	Input uncertainty $u(x_i)$	Sensitivity c_i	Standard component $u_i(y)$/µm
Gauge block calibration	0,025 µm	1	0,025
Gauge block temperature	0,023 K	1,150 µm/K	0,027
Gauge block CDT	0,577 × 10^{-6}/K	-0,010 K m	-0,006
Gear temperature	0,023 K	-1,448 µm/K	-0,033
Gear CDT	1,443 × 10^{-6}/K	0,019 K m	0,028
resolution	0,014 µm	2	0,029
Probe unidir. reproducibility	0,058 µm	2	0,115
Overall repeatability	0,074 µm	1	0,074
		$u(y)$	0,151

Actual calibration			$f_{H\alpha}$			F_α			$f_{f\alpha}$		
	$u(x_i)$		c_i		$u_i(y)$ /µm	c_i		$u_i(y)$ /µm	c_i		$u_i(y)$ µm
Scale factor, *x*	0.67	$\times 10^{-6}$	0.019	m	0.01	0.017	m	0.01	0.000	m	0.00
Scale factor, *y*	0.71	$\times 10^{-6}$	0.018	m	0.01	0.016	m	0.01	-0.001	m	0.00
Scale factor, *z*	1.20	$\times 10^{-6}$	-0.002	m	0.00	-0.001	m	0.00	0.000	m	0.00
Axis localisation, x	0.17	µm	-0.096		-0.02	0.018		0.00	-0.002		0.00
Axis localisation, y	0.17	µm	-0.089		-0.02	0.020		0.00	0.001		0.00
Axis localisation. z	0.17	µm	0.000		0.00	0.000		0.00	0.000		0.00
Axis orientation. about x	3.92	µrad	0.002	m	0.01	-0.005	m	-0.02	0.000	m	0.00
Axis orientation. about y	3.92	µrad	0.006	m	0.02	0.006	m	0.02	-0.001	m	0.00
Temperature variations	0.087	K	0.175	µm/K	0.02	0.155	µm/K	0.01	0.004	µm/K	0.00
Probing anisotropy	0.44	µm	1		0.44	1		0.44	1		0.44
CMM geometry (over a profile)	0.2	µm	1		0.20	1		0.20	1		0.20
Reproducibility $f_{H\alpha}$	0.16	µm	1		0.16			0.00			0.00
Reproducibility F_α	0.17	µm			0.00	1		0.17			0.00
Reproducibility $f_{f\alpha}$	0.17	µm			0.00			0.00	1		0.17
				$u_c(y)$	0.51		$u_c(y)$	0.51		$u_c(y)$	0.51
(*k* = 2)				$U_c(y)$	1.02		$U_c(y)$	1.03		$U_c(y)$	1.02

Actual calibration			$f_{H\beta}$			F_β			$f_{f\beta}$		
	$u(x_i)$		c_i		$u_i(y)$ /µm	c_i		$u_i(y)$ /µm	c_i		$u_i(y)$ µm
Scale factor. x	0.67	$\times 10^{-6}$	0.000	m	0.00	0.000	m	0.00	0.000	m	0.00
Scale factor. y	0.71	$\times 10^{-6}$	0.000	m	0.00	0.000	m	0.00	0.000	m	0.00
Scale factor. z	1.20	$\times 10^{-6}$	0.000	m	0.00	0.000	m	0.00	0.000	m	0.00
Axis localisation. x	0.17	µm	0.000		0.00	0.000		0.00	0.000		0.00
Axis localisation. y	0.17	µm	0.000		0.00	0.000		0.00	0.000		0.00
Axis localisation. z	0.17	µm	0.000		0.00	-0.092		-0.02	0.000		0.00
Axis orientation. about x	3.92	µrad	0.038	m	0.15	0.000	m	0.00	-0.001	m	0.00
Axis orientation. about y	3.92	µrad	0.014	m	0.05	0.025	m	0.10	0.002	m	0.01
Temperature variations	0.087	K	0.001	µm/K	0.00	0.003	µm/K	0.00	0.004	µm/K	0.00
Probing anisotropy	0.45	µm	1		0.45	1		0.45	1		0.45
CMM geometry (over a lead)	0.15	µm	1		0.20	1		0.20	1		0.20
Reproducibility $f_{H\beta}$	0.10	µm	1		0.10			0.00			0.00
Reproducibility F_β	0.16	µm			0.00	1		0.16			0.00
Reproducibility $f_{f\beta}$	0.09	µm			0.00			0.00	1		0.09
				$u_c(y)$	0.51		$u_c(y)$	0.51		$u_c(y)$	0.48
(*k* = 2)				$U_c(y)$	1.02		$U_c(y)$	1.02		$U_c(y)$	0.96

