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PhD Thesis

In-Process Measurement System to control Dimensional & Process Parameters

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A. Agenda

B. List of Abbreviations

2nd	Second
3D	3-Dimensional
A	Amper
AXI	Axis
Acc.	According
CIR_M	Circle Mitte
CIR_O	Circle Oben
CIR_U	Circle Unten
CNC	Computerized Numerical Control
CSY	Coordinate System
CYL	Cylinder
Calc.	Calculation
D	Diameter
DDR	Double Data Rate
DIN	Deutsche Industrie Norm
Diff.	Difference
EDM	Electrical Discharge Machining
e.g.	exempli gratia
FA	Total profile deviation
FB	Tooth trace total deviation
ff.	further following
ffA	Profile form deviation
ffB	Tooth trace form deviation
fHA	Profile angle deviation
fHB	Tooth trace angle deviation
fp	Individual pitch deviation
Fp	Total pitch deviation
FTS	Fast Tools Servo Systems

fu	Pitch error
GB	Gigabyte
GD&T	Geometric Dimensioning and Tolerancing
GHz	Gigahertz
HP-O	Hexagon Probe (Fibre-Optical)
HV	Vickers hardness
Hz	Hertz
ISO	International Organization of Standardization
IPCA	In-Process Control Approach
kHz	Kilohertz
KPI	Key Performance Indicator
kW	Kilowatt
m	Module
M3D3	High Accuracy Measurement of Large Complex 3D-Objects
MB	Megabyte
min	Minute
mm	Milimeter
Nm	Newtonmeter
pcs.	Pieces
PNT	Point
PRB	Probe
Rp	Pitch fluctuation
SPC	Statistical Process Control
TCO	Total Cost of Ownership
VDI	Verein Deutscher Ingenieure
vs.	Versus
WPM	Polish Rolling Machine
WPA	WPM Pulse Analyzer

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0. Introduction

The assessment of the economic efficiency in the application of coordinate measurement machines in the field of 3D-geometrical inspection as well as in surface parameter qualification can be derived from a cost-based risk assessment, because the process of the measurement of inspection characteristics in manufacturing companies mainly not directly represents a value adding activity to a product in an economic sense [99]. To evaluate the economic efficiency of CMMs one has always taken into account the potential cost for the a priori prevention of errors or the follow-up costs of an undetected error in and out of production processes in the field.

The cost of quality assurance using CMMs, are classified within DIN EN ISO 9004 into the field of „Error Prevention Costs“ or „Inspection Costs“. They are therefore economically justifiable then, when the (total amount of) potential quality costs (following DIN EN ISO 9004) are less than all considerable error-caused receivables by an insufficient or no quality assurance, coming out of [99]:

- incorrect production activities (internal rejects or rework),
- „non-conformity costs“ at the customer or user site,
- warranty receivables,
- penalties,
- product liability

The approach of a differentiated assessment in the selection of the adequate measuring device for quality inspection, coupled with the specification of essential steering parameters in manufacturing processes, usually leads to wide scope of the application of coordinate measurement application strategies.

As represented by several technical decision-making practice, in the selection of the appropriate coordinate measuring techniques, the approach for validation of the measurement methods are being defined, derived initially from the specification of the measurement task to be accomplished within the specific environment of task execution. In support of this practice national and international standards (GPS standards as well as accreditation standards, DKD guidelines, etc.) and specific industry or company standards form the necessary basics for the purpose [99].

In some cases, however, these principles are not directly applicable to the specific measurement task. In this case, analogies and other approaches are set for the review process in the validation of the measuring equipment suitability.

The desired objectives of the machine capability study (MCS) for the use of CMMs can collectively be described as follows [99]:

- Acquisition of influencing factors by device operators and the installation conditions,
- Informational, functional value of the measuring device,
- Indication of the correctness of the measurement results,
- Qualifying examination test of a measuring device for use on location,
- Representation of continuous monitoring of the measuring device,
- Comparative ability of various measuring devices,
- Accepted form of error analysis with regard to the causes of errors delivery.

After the efficiency analysis value determination, in current industrial practice the technical and economic appraisal of CMMs in its application is following as a further step. In the authors observations it is to be observed, that within production-oriented environment additional CMM features are to be highlighted, which can generate a special utility (value added) in the comparative competition and thus can influence the ranking in the purchasing decision also applied to the advised market expansion:

- Increased applicable Accuracy and Precision
- Increased Process Throughput, not only Measurement Throughput,
- Reliability, Robustness, Short Downtimes (MTBF, MTTR),
- Integration of measuring process into production processes,
- Function oriented assessment and tolerancing
- Increased information content in measurements, Relation of Form vs. Roughness
- Flexible variety of sensors

The elaborations within this doctoral thesis work “In-Process Measurement System to control Dimensional & Process Parameters” are aiming the assessment of enablers for an even further quality control approach, questioning if it can be possible to combine product and process parameter detection during the manufacturing process execution in precision mass production and derive or predict the later quality parameters of the component being produced?

1. Preamble

The growing demand on the efficiency aspects of industrial components and system assemblies increases the requirements of an adequate quality management regarding the critical components in their functional terms [54]. As the total quality demand increase is steadily being disproportionately driven by the shortage of raw materials, energy saving efforts and environmental regulations, the manufacturing processes must meet these challenges in all quality aspects. In compliance with the tight component tolerances in order to achieve efficiency gains in powertrain systems, mass production manufacturing processes must adapt or develop quality control loops coupled with feedback into their processes [87].

Figure 1 Powertrain CMM Application – Large Gear Measurement

Coordinate measuring technologies are widely used in industrial applications of quality assurance. Hereby specific features and characteristics of components and assemblies, in particular in the field of monitoring automated manufacturing processes are being determined. Considering the entire production process in its usual flow, Coordinate Measurement Machines (CMMs) (see figure 1) as well as other measuring devices are included as a kind of sensors in the so called quality control loops, which enable the stability control of manufacturing processes either in-line or, ideally as an in-process regulation.

The actual trends in the field of precision manufacturing are the driving forces in the development environment in the higher accuracy CMM industry in combination with the achievements of significant economic efficiency improvements and representing their future challenges. Some representative examples are the total capture of the components overall 3D-geometry using high accuracy sensing technologies, the measurement of border-zone surface properties using multi-physical principles and in-process quality control or inspection systems in connection to calibration chains with the National Metrology Institutes (NMIs) and its connected Laboratories, delivering resilient results of relevant process quality parameters [6,16, 50, 95, 135].

The potential impacts of the permanent increase the application and performance of CMMs can be summarized without entitlement of completeness as follows [99]:

1. Increase the information content of measurements and thereby the application field of CMMs through the use of multi-physical sensor systems which focus on the combination of dimensional- and inspection measurements in respect to form-, structure- and border-zone properties of components.
2. Establishing more precise, non-contact measurement methods, sensors, algorithms and software design for comprehensive (i.e. most complete and areal extensive) geometric quality control providing higher inspection rates and throughput.
3. Realignment of the geometric quality control from purely tolerance-related quality characteristics, to the definition of quality criteria for assessing the later functional properties of components and assemblies.
4. Future creation of open- or closed quality control loop systems following the "in-process metrology principle" throughout a better understanding of cause and effect relationships in geometry deviations and consequential an in-process control of manufacturing processes.

In its scope of In-Process investigations, this thesis work is generally based on the findings and technical elaborations of the PhD thesis of Dr. Tim Eichner with the title "Finding of geometrical parameters as a base of In-process metrology system in WPM gear forming" [27] which was published in 2013. The present work should be understood as its scientific and technical continuation based on that foundation work. In the basic work [27], the little-known rolling method using internally toothed work tools named WPM was determined. This WPM method was developed by Prof. Dr. Z. Marciniak at the beginning of 1970´s in Poland. A corresponding experimental machine WPM 120 including rolling tools is located at the University of Applied Science in Darmstadt and was used for the research. The aim of that study was to determine through tactile post process CMM measurements, significant geometric features on the resulting component geometry. These should serve as a basis for a future In-process monitoring approach of the rolling process. The potential features of interest were found and described. Among other features, the different tooth heights and the tooth tip forms dominate the compiled results. Using the WPM method with internal toothed tools an asymmetrical distribution of the blank material results on the circumference [27].

Within that foundation work roll samples were prepared at first, which were manufactured under controlled mechanical engineering conditions. Subsequently, these samples were geometrically measured on a tactile probing coordinate measuring machine Leitz PMM 654 using the Quindos 7 Software upfront the rolling sampling. The following geometrical measurements after rolling were divided into the conventional gear measuring according to DIN 3970 and special 2D-contour measurements on the toothing. With the tactile 2D-contour measurements, geometrical characteristics of the teeth were examined. These geometrical features have been declared typical for the metal forming by using WPM internal toothed tools [27]. It has been found that the resulting geometry of the examined samples is substantially dependent on the sample feed rate. In all other process parameters such as the blank material, no significant influence could be observed on the toothing geometry [27].

These geometrical specifics found during the research answered the question what should be measured during a production cycle to assess the quality of the process and even more the quality of the product outcome. These should serve as a basis for a future In-process monitoring approach of the rolling process. The features of interest were found and described. Based on that, the further research target is to pick up the prior results and continue the in-process metrology thought process [27]. Therefore the scope of this thesis work is set by assessing a wider in-process quality control approach, applied exemplary on the WPM splined machine elements using metal forming production techniques. This case represents a general application of precision components mass production using non-cutting production techniques reflecting the current requirement on advanced shaping technologies for process productivity improvements.

This thesis work is structured in the main chapters a shown in figure 2:

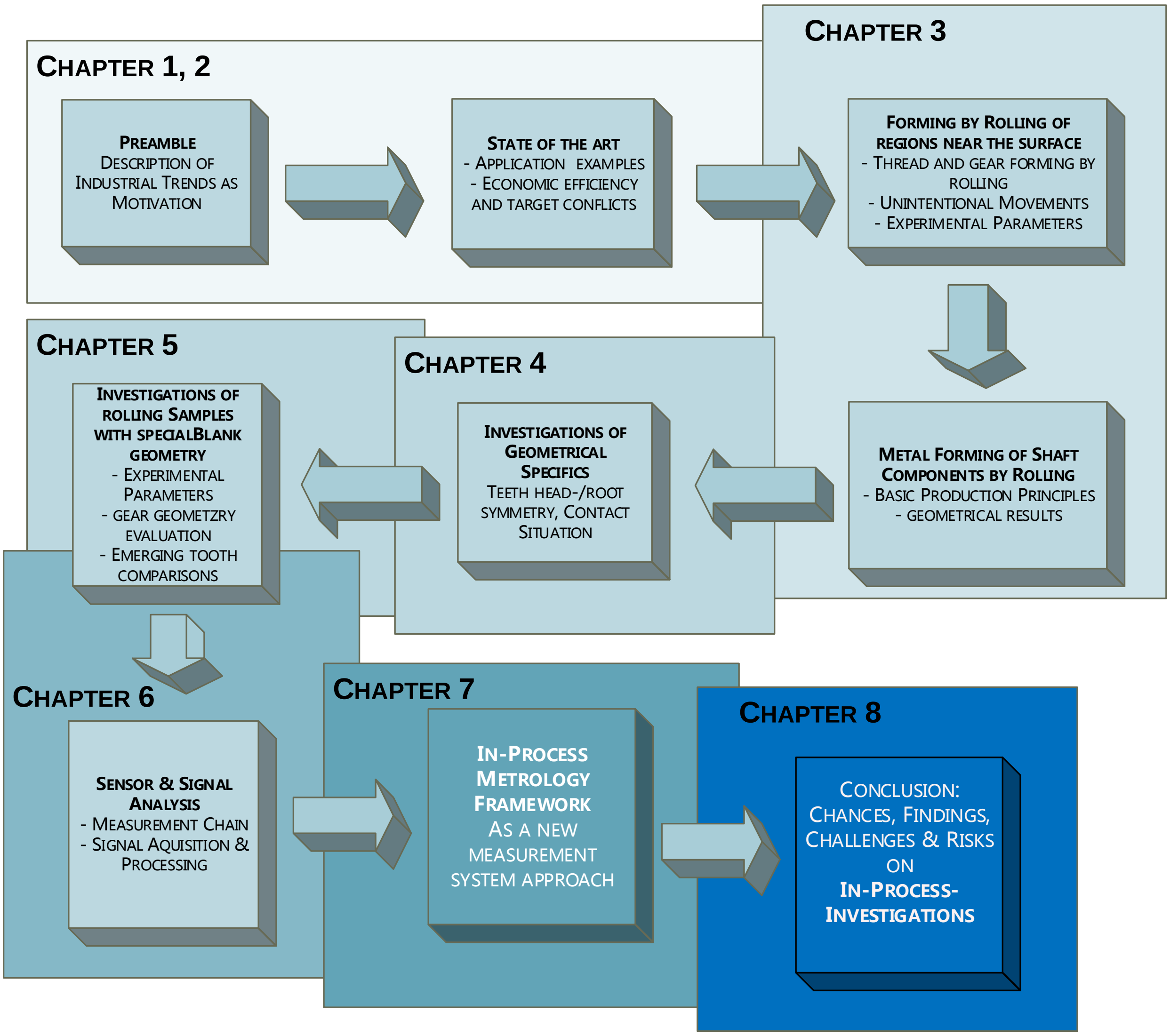


Figure 2 Thesis Structure

As an introduction to the scope of this thesis, the State of the Art trends in terms of current metrology framework applications in an In-Process metrology approach are elaborated within the chapter 2. Introducing to the underlying scheme of metal forming principles, in chapter 3 the basic principles of forming of regions near the surfaces are determined in order to show the relations between intended material distribution by work-tools and unintended effects related to parasitic movements e.g. of the workpiece during rolling.

In order to create continuity in findings and consistency in the argumentation, the chapter 3 summarizes the selected outcomes of the foundation thesis work [27] in terms of significance to this thesis work content, while in chapter 4 the prior findings are reflected into a theoretical analysis in terms of work-tool – workpiece kinematic interaction in regards to their imprint and error contribution to the in chapter 3 observed characteristics. In order to understand the root-cause of geometric specifics in WPM rolling in more deep, enhanced rolling sampling combined with further theoretical investigations specific to this thesis work have been carried out. Hereby WPM rolling samples of special blank geometries have been used that serve the investigation requirement on future In-Process control, described and analyzed as reported in chapter 5. Based on the determined new findings the stated In-Process framework approach could be formulated, whereby the sensor and signal investigations are assumed in the chapter 6 content. In chapter 7 of this thesis work, more generalized implementation considerations of an In-Process Metrology Framework as a new control approach is determined in terms of risks and opportunities. Finally this system approach leads into a newly established WPM test bench consideration, reflecting early finding of this thesis work, which is a current path and parallel scientific and industrial research project in execution outside of this thesis work and scope. As described in chapter 7, this WPM test bench was basically designed in the duration of this thesis work, respecting the detailed findings of the overall investigations but will be used in terms of further geometrical improvements for gear rolling methodologies using these thesis outcomes as a base for process monitoring and open-loop control. At the end the chapter 8 is concluding the In-Process Control approach of dimensional and process parameters in terms of prospecting the implementation impacts and remaining obstacles for final industrial applications.

2. State of the Art

Economic efficiency requirements in manufacturing processes in conjunction with a high precision of the manufactured components create an implicit target conflict of goals which can today be recognized in modern production sites.

The primary target of precision mass production is to generate as many comparable components in time as possible, whereby the application of higher productive manufacturing principles, such as incremental forming are becoming applicable (see figure 3). The target conflict resulting hereby is therefore affecting the quality assurance through related measurements within this mass production sites as well and can be characterized by the time consumption per unit being measured. The measurement time duration per unit is usually increasing driven by the quality requirement classification of the observed component. In consequence these components where only quality inspected by random sampling rates in mass production. The majority of the parts being produced is not being inspected and remain therefore only indirect controlled. The impact given by this fact can result in unexpected quality costs by failing components as the exact quality figures of the production lots can only be stated as

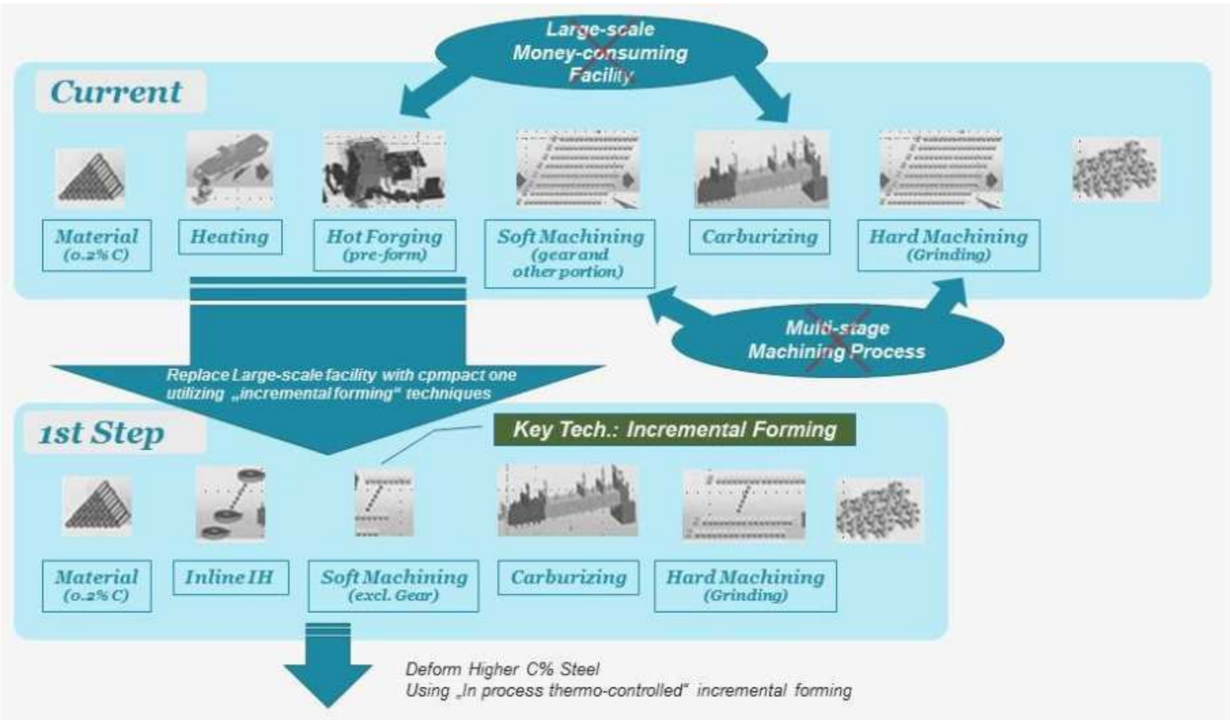


Figure 3 Manufacturing Chain Improvement by Incremental Forming (Example)

average or statistical quality values or trends and isn´t fully representing the production quality as a whole [45, 156, 157].

As an outcome of the majority number of all components usually remaining unmeasured, or uncontrolled, a potentially significant negative influence on the achievable average production quality of one production series could occur. Besides the requirements on the quality of the geometric measurement, the employed measuring instruments and devices limit the per unit time measurable components. The use of each measuring device requires a specific measurement period, defining the throughput per unit of time measurable components derived per part. The challenge of future quality control in mass production environments is defined thus by tend to have higher qualities of the desired measurement feedback with a simultaneous reduction of the expenditure measurement times. The resulting conflict of targets is so obvious [37].

Typical precision parts for mass production such as gears are being qualitatively characterized inter alia by their geometric shape. Ensuring the consistent geometry is thus one of the most important tasks of quality assurance. So the key questions are:

1. How many component geometries can be captured metrological in what timeframe?
2. How high is the quality standard of the applied geometry measurement?

Gears are precision parts whose geometry according to appropriate standards is to be measured [148]. If the quality demands on the post-process geometry measurements are of higher standards coordinate measuring machines (CMMs) are most commonly used. Actually the underlying methodology is usually a measurement by tactile sensors, which is driven towards the component to be inspected by a CNC-controlled machine. The trajectory paths and probing- respectively scanning speed defines in sum the expended time per component. In addition to the positioning and mounting of the to be measured component within the measurement machine results due to the standardized machine setting of the measuring points on the component, thus a finite total time for the particular geometry of the measurement [32, 159].

The quality of the measurement data is then also depending on how the individual measurement point is acquired from the CNC-controlled measuring machine. It can be stated that the quality of the measured data is more meaningful, the slower the individual measurement point is approached [86, 91]. If a high quality of the measurement is required, this automatically results an extension of the measurement time of the inspected component. This describes the technical aspects of the aforementioned conflict of objectives.

Figure 4 CMM Large Gear Measurement

In order to overcome this conflict, there are different development paths that are currently being embarked on the market. One way is to develop innovative sensors that are no longer tactile, but non-contact and are capable to detect large areas of a tooth optically and allow calculation of surface-related quality statements simultaneously. Another approach could be to better analyze and control the trajectory of the machine-side axis movements to higher dynamics. Here, however, clear limits are recognizable by the physics constraints. In how far in the future qualitative results of the tooth geometry measurement will be determined along these paths and nearly reaching the quality level of tactile measurements is currently under investigation of metrology institutes and companies but commercially not in sight yet [68, 88, 106, 129].

Future objectives in defining indicators on components quality are following:

- Functional driven KPI instead of tolerance driven (GD&T definitions 2013+)
- Increased quality information content in the measurement data
- Definition and evaluation of related measurement and process uncertainties.

Furthermore, the creation and extended usage of quality control loops based on:

- Cause-effect relationships

- Self-predictive quality feedbacks

can be assessed as general trends in workflow integrated quality control and applies to all aspects in the field of manufacturing metrology elements (see fig. 5) [33].

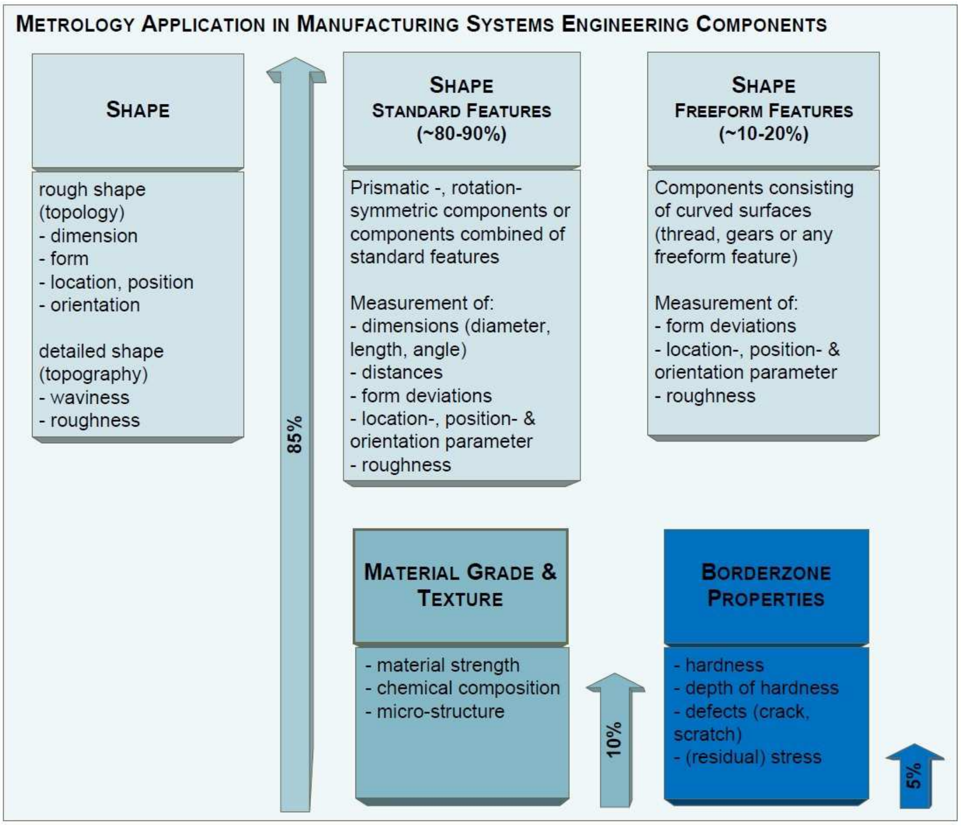


Figure 5 Manufacturing Metrology Elements [155]

The typical mass production of gears is characterized by the use of manufacturing chains in which different production processes are currently used.

Geometric pre-forming of gears are mostly realized by metal forming, which then receive their geometrical final shape by cutting, but also cold forming processes [49, 81, 90, 130, 131]. Each geometric intermediate stage is a subject to specific qualitative requirements that constitute the necessary technical baseline for the next step of production. In consequence, this means that even the geometry of all intermediate production stages would be monitored in workflows accordingly. The anticipated costs would then multiply the throughput time of each component and the efforts towards greater cost of production are diametrically opposite.

A potentially viable approach solving this problem area could be an in-situ and continuing considered an in-process control of the components already within the

machine of each production step to be applied [6, 107]. What is being meant hereby is not a conventional process monitoring of the machine and its functions, but the metrological determination of geometrical parameters on the components themselves during their processing. The significant advantage of this approach would be that no additional measuring time must be spent post processing. Of course, no quality standards of a coordinate measuring machine usage are to be expected in the so ascertainable measures. Nevertheless, already geometric deviations, asymmetry aspects or their trends could be identified and assessed within the series and trigger appropriate corrective measures at an early stage of the machine operator.
Finally, the question arises whether such a derivative corrective approach regarding the geometric quality within the individual production step would not lead to an overall higher standard of quality control than by sampling measurements of individual components [108].

2.1 Trends on workflow integrated Metrology approaches

Nowadays, Statistical Process Control (SPC) based on post-process measurements or In-Situ measurements are mainly the basis for the quality control on precise production processes. The efforts of precision industries to bring manufacturing cost further down are one-to-one related to quality control investigations. One aspect being mentioned before is to bring accuracy figures and measurement uncertainties to an improved level; another aspect is to increase the inspection rate on post-process measurements compared to the state of the art performance in order to improve lifetime related functional prognoses of related components e.g. by applying high-speed non-contact or multi-physics measurement systems [53, 77, 114]. Some representative examples supporting the stated arguments on actual trends are:

- the total capture of the components overall 3D-geometry using high accuracy sensing technologies [30],
- the measurement of border-zone surface properties in a total inspection approach using multi-physical sensor principles.

Some steps into In-Process quality control have been made so far and solutions are established either where precision requirements forced such a solution or parts were not able to be alternatively produced anyhow, e.g. in large scale aerospace carbon-composite bodywork applications [146].

The future In-Process measurement solutions will gain on importance as functional driven tolerancing will stepwise change the traditional way of part inspection and a In-Process metrology framework could in addition ensure a 100% inspection without any remarkable increase of part production times. Such In-Process quality control and -inspection systems once available need to be released in connection to calibration chains with the National Metrology Institutes (NMI), delivering resilient results of relevant process quality parameters [6, 37, 143].

In comparison to the classical field of post-process coordinate metrology, the In-Process approaches are targeting a higher integration level of the measurement technologies into the manufacturing workflows or even are enabling workflows for sensitive production processes in order to achieve its stability. Finally, improved economic efficiency in conjunction with higher quality gains in a production environment is the ultimate goal being set.

The most relevant publications and prior initiatives that represent the State of the Research have been investigated focusing on In-Process measurement applications that can be classified into the following categories:

1. Integrated functional metrology elements to execute Post-Process measurements inside machine tools working environment (In-Situ Metrology),
2. Integrated measurement (scale, sensor) frameworks to online execute position uncertainty related improvements or other geometrical corrections of a toolset in a machine tool, e.g. Fast-Tool-Servo (FTS) systems for work tool control,
3. Integrated Sensor devices to constantly monitor the state (health) of a mechanical assemblies in operating mode, such as large gear transmissions during lifetime usage (Inside-Sensoring),
4. Large scale metrology solutions using spatial metrology framework as a basic setup for robot control, e.g. in aerospace body manufacturing and assembly applications
5. The state of the Art sensor developments as such with special attention on non-contact metrology sensors, e.g. structured white-light sensing technologies in superplastic blade forming applications [61, 119].

Other general trends in the field of coordinate metrology applications and in the scope of the thesis work are the achievement of a higher autonomy of highly workflow integrated processes, modularity in terms of application fields and multi-physical sensor integration enabling a total inspection approach e.g. by verification of component border-zone properties e.g. on surface integrity or hardness specification [7, 34, 93].
Thereby the unified collection of workpiece information data being generated out of several sensor sources, data normalization and data processing and finally the interpretation and improvement feedback loop establishment are a subset of the inherent challenges. The following examples will outline the classification of the state of the research classification on the applications field of metrology frameworks in In-Process contents [6, 33].

2.2 Application Examples

2.2.1 Integrated Metrology Solution in a Grinding Process chain

The demand on steering and adjustment of high accuracy manufacturing processes generates a high expectation on measurement solutions for process control.
In the described example, a leading approach for the production of large freeform optics established by the Cranfield University of Technology shows the application of a integrated metrology framework into a newly designed ultra-precise grinding machine tool named BoX® machine for as being shown in Fig. 7 an integrated metrology frame, which mainly contains of a Invar material frame structure, a straightedge normal artifact, a short path interferometer and a contact probe is independently connected to the machine tool [113, 57, 97, 161].
The metrology framework allows a part inspection in terms of form deviation measurement in the situation (In-Situ) of the production and could feedback necessary modifications to the CAM system without removing the optical components from the grinding machine. The underlying metrological principle hereby is the relative comparison of the optical straightedge onto the optical surface via a measurement probe scanning the large optics component In-Situ on the grinding machine tool (see Fig. 6) [33,43,113].

Figure 6 Cranfield BoX® Machine

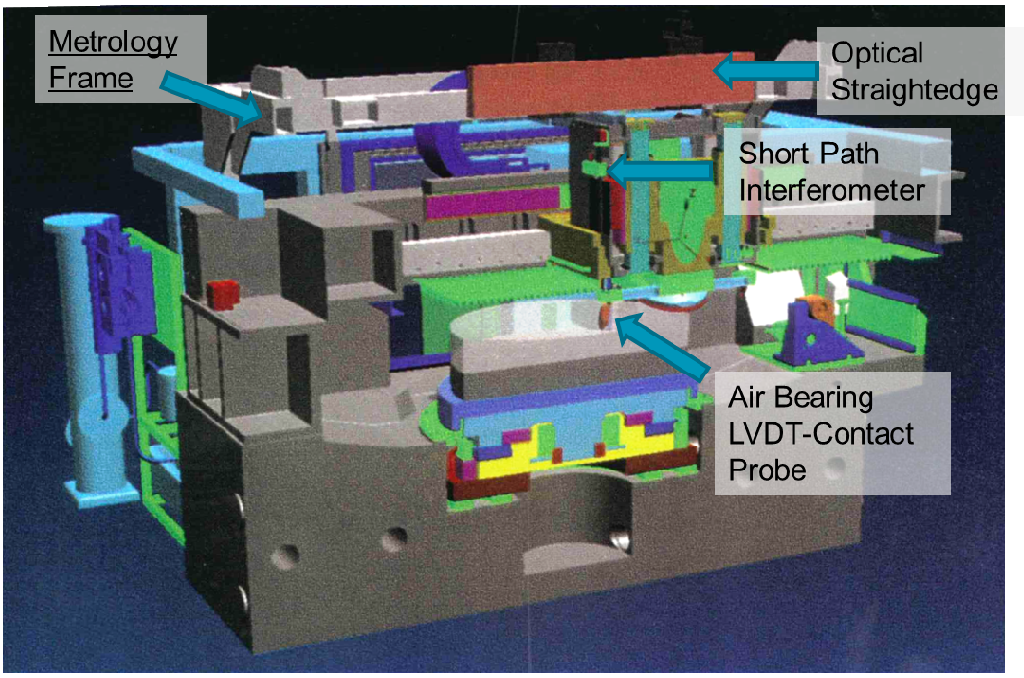


Figure 7 Integrated Metrology Frame for In-Situ form measurement application

As the accuracy demands of the large optics for scientific research applications need to be proven out, a post-process measurement cycle on a CMM (see Fig. 8) is implemented in the production workflow in order to ensure the required process capability [113].

Furthermore, the CMM inspection of the optics is used for qualification of the optics freeform design and to gather the required optics correction parameters of the residual errors on the parts before framework assembly [83, 144].

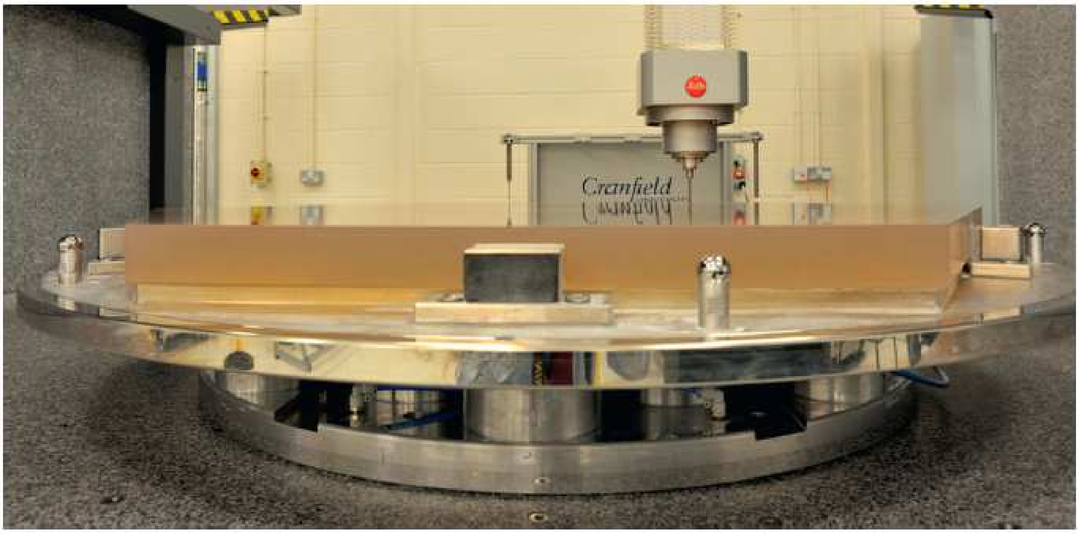


Figure 8 Post-Process Audit Measurement using a LEITZ PMM-F 30.20.10 / LSP-S4 (Low Force Probing) ; MPE_E 1,7+L/400m

2.2.2 M3D3 - Metrology Frame for CMM validation

Another application in regards to state of the art metrology framework is the M3D3-system established by the German National Metrology Institute PTB (see Fig.9) [158].

Within the usage of this Lasertracer based framework system the underlying context is the reduction of the measurement uncertainty effect on large scale metrology CMM applications. The system could be applied to error mapping tasks on CMMs or machine tools as well as a compensation tool [12, 53, 65, 82, 145].

In the measurement application, which is evolved in the scope of this thesis work, the measurement errors on a real component inspection will be re-verified by substitution of measured points by the metrology frame in a virtual measurement “dry run” without involving the part. During the dry run the CMM inherent remaining position errors that influenced the component measurement before are determined by the measurement of length changes between retro-reflector on the CMM stylus and the stationary interferometers by the M3D3 metrology framework based on multi-lateration of 4 Lasertracer in different positions and orientation. After plausibility check the CMM introduced measurement errors could be mathematically eliminated out of the previous measurement result of the inspected component using the calculation of reflector positions in 3D space by means of multi-lateration. The mobility and self-referencing of the framework system allows flexibility in usage on several applications in the CMM field. The uncertainty contribution of the M3D3 framework itself is in scope of actual research projects execution [84, 96].

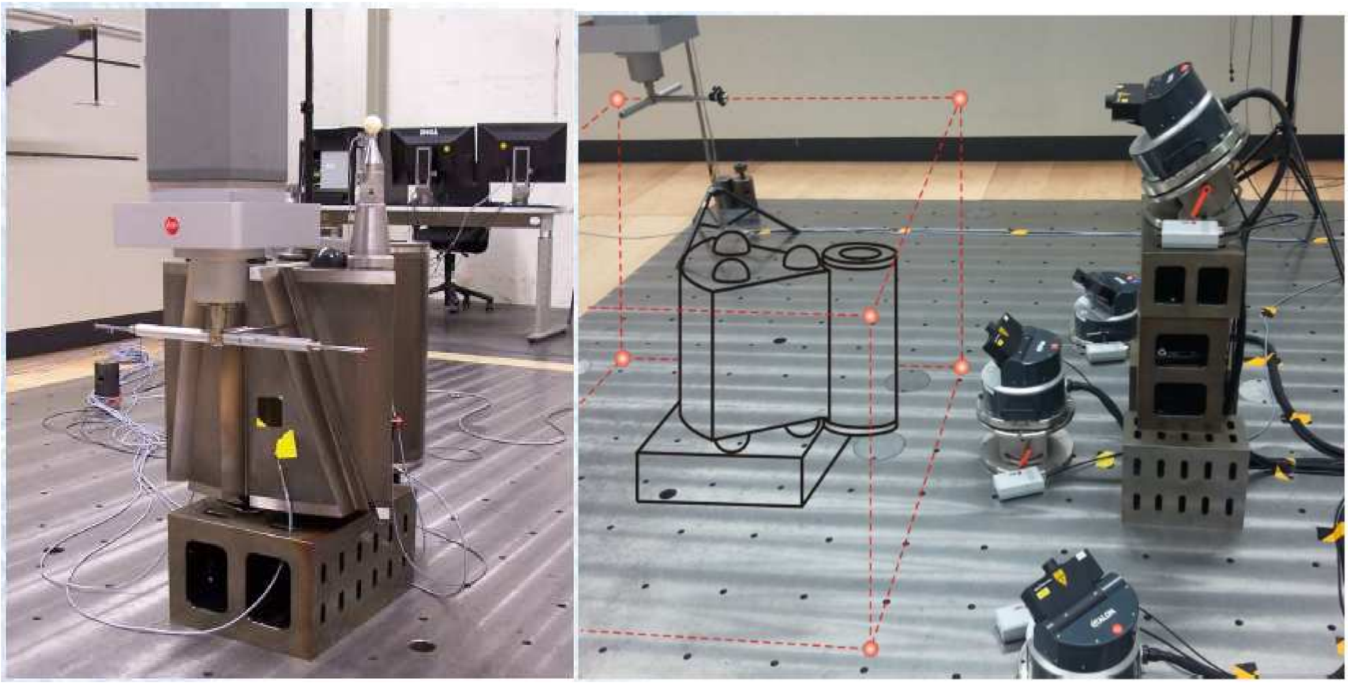


Figure 9 M3D3 – 3D-Mobile Multi-lateration Measuring System

2.2.3 Fast Tools Servo (FTS) control systems

Within the precise manufacturing processes, the production costs of related parts are significantly influenced by static and dynamic distortion phenomena. This phenomena could be theoretically monitored and eliminated by counteracted servo-manipulation of the contact point between workpiece and work-tool during part processing.
In the selected example, the costs for distortion removal by grinding or honing can sum up to more than 40% of the total production costs, when focusing on bearing rings for

power transmission applications [147]. Therefore, controlled work-tool path planning in a distortion engineering approach within the process chain is essential for efficient production targets. The path manipulation of the work-tool is being achieved by Fast Tool Servo Control Systems (FTS) in general [44]. In particular, to the posted example, an ultrasonic sensor is being used to directly measure the wall thickness of a bearing ring while the turning tool is manufacturing the part (see Fig. 10) [2,35,147, 120].

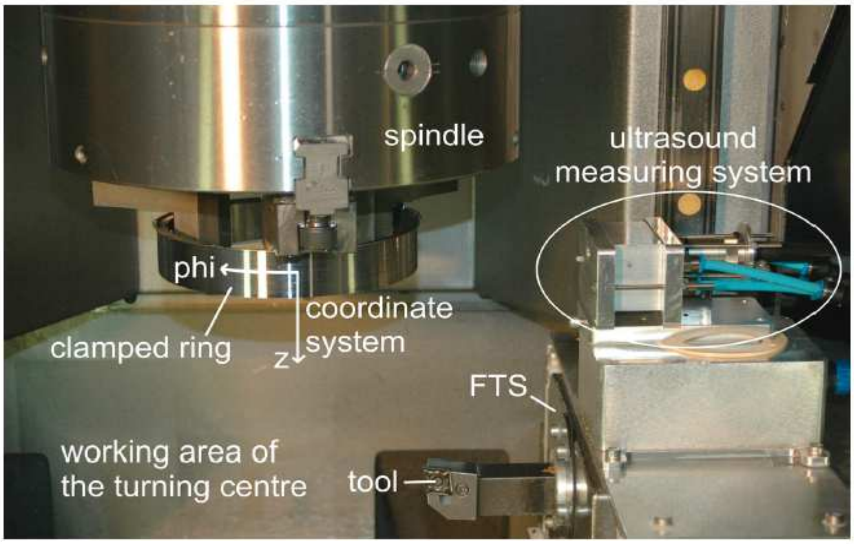


Figure 10 Working Space of turning center using FTS control

By applying self-predicting feedback loop algorithms, the wall thickness quality loss in terms of absolute value and form on a test setup could be limited to orders of magnitude after an adequate sensor system calibration. The In-Process sensor system setup is used in a direct production process steering approach of being the feedback loop for production stabilization. The quality inspection reduction in absolute post-process methodology cannot be seen actually in the field of FTS environment.

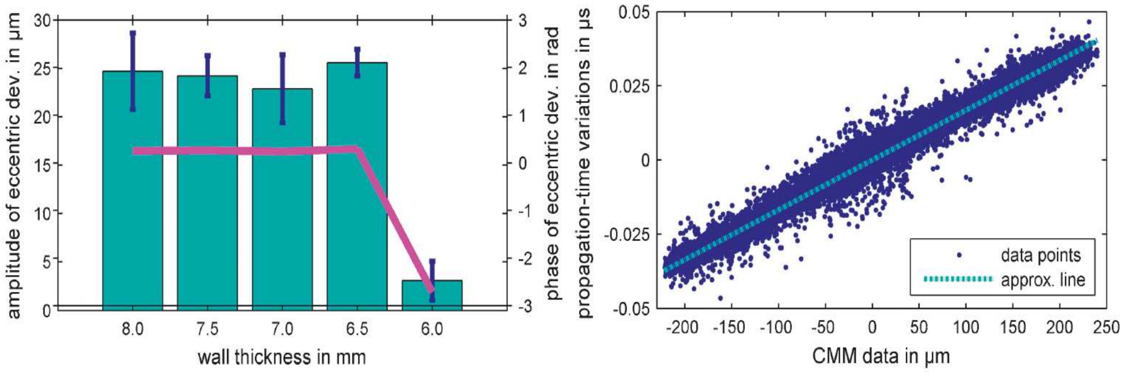


Figure 11 FTS example - wall thickness improvement

3. Forming by rolling of regions near the surface

Every mechanical component produced within an industrial manufacturing environment is passing through several stages of shaping. The overall scope hereby is outlined by economic efficiency aspects, realizing the adequate final shape of a component at lowest cost achievable, respecting the required quality constraints [63, 64]. The final shape of a mechanical component is generally defined by the geometrical specification derived from the mechanical contact and interaction and fitment with surrounding components achieving the targeted functionality. The components interaction and fitment conditions in order to achieve the required functionality are defined by parameters and tolerancing in the technical design, which initially defines the manufacturing technology to be applied and prospect therefore the baseline of the manufacturing costs. In the scope of components tolerances, the applied manufacturing technology inherently defines the bandwidth of achievable minimum and maximum feature deviations in the part geometry. The basic task for quality assurance aspects derive from the aforementioned interdependencies, finally observing how the targeted component tolerances defined in design parameters can be obtained and is being fulfilled by the manufacturing processes. In the context of this thesis work, the manufacturing technologies of forming and cutting are setting the scope of further investigations. Therefore, other manufacturing technologies as casting, EDM and others are not to be considered as it would extend the scope of the thesis outside the targeted aim [31].

The general principle of shaping components by forming and cutting are based on the application of working tools which are approaching a workpiece in a mechanical contact, influencing and displacing elements of the material volume based on the energy being introduced in order to achieve the desired geometrical property. In the case of forming methodologies, surfaces and edges of a work-tool are being moved towards the workpiece material in order to introduce a certain strain condition causing the material to plastically flow, as if chipping methodologies are applied the workpiece material elements are being removed by cutting in order to achieve a defined workpiece

shape. Thereby the workpiece sample to be machined into a final workpiece as well as the working tools are mounted and/or guided within a machine framework [133, 134].
The quality of the finalized workpiece geometry after machining is therefore influenced by:

1. The mechanical stiffness of the working chain represented by the machine frame structure, work-tool holder and workpiece clamping and
2. The guiding specifics acting between work-tool and the workpiece material elements being processed during machining.

Resulting reaction forces caused by the mechanical energy, being provided by the machine powertrain and introduced into the workpiece material causing the forming or cutting process, in consequence must be carried and directed through the machines work-chain structure. Elastic mechanical deformations in the work-tool clamping and machine frame structure are corresponding reactions. The quality of the resulting geometrical workpiece features after machining is deriving from the intended relative kinematic movement between the work-tool and the workpiece de-gradated by the unintended deformations of the mechanical framework structure.
Within the described relations of work-chains the geometrical pre-form of the basic material to be shaped by the work-tool interaction is of major importance. The pre-form geometry thereby defines the mechanical boundary constraints of clamping the raw shaped workpiece within the machines working chain mechanics. The detailed type of the mechanical clamping design within the machines work-chain is therefore defined by the geometrical characteristics of the pre-formed material. The geometrical characteristics of the pre-formed material itself is being defined by the type of Semi geometrical element initially being used and to be differentially shaped in each following production step (see fig. 16,17).

Metal forming is a very old technology for shaping components. One of the oldest methods of forming is the forging of metals [123]. Thereby, thru one or more tools the required energy for shaping is introduced into the material [28, 29, 31, 60, 62, 115,116].
The chipless manufacturing of gears by methods of rolling dates back to thread rolling, which was developed around 1925 in Europe [151]. Depending on the shape of the

rolling tools, a distinction is defined in the type of the rolling work-tools by PeeWee and RotoFlow, as shown in the following Figures 12,13.

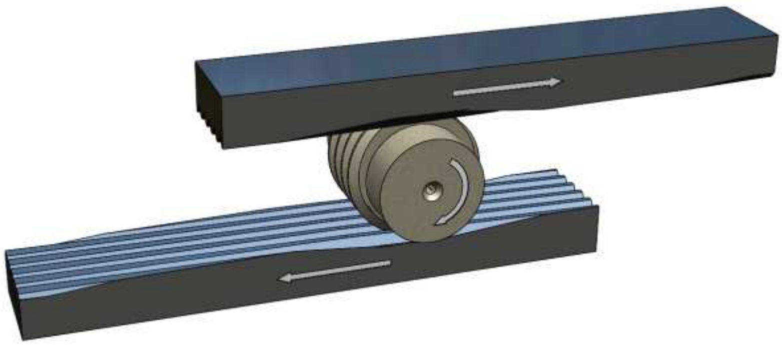


Figure 12 RotoFlow Thread Rolling

Figure 13 PeeWee Thread Rolling

In these methods, rolling tools are moved to the blank to be deformed, their tool contour is reproduced in the near-surface material areas of the initial sample. In contrast to the machining process mechanical energy is thereby introduced via the rolling tools in the material volume of the blank, so that the material is forced due to the resulting stress to a plastically deformation, guided into the open spaces of the work-tool geometry. Equally high are the specific rolling forces that can be depending on the thread geometry and size of the machine up to 1.000 kN [10].

The thread rolling following the PeeWee method is characterized by two rotationally symmetrical rolling tools, which constantly rotate in the same direction and continuously penetrate in the blank material (see Fig. 14). One of the tools will be moved towards the blank horizontally through the machines hydraulic system, which rests on a central ruler or is mounted between axially moveable tips.

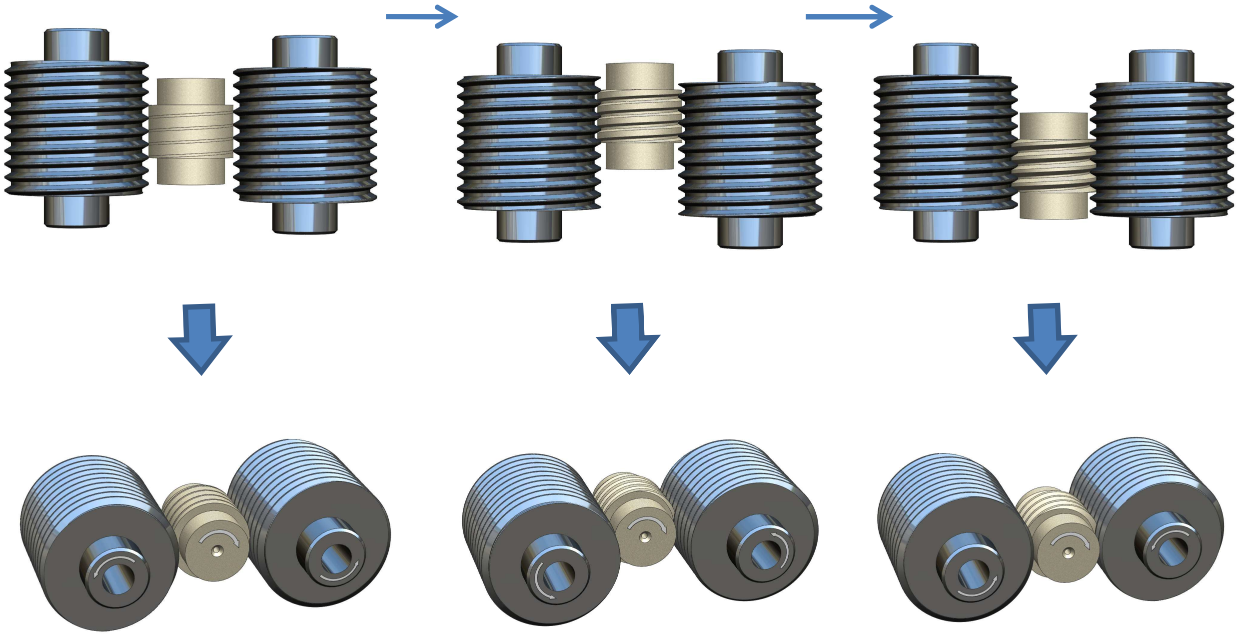


Figure 14 PeeWee Thread Rolling Sequence

The translational movement of the one rotating tool is pushing the tool against the surface of the blank, which is hold up by its opposite side of the surface against the second roller tool and the rolling ruler. A closed loop of the resultant forces between the tools, the workpiece blank, roller ruler respectively the tips of the machine frame is the result. The blank is put into rotation through the impact of the horizontally moving rotation of the tool, wherein the surface geometries of the two rolling tools imprints a helical shape in the material of the blank. The translational movement of the horizontally moved tool, vertical to the blank cylindrical axis, forces the continuous radial penetration-movement of the rotating tools [10].

The mechanical loads which were brought into the material by the tools, create high tension in the regions close to the surface of the blanks material structure, tensions which make the structure respond plastically. The material flows into the open spaces of the tool gap. The thread is completed after “n” turns, at the latest when the gaps of the tools mold geometry are filled. The number “n” of the resulting revolutions is depending on the machines provided mechanical energy. On the surface of the part a thread is formed.

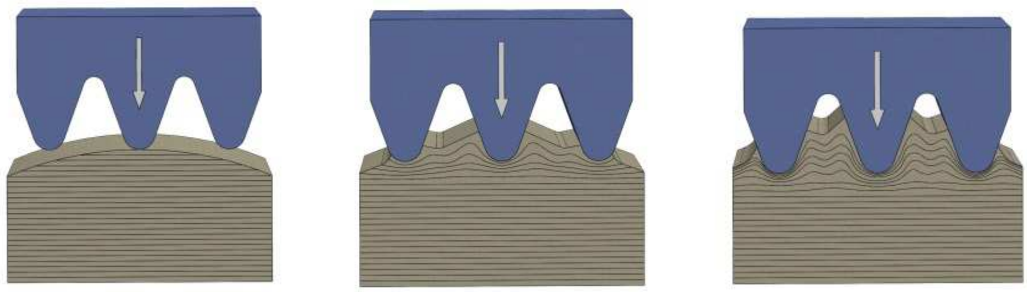


Figure 15 Solidification by Forming (Principle)

This shaping is accompanied by structural solidification of the deformed material, which leads to a higher mechanical strength of the thread root (see Fig. 15) based on the principle of strain hardening. This is a significant advantage of the non-cutting forming by the thread rolling, which is of similar importance at the non-cutting technologies of toothed profiles and will be discussed in later chapters.

3.1 Intentional and Unintentional Movements during Rolling

As a general rule a prismatic Semi pre-form provides a larger contact area for uncomplicated introduction of the basic material workpiece into the machines work-chain (see fig. 16, 17). A rotational symmetrical pre-form mainly provides none or minimal contact areas for reception, which results in a higher complexity of introduction into the machines work-chain. The selection of the basic material pre-form to generate a final workpiece is mainly linked to the economic efficiency constraints. Generally, it can be expressed that the pre-form Semi shape is being selected by targeting a minimum of basic material application combined with the least energy introduced in the shape change process in order to achieve the intended final dimensional shape of a workpiece [19, 23]. In terms of the general gear manufacturing principles a rotational symmetrical Semi material shape is being used due to the mainly rotational shape of finished gears (see fig. 16). If using a prismatic Semi shape in the case of gear production (see fig. 17), a higher grade of material application and high energy introduction will cause significant higher manufacturing costs, that badly impact the manufacturing economic efficiency targets [5, 63, 64, 78, 79].

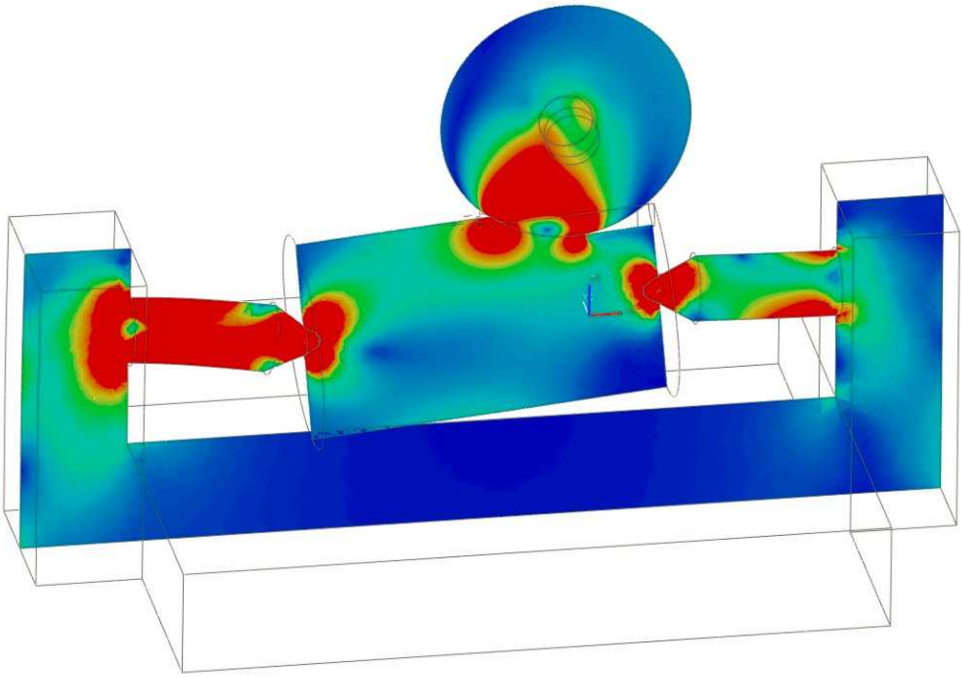


Figure 16 Load Situation (Grinding) on Rotational Symmetrical Workpiece

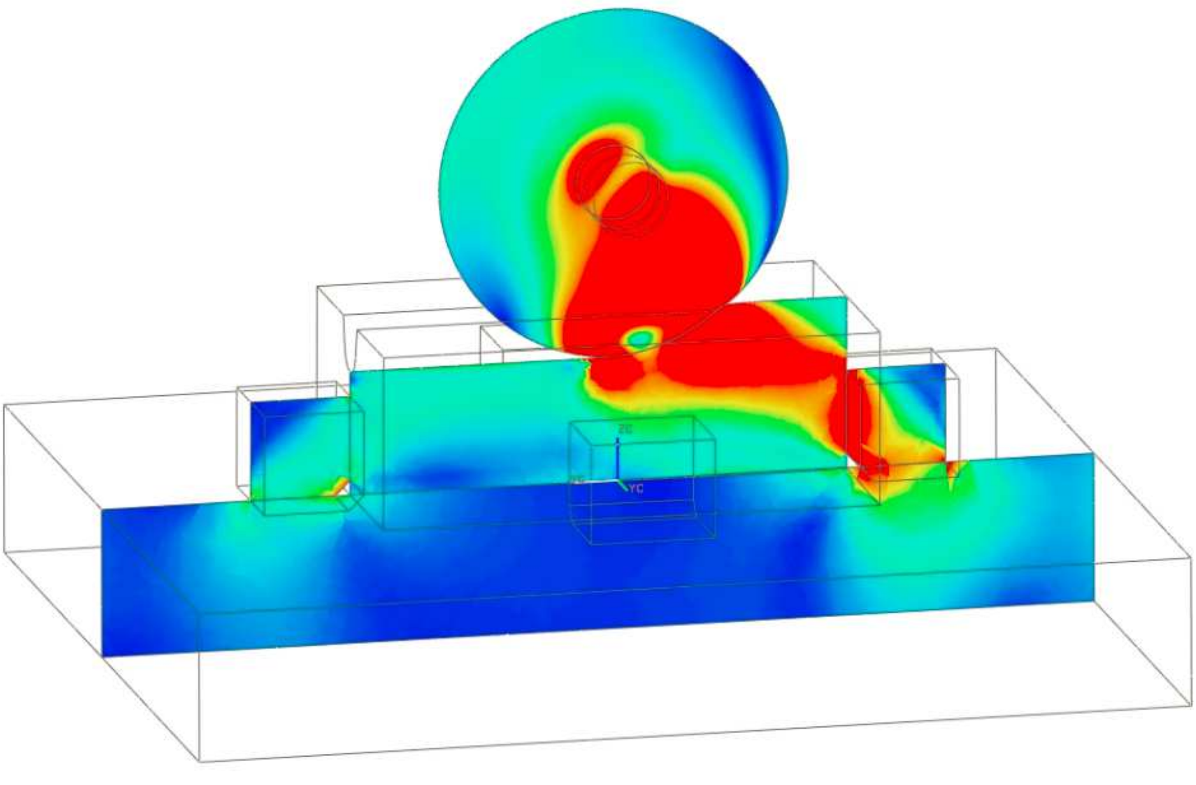


Figure 17 Load Situation (Grinding) on Prismatic Symmetrical Workpiece

The geometry of a toothed element is composed of a basic shape (for example a hole) and the teeth of the toothing that are arranged generally symmetrically on the periphery. In this sense, then the initial middle line of the main body is also the center axis of the teeth. The actual function of a gear is caused by the mechanical interaction of at least two or more gears (see fig. 18). According to the laws of teeth interaction in the contact area of two gears certain geometric situations have to be accomplished [27]. This results in the core conflicts and the problem of any teeth production. The centrally symmetric arrangement of the toothed elements of a teeth be given within narrow tolerances, in order for the equally symmetrically structured counter teeth in the interaction of the two can meet the desired function. From the perspective of production consequently the machining of a tooth or a toothed member element must be assured at all times either that reaction forces do not lead by shaping with tools to a geometrical displacement of the part during machining or the offset displacement of the toothed elements is being detected at any stage of production [109].

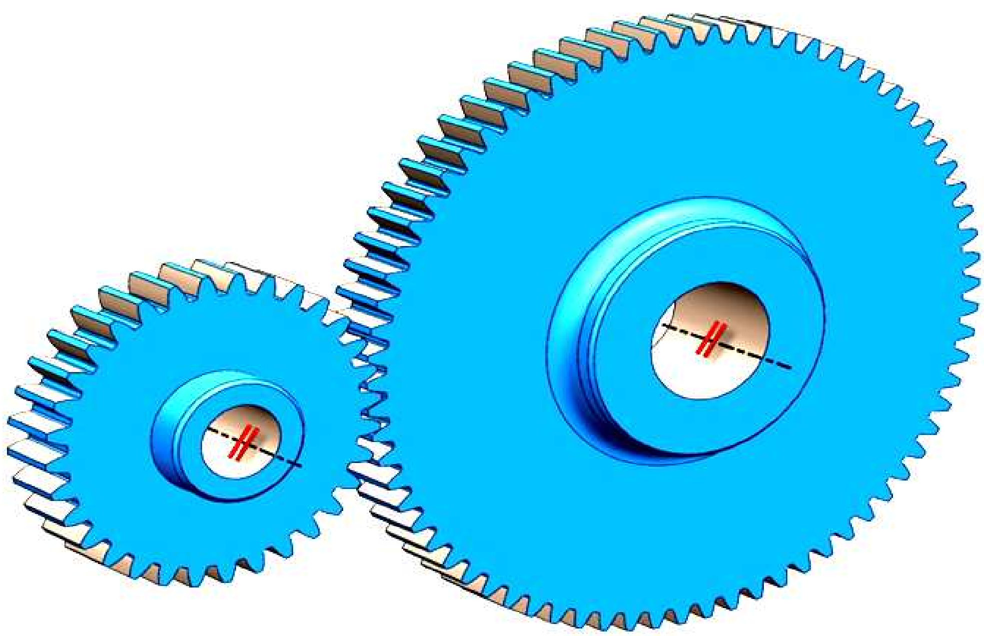


Figure 18 Ideal Contact Situation on Gear Pair

3.1.1 Thread Rolling

Looking at the thread rolling process in terms of movements of work-tools and workpiece, it should be noted that the rotational motion of tools and workpiece are the necessary conditions for the workpiece deformation as well as the horizontal translational stroke movement of the single tool. The workpiece geometry will be rolled over several times, but the desired thread contour is produced continuously. The axial movement of the partially deformed blank, shown in the image sequence (see fig. 19), is due to the fact that the geometric conditions of the transactions of the thread-like tool geometry and the resulting workpiece thread are geometrically coherent only at the beginning and end of the process.

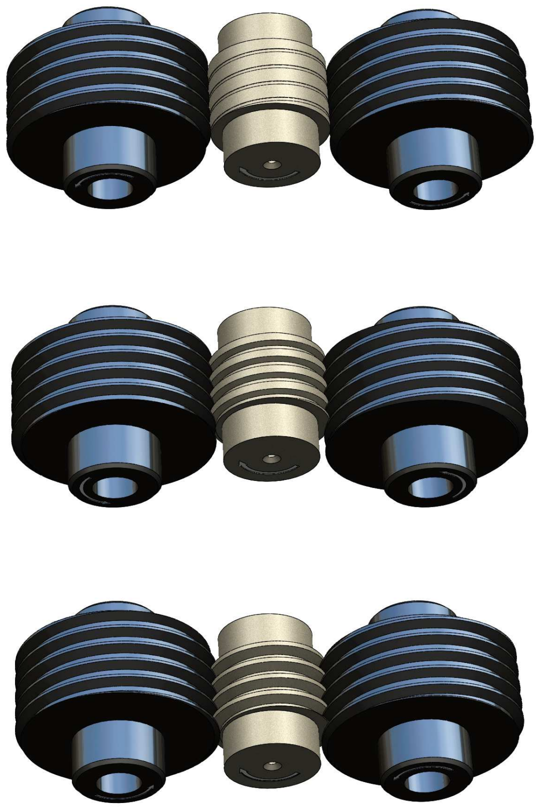


Figure 19 Forming Sequence in PeeWee Thread Rolling

In between, i.e. the emergence of the thread and the multiple over-rolling will unavoidable cause geometric conditions, which must lead to an avoidance-movement of the rolling-piece in axial direction.

The blank is moved axially during the forming, and returns toward the end of the deformation to its original position. It is a process-related necessary movement of the rolling part with respect to the tools. This means that the geometric conditions did change in axial direction but it does not mean that the geometric conditions did change in radial direction. The main forming direction in the case of thread rolling according to PeeWee lies in the radial and circumferential direction of the workpiece, the unwanted avoidance movement results in perpendicular direction thereto. This avoidance movement is therefore, and this needs to be emphasized, not harmful for the resulting thread geometry, because the component with its resulting thread is at any time of the forming guided through the flanks of the work-tool geometry in radial-/circumferential direction and therefore no negative geometrical influence on the rolling part is created. However, the prerequisite is that the width of the rolling tools is significantly wider than the length of the resulting thread [10, 80].

When rolling threads according to the RotoFlow method, nearly identical conditions arise, as shown in the images (see fig. 20). Two flat-die-shaped rolling tools carry on their blank facing surface an upwardly inclined thread contour and are moved by two identical counter-translational motions towards the blank which is generally mounted between tips. The stroke movement of the tools which generates the forming, proceeds according to the PeeWee rolling perpendicular to the axial avoidance movement of the workpiece during forming. In relation to the resulting thread contour during thread rolling according to the RotoFlow method, the flat-die-shaped tools guide and lead the blank that is mounted between tips as it happens when using the PeeWee-method, assuming that the width of the flat dies is significantly greater than the length of the thread being rolled. The differences between these rolling methods arise with respect to the guiding properties of the tools from their geometrical differences. The overlap of the flat back shaped tools, i.e. the contact areas in which these tools are in contact with the rolling sample part, tend to be larger compared to the rotational symmetrical work-tools of the PeeWee method [149]. Based on the resulting geometrical thread forms in the workpiece after rolling, no qualitative differences can be seen.

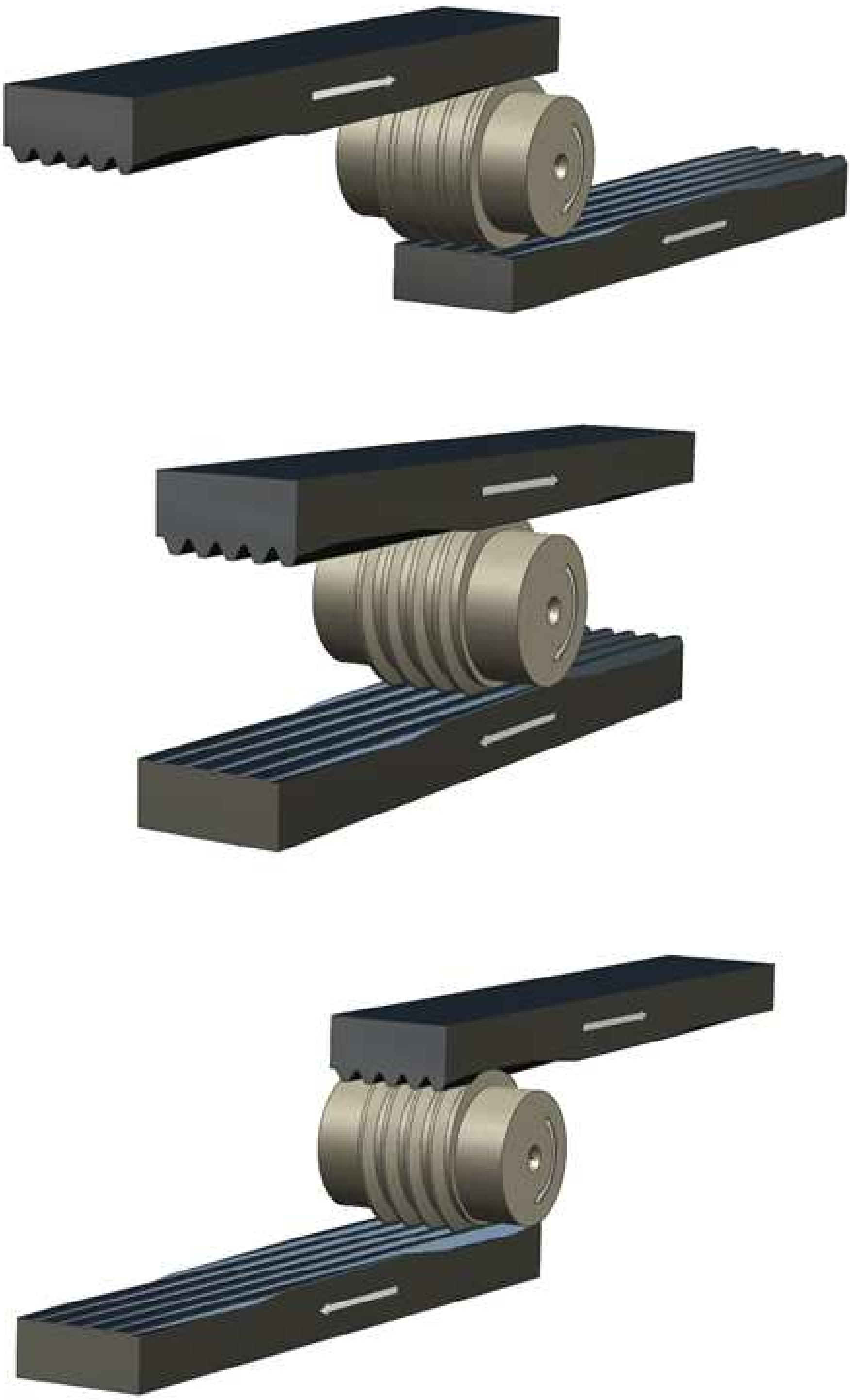


Figure 20 Forming Sequence in RotoFlow Thread Rolling

3.1.2 Spline Rolling Method PeeWee and RotoFlow

As in the present studies just straight toothing of spur-gears will be discussed, only those aspects will be examined in greater detail, which are of interest in that regards. The geometric movements caused as a reaction of the machined workpiece shown in the earlier thread rolling example are the result of forces encountered during rolling. This applies to the thread rolling principles as well as for the rolling of spur-gears with small externally toothed serrations or flat die-shaped work-tools following the above-described method [55, 56, 102]. The beginnings of the forming of toothings are therefore to be understood as an evolution of the original thread rolling. The following pictures show the forming by rolling of gears according to the so called PeeWee and RotoFlow methods (see fig. 21) [10, 136].

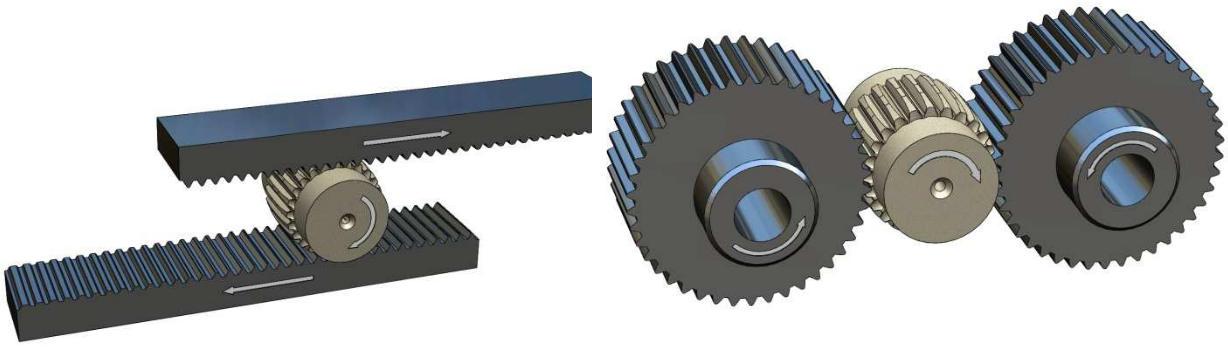


Figure 21 Spur-Gear Forming Comparison

During forming of toothings it is remarkable as shown in the pictures (see fig. 21) that in those combinations of work-tool and workpiece geometry other contact situations arise and allow other guiding characteristics of the tools in the process [52, 132]. During thread rolling the flanks of the tool geometry guide the workpiece axially and radially, whereby the unintended, but due to the process principle necessary axial avoidance movement must be oriented onto the work-tool geometry. When rolling a one-start thread, the forming tools teeth never leave the track of the resulting thread. Thereby it follows as a result that the tools continuously guide the workpiece axially and radially at the same time. In the case of the thread rolling method, the constant direction of the rolling tools rotation is of minor importance, since the resulting spur-trace as a figure of the tool geometry path within the workpiece material remains always the same and is repeated again and again in the longitudinal direction of the work-tools track [55, 56, 123, 124]. As the generated threaded geometry is evolving approximately perpendicular to the workpiece longitudinal axis, only a correspondingly small volumetric asymmetry of the components threaded shape occurs by the constant direction of work-tools rotation. Therefore, at any stage of forming transformation an ideal guide for the workpiece axially, radially and in the circumferential direction is provided given by the work-tools.

In the case of rolling gears, the work-tools guide the workpiece only radially and circumferentially. In the axial direction of the workpiece, the workpiece can move freely.

When rolling a spur-gear, in principle no axial forces arise that intend to shift the resulting axial toothing. However, when rolling a helical spiral-gear axial forces occur as described in the thread rolling before, which cause an axial movement of the workpiece during the sequence of forming process. The consequence is that the at the teeth of spur-gears every work-tool tooth imprints once per tool revolution by radially penetrating a tooth gap into the workpiece. The transformation hereby is taking place gradually, based on the individual tooth gap sequence of the workpiece. If each tooth gap gets hit by a tool tooth n times and if reaching each of the desired root diameter of the gear shape, then the forming process is completed. The number n of revolutions of the blank and the forming steps per workpiece tooth gap to the finished teeth are dependent on the mechanical energy that is being provided on the machine side for the forming transformation.

The boundary of the rollability of gear geometries is primarily given by the amount of material volume to be displaced resulting from the tooth geometry properties. The larger the deforming workpiece material volume per forming step, the greater arise resulting rolling forces that must either lead to unintended workpiece movement, or work-tool breakage. The reason is that following the PeeWee or RotoFlow method always the entire width of the work-tool geometry must be engaged with the workpiece toothing during rolling [48, 52]. Large deformation volume per progress step in the workpiece material is the result. In consequence, this means that in transition from tooth to tooth or during rolling of the n^{th} tool tooth contact to the next $(n+1)^{th}$ step, radial and tangential motion components occur and in case of providing to large deformation forces the created tooth contour gets destroyed. It is the question of involuntary movements of the workpiece contour relative to the work-tool geometry that results in negative consequences for the resulting gear geometry. As an assumption the overall rolling process target is to achieve a defined material distribution (e.g. gear teeth) in continuous material flow process, which in conclusion inherent creates several main target conflicts [18, 25]:

I. mass production capability vs. achievable component or feature accuracy
II. feature accuracy realization vs. the functional required material properties
III. System (re-)calibration and environmental compensation
IV. Measurement Uncertainty estimation of the involved metrology system(s)
V. Correlation & Traceability of In-Process Metrology as such

3.1.3 Rolling of Toothings after the WPM-Method / Principle of Motion of the Rolling Tools/Workpiece

The rolling principle following the WPM method developed by Prof. Dr. Z. Marciniak is characterized by two internally toothed rolling tools. The tools move to non-concordant, symmetrical and circular eccentrically courses, as shown in the following figure 22 [105].

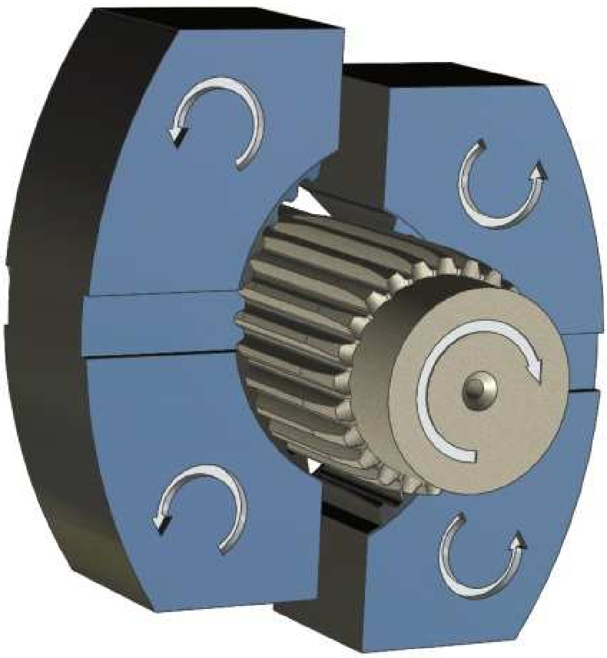


Figure 22 WPM Basic Set-Up

The WPM rolling process starts with rotating rolling tools. According to the machine side selected and pre-set eccentricity the tool approaches and leaves the teeth for each stroke related to the center of the cylindrical blank. The sample blank rotates with the same circumferential speed as the work-tool inner contour and is inserted axially between the rolling dies (see fig. 23).

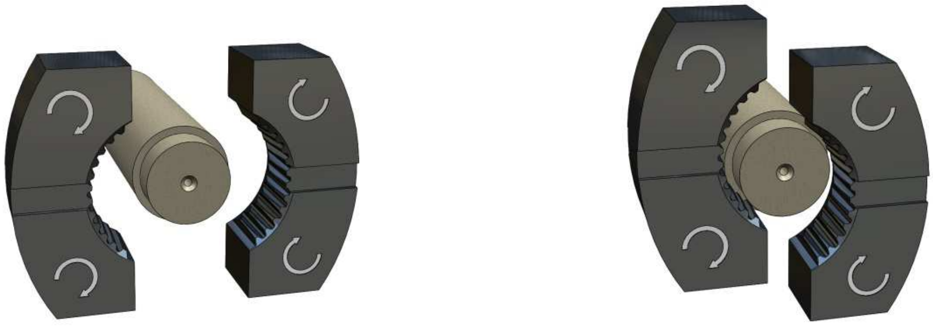


Figure 23 WPM Tool Eccentricity

The work-tool teeth cover the blank material and penetrate into it, so that the toothing is imprinted into the blank material. For each tool stroke consequently result in a rolling phase and a phase in which the tools are open. In the opened state of the tools, the blank is axially advanced forward and the rolling operation starts again (see fig. 24).

Figure 24 Forming Sequence in WPM Spline Rolling

At each tool stroke the teeth of the tools penetrate to their maximum depth into the material, so that at the entire circumference of the roll sample a complete toothing is formed.

The axial extent of the formed spline shaft is given by the number of tool strokes per time and the machine side set feed forward speed with which the workpiece is advanced axially (see fig. 25) [160].

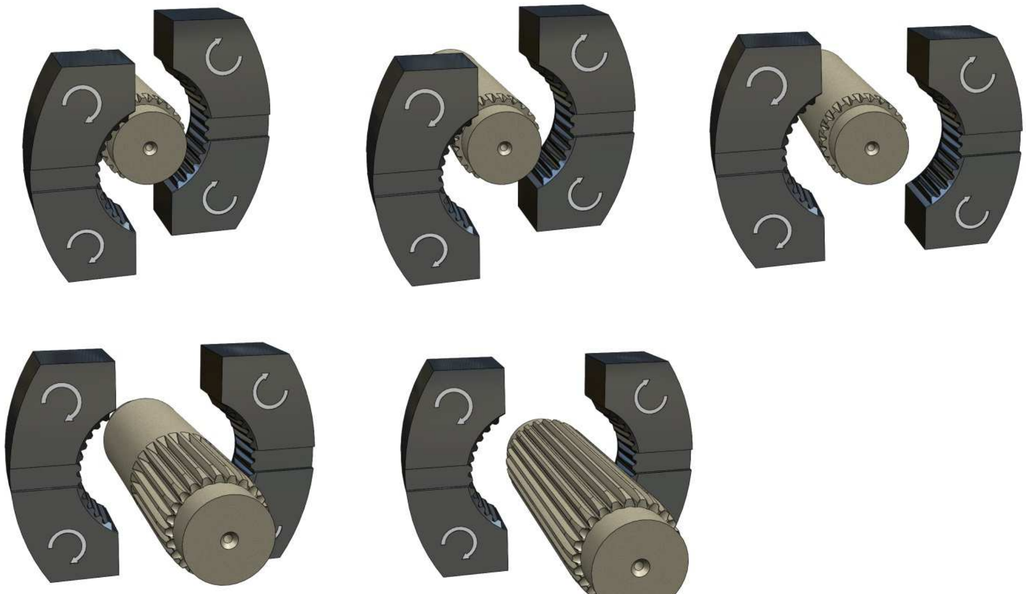


Figure 25 Complete WPM Tool Kinematic Sequence

Machine technology WPM 120 The available rolling machine WPM 120 (see fig. 26) is at the time about 35 years old and is in its original state [27]. Except for the replacement of V-belt drive technology, lubrication of bearings and the replacement of some electrical components no repairs were carried out on this machine in the past.

As following the structural design of the test machine is briefly described. The later performed geometrical analysis of the rolling samples revealed qualitative relationships between details of the machine design and the resulting gear geometries.