Actual calibration			f_p			F_p			f_r		
	$u(x_i)$		c_i		$u_i(y)$ /µm	c_i		$u_i(y)$ /µm	c_i		$u_i(y)$ µm
Scale factor. x	0.67	$\times 10^{-6}$	0.033	m	0.02	0.127	m	0.09	0.062	m	0.04
Scale factor. y	0.71	$\times 10^{-6}$	0.024	m	0.02	0.126	m	0.09	0.014	m	0.01
Scale factor. z	1.20	$\times 10^{-6}$	0.000	m	0.00	0.000	m	0.00	0.000	m	0.00
Axis localisation. x	0.17	µm	0.169		0.03	1.947		0.34	1.094		0.19
Axis localisation. y	0.17	µm	0.206		0.04	2.024		0.35	1.580		0.27
Axis localisation. z	0.17	µm	0.000		0.00	0.000		0.00	0.000		0.00
Axis orientation. about x	3.92	µrad	0.020	m	0.08	0.237	m	0.93	-0.020	m	-0.08
Axis orientation. about y	3.92	µrad	0.027	m	0.11	0.159	m	0.62	0.128	m	0.50
Temperature variations	0.087	K	0.271	µm/K	0.02	1.188	µm/K	0.10	0.422	µm/K	0.04
Probing anisotropy	0.35	µm	0.342		0.12	0.342		0.12	1		0.35
CMM geometry (over full section)	0.2	µm	1		0.20	1		0.20	1		0.20
Reproducibility f_p	0.14	µm	1		0.14			0.00			0.00
Reproducibility F_p	0.51	µm			0.00	1		0.51			0.00
Reproducibility f_r	0.59	µm			0.00			0.00	1		0.59
				$u_c(y)$	0.31		$u_c(y)$	1.35		$u_c(y)$	0.94
(*k* = 2)				$U_c(y)$	0.61		$U_c(y)$	2.71		$U_c(y)$	1.87

The input uncertainty due to the probe anisotropy is evaluated experimentally (type A). A reference sphere with negligible form error is scanned along a path designed to mimic the exact directions of contact when scanning the gear. This is done separately for the profile and the lead measurements.

The sensitivity coefficients for the scale factors and the axis localisation and orientation are evaluated by simulation: arbitrary scale factors and an arbitrary rototranslation is applied to all scanned points and then the derived values are evaluated again. These variations are imposed one at a time to identify individual effects.

The reported expanded uncertainty of measurement U is stated as the standard uncertainty of measurement multiplied by the coverage factor $k = 2$, which for a normal distribution corresponds to a coverage probability of approximately 95%.

In the evaluation of the standard uncertainty, the long-term stability of the object under measurement has not been considered.

REFERENCES

[1] ISO 701:1998 International gear notation – Symbols for geometrical data

[2] ISO 1328-2:1997 Cylindrical gears – ISO system of flank tolerance classification – Part 1: Definitions and allowable values of deviations relevant to flanks of gear teeth

[3] EN ISO 1:2016 Geometrical product specifications (GPS) – Standard reference temperature for the specification of geometrical and dimensional properties