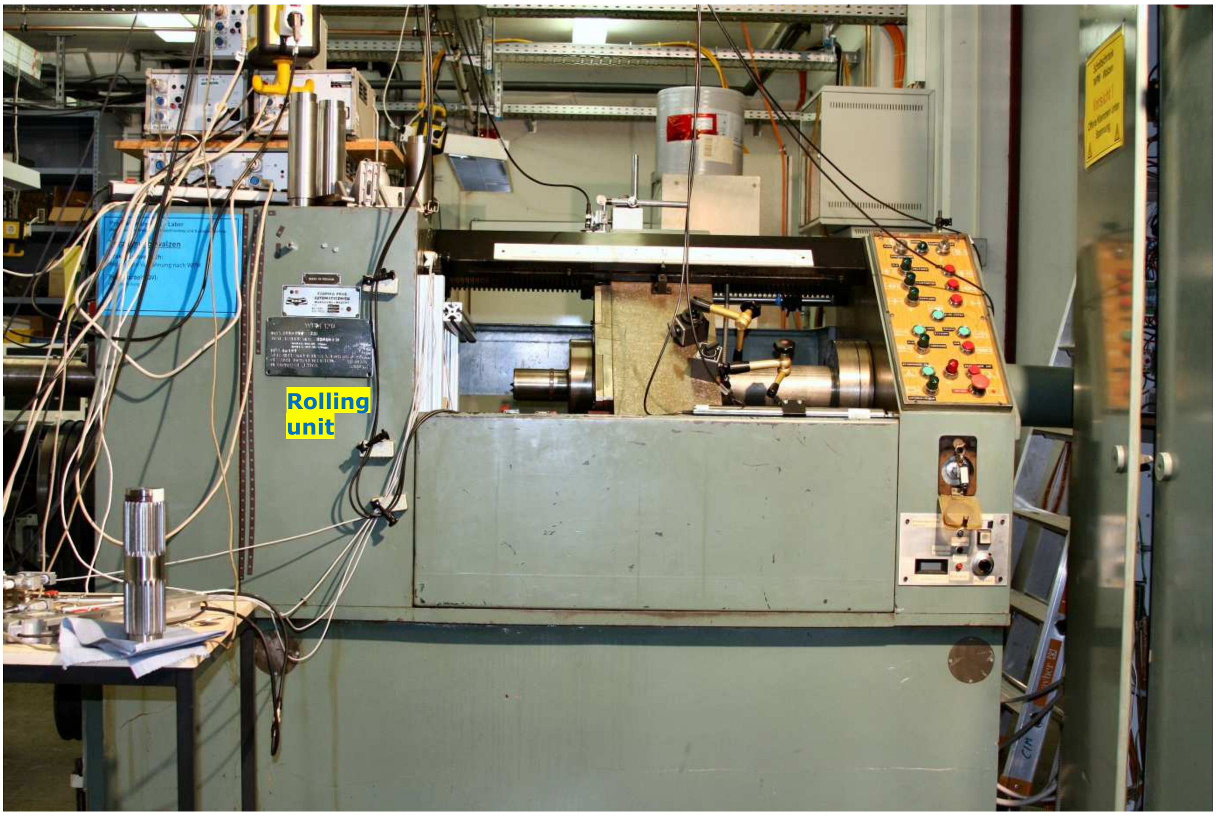


Figure 26 WPM-120 Machine Test Set-Up

Tool Movement A central main shaft runs through gears two sun-gear shafts. The sun-gear shafts are designed coaxial and drive through two gearboxes fours eccentric shafts. By rotation of the two coaxial sun-gear shafts the eccentricity of the four eccentric shafts can be adjusted in steps in synchronism mechanically defined and the same for all four eccentric shafts. Two opposing eccentric shafts lead overhung together each a cup-shaped tool holder who ever receives an internally toothed work-tool segment (see fig. 27,28) [27, 46, 140, 141].

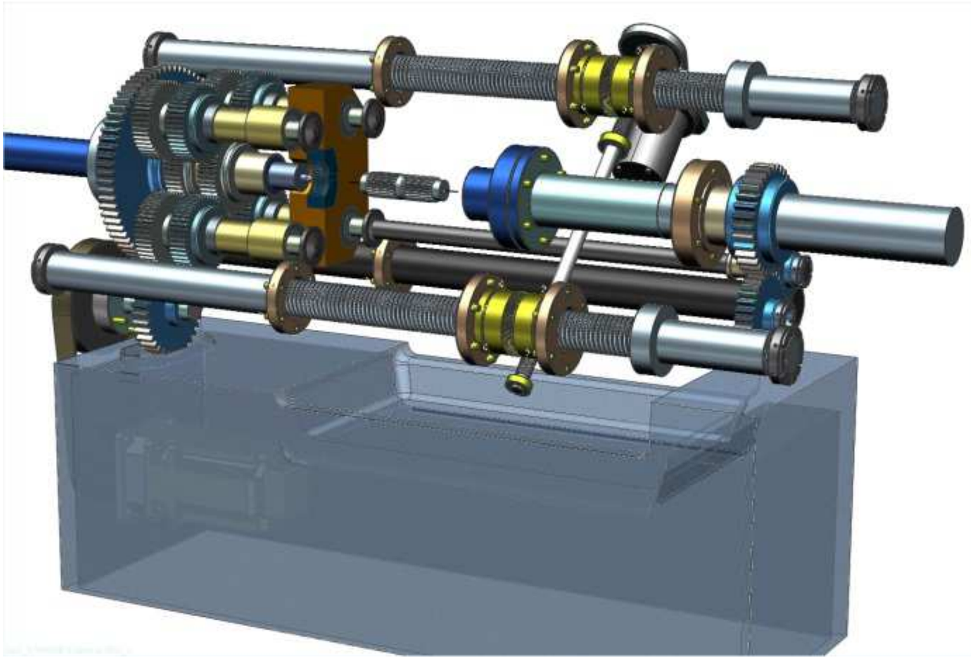


Figure 27 WPM 120 Power Train Principle

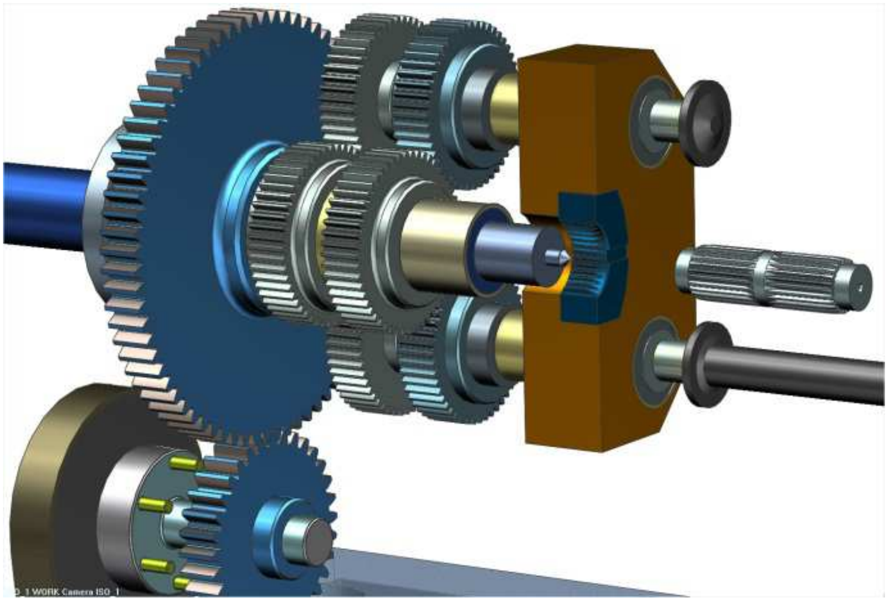


Figure 28 Power Train Principle Work-tools

The central main shaft can be alternatively driven with a small auxiliary drive motor and a worm gear. The auxiliary drive is connected via an electromagnetic clutch.

The auxiliary drive (see fig. 29) only allows a slow lifting movement of the tools in setup mode [27].

It serves to move, is defined prior to rolling, for example, when setting up the machine tools. After rolling a workpiece, the rolling tools can be moved over this auxiliary drive is completely open. The rolled workpiece can then be axially moved out of the tool room to remove the workpiece.

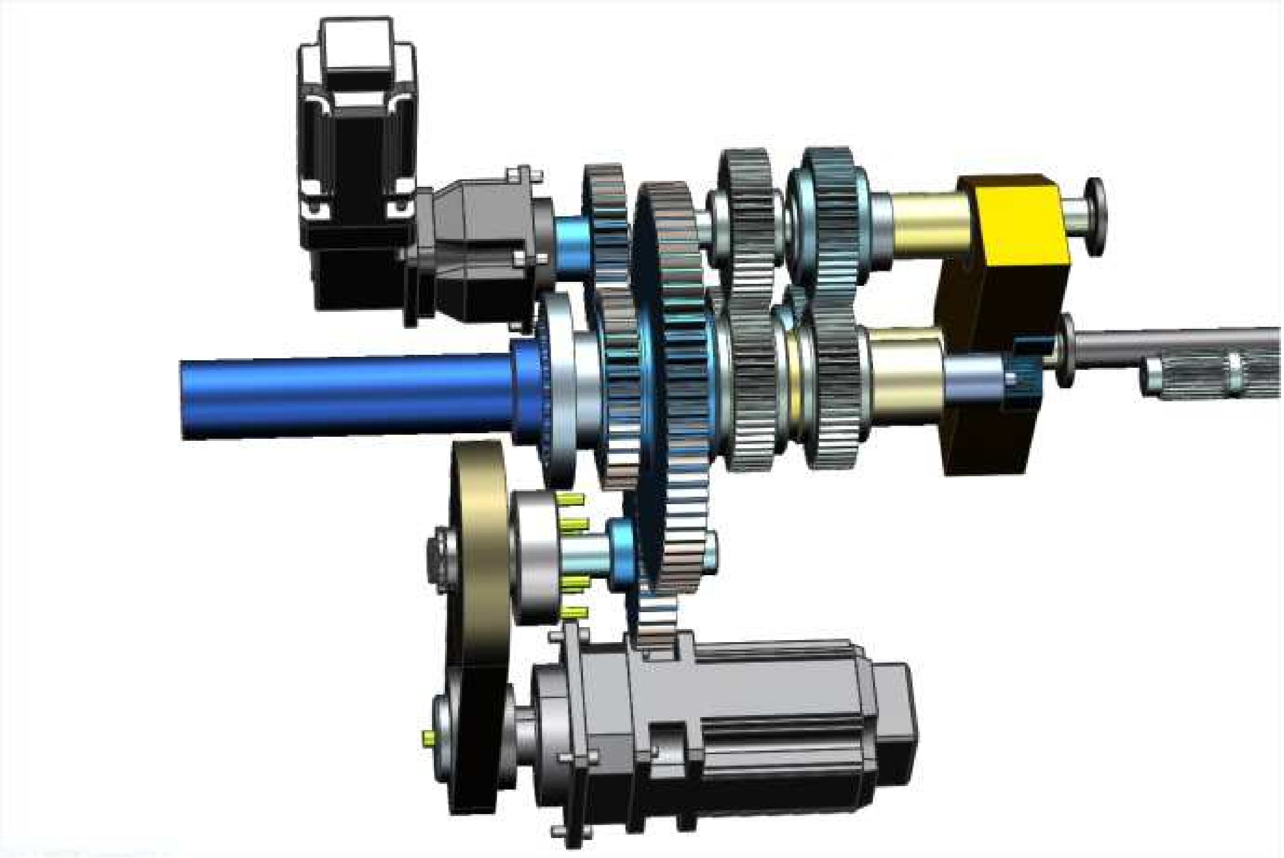


Figure 29 Kinematic Drive Train Tools

Workpiece mounting The workpiece is clamped between centering tips. Centered between the tools in image (see fig. 30) one of the two tips is shown, which is pushed by a hydraulic cylinder against the workpiece. The other side of the roll member is held by a spring-preloaded tip (see fig. 31), which is received in a sleeve [27].

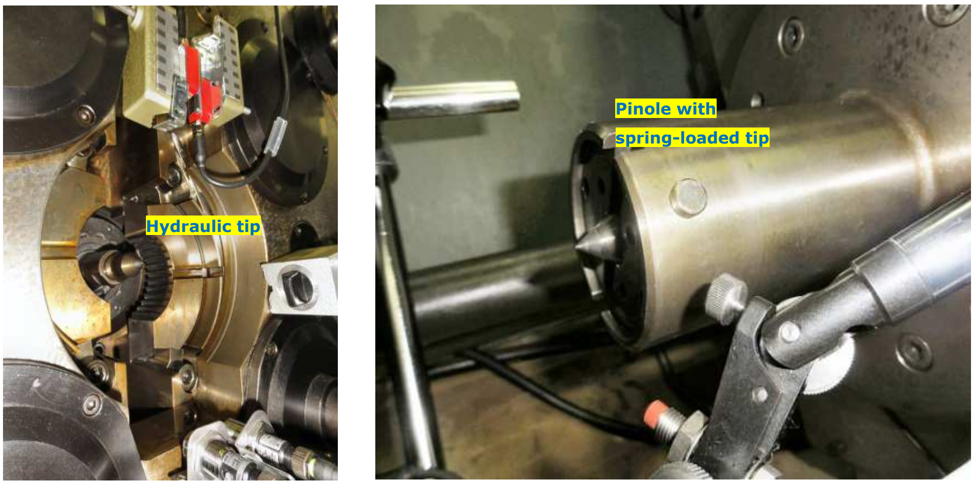


Figure 30 Workpiece Mounting

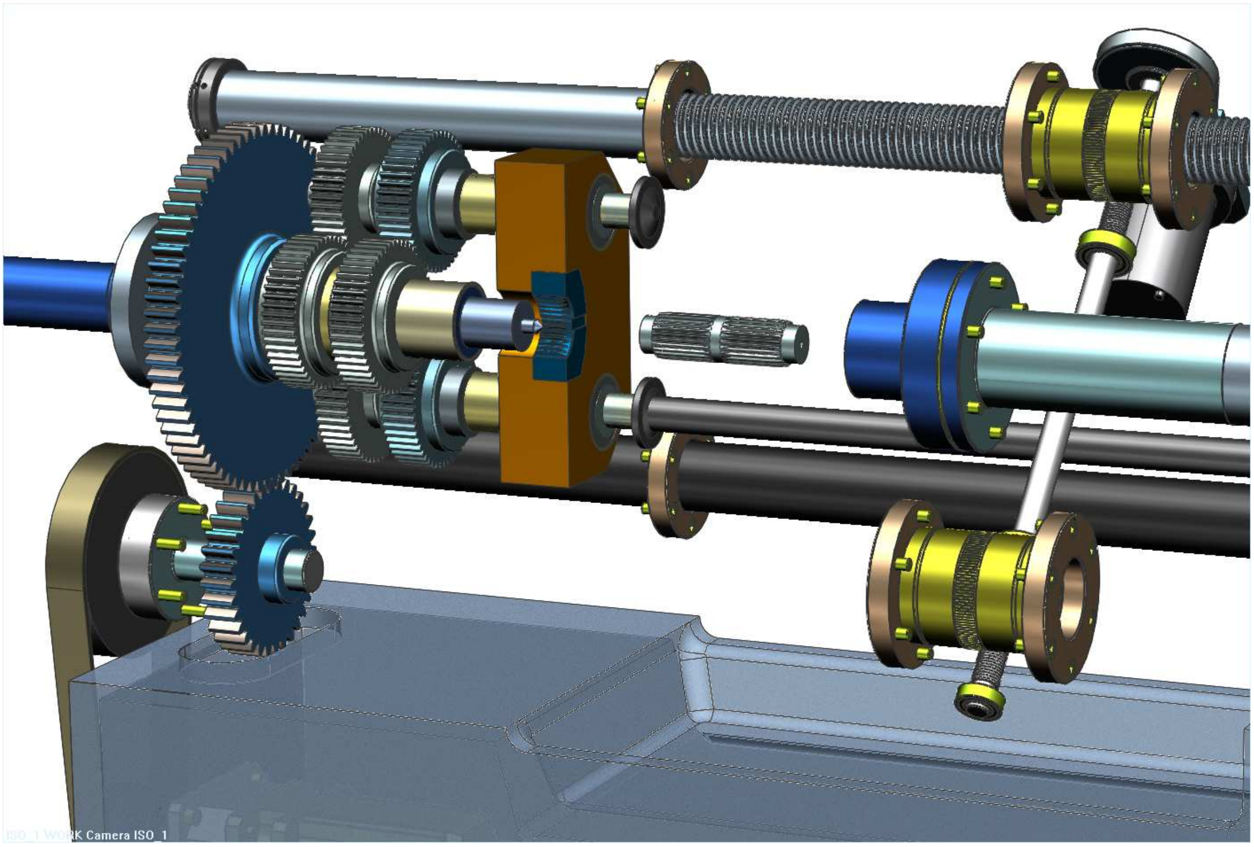


Figure 31 Workpiece Position Principle

Workpiece movement The installed state of a rolling sample is shown in Figure 32 [27]. The rolling sample is being clamped between the hydraulic tip and the spring-loaded tip. The visible sleeve is mounted for rotation in a feed forward slide.

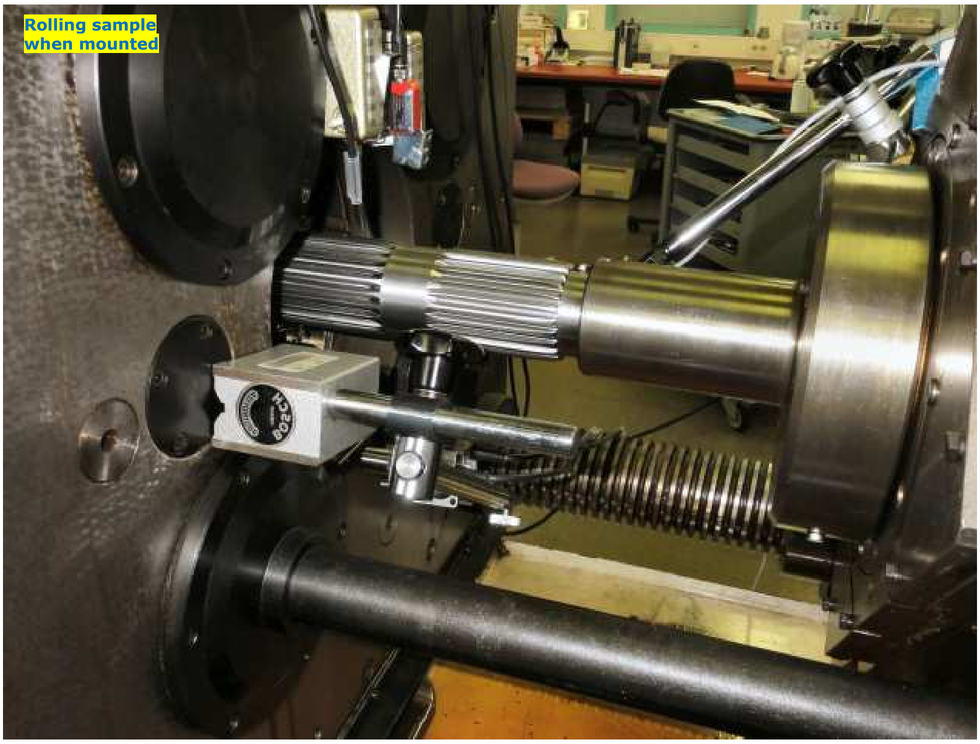


Figure 32 Workpiece Movement

The rotary motion of the spindle is directly derived from one of four eccentric shafts rigidly mechanically. The rotation of an eccentric shaft is a gear box fed behind the feed carriage and transferred to an axially displaceable splined shaft. The sleeve (see fig. 33) is driven from the rear of these splines for synchronizing the rotational movement of the workpiece with the rotational movement of the tool segments [27]. The spline allows the feed motor to move the feed slide axially without the synchronization of the workpiece rotational motion is lost when axial feed between the tool segments.

The axial feed of the workpiece (see fig. 34) between the rolling dies is achieved with a DC motor (power rating 0.8 kW), the rotational frequency can be adjusted by a lockable rotary potentiometer [27].

The feed drive is based on the feed forward and is attached thereto. By means of a belt and a slip clutch and a worm for each side of the feed forward (top and bottom) drives the respective worm wheel.

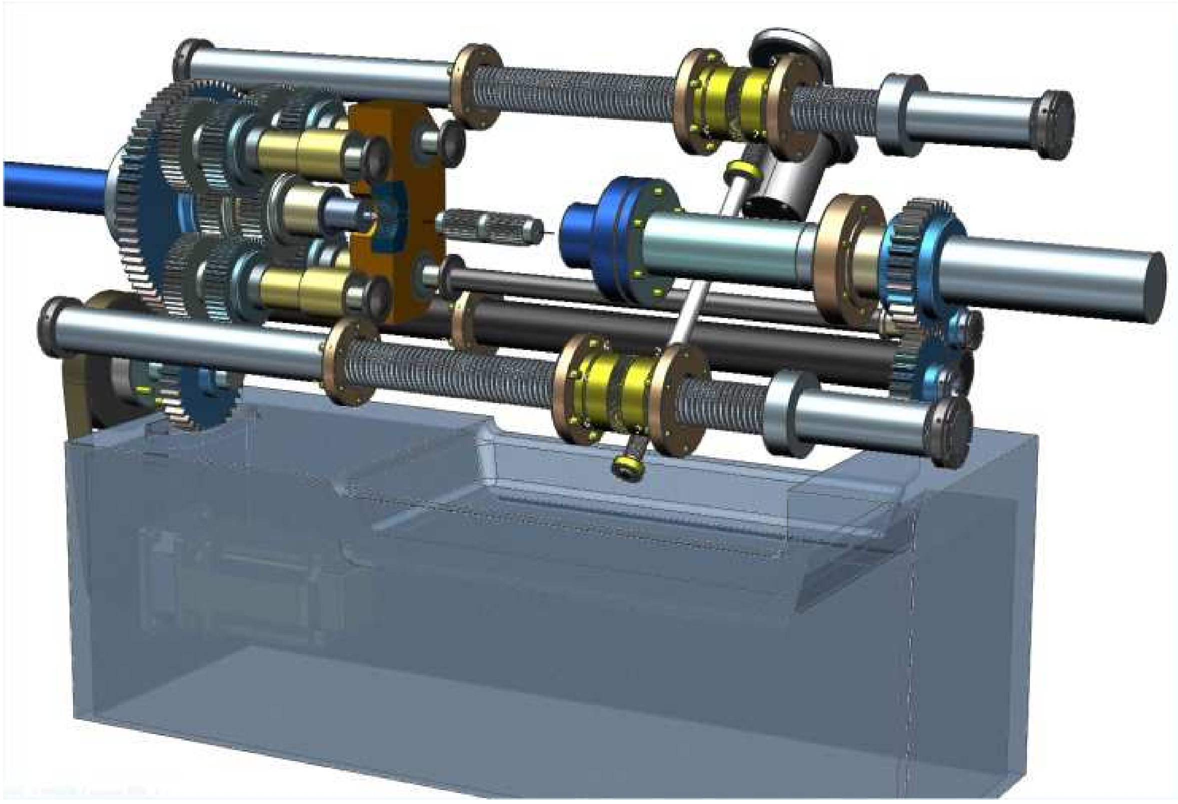


Figure 33 Kinematic Movement Workpiece

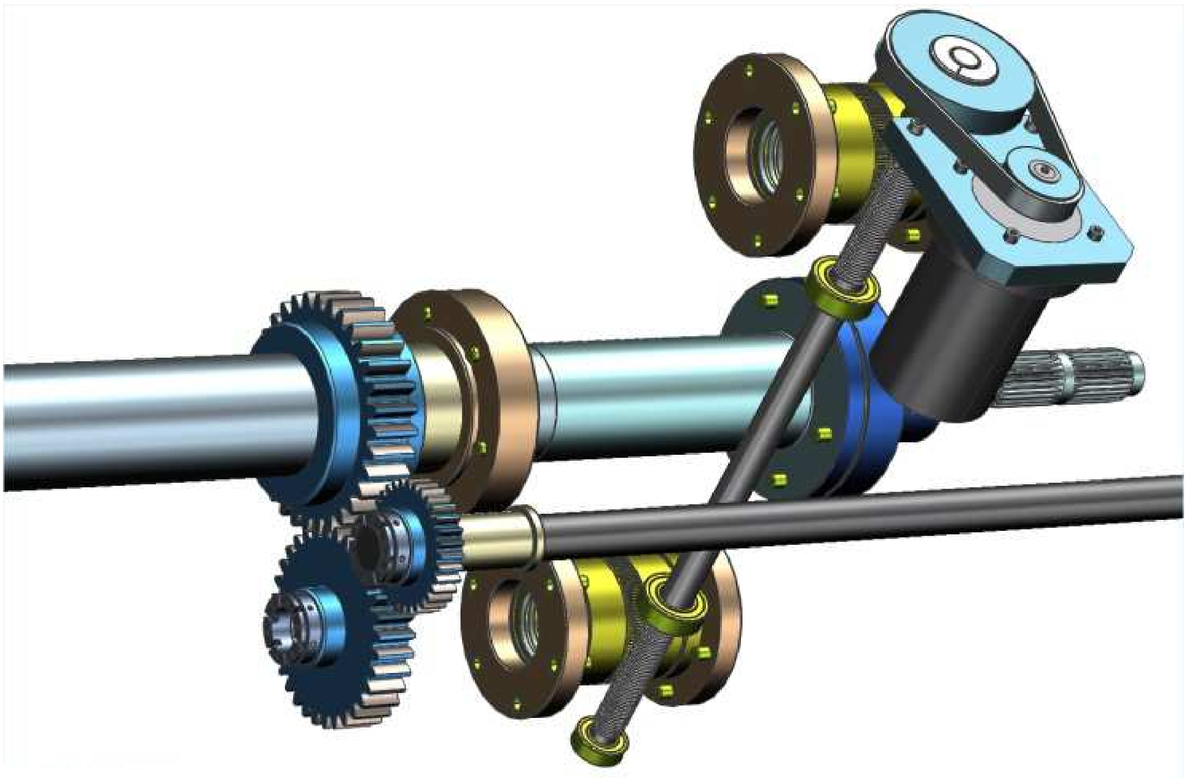


Figure 34 Drivetrain Feedrate Workpiece

The worm wheels are at the same time nuts that drive the feed forward on each of a large trapezoidal threaded rod up (see fig. 34) and down on the machine bed or in the feed slide and guide [27].

During rolling, the axial feed of the workpiece is blocked. The aforementioned slip clutch at the DC motor allows slippage. When the rolling tools are in the open position, the next advance step is initiated.

Evaluation of machine technology The design of the WPM test machine is very complicated. It must be remembered that this machine was constructed in the 70's; it is feasible that with today's modern drive technology, such as CNC simultaneous axes control, the quality results of the gear components would be significantly better.

The drive mechanism of the main drive and the feed forward drive is realized by gear pairs. Corresponding errors of the individual steps in connection with the various necessary rotational movements are the unavoidable consequence. The resultant of the toothed gear geometry component must be affected by it.

In anticipation of later discussions regarding the gear quality in the context of constructive details of this machine is to determine the following:

a) machine rotates only in one direction.
b) feed steps (reshaped volume per stroke) arise by chance since you are working against a hydraulic tip and a slip clutch in the work-chain.
c) The synchronization of the rotary movement of the workpiece when the tools are not in contact, is resolved to be questionable.
d) eccentricity of the tool adjustment.

The spline shaft rolling machine WPM 120 was designed for non-cutting production of long straight spur-toothings. Typical components are for example spline shafts.

The advantages of the gear rolling after the WPM methodology are the large overlap in geometrical coverage between the rolling tools and the blank and the gradual axial gearing. The large overlap leads to large contact areas of the tools with the material to be formed, by what outstanding guiding qualities of these work-tools to the workpiece is the result. Compared with the rolling methods like PeeWee or RotoFlow these tools guiding behavior of the inner geared work-tools is significantly better [71, 72, 126].

3.2 Experimental Parameters / Gages / Metrics

This Section 3.2 is intended to describe the general functional sub-assemblies of the machine design WPM 120 and their technical relationships. The thereby used measurement equipment, measured variable, general experimental parameters and the type of data acquisition were used unchanged for more specific investigations. For the special rolling trial runs covered in the later chapter 5 the special experimental setup, the sensors used and the data analysis will be described separately.

Variable experimental parameters The following parameters were varied:

a) Feed rate
b) Blank material
c) General blank geometry / Special blank geometry (see chapter 5)

a) The feed rate was already recognized in Mr. Tim Eichner's thesis [27] and its own preliminary tests as the main machine dimension with influence on the rolling action. It got rolled in all experiments with 100/200 mm/min. On larger feed rates were omitted because of risk of failure.
b) For safety reasons (mechanical failure) only annealed C15 material (1.0401) was used in the own experiments.
c) The blank geometry for the in the following described general experiments to verify the uniformity of machine functions were cylindrical blanks Ø = 62.3 mm, L = 240 mm.

Unchangeable machine parameters

d) The rolling machine WPM 120 operates with a stroke frequency of the rolling tools by 5 strokes / sec. The stroke rate on the machine side is fixed and cannot be changed. In combination with the maximum feed rate (~ 400 mm/min) results in a maximum toothed workpiece length of ~ 400 mm/min.
e) The adjusted eccentricity of the work-tool movement can be changed fundamentally. However, the rolling tools demand the eccentricity set-up of 12.92 mm in all experiments.

Measured Variables During attempts to produce the spline gear samples with specific geometric properties, the following measures were recorded:

A) path over the time S = f (t)

B) power main drive PMD = f (t)

C) power feeding drive PFD = f (t)

D) stroke frequency of the rolling tools n = f (t)

Position measurements on the feed slide In order to detect the current position of the slide precise, two high-resolution distance measurement sensors (1, 2) were used [27].

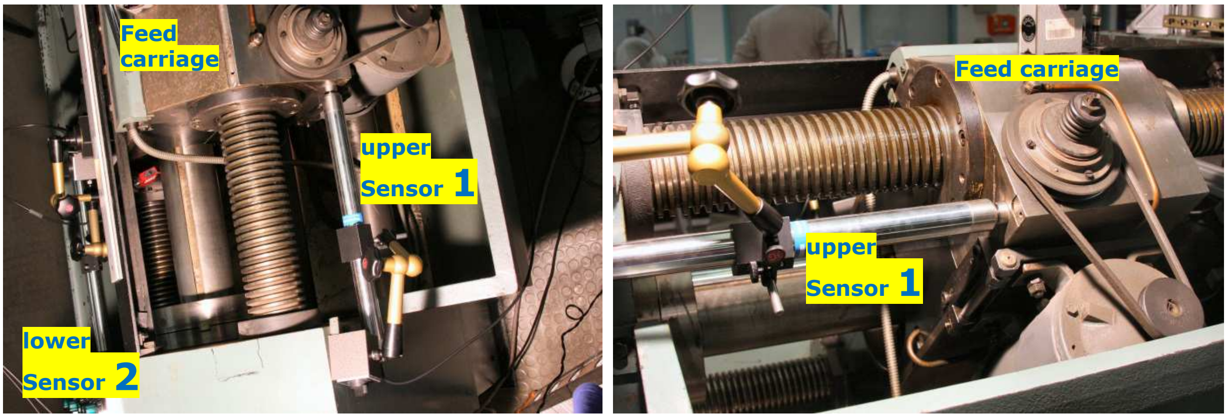


Figure 35 Position Measurement Feed Slide

The feed slide sits on two massive trapezoidal spindles and will be moved axially by two trapezoidal nuts. The movement of this feed carriage is important for the axial movement of the workpiece. In this respect, it should be ensured through the use of two identical path sensors right next to the trapezoidal spindles that same trips are made in equal times on both sides of the slide (see fig. 35). A possible nodding or tilting of the feed carriage would be transferred to the rolling geometric sample and thus negatively affect the geometry of the teeth results after rolling.

Position sensor device The feed path over time was measured. The signal acquisition was realized with two identical sensors which are described in table 1 regarding their technical specifications. For the current slide position, the respective feed rate can also be determined with the software TwinCAT2. Is the carriage returned to its starting position (workpiece change), then both encoders are set to an equal starting value before the next rolling attempt will start.

Table 1: Sensor brand - Sony magnescale

Typ	DK155 PR5 selection 2µm
Measuring stroke	max. 155 mm
Resolution	incremental system 0.5 micron resolution
Max deviation	guaranteed under 2µm
Design	cylindrical 32 mm
Mechanical coupling	clamped on the outside diameter Φ32
Spindle Φ8	magnet Φ22 with very strong adhesive force
Outpuinterface	2 shifted by 90°, and each also inverted square signals with TTL level
Signal processing	Beckhoff
Typ	32-bit incremental BeckhoffEL5101
Max frequency	over 4 million increments / s
Max interpolation	1/256 bit mircoincrements
Interface	Ether CAT
Counter over/underflow	CNC axis software Beckhoff Twin CAT NC

Because of the trapezoidal spindles clearance, the feed carriage tilts when reversal direction moving at the start of the rolling, therefore, there is always a small path offset, which makes the uniformity of the carriage movement very clearly visible.

Measurement uncertainty of the position measurement A significant measurement uncertainty could arise from the installation position of the sensors. For non-parallel mounting position of both sensors differences could be measured, which do not correspond to reality. However, these differences would be negligible small compared with the slope errors of the trapezoidal spindles and partially uncontrolled slippage of the slip clutch on the feed drive [12].

Power Measurement For measuring the power consumption of the 7.5 kW main drive motor for the eccentric tappet of the rolling mill, a high-speed three-phase active power interpretation measuring system of the latest state of the art is used. The same measurement setup with an identical but configured suitably for the smaller rated power meter APM380 (see fig. 36, technical specification see table 2) [27] is also used for the axial feed of the workpiece with the DC motor (rated power 0.8 kW). There, however, when the line-side feeding of the one-quadrant amplifier. Since no intermediate circuit and also no significant energy storage exist, is measured also very close to the engine and thus on the process.

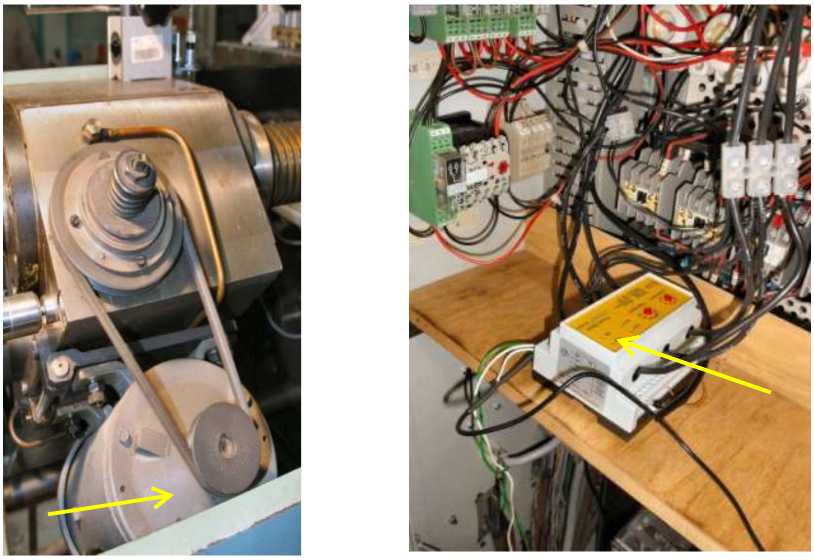


Figure 36 Power Measurement Set-Up

Table 2: Sensor brand - Ulrich Buhr Industrieelektronik Soltau (sales DE) Hydria Elektronik ApS - Vodskov / Denmark

Typ	Unipower APM380
Voltage	230 - 575V switchable
Current range	1 - 80A (max. 140A), switchable
Accuracy	Class 2
Frequency range	10 Hz - 1 kHz
Pulse and Analog outputs	programmable
Digital filter	programmable

The analog measuring output is programmed to 0 ... 10V for the respective scale value and again with a 16-bit differential input to a Beckhoff - analog / digital converter EL3104 EtherCAT bus recorded digitally (Input filter limit frequency: 5 kHz sampling rate 1 kHz, no oversampling).

Measurement uncertainty of the power measurement In the selection of the measuring range, a compromise between the resolution and the full scale had to be made. When starting the machine, very high power peaks can be seen. This power peaks of the main drive were previously recorded separately only once for documentation. For the main tests of the full scale of the measuring range has been adapted to sense the resulting in rolling power gradients [12, 27, 59].

The drivetrain of the movement mechanics of the rolling tools is associated with high friction parts and very large flywheel masses. The friction parts were seen to be strongly temperature dependent. The lubrication system of the machine always took a long duty cycle until stable, constant conditions were set. As a result, the main experiments were always carried out only after an operating time of the machine at least 3 hours duration.
It was noticed, that at the feed drive the influence of the slipping-clutch is speed-depending. Without having a discussion about the results at this point, it is to be noticed that the clutch of the feed-drive rarely, but hardly traceable slips. Whereby, the results of the performance measurements at the feed drive are naturally influenced. All the above-mentioned shortcomings of the available rolling machine are quite obviously due to the high age and the resources available in the 70's drive technology.

Stroke frequency of the rolling tools To make sure that the manufacturer's specification of 5 strokes / sec is indeed satisfied, the time interval of the cycle of movement of the cradles of the tools has been detected. As shown in the image (see fig. 37), the front edge of the right cradle was approached with an inductive probe. Moves this edge by the magnetic field of this button, a signal is generated in high resolution. The time interval between multiple strokes, or during all the rolling phase, was detected. [27]

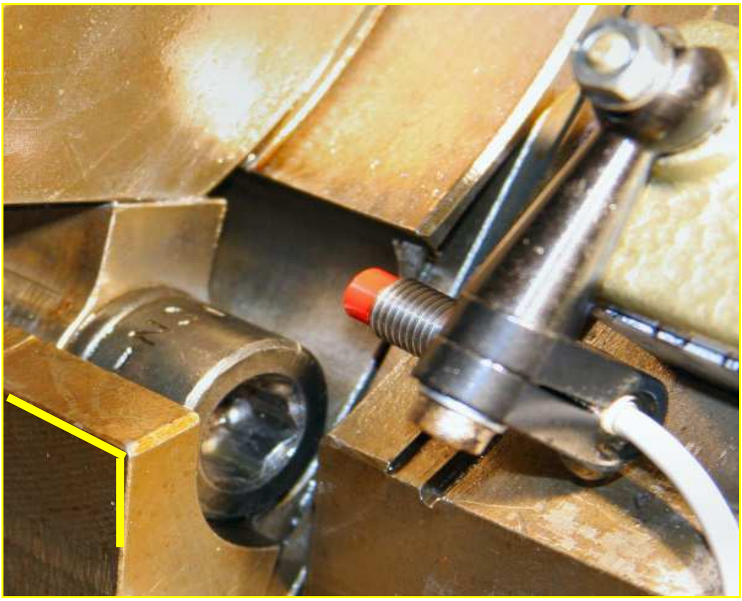


Figure 37 Sensor Set-Up Stroke Frequency

Table 3: Sensor brand - Leuze electronics inductive probe

Typ	IS 208 N5
Operating range	0…2.0 mm
Switching frequency	5kHz, installation position not flush, stainless steel
Accuracy	Class 2
Frequency range	10 Hz - 1 kHz

The output signal is connected to an input terminal Beckhoff EL1018 recognized on the EtherCAT bus.

3.2.1 Data Acquisition / Analysis

The measurement data were acquired with a Beckhoff controller system. It is a system containing a CPU-Intel Pentium M 1.8 GHz, 1 GB DDR Ram, 64 MB Compact Flash card with an EtherCAT real-time field bus interface. The measuring system and the installed software TwinCAT allows throughout the acquisition of measurement data in real time. The system structure is modular, making it easy to integrate data collection optimally designed slots per channel on the Ethernet bus special [39, 74].
So It is possible to acquire digital and analog measurement channels with a sampling rate of several 100 kHz at 16 bit resolution. Special digital inputs for recording period and / or event measurements can be marked with time stamps in the processor clock. Thus, an accurate synchronization of the measurement signals, for example, to determine the temporal sequence of signals is possible. Through self-developed software, the measurement duration, number of channels and the respective resolution of a measurement channel are problem-oriented scalable. The data files collected were transferred over a local network on a Windows PC and evaluated there with the software DIADEM 2012 an internally generated analysis program [46].

3.2.2 Machine Technical Results and Review

A detailed graphical display of all results is omitted here. The aim of the mechanical tests shown in the following was not a systematic analysis of the machine technology. It should only be shown that the uniformity of the respective rolling tests was ensured as the basis for the subsequent specific geometric studies. The graphs shown in the sequence are thus to be understood as examples to explain the technical aspects.

Distance / time - course of the feed carriage These measurements had to determine in how far yielded identical course-time-distribution all rolling samples and each set feed rates are identical. This is, as already mentioned before, of importance for the per step deformed volume of the workpiece blank material [27].

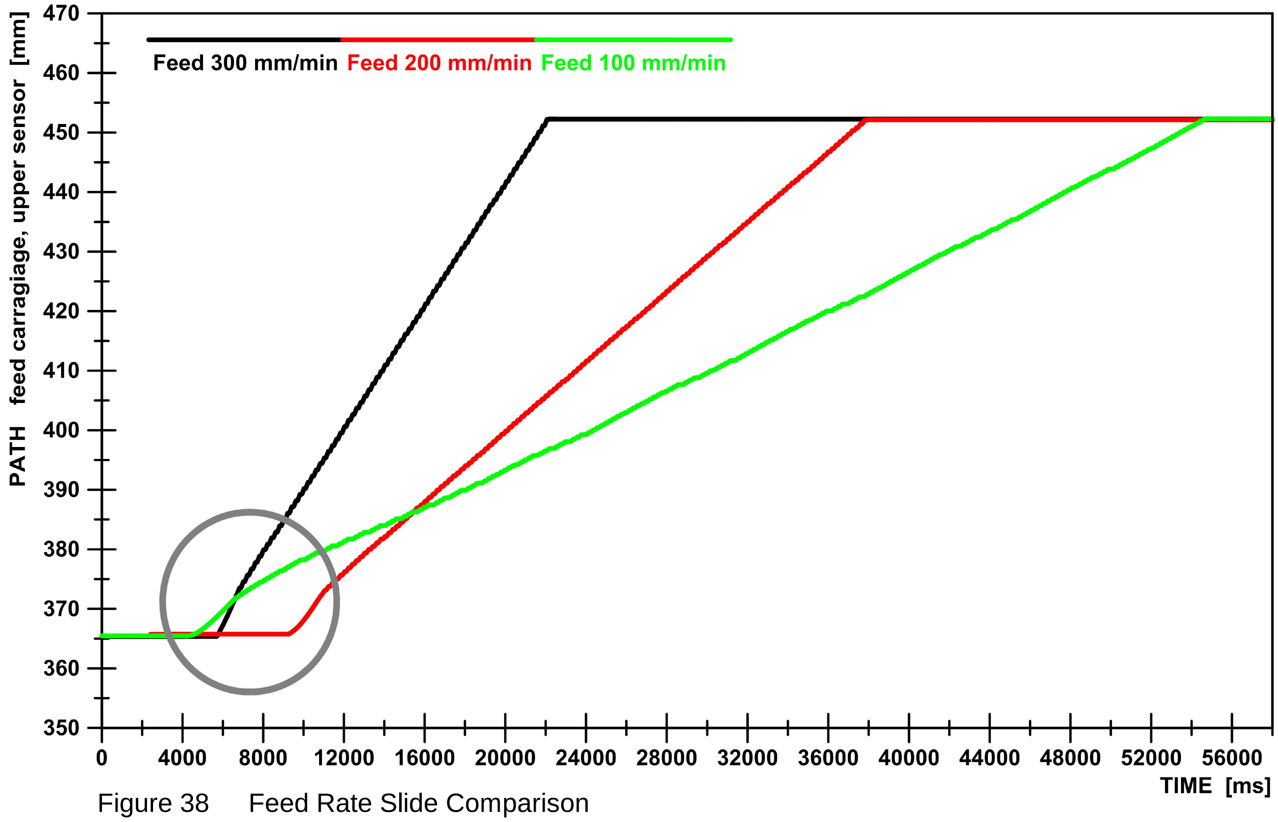


Figure 38 Feed Rate Slide Comparison

The image (see fig. 38) indicates the resultant course-time-distribution at the feed rates 100/200 mm / min. The graph shown here are taken from the upper sensor-1 (Fig. 35) at the top of the slide geometry. The graphs shown are original data without any data manipulation. It shows an example of the resulting time-time-distribution that for all parameter combinations was nearly identical.

In the chart (see fig. 38) the initial portion of the feed movement is marked by a circle. The starting points shown therein are not the same, because the start of the movement and the start of data recording have been initiated manually. An identical starting time could thus not be realized. One recognizes the beginning of the slide movement through the first bend in the curves. According to the adjusted feed rate thereafter rising blending are different in each case on a very short distance. Within this short path (circle) the tools meet the blank, where they are slowed down, so that a second tilt results in the course-time-distribution. During the further process of the graphs increasing curves arise according to the set feed rates. They proceed into a horizontal course at about 450 mm. The feed slide is then in its final position. The time period within the final position is optional, since the return stroke of the carriage movement was triggered by hand.

At all rolling experiments, identical rolling course-time-distribution with minimal deviations could be seen. As far as the feed movement of the respectively set feed speeds, all samples were rolled under the same rolling conditions.

The measurements of paths with two sensors on the feed slide (Fig. 35) had the target to detect, in how far the slide moves on the two trapezoidal spindles symmetrical. A tilting of the slide would affect the center position of the roller part negatively. It should also be determined whether the intermittent rolling process can be reflected in levels of slide movement. The following chart (see fig. 39) indicates a period of one second process time, which course-time-distribution appears greatly enlarged [27].

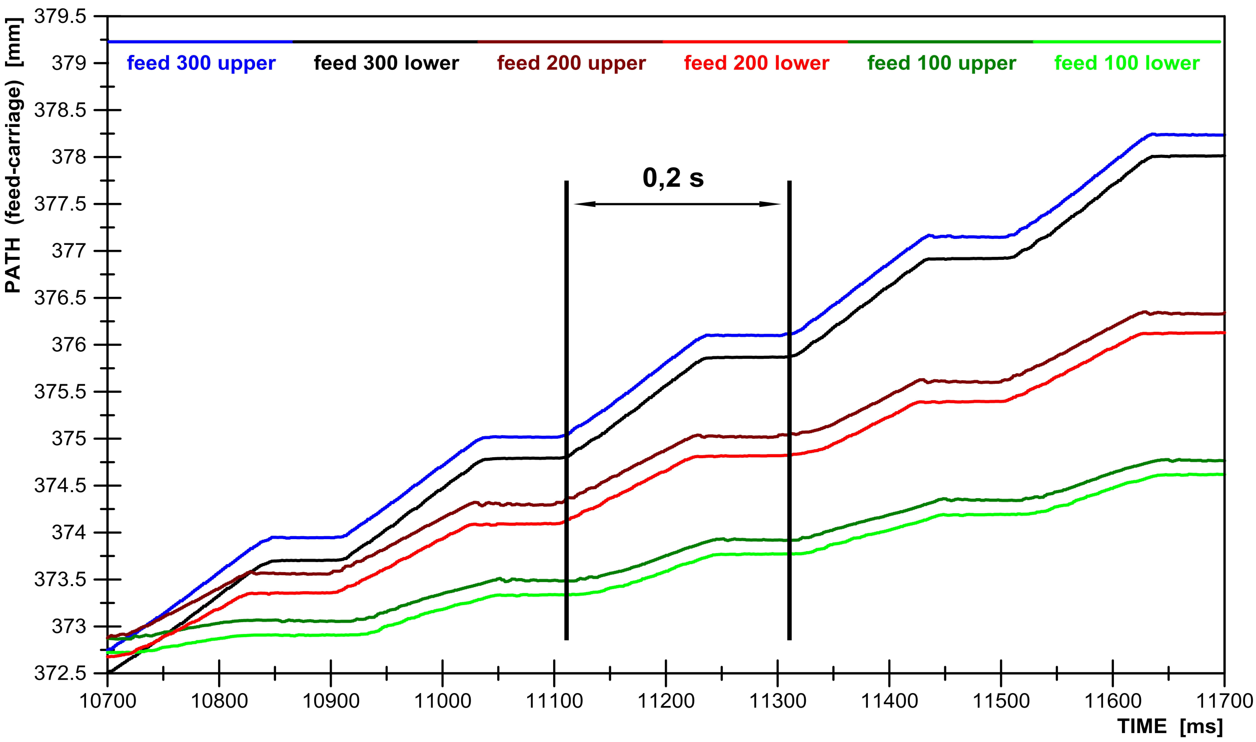


Figure 39 Feed Rate Slide - Enlarged Path / Time

Shown are, for both each feed rate, both signals of the course-sensors (1+2 on the feed slide in y-direction slightly displaced so that the individual profile is clearly visible.

Without this manipulation, both graphs would be identical on each other and be indistinguishable. These data are shown in the chart (fig. 39) without any further manipulation. It can be seen that both displacement sensors provide almost identical values. A tilting of the feed carriage during movement can thus be excluded.

Based on a bend in the curve progression an increasing curve is following according to the set feed speed. Then a further bending occurs, and the curve enters into a horizontal course. This is the period in which the tools are in contact with the blank, and therefore the blank cannot be displaced axially. Then, from the release of the tools the next bend happens and the workpiece blank continues to be advanced.

The intermittent rolling process can be clearly detected again. Furthermore, it can be seen that at the largest feed rate and sharp bends (open transition from the rolling phase to position tools) result in the courses. With decreasing feed rates result rather smooth transitions between these phases of a movement cycle of the rolling tools. An explanation for this is that the forward movement of the carriage is stopped by the contact with the rolling tools.

However, the feed drive continues to function even at this stage. Namely against a slipping clutch, which then slips when the tools are in mechanical contact with the blank. As smaller the advancement steps in axial direction between the tools (slow feed speed) as smaller the per step-feed deformed volume and therefor the contact area of the tool with the material. The contact area between the rolling tools and the blank material increases with increasing feed rate, resulting in better management result from larger contact areas and thus greater resistance to relative motion between the contact partners.

Performance measurement on the main drive The graphs in the chart (see fig. 40) show the power of the main drive of the rolling tools. The larger the feed rate, the greater is the volume per unit of time to be formed.

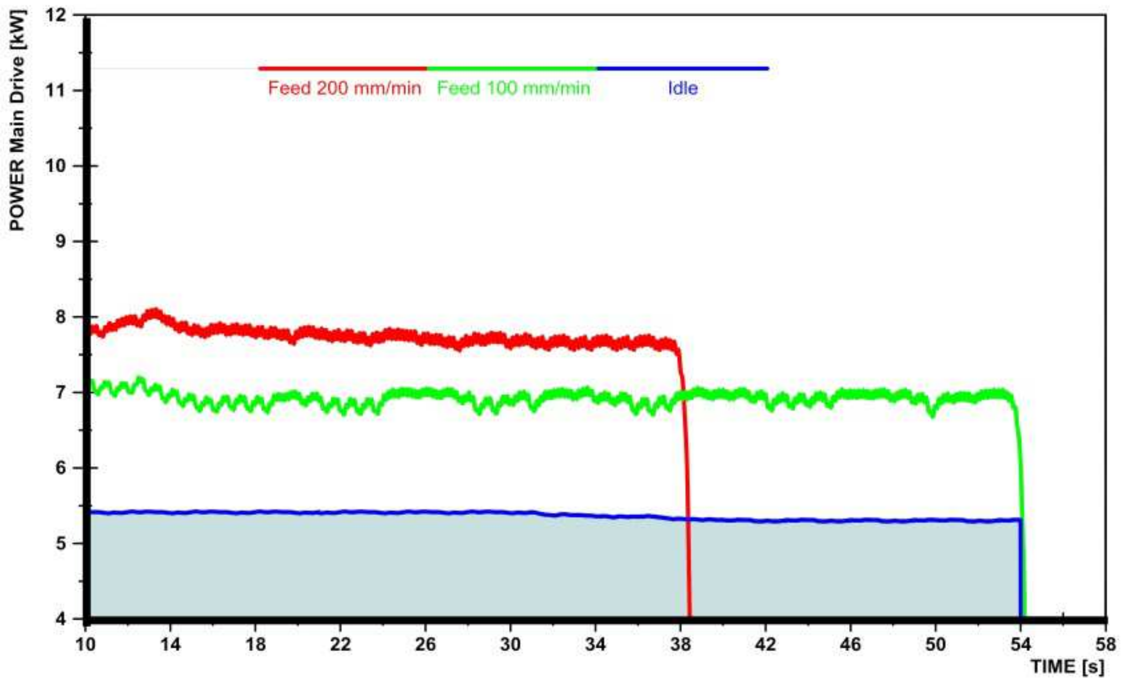


Figure 40 Power Consumption Comparison – Main Drive

The larger the volume to be formed, the greater is the power requirement. In order to create an identical starting point for all rolling trials, all the initial points of consideration were related to the time 10 seconds after the start of the main drive. In addition, all performance curves were smoothed (filter Tschebytscheff 2nd order 5 Hz), because totally irregular power peaks appeared. These occurred extremely irregular in all parameter combinations and were to associate with the rolling process in any way. The applied smoothing of the graphs only affected the courses slightly.

The material C 15 (1.0401) was especially good to reshape in forming by WPM rolling, whereas the C35 (1.0501) and C45 (1.0503) caused problems. Loud noises and very rough running of the machine were observed at the higher material strength.

Since in any case no significant difference between the roll results was observed within a combination of parameters, all the planned rolling series were not carried out. In particular, series with high-strength material were dispensed. The machine WPM 120 could have been damaged.

In principle, all parameter combinations showed approximately the same results, independent of the materials or blank geometries used in the experiment. This statement refers primarily to the central aspect of their own work to determine which the geometric features can be explained on the geometry of all rolled splines.

Performance measurement at the feed drive The following chart (see fig. 41) is an example of a graph in which the power consumption of the feed forward drive has shown over time. Shown are the profiles of the two feed rates and the respective idle power.

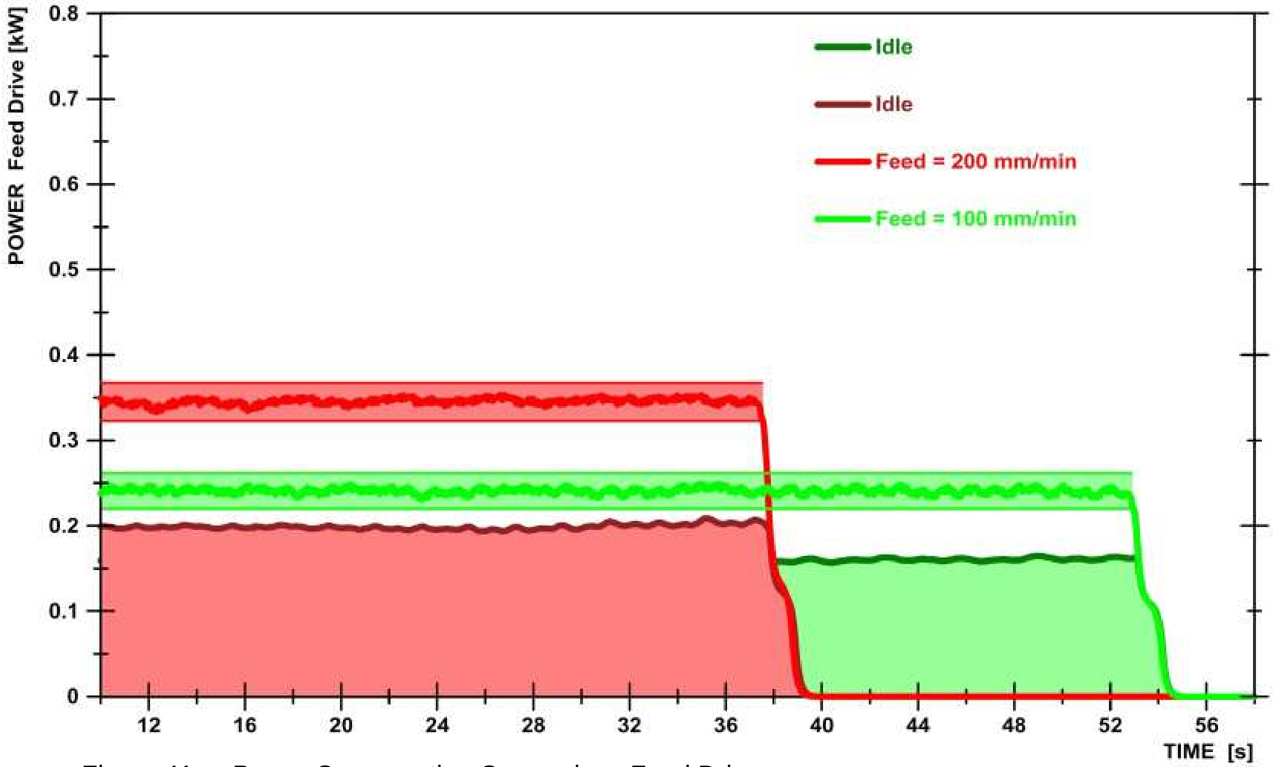


Figure 41 Power Consumption Comparison Feed Drive

It can be seen that in the feed-speed becomes greater the associated idle power increases. Furthermore, it shows in the form of horizontal bands colored in the maximum and minimum deviations recorded performances. On the representations of other curves has been omitted, since it does not increase knowledge. An influence of the strength of the rolled materials on the feed-performance could not be found. For all combinations of parameters approximately the same results were obtained [85].

Stroke frequency of the rolling tools The chart (see fig. 42) shows the resulting signals of an inductive sensor (see fig. 37, table 3). At each passage of the front edge of the shell of the work-tool results a signal. For each tool stroke results a signal whose distance is always identical to each other and is 0.2 seconds. This is the same time interval, which was already observed in the displacement measurements on the feed slide. The machine works with 5 strokes / sec, as indicated by the manufacturer [27].

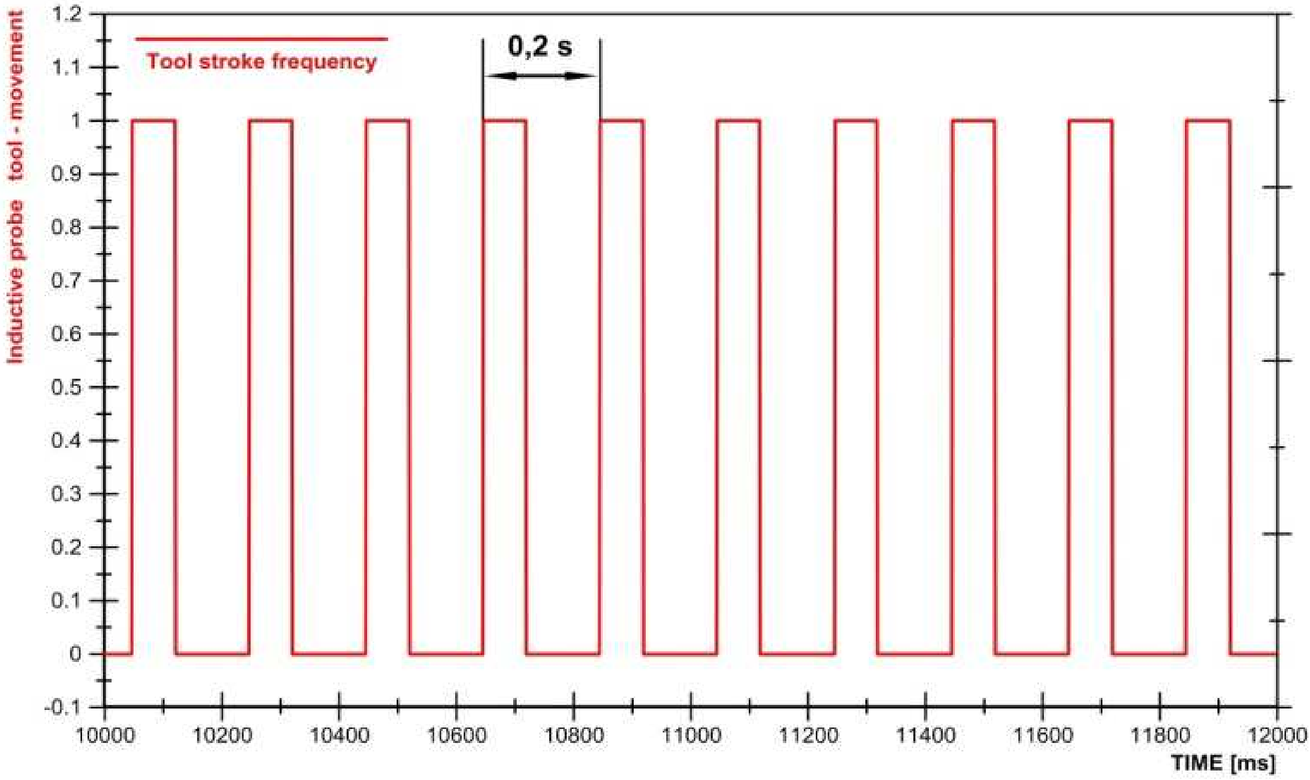


Figure 42 Work-Tool Stroke Frequency

3.3 Toothed Machine Elements

Toothed machine elements are components with specific geometric functional elements. The function items displayed serve different purposes, such as the transmission of movements and / or torques. The geometric structure of a toothed member can be divided into major and minor functional components. In this sense on a toothed machine element the teeth stands in the foreground of attention. The teeth of such a component are thus the main functional elements. Usually toothed components are paired with another toothed member, whereby the intended mechanical function is formed (see fig. 43).

Geometric areas or surfaces of the main functional elements of a toothing are called main-functional surfaces [38]. The following comments relate solely to spur gear teeth as in the following pictures are shown as an example [27, 55, 56].

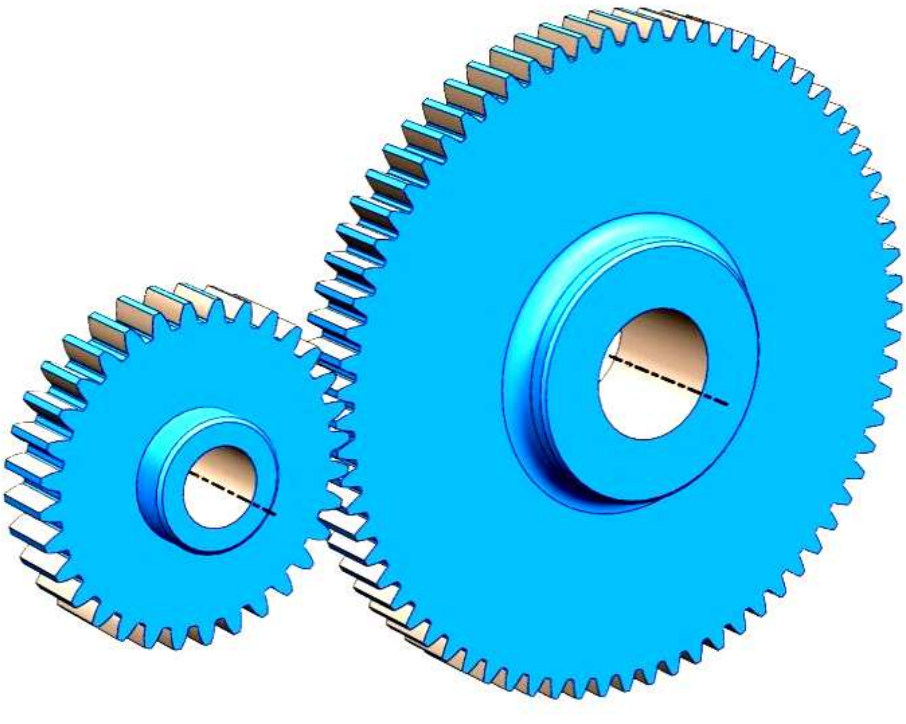


Figure 43   Straight Gear Pair

Figure 43 shows a gear pair of two externally toothed components. The rotation of one gear wheel is transferred to the other and the ratio of the rotational movement corresponds to the ratio of the respective numbers of teeth [41]. The case transmitted torques is inversely proportional to the respective speeds. The main functional elements of the two components, i.e. the teeth determine the mechanical function of the pairing. The mechanical function is thus realized in this example, the edges of the main-functional surfaces of the teeth [27].

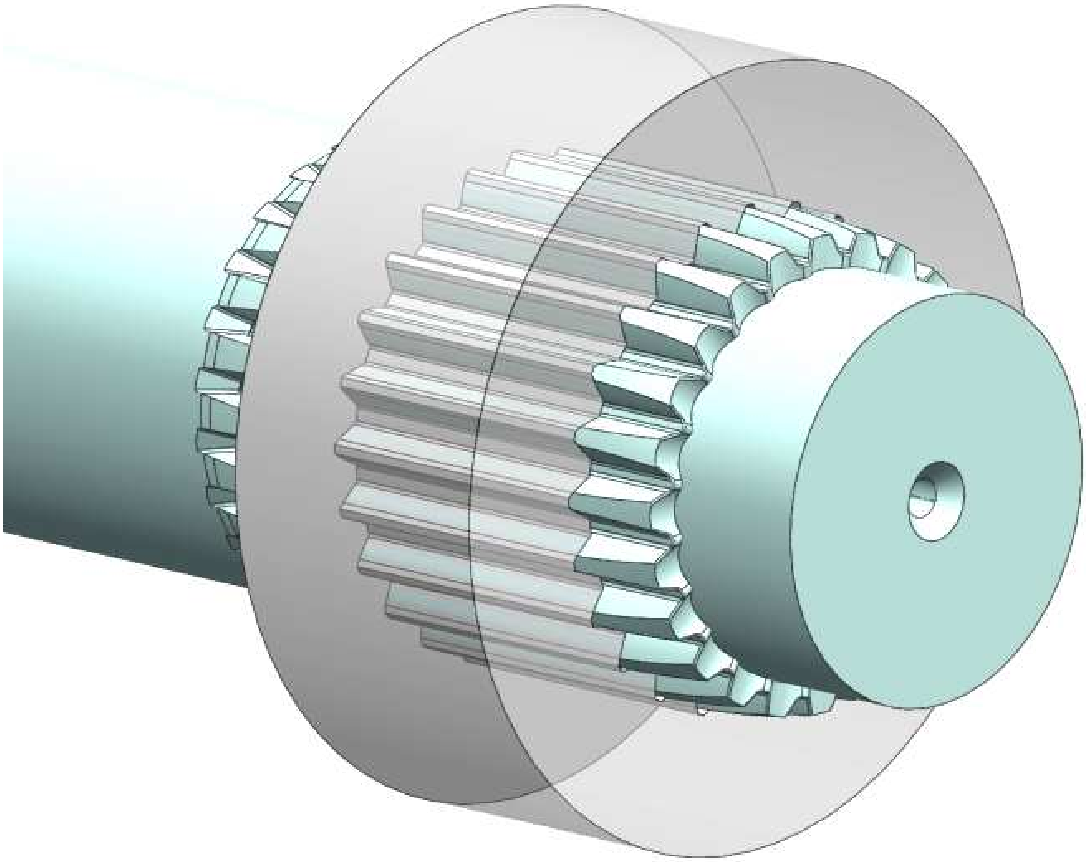


Figure 44 Toothed Shaft / Hub Combination

Figure 44 shows another gear pair in which a toothed shaft is received in an internally geared hub. A relative movement between the two workpieces in the circumferential direction is not possible [46].

Such a connection of two toothed components used to transmit torque while permitting axial displacement. It is a typical shaft-hub connection, as it is often used in the automotive industry in precision mass production. The hub is visualized in transparent mode for sake of clarity [11].

The examples shown above are intended to clarify how different the functions of toothings at toothed components can be. For the sake of good order, it should be noted that these two examples are only two of a large number of other applications of splines. Not always a teeth is placed on a rotationally symmetric base-component. Often, gears are part of a rod-shaped component. Typical examples of the linear array of teeth are racks or rack-like parts. It is noteworthy that almost always toothed machine elements are paired in industrial use with another component. Then arises only through the interaction of the paring of gear teeth intention to mechanical function [11].

3.3.1 Spline Shafts / Typical Components for Rolling after WPM

The rolling machine WPM 120 described before was designed for non-cutting production of straight tooth profiles of great length (~ 440 mm) and moduli up to m = 3.5. In the present work the performance of the existing rolling machine were rolled splines according to DIN 5480. The available rolling tools were suitable for rolling a set of teeth with the following data of teeth z = 24, m = 2.5 module, pressure angle α = 300, helix angle β = 00 (example see fig. 45) [27].

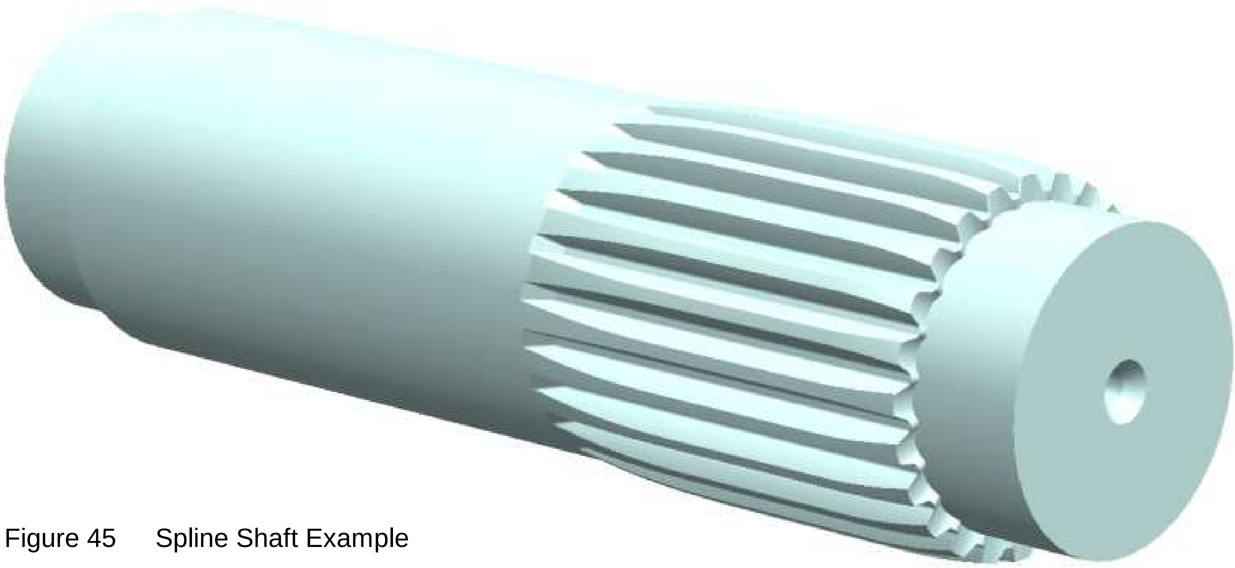


Figure 45 Spline Shaft Example

The gearing described above is often only a part of the geometry of a cylindrical machine element. Tooth-shafts, often called spline shafts are mass-demand parts that are needed, for example in the automotive industry in very large numbers. Splines are usually coupled with an internally toothed hub. This component combination, they are called mostly shaft-hub connection (see fig. 46) is used to transmit torque and allows axial displacement of the shaft against the hub [46].

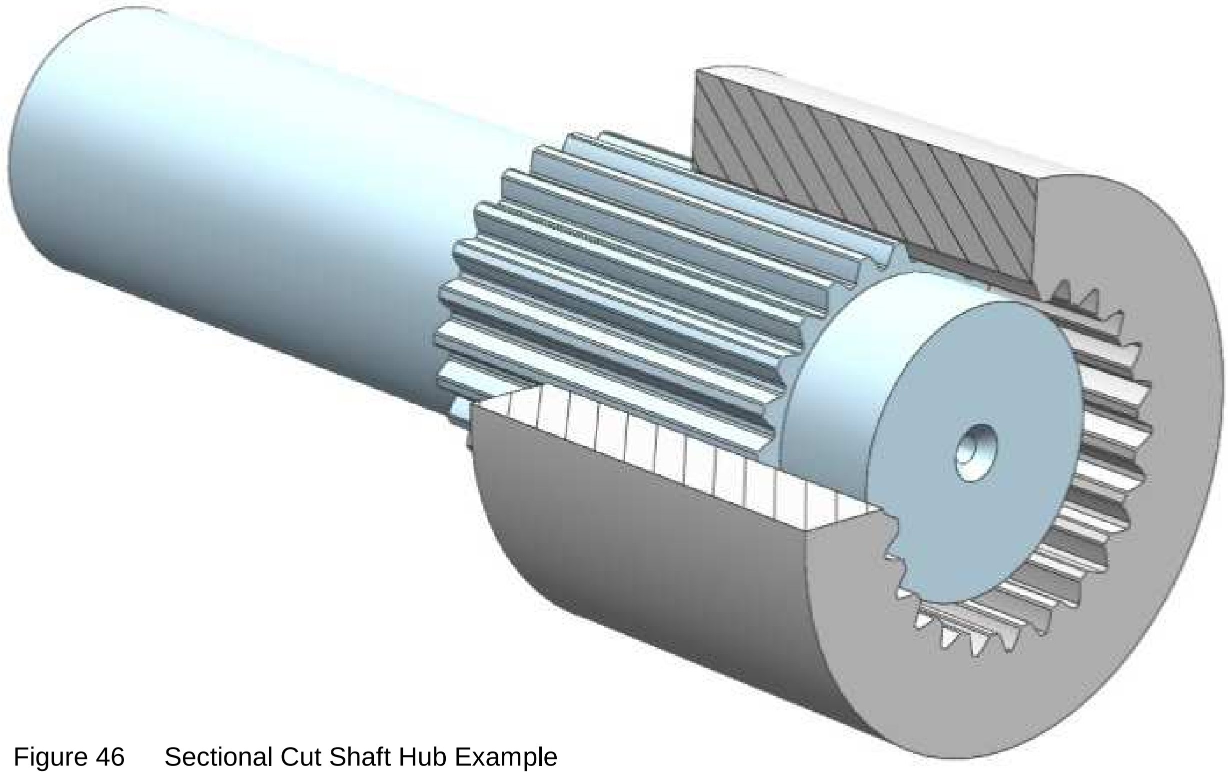


Figure 46 Sectional Cut Shaft Hub Example

The geometric ideal situation to be aimed at this pairing is that the center of the external-tooth shaft and the center of the internally geared hub in the assembled state are identical [27, 46, 89].

Typically, the short center line of the hub and the long shaft are shown offset (see fig. 47). The deviation from the ideal pairing of hub and shaft would have the technical application of the combination material adverse consequences. The symmetry of the load distribution on both machines elements would be disturbed [27].
The geometric contact points or contact surfaces of the two components should therefore perfectly symmetrical with respect to an identical result center after fabrication. This claim, technically, means that the function elements (teeth), based on both components at the same center in the shape and position should be made absolutely identical. Only the major functional areas of the two gears at the same locations in the room have the ideal mechanical contact. This is the production-technical challenge that must be overcome in the mass production of such teeth pairings.

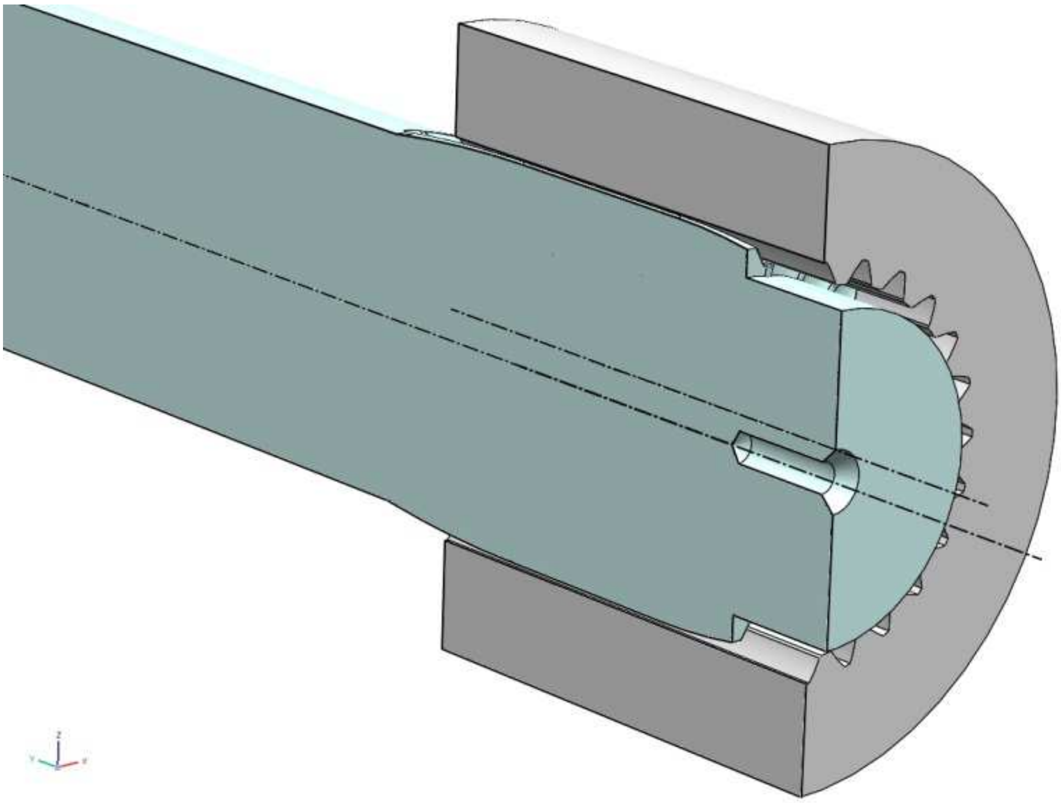


Figure 47 Center-Axis Alignment Problem

In the present work, spline shafts in accordance with DIN 5480, are in the center of attention. In simple terms, in such a gear pair, the centering of both machine elements against each other results as a problem. Accordingly defined in DIN 5480 T1 various types of mutual centering are introduced. To illustrate these geometric relationships the following images, show this fact through a transparent illustration.

Flank centering Centered in the cross connection, the edges of both teeth are used as areas for torque transmission, to guide in the axial movement and also to centering (see fig. 48). The tip circle and root circle-diameter of both elements must therefore be with this type of connection is formed in such a way that they do not allow any mechanical contact between the components. Only the main functional areas of the two elements define the quality of the centering of the parts against each other. The gear production technology related backlash between the two components defines the quality of the fit [13, 27].

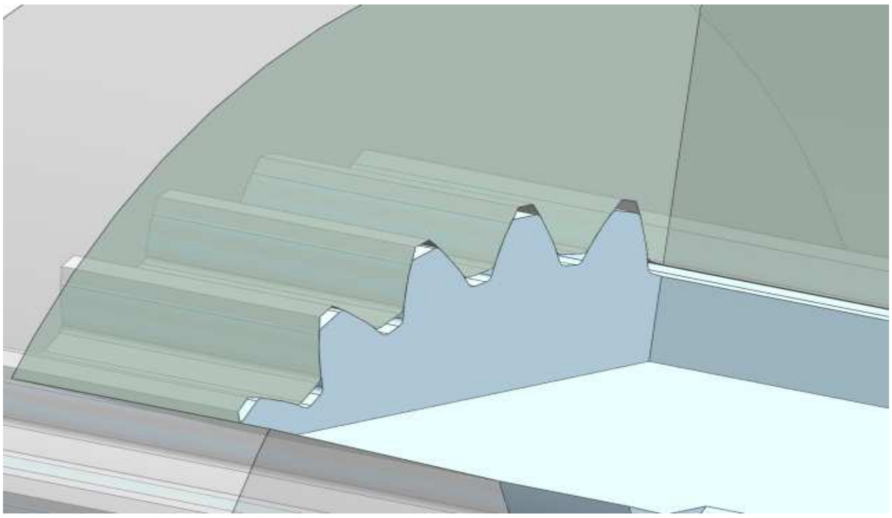


Figure 48 Flank Centered

Diameter-centered Diameter centered connections of shaft and hub are centered in the outer diameter of the hub-root diameter and the shaft tip diameter, if it is an external centering (see fig. 49). Or they center themselves on the hub-tip diameter and shaft root diameter, if it is a self-centering (see fig. 50). In both cases, this type of centering must always be provided sufficient backlash between two elements in order to avoid over-determination of the centering. By measuring centering means require a considerably larger production costs because of the resulting tolerances so that this type of shaft-hub connection is used in industrial applications rather rare [27, 118].

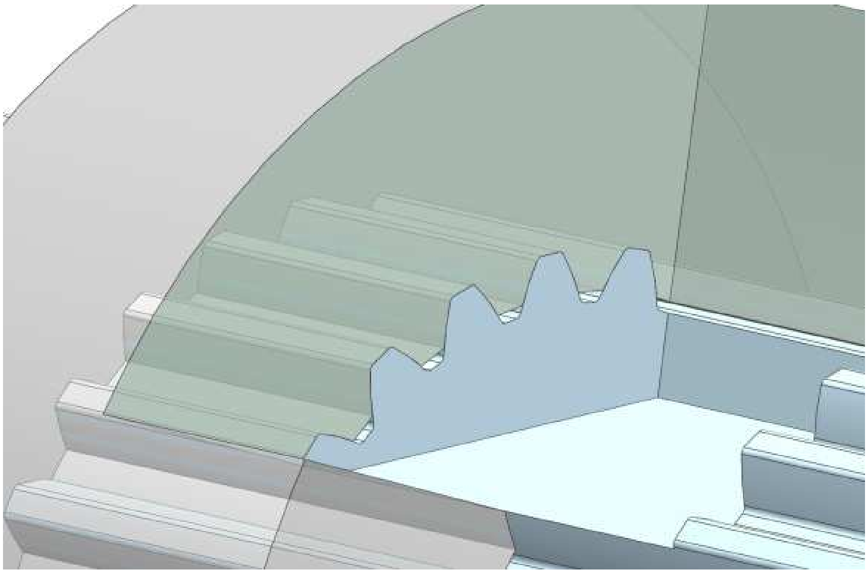


Figure 49 Head Centered

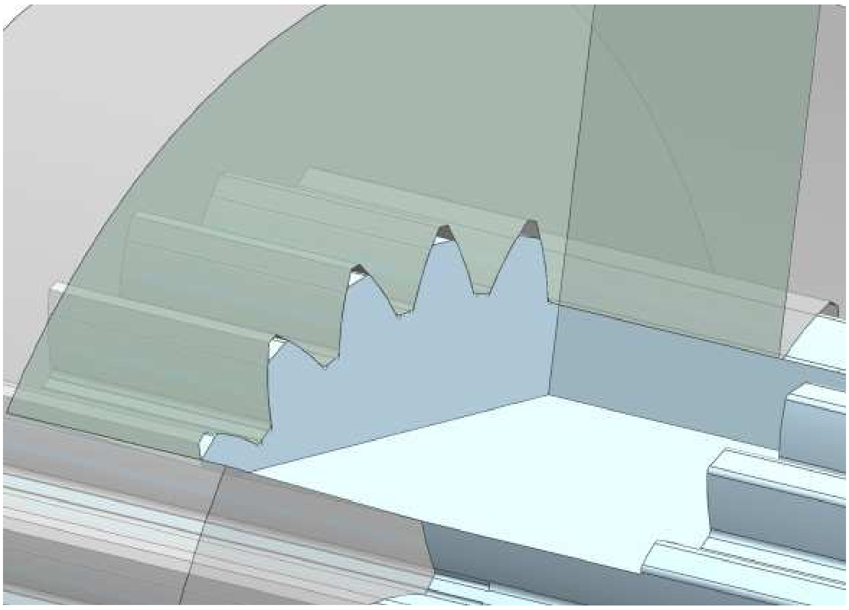


Figure 50 Root Centered

3.4 Advantages of the Rolling Process vs. Machining

Material savings According to DIN 5480 spline shafts m = 2.5, z = 24 a tooth tip diameter of 64.5 mm defined. This blank diameter must be at least pre-manufactured before machining the gear features through chipping production technologies. If the same toothing is produced via rolling methods, then just an initial blank diameter of 62.3 mm is necessary. At a given tooth length of 200 mm a material saving of 0.172 kg per toothed component can be achieved. Therefore a considerable economic advantage results through rolling processes [27].

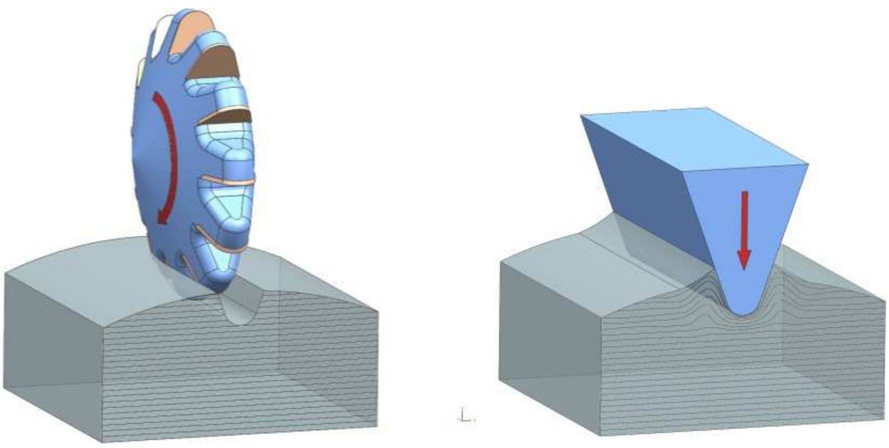


Figure 51 Material Displacement Cutting / Forming Principle

This is especially true if this spline shafts are produced in large serial batches like in mass production. The following figures are intended to illustrate this relationship [27]. When machining by chipping technologies, material is lost, because the initial diameter must be greater than during rolling (see fig. 51, 52). When rolling is considered, a smaller initial diameter is sufficient because the material flows into the gaps through the material penetration of the tool wedges by the penetration of the tool wedges [18, 24, 26, 27].

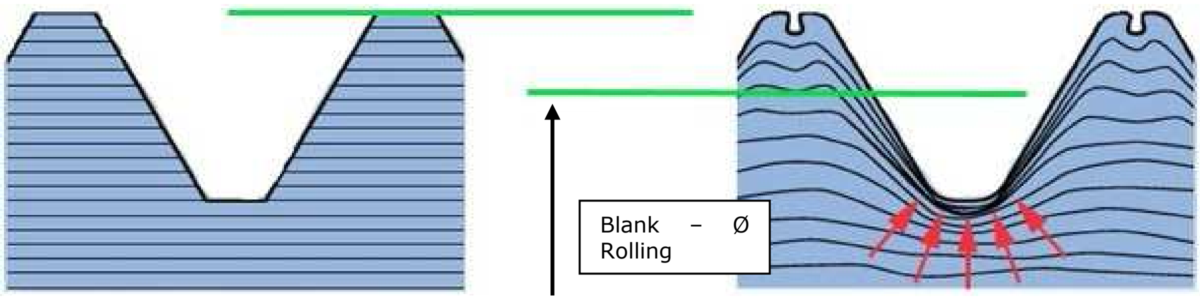


Figure 52 Material Saving / Solidification

Solidification of the material structure The picture (see fig. 52) shows the material structure how it is produced during the rolling process. The by previous processing steps such as extrusion (semi-finished products - manufacturing) generated alignment of the crystalline structure of the steel runs approximately linearly through the material [27, 36].

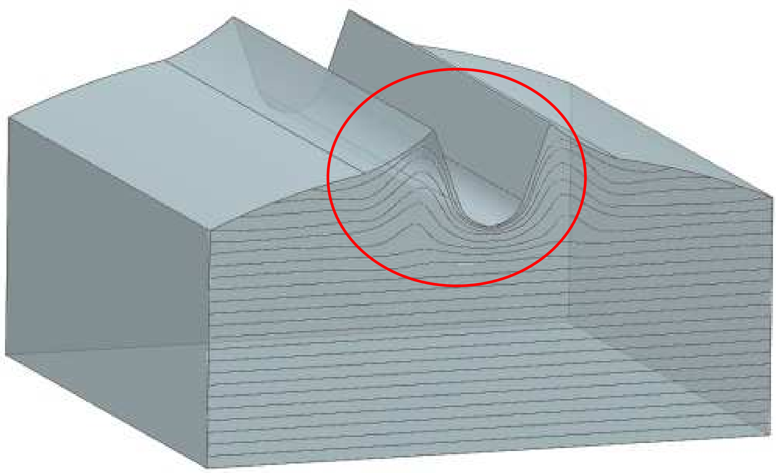


Figure 53 Solidification Detail

The penetrating tool wedge displaces the material, so that the structure adapts to the wedge-shaped tool geometry. The processes involved in the flow of the plastic material

structural changes lead to a strain hardening of the material where it has flowed most. The largest texture consolidation is noted in the footer of the resulting tooth gap. Depending on the material and, for example, the carbon content of the steel, an increase of the material strength of up to about 20% can be detected here. The enormous advantage is that where the biggest reaction stresses occur under load in the material, the largest material compression is available. The toothing is therefore generally able to perform at higher loads, as it may be the case with a gearing made by a type of machining, where the originally existing semi-material structure is being cut.
The attached picture (see fig. 52) shows a fragment of the volume of a rolled spline. It can be seen the course of the harmonic structure of lines, as described above. The facts described above are not new. Since decades, we know that rolled threads to e.g. steel screws are much more durable than machined threads produced. The material-technical aspects and advantages of the material hardening in the notch root of a thread to those in the rolling of serrations very similar.
The aforementioned advantages of rolled gearing production are facing the disadvantages of the large reaction forces and thereby caused undesired movements of the material volume during processing.
During machining, guiding characteristics of the material volume through the cutting tools result. However, neither the mechanical energy transmitted in the contact area work-tools / workpiece, nor the resulting thereby unintended distortions of the machined component are comparable [17].
In summary it can be said that the production of toothing provided by rolling both economic (material savings), and mechanically functional benefits (solidification) in opposite to cutting processes. On the other disadvantages due to unintended movements between the tool and the material volume as a result of large deformation forces can hardly be avoided, which negatively affect the resulting geometric component quality in consequence.

3.5 Geometric Results when WPM-rolling

Considered in this study an earlier work [27] progressed roll samples were extensively studied on a coordinate measuring machine LEITZ PMM 6.5.4 and determined their dependence on different experimental WPM parameters. In this respect, to be repeated the measurement results shown in the following underlie at this point not all be measured technically oriented framework at the measuring machine (measurement strategy, etc.). Starting points for this own work were the previously identified findings, based on the measurements in accordance with DIN 3960 and, most significantly , the findings were determined by measuring specific contour sections on the rolling samples [27]. In the sequence listed and therefore are to be discussed, only the results that are major relevant for a purpose of this work are presented here. The following results are shown highly summarized and compressed. The following diagrams were determined on the rolling samples of length 500 mm.

All samples show typical geometric characteristics and particularities for forming by WPM rolling. It involves process- typical features that are due to the active system rolling tools / workpiece and the machine technology. Already by a visual inspection, as shown in picture Fig. 54, significant geometric features can be seen in the longitudinal direction of each rolled sample. As a scope of this work these results and especially their root-causes are to be determined and analyzed.

In Figure 54 it can be observed, that at the inlet toothing area on the left decreases. This is due to the fact, that at the beginning of the deformation the inlet zone is missing material and therefore the teeth may not develop fully [27].

For the area to the right, where the last contact of the tool with the sample passed through the roll, the teeth are not completely formed, as well, because the geometry of the tool does not allow a complete tooth shape. All results presented in the following are affected by this typical form error of the entire toothing.

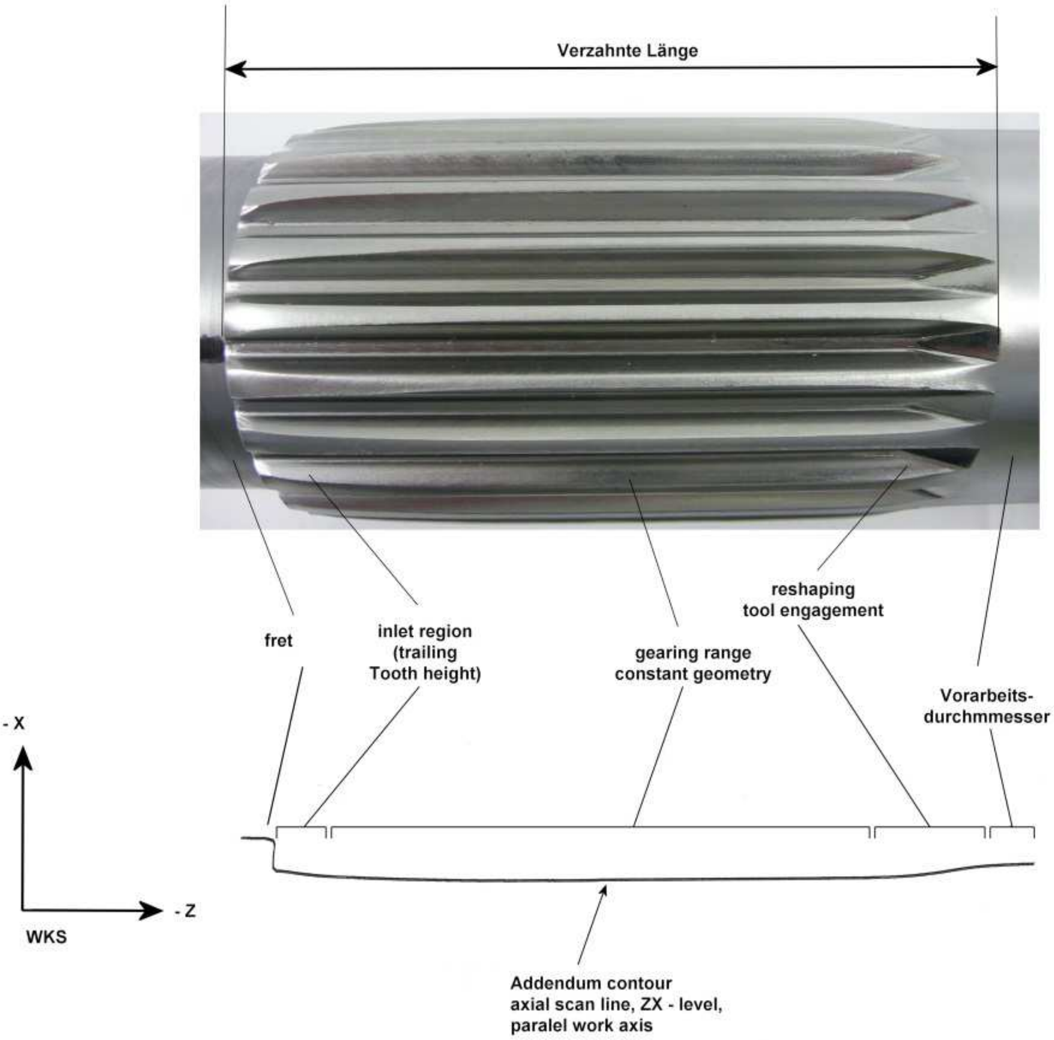


Figure 54 Resulting Deformation Zones

Pitch / Runout In previous researches, it was found that the sizes of the pitch deviations are dominated by the position of the workpiece in the rolling machine, the kinematics tool / workpiece and in particular the blank geometry (eccentricity of the center holes) [27, 47].

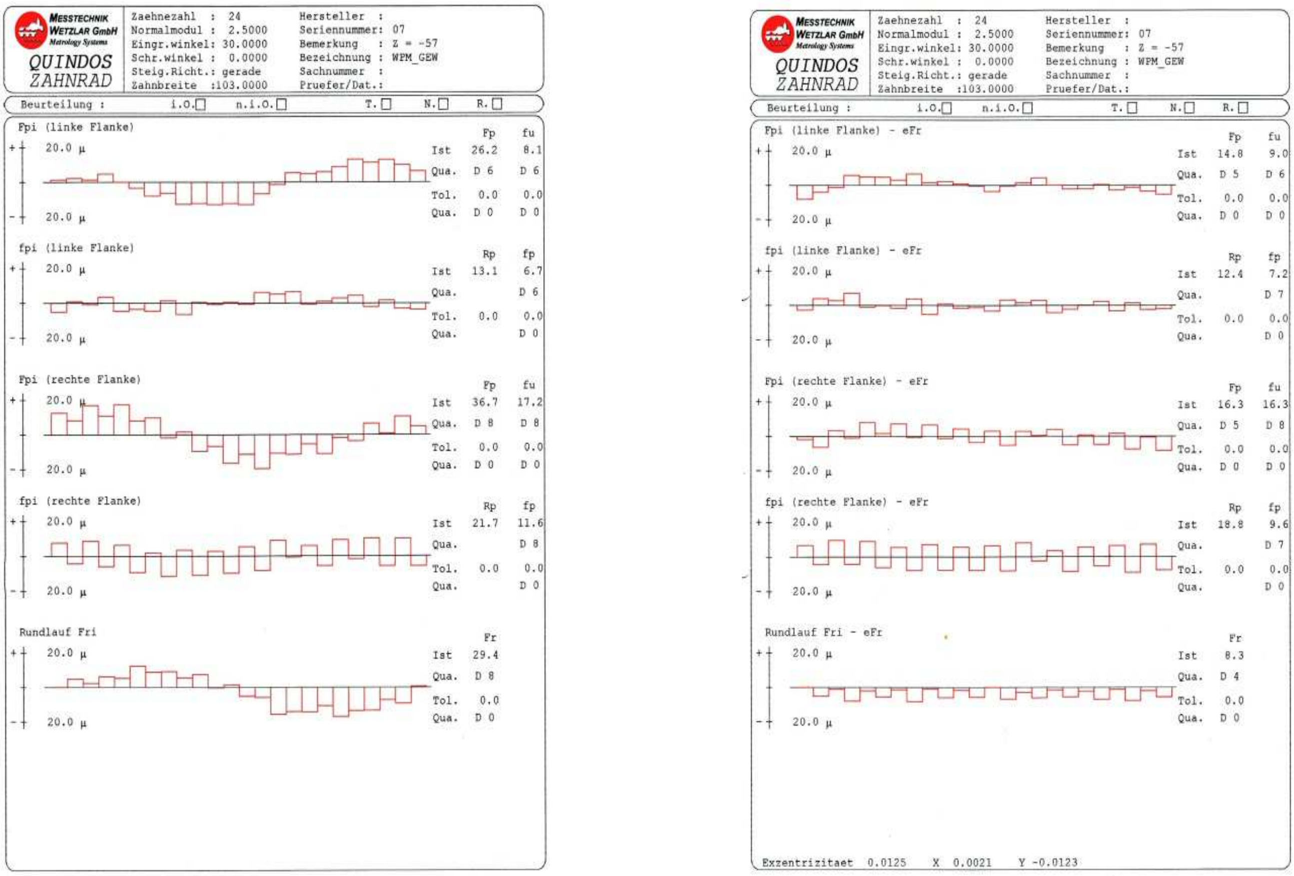


Figure 55 Pitch and Runout Report Example

From absolutely dominant importance for the pitch result is understandably the eccentricity of the position of the center holes over the cylinder surface in the rolling samples. The larger the detected errors of eccentricity, the worse the pitch result (see fig. 55). The pitch result is noteworthy, when measured at different heights of a rolling sample. Hereby considerable differences can be observed (see fig. 56) [27, 34].

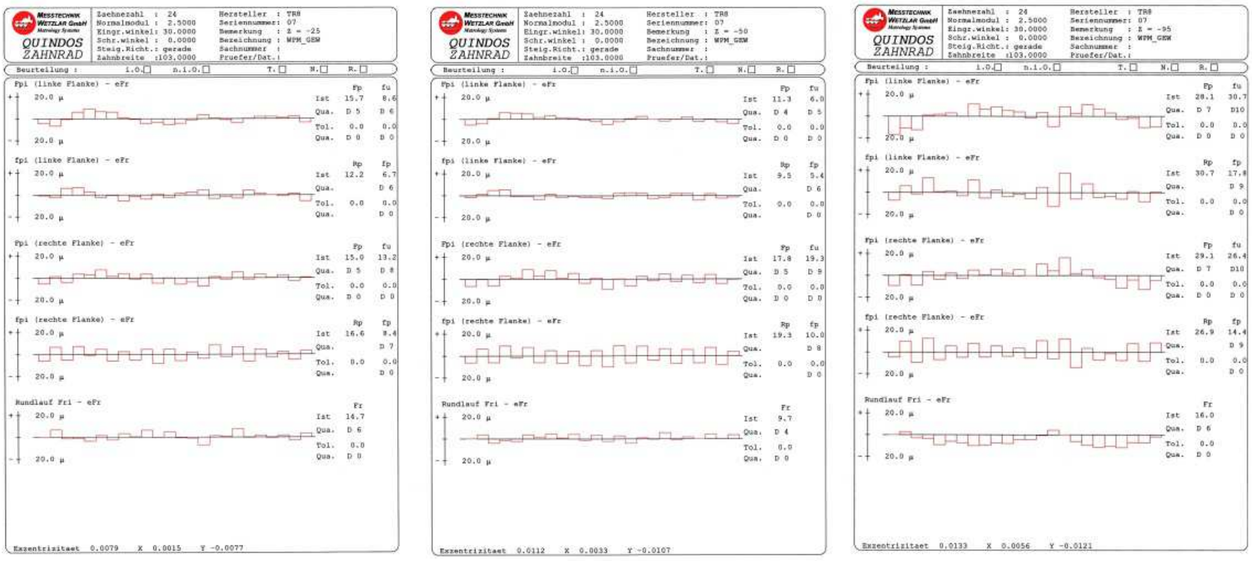


Figure 56 Pitch and Runout 3-Zone Report

The Figure 56 shows that between the start and end zone of the toothing, considerable differences of pitch and runout are resulting. While at the beginning of Z = -25 and Z = -50 approximately the same deviations for pitch and runout were measured, significant errors are to be observed in the area of the last work-tool contact. In this area, as noted above, the teeth are not fully formed and, as it will be shown later with reference to the contour of sections, the head shapes are formed asymmetrically.

Profile deviations Among other special features of the profile shapes are considerable differences apparent in the head area of the teeth, and especially the head heights. The left and right sides of each tooth gap are formed at different heights. This applies, in principle, for each profile measurement at all axial levels alike.

Tooth trace deviations Each tooth gap at each roll sample in principle shows the same tendency (see fig. 57). The right side of each gap shows small deviations from the ideal line, whereas always the left flank of the gap varies widely [27].

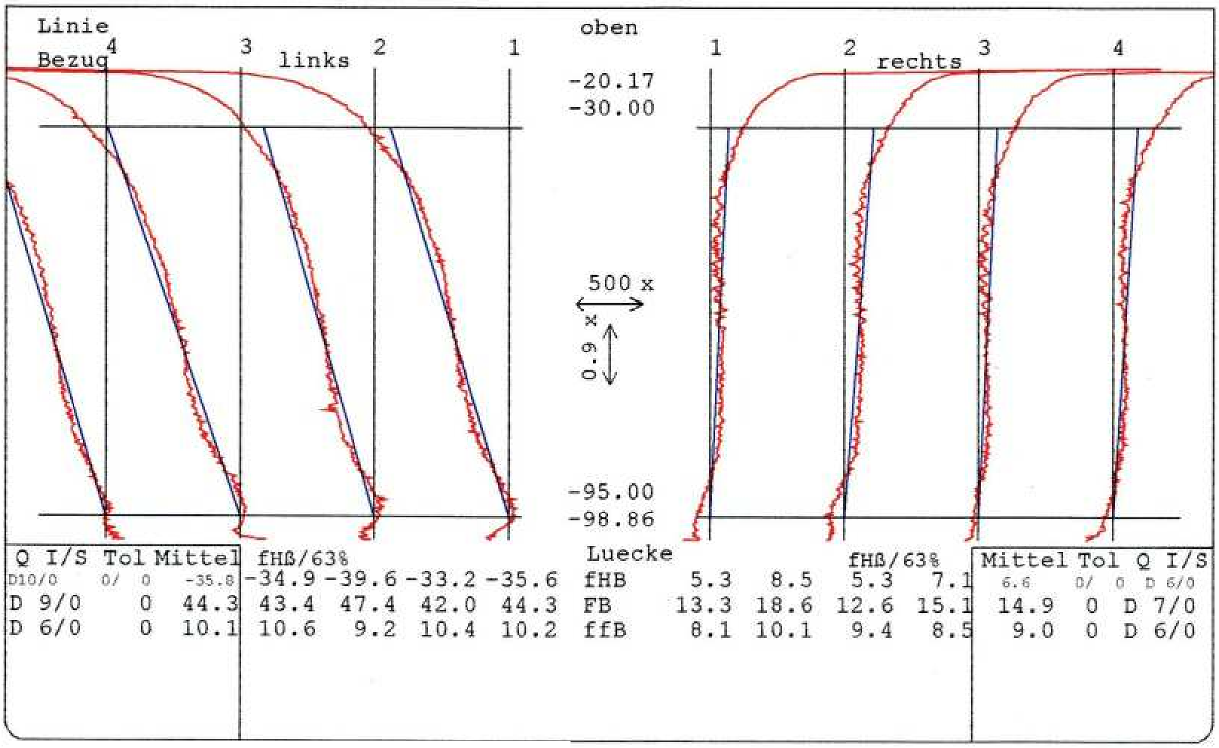


Figure 57 Tooth trace total deviation

Root circle diameter At the root diameter of all rolling samples, collected in each 24-tooth gaps, results in very low roundness deviations on the order of less than 0,01 mm (see fig. 58). This statement is valid for all combinations of parameters of feed rate and the blank material. The root diameter remains constant within very narrow limits, which will be of central importance for further considerations (in-process measurements) for the assessment of the deformed geometry of the teeth [27].

Tip circle diameter It can be seen in figure 59 that significant differences in the head height of each tooth of each rolling sample occur, regardless of the axial location of the rolled sample where these measurements are carried out. Significant differences in all the tooth tips with always the same or similar constant rhythm of the differences are distributed over the circumference of the gearing [27].

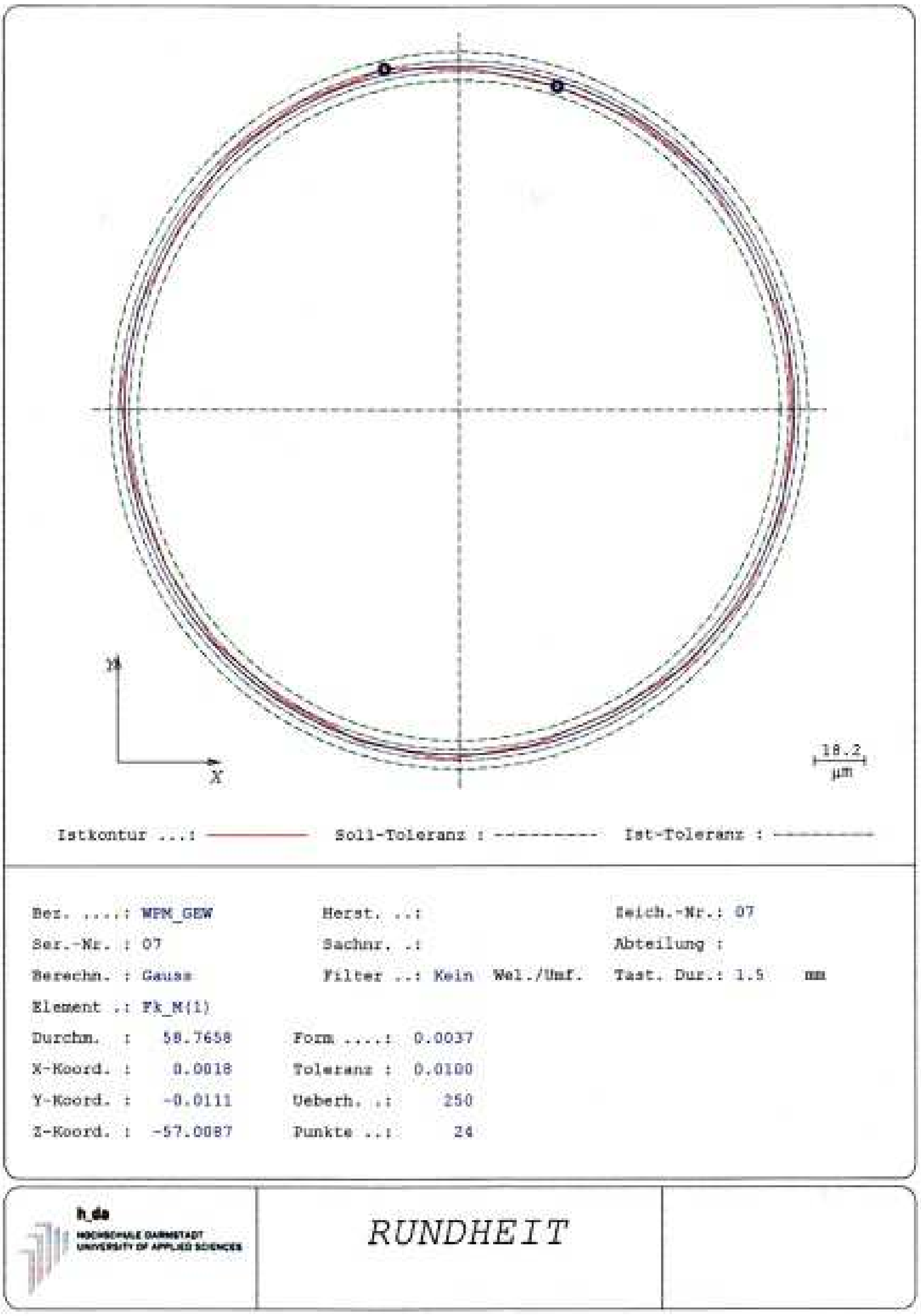


Figure 58 Root Circle Deviation

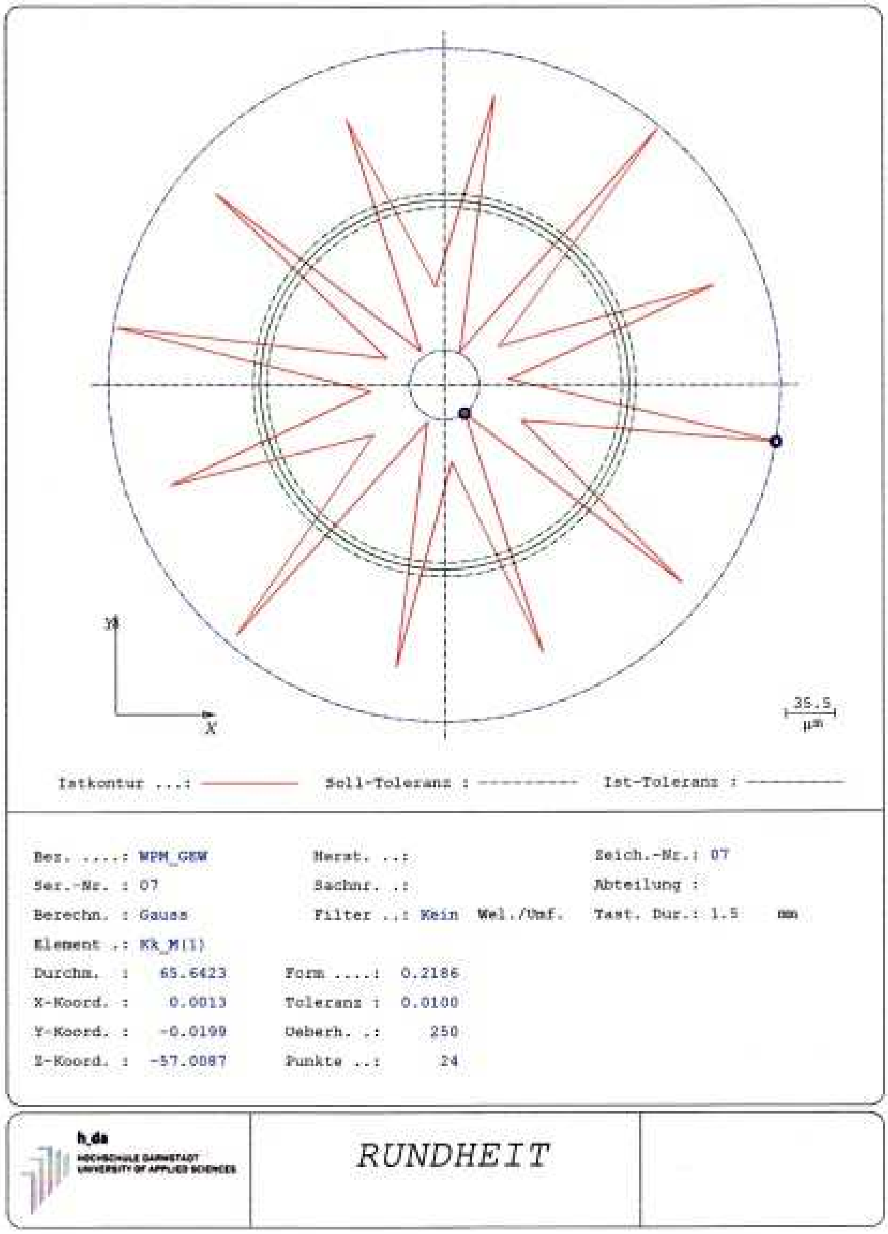


Figure 59 Head Circle Deviation

The above listed geometrical deviations on the rolling samples prepared by the non-cutting WPM method were calculated conventionally according to DIN 3960. The significant and targeted outcomes for the own work are the results of the foot and the tip circle diameter. The base circle diameter is represented as a function of the feed rate is approximately constant within narrow limits of the technical equipment settings in figure 60. In contrast, the tip circle diameter is significantly dependent on the feed rate.

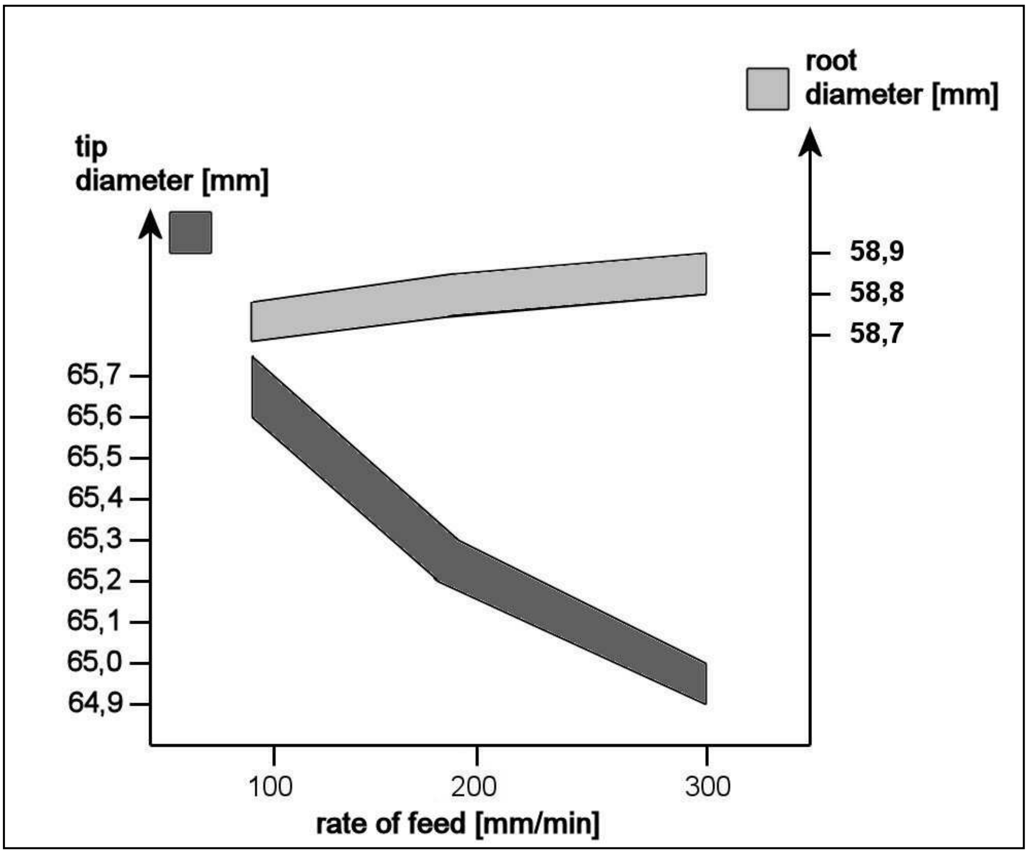


Figure 60 Development of tip- / root diameter per feedrate

Apart from the results shown previously determined on a CMM to DIN 3960 were in the prior studies [27,42] also longitudinal and cross-sections contour measurements performed on the rolling samples. These results are summarized below.

For orientation purposes reference is made to the image that shows the completed cut layers on the roll samples (see fig. 61) [76].

The different profile shapes of the cross sections with respect to the axial position of the measuring point (cut-off) shows an example of the accompanying picture (see fig. 61).

As previously addressed, resulting in the entry area little tooth shaped heads. Between the axial position z = -25 / -30 filled head shapes are increasingly noted which in the middle sample region at z = -70 have their maximum forming. By no later than the axial approximately z = -90 the head heights are rapidly reduced.

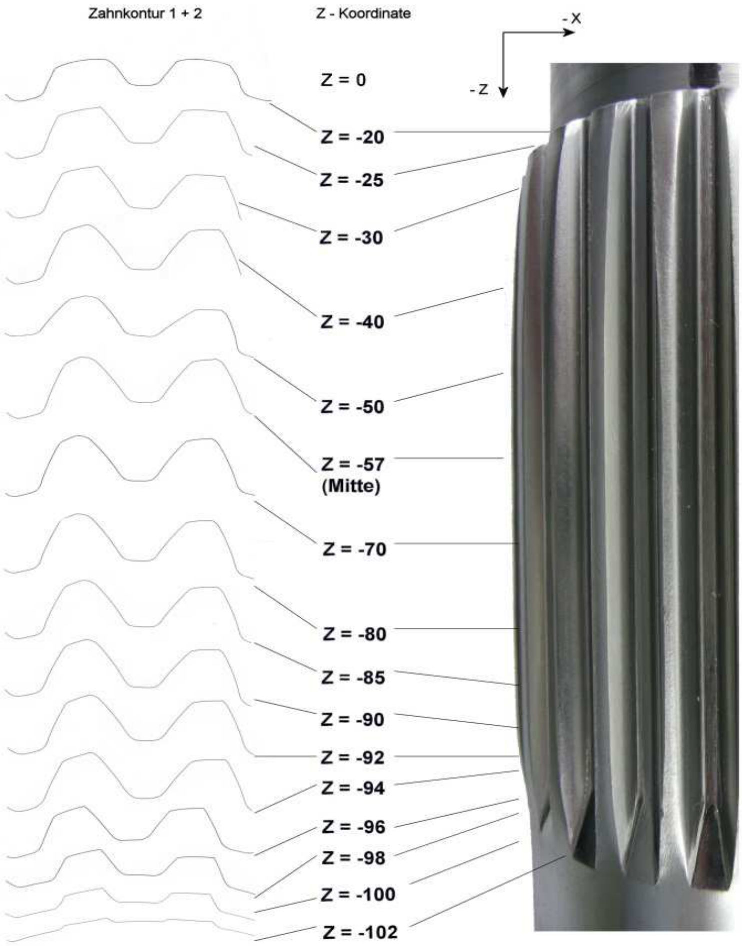


Figure 61 WPM sample - spline contour development

Figure 62 is an example of cross sections of the tooth shapes of the central region of a rolling sample. It can be seen that each tooth has a high and a low gear side thereof. This applies, in principle, for each tooth roll all samples, when the teeth are formed more or less completely. In the inlet end portion and the forming process vary the tooth shapes [27].

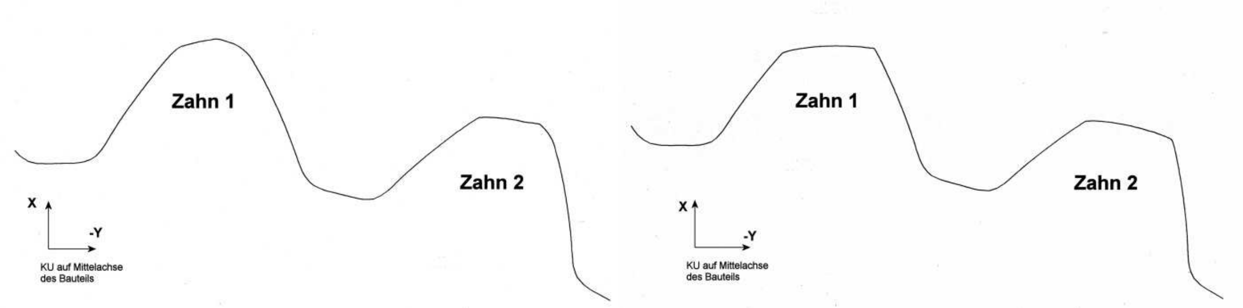


Figure 62 WPM teeth contour detail

4. Geometrical Investigations on WPM-samples - basic root-cause analysis of tooth shape and heights

The initial points of this own work were determined by the outcomes of a prior doctoral thesis, earlier summarized in chapter 3.5 [27], whereby significant geometrical characteristics have been observed on spline gear samples being manufactured using the WPM metal rolling method.

These significant characteristics can be summarized as being defined by the:

- Constant tooth root diameter (within close tolerances)
- Different tooth shapes and tooth heights
- Recurrent observed single directional tooth flank error

All remaining parameters which describe the general geometrical quality of the spline shafts have been collected and analyzed. However, it is a matter of fact that those quality parameters are showing a high variance in their sample distribution over the several test series. Therefore, the remaining quality parameters beside the selected significant once cannot be successfully used as a base for further investigations.

A successful base for investigations would have been stated, if e.g. a pitch error or gear profile error could have been explicit assigned to a mode of action between workpiece and work-tools within the WPM rolling process. Furthermore, it must be extinguished that the permanently observed geometrical characteristics are being directly or indirectly the cause for the high variance in deviations of the pitch- and runout errors.

Insofar the tooth properties and the single directional tooth flank error represent the foreground of the own investigations, which are being examined and analyzed within the following abstracts.

In the previous chapters the special relevance on the guidance characteristics of the WPM work-tools regarding the workpiece in the forming process was highlighted.

Those guidance characteristics tends to preserve of even higher importance as higher the inherent forming forces caused in the effected contact zone between work-tools and workpiece sample will get.

In a fundamental examination concerning the gear rolling process, a symmetrical distribution of teeth on the circumference of a cylindrical forming sample can only be

obtained in a gear rolling process, if any work-tool contact in scope of a tooth level creates a balanced material distribution on the outlined workpiece contour [71, 72, 152]. This examination on balanced material distribution is even more relevant with regards to the WPM gear rolling method as the fully established gear profile on the workpiece circumference is being created along quite a short axial range on the workpiece length.
This WPM related statement is only fully valid on work-tool spatial positions, where the eccentrically work-tool kinematic motion reaches its deepest penetration position into the workpiece sample material [20].
The following illustration (Fig. 63) shows a single WPM work-tool, stating the segmented forming zones, the pre-forming-, final-forming- and the calibration zone.

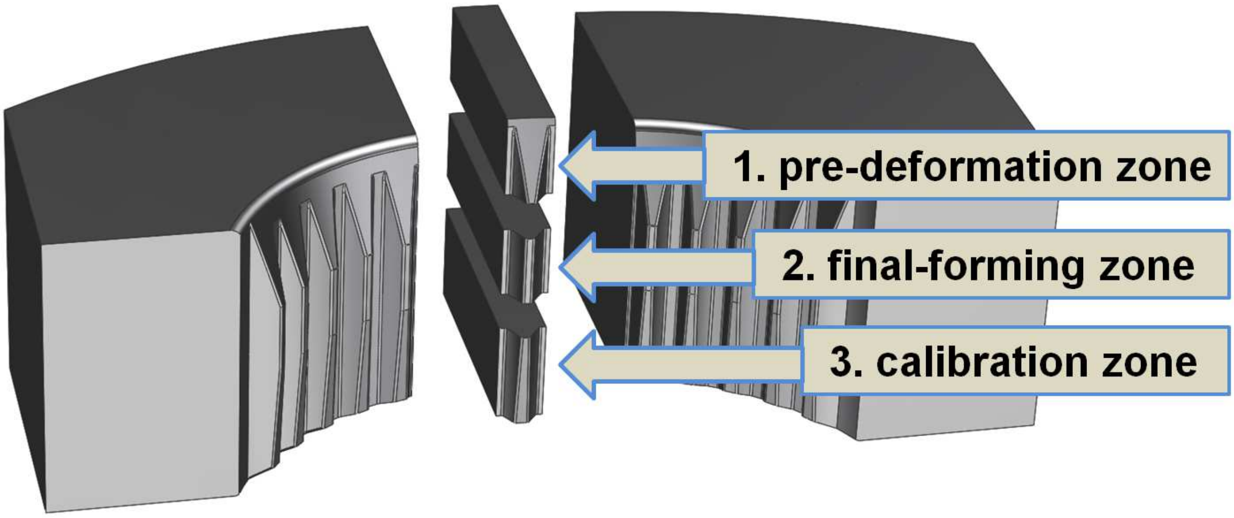


Figure 63 WPM Work-tool Zones

The deepest point of penetration of the WPM work-tool with respect to the workpiece original surface position is defined by the final-forming zone, which is defined by a cylindrical gear shaped geometry that follows by intersection a conical pre-deformation zone.

4.1 Eccentricity in WPM-Rolling Method

The starting point for further investigations is defined by the deliberation that an even distribution of teeth on WPM spline samples showing identical tooth shapes can only result, if balanced materials flow in its circumference distribution occurs.

The Accountability for the material distribution on the circumference of the workpiece can be summarized by the:

1. Work-tool eccentricity defined by the WPM machine pre-setting and
2. the appropriate preliminary outer diameter of the workpiece sample.

As of all gear samples in the experimental forming series show the complete number of 24 teeth [27] on the spline shafts and all the samples are showing approximately an even root diameter the assumption could be stated that the prior defined boundary conditions being the preliminary outer diameter of the semi samples and the preset work-tool eccentricity are suitable with regards to the involved geometry of the geared tools. In a simplified determination the geometrical relationship of the work-tool geometry, the eccentrically work-tool kinematic motion and the preliminary workpiece semi shape are correct synchronized at the start and end of each work-tool forming stroke.

Considering the facts, the question arises:

“Why does the resulting shape on all spline samples out of the WPM forming experimental series feature geometrical specifics defined by the unsymmetrical tooth shape / tooth height and the single directional flank error in each tooth gap?” [27]

In a first assessment one could suspect that the unavoidable eccentricity of the centering bores in the semi samples drilled during the preliminary manufacturing are the root-cause for such an outcome. In order to proof that supposition, a special set of semi samples having a intentionally higher eccentricity of the centering bores were being manufactured and rolled by using the same WPM parameter setup like in former experiments. The results on pitch and runout errors on those specially prepared samples showed a slightly decreased quality, the tooth profile errors and flank error resulted roughly identical to prior testing. The single directional flank error occurred in the same order of significant bandwidth compared to former test series on other rolling samples. The generated higher radial run-out due to the intentionally worsen eccentricity of the semi samples (see fig. 64) results in a detectable influence on the tooth profile geometry which anyhow is less significant than the order of magnitude of the initial worsening of the sample run-out.

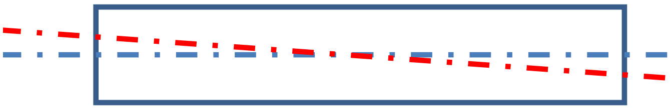


Figure 64 Initial Sample run-out Scheme

In this context it is of certain importance to recall the overall target of this thesis work, which will outline an In-Process measurement strategy on relevant feature parameters and proof out these statements on the prediction regarding the actual WPM gear forming process. Therefore, the geometrical characteristics being determined on all rolling samples in an experimental series, elaborated in the prior work [27] on WPM specific parameters, are in principle a distinguished scenario to be captured during the gear rolling process. In the case of providing adequate sensor systems to be applied within the WPM forming process, such In-Process measurements could be extended in the usage of determining the qualitative conclusion on the gear forming process as such and furthermore on the counteractions in regulating the forming process by modification of relevant parameters in the control unit. As a basic requirement for an In-Process parameter modification, a detailed understanding of the root-cause between the geometrical characteristics that's being generated on the geared forming samples and the relevant process indicating parameters must be accomplished.

Another aspect in that context is the role of the workpiece sample total length, that has been set to 240mm in all prior experimental sets [27]. The longer the sample length will be, a higher order of amplification of the unavoidable eccentricity effects that occur through the workpiece clamping between the two center tips could be expected. The worsening guiding quality of the centering tips to the workpiece sample then could in an unfavorable case work against the guiding quality of the WPM work-tools. In consequence to that scenario, a higher misalignment of the workpiece centerline (see fig. 65) can occur before a work-tool contact at each working stroke in the forming process. A single directional flank error that occurs systematically on always one side of a tooth gap could be generated by that reason [17].

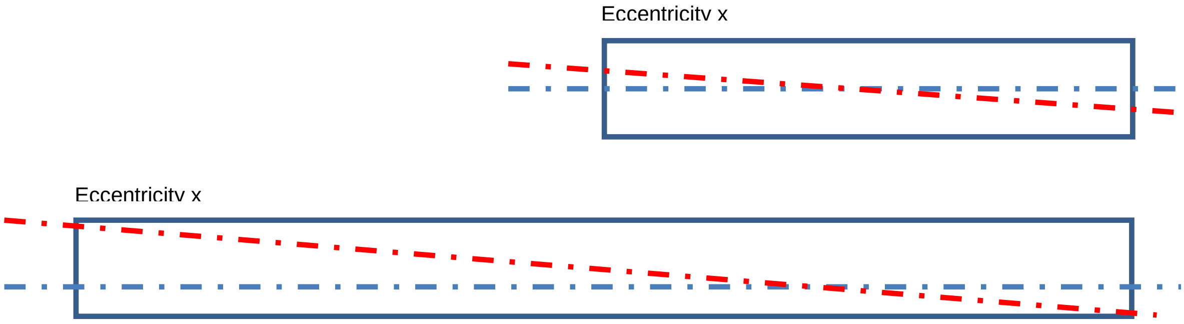


Figure 65 Runout - sensitivity on sample length

Beside the semi-sample initial eccentricity error and their total length being a potential cause of unintentional workpiece deviations, the forming press mechanics could as well contribute to position and geometrical errors of the forming sample relative to the work-tools. Following that assumption, a detailed analysis of the centering tips behavior and their quality of workpiece guidance need to be assessed during the forming process duration time and so along the feedrate axis travel range. The workpiece guidance of the centering tips has previously been analyzed [27] without the additional load parameters of the forming process. The resulting centerline displacement could be determined to be below 0,01mm in that test scenario, which was later on again verified within this scope of work and could be assessed to be adequate regarding the coaxiality adjustment of the centering tips in the context of this works expectations. In addition, it was determined, that the centering tips are mounted embedded in roller bearings. It is unknown so far how the necessary bearing play contributed to the total workpiece displacement uncertainty figures [59]. In this regards it needs to be considered, that the spatial position of the forming sample, where the work-tools are acting perpendicular to the feedrate axis, the axial feed position is changing incrementally stroke by stroke of the work-tools. The workpiece wanders through the forming work-tools, whereby the centering tips are moving in feed direction incrementally relative to the plane of application of the forming forces by the work-tools. At any one time of a work-tool stroke, the point of application of the forming forces into the workpiece in relation to the unsymmetrical axial distances to the centering tips (see fig. 66), are producing variable response moments with respect to the workpiece centerline. Variable elastic reactions of the involved mechanical machine framework could be a reasonable consequence.

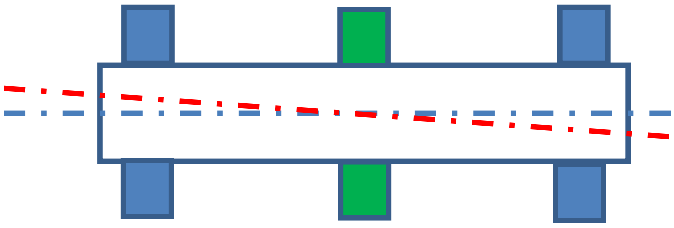


Figure 66 Runout – sensitivity to work-tool (green) position

That consequence could possibly have a significant effect on the contact situation between work-tools and workpiece during the forming process; esp. because the mounting design of the two centering tips is non-identical. This additional constraint also results in variable response displacements at the both ends of the workpiece sample during the forming process. On the other hand, it can be assumed that the forming work-tools with its wide range of overlap on the emerging spline geometry in conjunction with the machine provided deformation energy is dominating all other mechanical reactions in the response chain perpendicular to the workpiece centerline axis. This is quite certain valid at the time, when work-tools and workpiece are engaged in contact during the forming process, but it is to be assumed as uncertain when the work-tools are disengaged having no contact with the workpiece and the mechanical system is axially pre-loaded by the axial feed forward motion [59].

All aforementioned considerations being discovered were based on the working principle containing the work-chain elements of a work-tool, tailstock for workpiece clamping and the centering holder attached to the workpiece centering features. Those elements can be certainly assessed having a less or higher importance on the finally resulting gear rolling sample quality being manufactured. The geometrical characteristics, defined by different tooth shapes and the single directional flank error being observed in every tooth gap instead can´t be correlated with an elastic deformation scenario of the overall mechanical working principle [75].

The unsymmetrical yielding behavior of the workpiece material which basically causes the unsymmetrical tooth shapes must be dominantly derived from the radial movement of sample material elements within the metal forming process. The specific work-tool kinematic movement itself in acting contact plastically forming the sample material must be the root-cause creating the geometrical characteristics. As the interacting work-tool forces resulting in the rolling process are dominantly higher than all the elastic deformations in the related mechanics and frameworks holding the workpiece, they must influence the resulting geometrical characteristics the most.

4.2 Geometrical Assessment of WPM Work-tool-Contact

The following explanations are targeting the theoretical analysis of the WPM work-tool-contact situation on the workpiece material elements during the tooth forming process arriving from CAD data analysis of the real WPM machine setup. As being stated in earlier remarks it is to be assumed that the kinematic movements of the WPM work-tools as such are providing a major impact on the unsymmetrical material distribution creating the spline gear geometrical characteristics. The underlying work-tool kinematic path is thereby defined by coordinated eccentrically movements generating an imprint of the work-tool geometrical inner-gear shape into the rotational symmetrical shaped workpiece (see fig. 67).

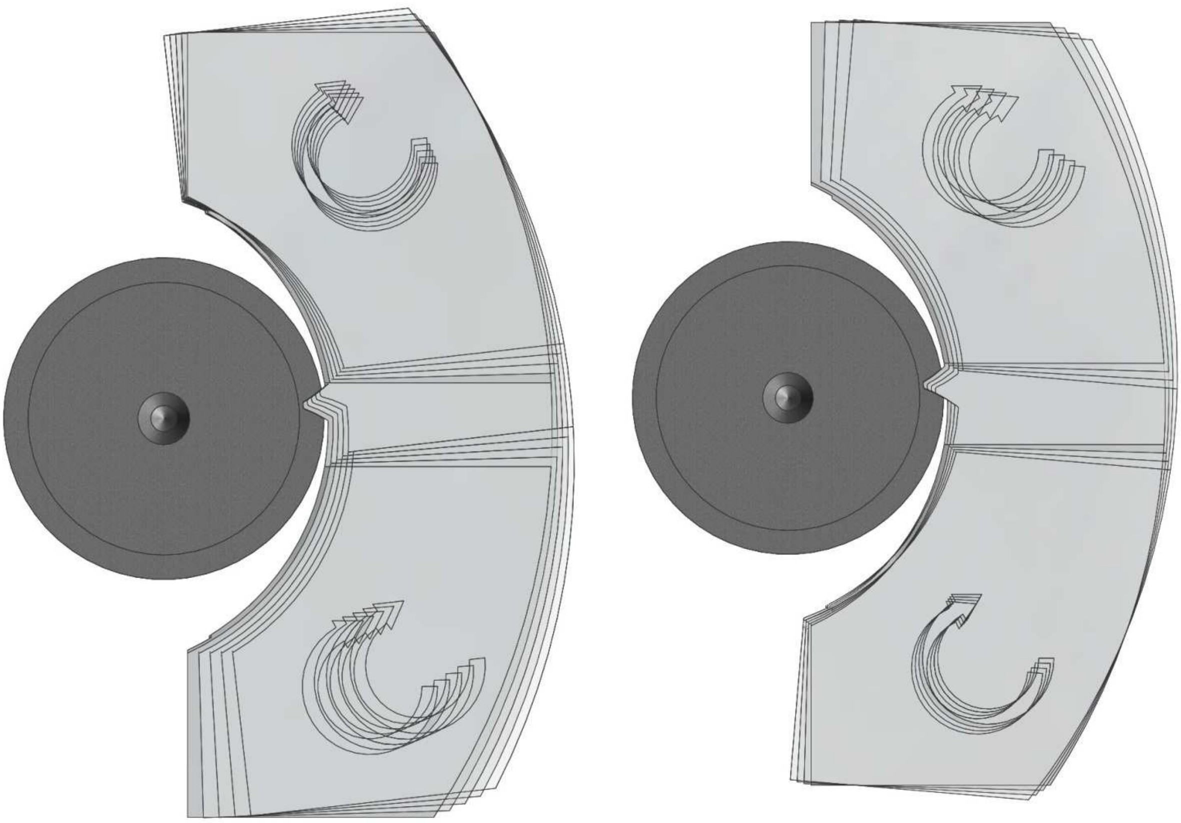


Figure 67 WPM Work-tool kinematics

By having a closer view on the example situation to generate only one single tooth placed close to the center of the work-tool setup (see fig. 68) during the WPM rolling process it can be observed that one flank of the final spline gear gap is formed by the intrusion of the work-tool tooth while the corresponding gap flank of the spline gear is formed by the departure movement of the work-tool tooth in contact.

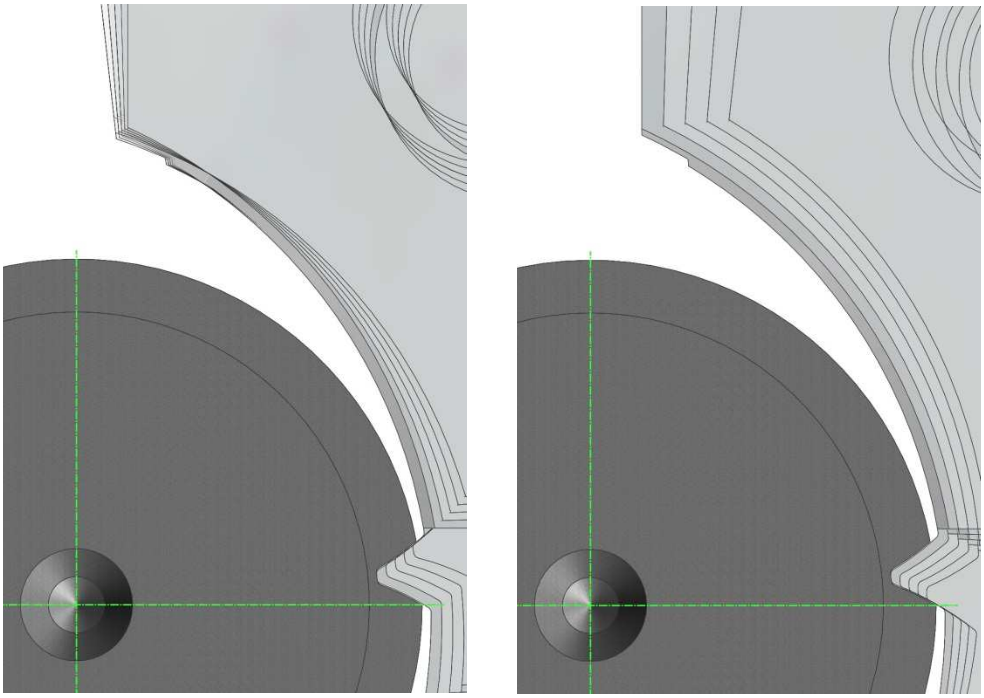


Figure 68 Detailed WPM Work-tool trajectory scenario

Within this and the following kinematic reviews of the one-tooth situation the workpiece rotational movement is not taken into account being the fixed base of view and the work-tools are creating the complete kinematic movement. This simplification can be set for the basis process assessment. Further on reviewing the kinematic movement of the work-tools it can be seen that the center of rotation of the work-tool doesn't correlate with the center of the workpiece, it is furthermore described by a systematical eccentricity which is set within the machine setup.

By having a closer view on the resulting contact surface between work-tool-workpiece on the point of maximum intrusion (see fig. 69) through a transparent work-tool scenario in the used one-tooth setup an systematical unbalance trend of the contact surface (red) compared to the workpiece center can be seen.

The stated systematically asymmetry between left and right flank of the resulting gap cannot yet be clearly visualized due to the choice of a work-tool tooth placed very close to the work-tool center region. By changing the scenario into an engagement situation of all work-tool teeth being involved (see fig. 70) the sectional unbalance of the work-tool imprint onto the evolving spline gear workpiece can be clearly recognized.

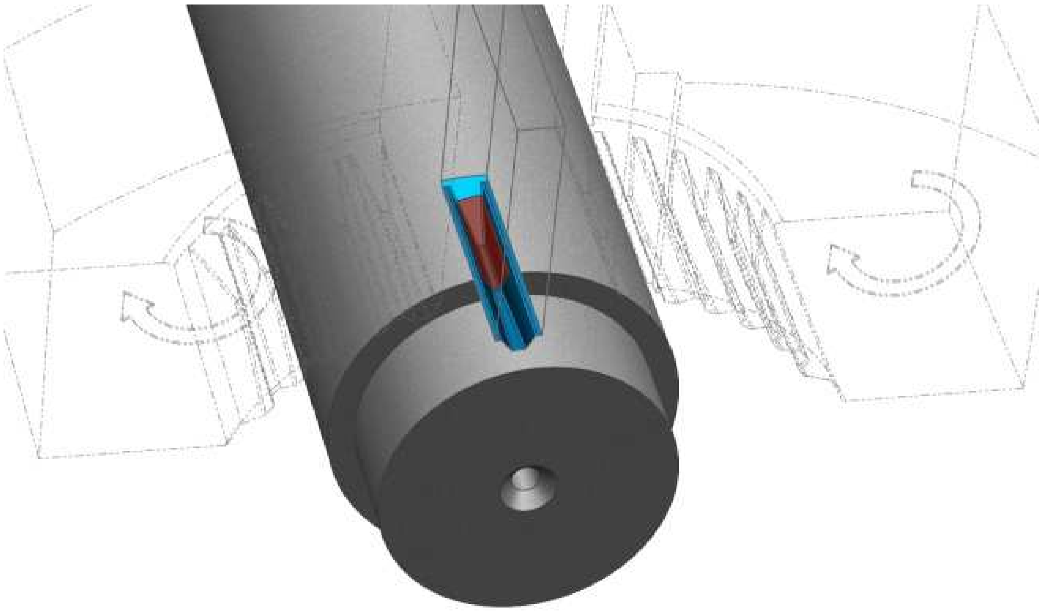


Figure 69 Resulting Contact Zone (one tooth)

As an early conclusion out of this contact zone scenarios it can be shown that an unsymmetrical imprint of the work-tool teeth setup is generated into the spline gear workpiece based on the angular position of the single workpiece tooth.

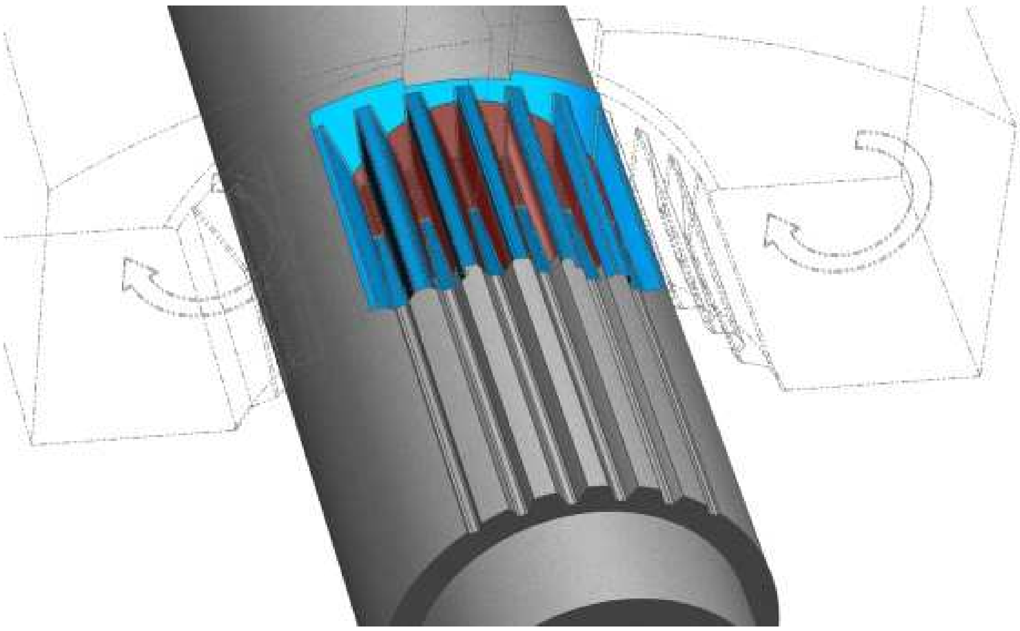


Figure 70 Resulting Contact Zone (multiple teeth)

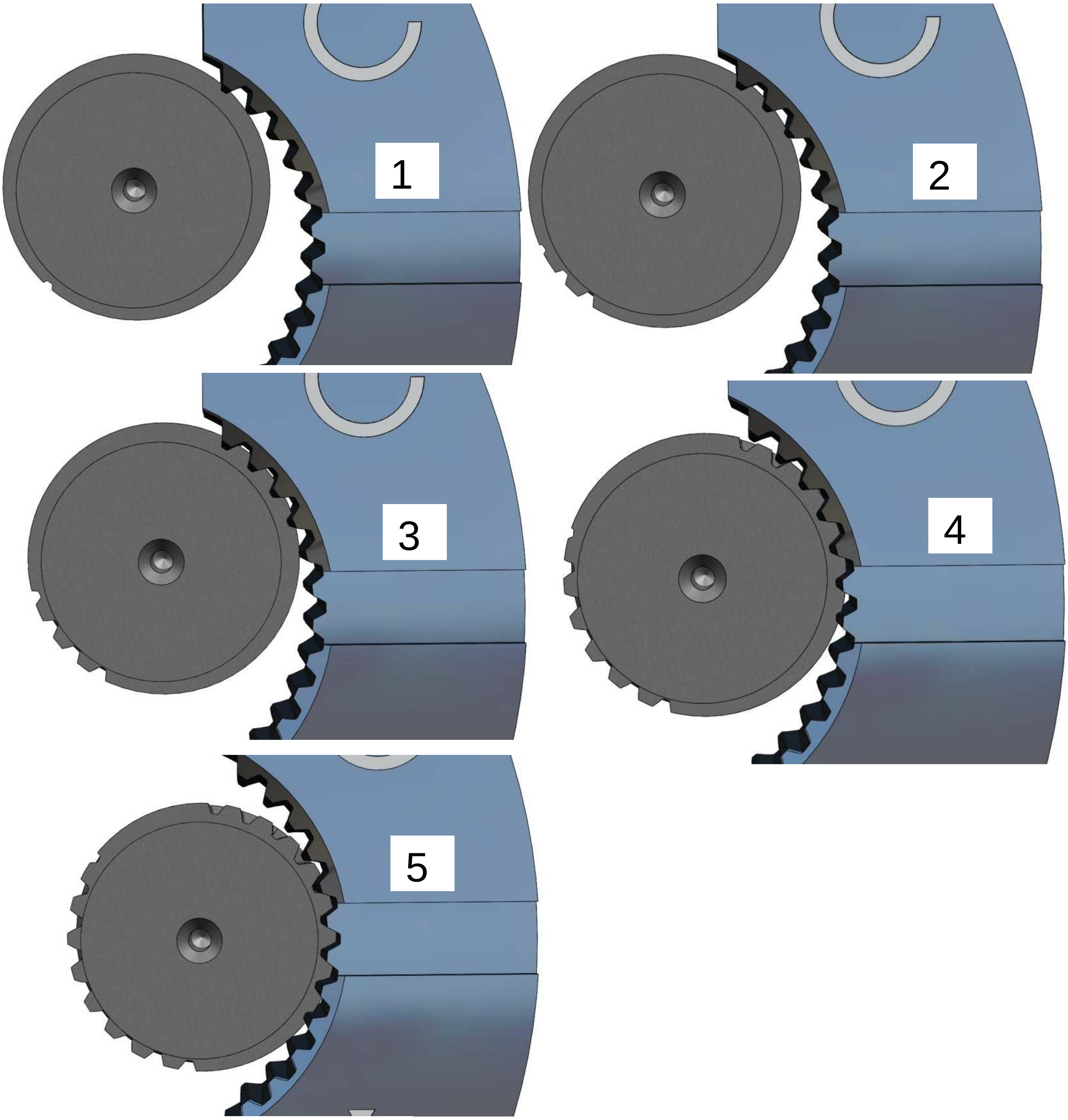


Figure 71 Sequence of Intrusion

In a more extended work-tool - workpiece setup (see fig. 71) the sequence of intrusion and disengagement of a work-tool (only one site work-tool being shown) is represented. Due to the un-blanked second work-tool body, the resulting teeth shape in the workpiece during one single stroke of the tools can be visualized. In comparison to the prior exercise the workpiece relative movements are now considered as well. It can be observed as stated before that the tooth shape is strongly different depending on the angular position on the workpiece. It can also be seen that during one stroke of the work-tools only a few teeth on the workpiece circumference are being shaped and for completing the teeth geometry several work-tool strokes are needed. This systematic includes the complete disengagement of the work-tools within the workpiece feedrate step that could be a root cause of further inaccuracies of the arriving spline gear shape. On the other hand several teeth are processed in parallel in the forming process which expresses again the excellent guiding behavior of the work-tools to the workpiece.

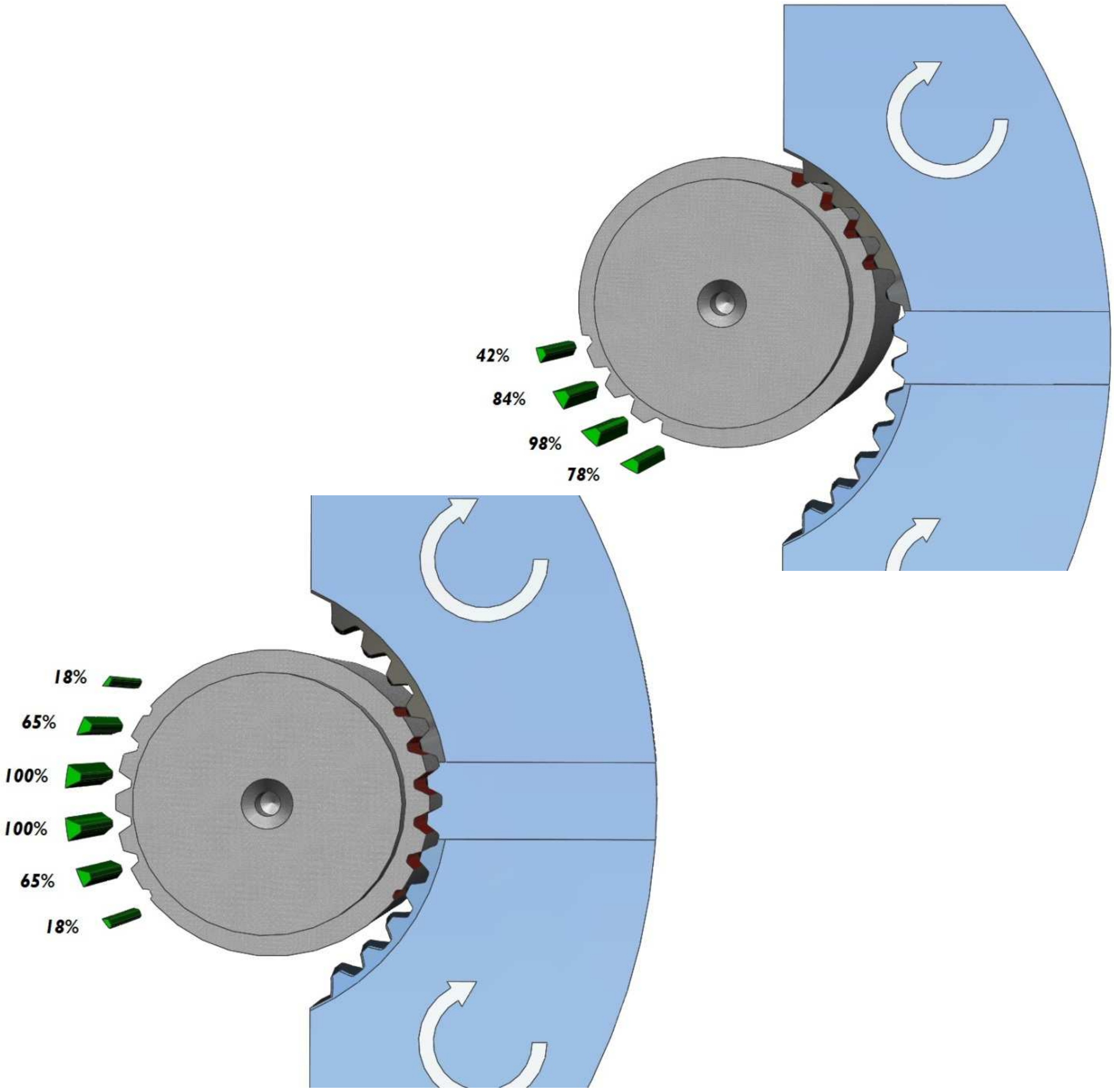


Figure 72 Unbalanced Active Forming Volume

In conclusion to this theoretical analysis an unbalanced material volume (see fig. 72) is being processed by the work-tools imprint behavior depending on the work-tool - workpiece relative position during the forming stroke.

It can be stated that only the minority of tooth on the workpiece sample are formed to its complete final shape in every work-tool sequence. Reviewing the WPM forming process in a more detailed approach a qualitative unbalance of the teeth actually being formed during one stroke can be calculated in a theoretical assessment. Hereby the actual tooth volume (see fig. 72 in green) being processed per work-tool position is visualized compared to the ideal volume of a complete toothed gear. As far as a more detailed view on the intersecting forming material volume between work-tool and workpiece is concerned the Fig. 73 represents a qualitative chart of the actual case study being analyzed. It is especially to be mentioned that as an overlay effect on the consistent increase of the forming volume during the first phase of the work-tool stroke and the decreasing phase of the stroke volumes timing occurs as waviness shaped behavior of the characteristic line shown in the chart (Fig. 73) as a detailed view.

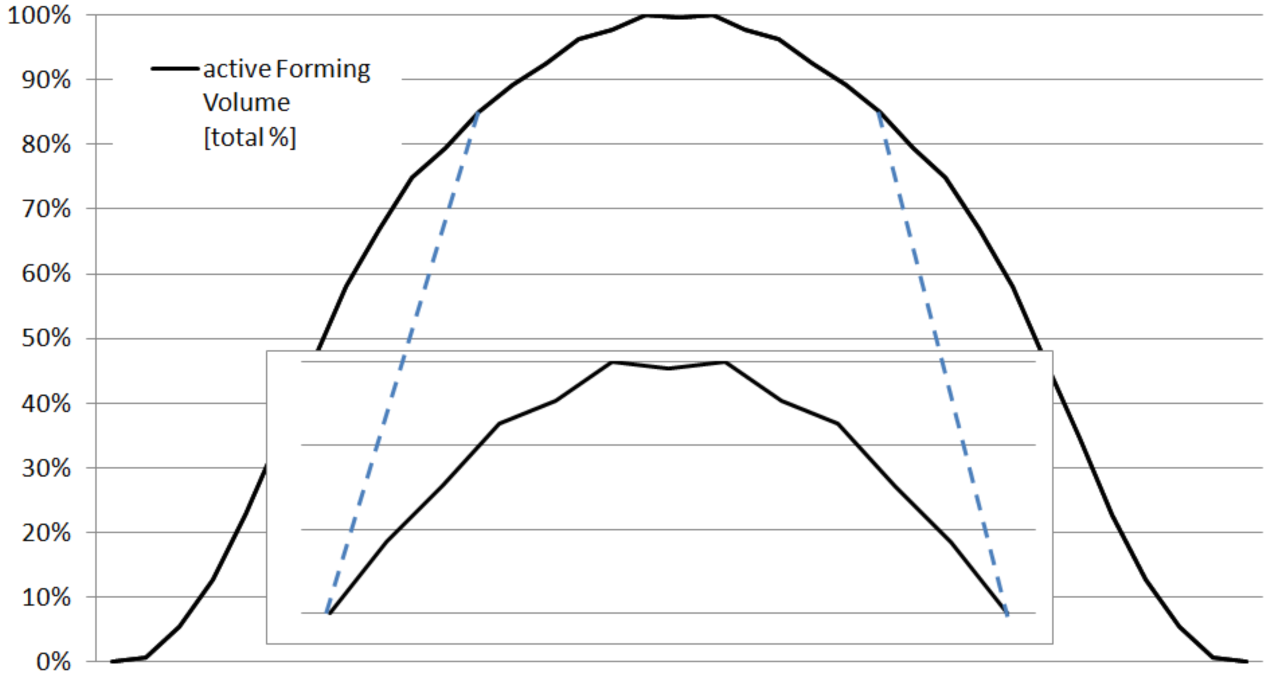


Figure 73 example of active forming volume per work-tool stroke

The described waviness behavior of the within the WPM process active forming volume examination becomes even more evident, when generating a complete scenario of

WPM work-tool position step overlay per one working stroke within a detailed CAD view environment as being shown in Fig. 74 for visualization.

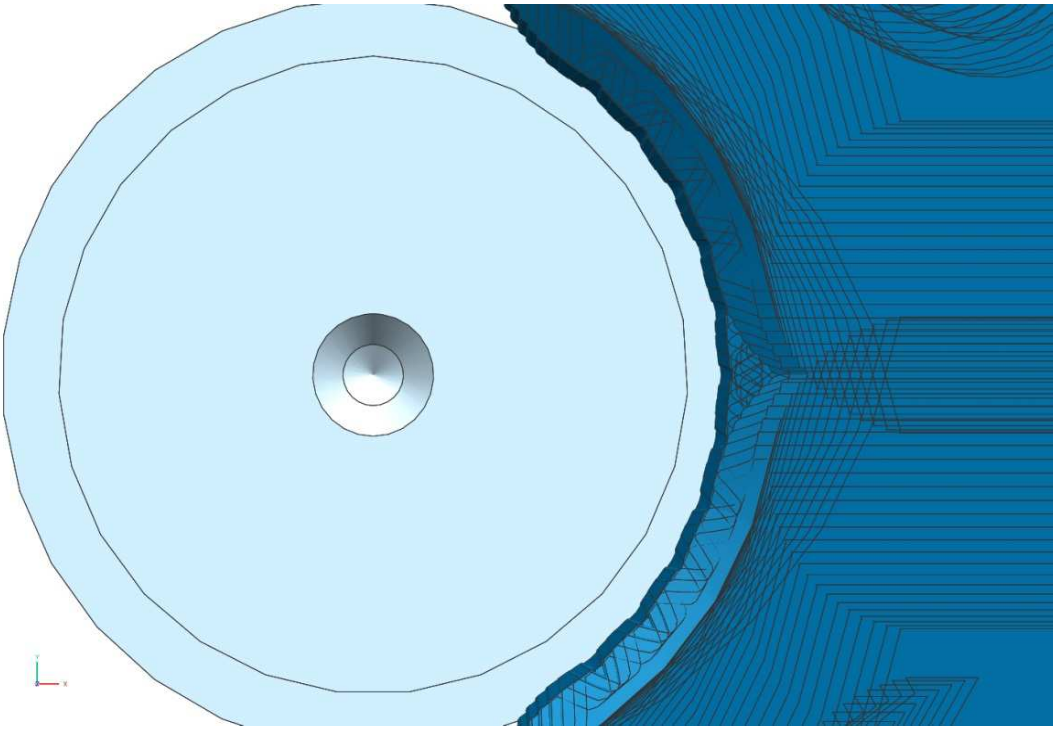


Figure 74 WPM Work-tool position step overlay

It can be clearly observed within such a trajectory analysis that a waviness alternating systematic behavior generally occurs during the WPM kinematic movement of the work-tool while approaching the workpiece during a forming stroke. This basic finding is a fundamental element of the theoretical analysis and a major root-cause for special geometrical characteristics of the spline gear shape to be manufactured, esp. regarding the alternating shapes of every tooth $^{(n+2)}$.

Based on this facts it can be concluded that the unbalanced forming process with its discontinuous guiding steps of the work-tools onto the workpiece and the behavior generating each tooth finally in a non-constant forming cycle it must finally will result in an unbalanced geometrical property of the tooth heights and the tooth shape in a left-/right flank profile comparison. In order to further support these findings another separate theoretical exercise is being processed. To arrive into a better understanding of the asymmetric material distribution and in order to clarify the root-cause especially of the tooth trace error another analysis will be outlined (see fig. 75) [20].

Within the described assessment a more sophisticated WPM work-tool kinematic movement is executed in another CAD-based trajectory study. In major difference to the earlier explanations (e.g. fig. 74) the workpiece is hereby considered to be a fixed element. The intersectional volumetric elements between one work-tool and the workpiece during one stroke cycle are reviewed for different work-tool-tooth position scenarios and are now representing the center of interest.

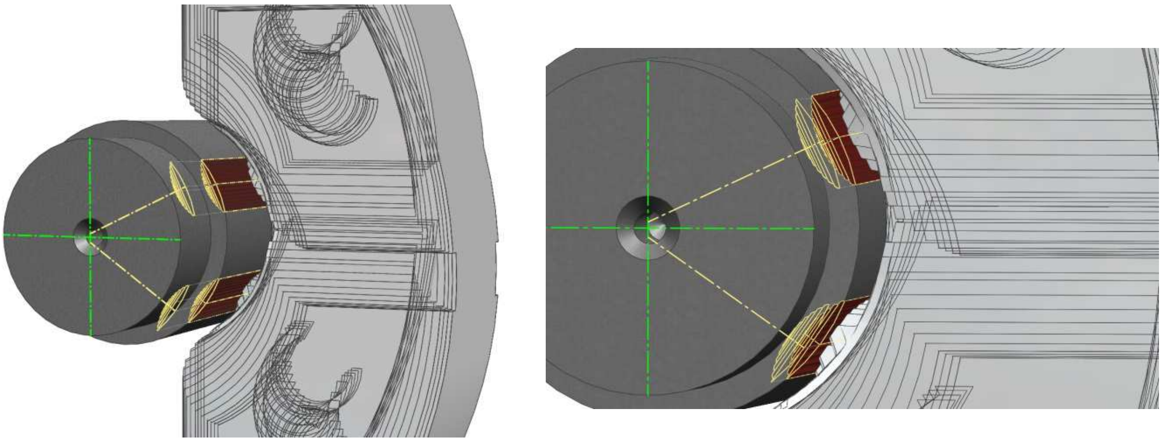


Figure 75 Forming Volume Intersection Study

As being shown in more detailed view (see Fig. 75, 76) on this study the work-tool trajectory positions are being shown for two angular tooth positions only. Furthermore, the smeared intersectional forming volume on the fixed positioned workpiece has been eroded (red surface) from the workpiece.

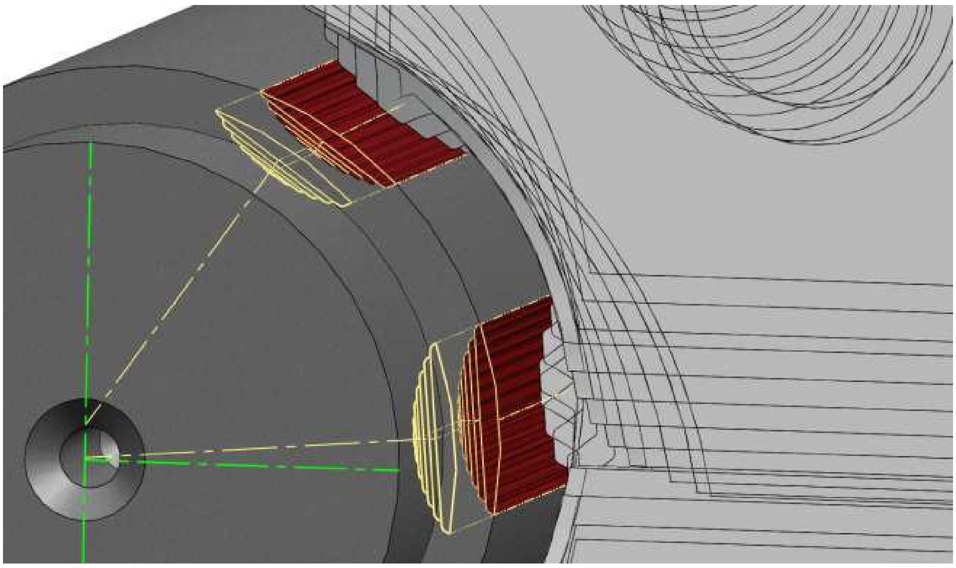


Figure 76 Forming Volume Intersection Detail

It can be observed that the intersectional volume being eroded from the workpiece-work-tool contact zone is clearly of different volume for the shown two tooth positions (yellow lines). By blanking the work-tool half-shell out of the analysis picture and adding a dimensional information in the CAD view on the study (see Fig. 77, 78), a clearly defined tooth trace error can be discovered [19, 21, 69].