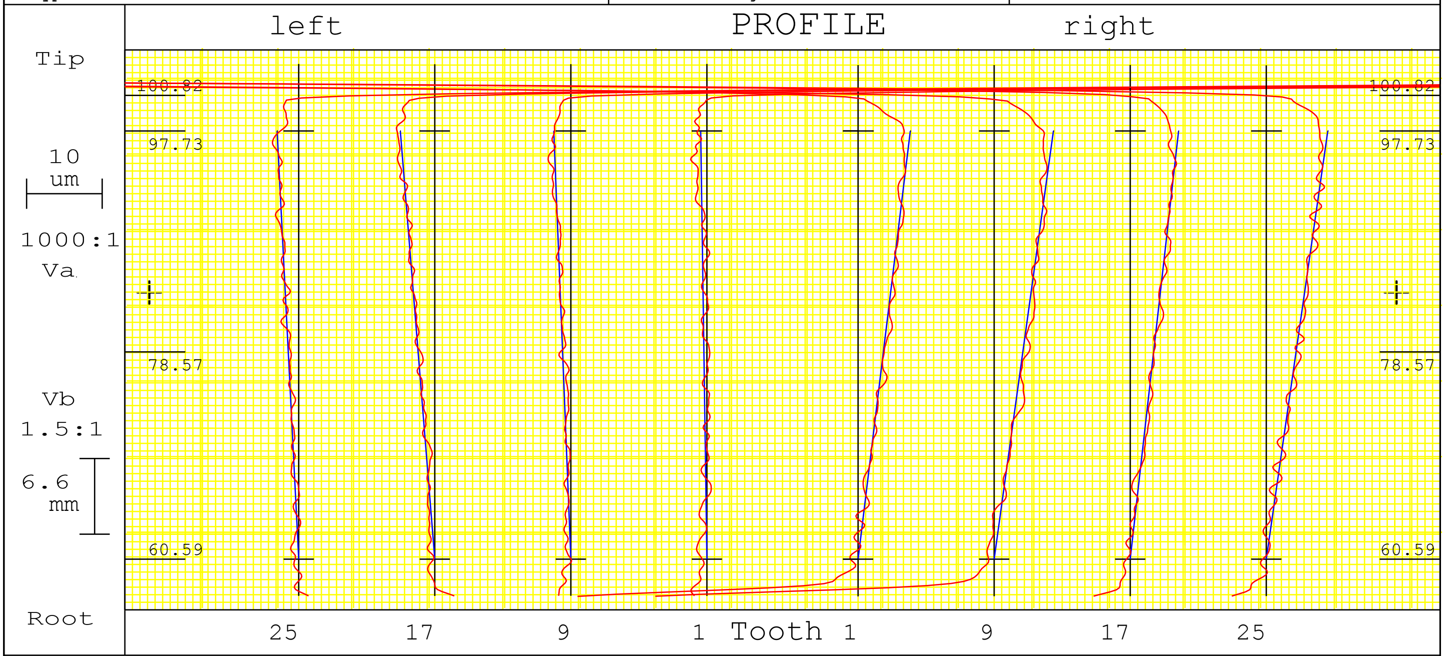
ATTACHED DOCUMENTS

Annex A: Graphical report of a measurement repetition.