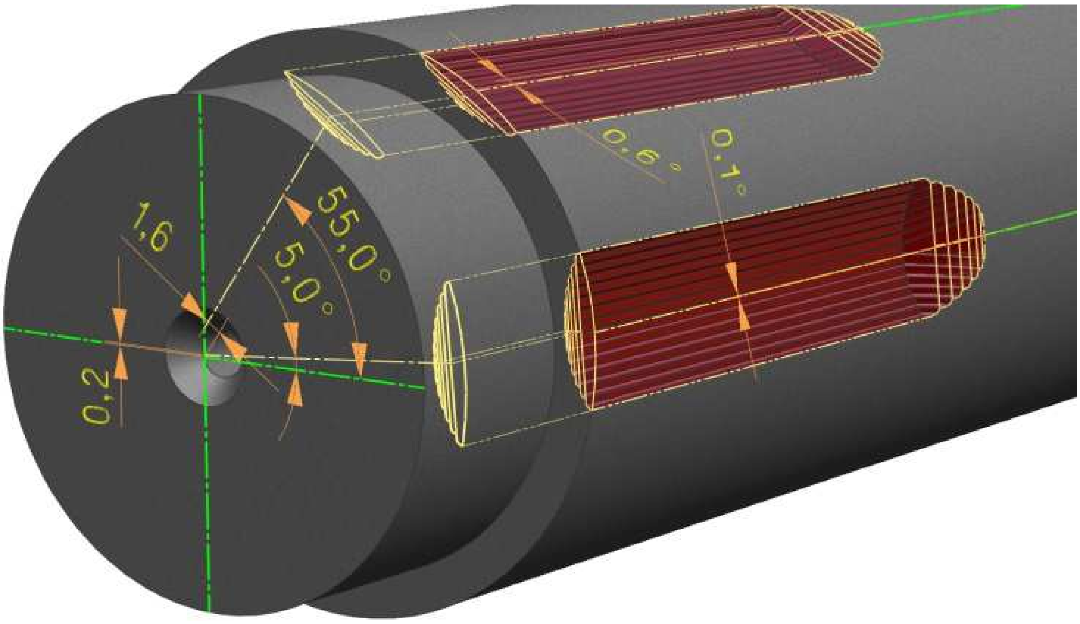


Figure 77 Intersection Volume Analysis (study position 1)

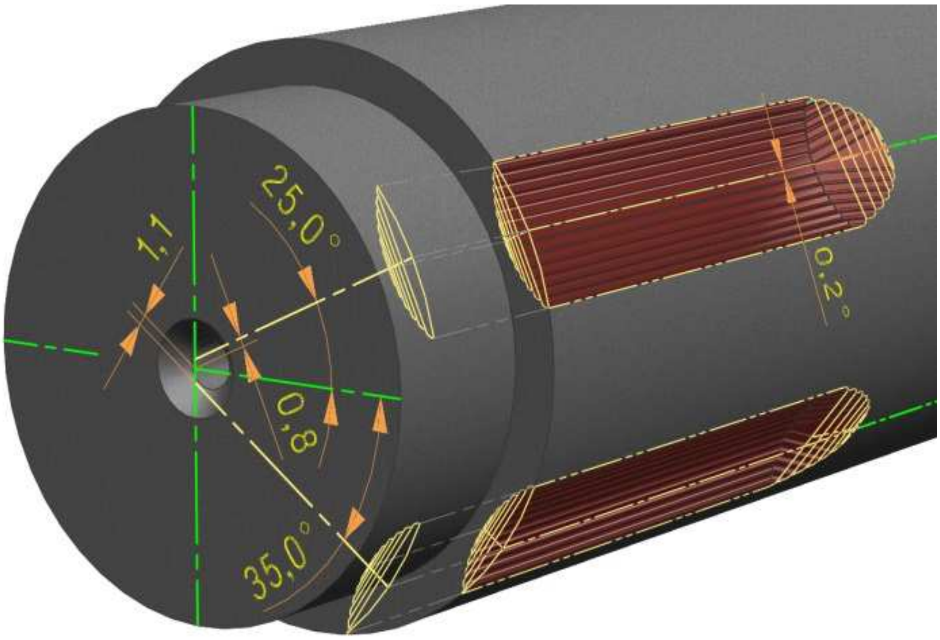


Figure 78 Intersection Volume Analysis (study position 2)

It can be found that the discovered tooth trace error in the length direction of the fixed workpiece scenario is of different range depending on the angular position of the work-tool tooth within the CAD-based study (compared Fig. 77 to Fig. 78).

What can be found as a systematically finding of this assessment is the relationship of the absolute tooth trace error based on a tooth angular position during forming. It can be stated that as closer a work-tool tooth is acting to the center of the half-shell work-tool setup and the more aligned the work-tool centerline is with the workpiece centerline (see fig. 79 , Pos. No. 4), the less distinctive is the tooth trace error as a trend conclusion.

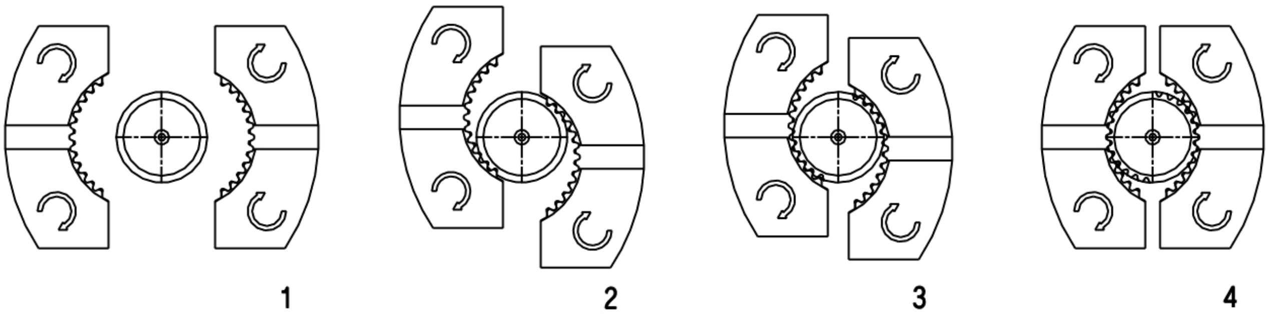


Figure 79 WPM work-tool position scheme

Summarizing the outcomes of the prior survey it can be stated that:

1. The systematical tooth profile error combined with the systematical tooth height error and
2. The tooth trace error to be observed on a spline gear sample

can be deduced from the theoretical assessment out of the CAD scenario and therefore being a fundamental characteristic of the WPM working principle in this consideration.

4.3 Summary of tooth geometry investigation

In special regards of the tooth head geometrical shape being explored in the prior examinations (see Fig. 58 ff. as an example) the conclusion will arrive that in order to shape a tooth of complete height there must be a missing portion of provided basic material during the tooth forming process steps. In theory one could increase incrementally the pre-defined Semi sample diameter e.g. by 0,01 mm steps before forming until one arrives to a completed tooth shape in height. The described procedure is however causing the difficulty that during every stroke of the work-tool sets every tooth gap within the work-tool would be filled up by the basic workpiece material during intrusion. In consequence this load situation of increased unbalanced stress in the work-tool-workpiece contact situation would cause additional reaction forces on the workpiece sample being clamped between the machine centering tips within the work-chain. The arriving additional reaction forces would force the workpiece sample into unexpected compensation movements based on distortions that occur and finally must lead into a damage or crack of the work-tool elements. In consideration of a industrial application scale of the WPM methodology it is to be assumed that it is not achievable to manufacture the work-tool half-shell elements identically shaped and to control the Semi sample diameter in such a high precision manner that the basic problem of damaging the work-tools by complete tooth heights generation won´t occur. Even if such manufacturing objections could be disproved the fundamental finding need to be taken into consideration knowing that a geometrically complete shaped tooth would have been generated under unbalanced constraints in its forming process history. These facts could cause in consequence different load and therefore wearing behavior during the case of lifetime application of such a geared component as well as asymmetric behavior of the teeth geometrical consistency during heat treatment processes [1, 92, 111]. As far as the manufacturers manuals according the WPM-120 machine is concerned there are no recommendations to be found as a point of reference avoiding the described scenarios.

5. Investigations on Rolling Samples with Special Rolling Geometries

In the following chapter experiments and studies are described that have the underlying target of achieving additional findings on how far the detected geometric features are inevitable and inherent typical for the process of the rolling samples such as asymmetries of head shapes and edge lines, or if they are caused by a random combination of parameters. Only if these features are typical for the determined process, a particular technically feasible and economic suitable system of a metrology framework for rolling following the WPM method can be developed. In the same sense, the following analyses, the power consumption of the main drive and the related geometry measurements are to be seen and understood in a more enhanced detail than in the earlier study [27].

In the previous chapter 4, the contact conditions between the tool geometry and the emerging on the blank tooth geometry were investigated. It was found that during the winding off the work-tools on the circumference of the rolling sample, a one-sided tool surplus arises. For this constraint, the geometric conditions which are composed of the tool geometry, the blank diameter and the machine-set eccentricity of the tool movement are responsible.

Since the construction of the rolling machine WPM 120 only permits the same rotational direction, at each of the resulting workpiece tooth inevitably resulting material volume excess necessarily lead to unbalanced high up carrying teeth and thus to a single-ended contour gap between two teeth. Hence arise at the periphery of each rolled sample 24-sided unbalanced generated gaps that must lead to an overall slightly helical overall contour in the axial direction of the workpiece. In this way the observed unilateral tooth direction error can be explained in each generated tooth space.

The geometrical specifics of the tooth head shapes asymmetry and the single-ended tooth gaps of the teeth produced in WPM rolling are mutually dependent. To verify these statements special blank geometries were rolled. The underlying idea is that the previously established assumptions must arise in principle identical for almost each blank geometry. It should also be excluded by the rolling experiments described in the following that the above statements being made are not the result of a random combination of geometrical contexts, but that the one-sided volume excess must in principle result conditionally with other combinations. The rolling after the WPM method is based on the sensitive tuning of the machine conditions (direction of rotation, tool geometry, eccentricity) with the blank diameter. When too large blank diameter is selected the blank sample is a risk for tool breakage, for a too small blank sample diameter the desired tooth profile is formed only incomplete.

In order to prove that the one-sided volume excess has generally accrue per tooth shaped, including a variation of the blank diameter, conical and stepped rolling samples were prepared, processed in rolling and geometrically examined. The geometry employed here can be found in in the images below (see fig. 81, 82) [20], while a selection of representative geometrical measurement results are collected within Appendix 2.

In Chapter 4 of the problem of the wobbling motion of the processed workpiece has been raised, which can have a more or less influence on the geometric features of the rolled teeth. Involuntary movements of this kind, as previously stated, be caused by the eccentricity of the center holes in the blank, by the leadership qualities of top recording per se and by mechanically induced axially asymmetric load distributions through the forming process. The latter could be the bearings of the peaks themselves deform elastically with the consequence of an unintended tumbling motion of the blank. To obtain additional information here as well, in addition to the blank geometries described above also particularly long blanks were made, rolled and then measured geometrically. A typical geometry of a long blank exemplifies the following image (see fig. 80). In contrast to the set of prior series [27] blank-blank-length of 240 mm hereby lengths were used provided up to 500 mm with corresponding sensors in the own experiments [98].

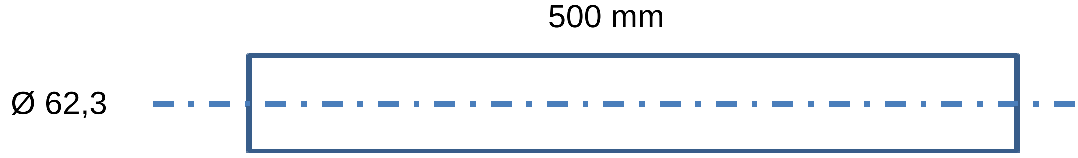


Figure 80 Long Blank Drawing

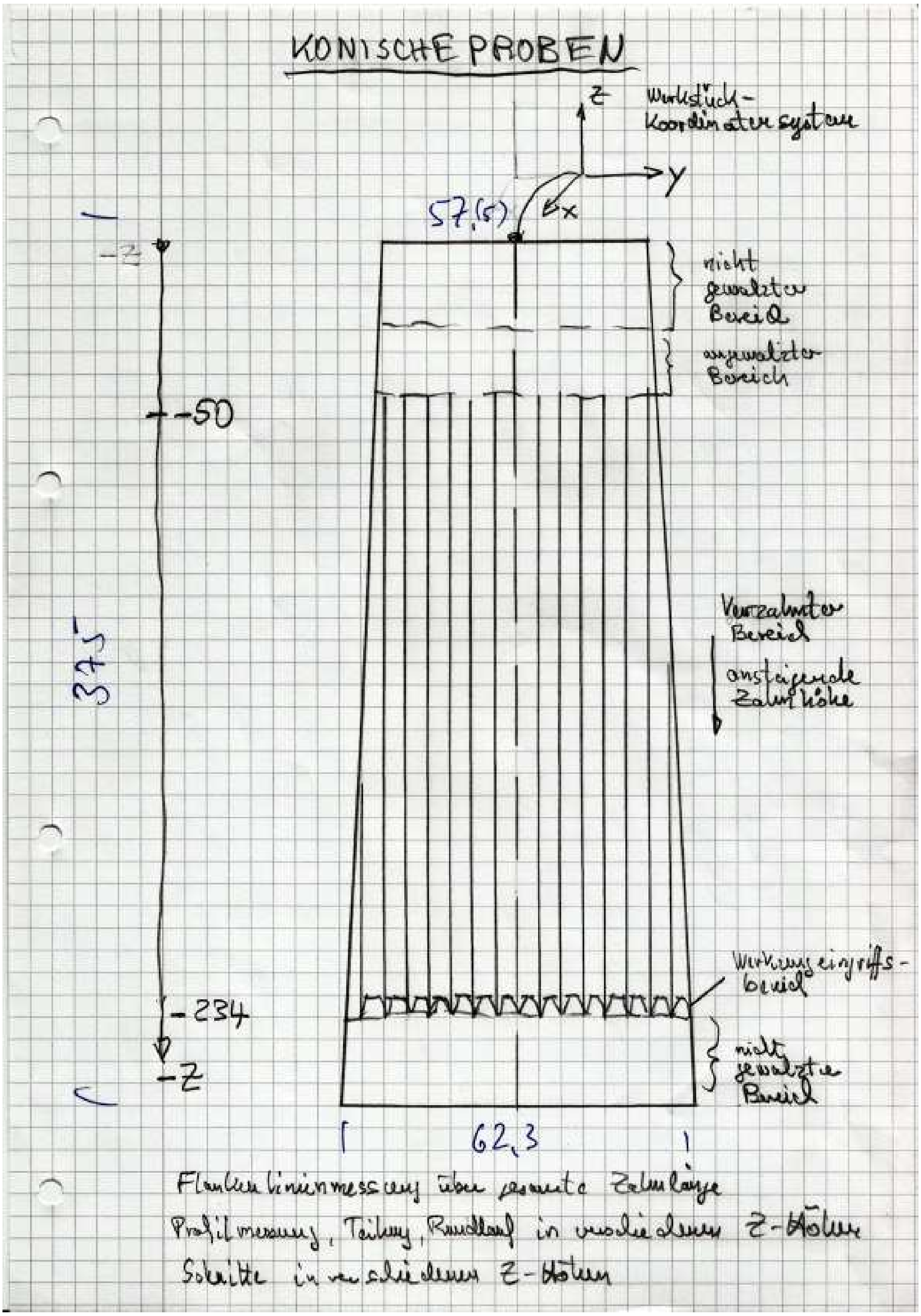


Figure 81 Conical Sample Drawing

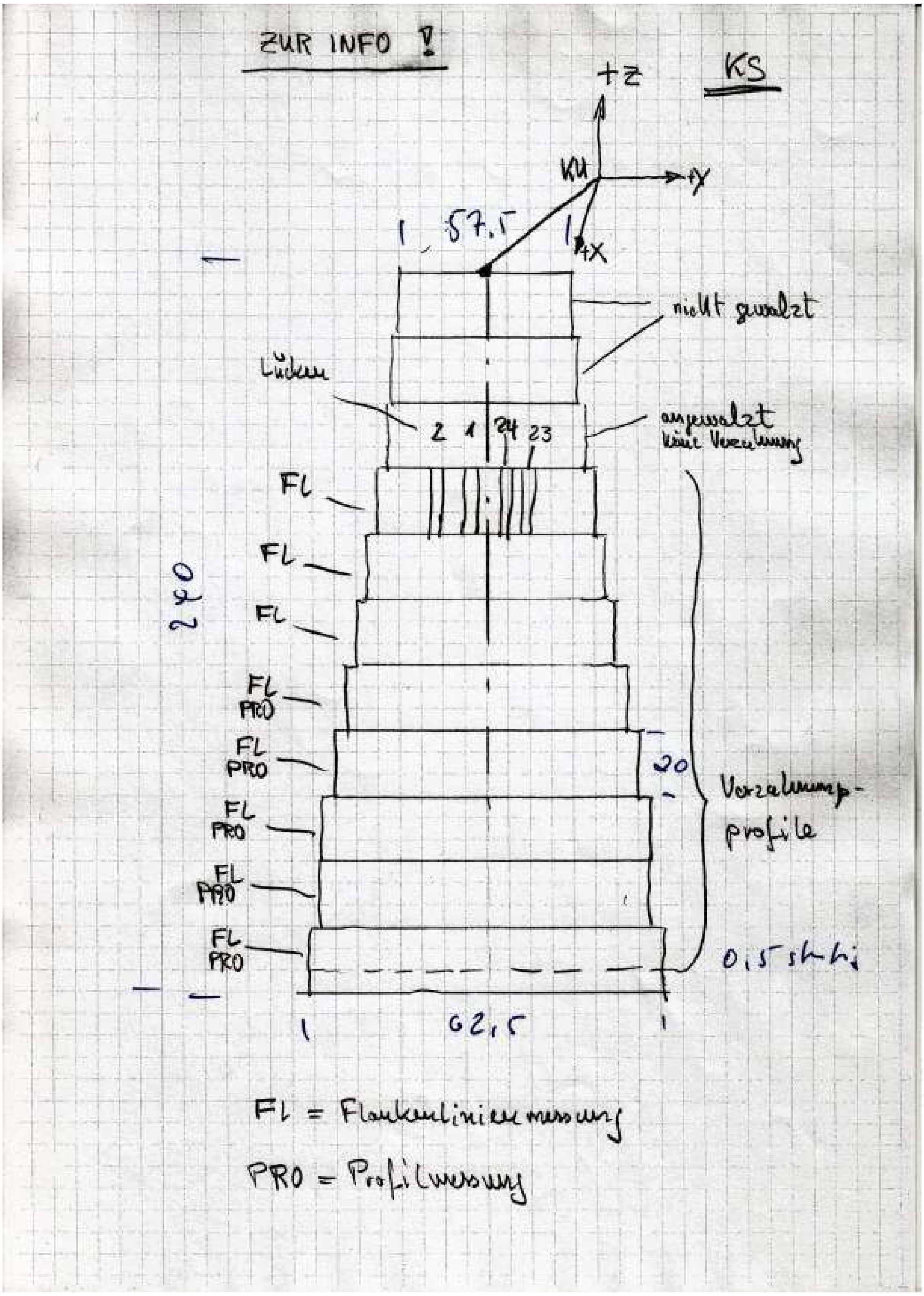


Figure 82 Stepped Sample Drawing

5.1 Experimental Setup / Test Procedure

The rolling experiments within this Thesis work were performed with the same machine-side configuration, tool setup and sample preparation, blank geometry measurements / evaluations carried out, as in earlier experiments of a prior study [27]. That's why the general experimental setup should not further being explained (Section 4.2). In Chapter 6.1 of this Thesis work the aspects are examined, which are important and relevant in terms of the experimental setup and implementation of the experiments using special blank geometry [4, 14, 51].

5.2 Results / Discussion of Rolling Trials / Special Blank Geometries

5.2.1 Unintentional Movements with and without Load

According to the experimental setup described above, the following test results were obtained. Consequently, the results are described in the use of one exemplary long blank (500mm) on behalf of all geometric shapes of the blanks (experimental setup see fig. 83, 84). All other special blank forms, tapered (see fig. 81) and stepped (see fig. 82), are giving identical results of unintended movements.

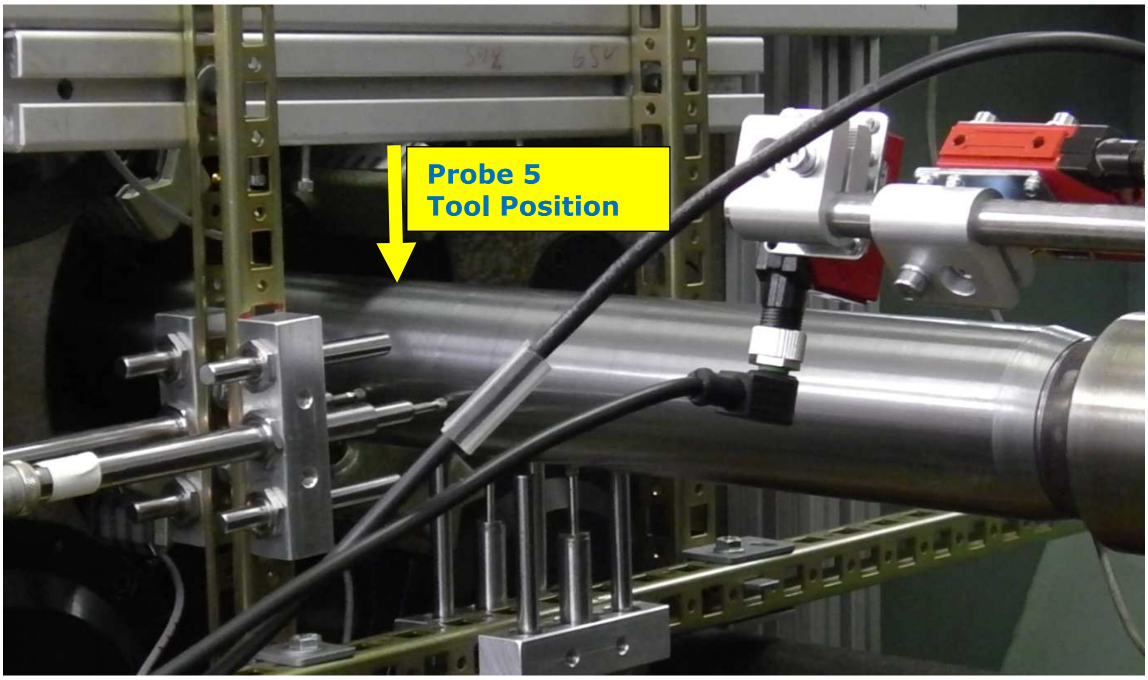


Figure 83 Experimental Set-Up – Workpiece Eccentricity at Tool Position

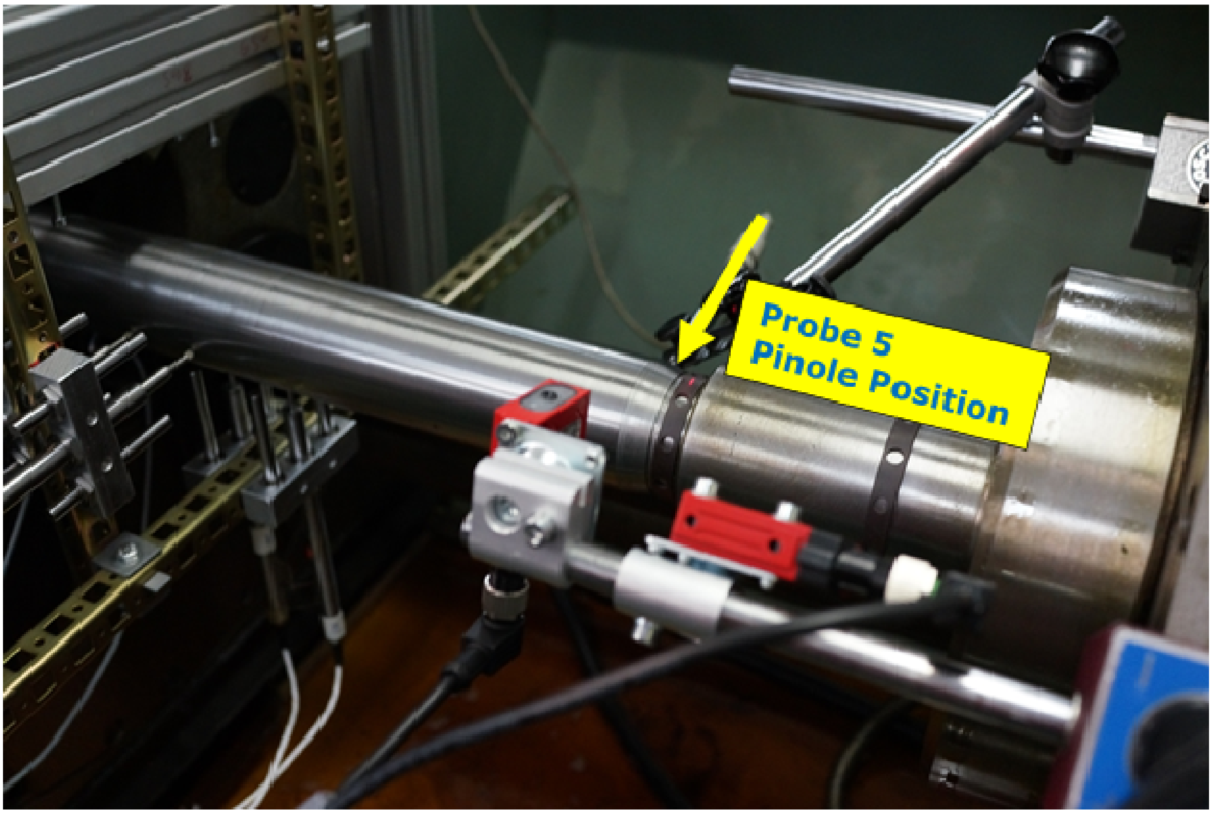


Figure 84 Experimental Set-Up – Workpiece Eccentricity at Pinole Position

After switching the machine on a slow rotary motion mode of the blank was set-up, the simultaneous rotation of the sleeve now permits, as shown in the image (see fig. 84), the eccentric movement of the cylindrical surface of the blank in the tip rack compared to the eccentric movement of the receiving sleeve and without load by the rolling tools.

It can be seen (compare fig. 85) that significant deviations from the relative starting positions of the touch points result in two graphs on the blank and the quill. The graphs are shown indicate readily apparent a phase shift, which can be explained by the random position of the blank in the rotational direction opposite the quill. The aim of this experiment was to determine to what extent the production-related eccentricity of the mounting holes can be reflected by the tools in the test under the condition of slow rotational motion without load.

On the blank results a deviation in the order of 0,1 mm can be recognized at a spindle and at the sleeve at about 0,04 mm deviation. For all the investigated blanks approximately the same deviations from the peak center were observed in these measurements and are corresponding to the previously measured on the CMM eccentricity of the blank samples clamping counter-holes. Resulted in the sleeve again and again approximately the same variations in the order of magnitude from 0,04 to 0,05 mm.

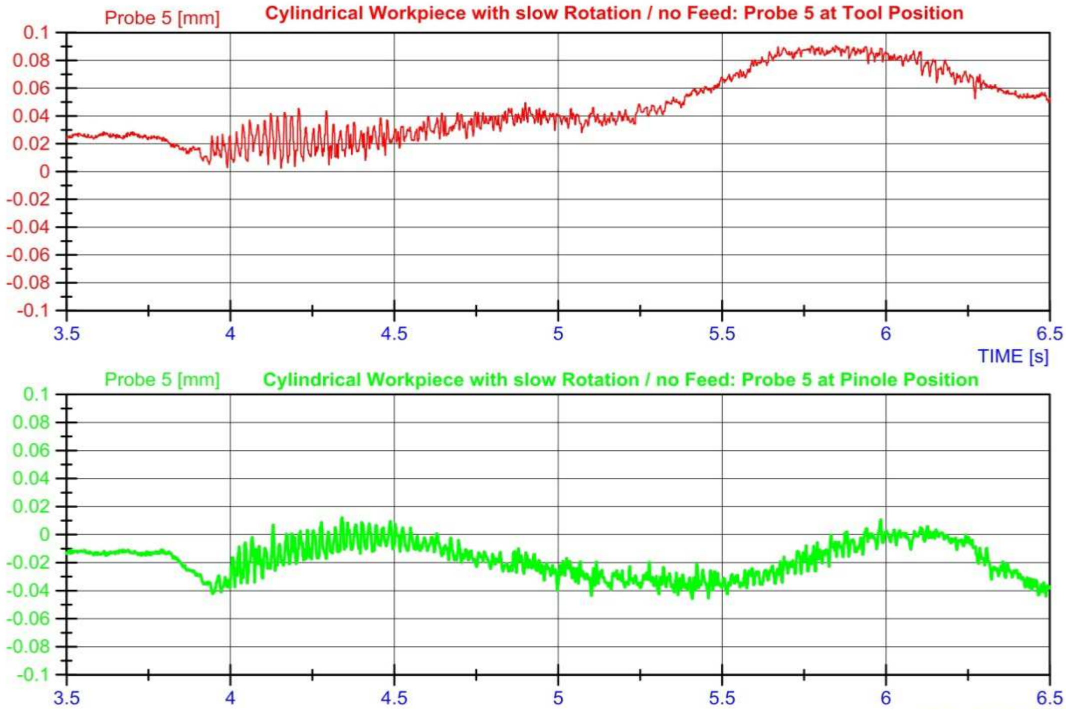


Figure 85 Workpiece-Eccentricity – Tool and Pinole Position

Under the same measurement conditions and at the same geometric locations on the blank and the quill the unintended evasive movements of the blank and the quill were measured under rolling process loads, that is a measurement during the deformation. The following chart (see fig. 86) shows as a typical example for all the rolling trials a nearly identical movement of the blank / Pinole under load.

On the blank arising perpendicular to the measuring direction of the probe relative deviations from the unloaded starting position in the order of up to 0,35 mm. Thus unintended movements are incorporated through the resulting force acting on the blank rolling process, which are more than a factor of ten greater than the unloaded state. When the quill is evasive movements arise in the measuring direction a value during the unloaded state of about 0,04 mm encounters up to almost 0,3 mm under load [128]. The length of the blank has in this context only the importance that the reaction moments from the load increase in size in proportion to the distances between the axial force application point and the bearing points at the tips. A significant increase in the deflection movement of the blank as a result of an increase in length of the blank could not be clearly established.

Figure 86 Workpiece-Eccentricity – Tool and Pinole Position (load situation)

You may experience greater local stresses occurring at greater elastic deformation between the clamping pins and its mounting in place so that the measuring principle used here, main measurement direction perpendicular to the blank symmetric centerline / Pinole, this cannot be detect [117].

Each tool contact moves the rolled workpiece from its initial position as well as any tool load causes elastic deformation of the sleeve or its bearing. The geometric behavior of the active system blank / tip mounting / tip holder is dominated heavily by the mechanical action of the rolling forces. The related chart (see fig. 87) shows an enlargement of a total tool travel with their determined positional changes of the blank. One can see that obviously the first contact between the cylindrical roller part and the tools the roller part initially postponed by several tenths of a millimeter, then, during the rolling action, the rolling part is moved back, then nearly to return to its starting position at the end of the contact. In synchronism with the alternate motion of the rolling part is a nearly identical movement of the quill. It remains to note that the guiding qualities of tip mounting and concentricity quality of the Pinole are dominated by the acting rolling forces. The rolling part is mainly guided by the worktools, which explain the observed behaviors in the experimental results.

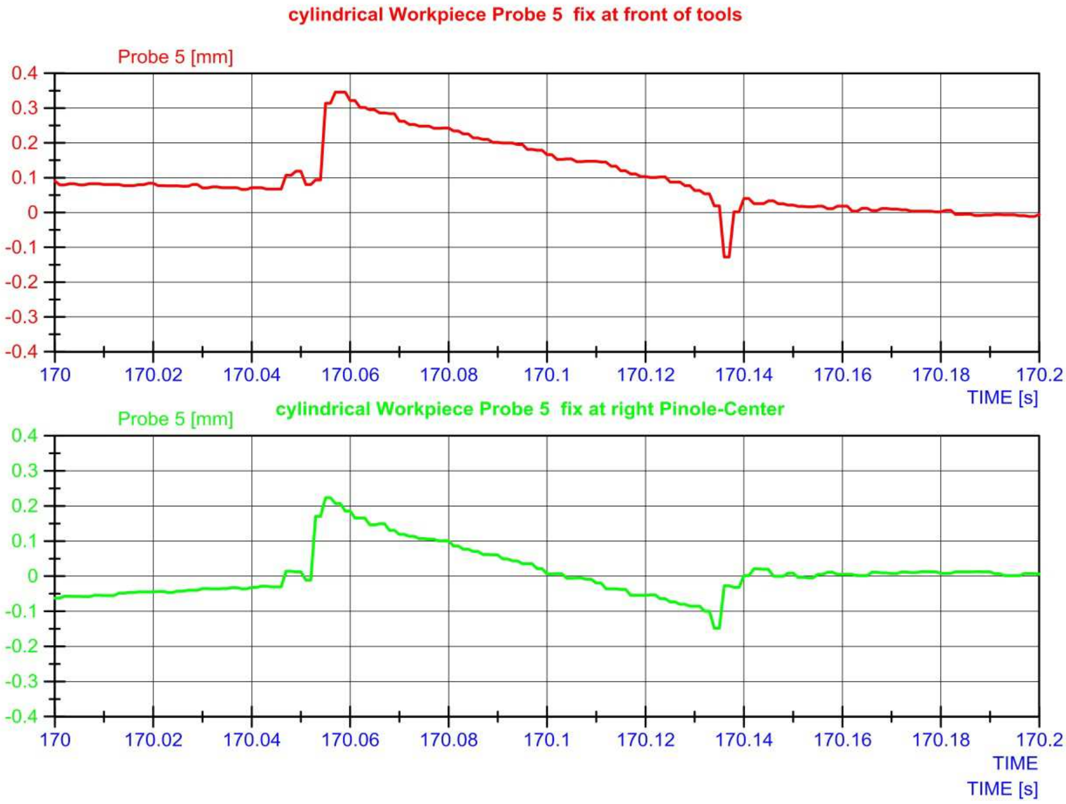


Figure 87 Workpiece-Eccentricity – Tool and Pinole Position (single stroke)

5.2.2 Power Consumption on the Main Drive

The chart (see fig. 88) exemplifies the Power consumption of the main drive when rolling a cylindrical blank. This diagram has already been shown and discussed in Chapter 4. Should be repeated to note that these data were strongly smoothed (1 Hz), creating the tendency of the course of the results is evident. It is evident that with more or less great regularity similar sequences resulting in sections. At the big feed (200 mm / min, red) are pushed together, these sequences, the small feed rate (100 mm / min, green) appear time stretched.

Without wishing to discuss at this point the resulting power curves in detail it is noted that the average of the entire time interval (10-54 sec) result approximately horizontal gradients are to be observed. Obviously approximately the same material volumes are deformed in the same time intervals, according to which same-forming energies are converted into the machine.

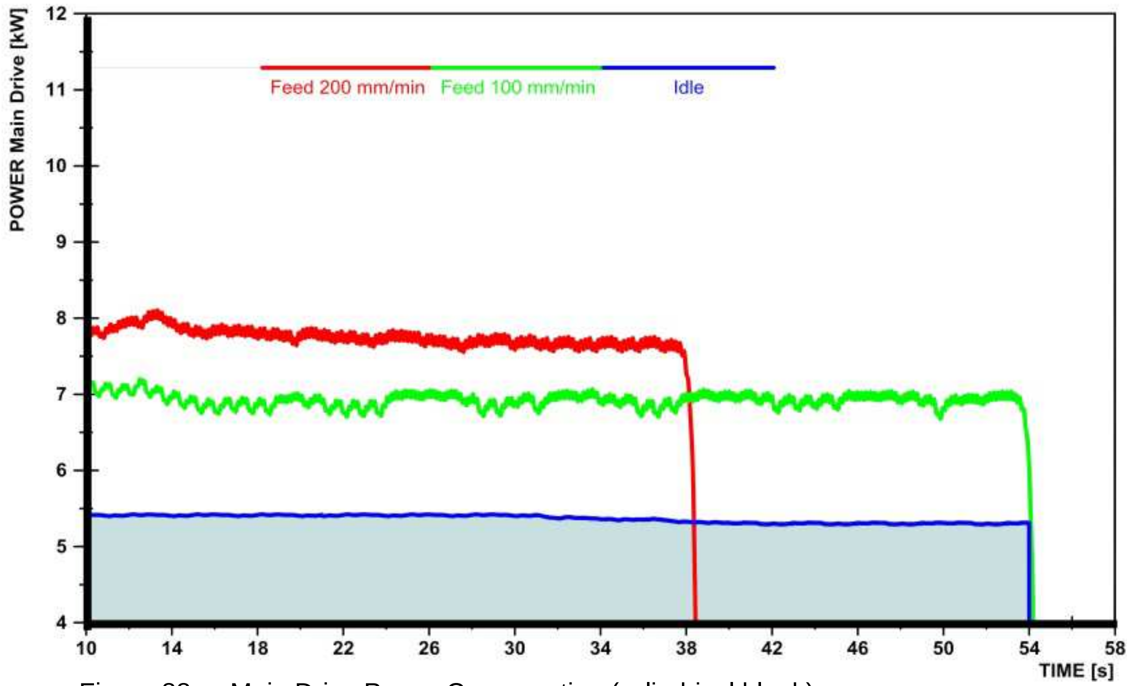


Figure 88 Main Drive Power Consumption (cylindrical blank)

The following chart (see fig. 89) shows the variation of the resulting power consumption at low feedrate (100 mm / min), indicating the results at the use of a conical blank.

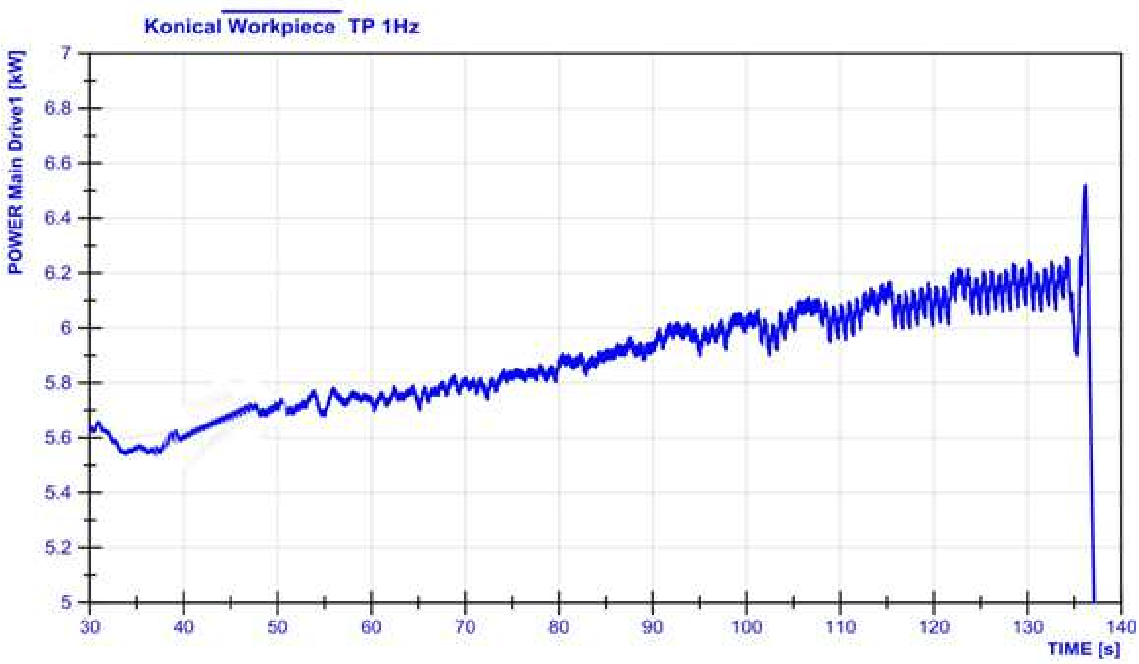


Figure 89 Main Drive Power Consumption (conical blank)

The use of a conical blank has the consequence that the blank is at the prcess start condition already located between the work-tools before the tools physically contacting the blank. The inlet conical zone of the tools have thus for the first mechanical contact no meaning. First, the cylindrical part of the tool geometry begins to scrape over the surface of the material (see fig. 89 @ t ~ 40 sec) without a significant forming conversion can be observed. Then, however, the first part of the work-tools penetrate in the geometry of the blank material and with increasing number of strokes and feed forward at the same time a contact profile is formed.

The profile increases progressively until the maximum possible preparatory diameter is reached. Accordingly, the result of the course of the Power consumption on average approximately linear trend with generally rising amplification can be determined. The curve shown can be explained by the fact that with the conical blank sample material volume to be shaped generally increases and the amount of energy required for the conversion increases linear accordingly. The graph in chart (see fig. 89) can be compared with the green graph in the earlier figure 88, since the machine side passed the same test conditions. Note that the scales of the axes are different in the images.

The following chart (see fig. 90) shows an example of a graph that the power consumption during the rolling of a stepped blank while fig. 89 shows at the same machine technical parameter combination, as when rolling a tapered conical blank [20].

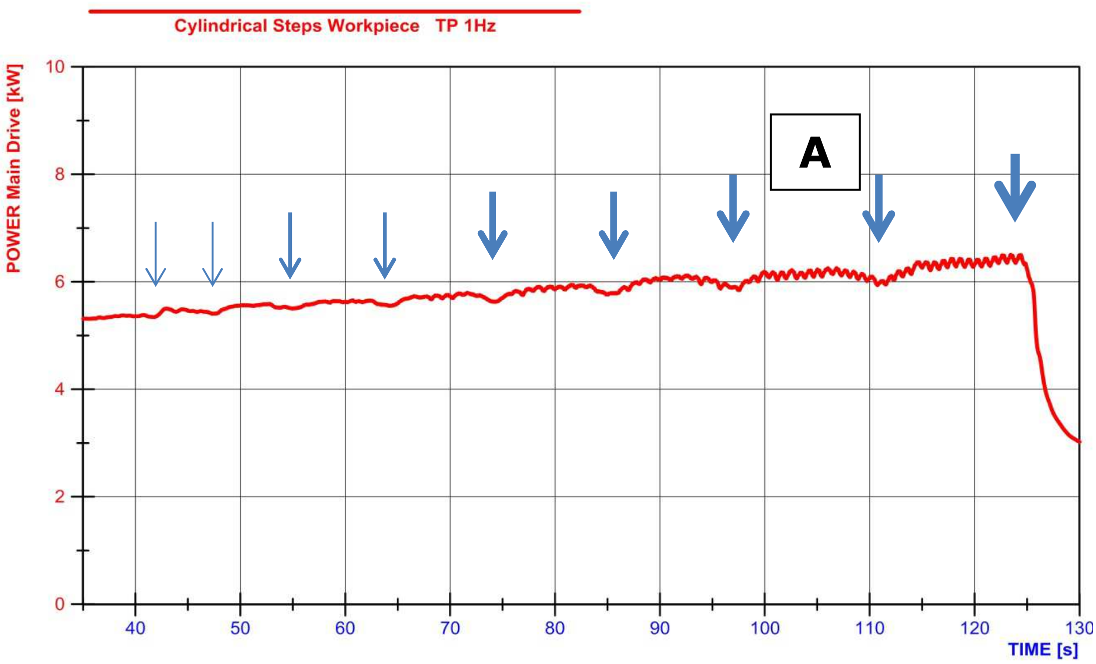


Figure 90 Main Drive Power Consumption (stepped blank)

Marks registered in the diagram by arrows indicate locations on the graph which are to assign the initial blank sample segments that can be recognized. These segments widen relative to the time axis, which is explained as follows. At the beginning of the process there is a stage of the blank between the tools, the diameter is too small, as this a forming transformation can happen. After further advance feedrate movement (see fig. 90 @ t ~ 41 sec) take the tools on a workpiece geometrical step whose diameter has increased by 0,5 mm. First creating a contact with the top of the conical inlet forming zone of the tools and blank material is displaced.

After 20 mm of feedrate advance the conical inlet zone encounters a 1 mm wide and 5 mm deep cut-in feature in the blank. The same applies to the following per tool stroke of the cylindrical part of the tools to the material, resulting in an increase in the material to be formed per work-tool stroke. After each cut-in the diameter of the blank increases, thereby further increase the energy required for the transformation is explained.

Since the work-tool area in contact with the blank material is extended axially, the reshaped forming volume increases. What explains the fact that the time interval between the "arrows" increases. It should be noted that this does not documents a decrease in the forming strain-rate, but indicates the course of the increase / decrease of the reshaped volume per stage in the axial direction.

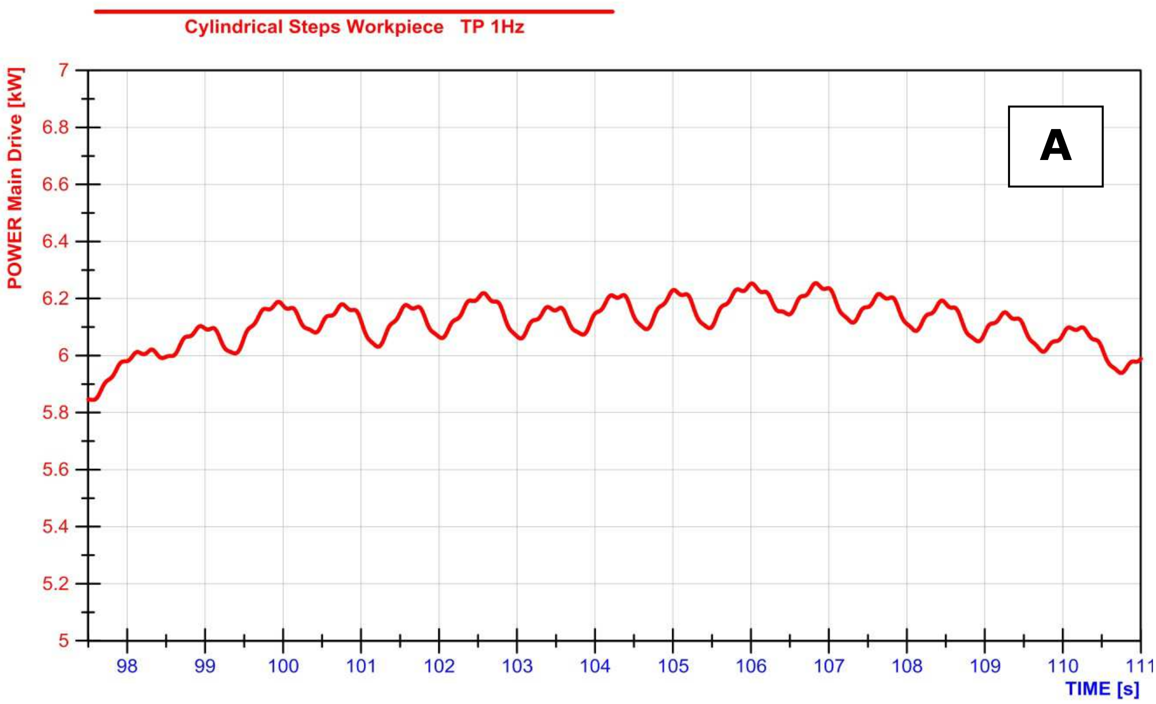


Figure 91 Main Drive Power Consumption (stepped blank in detail)

The further elaborated diagram (see fig. 91) shows for comparison reasons an enlarged section (A) from the diagram of the stepped blank analysis in figure 90. It can be seen that the conical inlet zone of the work-tool is incident on the next step, and after a further advance in accordance with the conicity of the sample, the volume of the tools offered material increases, followed by a nearly linear region in which the cylindrical part of the working tools act on the workpiece. This tooling zone implements the largest range of material displacement and requires the greatest amount of energy. With feed advances the active portion of the cylindrical tool range further decreases.

The conical outlet area of the work-tools follows with increasing influence on the energy demand. In consequence of the energy requirement decreases because now tend to be less volume is deformed. Such a segment as shown in figure 91, marked "A" does not point primarily to the energy requirement, which must be expended within this stage, but is basically a reflection of the influence of the tool contour constitute or damage caused by the contour of the tools energy consumption, that explains the different time intervals in the chart as well [127].

As a limiting factor it has to be considered, of course, that this interpretation of the graph in figure 91, due to the overall width of the work-tools of 50 mm in total and the length of each workpiece stage of 20 mm also overlaying energy components of the forming transformation of the front of and behind lying step levels are being mapped. As related to the geometric axial length of the respective workpiece step-stage, owing to the total width of the work-tool is also involved in other steps simultaneously. Noteworthy, however, is that still a required course of rolling strain-energy results that can be ordered on the active work-tool contour zone.

The earlier statements made above do not only affect the selected segment as shown in the chart figure 89, but in almost identical form for all other segments of all conical blanks were rolled.

Another aspect in this connection is the fact that for each tool stroke obviously not the same volume of material is deformed per stroke. What emerges in the undulating curves in each area of all segments? An obvious explanation for this could be that the massive smoothing of all graphs shown here, the power consumption behavior is responsible for this. Against this assumption it is the fact that the magnitude of this ripple remains approximately constant under the same experimental conditions and details of the forming actions are mapped as being theoretically expected.

Also showed the analytical view in Chapter 4 that from stroke to stroke is not always the same gap with the same teeth of the work-tools that have workpiece contact. And, with open tools may well happen a dynamic offsetting of the resulting rolling workpiece tooth contour against the acting work-tool contour, what can result in small differences in the to be shaped volume and finally must result in slightly different rolling strain-energy values. Which then could indirectly also explain the constancy of the frequency of the determined ripple effects.

5.2.3 Comparison of the geometry results according with DIN 3960

As already stated above, the same CNC programs, probe calibration routines and CMM measurement strategies were applied for the following geometric investigations on the PMM 654, as described in detail in the earlier thesis work [27]. Therefore, details are not to be reported here no further.

The following investigation is a comparison of the measurement results determined on the special blank geometries, which are in fact

a. Long blank samples (see fig. 80)
b. tapered (conical) blank (see fig. 81) and
c. stepped blank design (see fig. 82).

In all the results that are shown in the sequel, (100 mm / min feed rate) was basically rolled with the same machine-technical pre-setting.

As in all examined toothings being generated resulting in nearly the same results, the following charts are intended as exemplary. Results shown in the graphs are measured from left to right starting at the beginning of the roll sample teeth, in the middle and at the end of the toothing. Also it is to be investigated as to what extent the resulting axial overlaps the blank through the rolling tools influence the resulting tooth geometry and how one can in principle describe the guiding properties of the tools [17].

5.2.3.1 Measurement of Pitch / Runout Errors

The results of the pitch measurements vary considerably in the different rolling samples, so that the runout results should be at the forefront in the following discussion. Although these are only a summary assessment (see appendix 2 for details) of criterion but representing an adequate investigation in regards of the initial goal.

Cylindrical blank (long) The attached diagrams (see fig. 92) show the pitch error / Runout on a long cylindrical blank. In this blank, the conical work-tool geometry of the inlet zone first strikes the material, accordingly poor guiding characteristics of the tools is established at the beginning. With increasing axial movement of the blank feed between the tools, the cylindrical forming zones of the work-tools start to act. These namely achieve the deepest penetration into the material into which material flows now higher on a corresponding work-tool tooth profile as the blank is formed. The higher the resulting tooth profile is generated on the blank, the better the tool contour itself lead the blank.

According to this described timing in WPM forming resulted in the beginning of the toothing (left chart in fig. 92), i.e. in the area where essentially the inlet zone of the tools introduced the forming transformation, a poor value for the runout of Fr = 33,5 microns were measured. In the middle portion of the spline sample all tooth spaces of the tools at each stroke of the tools are physically in contact with the material.

The tools now guide and lead the blank axially and radially with their complete geometrical coverage. Accordingly, to this observation, the resulting good concentricity results are in the blank middle area of Fr = 8,1 microns and at the end of the blank gearing Fr = 8,45 microns. The quality of the tools guidance behavior determines the quality of the resulting tooth geometry [20].

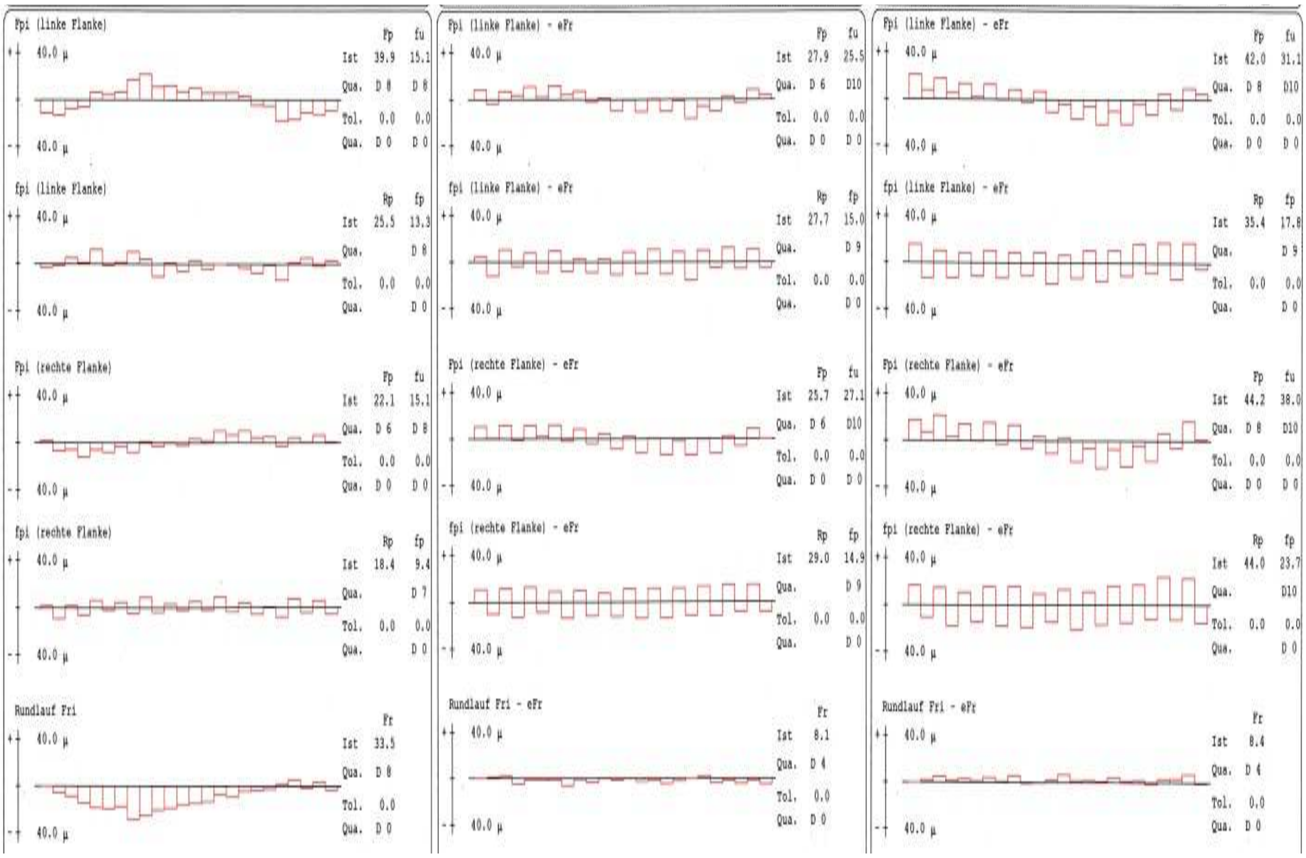


Figure 92 Pitch / Runout error data for cylindrical blank example

Conical blank

A tapered blank is pushed from the feed drive between the tools. In difference to the cylindrical blank, the first contact between the work-tools and the material of the cylindrical portion of the tools is realized, as the diameter of the blank does not reach the inlet zone first. After further feed advance however, the overlap between the tools and the material widened.

Depending on the cone angle of the blank to the cone angle of the tool inlet now increases the contact area of the work-tool / blank material. At the same time the conical tool runout loses, depending on the ratio cone angle at the tool outlet to the cone angle of the blank, partially the contact with the conical blank.

Thus, it is a contact length of the tool resulting in a function of the geometric relationships, which is shorter than in case of a cylindrical blank. The runout in the diagrams for the conical blank (see fig. 93) it is shown the relationships described above.

In the left part of the diagram the runout at the front of the teeth is described with a runout value result of Fr = 39,8 microns, in the middle area of a value Fr = 22,9 microns and at the end of the rolled teeth a value Fr = 22,6 microns.

Although the entire tool shelf-width is covering the blank, in case if the conical blank it is resulting in a lower contact length on the blank material to be shaped, as described previously, with a correspondingly poorer guiding properties. These are then to be recognized on in the results of the geometry measurements.

So it can be concluded that the lower coverage of the tool contour in the contact area with the reshaped material leads to poorer leadership characteristics of the tools and thus to poorer runout qualities.

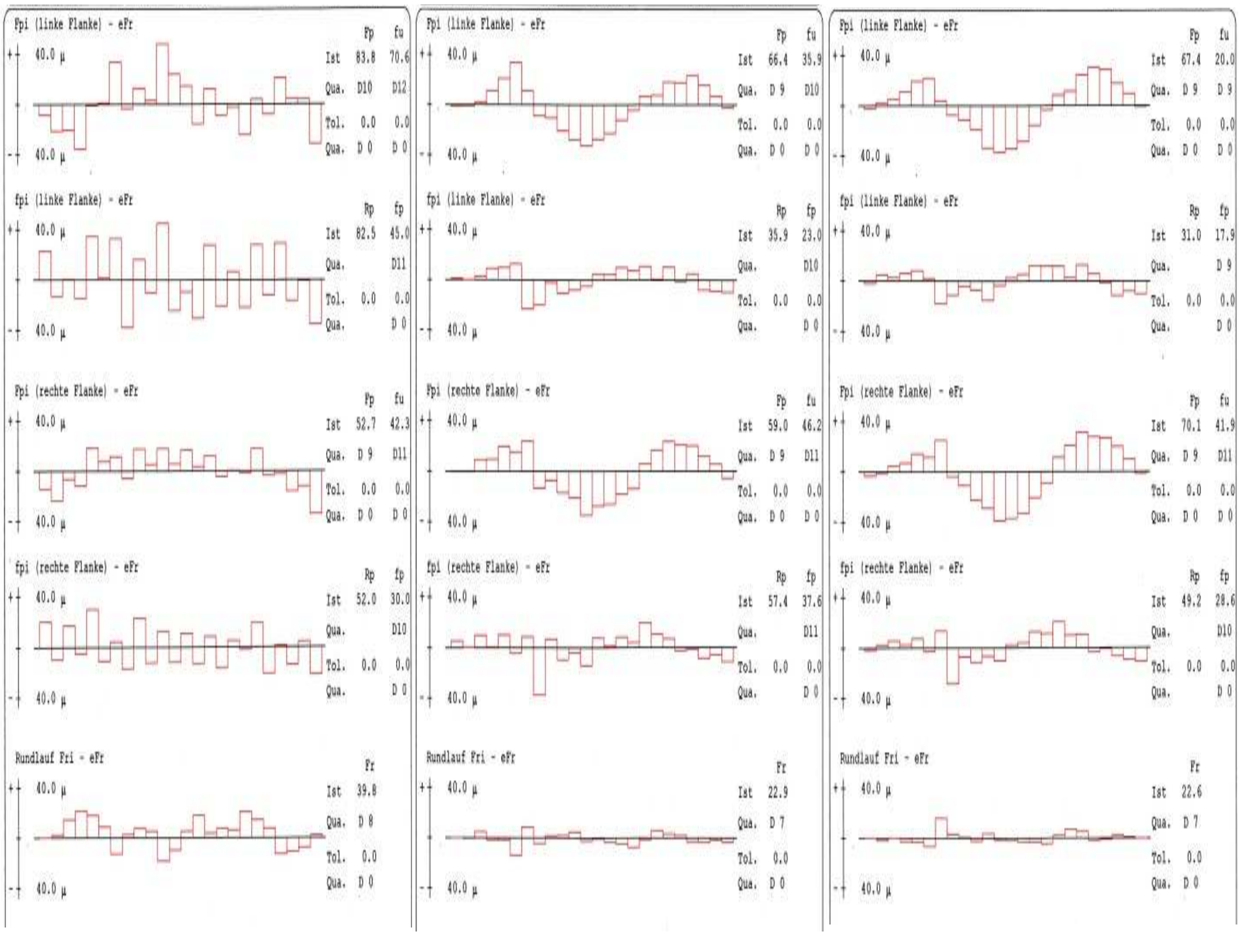


Figure 93 Pitch / Runout error data for conical blank example

Stepped blank In a stepped blank containing graded zones od increased diameters, other geometric ratios between the tool contour and the blank geometry than in a cylindrical blank with the correct preparatory diameter Ø 62,3 mm yield.

Depending on the diameter of the first step either exceeds only the cylindrical contour of the work-tool approaching the material, or in addition, a small piece of the axial length of the inlet conical zone of to the work-tool gets in contact as well.

Depending on the feed the blank moves axially between the tools, the greater the area of contact tool / material arises. The tooth height of the material flowing up to that point is constant over the axial length / width of the first stage on the blank. Wherein at the width of the first blank stage of 20 mm meets the front contour of the tools, in other words, a larger portion of the tapered work-tool inlet zone is already forwarded to the next step on the blank.

At the same time further back tool areas are still in contact with the material of the first stage on the blank. In consequence there is an increasingly better guiding quality by the tools because increasingly more material of the blank is getting formed into the tool gaps and the contact area and therefore the contact surfaces between the tools and the material increases.

The following diagrams in figure 94 reflect this relationship again by the measured runout error qualities. At the beginning of the forming transformation, i.e. at the beginning of the toothing, the teeth leads is a poor value of Fr = 31,1 microns, in the middle blank area Fr = 11,5 microns and 12,1 microns at the end of the blank workpiece. As with the blank geometries discussed above significantly worse runout qualities found at the beginning of the teeth even with the stepped blank.

Responsible for this finding is the lack of available material to be displaced by the forming process at the beginning of rolling. The larger the contact area of the tool with the blank material in the axial direction and in consequence leading to an increase of the deformed material, and thus the contact surfaces increases, the better the result in tooth shapes and esp. in this content the better results in the measured concentricity qualities the tool geometry.

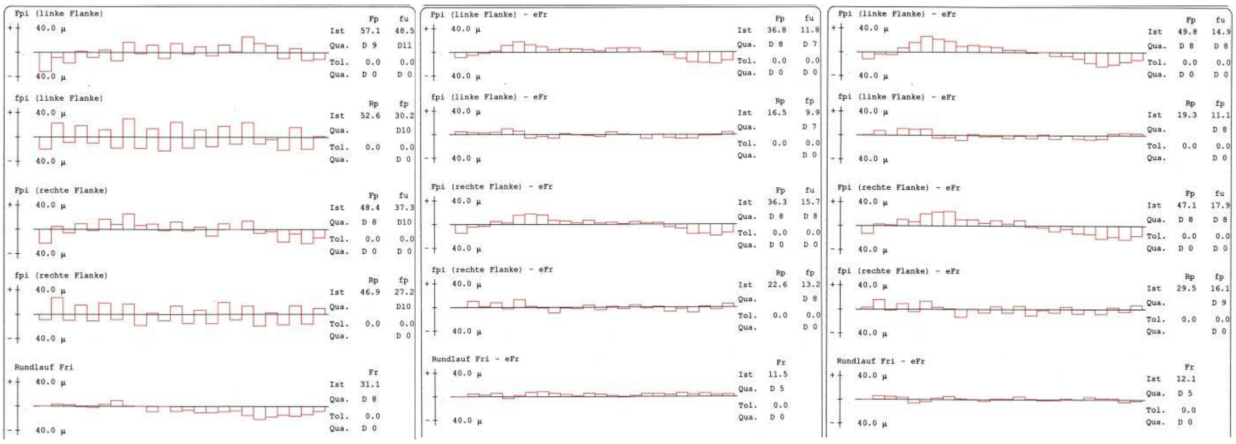


Figure 94 Pitch / Runout error data for stepped blank example

5.2.3.2 Measurement of Profile Errors

In the following selection several charts are shown that represent the results of the profile deviations on a long cylindrical blank (length of 500 mm). The focus of this study is not the assessment of the profile qualities per se, but rather the question of how far a systematic approach can derive a classification for the rolling action as a whole.
Exemplary arbitrarily selected measurement protocols of different tooth gaps are shown because all profile measurements have the same basic tendencies. The machine-technical settings were again identical for all rolling samples [150].

Cylindrical blank (long) The following chart (see fig. 95) shows three diagrams of the profile measurement on a cylindrical roller specimen at different levels of the gearing. From top to bottom results at the beginning of the toothing profile, in the middle and at the end are shown.
It should be noted that the measurement software Quindos 7 being used in all but as well in the profile measurement claims a complete-related “gap-free” visualization and presentation. In this respect, the profile shows LEFT related to a tooth center the RIGHT side when facing the same direction of the view.
The results show that the left side of each gap has a higher shaped involute than the right side of the gap. The differences appear in the order of 1 mm [153]. This statement is confirmed by the earlier theoretical considerations (see chapter 4) and the head shapes shown later, which were determined by a series of average measurements.

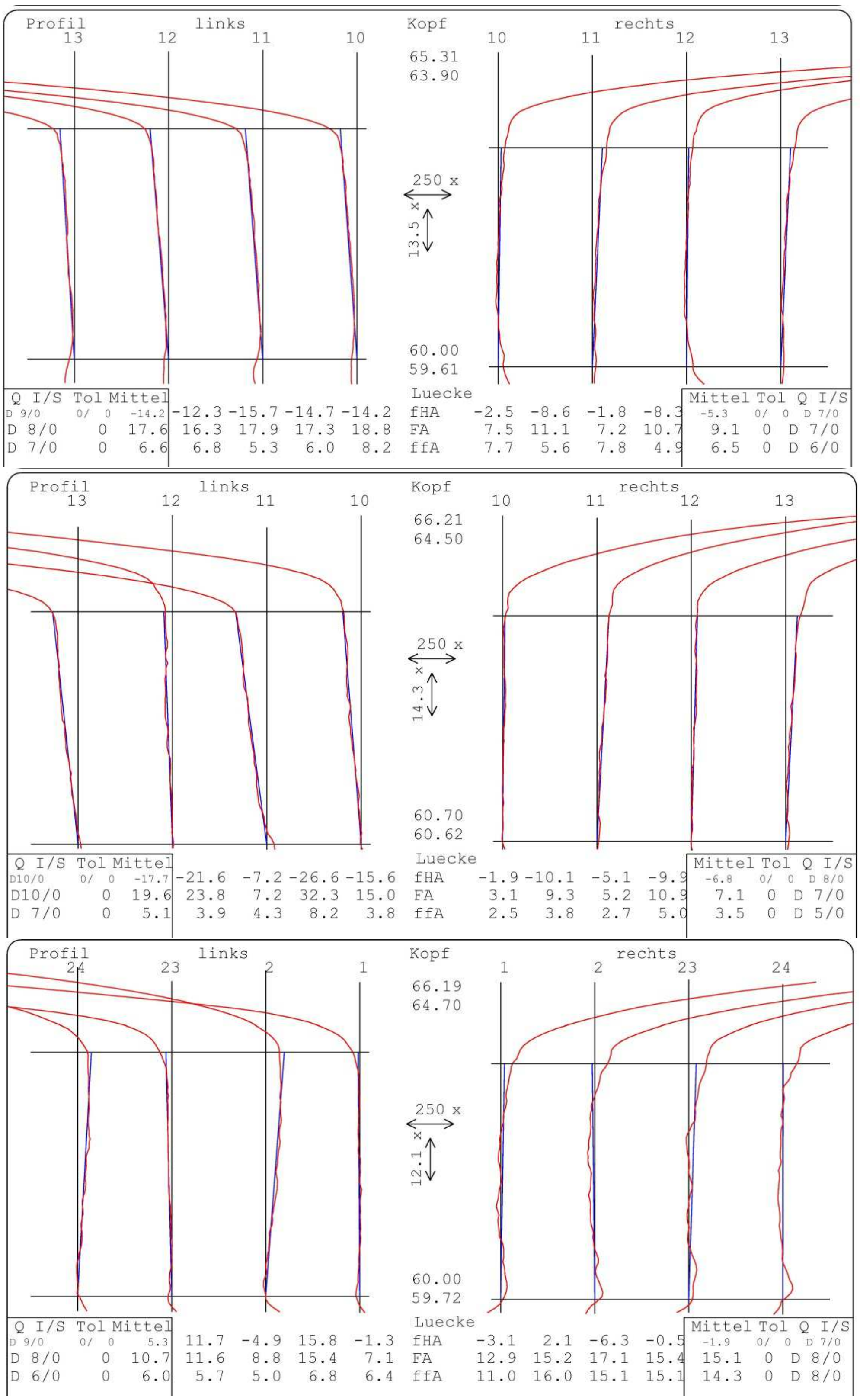


Figure 95 Resulting Profile Error data for long cylindrical blank sample

The right side of each tooth flows on always significantly higher than the left side. The results of earlier WPM works [27] are being confirmed here.

Also, the diagrams (see fig. 95) indicate that the gap-related right profile shape, i.e. the left side of the tooth emerged; lead to qualitatively much better profile shapes on all teeth (involute) results [40].

Conical blank The next figure (see fig. 96) shows diagrams that were determined for profile measurements on a conical sample. Shown here are the results in four equal tooth gaps at different height levels of the gearing.

The chart to be examined comes from measurements at the beginning, including those from the middle and then at the end of the gearing. The selection of the roll sample, as well as the selection of the tooth gaps shown here is arbitrary. All results from all other rolling experiments with conical blanks show the same tendencies.

It can be clearly seen that the sample in a conical blank shape totally the lack of material in forming is evident, (please refer to the comments in the segment on pitch / runout errors), no reasonable shape of the tooth profile can be achieved. The lack of material provided to the forming process here also has the consequence that the guiding quality of the tools due to lack of contact surfaces between the tools and the material does not allow for proper evolving profile.

But it should be noted that the even at the beginning of the transformation occurring material deficit, as well can be noticed with the same tendencies arise as in the cylindrical blank. The left side shows gap significantly poorer profile qualities, such as the right.

The middle diagram, so meaning the profile measurements in the middle of the teeth, is showing more shaped teeth with significantly better profile qualities. The lower diagram shows the same trends as the teeth or middle of the teeth beginning. The tooth gaps arise at all levels of the measurements shown here as an unbalanced situation at different heights up on the teeth heads [20, 73].

Noteworthy is the comparison with the profile results out of the cylindrical blank geometry. In the cylindrical rolling samples, the same asymmetries are discernible. However, the material and the resulting deficit in consequence by poor guiding quality of the tools in the conical rolling sample case results in each tooth gap to significantly worse profile qualities of the right profile side than in the cylindrical blank geometry.

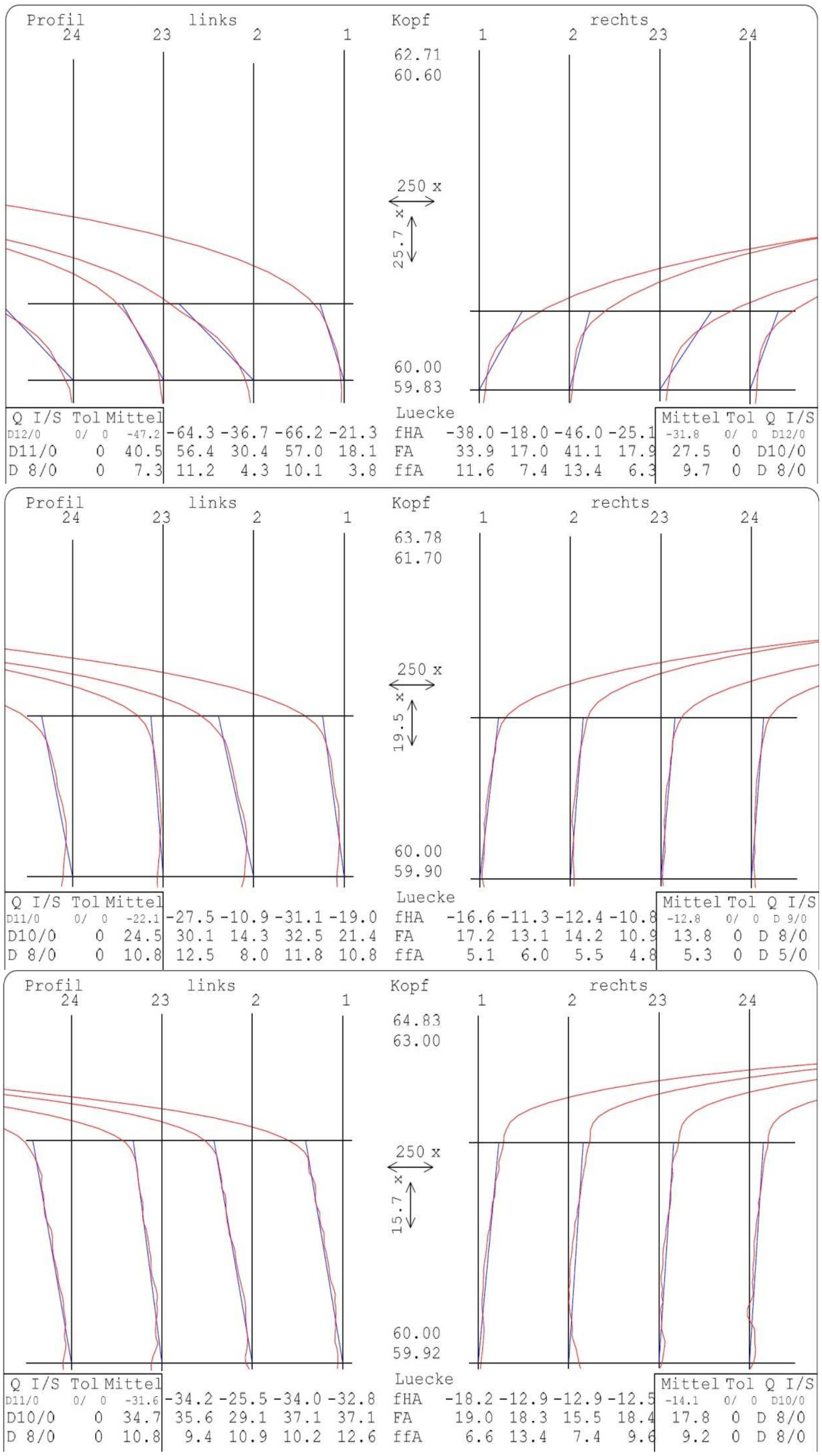


Figure 96 Resulting Profile Error data for long conical blank sample

Stepped blank The upcoming chart (see fig. 97) profile shows plots of measurements from top to bottom from the start, middle and end of the toothing generated on the stepped blank sample. Also the selection of the sample and the roll gaps shown here is arbitrary, since all the other roller portions show almost the same results. As noted already in the conical blank geometry, lack of material deteriorates the quality of guidance of the tools with the observed consequences for the resulting profile shapes.

At the beginning of one of the rolling test, the tool strikes a cylindrical material structure, however, compared to a much smaller diameter of the material sample up to the correct required diameter of 62,3 mm.

It forms out a tooth shape; however, as already established in the conical sample, with significantly poorer profile shapes than with the cylindrical rolling sample with proper preparatory diameter. Even here, so at the very beginning of the teeth resulting clearly discernible differences between the right and the left side gap. On the right the resulting profiles are shorter, but better quality, left the profiles are formed higher, but poor quality. This tendency in the profiles of the middle gear area continues identical up to the end of the teeth, where high flows up profiles are visible.

It is noteworthy that obviously profile errors resulting in the beginning of the forming transformation, almost identical with conical and stepped blank geometry, not be corrected later in the forming, not even when towards the end of the stepped blank the correct preparatory diameter is available for the conversion. One explanation for this is that only good quality overall profile shapes form appears, when the material distribution represents an optimum total at the periphery and in the axial direction of the teeth. Only then it will obviously lead good guiding characteristics of the work-tools to provide profile shapes of high quality [20].

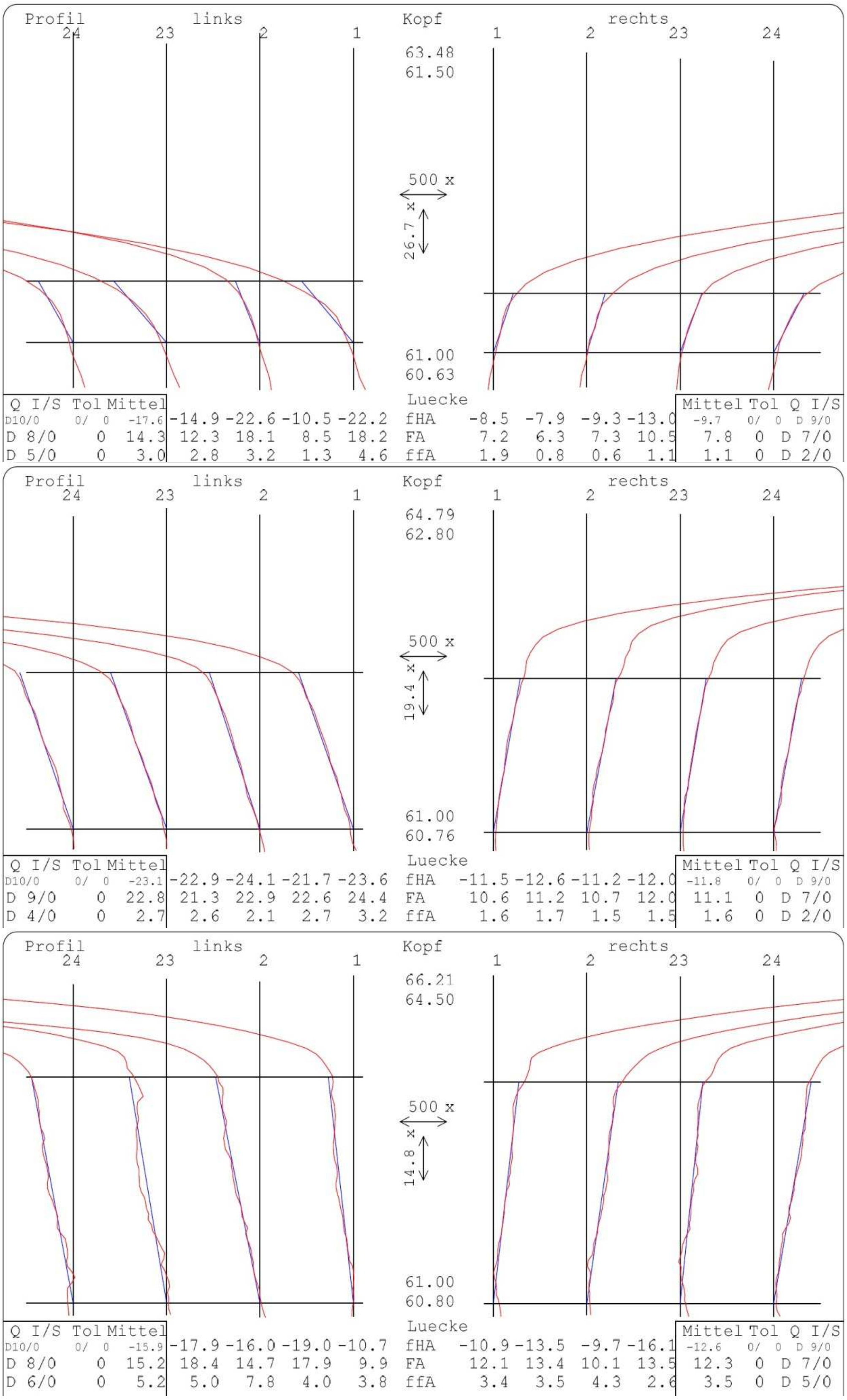


Figure 97 Resulting Profile Error data for long stepped blank sample

5.2.3.3 Measurements of tooth direction errors

The measurement results of the tooth direction error scatter significantly in all gears samples produced by WPM rolling. Therefore, the following figures show examples of the results of selected tooth gaps that allow an interpretation based on the blank geometry employed here.

Cylindrical blank (long) According to DIN 3960 tooth direction error of a cylindrical blank partly in the tooth height of the pitch circle were measured. The following measurement charts (see fig. 98) show in the upper diagram the tooth gap region 1, 2, 23, 24 and in the lower area of the tooth gaps 10, 11, 12, 13.
Thus, the results presented belong to gaps that displaced by about 180° on the circumference of this rolling sample. It is a rolling sample with an acceptable variation of the tooth direction error. However, this result shows significant differences.
In the range 1, 2, 23, 24 stated in the upper diagram, the measured values for the left side of the gaps $f_{H\beta}$ = 54,6; 63; 61,8, 56 in contrast, the area of 10, 11, 12, 13 in the lower diagram of the left-hand side of the gaps $f_{H\beta}$ = 89,1; 82; 84,6; 88,1. For the right-hand flanks of the gaps are obtained for the two areas also have significant differences, although to a significantly smaller extent.
Relating this specific result to the measurement results of the profile measurements described above, it should be noted that site-related where the large profile errors are to be determined the larger tooth direction errors occur. Great profile error and tooth large directional errors are mutually dependent. There has also been, in principle, the right side of each gap have the better quality results [20].

Conical blank Although the DIN 3960 prescribes the measurement of the tooth direction error on the height of the pitch circle, shown charts was in the reports (see fig. 98) not measured at the height of the pitch circle, but on the tooth height that allows a continuous tooth direction measurement, required by the application. In the case of the conical rolling sample, in the initial regions of the teeth too little material had been incorporated, the available tooth contours were too few developed in forming. Since in these studies no detailed determination of gear quality was at the forefront, but a qualitative assessment of the material distribution and in connection therewith guiding properties of the tools was so moved. Re-measurement results from different peripheral areas of the toothing are being shown.

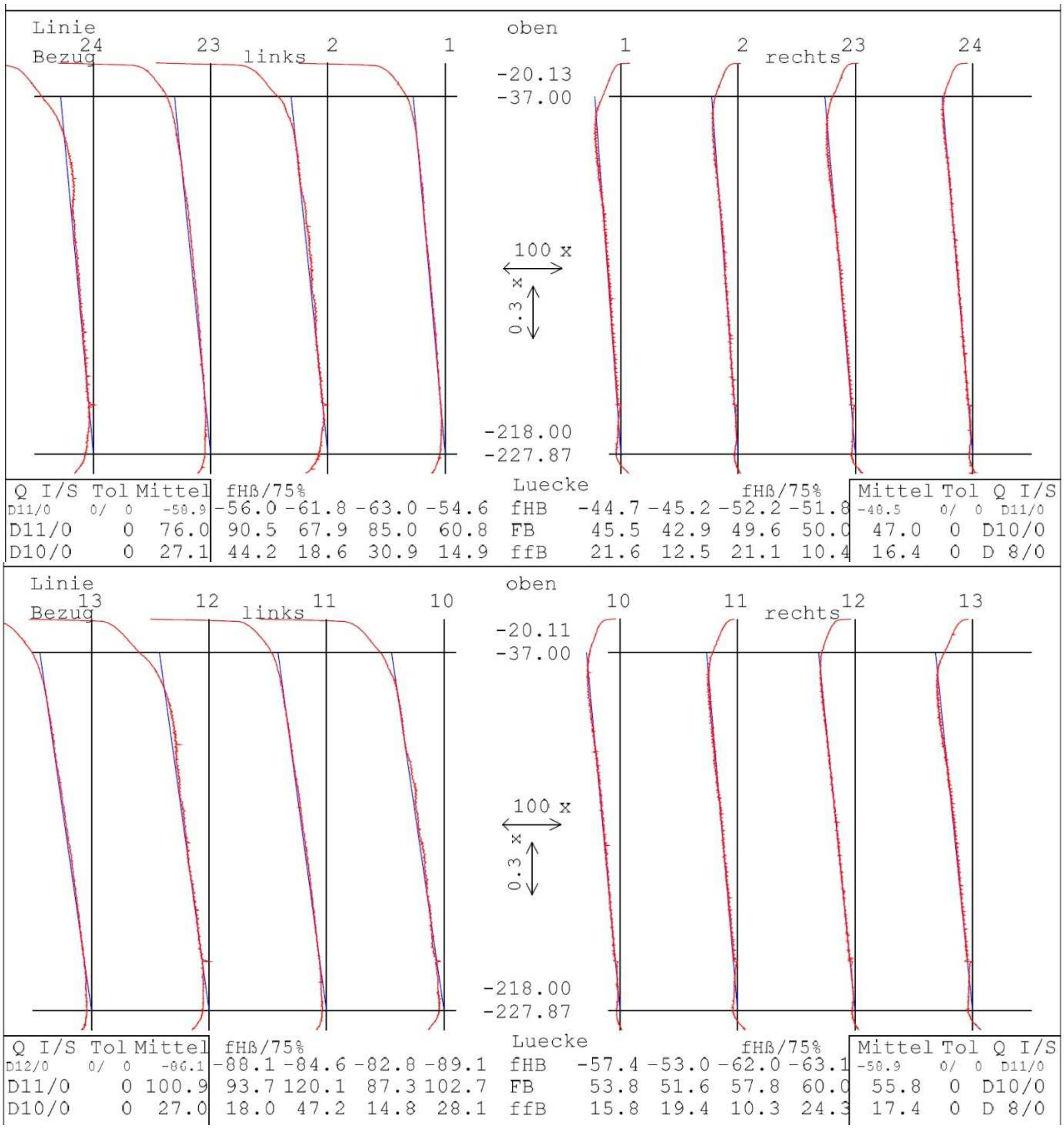


Figure 98 Resulting Tooth Direction Error data for long cylindrical blank sample

In the upper diagram, i.e. in the beginning area of the teeth, massive tooth direction errors result in value from up to $f_{H\beta}$ = 142,3 at the left edges of the tooth gaps, whereas yield maximum values for $f_{H\beta}$ = 64,6, right flanks in the lower diagram. It is noteworthy

to recognize that at the same rolling sample, as in the lower diagram, relatively good tooth direction error of at most fHβ = 15,5 found on the opposite side of these teeth.
In summary, it should be noted that always the left tooth flanks have significant tooth direction error, whereas the right flanks partially come up with surprisingly good results. Here, too, the asymmetrical volume distribution must be responsible to the extent of the teeth well.

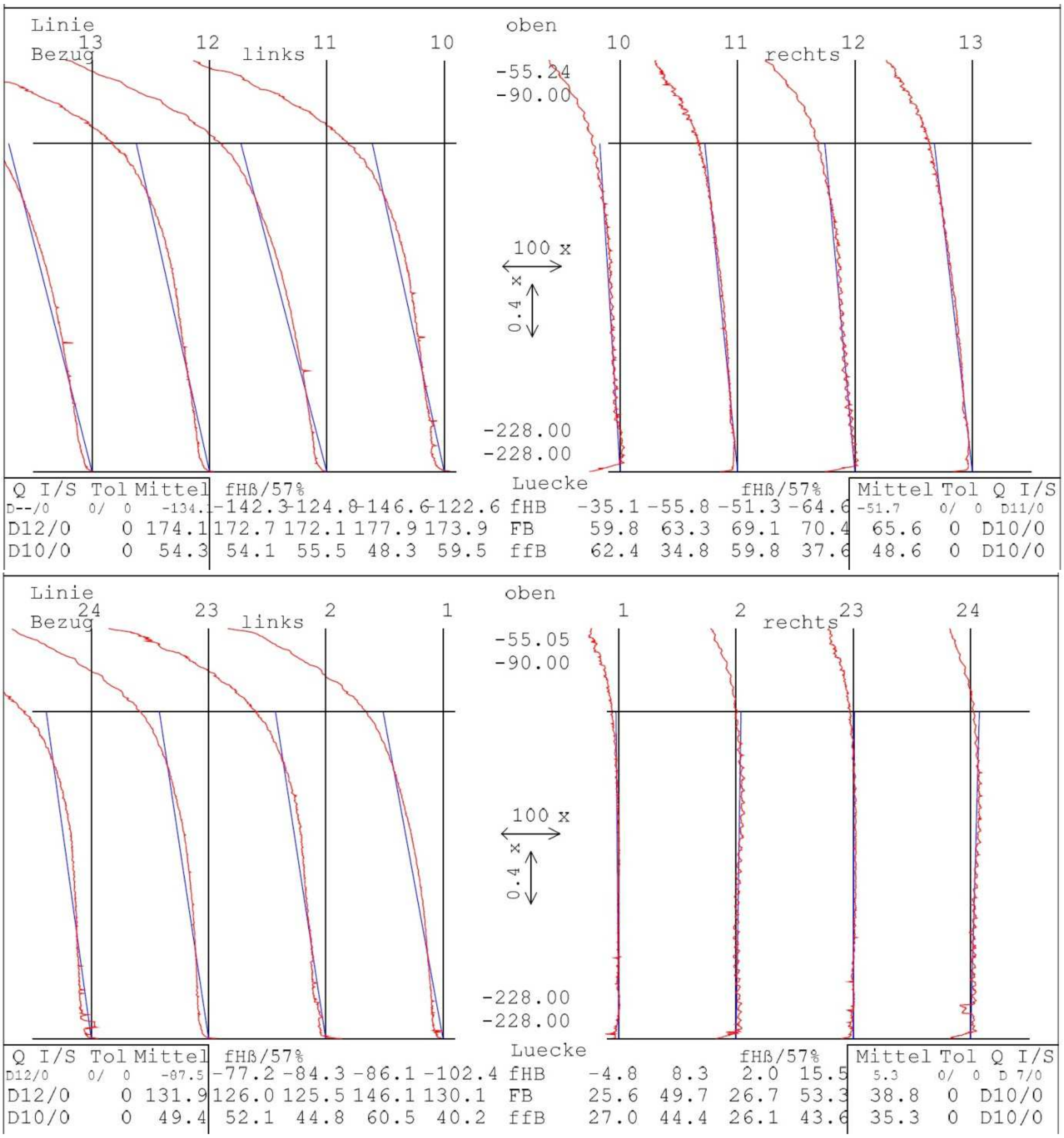


Figure 99 Resulting Tooth Direction Error data for conical blank sample

Stepped blank According to DIN 3960 tooth direction error of a stepped sample partly in the tooth height of the pitch circle were measured, where existing. The following measurement charts (see fig. 100) show in the upper diagram the tooth gap region 1, 2, 23, 24 only, as in the lower toothing area, no teeth where formed out to be measured according DIN 3960 standard.

It is a rolling sample with an acceptable variation of the tooth direction error. However, this result shows smaller differences in absolute value related to the charts before, but it needs to be taken into account, that the available flank length for measurement is limited by the step length of 20 mm. In conclusion the trends to be detected are in convergence to the long cylindrical blank example.

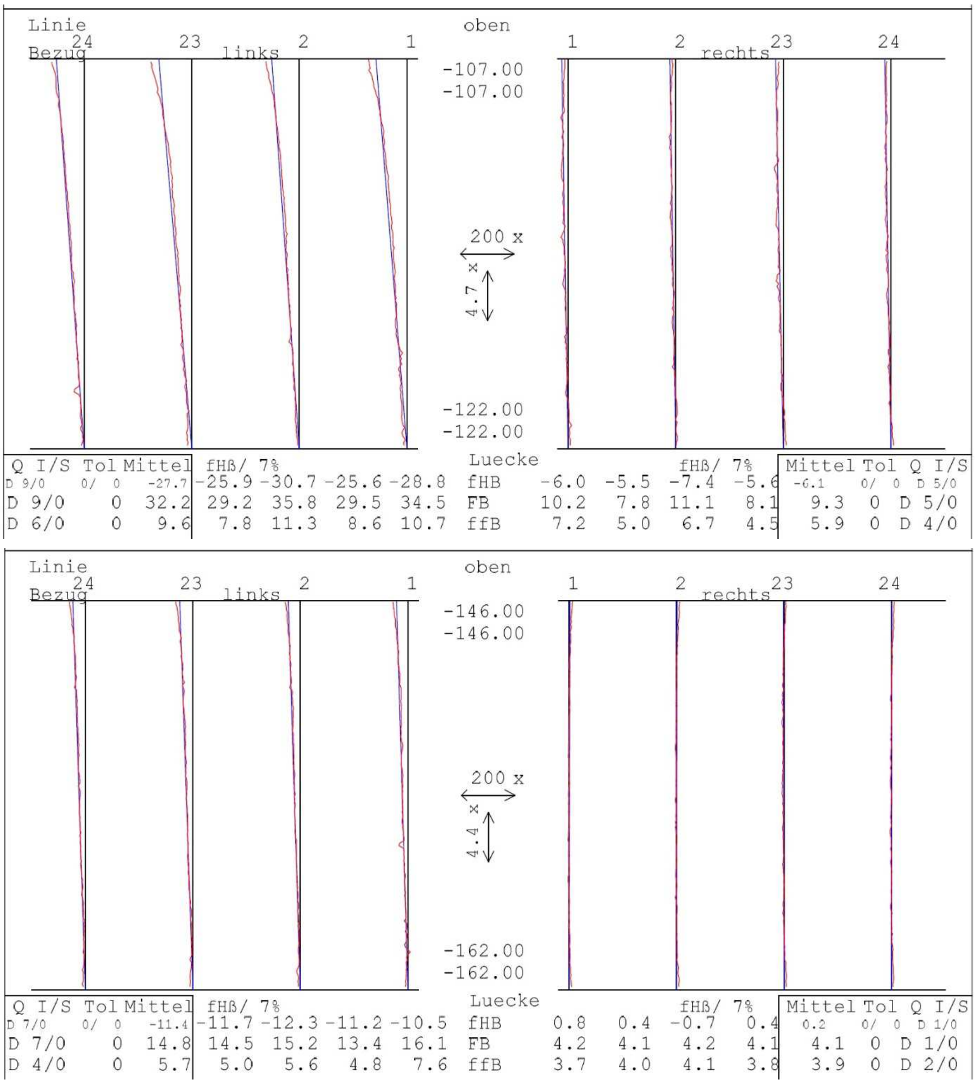


Figure 100 Resulting Tooth Direction Error data for stepped blank sample

5.2.4 Comparison Study of the emerging tooth contour

The following considerations will outline the thought process on how the geometrical characteristics can be clarified in terms of their evolvement during the WPM specific rolling process. This CAD-based assessment is required being able to elaborate potential control parameters in a considerable quality control loop approach. Therefore a theoretical assessment of the CMM acquired data, described in earlier explanations (see chapter 5.2.3.2) is being executed. The target of this examination is to more deeply understand the underlying root-cause of the WPM specific gear profile shapes (see fig. 62) being an inherent "fingerprint" of the process that has been analyzed as a foundation to this Thesis work.
As a starting point for a theoretical tooth generation assessment the blank samples using special geometry pattern had to be reviewed again in more detail.

Stepped Blank As can be seen in the detailed visualization of the CMM executed 2D- contour measurements (section definition following fig. 61) of the stepped blank sample (see fig. 101), the emerging behavior of the teeth are not to be considered symmetrical evolving.

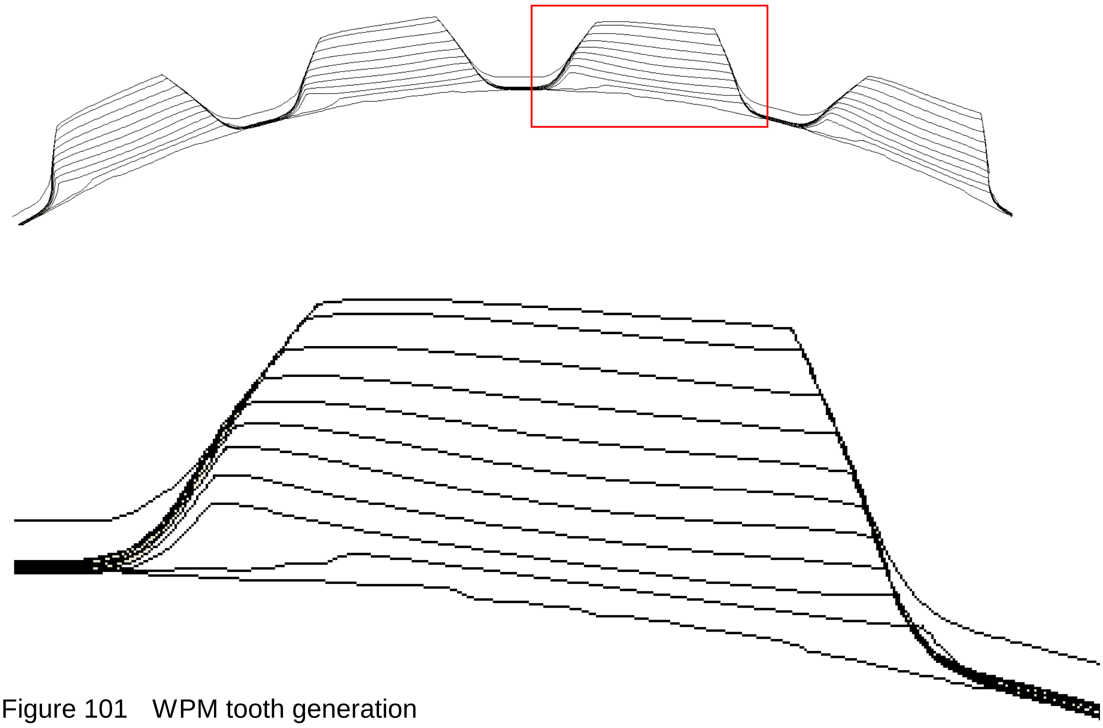


Figure 101 WPM tooth generation

As shown in the more detailed view it can be observed, that the left-site flank of the emerging tooth profile follows a systematic, but strongly different characteristic than the right-site flank of the tooth profile in terms of their material volume distribution during growth into the space of the work-tool tooth gap. It is to be stated, that a systematical unbalance of the tooth being generated occurs during WPM rolling. In a more detailed examination it is to be reviewed, in how far the unbalanced material distribution is carried out, comparing the left-site of a tooth geometry (see fig. 102 - green box) to the right-site of a tooth geometry (see fig. 102 - red box) [20].

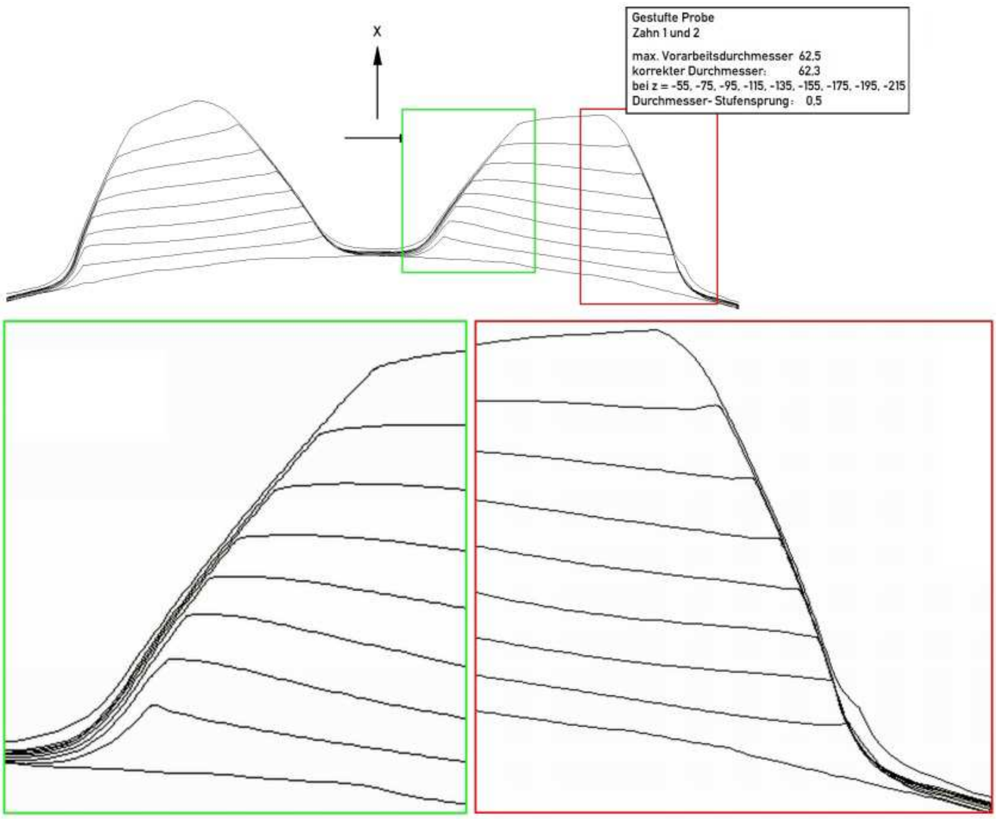


Figure 102 WPM tooth asymmetry

Taking into account the a priori known rated step of 0,5mm in diameter per step in the plank sample geometry, a 2D-areal analysis of the visualized forming steps (see fig. 101, 102) of the tooth material distribution of one exemplary tooth during forming can be determined (see fig. 103). Herby a strong unbalance of the left-to-right flank material distribution in relation to a virtual centerline of the tooth pitch can be found esp. at the early stage of tooth generation. As a further trend during tooth emerging the asymmetrical material distribution is being reduced to a final state, representing the final tooth shape and showing the typical tooth head shape being observed.

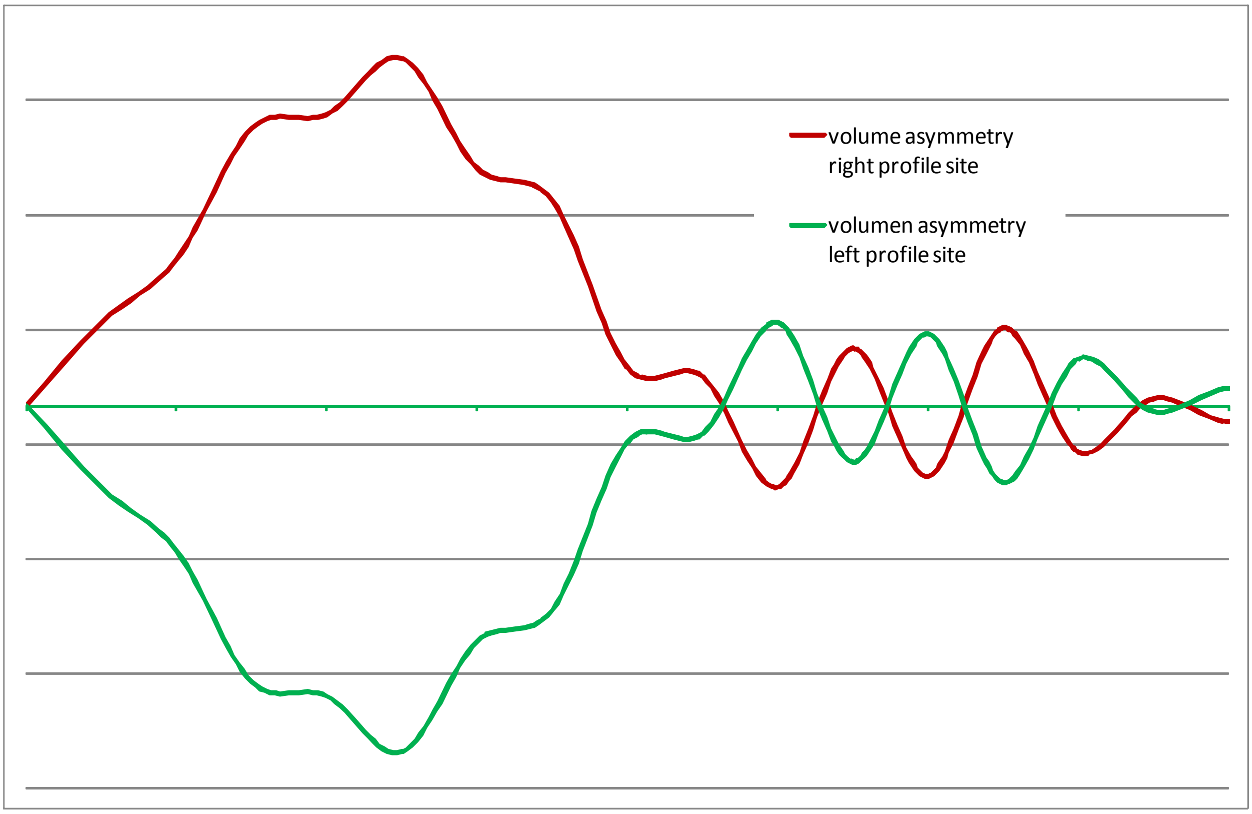


Figure 103 WPM tooth asymmetry analysis - stepped blank example

By importing the stepped blank final profile data into a CAD system, this mentioned typical final shape state can be visualized as follows (see fig. 104).

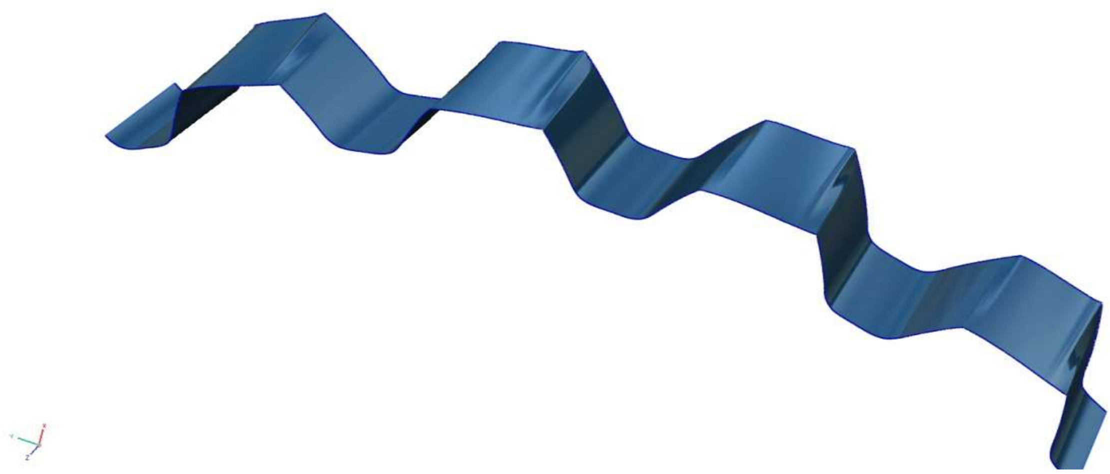


Figure 104 typical tooth head shape - stepped sample

Conical blank Within the next theoretical investigations the CMM measurement data of the conical blank 2D-contour sections are in the scope of determination (see appendix 1). The focus hereby again is set on the unbalanced material distribution during the emerging phase of the WPM teeth rolling process. Therefore, the 2D-contour section line data out of the CMM measurement has been imported into a CAD system (see fig. 105) as ell and geometrically examined. It can be observed at first that the typical asymmetry of the emerging teeth is visible in the conical blank sample as well and therefore occurring to by WPM process inherent.

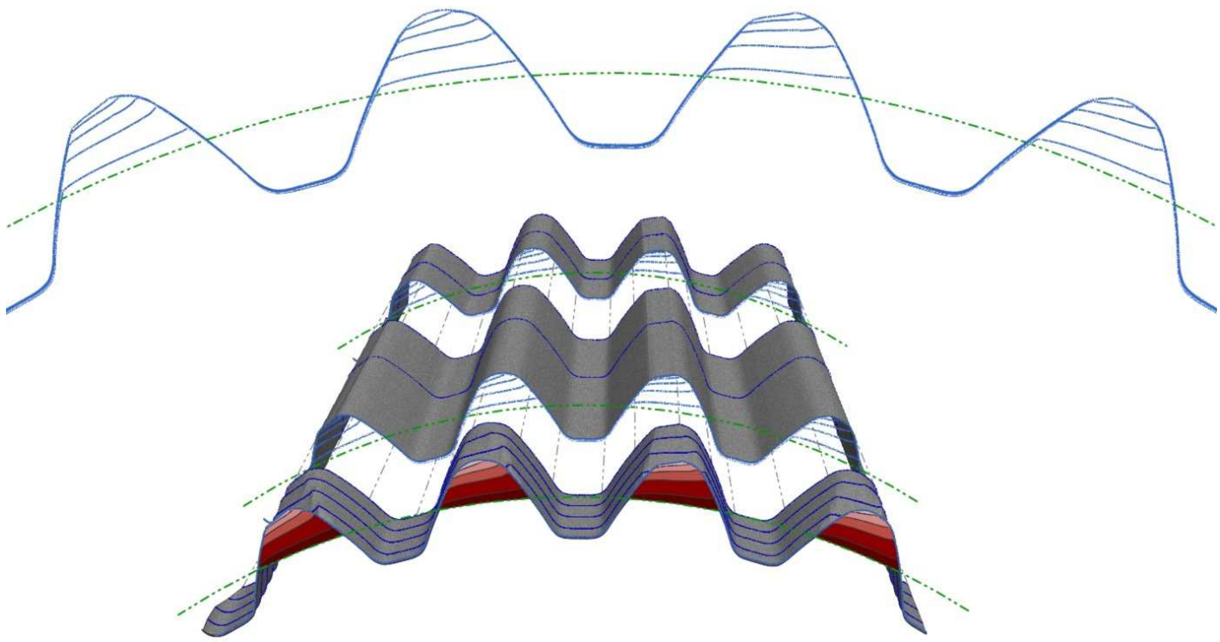


Figure 105 CAD Import 2D-Contour lines

Comparable to the earlier findings on the stepped sample example, the left-to-right flank profile unbalance can be observed on the conical blank as well and in the same order of characteristics of an overflow from the right flank site direction, to be observed on the tooth heads shape. Furthermore a systematic difference in the tooth head shape appearance between a tooth n and tooth n+1 can be stated (see fig. 62 for reference).
These observations can be observed within the standard measurements after DIN 3960 within the reporting of the pitch- / runout error (see fig. 94) and in the roundness evaluation of a rolling sample as well (see fig. 59 for reference). Based on these observations the question about a better understanding of the root-cause has to be raised. Therefore a deeper assessment has been accomplished.

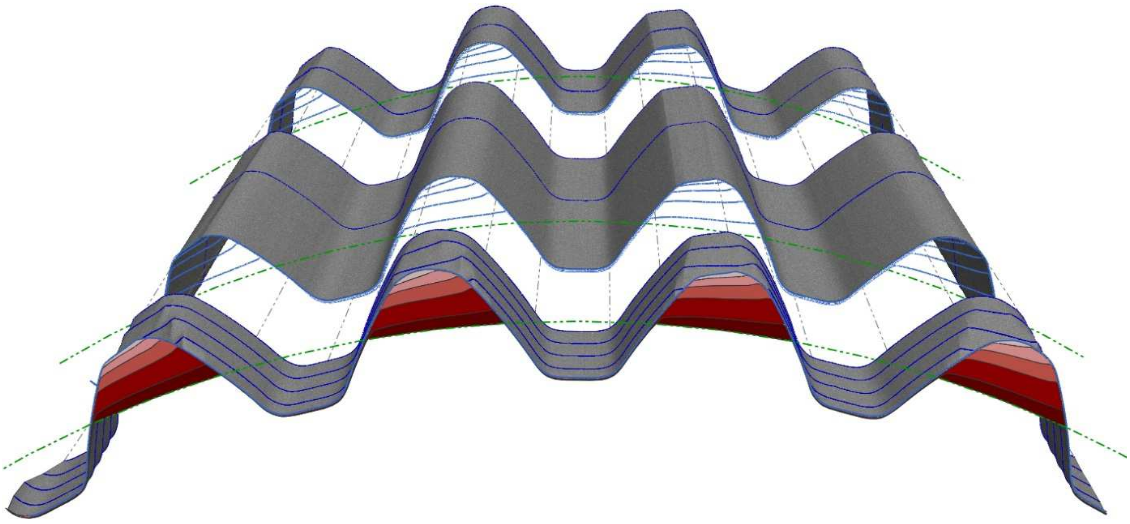


Figure 106 2D-Contour lines detail

Thinking of a more detailed investigation in terms of asymmetry aspects in WPM rolling, it has to be distinguished in the analysis between the area of forming zones (see fig. 107) that have been imprinted by the work-tool teeth (in this work being named as "negative forming zones"; shown as "green" areas in fig. 107) and the areas that have emerged by a material flow into the work-tool gap-spaces (in this work being named as "positive forming zones"; shown as "pink" areas in fig. 107) [18, 21].

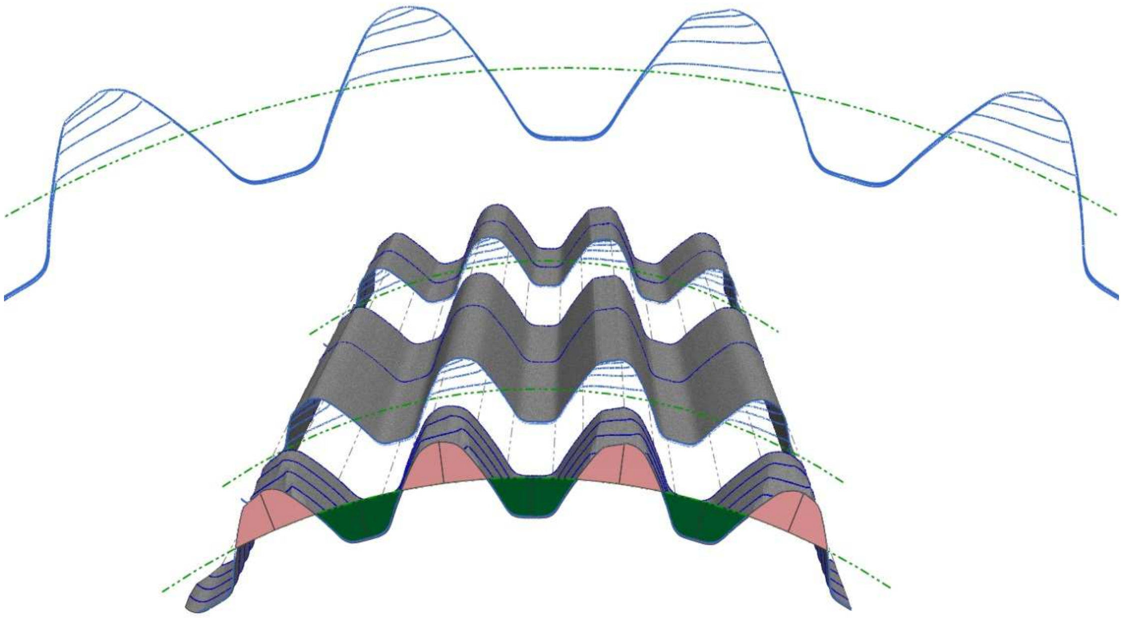


Figure 107 material distribution review (-/+ zones selection)

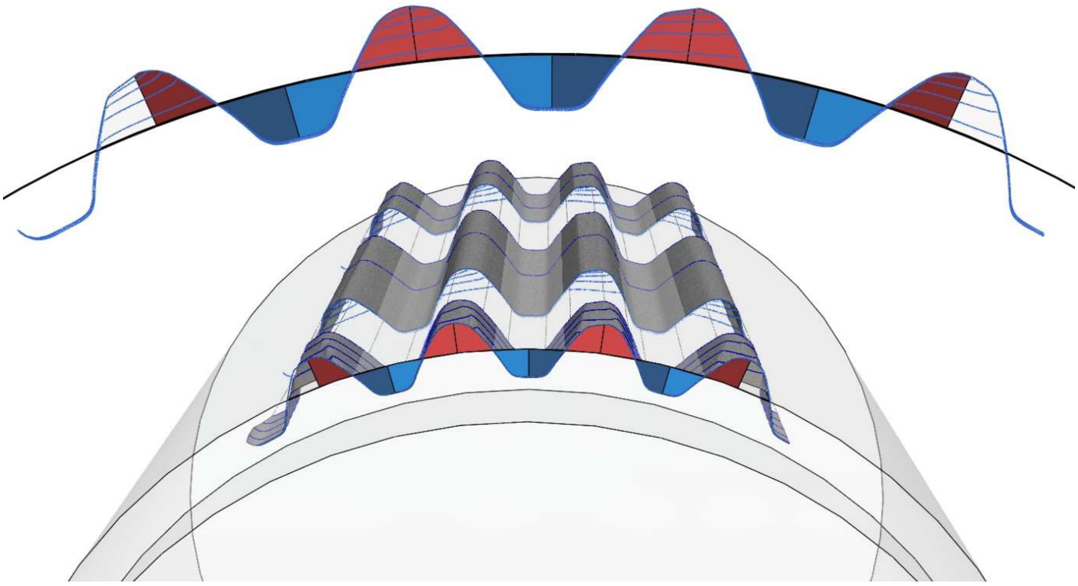


Figure 108 left-/right site flank

The negative- / positive forming zones are in a mathematical analysis thereby separated by the preliminary ideal blank diameter, in this case 62,3mm (see fig. 107; "green" middle line) in order to transfer the thought process to the cylindrical blank standard scenario. In a further abstraction level of investigation the negative- and positive forming zones could be even more distinguished in a left- and right flank site of the profile geometrically separated by the tooth pitch centerline (see fig. 109,110).

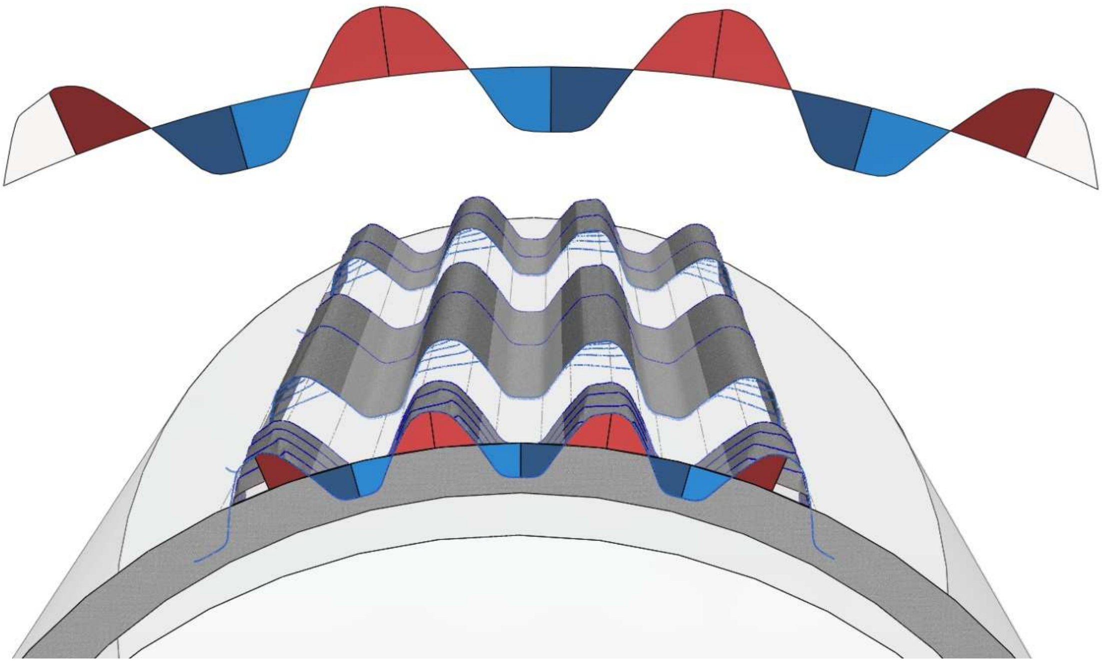


Figure 109 material distribution detail (I)

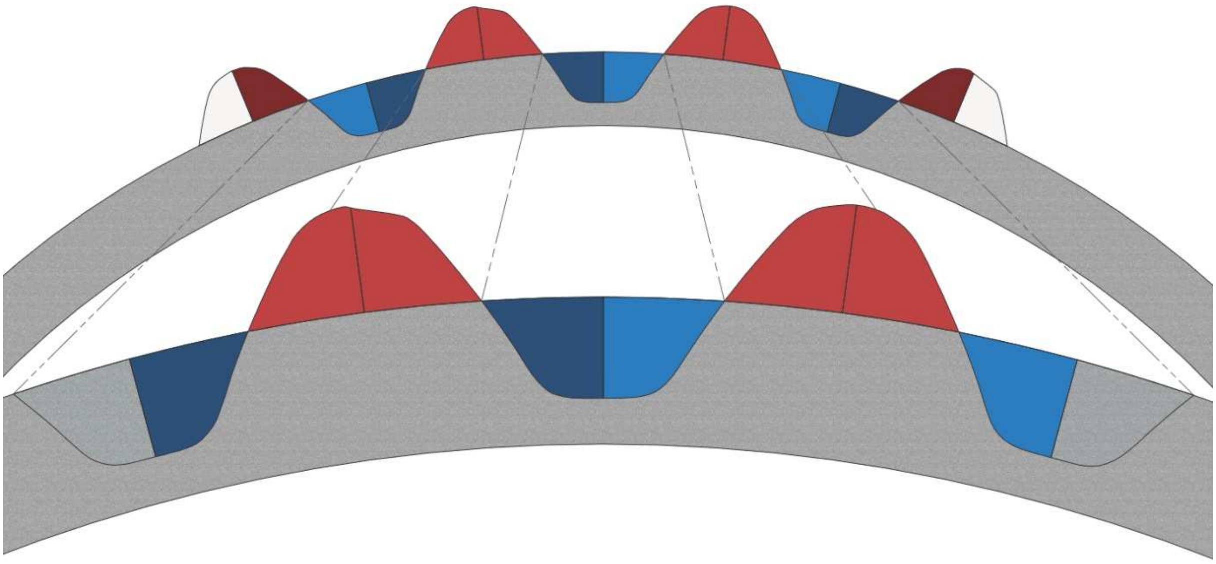


Figure 110   material distribution detail (II)

By visual comparison of the shown positive-/negative zones as well as the left -/ right portions of the tooth profile section (see fig. 110,111) it can be seen, that some systematic distribution element scheme is getting visible. It can be found that as well the positive- and the negative forming zone follow a similarity rule in their appearance between a tooth = n and a tooth =n+2 like already stated earlier but also that the distribution elements occur to become mirror symmetric in shape (see fig. 112).

The root-cause for such a result can be defined by the working kinematics principles of the work-tools [47].

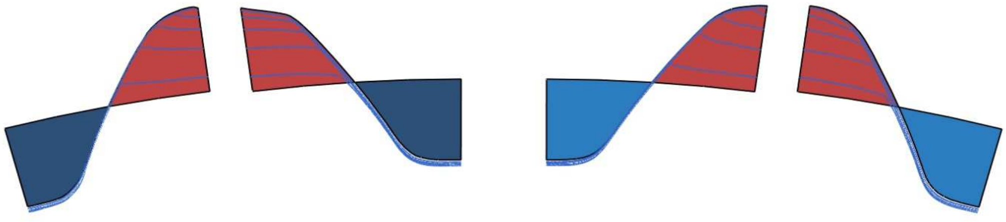


Figure 111   distribution elements (I)

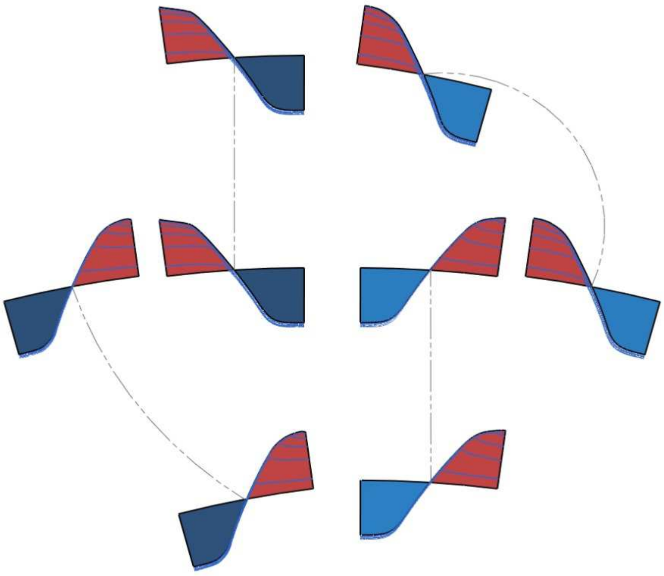


Figure 112 distribution elements (II)

Within the earlier analysis of the work-tool contact zones (chapter 4.2, see fig. 73, 74) some mirror-symmetrical process observation has been theoretically outlined.

Within the deeper assessment based on real case 2D-contour measurements of the conical blank this observation can be supported by the evaluation of the distribution elements (see fig. 112) and visualized in terms of their unbalanced properties in the concluding chart (see fig. 113) as following view (the mirror symmetries to be noticed):

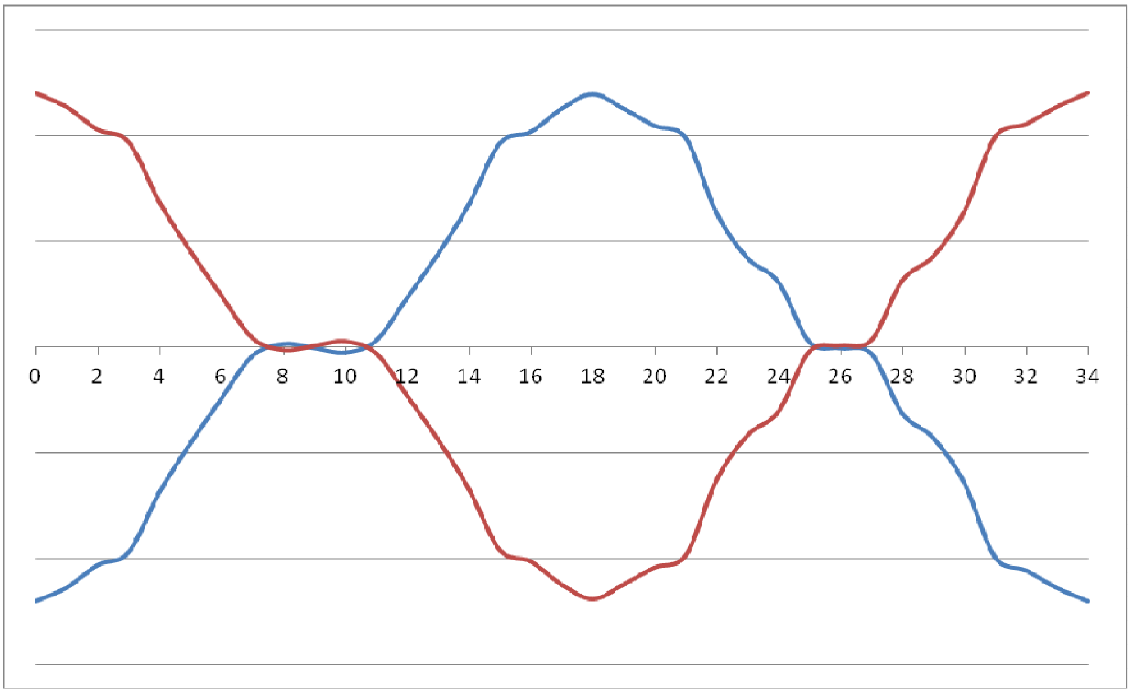


Figure 113 qualitative unbalance of tooth geometry during work-tool stroke

Finally, and in order to achieve a comparative link to the stepped sample explanations in fig. 103, the tooth material distribution of one exemplary tooth out of the conical blank sample during forming can be determined as shown below (see fig. 114).

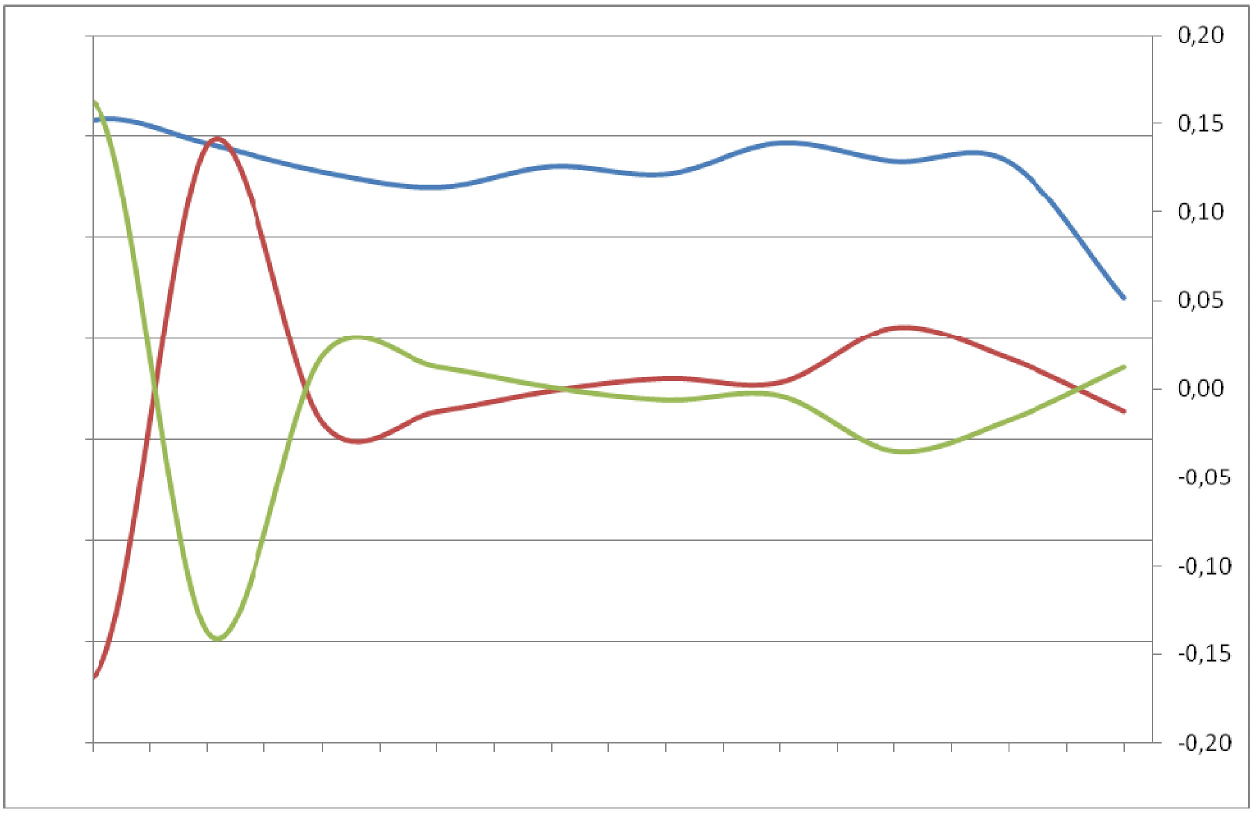


Figure 114 WPM tooth asymmetry analysis - conical blank example

Within this chart the mirror symmetric process behavior of the emerging tooth separated into left-to-right flank of the tooth profile (in relation to the ideal tooth shape) can be determined as well and supports the outcomes in analogy to the findings within this chapter 5.2 [20].

Further findings could still be derived from the gathered data and analysis being prepared but this further procedure wouldn´t add anymore content in the scope of this thesis work as it is not the goal of these examinations to develop a new WPM forming process environment.

5.3 Summary of the special geometry sample rolling

In conclusion of the WPM forming procedure of rolling samples using special basic geometry blanks it can be stated, that the a priori existing eccentricity of the prepared blanks, defined by its counter-hole centering features and due to the elastic deformation of the clamping and mounting mechanics of the WPM frame structure, the evolving pitch / runout error of the spline shafts is being influenced in negative manner.
Anyhow the majority of the final geometrical influencing parameters are given by the forming forces and the geometric specifics of the work-tool kinematic movements.
The results of the spline shaft geometrical measurements are therefore dominated by forming process itself. Therefore, it can be assumed, that the geometric specifics and workpiece characteristics (see fig. 115) as i.e. asymmetric tooth profiles and head shapes as well as the one-sited dominant occurring profile error to be observed at the series of WPM gear rolling samples indeed are being caused by the forming process specifics itself and not by pre-existent errors in workpiece centering and alignment issues in an unloaded situation. The underlying assumptions supporting the thought process within chapter 5 investigations are being confirmed finally by the discovered results. The outlined geometrical relationships supported by theoretical investigations and proofed in the examinations based on the post-process measurement data of the test samples describe the asymmetrical material distribution of the workpiece is finally caused by the guiding properties and kinematic path of the working tools. In addition, it can be stated that the geometric specifics generated by the WPM forming process do have an influence on the material texture as shown in exemplary figure below [36,100].

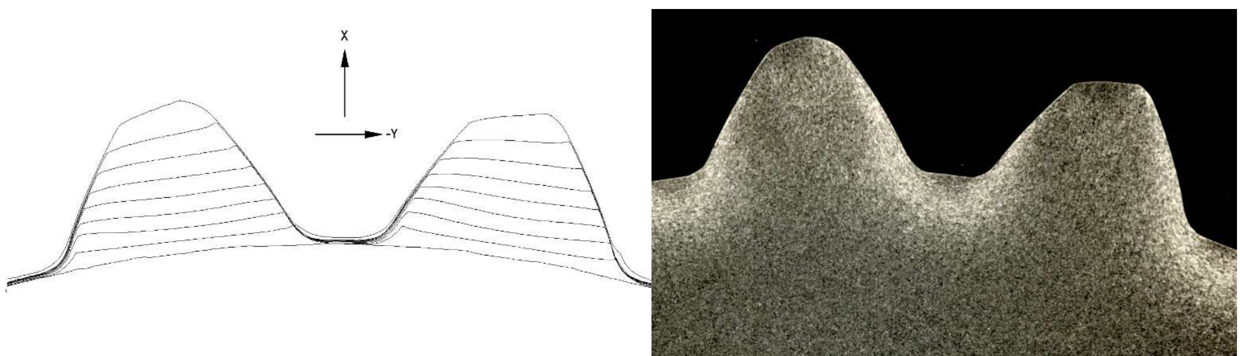


Figure 115 conical blank - emerging tooth asymmetry vs. metallographic analysis

6. Sensors and Signal Analysis

The process quality of machine tools is mainly determined by the achievable repeatability of the relative motion between the tool and the workpiece.

The physical quantities that have to be measured for monitoring and analysis of this WPM rolling process, in principle, are of a spatial position of the two tools and the feed position of the workpiece and, secondly, the angular position of the eccentric shafts of the tools and the angular position of the rotary drive of the workpiece.

The workpiece feed is coupled via a slip clutch to the drive train, so here fluctuations in the feed path can be expected per stroke [117].

As such sensors are not present in the existing machines and directly measuring the angle encoder could not be retrofitted because of the confined working space of the machine, laser optically or inductively operating proximity sensors were used at selected components of the drive train can be attached modular and minimally one or more multiple deliver pulses per revolution [8, 9, 65, 154].

The measurement of the workpiece feed rate, however, has been realized with an incremental linear scale (linear encoder) because the installation conditions allowed it above the workpiece carriage. The advantage of this linear scale is the direct measurement of the carriage position with high repeatability.

The entire measurement chain of the sensors that detect the movement of selected elements of the drive train of the rolling machine is shown and described below. In the first section (chapter 6.1), the emphasis is on explaining the sensor to the drive components of the drive train, is then in the second and third section, an analysis of the signals with respect to the constancy of the time behavior at steady load operation (idling), and a comparison of the stroke of the tools and the workpiece holder (sleeve) is performed.

6.1 Sensors and Measurement Chain

6.1.1 Sensors

Generally speaking, sensors are defined as sensors that implement a certain physical quantity into another physical quantity for better handling. [58]

6.1.2 Sensor Signals

From the multitude of partly redundant sensors, applied in a metrology framework into the WPM rolling test machine (see fig. 116), the following sensor signals have proven to be most important for a detailed analysis of the temporal behavior of tool and workpiece side of the WPM-machine during the rolling process:

a) drive shaft, measured at 2 change gears, 2 or 60 pulses per revolution)

b) workpiece holder (Pinole, 1 pulse per revolution)

c) Tool holder (signals eccentric 1-4, the one pulse per stroke)

d) laser sensor on the workpiece (9 pulses per revolution) [65].

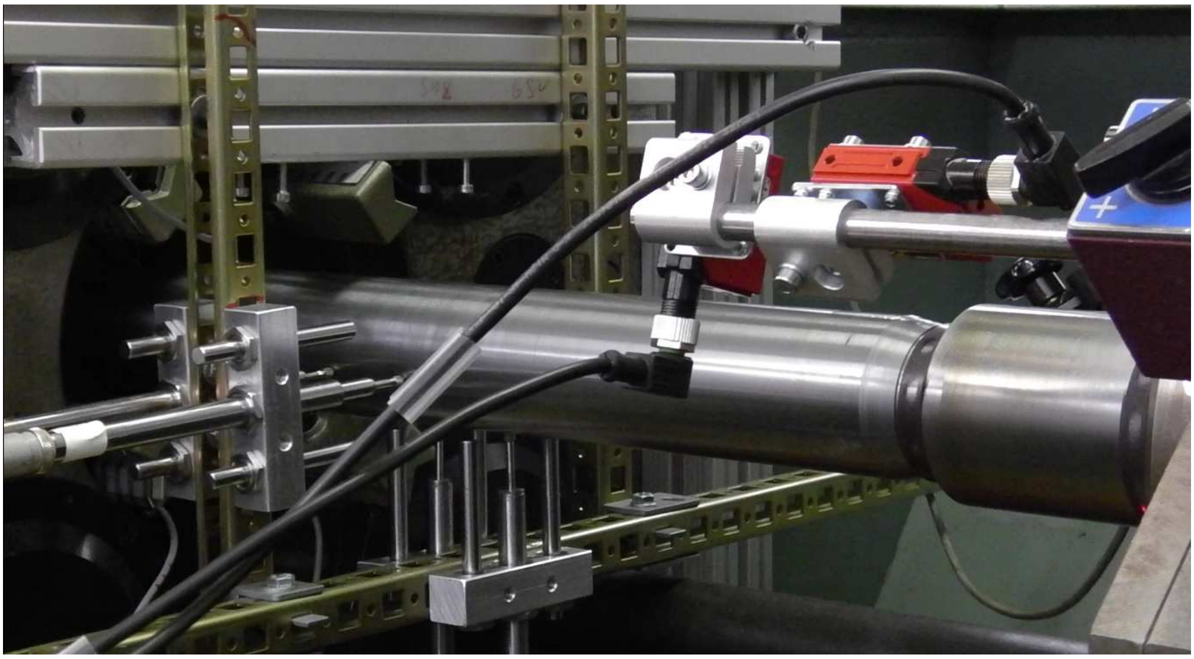


Figure 116 WPM 120 experimental metrology framework setup

6.1.3 Sensor Technology

At the minute wheel of the drive train and the workpiece holder (sleeve) of the following type of a laser optical reflective sensor was used with the following technical data (see fig. 117) [65]:

Type: Leuze HRTL 8/66-150-S12
HRTL8 - Laser diffuse reflection light scanner with background suppression, range of operation: 10 to 150 mm
f_s = 2 kHz, 8 µs Impulse, t_{anspr} = 0,25 ms

Figure 117 Specification of Laser Optical Reflective Sensor

On the tool holder (tool carrier) of the two half-shell tools have been on both sides, both the upper and the lower end retrofitted inductive proximity sensors, which have the following technical data (see fig. 37, 118):

Type: Leuze IS208 MM/4NO,
Inductive proximity switch, Sample rate f_s = 3.5 kHz; Range of operation 0 to 3.2 mm, maximum range: 4 mm, Delay $t_a \approx$ 0.2 ms, Reproduceability < 5 %

Figure 118 Specification of inductive switch

The mounting means are electronic and can be moved easily changing the workpiece and handling in the work area. The location is therefore not the same for all experiments, but may vary from one test to the next.

6.1.4 Signal Processing (Measuring Chain)

The further processing of the sensor signals is done according to the following scheme image:

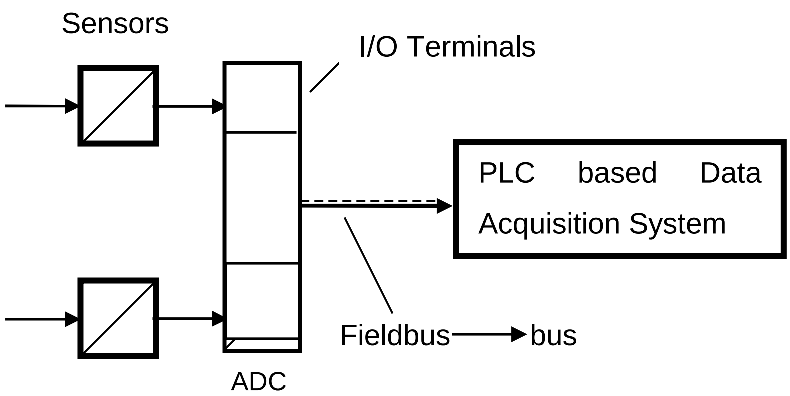


Figure 119 sensor measurement chain principle

The above chart (see fig. 119) shows that the logical measurement chain of the sensors which are connected to a decentralized I / O-interface terminals of the PLC system. These I / O terminals are in turn connected to a bus coupler, the (100 Mbit / s Ether-CAT, transmission rate) transmits the signal information digitally via a field bus to a PLC system, which handles the cyclic real-time data acquisition and the measurement data with a sampling rate of 1.000 s^{-1} and a repeatability + / - 50 ns (acquisition cycle time 1 ms, jitter 50 ns).

6.2 Signal Acquisition

6.2.1 Analog Sensors

These sensor signals are analog, i.e. to form the time characteristic of the sensor converted by the physical values from a value constantly. A temporal continuity is not provided, but it is sufficient a temporally equidistant time series.

Since then, the data is collected with a sampling frequency of 1 kHz (fS = 1.000 S / sec), corresponding to a time frame of tS = 1 ms). The temporal variations (jitter) in the transmission of the remote I / O terminals to the PLC data acquisition system is through the use of a fast fieldbus (EtherCAT ®) is very low (about 150 ns). The analog-to-digital converter used to have a conversion time of 10 microseconds and digitize the analog measurement signals thus sufficiently rapidly.

6.2.2 Digital Sensors

These sensors provide a so-called "digital" (binary) signal, that is only of a two-valued values kind of {0, 1}. Technically, these logic signals can be directly connected to the digital inputs of the PLC and require no analog to digital conversion more [65, 155]. With the laser reflex sensors and inductive proximity switches above, there are those sensors whose internal signal processing is discussed in the following section 6.3 principles after.

6.3 Signal Processing (Online Signal Processing)

6.3.1 General

The first stage of the signal processing occurs in the sensor itself; here the measured variable, i.e. the physical quantity to be measured is transformed, according to the sensor principle into another physical - size implemented for the purpose of transmission and processing - mostly electric. Subsequently, the reaction is carried out in an electric voltage signal in a measuring amplifier, which is integrated in modern sensors in the sensor housing.
The sensor output is usually an electrical voltage signal in the range from 3,3 to 5 V, 24 V for the occasional switching signals.

The signal processing steps of analog sensors with binary output are shown schematically in the figure below (see fig. 120) are shown.
The sensor (a) converted the measure d (, distance ') according to the measuring principle to an analog electrical output which is fed to a Schmitt trigger with hysteresis to generate a possible steep-flanked rectangular pulse signal. This pulse signal is in the last stage, if necessary to a higher level, for example, 24 V amplified. Optical sensors are commonly connected operate to compensate for the undesirable influence of the

ambient light [43, 66, 67]. In the present case there comes a red laser is used, which on the measurement principle of the diffuse reflection light scanning (Laser diffuse reflection light scanner) detects the distance with a sampling frequency of fs = 2.000 Hz [15, 61, 94].

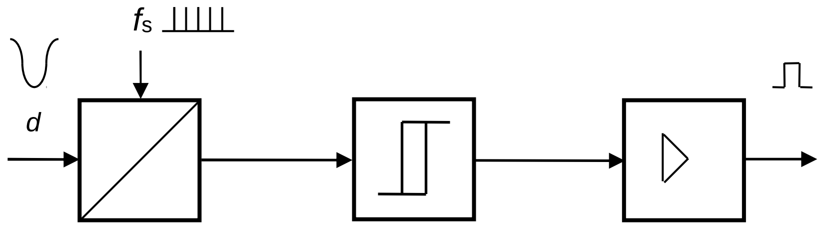


Figure 120 signal processing chart

It follows a computational latency of max. 0,5 ms; specified in the data sheet, the delay is, however, better it is from 0,25 ms.

6.4 Signal Processing (Offline Signal Processing)

For evaluation of the pulse signals described above, a computer program "WPA" (WPM Pulse Analyzer) was created that reads the selected measurement channels from the output files of the PLC data acquisition system and is able to analyze interactively predetermined signal-pairs regarding periodicity and time offset.

With the help of the pulse analysis program following quantities can be determined:

a) the period duration of the work-tool stroke
b) the period duration of the workpiece revolutions
c) the time offset between two arbitrarily selectable pulse signals
d) the angular offset between any two selectable signals
(only for rotationally-periodic processes)

6.4.1 Analysis of the Four Tool-Eccentricity Signals

To study the behavior of the two tools four proximity sensors were mounted in the working area of the machine. The location of these sensors is at least during a

Rolling experiment kept constant. Changing the workpiece, it may result in contact with this magnetic holder, so that their absolute position may shift.

Thus, the analysis of the variable in its absolute position sensors can gives only relative statements during a trial; the signals in their time so only able to give information on any changes in the tool position during the test, there are no absolute comparisons with subsequent experiments possible.

Subsequently, the process flow is described and shown the limits of the analytical possibilities of these sensor signals (see fig. 121) based on the four tool-Eccentricity signals.

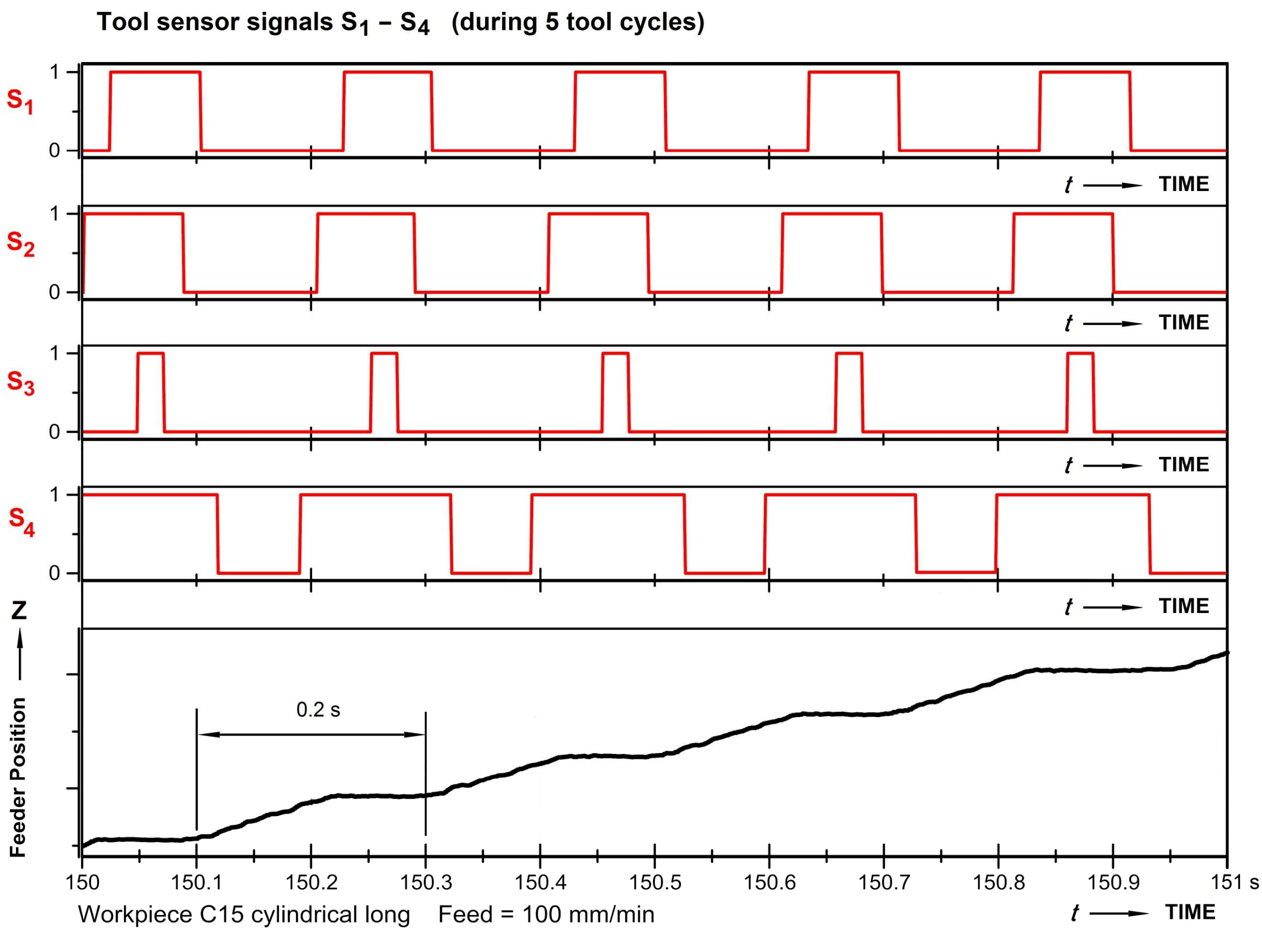


Figure 121 work-tool eccentricity signals

The interpretation of the first two signals (S1, S2) is as follows: signal S2 rises from signal S1 because the bottom edge of the right tool at first approaches the sensor; only afterwards dips the upper edge of the right tool in the response range of the sensor 1.

As mentioned allows the ad hoc fixing the sensor holder against any attempt absolute statement but the signal analysis provides only statements to changes in the temporal relative position of the two pulse signals during a rolling experiment and allows it to conclude that any changes in position of the tool. The duration of the pulses indicates, as long as the upper or lower edge of the right tool during a tool stroke cycle is in the vicinity of the sensor. Due to the limitations of the installation of the sensors in the workspace very different time and location of the sensor signals arise from one another. The signals of the sensors of the tool left (S3, S4) are significantly different in comparison to the right tool in its duration; However, this only means that they are the position of the two sensors was so in the current rolling test that sensor 3 (top left tool) was positioned farther from the tool. It is also important here that it can close during the rolling process on the occurrence of changes in position of the tools from the changes in the time interval of the respective signal edges.

As the stroke rate was adjusted to about 5 s^{-1}, it can be seen in the timing of feeding the Z (t) is the phase of the linear increase (phase advance) and the stoppage (stage of rolling, the tools are in gear); both phases require approximately 0.2 s total, an excerpt from five strokes is shown.

6.4.2 Time Analysis Tool – Workpiece

The diagram chart (see fig. 122) of the further analysis is the result of an example for channel 3 (Sensor 1 of the tool holder) and Channel 7 (sensor on the workpiece holder) shown in fragmentary form.

One recognizes the temporal relation of the workpiece rotation drive, measured on the workpiece carrier (quill) to the strokes of the tool, measured at the eccentric-1. The signals are not synchronized and do not have the same frequency, the rotational frequency of the eccentric in relation 34/24 is higher than the workpiece rotational frequency. The analysis of the time interval results in a periodically decreasing stepped curve, from which a periodical saw-tooth-shaped profile can be seen.

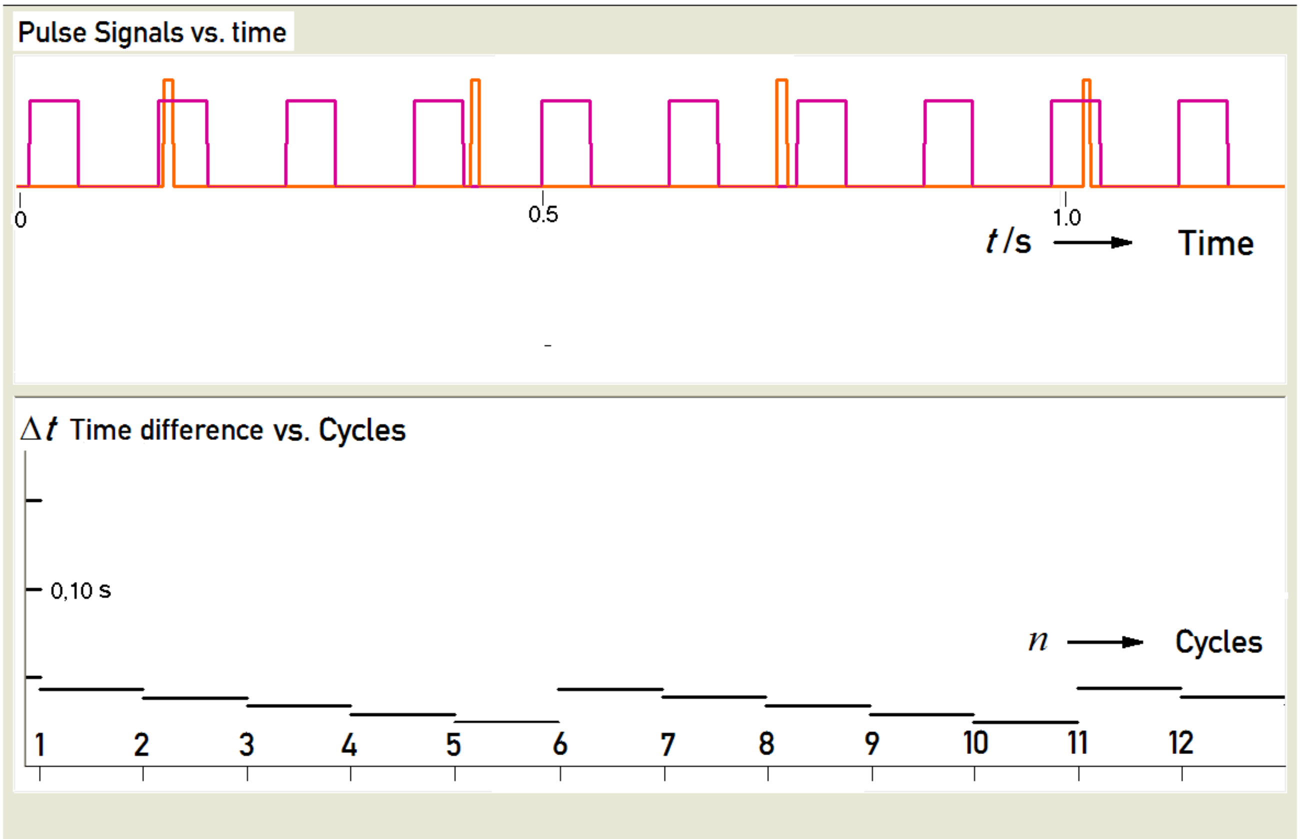


Figure 122 Work-tool / Workpiece signal time analysis

6.4.3 Temporal Consistency of the Tool Signal

A more detailed analysis of the temporal consistency of the four tool eccentricity signals was performed; it is exemplarily shown in Figure 123. The gray curve shows the signal eccentric 3, the white signal, the eccentric cam 4th. From the analysis result data in the figure above you can see that the period of the excenter-3 signal after booting to the values of 0.204 to 0.206 s varies, a stroke frequency of 2.451-2.463 corresponds to s^{-1}. The dispersion is mainly due to variations in the drive speed and in a small proportion to the quantization error in the sensor detection signal (+ / - 1 ms) due. A smaller proportion can come to a scattering of the trigger point of the sensor [112].

Result Data

#	t_Pulse1	dt_Pulse1	f_Pulse1
0000	7,950	0,0000	0,000000*
0001	8,216	0,2660	2,409639*
0002	8,426	0,2100	2,439025*
0003	8,634	0,2080	2,439025*
0004	8,838	0,2040	2,450980*
0005	9,044	0,2060	2,456999*
0006	9,250	0,2060	2,463053*
0007	9,454	0,2040	2,450980*
0008	9,658	0,2040	2,463059*
0009	9,862	0,2040	2,450980*
0010	10,065	0,2030	2,463053*
0011	10,269	0,2040	2,463053*
0012	10,473	0,2040	2,469137*

#	t_Pulse2	dt_Pulse2	f_Pulse2
0000	8,281	0,0000	0,000000
0001	8,696	0,4150	2,409639
0002	9,106	0,4100	2,439025
0003	9,516	0,4100	2,439025
0004	9,924	0,4080	2,450980
0005	10,331	0,4070	2,456999
0006	10,737	0,4060	2,463053
0007	11,145	0,4080	2,450980
0008	11,551	0,4060	2,463059
0009	11,959	0,4080	2,450980
0010	12,365	0,4060	2,463053
0011	12,771	0,4060	2,463053
0012	13,176	0,4050	2,469137

#	t_Pulse12	dt_Pulse12	W
0000	8,281	0,065	88,0
0001	8,696	0,062	107,3
0002	9,106	0,062	108,4
0003	9,516	0,062	109,4
0004	9,924	0,062	109,4
0005	10,331	0,062	109,4
0006	10,737	0,060	105,9
0007	11,145	0,062	109,4
0008	11,551	0,062	110,5
0009	11,959	0,062	109,4
0010	12,365	0,062	109,4
0011	12,771	0,062	109,4
0012	13,176	0,061	107,6

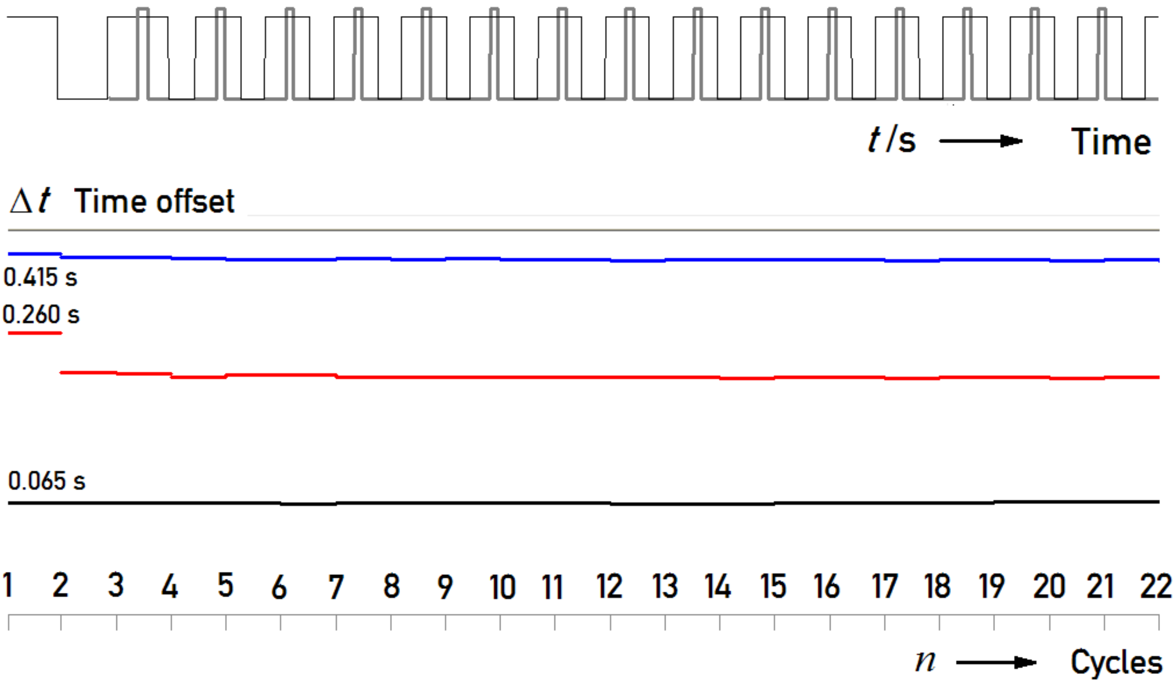


Figure 123 Work-tool stroke signal consistency analysis

One recognizes the speed power-up at the beginning of the measurement, a corresponding reduction from the period per revolution. The subsequent steady state shows little variation, as you can see also the table of values in the upper part of the screen dump. The period (3rd column, dt_Pulse1) remains very constant at the value 0.2040 and varies by only 1 ms, which is due to the temporal resolution of the data acquisition.

6.4.4 Temporal Stability of the Workpiece Rotation Drive

The use case shown in Figure 124 was selected for analysis of the temporal consistency of the rotational speed and the angular position at various points in the driveline. Here, a signal from the drive shaft to the rotational drive signal to the workpiece (spindle) is analyzed.

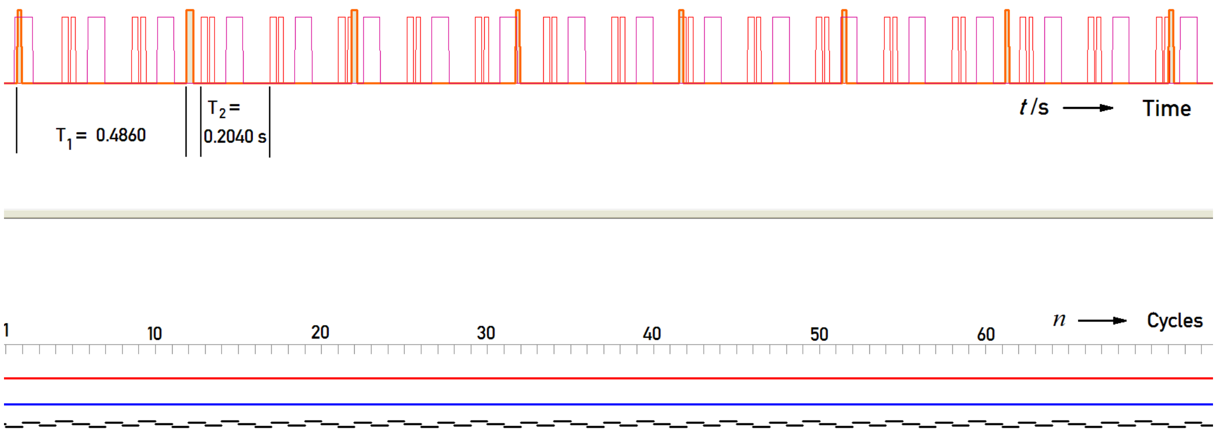


Figure 124 Workpiece rotation signal consistency analysis

The double pulses shown in red are being acquired from the laser reflection sensor on the minute wheel, so the middle of the drive train on the right side of the machine; the individual pulses (orange) shown increases have been so recorded at the Pinole the workpiece rotary drive. The pulse analysis provides both the two period durations, and the time offset between the rising edge of the second doublet pulse, based on the rising edge of the quill pulse (sensor to the tool holder) [65].

The time difference is greatly exaggerated black on the revolutions of the spindle.
It is recognized periodically with a characteristic pattern every 3 + 2 turns. Also, the curve shown in Figure 125 of the two sensors on the minute wheel of the drive shaft and the eccentric, as measured by the tools shows the good consistency of the ratios, suggesting an angular displacement below the measurement resolution.

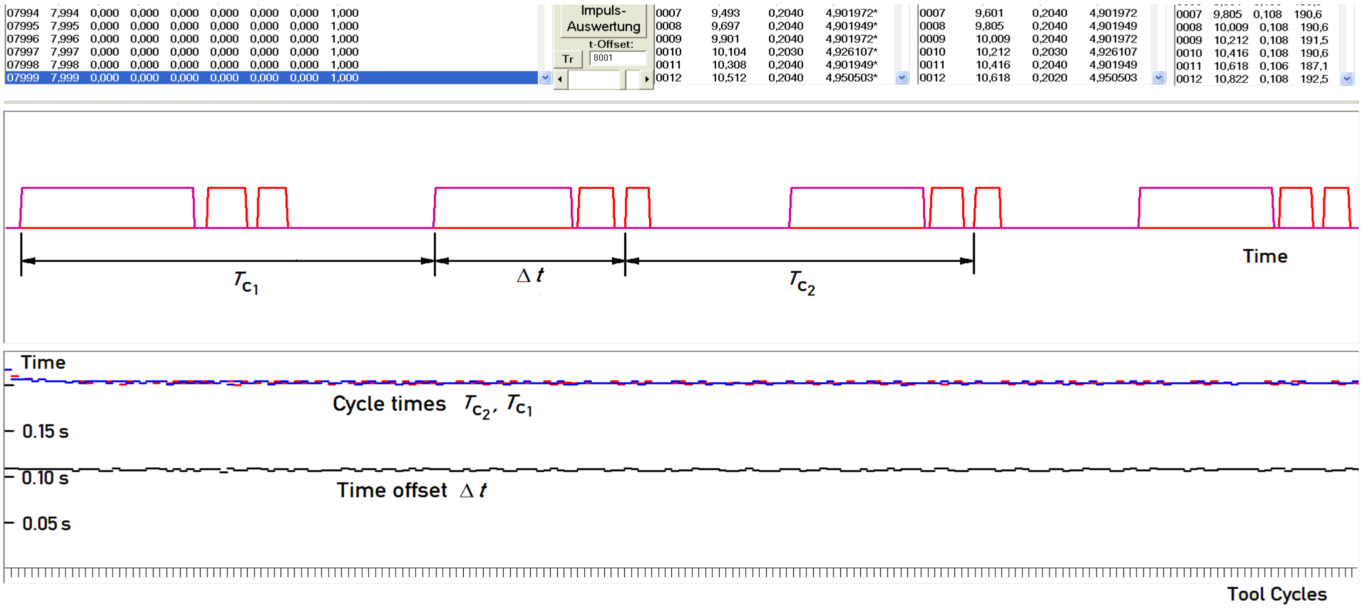


Figure 125 Workpiece angular position consistency analysis

6.4.5 Comparison Tool and Workpiece Mounting

The hardest part of the investigation of the temporal behavior of the drive train of the WPM rolling machine is the comparison of the eccentric strokes with the rotation of the workpiece. Since the rotational frequency of the eccentric to the rotational frequency of the workpiece rotation drive according to the number of teeth ratio 34: 24 behaves, results from the analysis of the time interval between the signal from the quill and the signal from the eccentric periodic beat, as shown in fig. 125 can be seen as falling stairs (see Fig. 126).