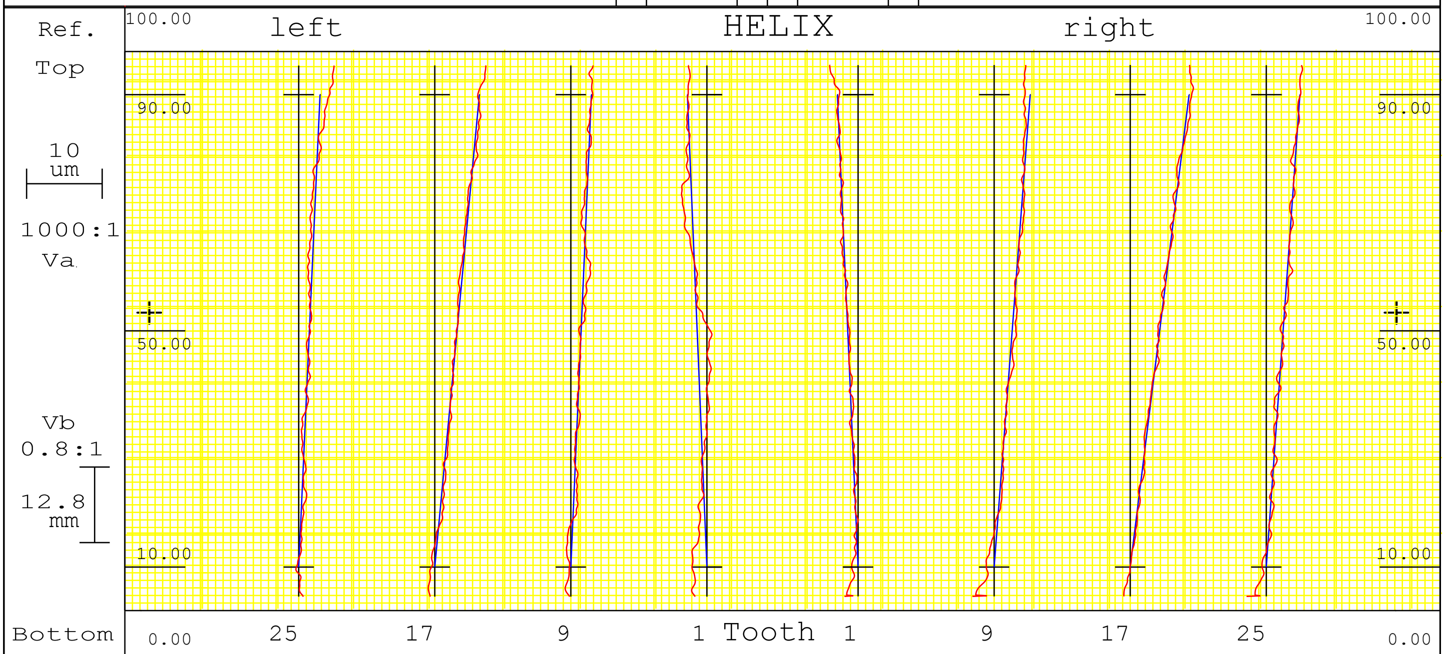
HEXAGON METROLOGY — QUINDOS GEAR

Cylindrical Gear Profile/Helix

Prog.Name: DRIVETRAIN		Operator: DC	Date: 09-JAN-2017 09:07:56
Type: Master gear		No. of teeth 32	Face Width 100.000mm
Drawing No.:		Module m 10.0000mm	Length Ev. La 37.140mm
Notes:		Pressure angle 20.0000	Length Ev. Lb 80.000mm
Part/Mach. No.:		Helix angle 35.0000	Addend.mod.fact. x -0.030
Meas.Device: PMC 12 10 7 #216		Base circ.dia. db 356.9943mm	Stylus dia. 3.000mm
Q-Type: DIN 3962 + VDI	Unit: mm	Base Helix angle 32.6146	Filter G50 1.33mm / G50 3.33mm



	meas.[um]				Qual.	Tolerance Qua.				Qual.	meas.[um]			
fHAm	2.6													7.3
fHA	2.9	4.6	2.3	0.8	4	0/ 0	0	0	0/ 0	6	6.9	7.8	6.4	8.1
FA	3.7	5.0	2.9	2.7	3	0	0	0	0	5	7.3	7.9	6.7	8.1
ffA	1.7	1.7	1.7	2.3	1	0	0	0	0	1	2.0	2.3	1.9	1.9



				fHß/80%							fHß/80%			
fHßm	-2.2													-3.6
fHß	-2.8	-5.9	-2.7	2.6	5	0/ 0	0	0	0/ 0	6	2.7	-4.8	-7.8	-4.5
Fß	4.5	7.0	3.6	4.0	4	0	0	0	0	5	2.8	5.3	8.4	5.4
ffß	1.9	1.2	1.6	4.1	3	0	0	0	0	1	1.2	1.7	0.9	1.3

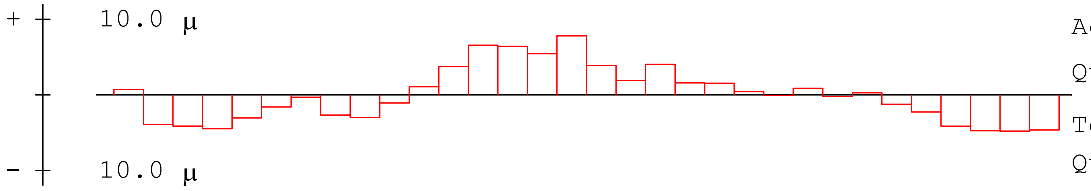
HEXAGON METROLOGY

QUINDOS GEAR

No. of teeth: 32	Order No. : NGML - DriveTrain
Norm. Module: 10.0000	Identity No.: 400 Msster Gear
Press. Angle: 20.0000	Comment :
Helix Angle : 35.0000	Title : Master gear
Hand of Lead: right	Part No. :
Facewidth :100.0000	Inspect/Date: DC/09-JAN-2017/09:52