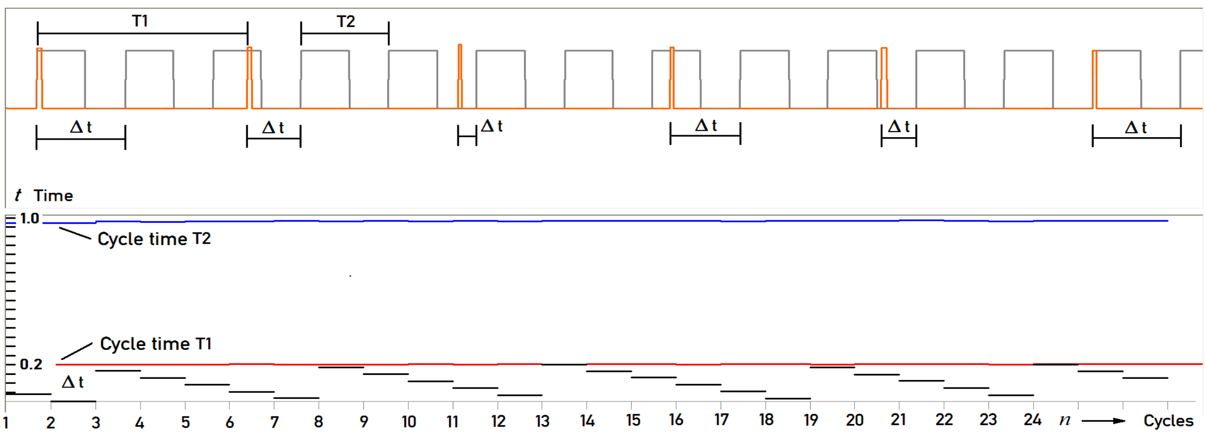


Figure 126 Work-tool / workpiece signal periodic comparison

The periods of the tool eccentricity signals (T1) and the workpiece drive (T2) are constant in the detection accuracy and the speed variations of the main drive. The time difference between the two signals has the expected decreasing stepped reduction of the time interval of the signal edges, since the ratio between the eccentric shaft and rotation of the workpiece is a non-decimal finite.

6.4.6 Comparison Workpiece and Workpiece Mounting (Quill)

6.4.6.1 Workpiece Rotation - Entire Course of the Rolling Process

The total course of a WPM rolling cycle below, (see fig.127) shows a rolling process at the top of first red in the time course of driving power of the feed path, and the pulses from the sensor at the sleeve and the four pulses per revolution of workpiece.

At the beginning you can see the maximum of the measured electrical power input (red curve). It is the ramp, that is, the acceleration phase of the main drive, wherein stationary workpiece feed (black curve). The spindle is already rotating, recognizable by the impulses of the quill signal (yellow, 1 pulse per revolution of the workpiece mounting) [70]. The chosen in favor of an overview of the entire rolling process time scale leads to a crowded representation of the pulses (yellow = quills pulses , green = workpiece pulses) , but these are examined more in higher temporal resolution below.

The observed change during the rolling process of the time offset of the first workpiece relative to the pulse at each pulse quill revolutions of the workpiece holder is shown in the lower part of the chart (see fig. 127); the occurring time offset is in the range Δ tn = 0:18 to 0:15 s (left chart axis) and has a clearly discernible tendency to fall. To facilitate interpretation of this temporal offset between the quill pulse and the first pulse of the four workpiece impetus was from the time offset and the period of each rotation n the angle between the workpiece and the workpiece holder (s) is calculated and a corresponding scale graduation in degrees on the right side as follows generate the graph.

$$\varphi(n) = \frac{\Delta t_n}{T_n} 360°$$

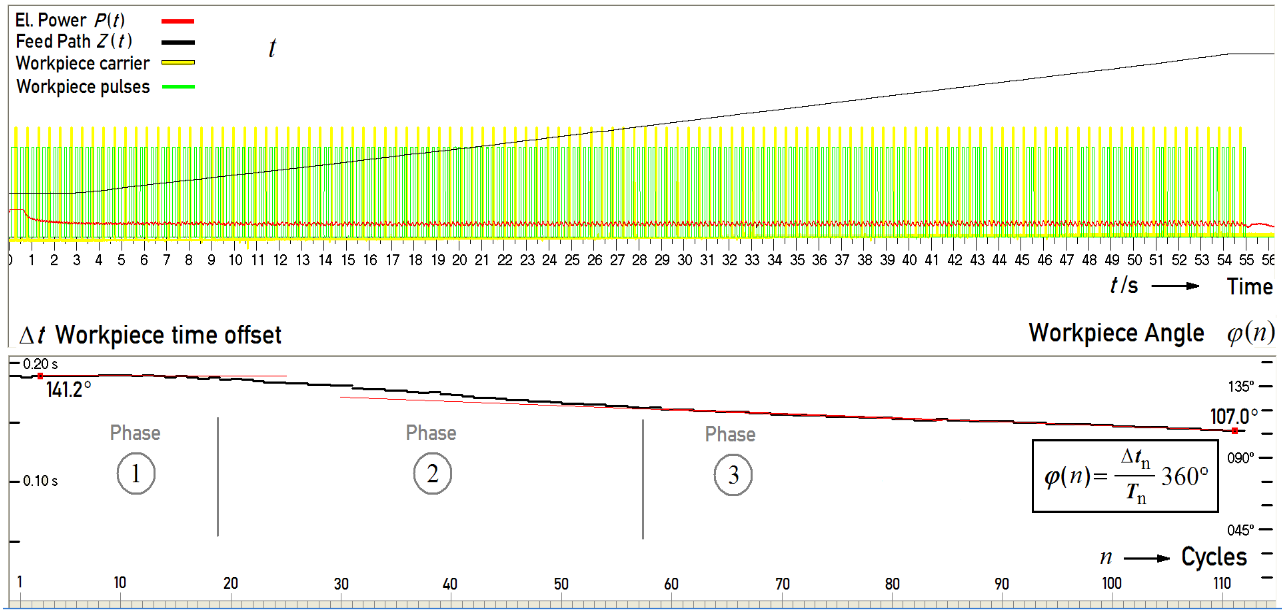


Figure 127 WPM rolling cycle analysis

The observed angle changes obviously from an initially constant phase onto a sliding scale sloping transitioning into an approximately linear decrease of the angular offset in small increments by each revolution of the workpiece holder. The change of the workpiece angle over the entire rolling process is approximately 141,2° -107,0° = 34,2° spread over approximately 100 revolutions. This results in an average angular displacement of about 0,35 ° per workpiece revolution.

For these three different patterns, the rolling process has been divided into three phases (see fig. 127). Subsequently, the individual measurement signals are first explained, and then investigated and described the three phases in greater detail.

6.4.6.2 Explanation on the Measured Signals on the Workpiece

In Chart (see fig. 128), the measurement signals are shown as a function of time in the upper part, as detected by the sensor:

Drive power P (t) (red), axial feed Z (t) (black), the pulse of the workpiece holder (1 pulse per revolution Pinole, gray) and four work-tool pulses (green), which were recorded on the workpiece circumference.

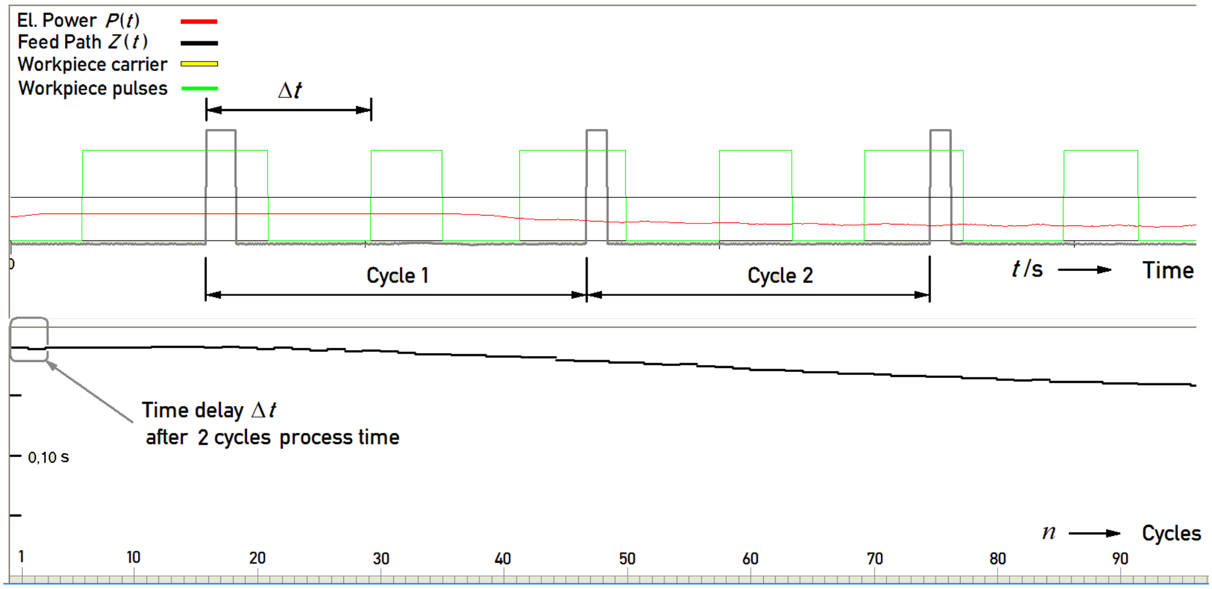


Figure 128 WPM rolling cycle - workpiece signal detail

It can be seen that the workpiece relative to the workpiece holder (quill) shifts slightly over the course of 95 work-tool strokes again and again in the circumferential direction. At the beginning of the process, the cycle 1 to cycle 20, the angular position of the workpiece is not constant and only depends on the random installation position of the workpiece relative to the workpiece carrier.

From cycle 20 onwards occurs at each workpiece revolution to small, which accumulate time shifts. This leads to the conclusion that the rolling tools, the workpiece is rotated in each case upon engagement under load by small angles. This could be shown with this analysis, both qualitatively and quantitatively and is explained below in detail at the various stages of the process.

6.4.6.3 Detailed Phase-Explanation / Measured Signals on Workpiece

Phase 1 In phase 1 (in figure 127, left), a native of the workpiece clamping process workpiece angle remains approximately constant, the value varies only in the context of the resolution and measurement accuracy to + / - 0.1 °.

This phase angle is nearly constant before or when the acceleration phase of the main drive is stopped and the feed movement begins, recognizable by the linear increase of the feed path; only when the first tool - workpiece contact takes place, i.e. after the 19th revolution of the workpiece holder, a first slight change of the workpiece angle is recognizable (start of phase 2).

Phase 2 Here is a lightweight, progressively decreasing change in the workpiece angle for each quill rotation determine. The workpiece angle increases with each revolution from further; After 38 revolutions goes phase 2 to phase 3 on (see fig.129).

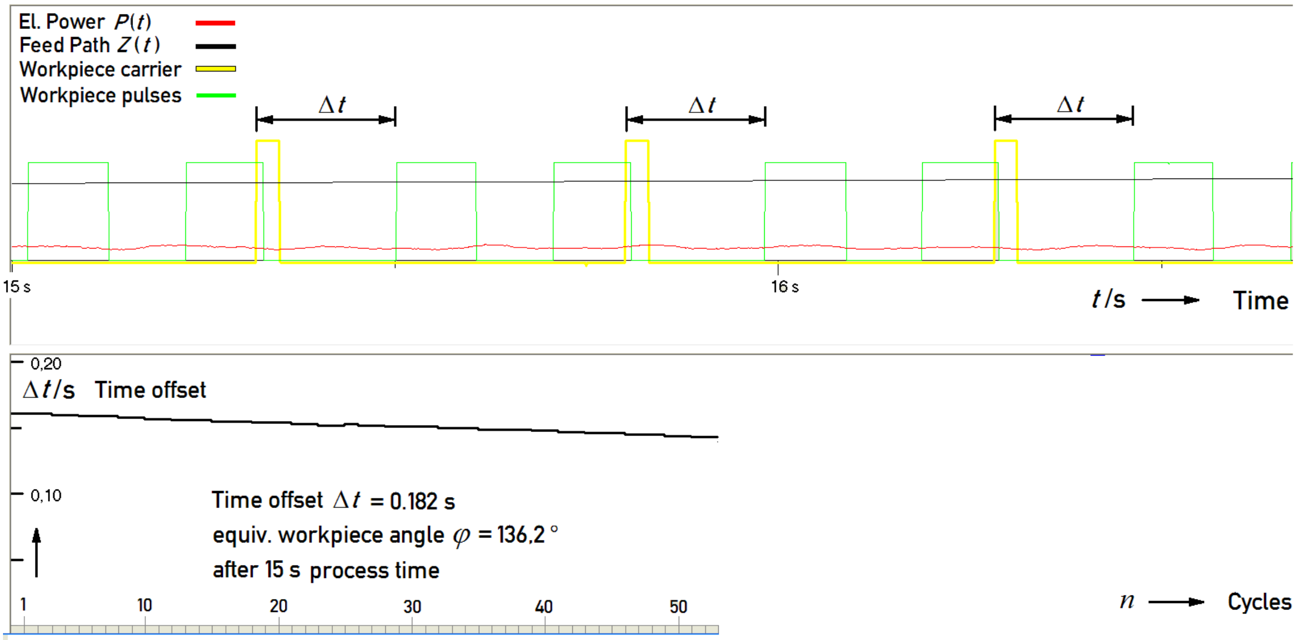


Figure 129 WPM rolling cycle - phase 2 analysis detail

Phase 3 In Phase 3, an approximately linear angle curve can be seen; the red line that is superimposed on the measured values. The following diagram (see fig. 130) shows the sleeves and workpiece pulses after 30 s rolling time.

The (green) Workpiece impulses are now well ahead of the quill pulse; the time interval between the pulses has decreased to 0,161s; that is, the corresponding workpiece angle has migrated from an initial 140.3° to 120.5° in the meantime [70].

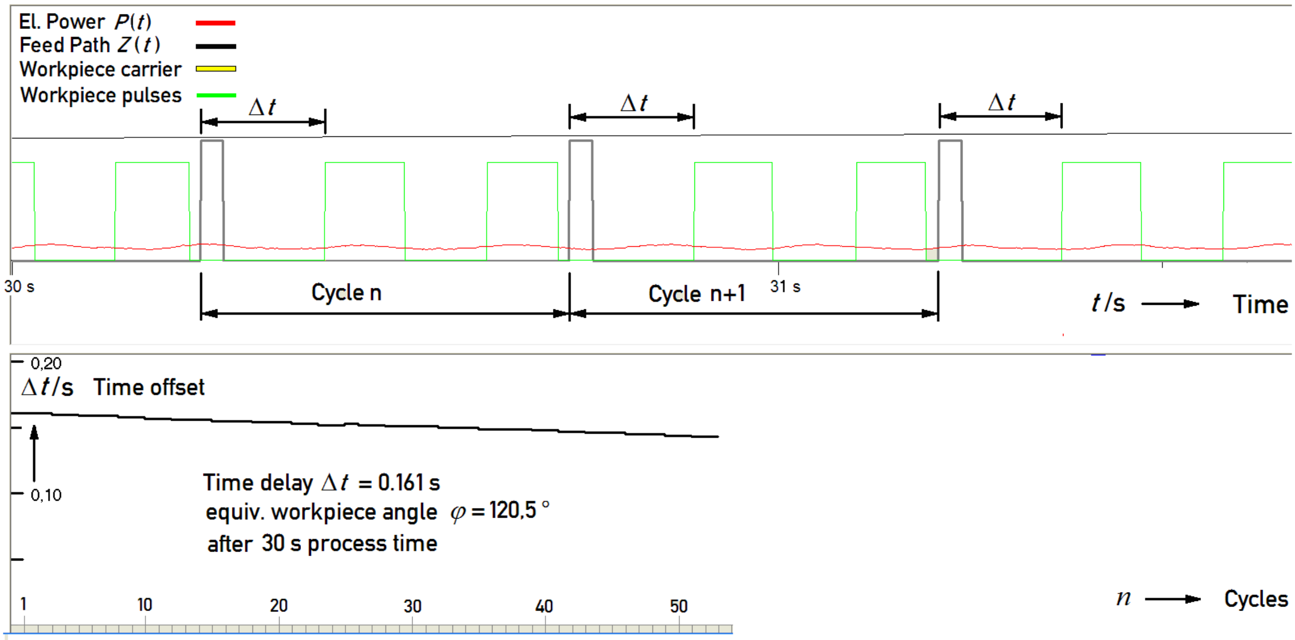


Figure 130 WPM rolling cycle - phase 3 analysis detail

Conclusion It could be shown that a time analysis of signals, which are supplied by inductive or laser-based distance sensor, quite new information about the behavior of the rolling machine and its drive components, can be obtained.

The explanation for the observed rotation of the workpiece between the clamping tips can be explained by the geometry and kinematics of the tool engagement specifics; measurements were reproducible a beginning at the beginning of the rolling process, in the first tool-workpiece contact on each revolution of the workpiece holder, a first small but then increasing rotation of the workpiece in the tips mounting which progresses linearly at a value of about 0,3°-0,4° per rotation in the further course of the rolling process as an indication of a sub-optimal process inherent work-tool engagement behavior that has been determined within the theoretical WPM rolling process analysis shown in chapter 4.2 (see fig. 77,78 for comparison) [39, 47, 104].

7. In-Process Metrology Framework as a New Measurement System Approach

A major change in future production processes can significantly change the role of metrology solutions for process control and vice versa the improvement of the efficiency in metrology solutions could imply benefits for production workflows [37]. The industrial significance of metal forming techniques and even net-shaping technologies such as additive manufacturing is rising in regards to their importance in the field of mass production applications [2].

This chapter will give an outlook on an In-Process monitoring approach, whereby geometrical feature quality constraints can be determined based on the targeted component feature specification to be observed. The use case of WPM rolling will be further continued as a base for those investigations and as findings are being elaborated in prior chapters.

The outcome of the systematical approach consolidating such an analysis can be used:

- in Root-Cause Analysis, where forming process irregularities causing geometrical irregularities,
- to Qualify a gear forming process On-line during the gear production,
- to Collect stability parameters of the process and
- for Characterization of the forming process on knowledge based interpretations.

Some inter-relational findings on process parameters specifics can even be seen as base for a model-process that could extend its application to an Inside-Sensoring approach for lifetime monitoring of technical systems in the future and therefore create or interact with further scientific research fields.

7.1 Introduction

The principle of coordinate measuring technique is based on the fundamental relationship of the contractual design of a coordinate measurement device and the measurement accuracy. If it comes to integrated metrology frameworks this paradigm changes into purpose driven setups of metrological elements depending on the measurement task or gauging application.

Today a Metrology Framework as a mature technical setup is mainly known esp. in large scale metrology application such as Laser tracker based assembly operations e.g. in aerospace body frameworks or guides manufacturing operations on such large structures. The motivation and demand for such an approach was driven by the technological challenges that had to be accomplished combine with the high cost ratios of the large components being produced.

In the field of commoditized mass production of precision components and not limited to prior explanations (see chapter 2.2.1), the stability control of the process parameters leading e.g. into components feature accuracy combined with requirements on functional surfaces in respect e.g. to tribology- and wear behavior over lifetime or even aesthetical properties generated the intrinsic requirement for new metrology framework approaches [99]. The merge of a product feature or drawing centric metrology approach with manufacturing process focused thinking is a current underlying industrial trend [100] relying on new directives in terms of process control by almost real-time or predictive feedback loops [147]. Respecting this trend it can be observed that metrology equipment investments are currently moving into In-Line applications close to manufacturing processes and based on quality requirements even into machining processes in order to provide the required feedback loops at reduced production cost [45, 100].

In regards to the scope of this thesis work the Originality of the new metrology framework approach is mainly represented by focusing on a detailed analysis of:

- the complex interdependencies between working-toolsets movements and workpiece geometrical characteristics in the WPM gear forming process combined with the relation to relevant process parameters
- Usage of internal geared rolling tools (WPM methodology) as a research platform
- in almost real-time dimensional and process parameter acquisition.

Therefore, the Novelty of the considered measurement setup can be stated as:

- the combination of different sensing technologies for process monitoring
- the On-Line process quality prediction out of the sensor data correlation results using the geometrical- & process parameters being acquired.

In Summary the scope is determined by the fully integration approach of dimensional metrology & process parameter monitoring as a base for process quality control [19, 20, 101, 121].

The geometrical characteristics at splined machine elements manufactured by rolling processes are unique for certain classes of rolling methods and the specifics can be found in functional as well as in non-functional tooth areas [27]. The central question being answered in the findings of prior chapters is, if the geometrical characteristics are direct or indirect related to certain process parameters? As this is the case for the content of this work, the monitoring and evaluation of these relevant process parameters allow a review of the rolling process as such and the prediction of the resulting component qualities [103].

7.2 Challenges and limitations of In-Process measuring technology in metal forming applications

The overall rolling process target in metal forming is to achieve a defined and feature driven material distribution (e.g. gear teeth) in an incremental- or continuous material flow process [18, 22, 59].

This basic assumption inherent contents several target conflicts for In-Process measurement setups, which can be stated as the:

- mass production capability vs. achievable component or feature accuracy
- feature accuracy realization by achieving a defined and balanced material distribution vs. the functional required material properties
- System (re-)calibration and environmental compensation
- Measurement Uncertainty estimation of the metrology system(s)
- Correlation & Traceability of In-Process Metrology as such

The metrological challenges of In-Process control in Gear metal forming processes can therefore be characterized by the:

1. Non-linear material forming behavior (strain-hardening, flow curve characteristics)
2. DOF of the workpiece during forming process
3. Kinematic movement and Workpiece guidance properties by Work-Toolsets
4. High forming / reaction forces and related misalignments and distortions

5. Complex & multidimensional Work-Tool – Workpiece interaction
6. Influences of the Work-Tool geometry and kinematic movements

The typical geometrical feature characteristics are located on the accessible surface of the rolled parts and targeted to be therefore detected by suitable sensors (non-contact) within the forming machine and during the production process. A special attention should be spent to the capture of typical shapes and edges to be recognized perpendicular to the centerline of the spline shaft (Fig. 131) [100]. In terms of accessibility and real time recognition of dimensional parameter trends, the distinguished view of functional areas and non-functional areas (see fig. 131, 132) in terms representing a correlation for the quality degradation combined with the relevant process parameters. As derived in the findings of this thesis work the specific characteristics (see chapter 5, 6) the non-functional areas like the gears head/root are representing the unbalanced behavior of the WPM process consistent to the functional areas of the involute tooth geometry as they are evolving in the identical manner during forming (see fig. 101). But comparison to accessibility the non-functional areas are easier to be observed In-process as they are located at the circumference of the workpiece.

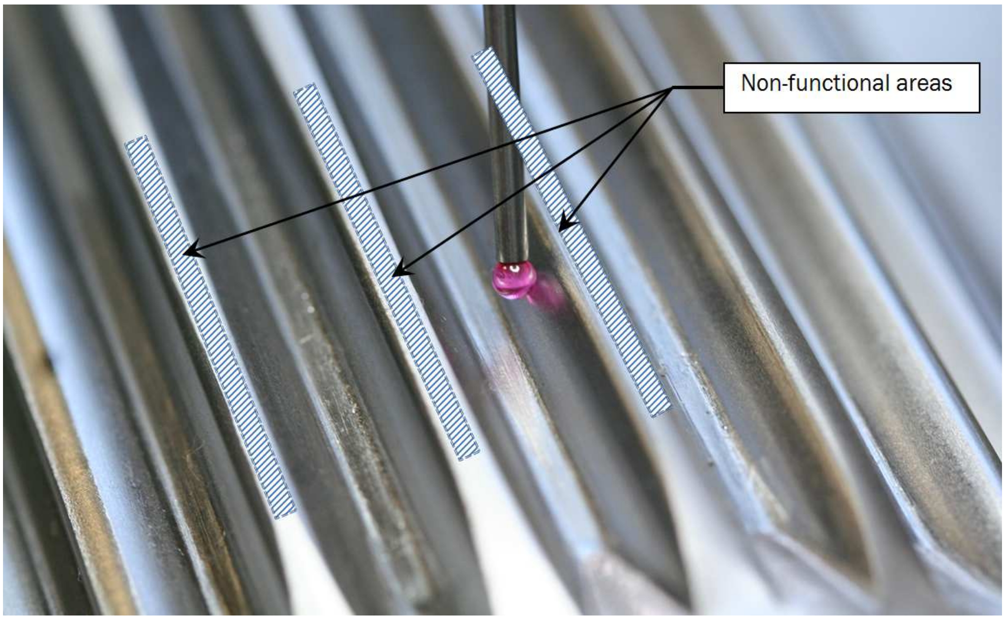


Figure 131 Separation of Tooth Areas (I)

This mentioned the dimensional gear parameters are to be represented by non-functional geometrical features (see fig. 132) and correlated to inherent process parameters, within this study mainly to the feedrate interaction of the toolset [19, 24, 100].

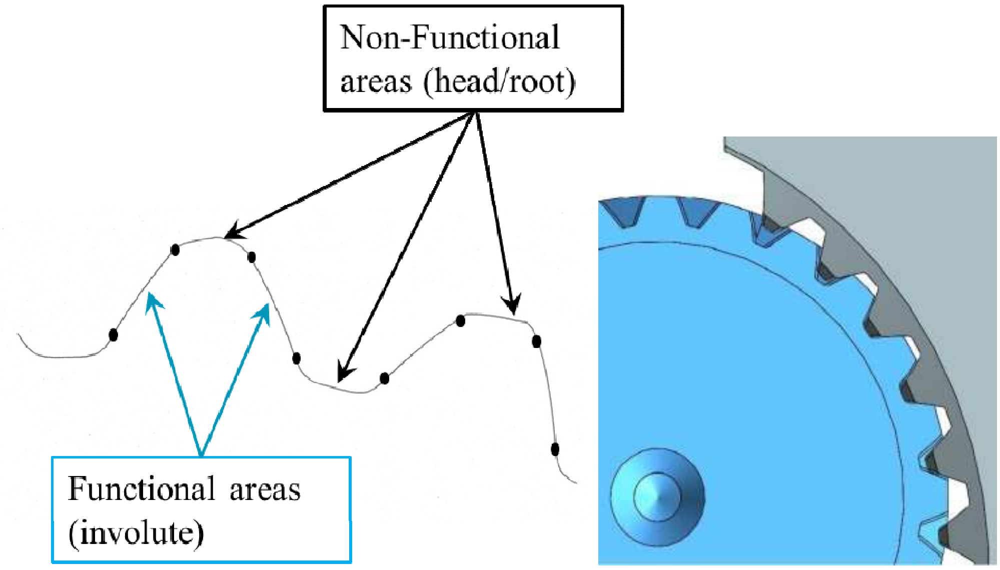


Figure 132 Separation of Tooth Areas (II)

7.3 WPM 120 Implementation Considerations

Within the present thesis work, the out coming root-diameter deviations have been observed more accurate within the production batch (see chapter 3.5/Fig. 60). In that case this system parameter could be a stable base for referencing an in-process measurement sensor setup tracing relative geometrical changes according to this reference element.

Looking more detailed into the WPM rolling processes for splined machine elements that has been determined in practical research tasks [27, see chapter 4], the achievable feature accuracy figures can be prospected as interdependent from relevant process parameters like:

- workpiece feedrate = actively deformed volume / time,
- linear-/rotational velocities of workpiece and work-toolsets,
- drive systems power consumption,
- preload- and process forces,
- machine frame structure and guideway deformations.

Further aspects of interest in the implementation context of a metrology framework can be listed as follows:

- local specifics like already described shapes and edges of the spline geometry are to be observed within the total length of the forming zone,
- typical tooth shapes are unique to the reviewed process forming stages (see chapter 4),
- Detectable metrological changes on geometrical features within the specific rolling method indicated by variations of relevant process parameters.

These aspects could indirectly being associated with a change in the final component quality. As an example regarding experimental sensor system setup in the existing WPM spline shaft forming machine, the illustrated arrangement sketch (see fig. 133) can be seen as an initial idea in order to monitor the relevant parameters [20, 100]:

- pitch-/runout eccentricity
- profile asymmetry
- flank direction
- head circle diameter
- head direction.

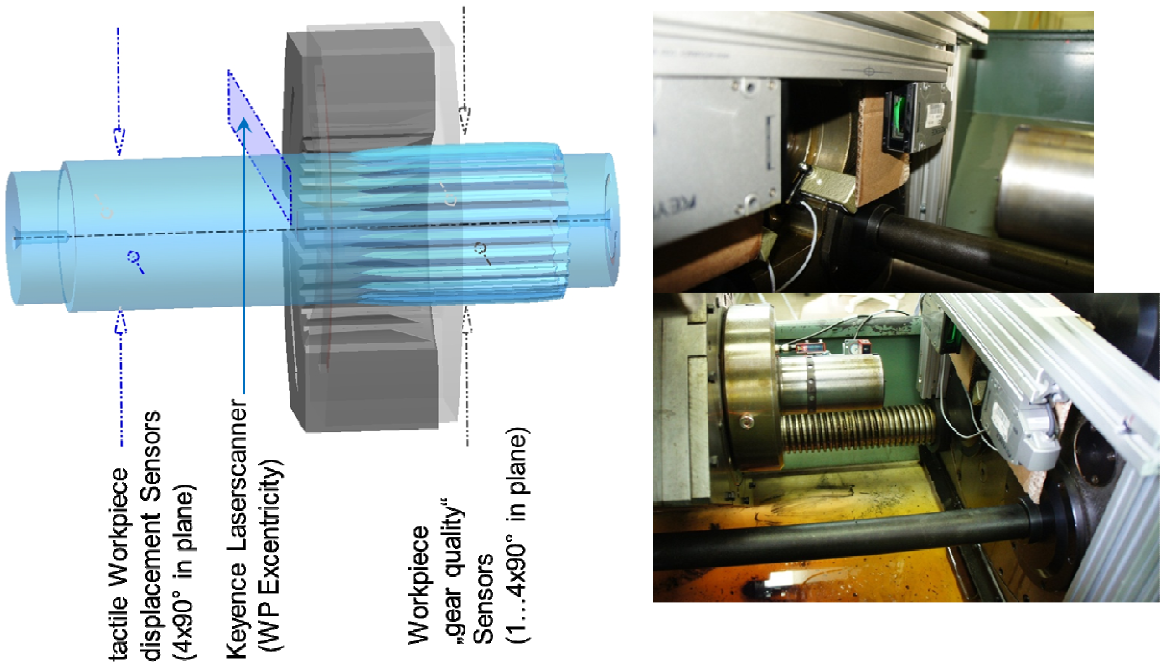


Figure 133 Example WPM 120 In-Process Experimental Sensor Setup Principle

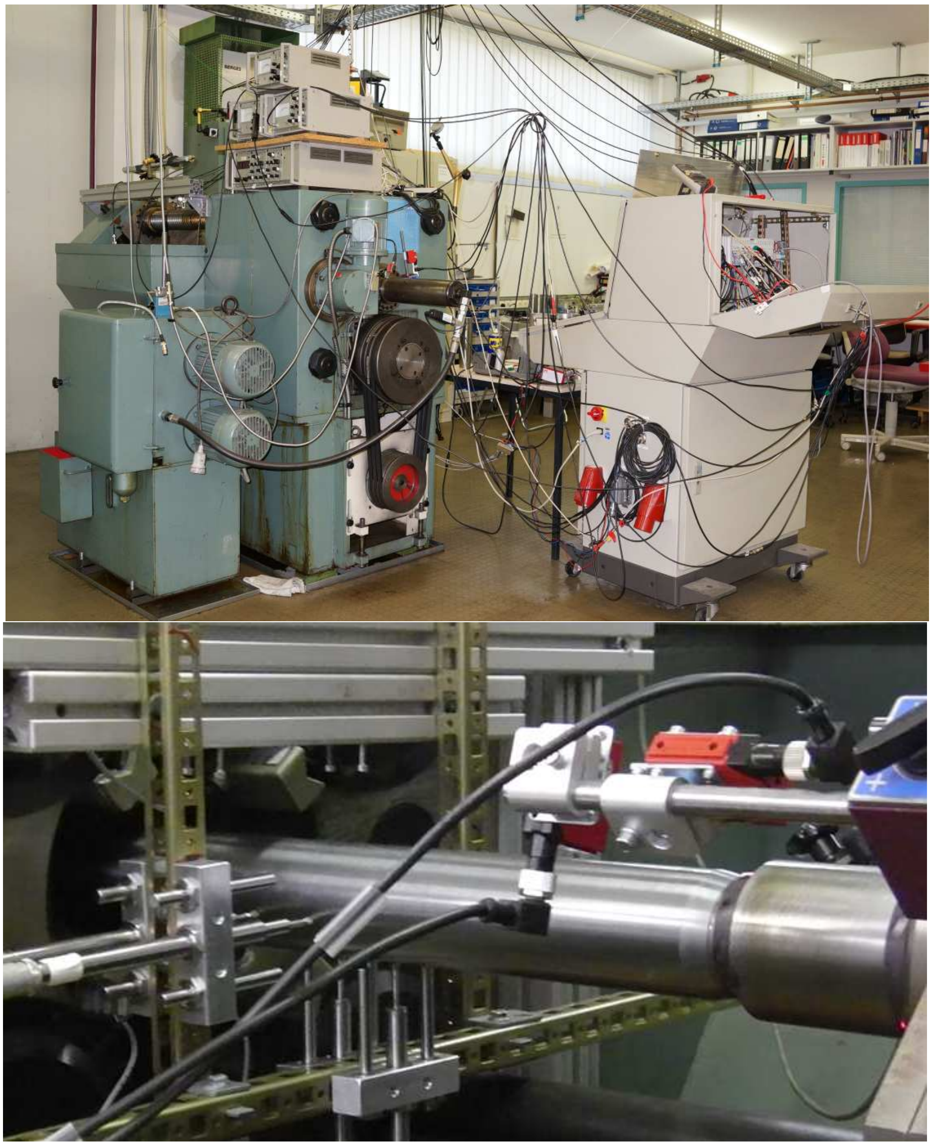


Figure 134 WPM 120 Metrology Framework Scenario

The implementation proposal described as a first WPM 120 In-Process Metrology Framework approach (see fig. 133) has been executed within this thesis work into the original WPM 120 gear rolling machine (see fig. 134) as the sensor setup is elaborated within chapter 6 and was used as a base for the data acquisition serving the analysis of samples using special blank geometry (see chapter 5). After the detailed analysis task had been executed and conclusion did arrive out of the theoretical investigations reflected with the real process indicators, it has been concluded, that a more flexible WPM test-bench should be designed following the In-Process metrology framework aspects from scratch. The implementation considerations concerning such a WPM test-bench have been summarized in chapter 7.4 as far as the current non-disclosure agreement placed between the connected research and industrial partners do allow details in scope of this thesis work but taking into account that the new WPM test-bench has been designed based on the In-Process Control assumptions of this work.

In addition to the gear geometry characteristics, the material structure and texture changes caused by the material re-distribution during forming and related to the non-linear material behavior resulting i.e. in work-hardening based on the materials flow curve characteristics [142].
As a matter of fact [45], specific to feature accuracy realization, a process internal conflict with the functional required material properties, like:

- grain texture,
- hardness and depth of hardness,
- introduced residual stress,
- roughness changes and surface damages/cracks,

cannot be avoided (see fig. 135) and therefore it limits today the application of gear forming technologies in its industrial application [7,45, 93]. The combination of feature related dimensional accuracy constraints and the surface / texture related integrity parameters define in such a use case the bandwidth in regards to expected performance and lifetime expectations of such geared components [19, 45].
The visual correlation between the geometrical characteristics i.e. of a spline shaft gear profile error development compared to the analyzed material structure (see fig. 135) is significantly high in the reviewed rolling process [20, 137, 138]. This observation could be amongst others a base for in-process monitoring approach. The border-zone quality prediction combined with the collection of relevant process parameters, integrated into an overall in-process measurement system approach are further intellectual aspects.
It is to suspect that a contact under load between the tools and the blank / sample lead to geometric changes in the center position of the sample (work eccentricity) [122].
Still it is not known to a sufficient proportion how the unbalanced WPM material distribution principle on the circumference of the sample occurs in detail. Ideal would be if one could detect a difference in the work hardening between the left and right flank of each tooth. This influences the functional properties and therefore the lifetime of a gear shaft. Another feature of the in process interpretation of the rolling process might be the

condition of the rolled surfaces of the workpiece. This statement relates to the roughness of the surface and the formation of cracks on the surfaces.

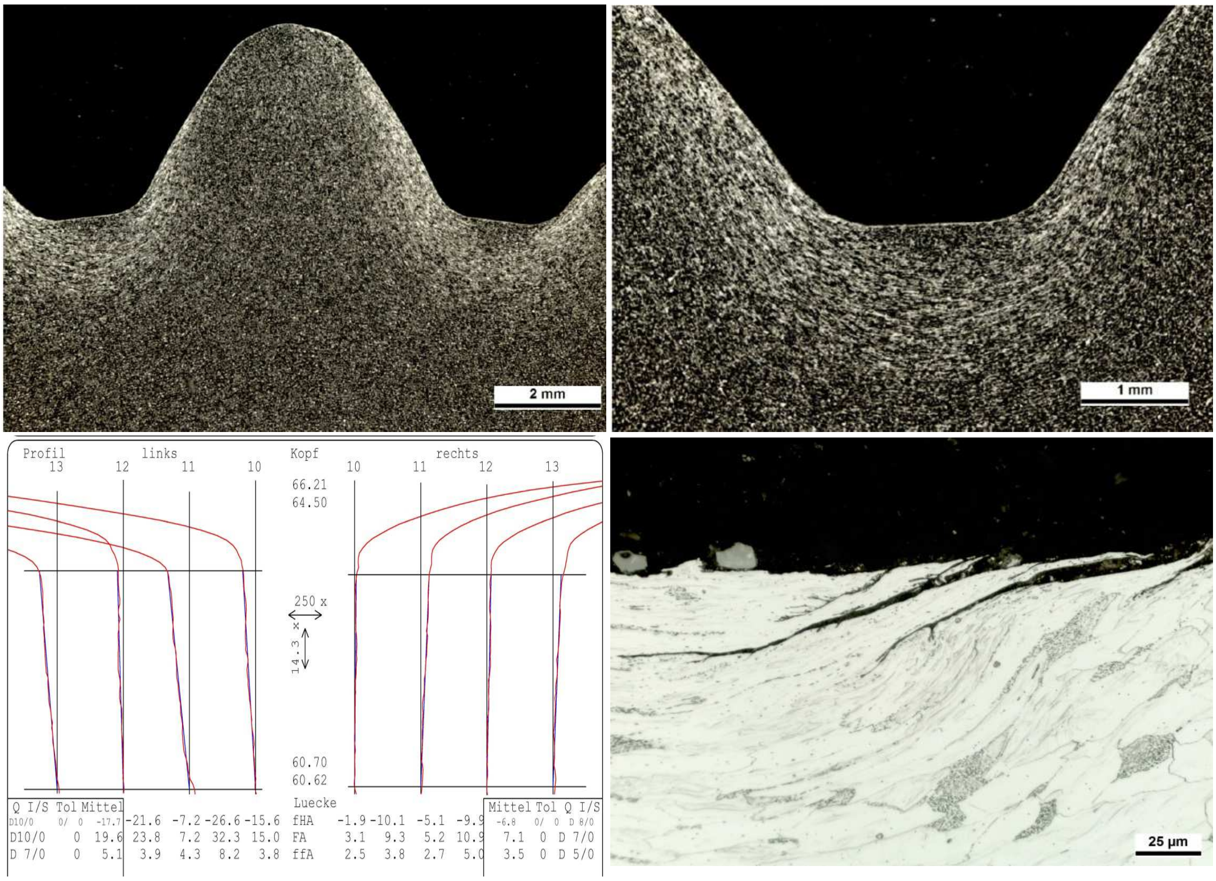


Figure 135 Metallographic specimen of WPM rolled spline shaft, material C15

7.4 WPM Test-bench Considerations

The future in-process quality control systems require special considerations for the metrology framework integration into structural machine tool concepts. Fig. 136 represents a simplified view on this approach as far as the WPM gear rolling process is concerned. It can be recognized that based on the findings out of chapter 5 and considering the experiences gained on the WPM120 integrated measurement setup (see chapter 6) a future WPM production test-bench has been designed following the principle of being able to position dimensional sensors in a way, that the work-tool movements and the workpiece alignment / distortion during rolling can be monitored in order to decide or predict quality related results:

1. without the requirements of additional post-process measurement,
2. related to system parameters to be investigated that are representative and sensitive enough to build up quality control loops based on its outcomes,
3. predict the potential process parameter adjustments for the n+1 part to be manufactured and

finally target a dedicated quality control approach (open- or closed loop) based on sensor framework feedbacks integrated within the test-bench control loop.

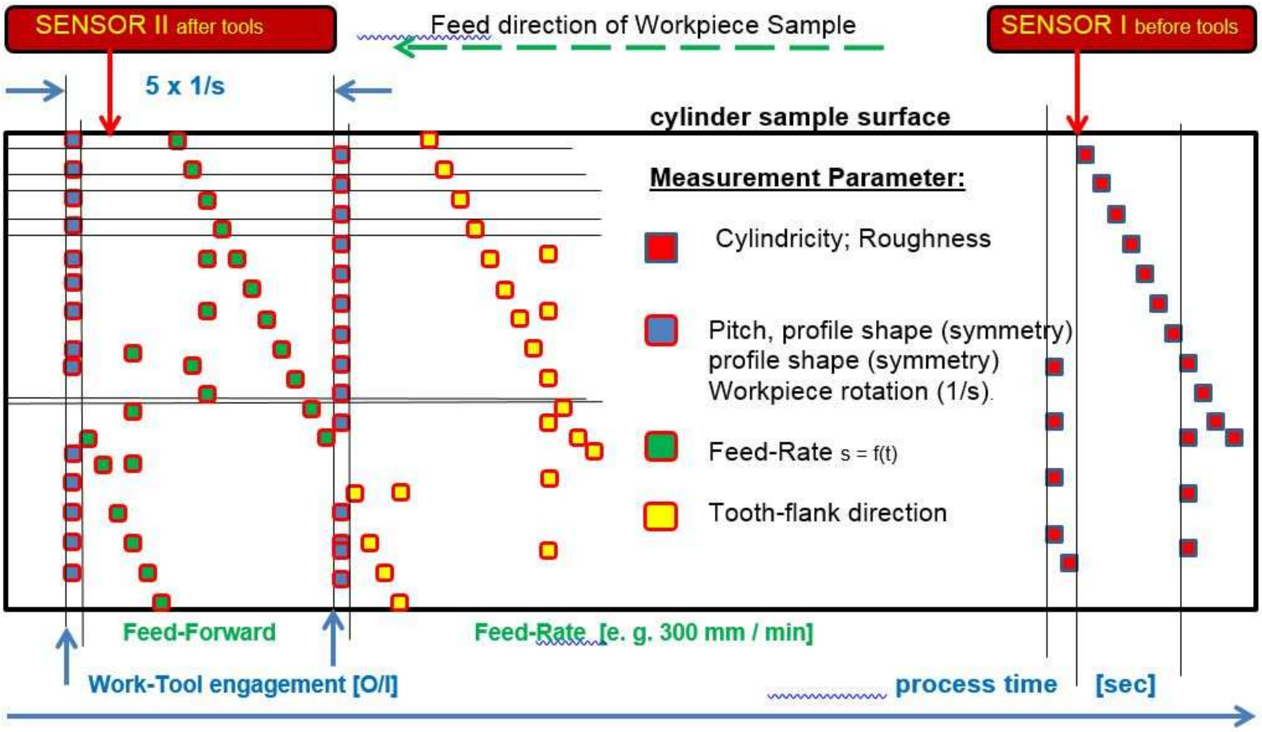


Figure 136 Measurement Strategy - IN-Process Metrology Test bench

In order to fulfill the stated target requirements, the WPM test-bench (see fig. 167) has to provide certain functionalities that are new to the WPM 120 gear forming machine before. As a selection of these additional functionalities the following requirements have been foreseen in the test-bench design as machine tool objectives being able to overcome the tradeoffs determined in this thesis work:

- ability to alternate fast work-tool CNC controlled movements in terms or their rotational working direction

- ability to move the work-tool CNC controlled independent from each other in term of their relative position and stroke-speed against each other but also in terms of their absolute position and stroke-speed within the forming process related to the workpiece
- ability to change eccentricity and therefore the grade of forming depth of the work-tools into the workpiece on the fly
- ability to clamp the workpiece in its rotational position and being able to manipulate the workpiece position within the process by CNC moves during the work-tools stroke not being in workpiece contact
- ability to move the workpiece CNC controlled in axial feedrate direction through the work-tools interaction

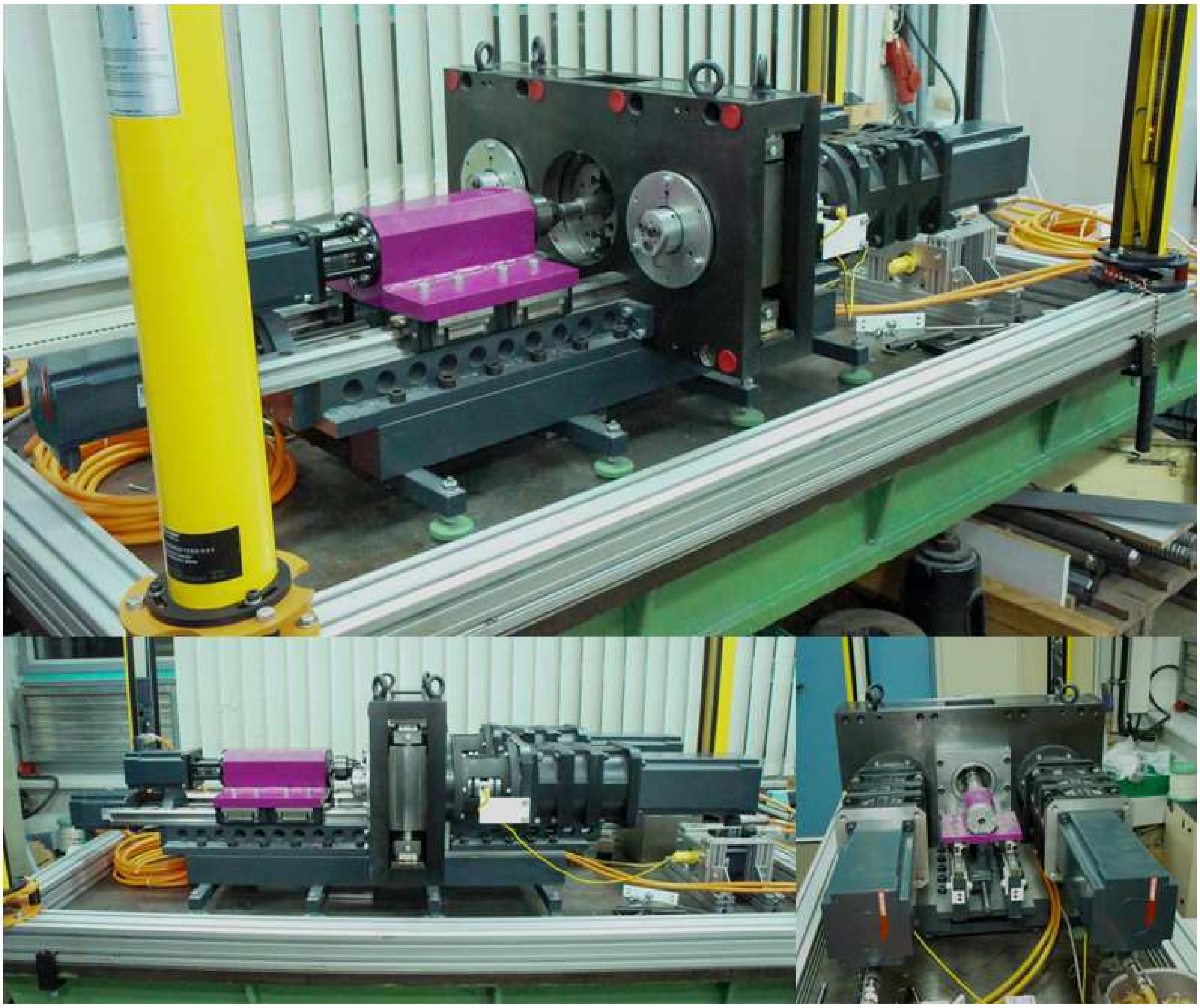


Figure 137 WPM test-bench – research In-Process Metrology framework

In regards to the targeted In-Process Control Approach the following Metrology Framework objectives have been foreseen in conjunction with the machine tools process characteristics (please see fig. 138 as an indication for the foreseen metrology framework space requirement, as more metrological and Sensor framework; more details are currently covered by a non-disclosure agreement):

- ability to monitor the work-tool drivetrains power consumptions in high resolution (see fig. 36)
- ability to track in real-time the work-tool half-shell position in 4D space (3D-coordinates and latched time information)
- ability to track in real-time the workpiece center-axis position in 4D space (3D-coordinates and latched time information)
- ability to track the workpiece axial position in feedrate direction
- ability to track workpiece evolving gear shapes in the non-functional areas (see chapter 7.1) as several 2D-sections individual to the work-tool forming zone (see fig. 61, 63, 140)
- ability to create an overall referencing system in order to manage the individual delay and relative real-time position in 3D-space of the involved sensors in usage

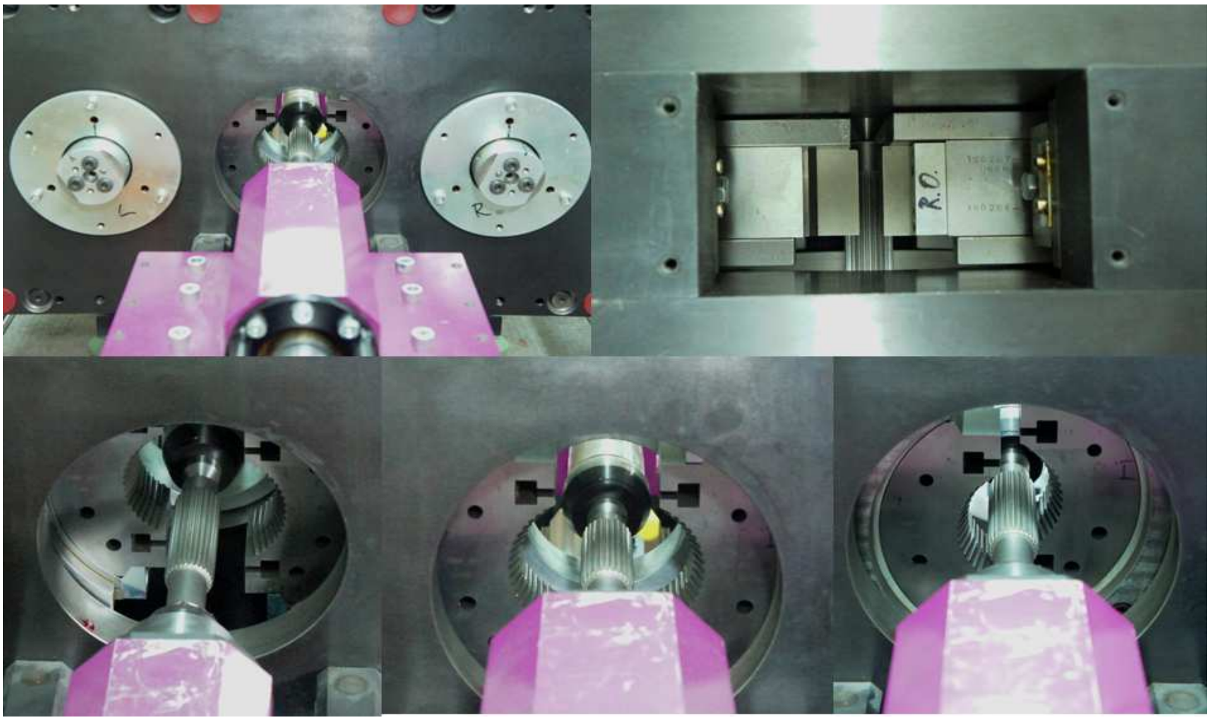


Figure 138 WPM test-bench - In-Process Metrology framework approach

The overall system calibration during the described experimental stage is done by usage of dedicated workpiece blank samples applying the specific outcomes of the experiments described in chapter 5. In a future design approach on WPM In-Process metrology frameworks implementation, the monitoring of surface parameters, e.g. roughness, structural cracks and work-hardening additional sensor systems but also constructive barriers in the machine tool structure remain to be overcome.

8. Conclusion

Changes in the specific geometrical and process related characteristics in combination with mechanical and technical measured variables can be detected and interpreted in the individual process or the production life of many toothed components. The monitoring of the uniformity of an ongoing mass production by metal forming techniques stands in the foreground. It can be assumed, that the production takes place under the same conditions, if the results show nearly identical head and foot geometries. Fluctuations in the corresponding measured values strongly indicate that the rolling conditions must have changed [27, 139].

The acquisition of geometrical features with non-tactile sensors based on detailed indication regarding the contact situation between the work-tools and the workpiece material will be set as a holistic starting point for the application of in-process monitoring systems. Considering the geometric relationships on the resulting workpiece geometry, a detailed analysis of the material work hardening combined with the resulting surface characteristics lead to a comprehensive in-process quality control of rolling methods.

Concluding the outcome of this thesis work, following findings can be assumed:

1. The WPM rolling results are showing typical geometrical characteristics in the tooth areas.
2. The geometrical characteristics (i.e. pitch-/runout eccentricity, profile asymmetry, flank direction) can be noticed in the functional- and in the non-functional tooth areas (i.e. head circle diameter, head direction) and a correlation function between these areas could be evaluated.
3. A correlation function between these geometrical characteristics and related (direct / indirect) process parameters can be evaluated and monitoring of these process parameters allows a review of the rolling process in a quality control loop.
4. The typical geometric feature characteristics are located on the surface of the rolled parts and can therefore be detected by suitable sensors (non-contact) within the machine and during the production processes = In-process.

Considering the aforementioned findings, the level of quality loss in the WPM process and therefore finally in the workpiece could be determined within a root-cause analysis and will be driven by [110]:

1. initial unbalances and weaknesses within the rolling machine mechanics or drive systems,
2. workpiece centerline eccentricity caused by process forces /- torque or initiated by work-tool contact within the active forming zone,
3. Workpiece deformations or distortions caused by process forces /- torque.

The Main Challenges for the application of the new metrology framework approach as an In-Process metrology framework solution can be summarized as:

- Shop Floor System Environment
- Sensor Systems integration and Real-Time data acquisition
- (model based or experimental) correlation determination of multiple parameter combinations
- Data Analysis and Data Fusion using sensor data from several (multi-physical) sources
- Real-time quality control feedback loop based on combinations of interpreted sensor data and obtained correlation rules in order to determine and control the manufacturing process stability

Based on the conducted work an In-Process Control Approach (IPCA) can be based on the following steps (see fig. 139):

- collecting of multi-physical process parameters
- run a post-process measurement assessment of the tested samples in order to
- create a “process fingerprint” model and
- find part quality (functional- and non-functional areas) vs. process parameter related correlation functions of at least 2nd degree of parameter correlation
- validation of the Quality Control Loop against production rationales.

Beside the multi-physical sensor system framework the underlying interpretation software establishment incl. the real-time quality control loop functionality becomes a major building block of such an approach. Within this interpretation software it should be possible to execute the described signal processing in real-time, the data-correlation and deviation analysis leading into the final step of a process control modifications and optimizations to be carried out in open- or closed loop approach on the quality parameter achievements. In addition a consideration of A priori knowledge as well as statistical monitoring of parameter and deviation trends should extend the possible application of such an approach into a Process Interpretation Chain, as follows (see fig. 139):

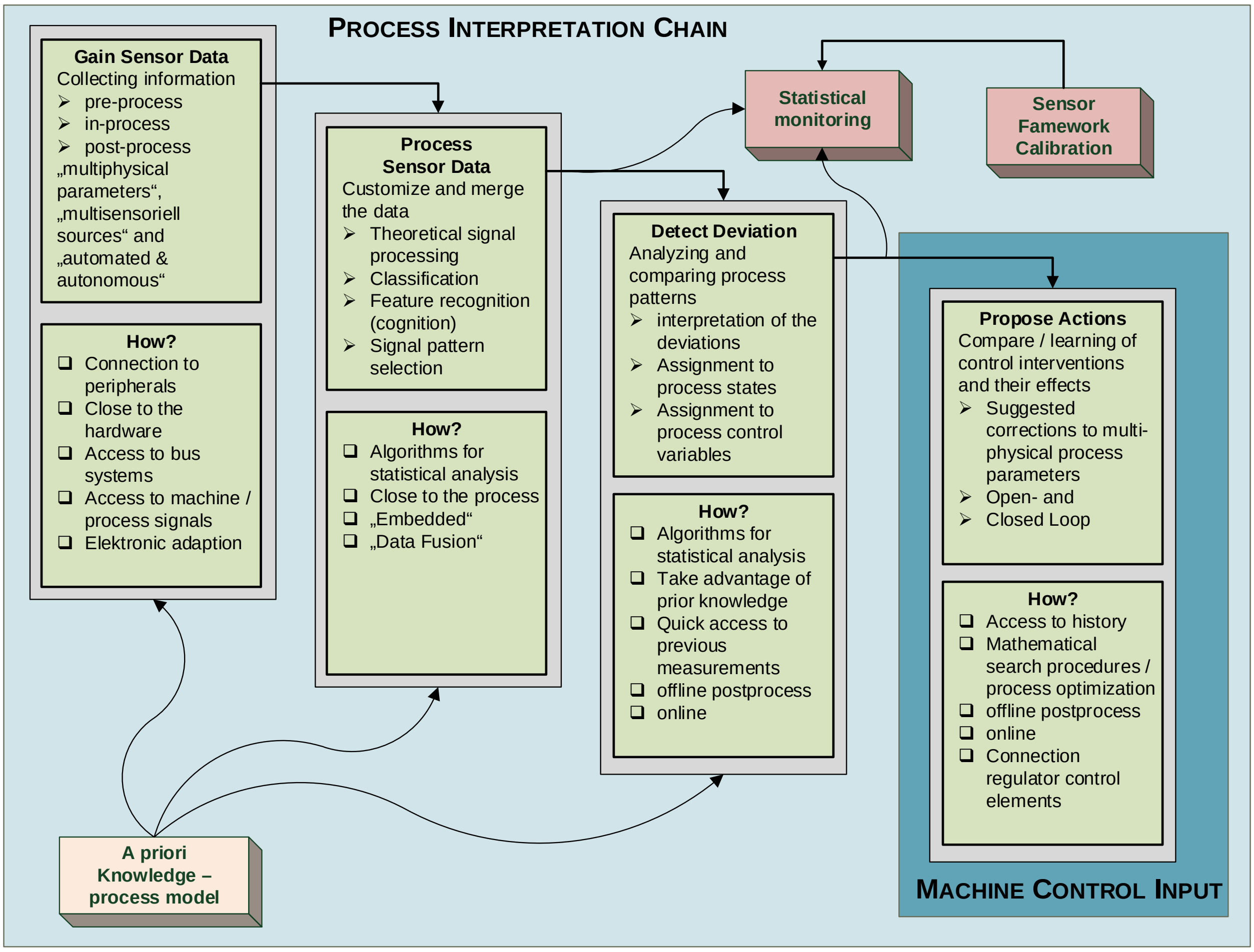


Figure 139 Interpretation Software Requirement Scheme

In order to feed the Process Interpretation Chain, being able to generate a reference to achieve traceability in the results and create a trust level for execution, finally the core thought process for new process applications should be the collecting of multi-physical process parameters, the execution of a post-process measurement assessment on the test samples in order to create a unique process fingerprint; further on find part quality vs. process parameter related correlations in order to validate the base for the applications of the described In-Process Control Approach (IPCA).

Finally the stated elaborations within this doctoral thesis work “In-Process Measurement System to control Dimensional & Process Parameters” were initially claimed to aim the assessment of enablers for an enhanced quality control approach, questioning if it can be possible to combine product and process parameter detection during the execution of the manufacturing process, mainly applicable in precision mass production. Taking this thesis into account it can be summarized, that such an innovative IPCA can be developed, assuming a core understanding of the process representative parameters in its relationship and interdependency. These relationship could be derived from theoretical simulations or model based estimations combined with practice and experiments to be carried out. Further options achieving even a closed loop IPCA within the targeted workflow could be advanced statistical methods or hybrid combinations of several methodologies in quality control loop establishment.

Within the WPM process related analysis, simulations and practical experiment works the evaluation chain of CAD based theoretical assessments and simulations combined with the analysis of geometrical post-process and reflecting the relevant WPM process parameters regarding the discovered geometrical characteristics shows, that describable interdependencies between process and geometrical parameters can be predicted. Furthermore it has been discovered, that specific to forming by rolling, geometrical characteristics are reflected within the material texture as well, due to unbalanced material distribution during the manufacturing process. Finally it has been projected, that even complex geometrical measurements are being able to at least partially executed in an In-Process environment (see fig. 140).

Based on the analysis and findings discovered within this thesis work, the following future risks of an In-Process metrology framework are to be considered from the Author´s perspective:

- Sensor & System Calibration in direction of achievement of Traceability
- In-Process Measurement Uncertainty evaluation and statement [12]
- Advanced Metrology Frame System Integration into Machine Tool processes
- Quality control loop model stability (if applicable) in workflow fluctuations
- Unconsidered and/or unexpected disturbance variables (thermal, vibration, environmental).

The future success of an In-Process Control Approach (IPCA) can only be accomplished, if the metrology framework aspects are considered in the ranking of the same level of importance than the work-process design aspects themselves.

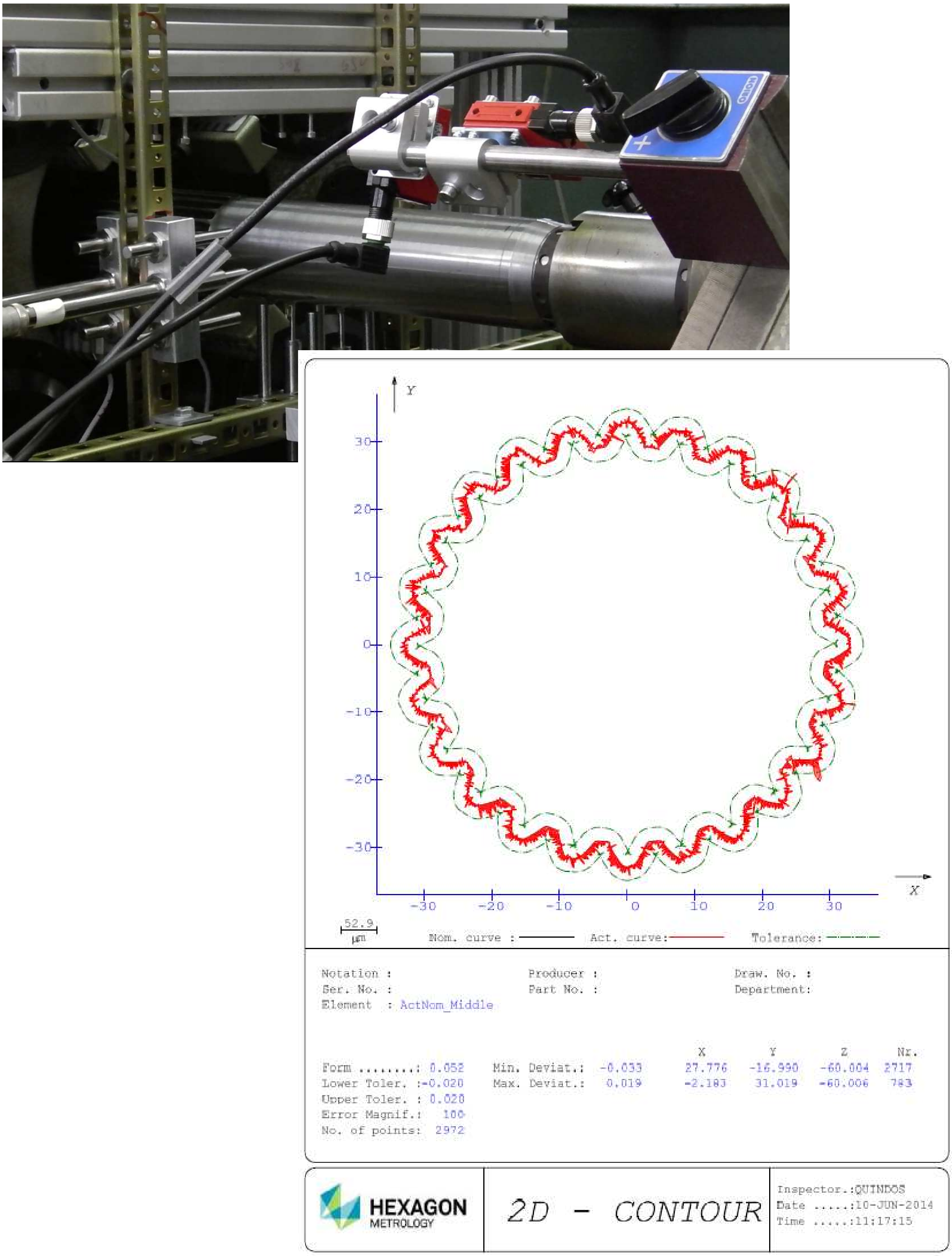


Figure 140 WPM 120 Metrology Framework/2D-contactless measurement plot[1)]

[1)] HP-O – Hexagon Manufacturing Intelligence 1D-probing fibre optical sensor (see Appendix 3)

9. Abstract/ Streszczenie

The subject of the present Thesis work concerns investigations on process improvements to the production of splined shafts by applying a metrology system to the applied rolling technology. On an industrial scale, they are made in series production using a succession of different manufacturing processes. The increasing demand of high precision machine elements manufactured in mass production results in a target conflict with respect to quality control of the production lots, esp. if metal forming techniques are the production principles. Usually individual parts are measured post process in form of random checks. This type of quality assurance is highly patchy and costly. The aim is thus to capture quality-related characteristics of the components in future integrated within the producing machine. In the case of the present work, the WPM-rolling was used in the final machining of the toothing. This method is a clipless process with internal gear rolling tools, which was developed in Poland by Prof. Marciniak in the 70s. The method is particularly suitable for the high speed production of splined shafts. The goal of the own investigations is to determine significant geometric feature characteristics of the toothed components that are suitable as a base for future In-process measurement parameters within the machine. For this purpose, different rolling series using special blank geometries were performed on a rolling machine WPM 120 [105]. The technical process data of the WPM 120 were collected to ensure that all toothed components were produced under nearly identical conditions. By post-process measurements the geometric quality of all parts in the series of special blank geometry was recorded and evaluated. Through special section measurements on the splines in axial and radial directions, geometric characteristics indicating a process “signature” imprinted into the gear components could be detected. The majority of the final geometrical influencing parameters are given by the forming forces and the geometric specifics of the work-tool kinematic movements which has been assessed in theoretical investigations of the work-tool / workpiece contact zones and proofed in the analysis of experimental data regarding simulations of the emerging teeth. Using corresponding sensor systems provided inside the machine, these geometric features can serve as a reference base for a future In-process measurement framework.

Appendix 1: Contour Measurements special geometry samples

- Conical sample blank

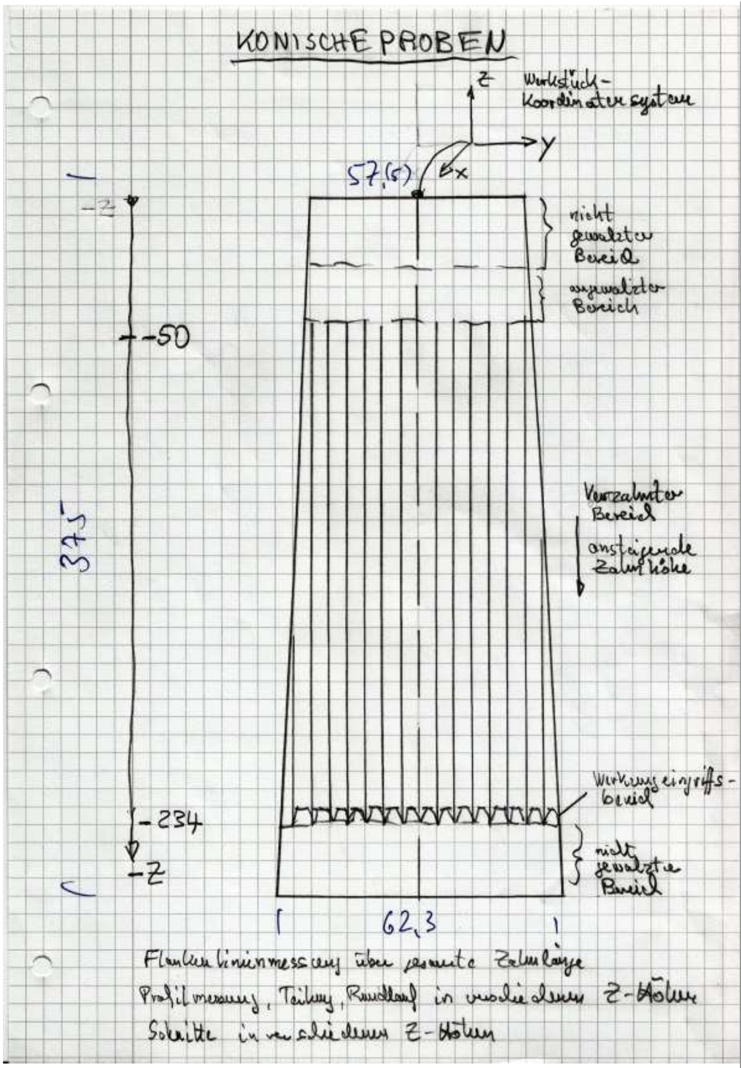
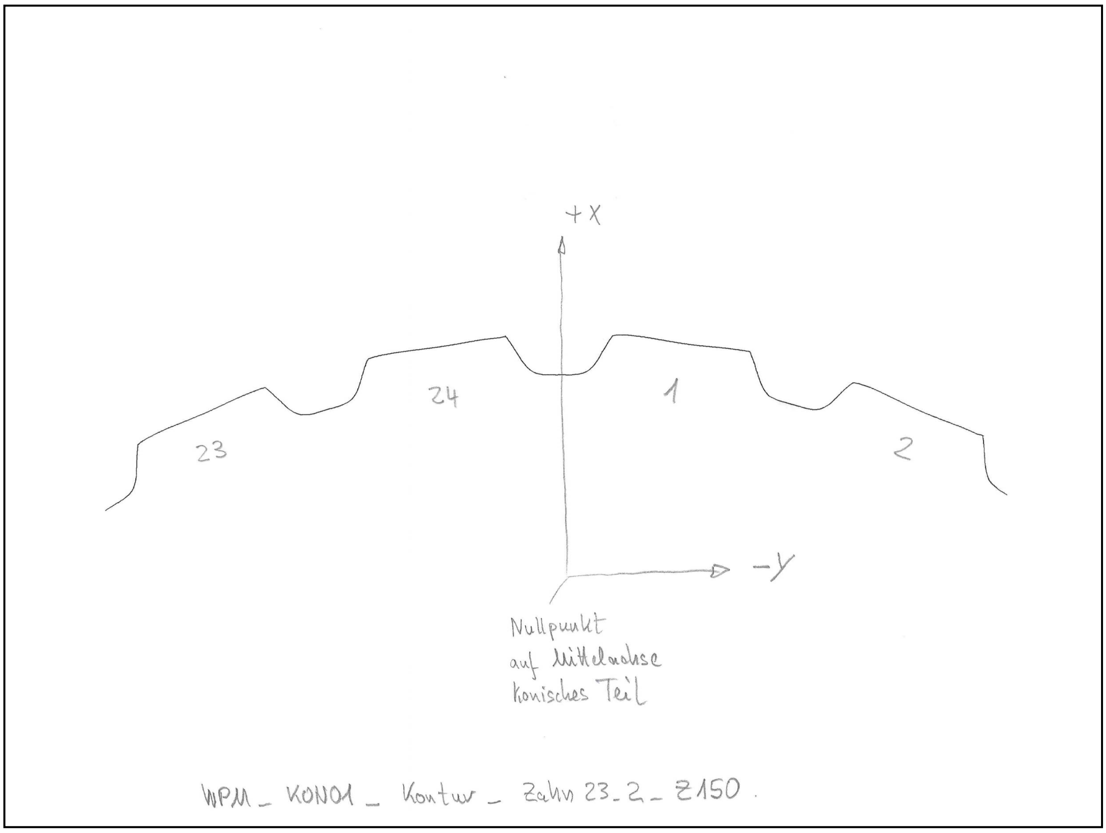
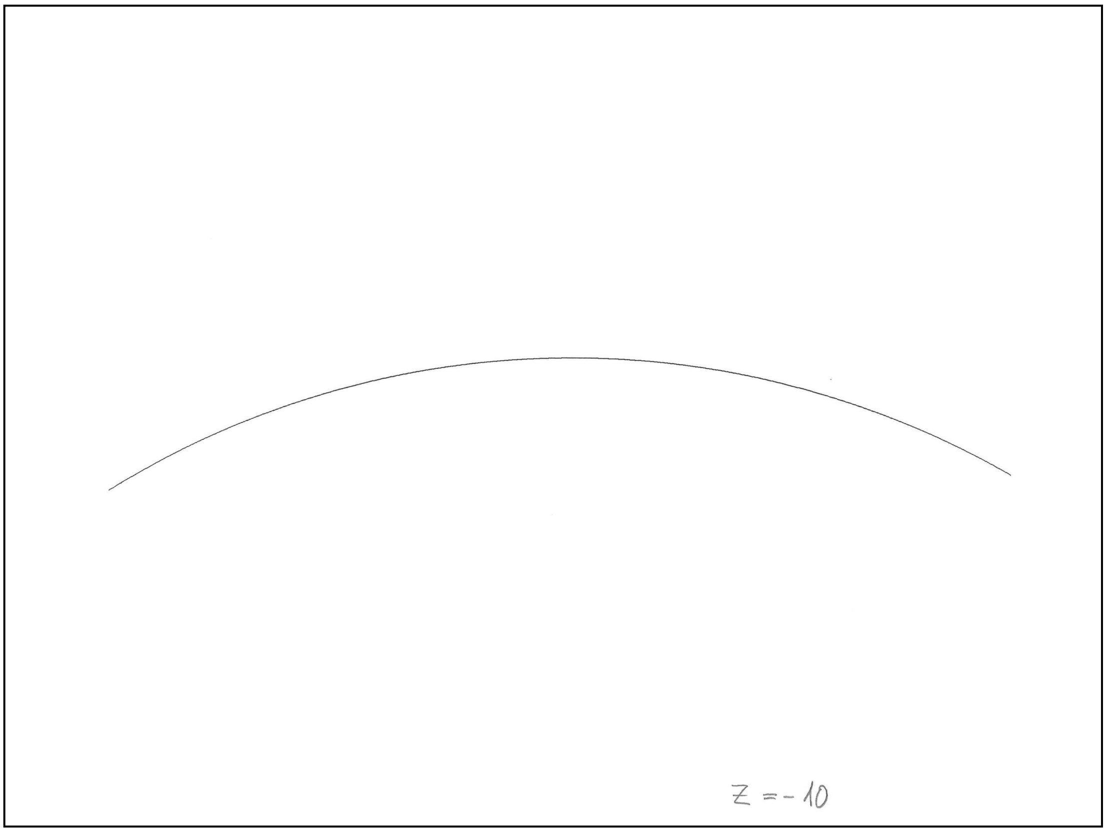


Figure 141 Conical Sample Drawing (Details)


+x
24
1
23
2
-y
Nullpunkt
auf Mittelachse
konisches Teil
WPM_KON01_Kontur_Zahn 23_2_Z150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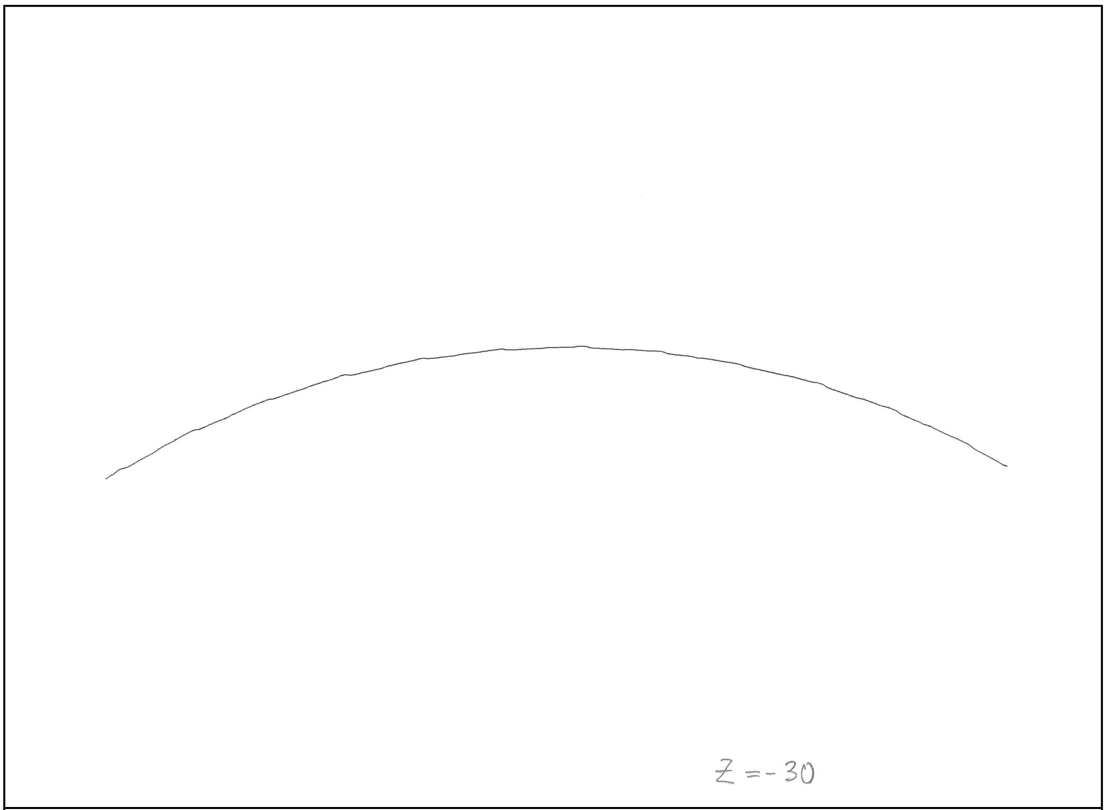
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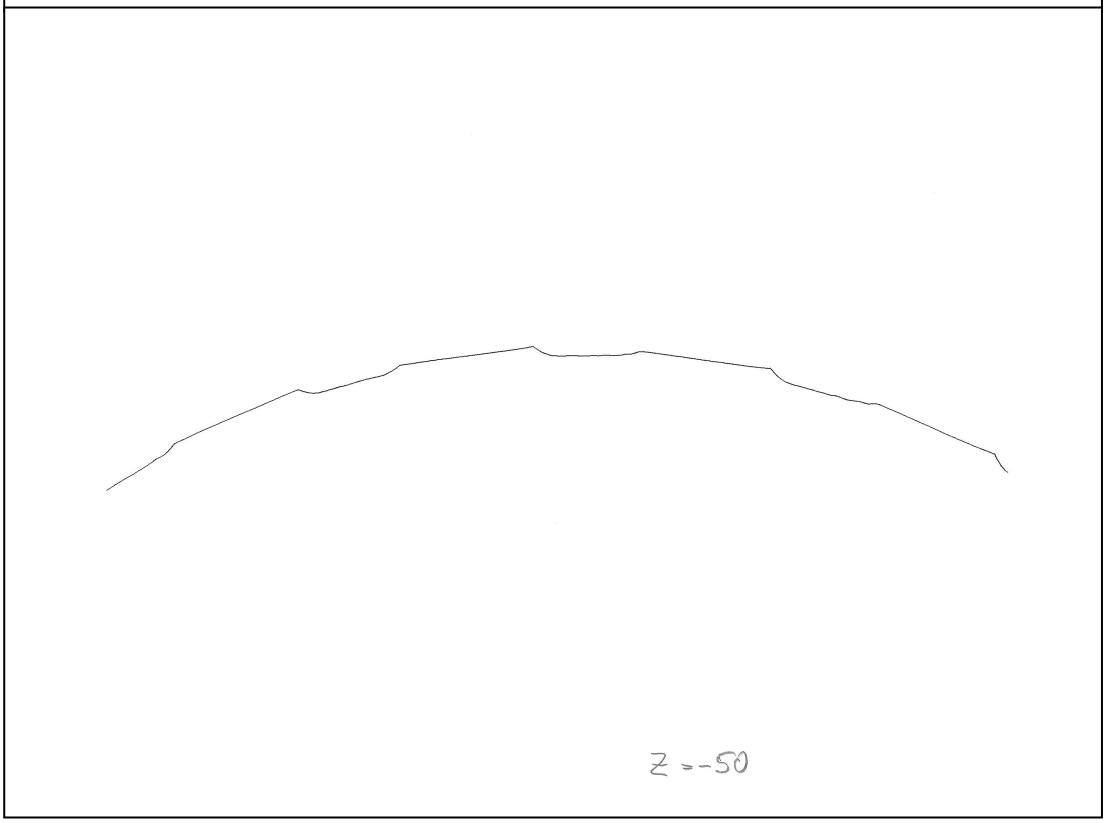
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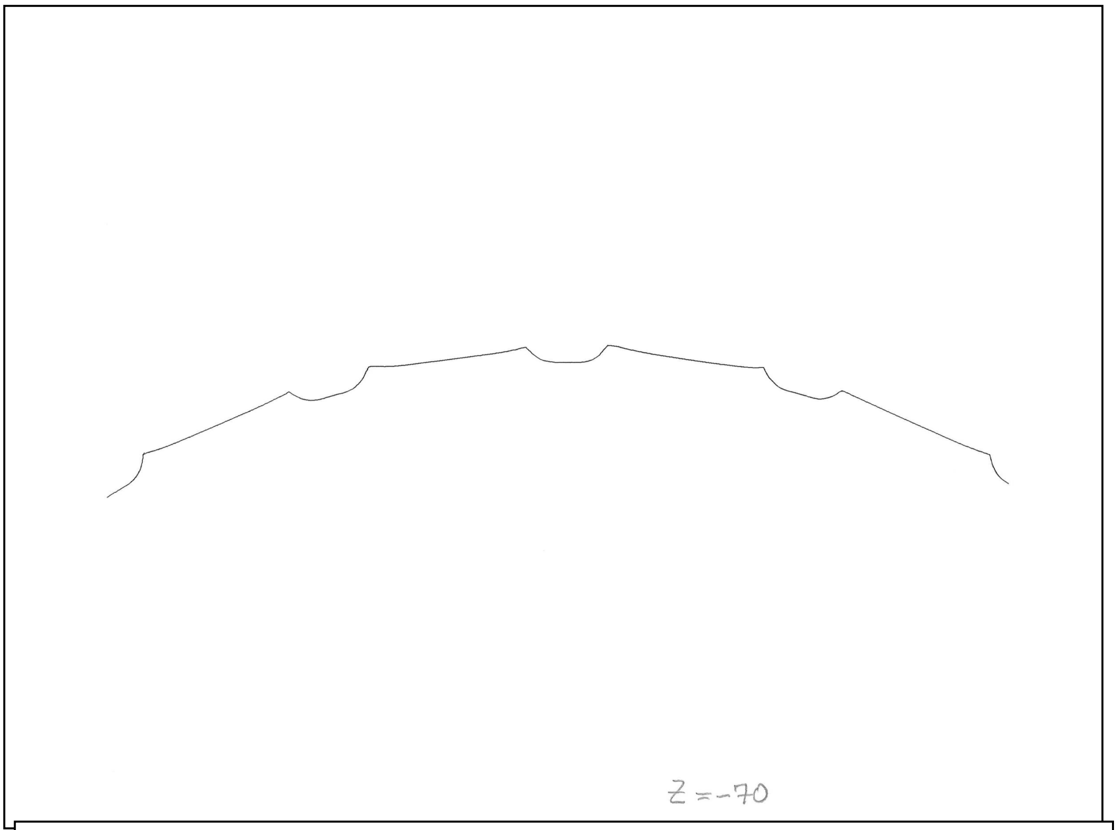
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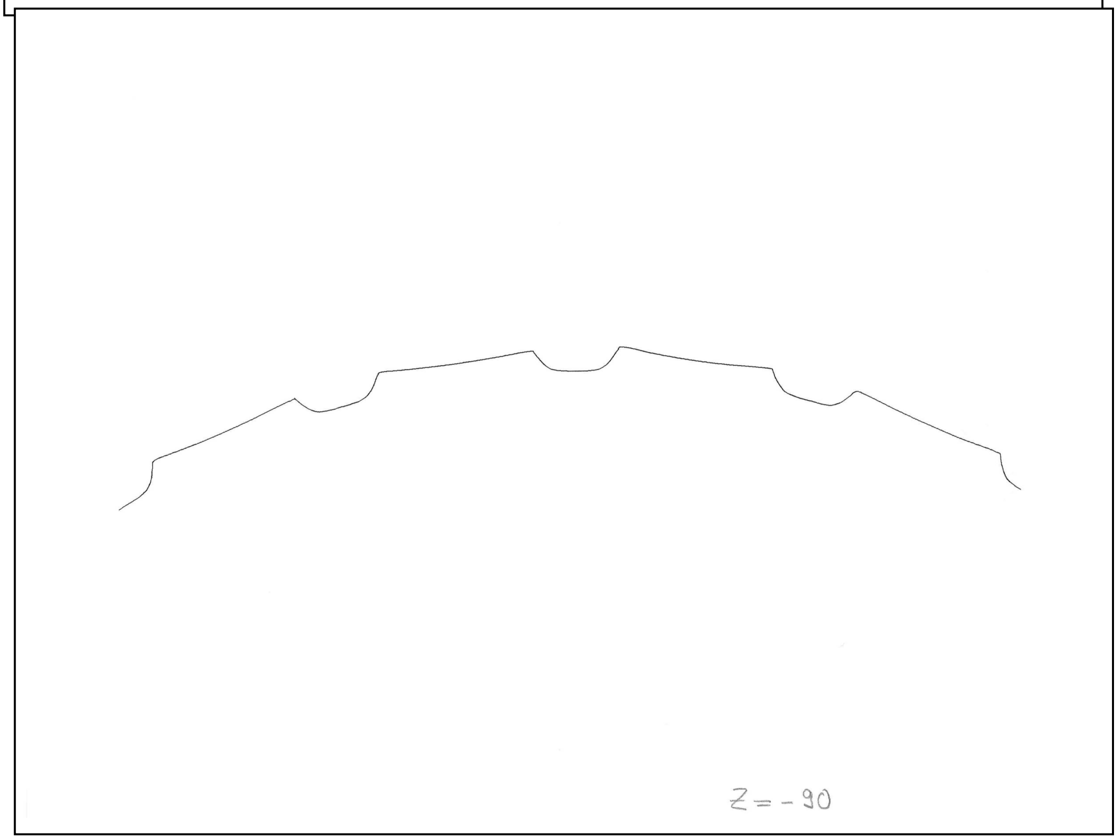
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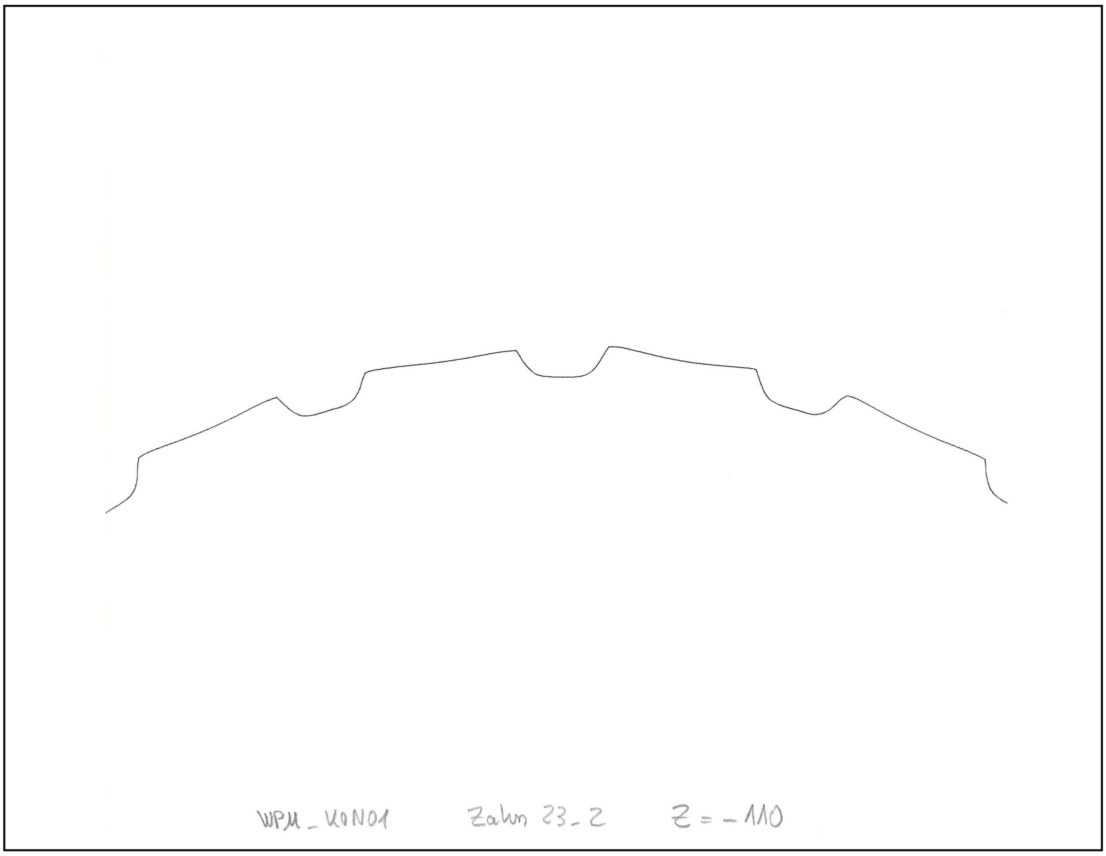
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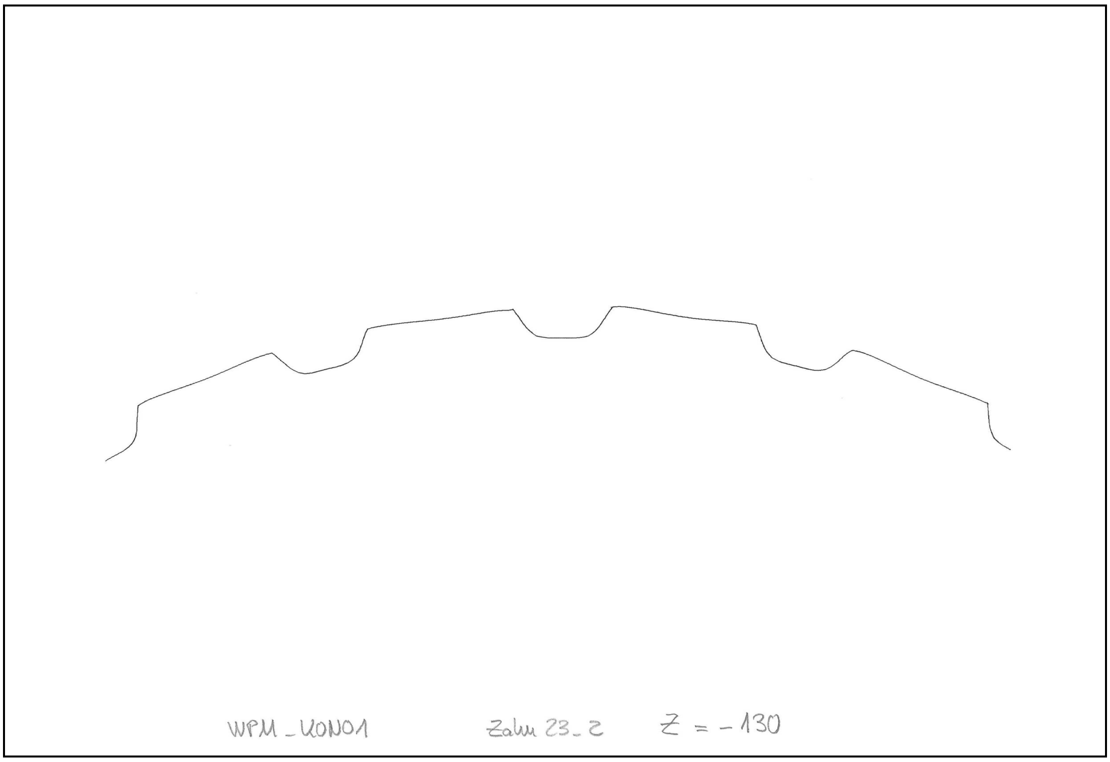
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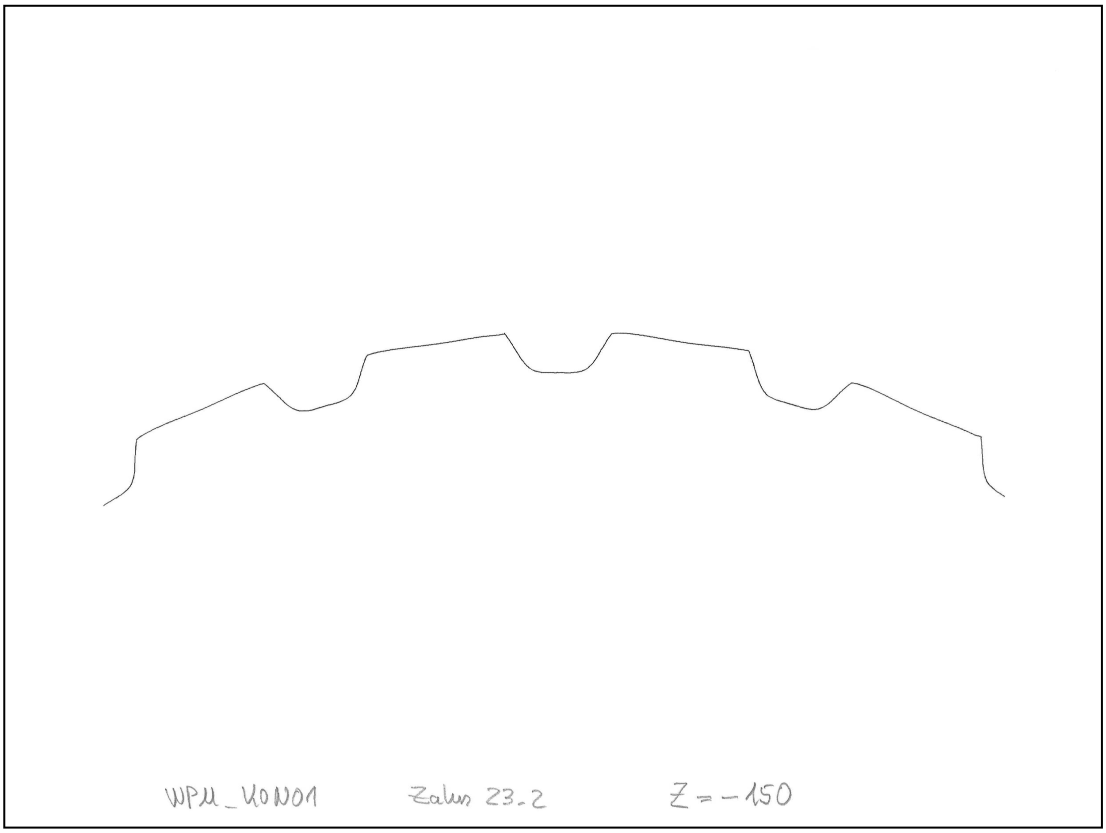
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Zahn 23.2
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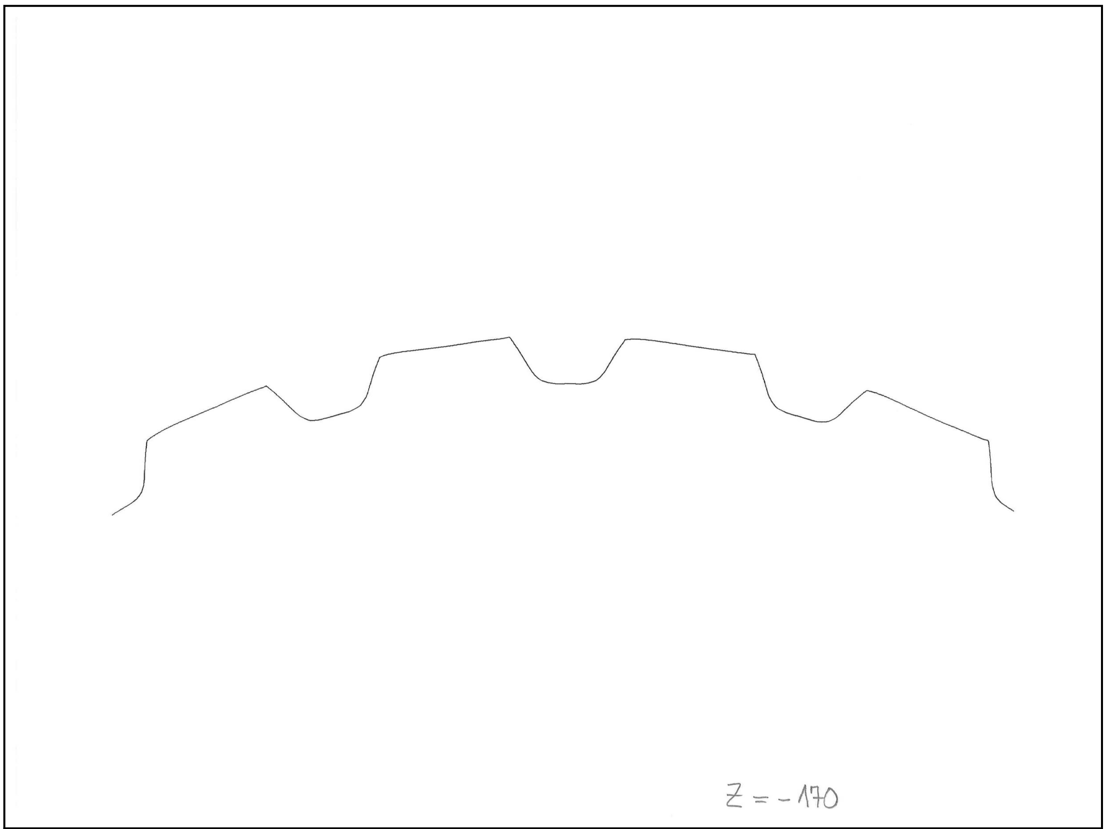
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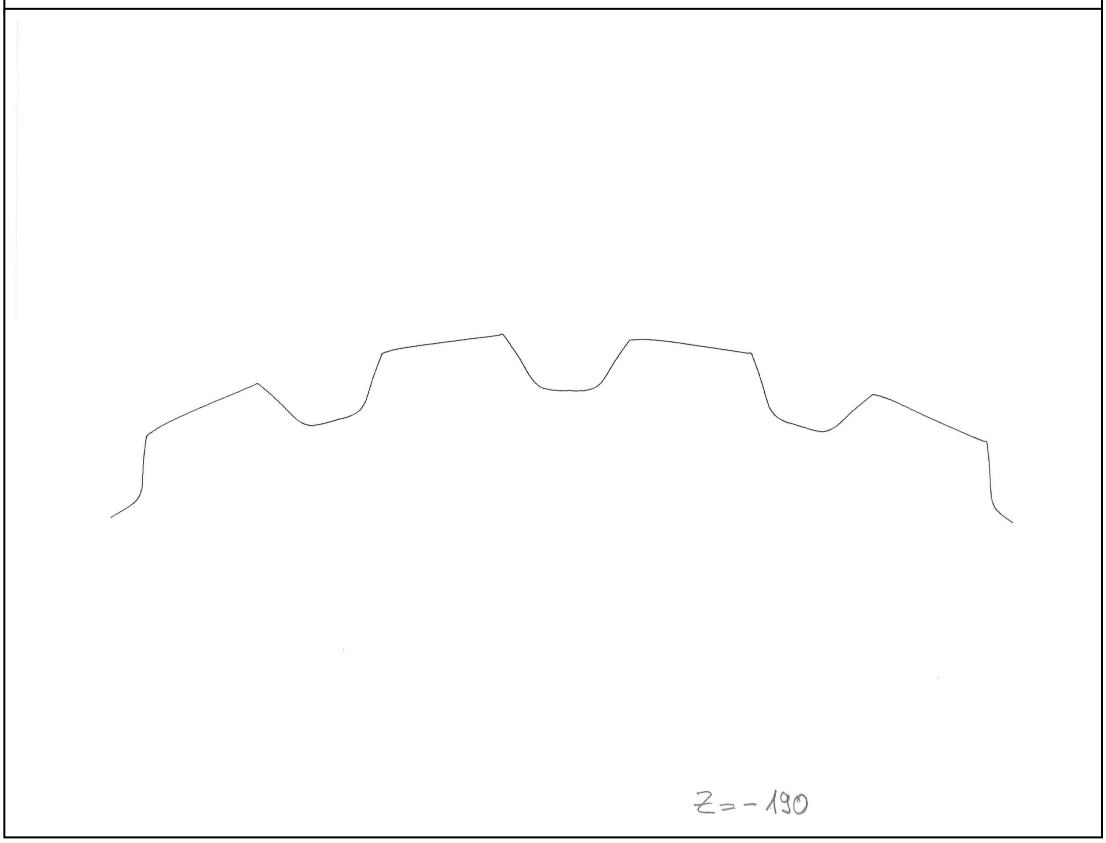
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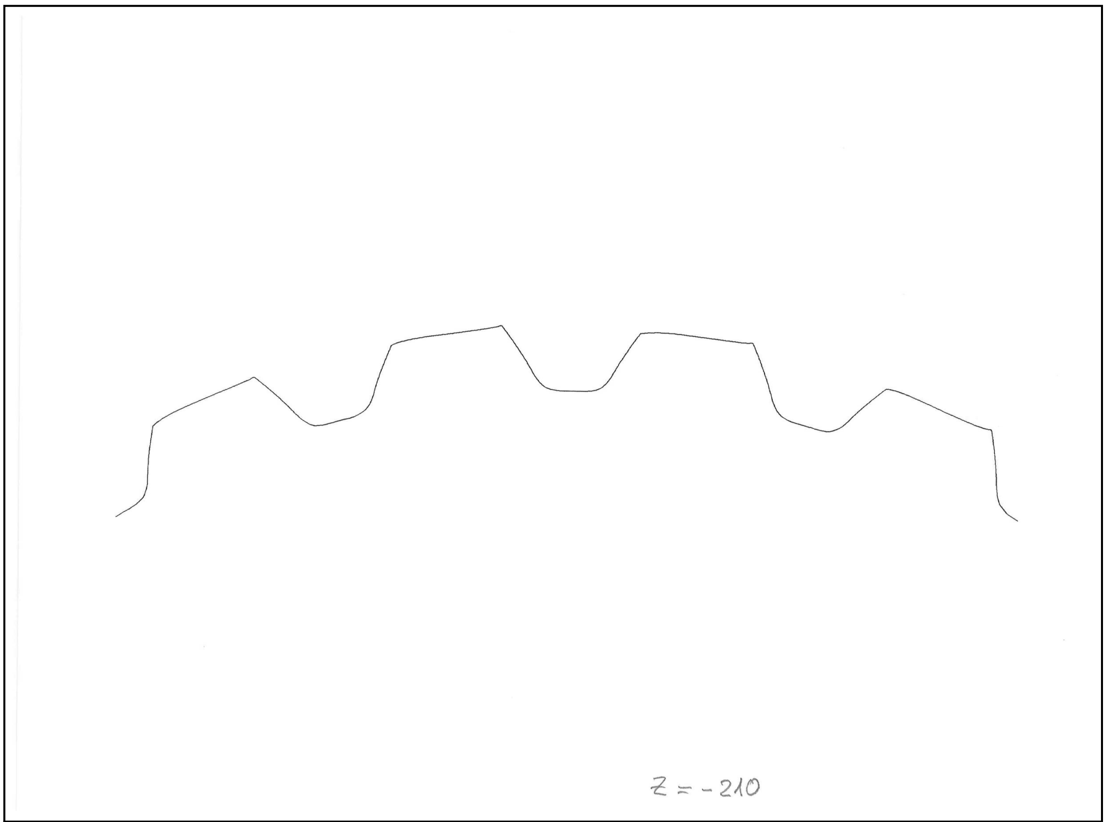
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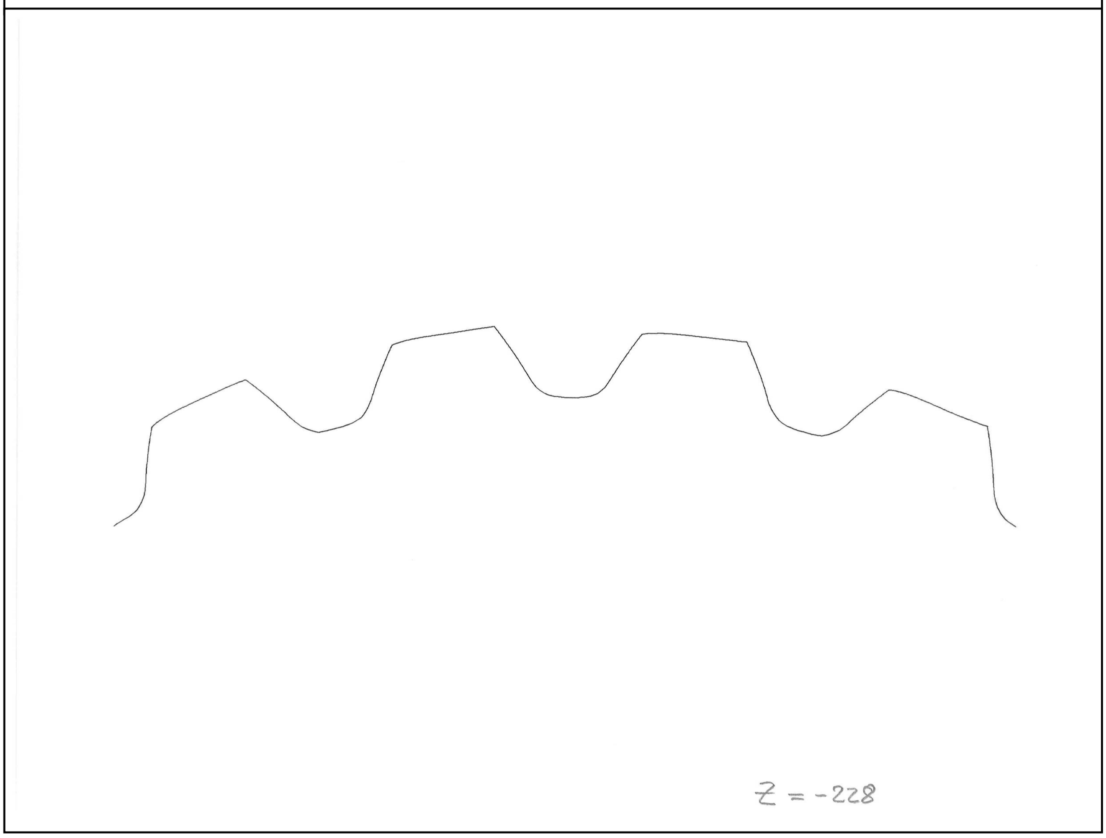
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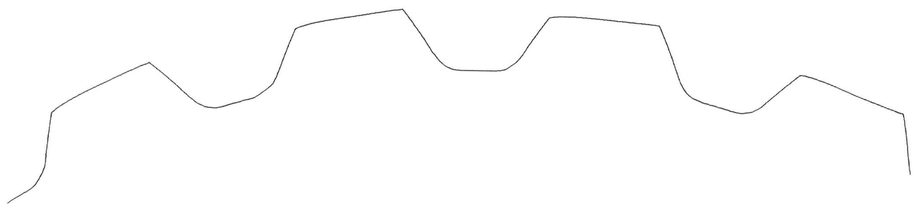

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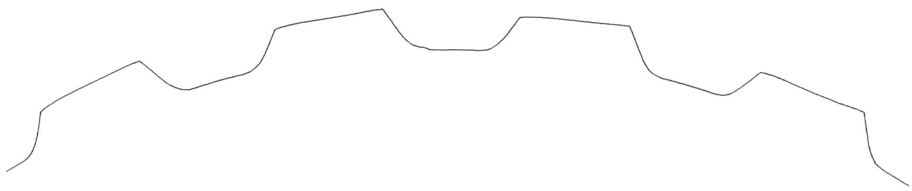

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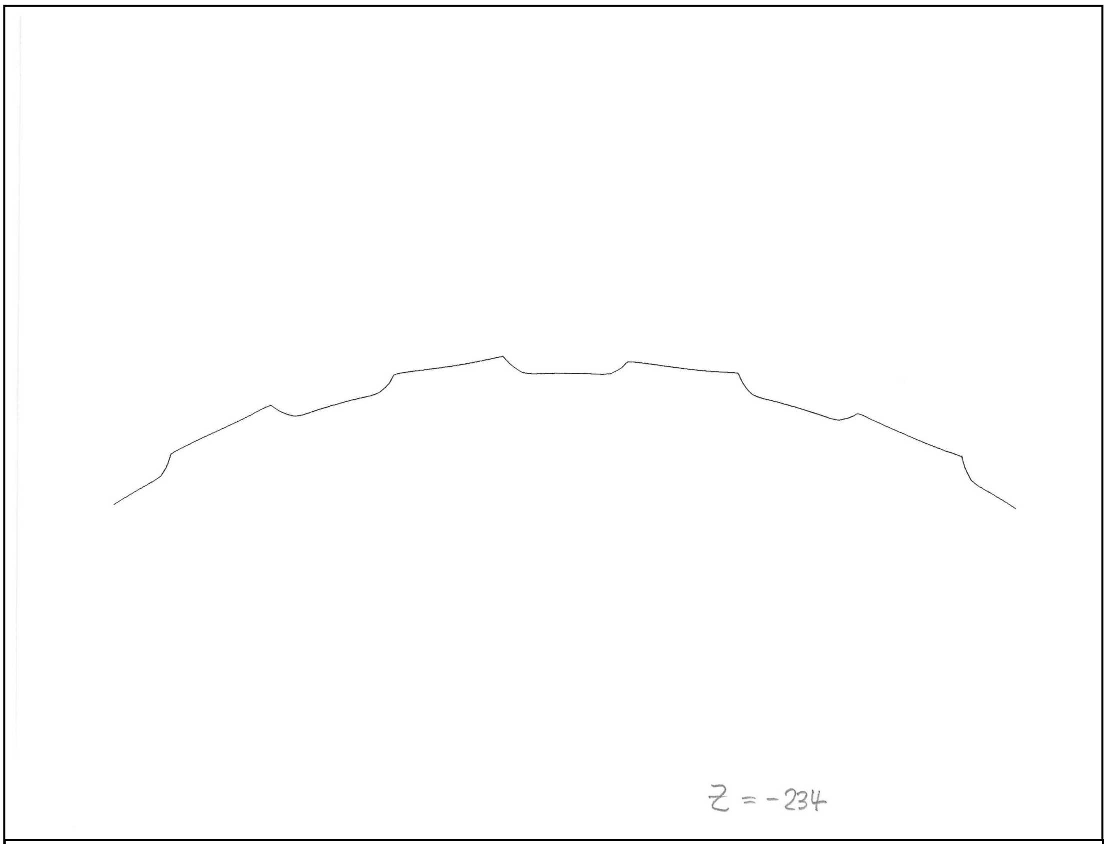
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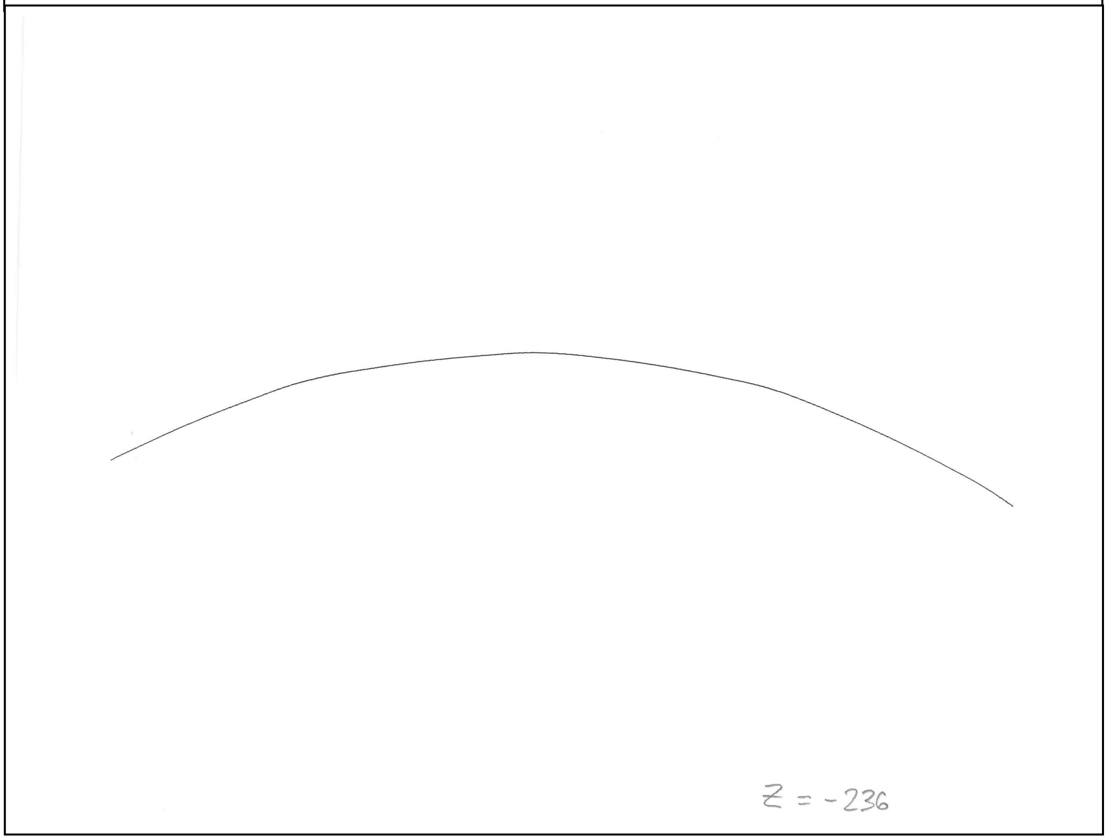
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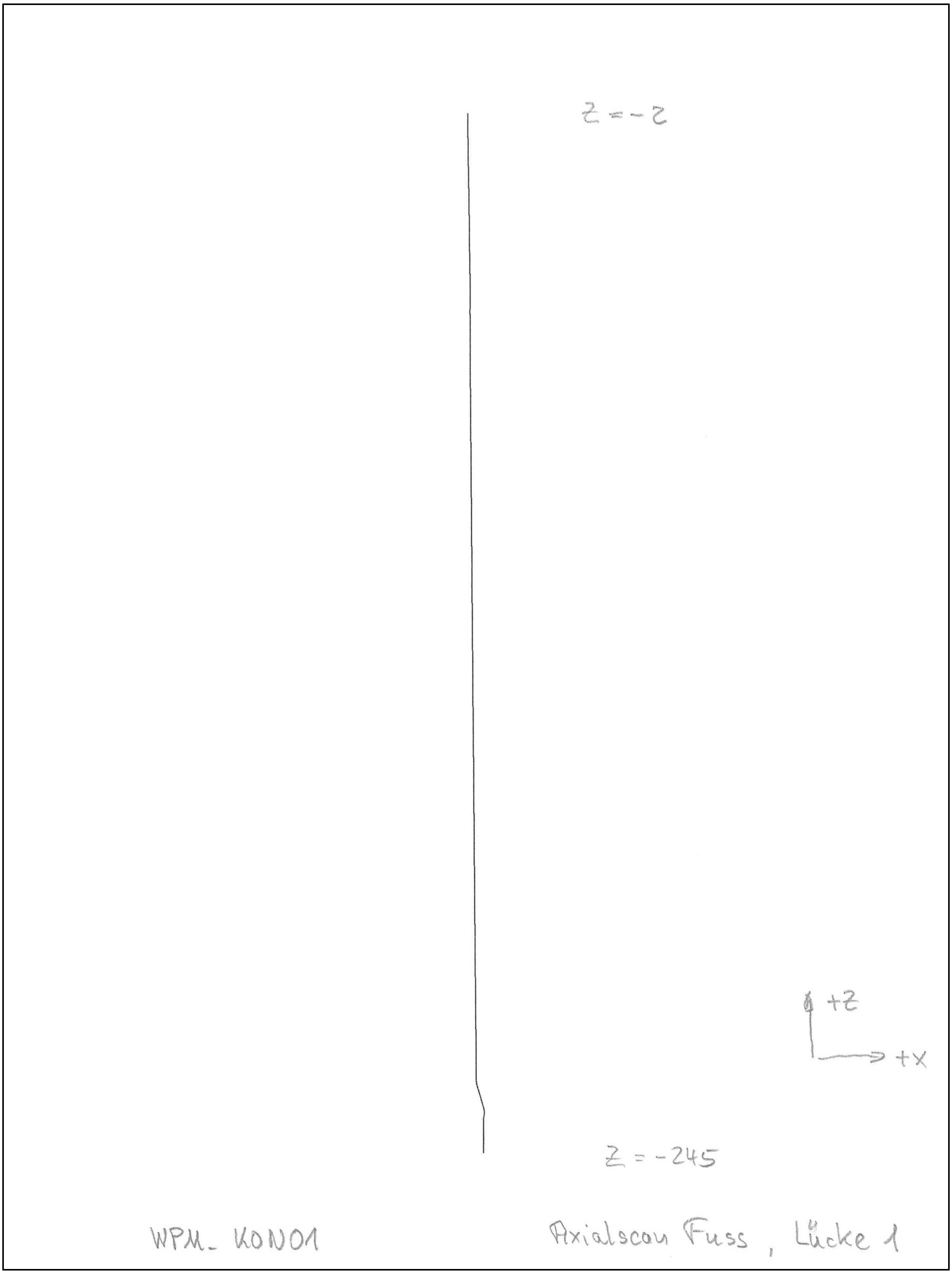
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+X
Z = -245
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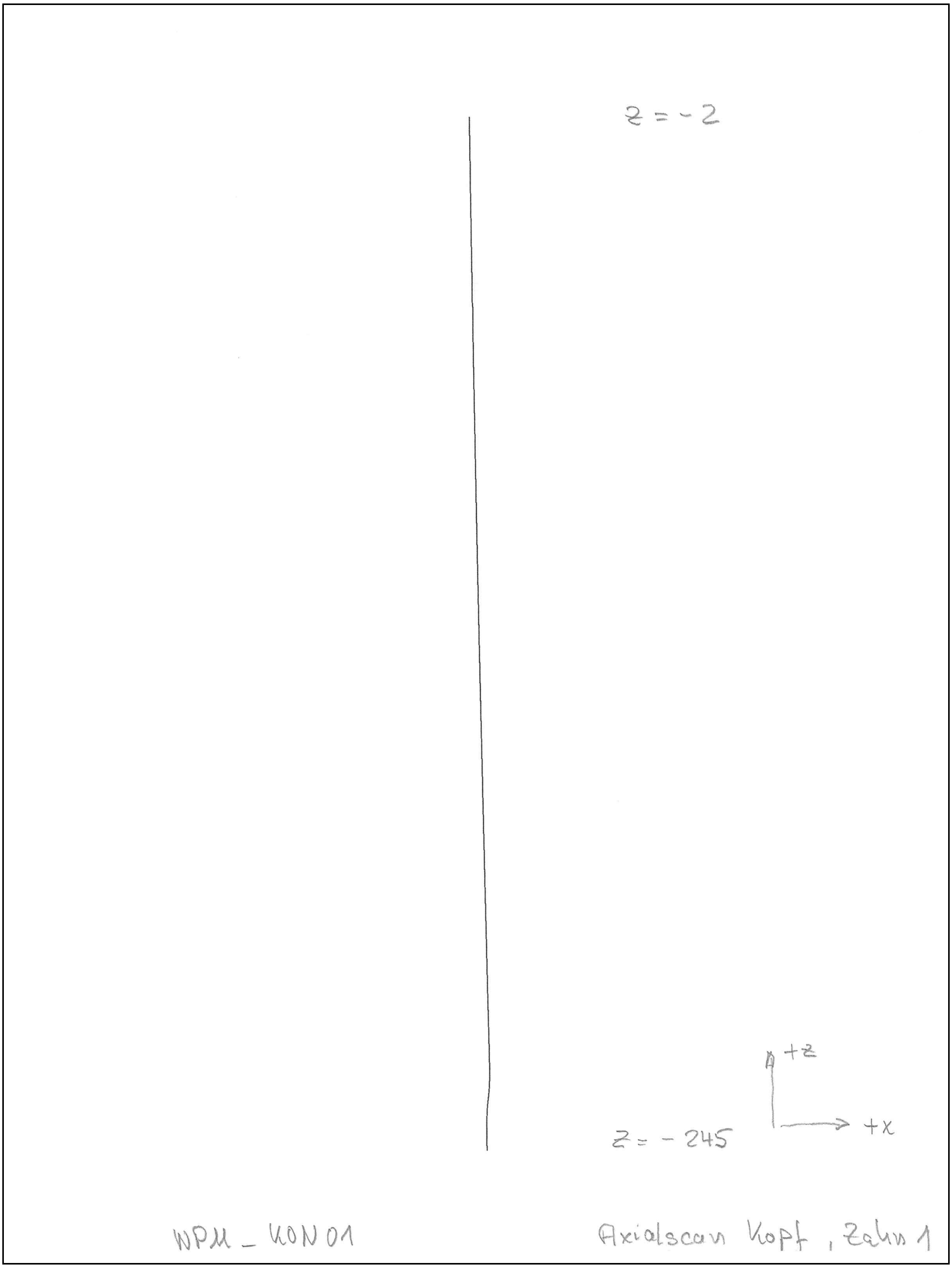
Axialscan Fuss, Lücke 1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+z
+x
z = -245
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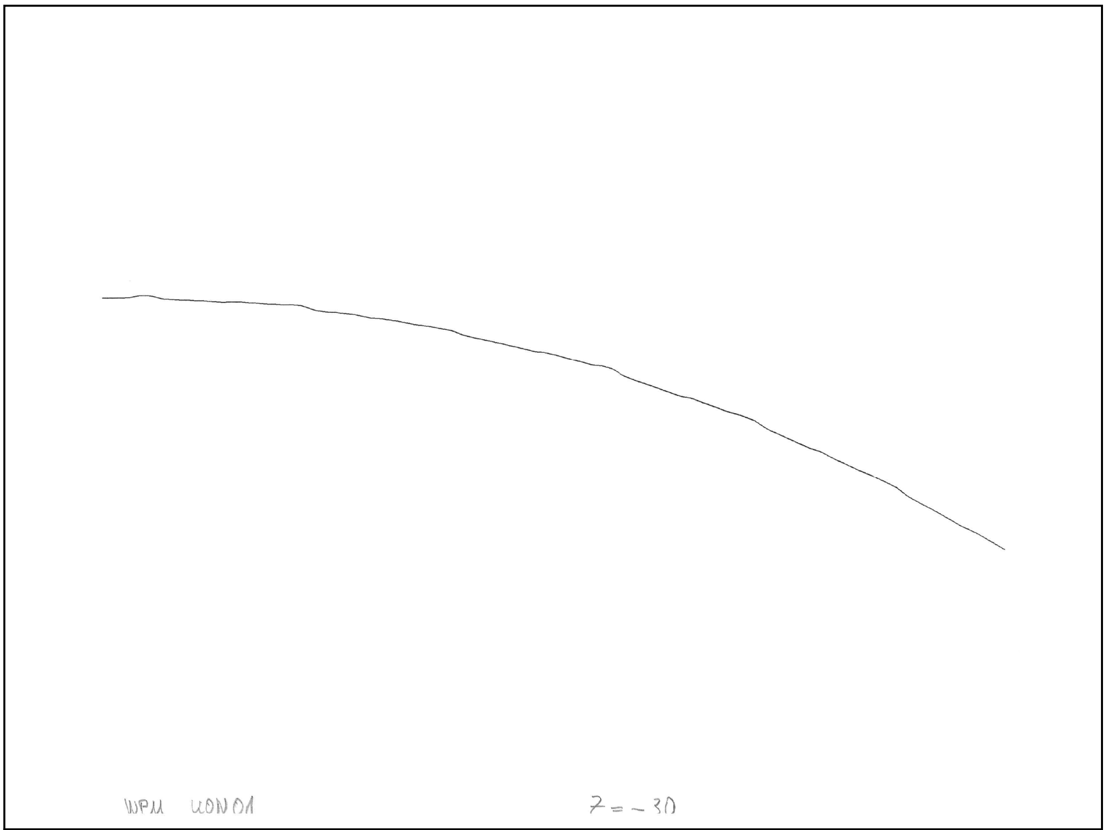
Axialscan Kopf, Zahn 1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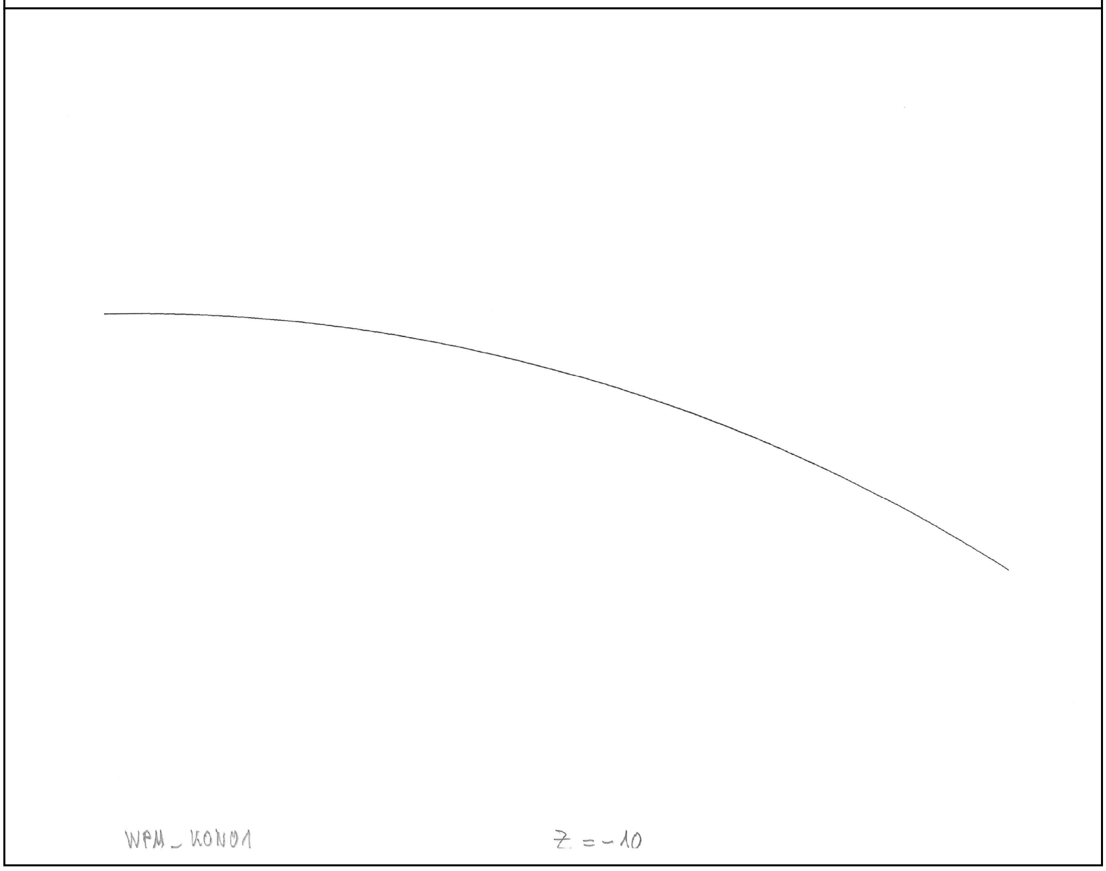
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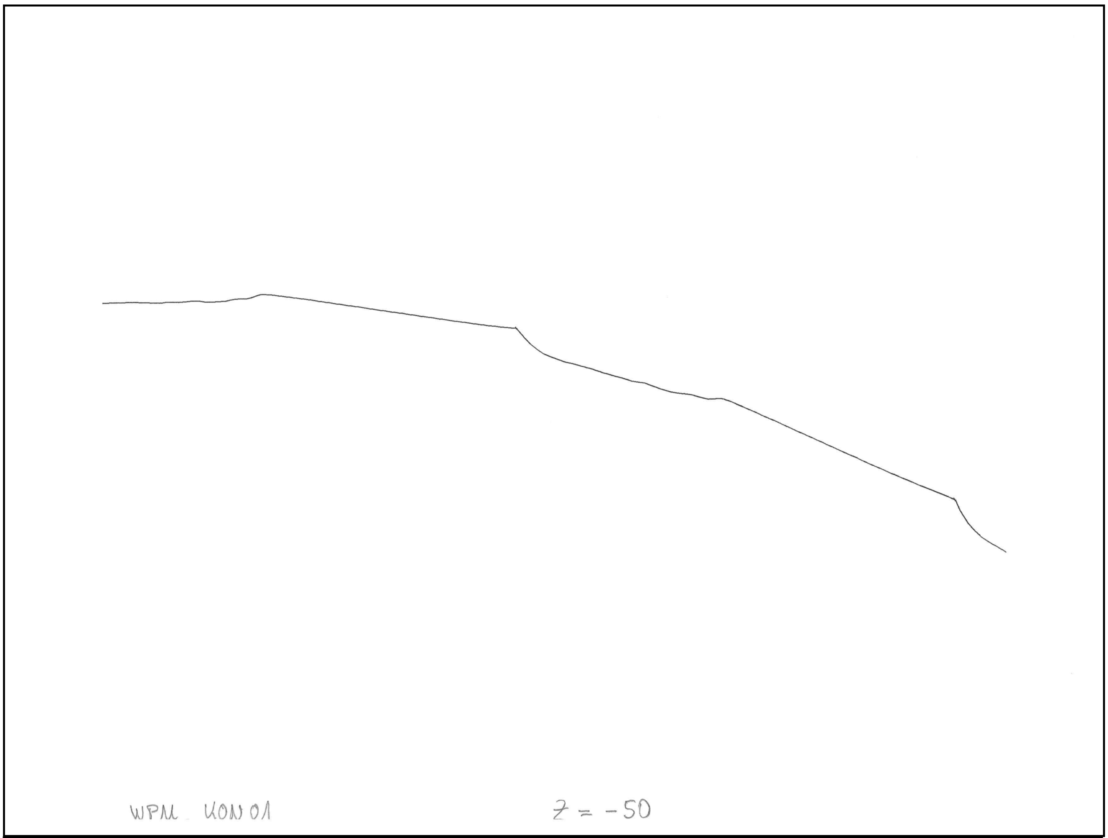
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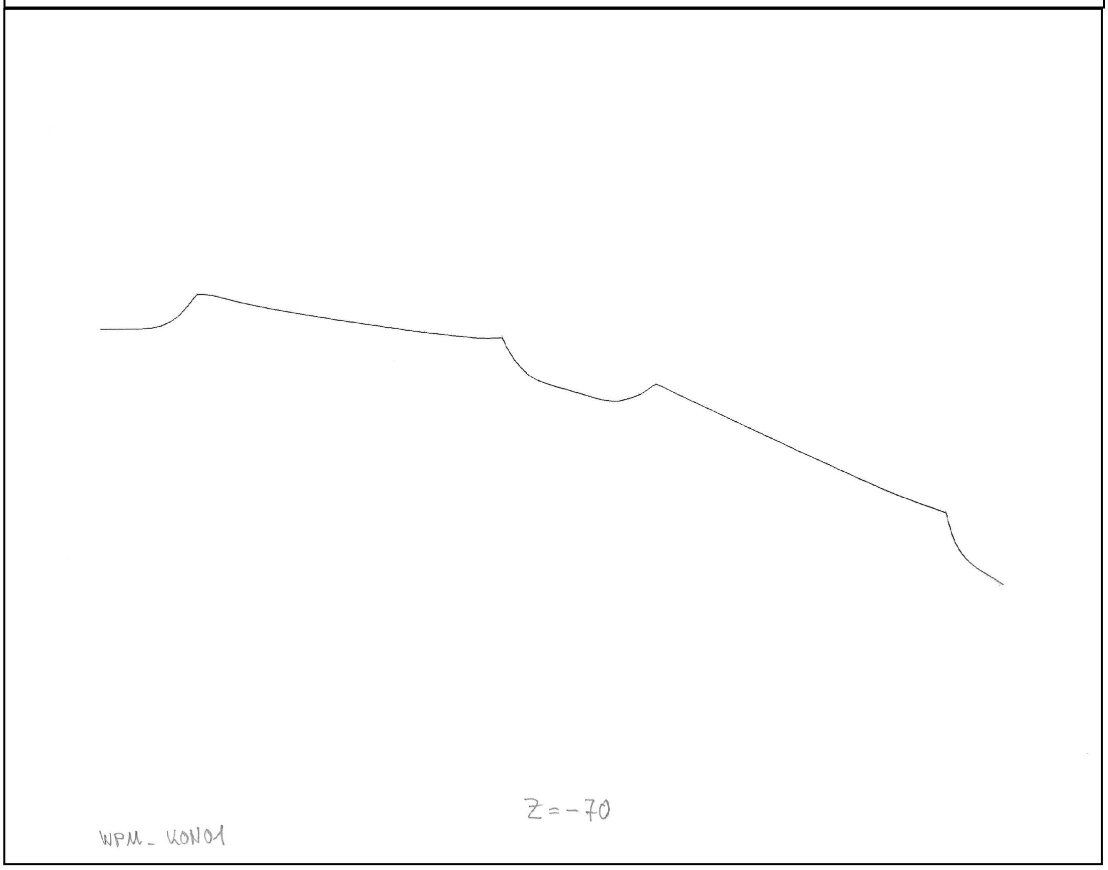
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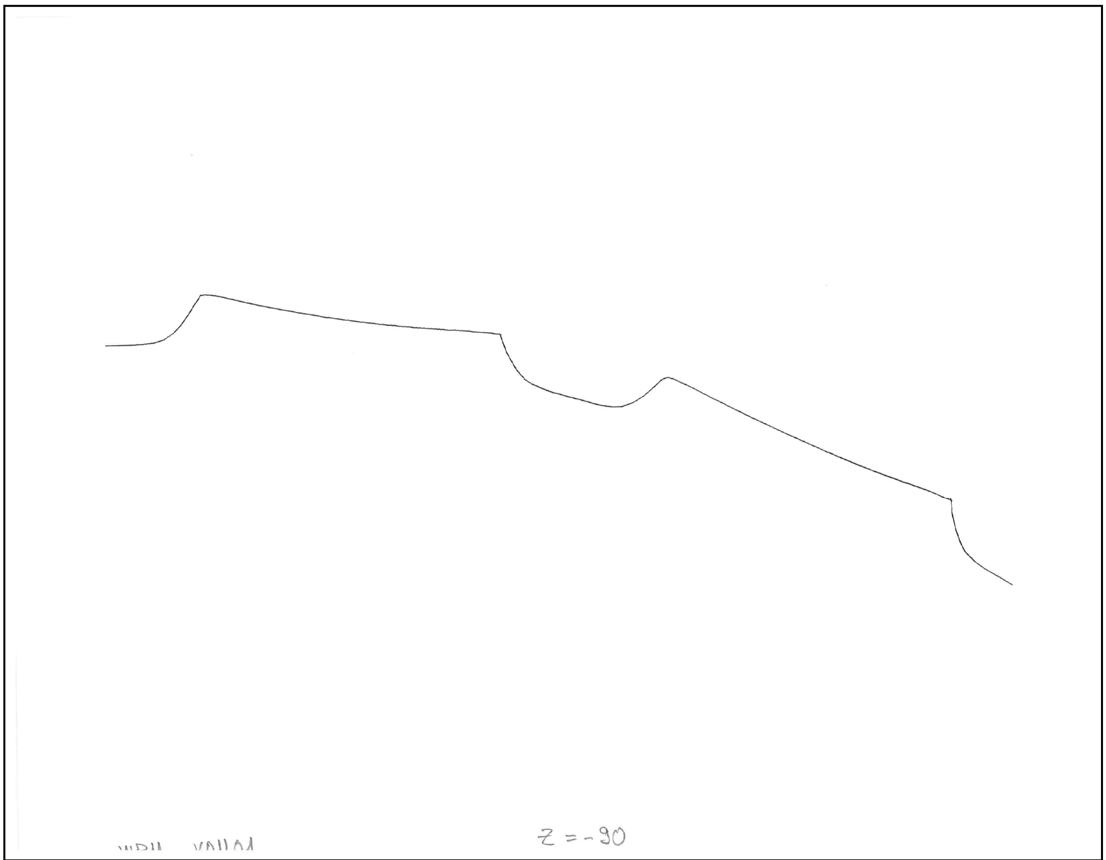
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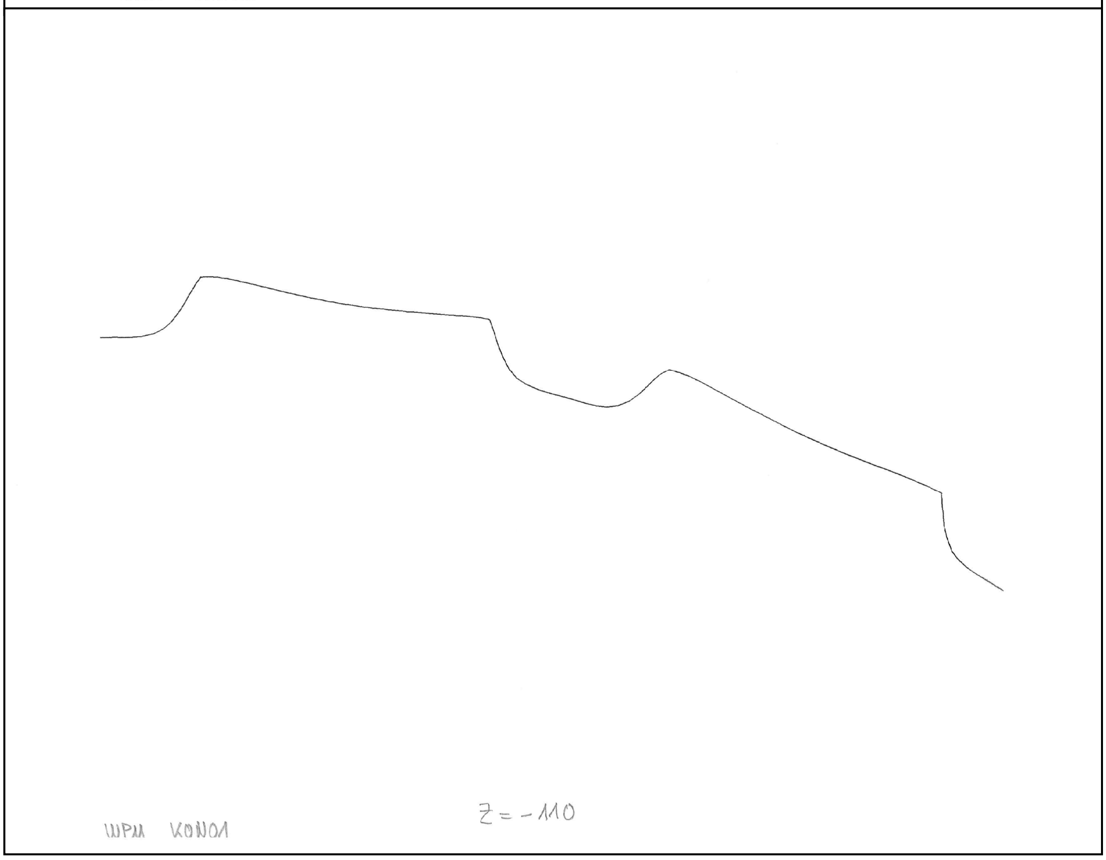
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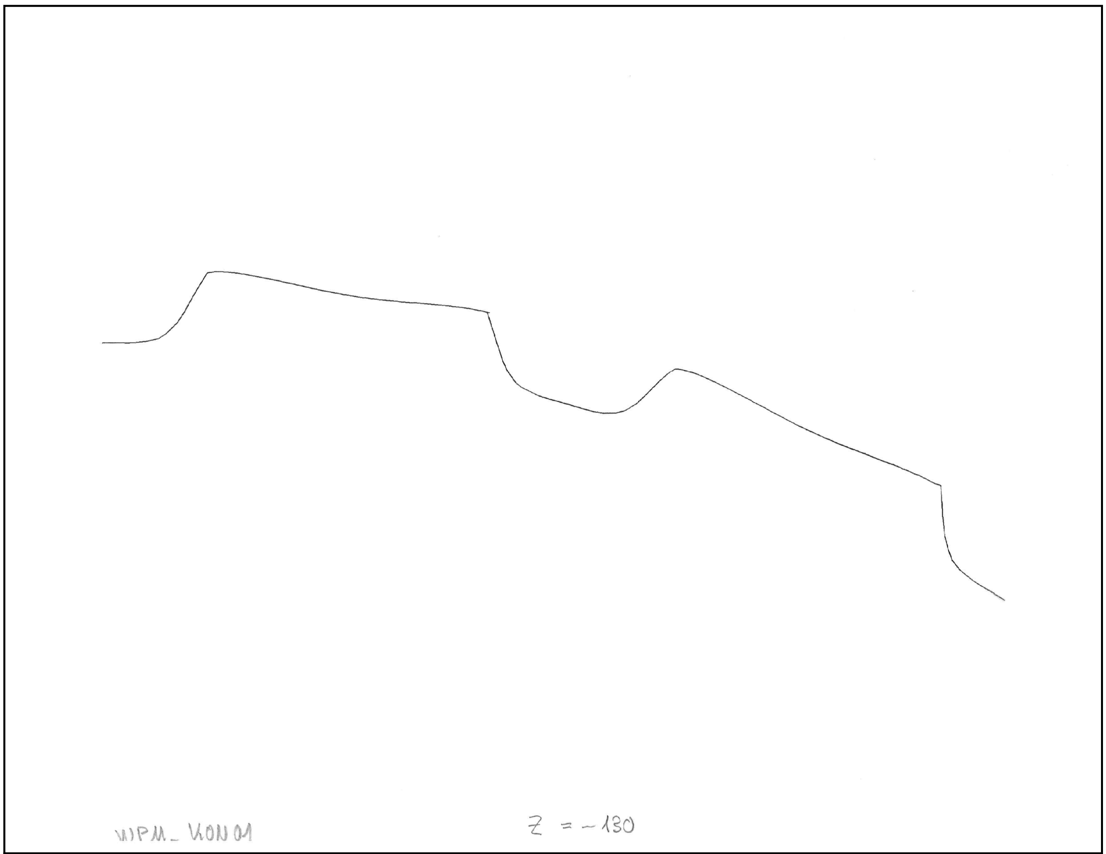
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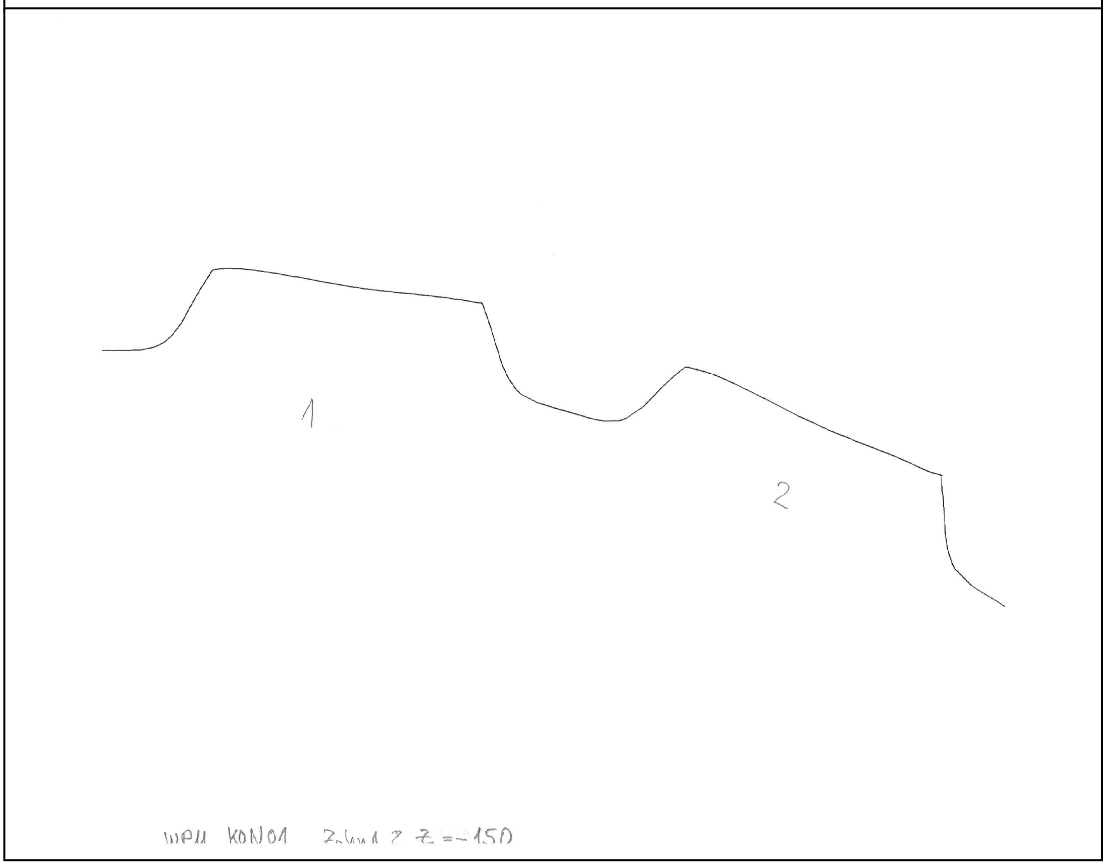
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2
KON01
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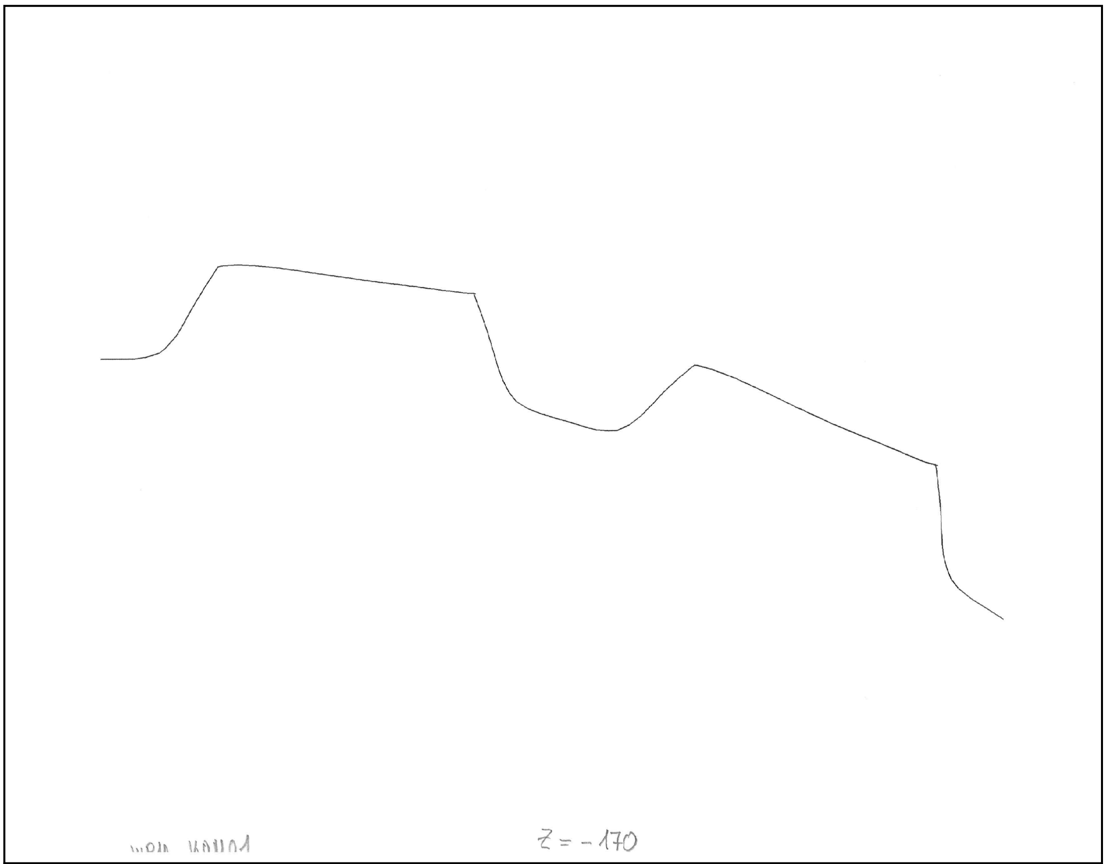
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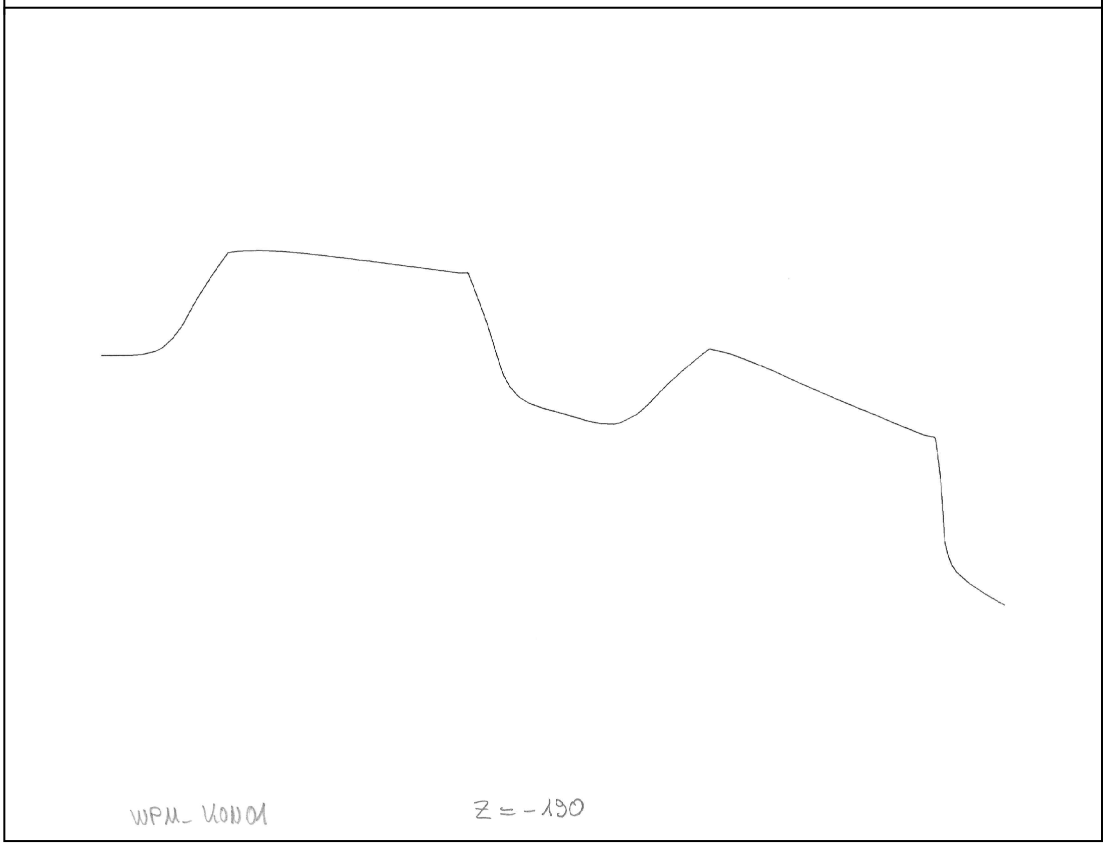
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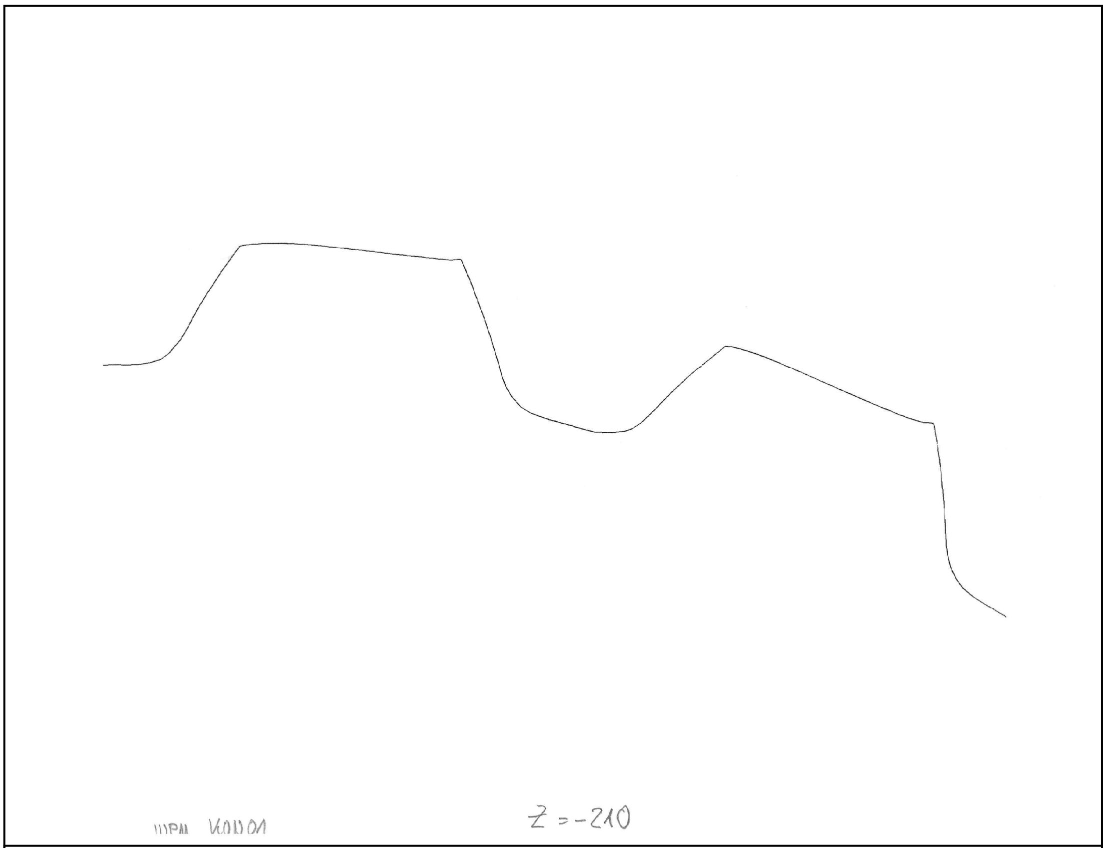
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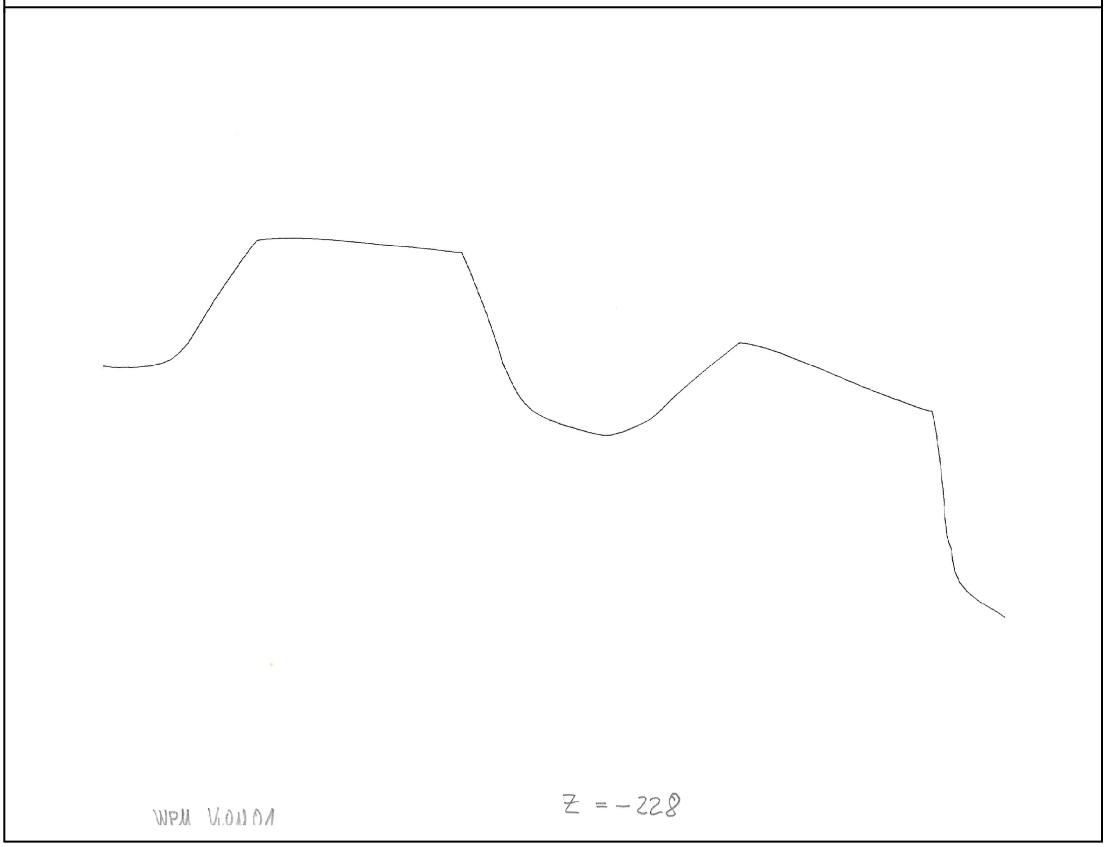
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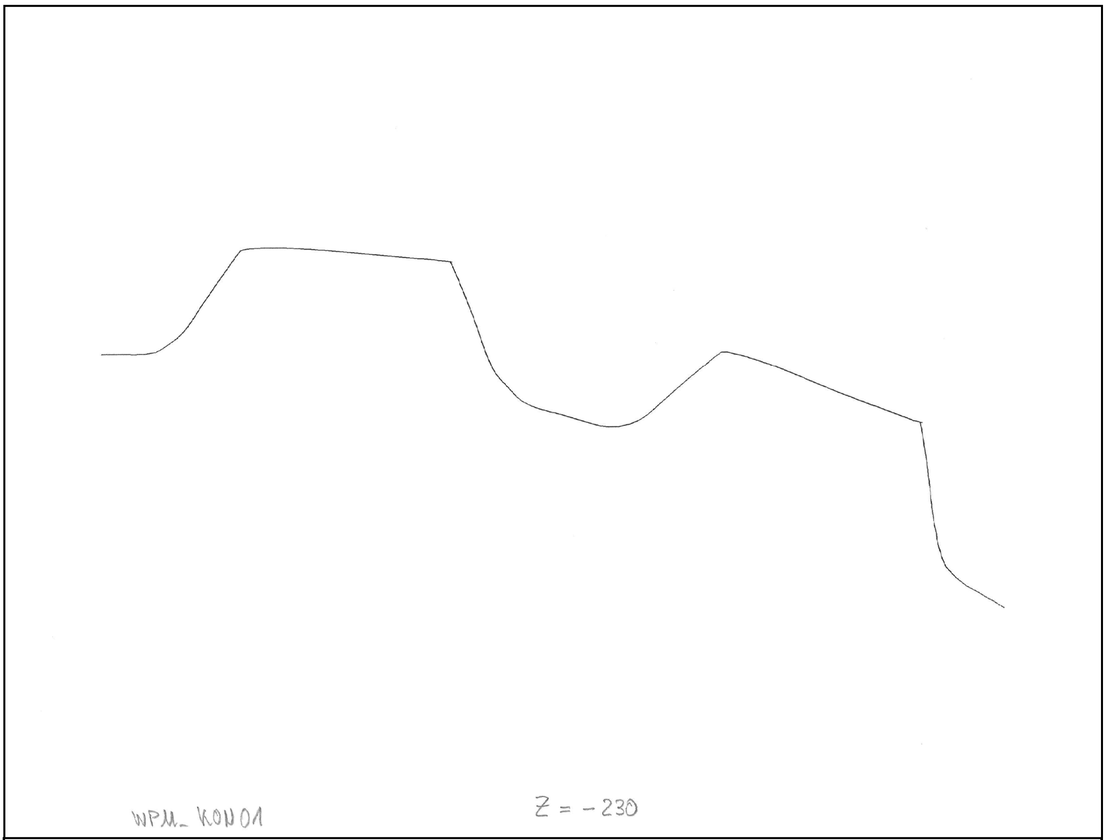
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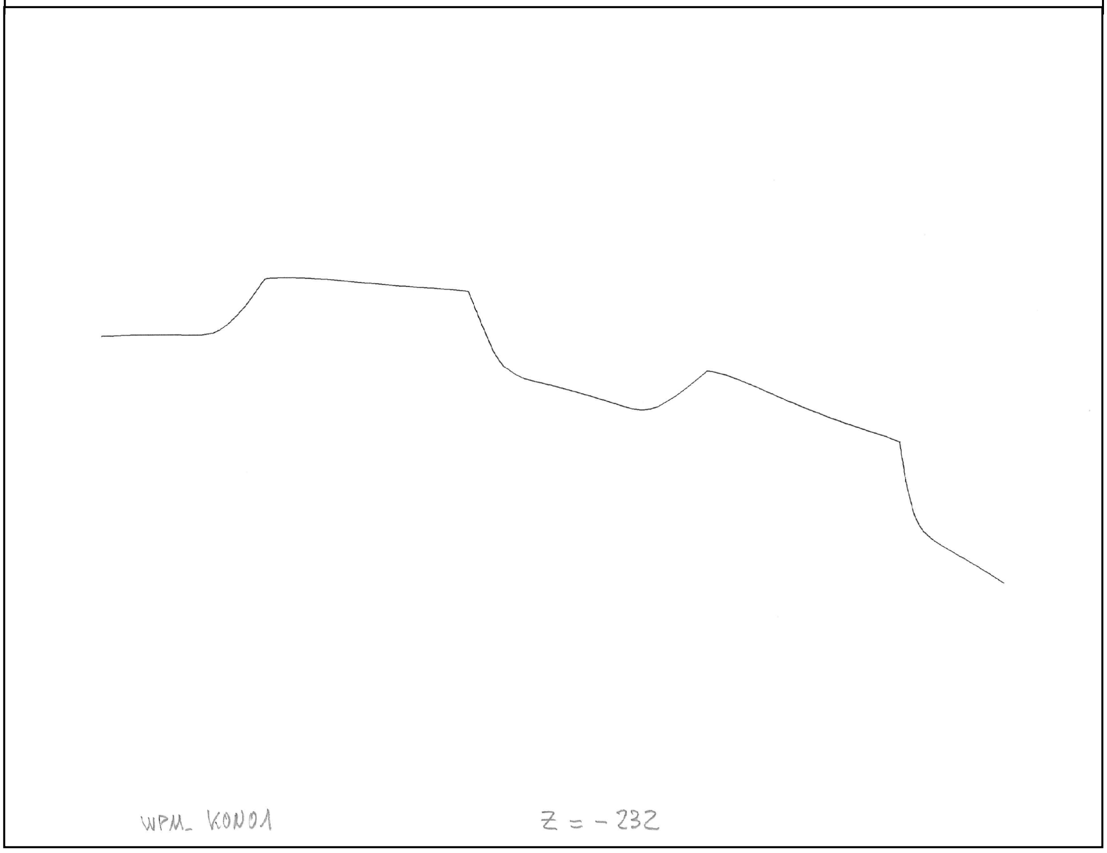
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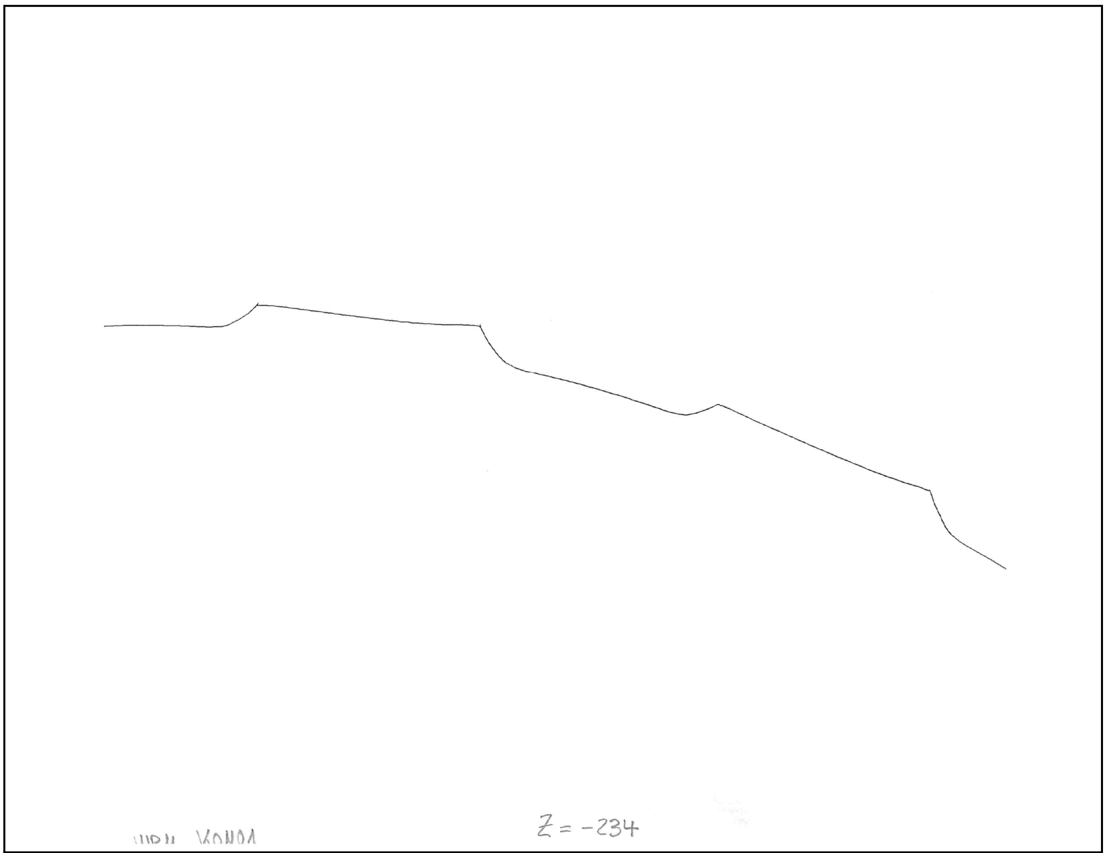
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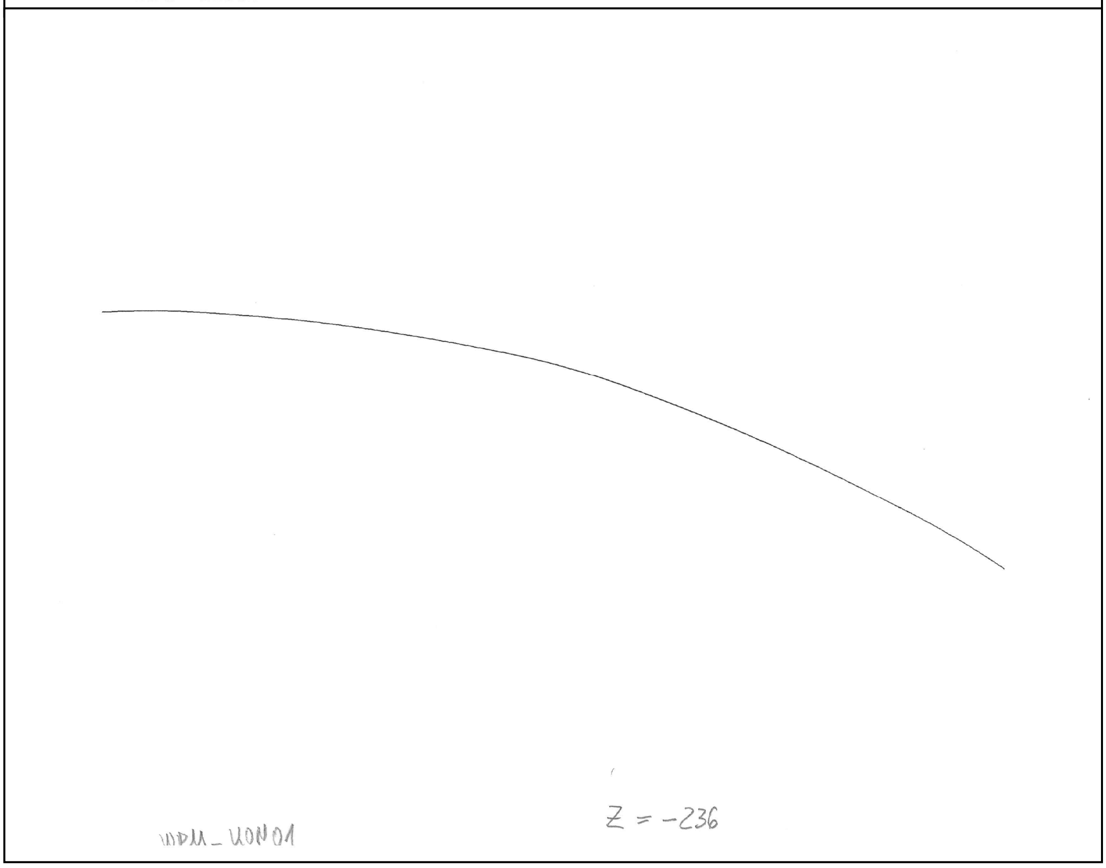