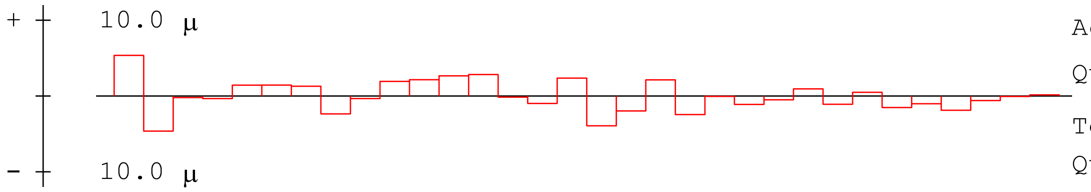
Result : o.k.☐ n.o.k.☐ A.☐ W.☐ R.☐

Fpi (left flank) Q-Type: DIN 3962



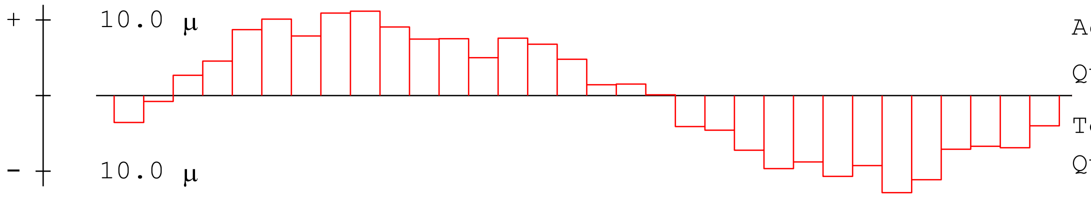
	Fp	fu
Act	12.6	10.0
Qua.	3	5
Tol.	0.0	0.0
Qua.	0	0

fpi (left flank)



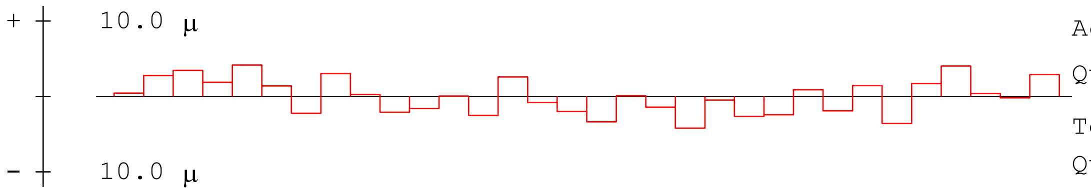
	Rp	fp
Act	10.0	5.4
Qua.		4
Tol.	0.0	0.0
Qua.		0

Fpi (right flank)



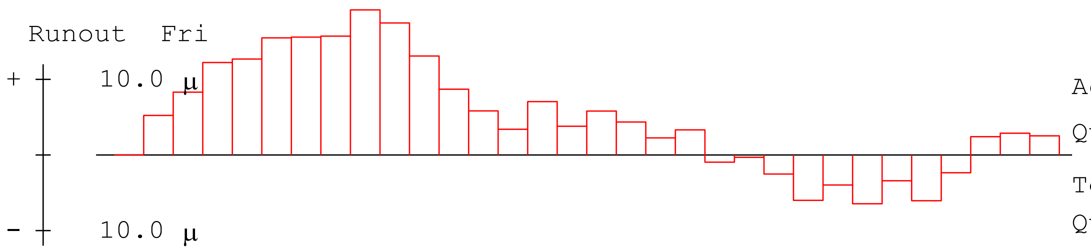
	Fp	fu
Act	24.0	5.3
Qua.	5	4
Tol.	0.0	0.0
Qua.	0	0

fpi (right flank)



	Rp	fp
Act	8.4	4.2
Qua.		4
Tol.	0.0	0.0
Qua.		0

Runout Fri



	Fr
Act	25.6
Qua.	6
Tol.	0.0
Qua.	0

Dimension over balls nom (0.0000, 0.0000) Probe Diam. 18.0000
R_{Md} 0.0129 max 416.3035 (4, 20) min 416.2906 (12, 28) Aver. 416.2976
Effective Tooth Thickness (Spline) = 18.5429 nom (0.0000, 0.0000)