Z = -236

- Stepped sample blank

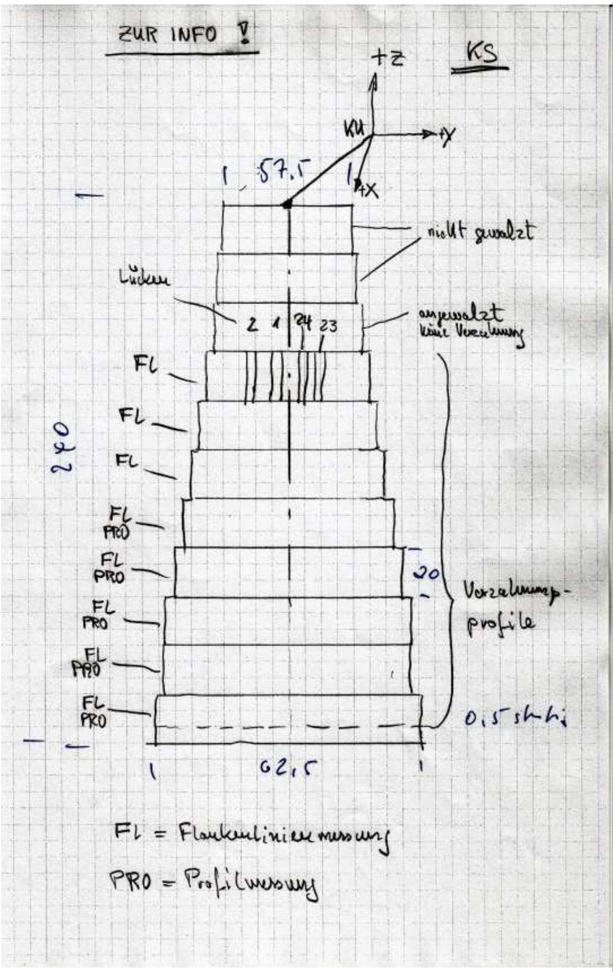
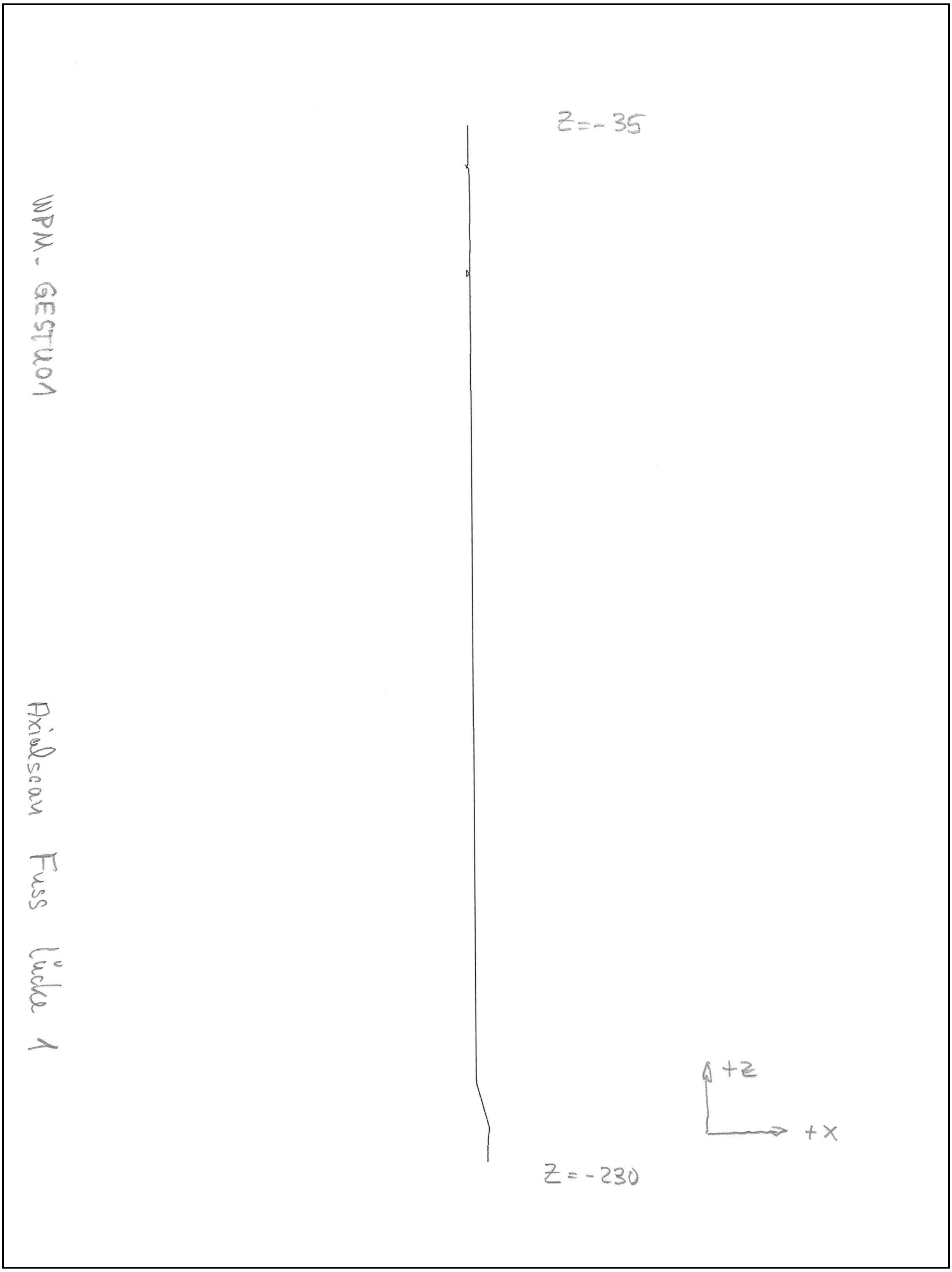
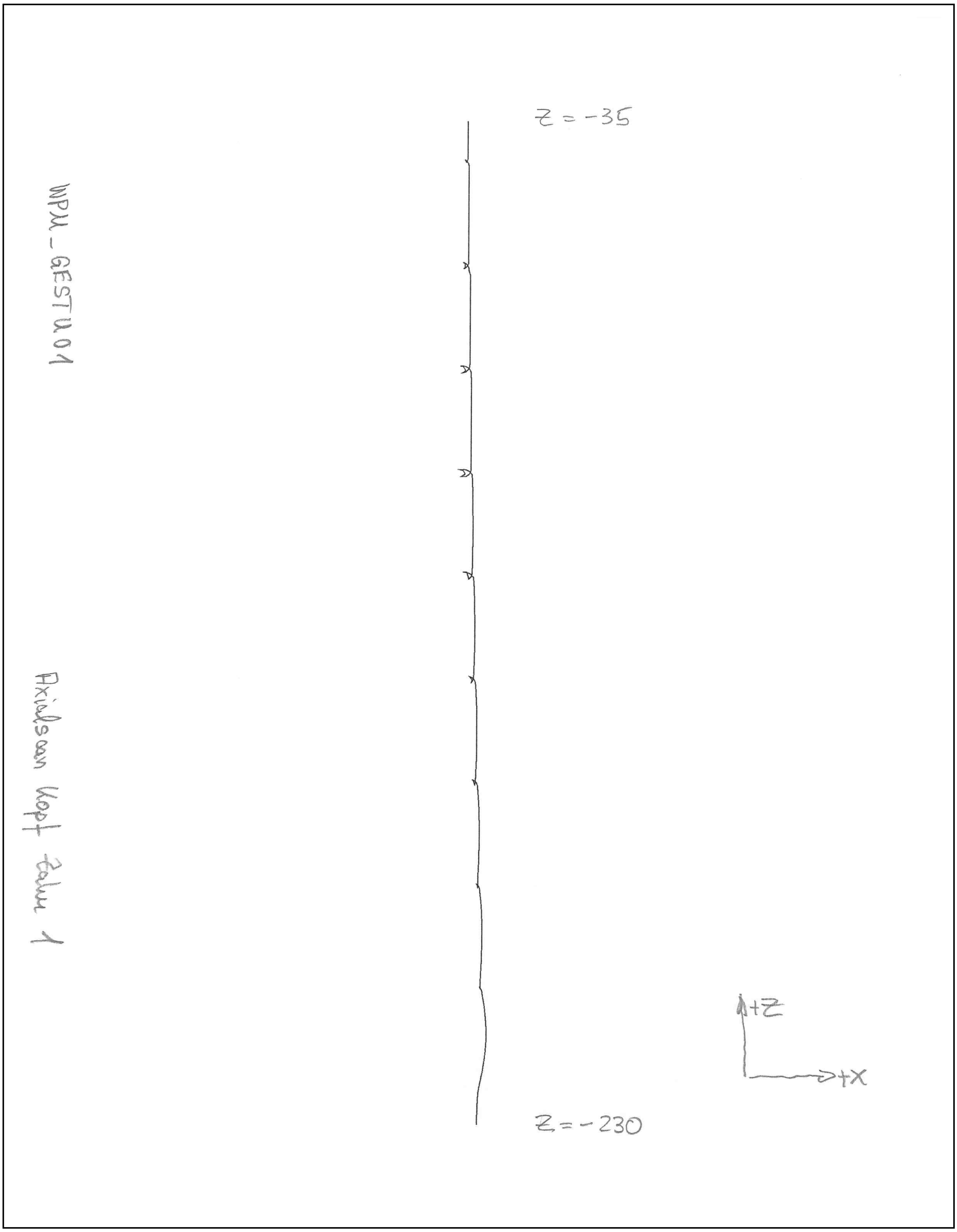


Figure 142 Stepped Sample Drawing


WPM-GESTU01
Axialscan Fuss Lücke 1
Z=-35
Z=-230
+Z
+X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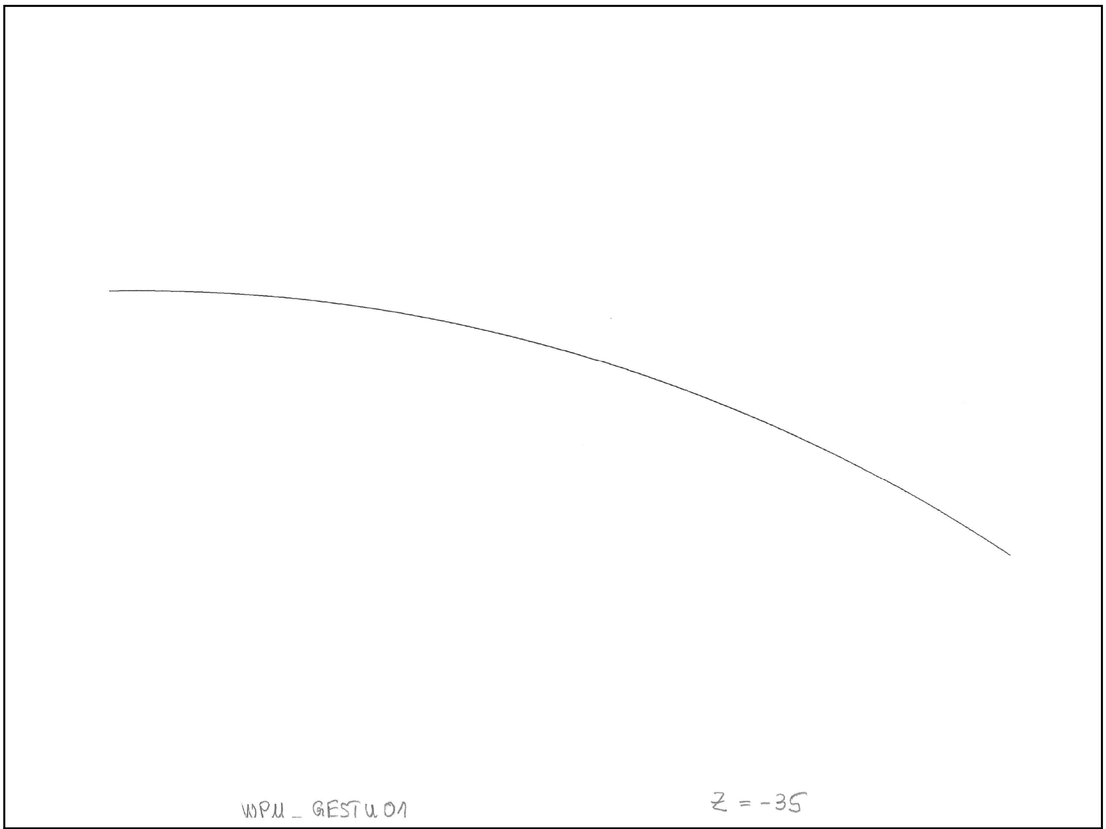
Z = -230
+Z
+X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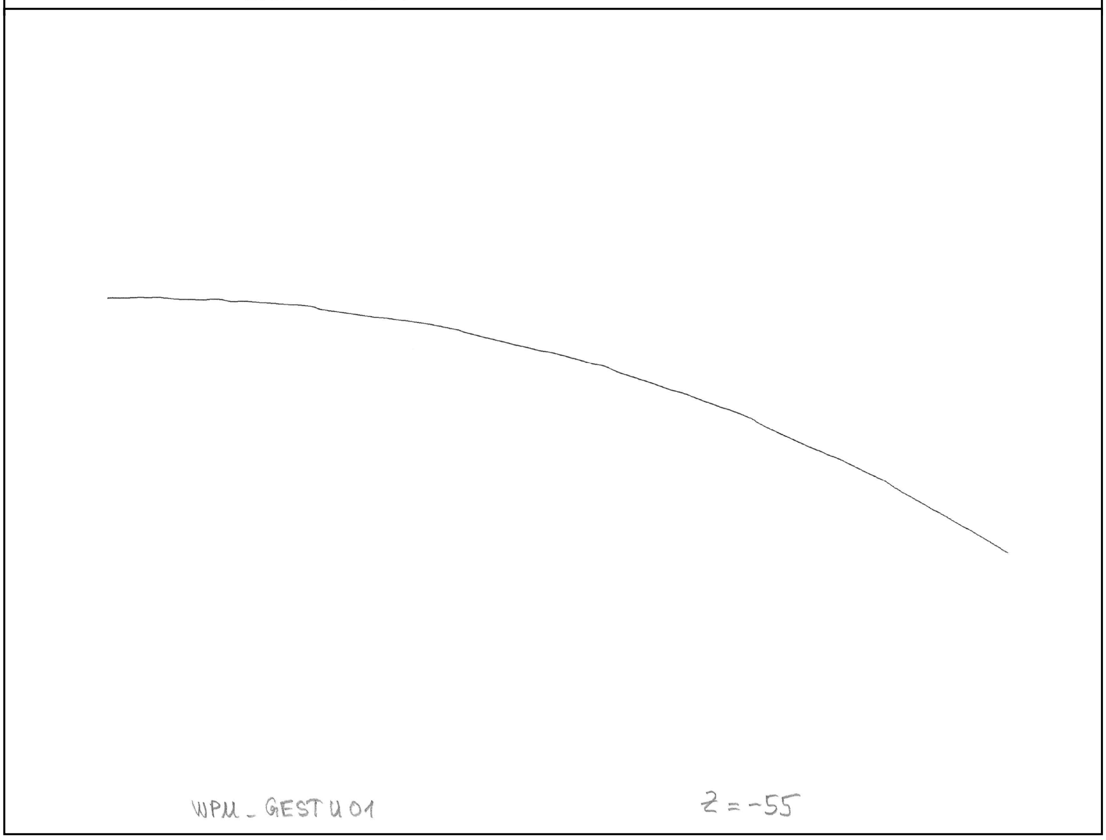
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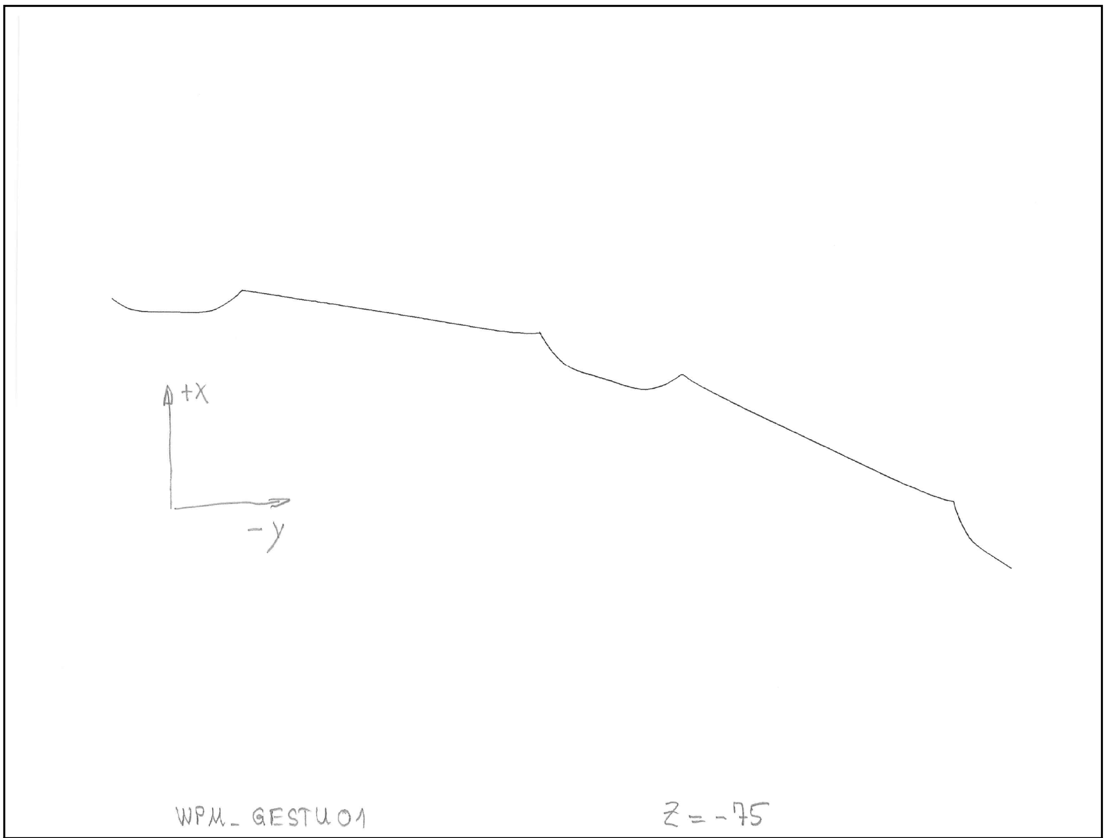
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-y
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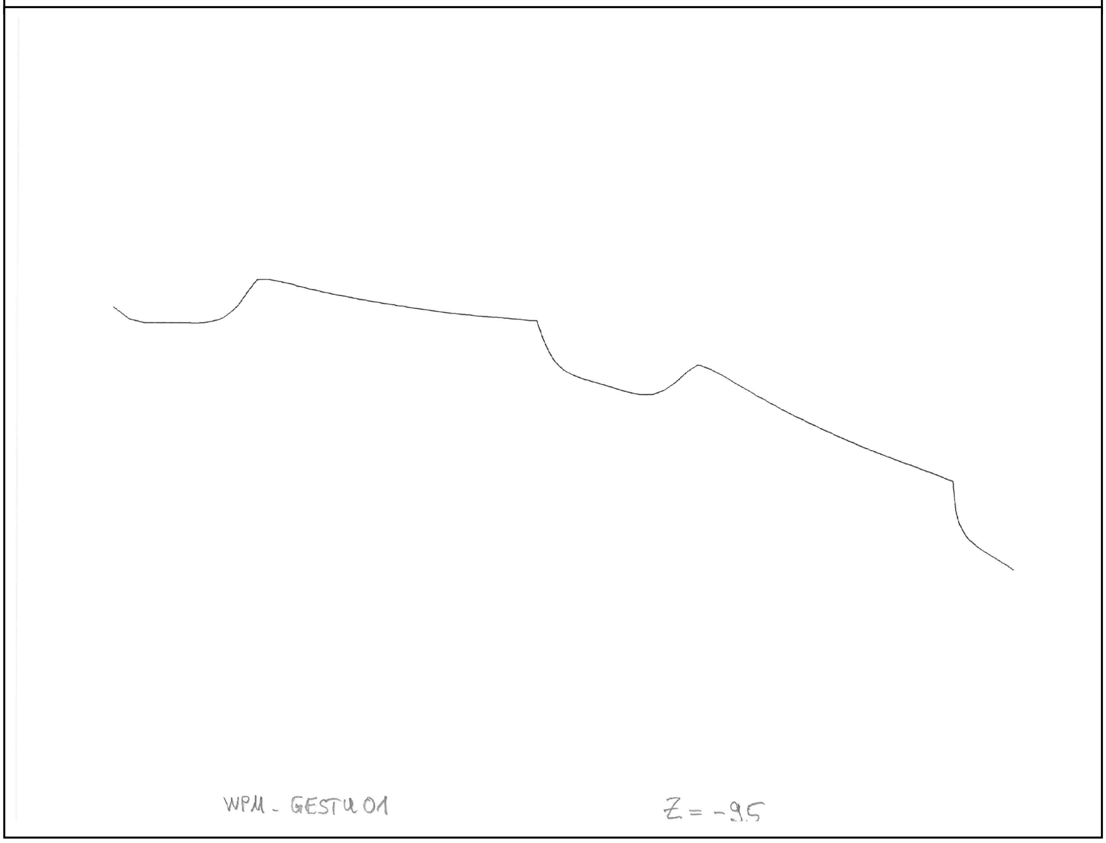
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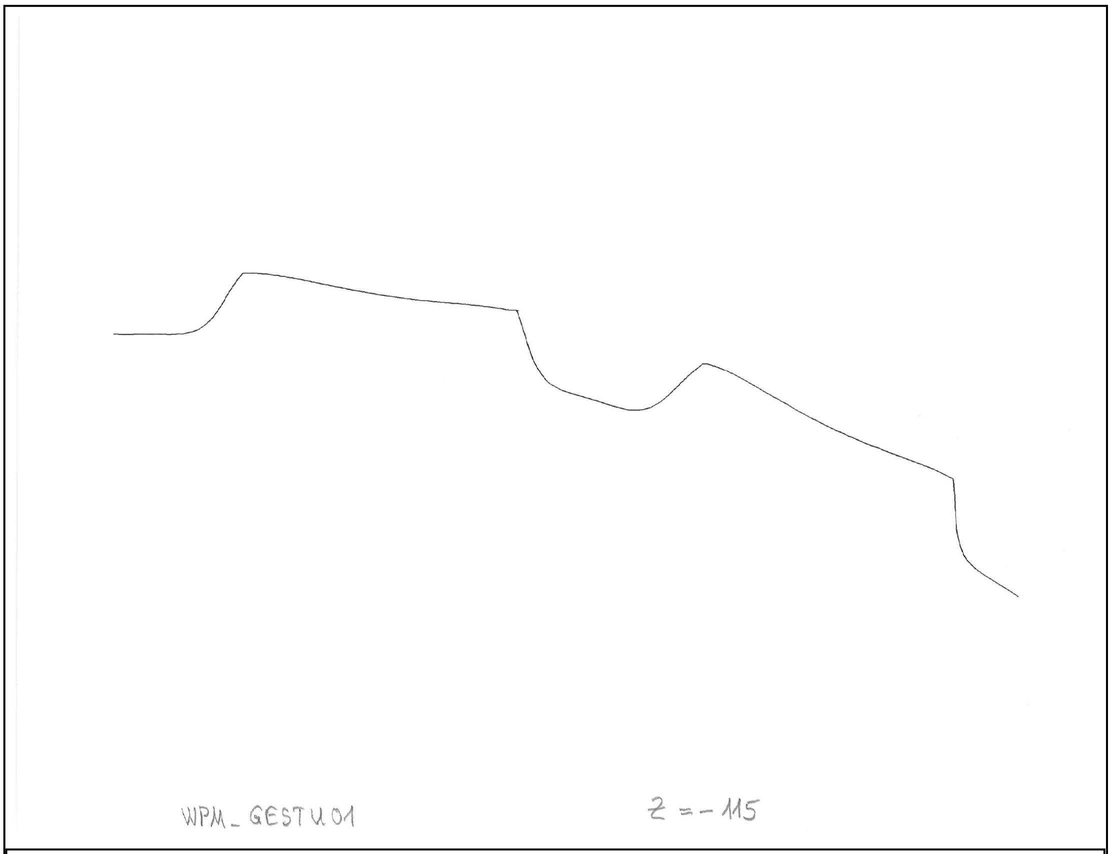
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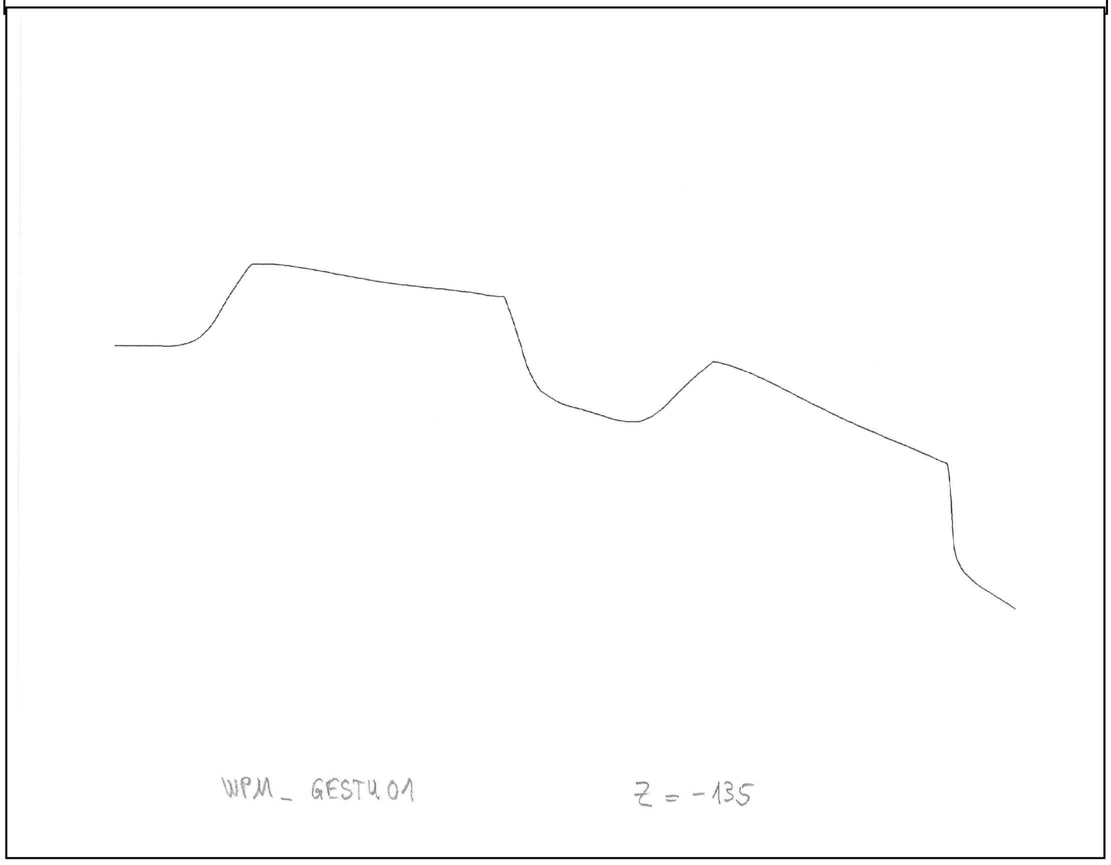
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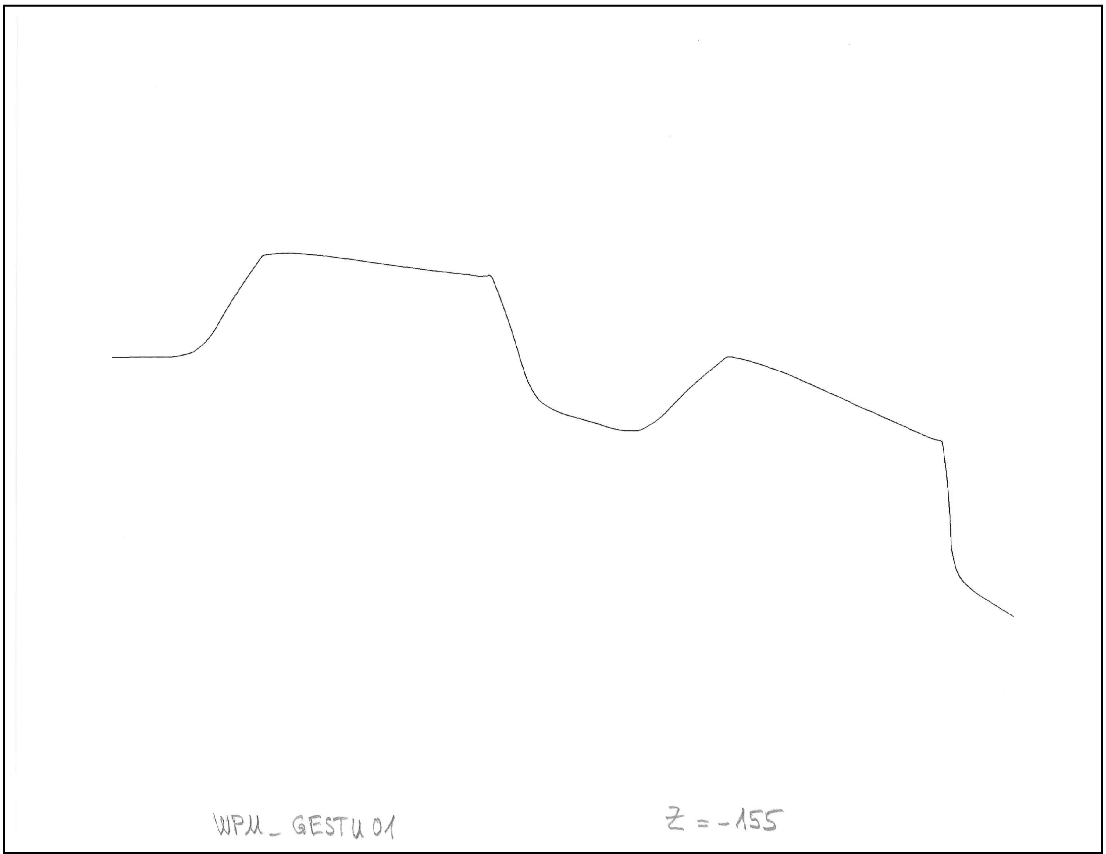
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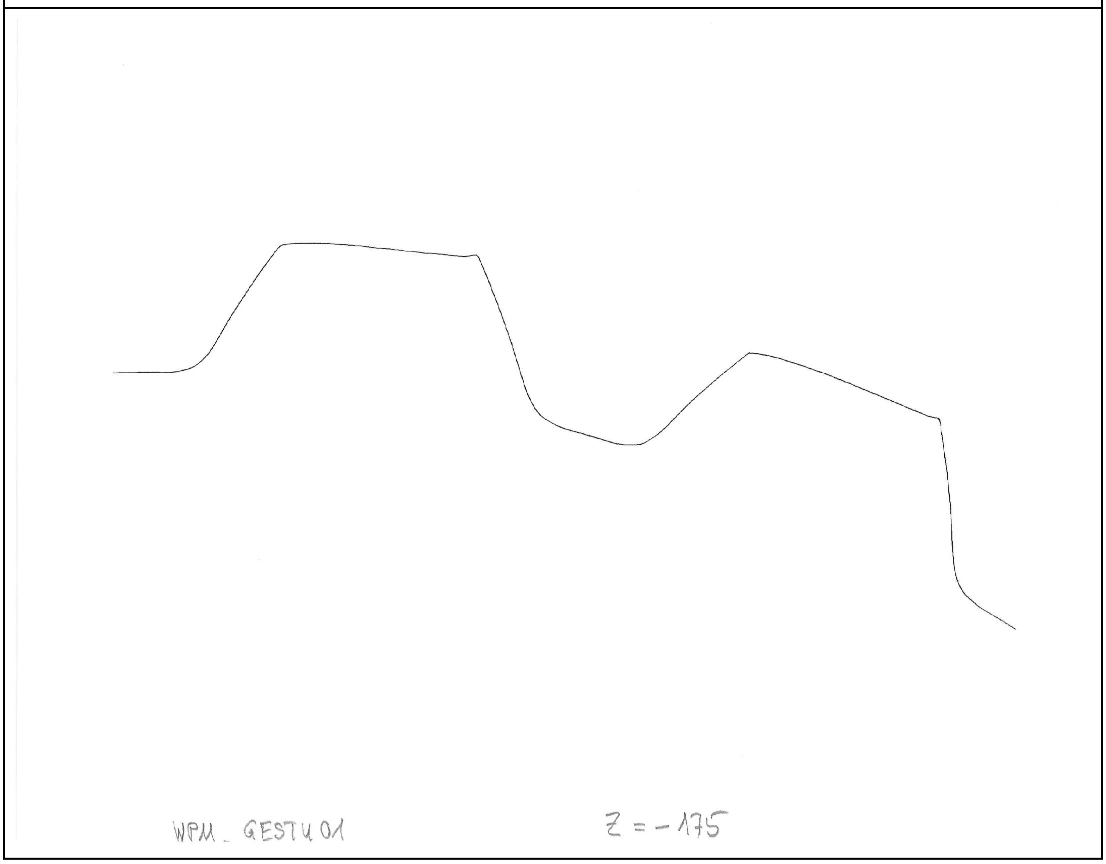
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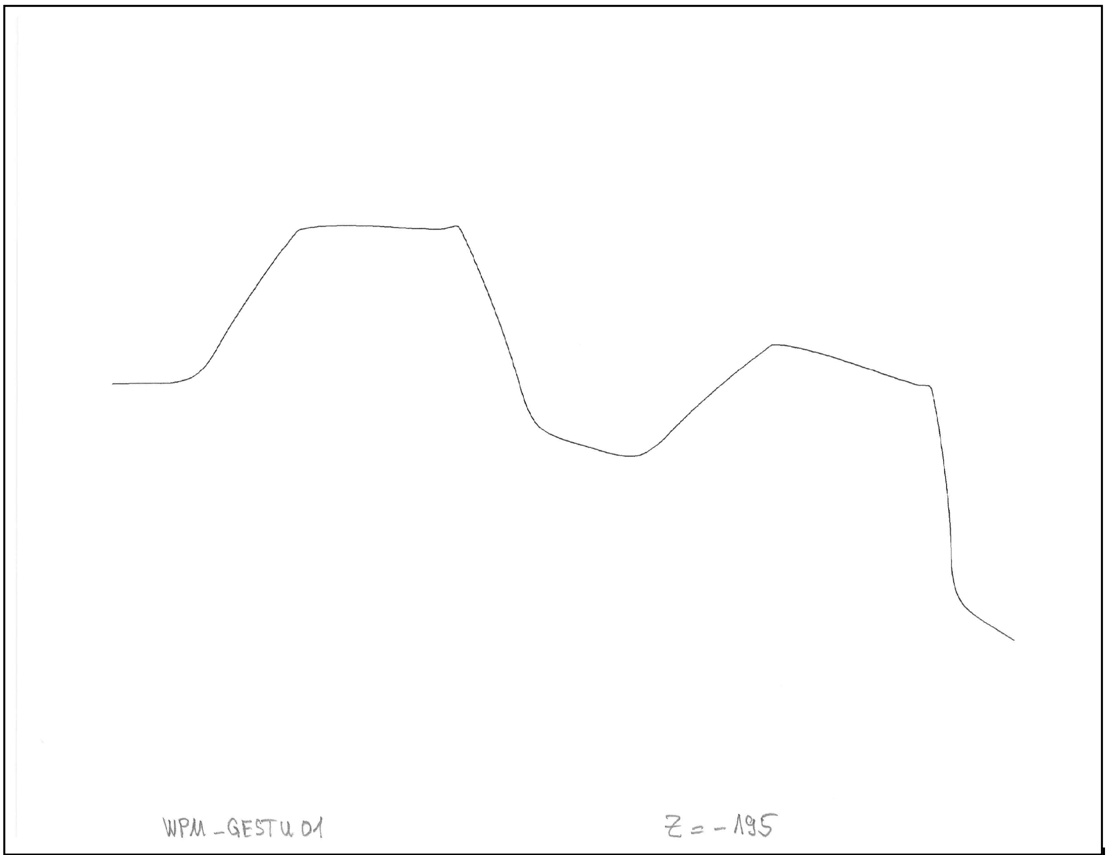
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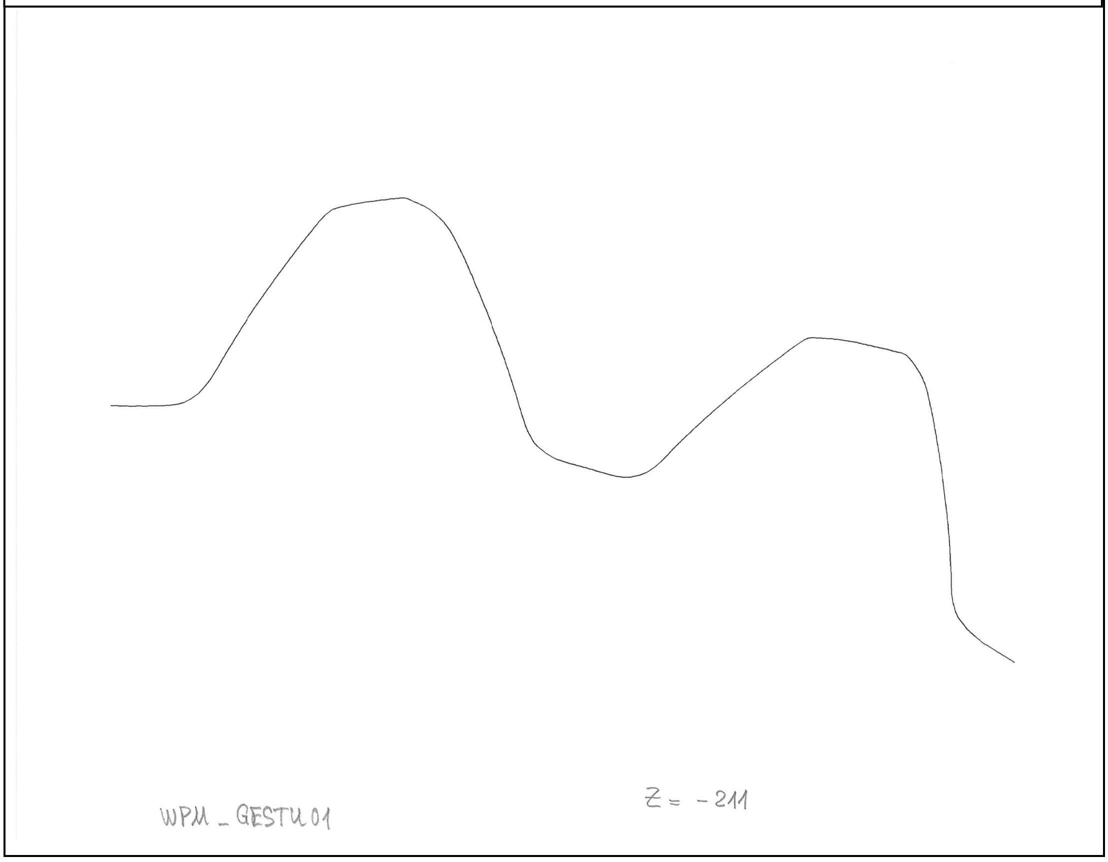
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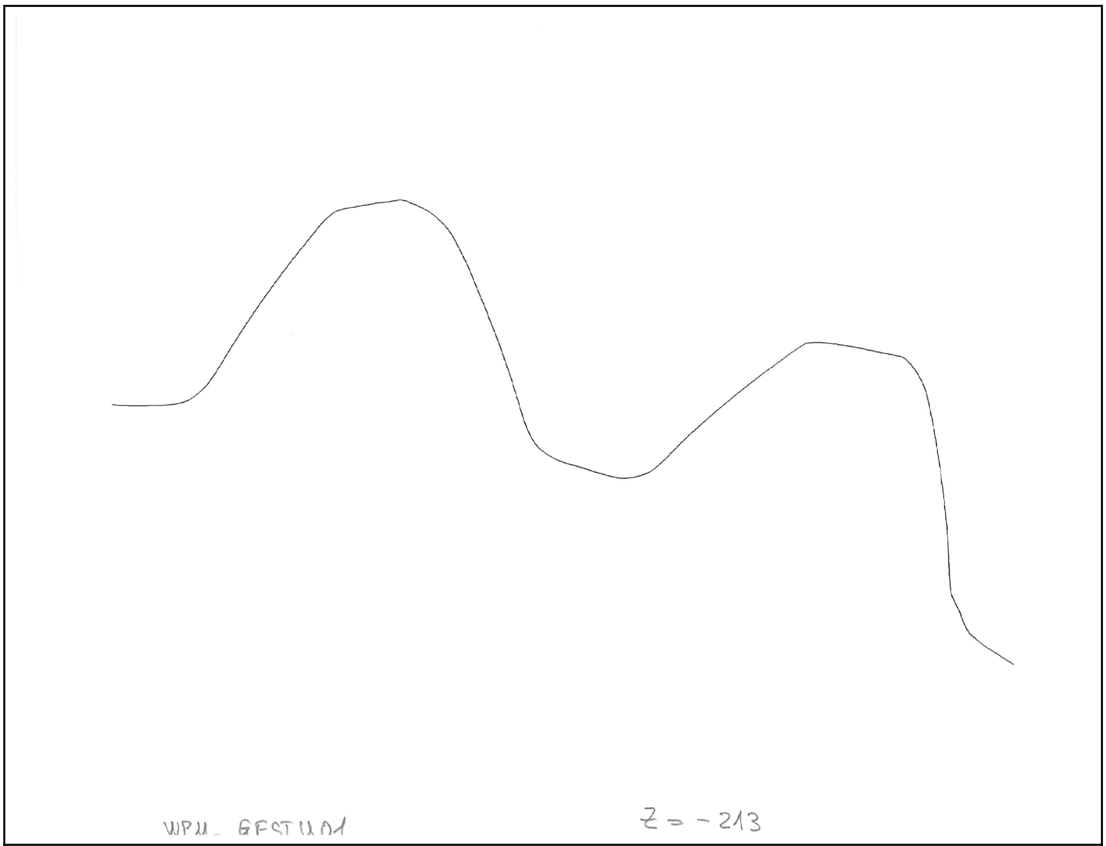
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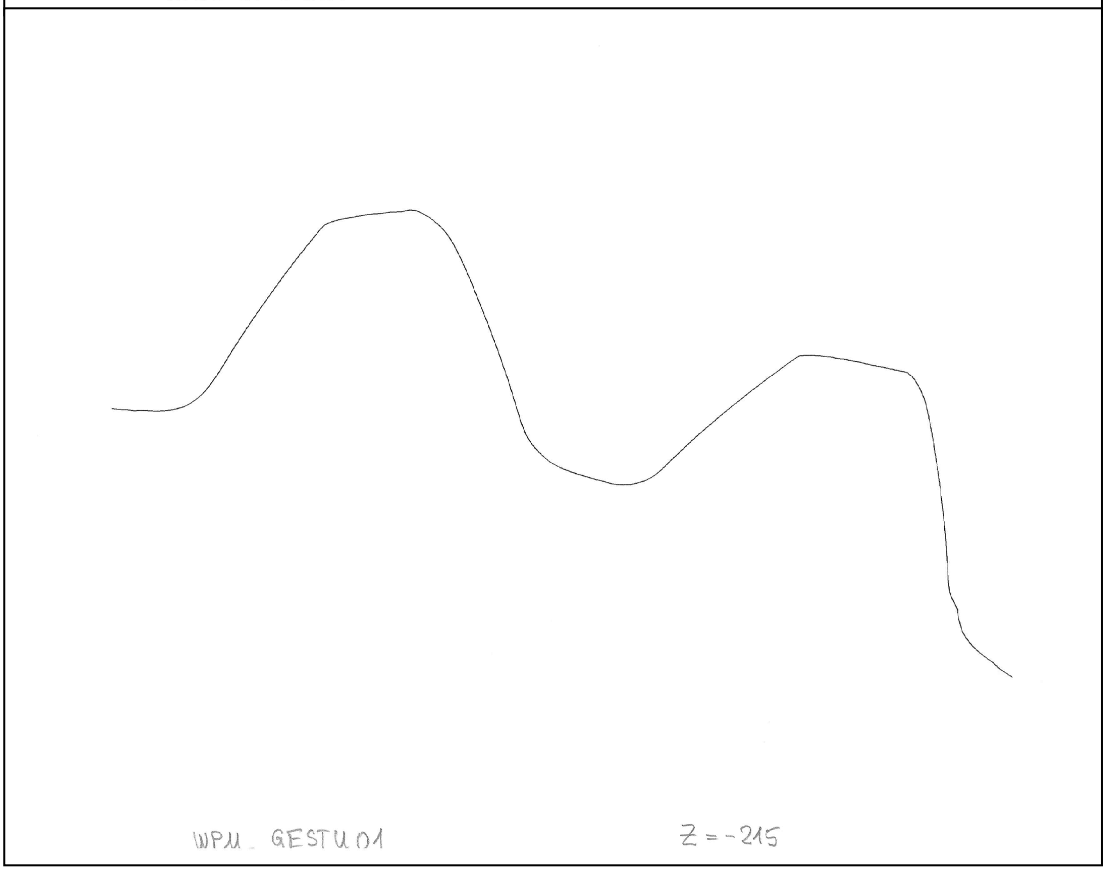
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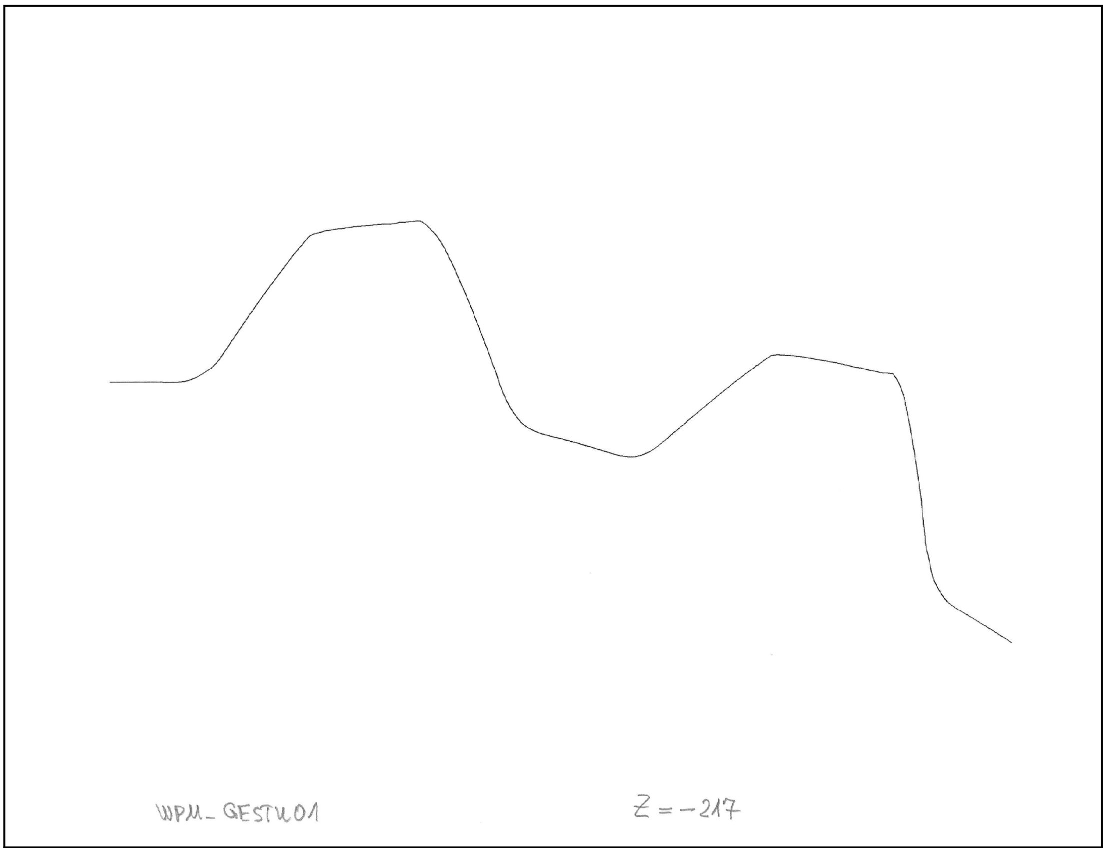
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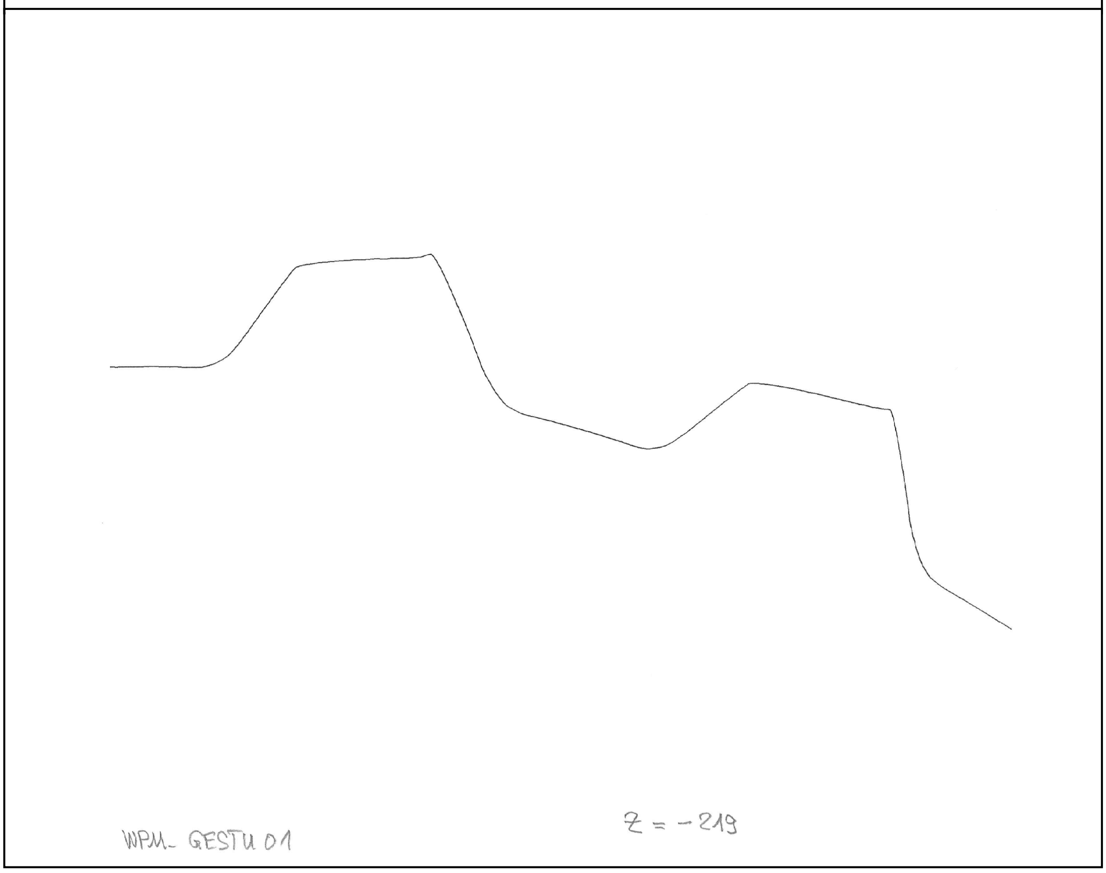
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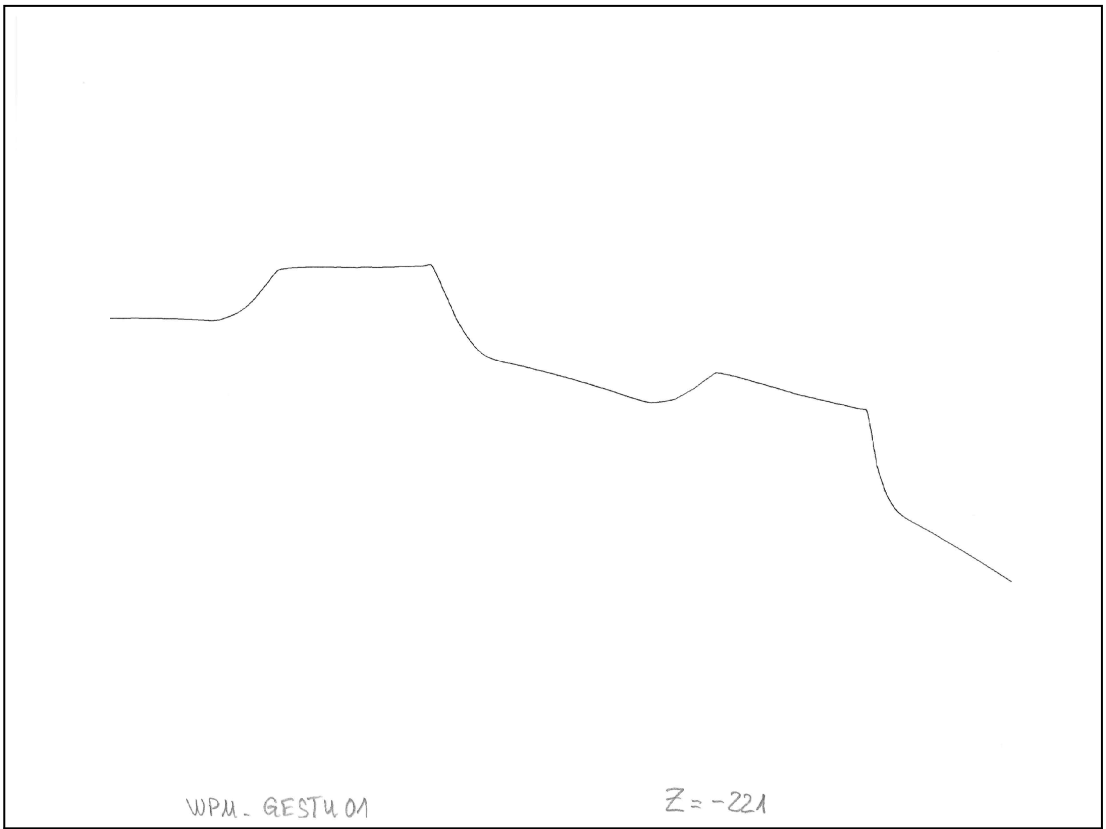
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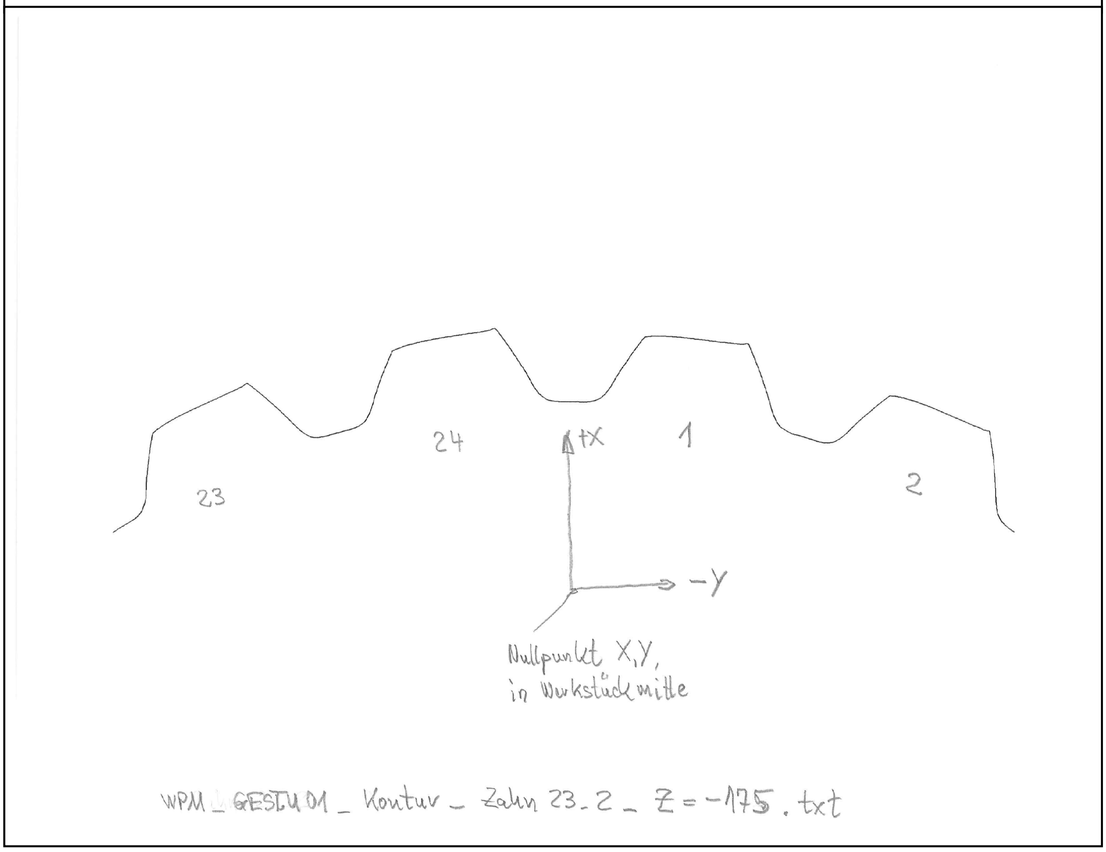
23
24
+X
1
2
-Y
Nullpunkt X,Y,
in Werkstückmitte
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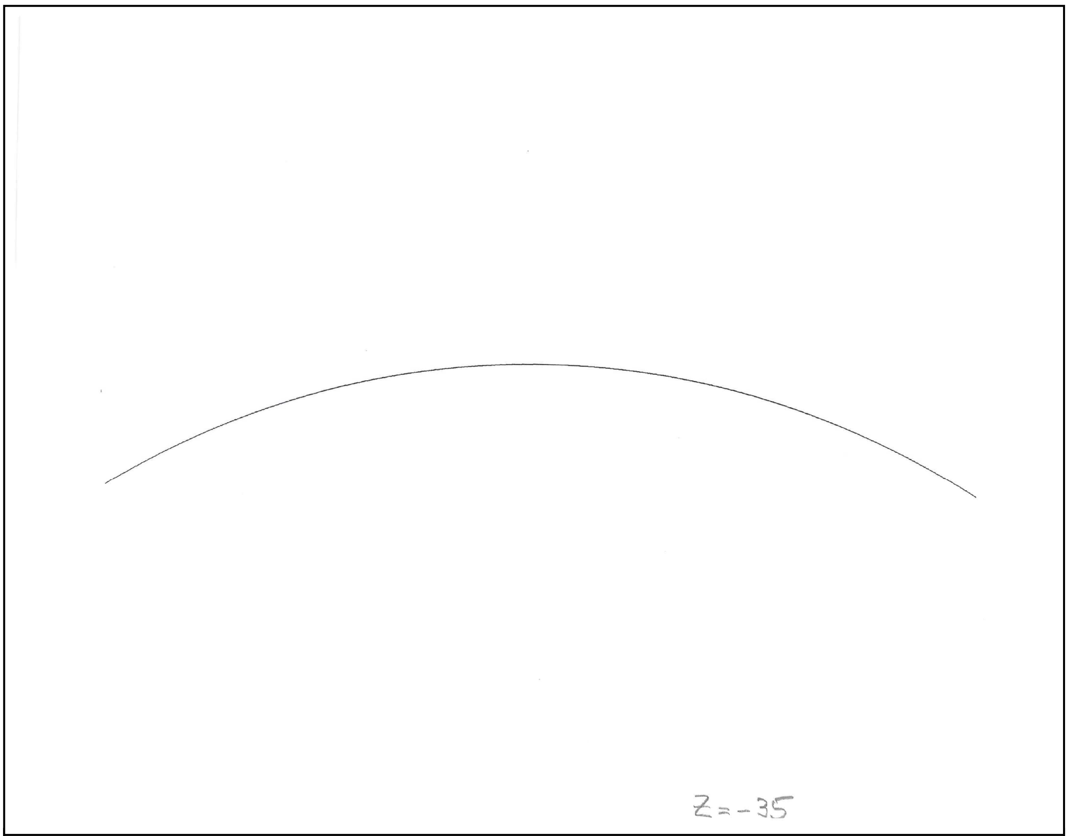
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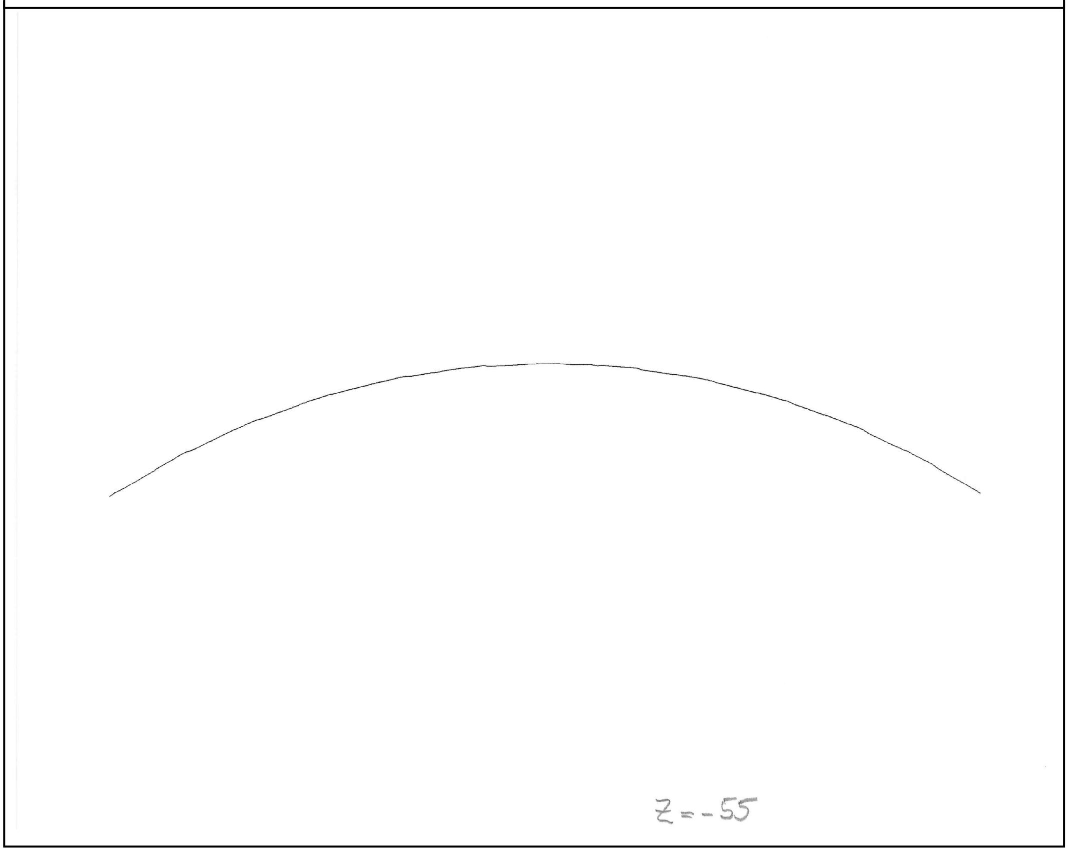
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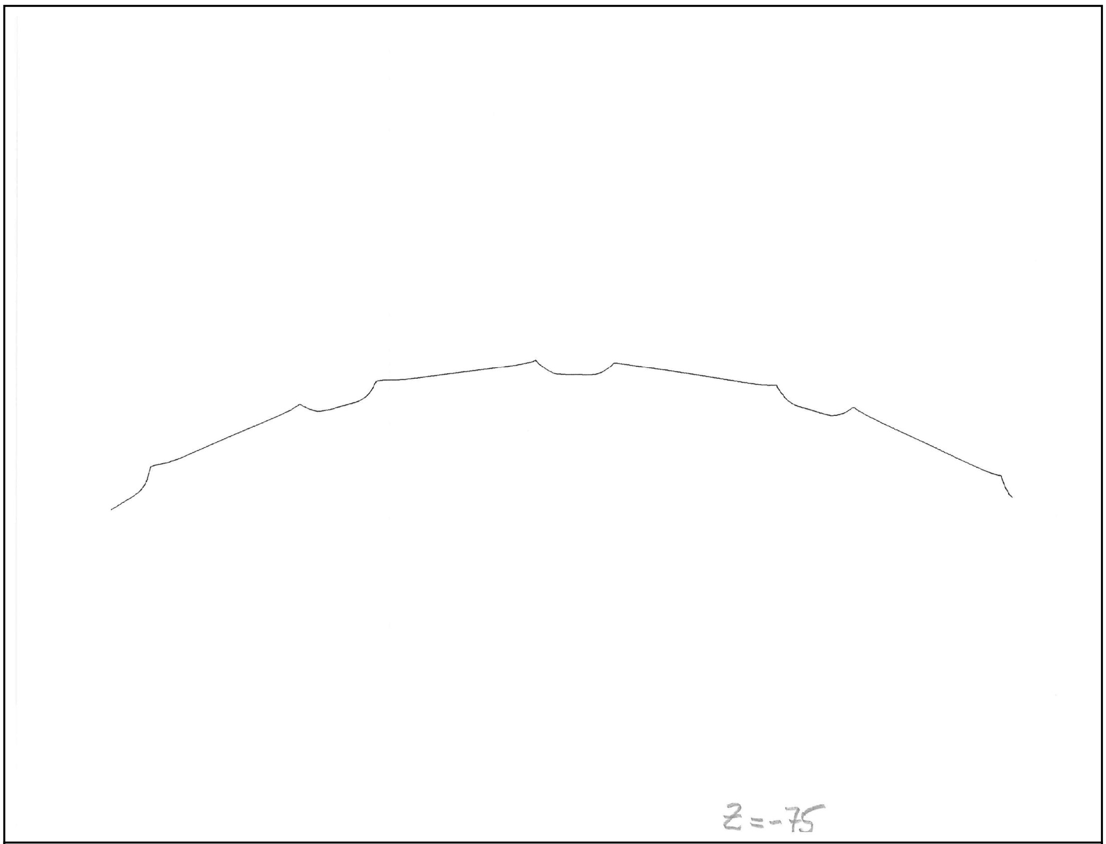
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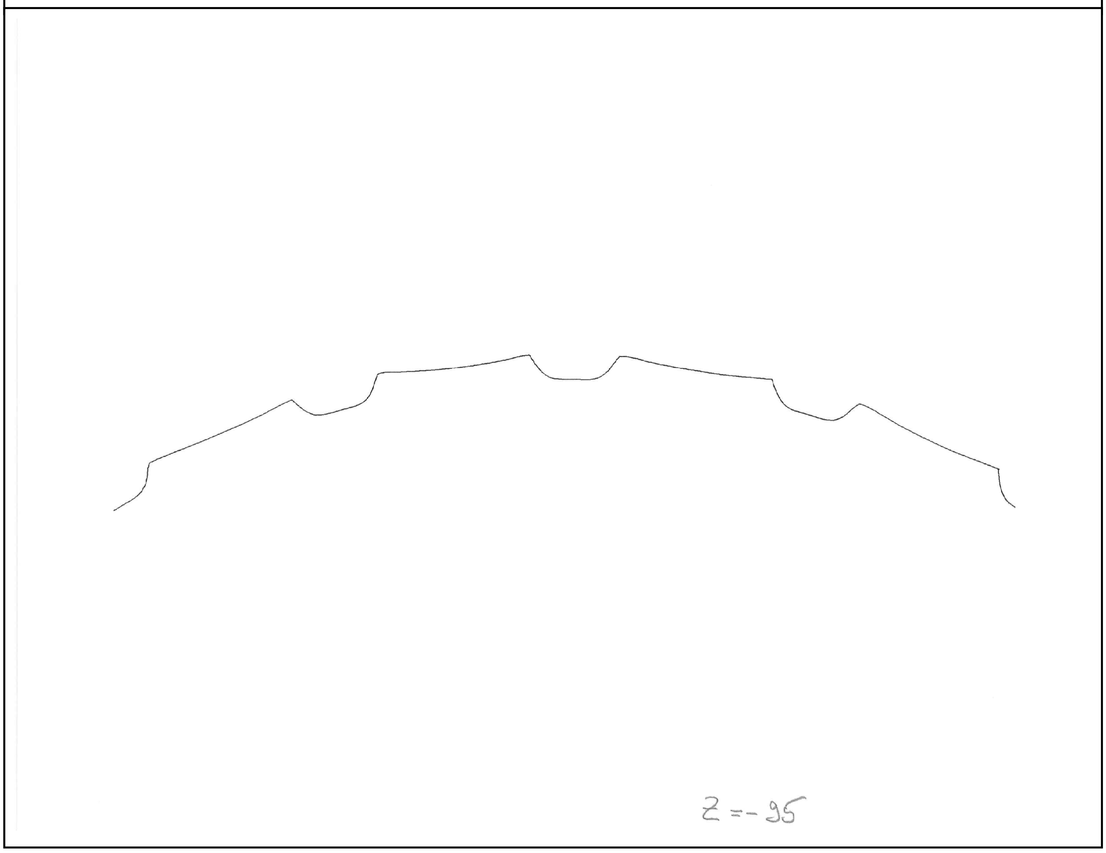
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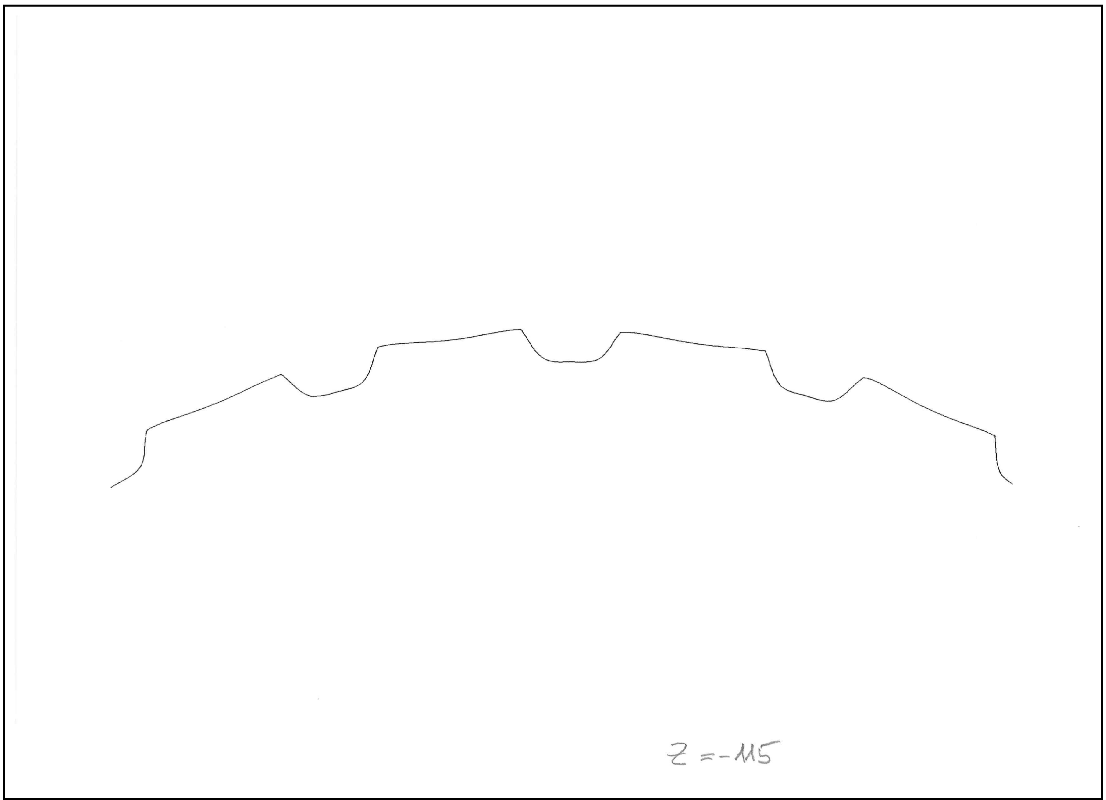
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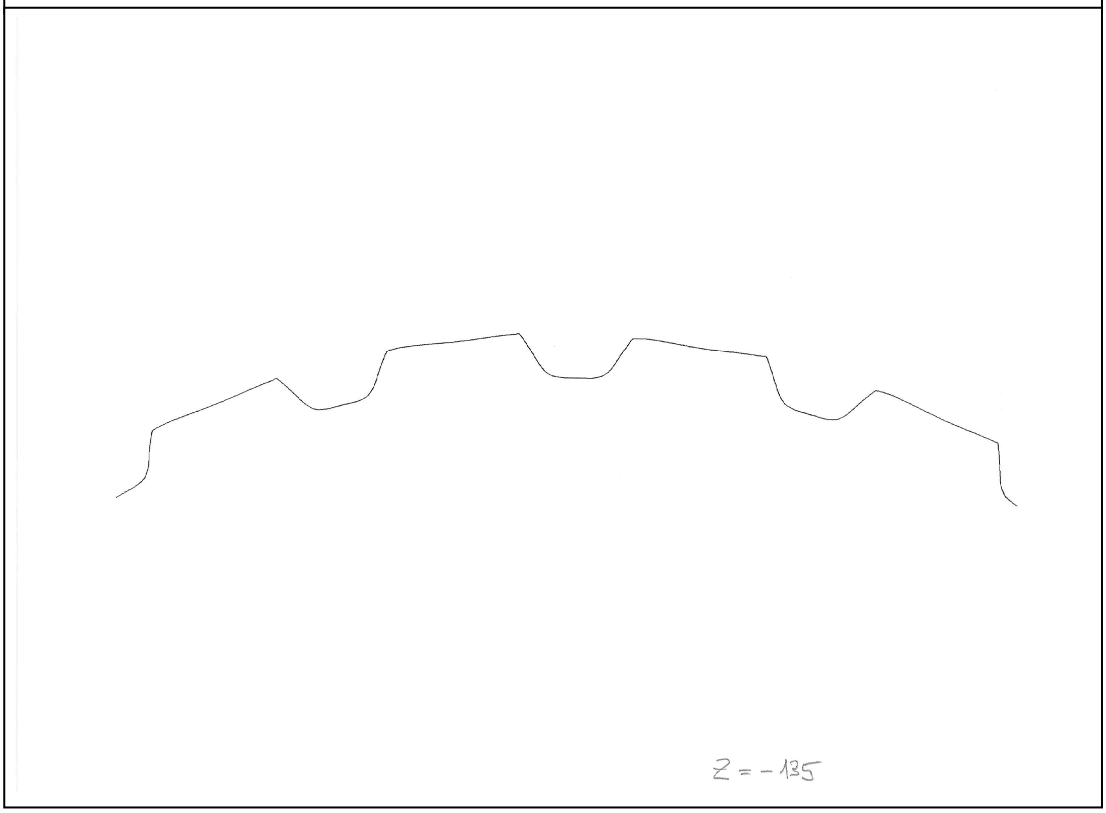
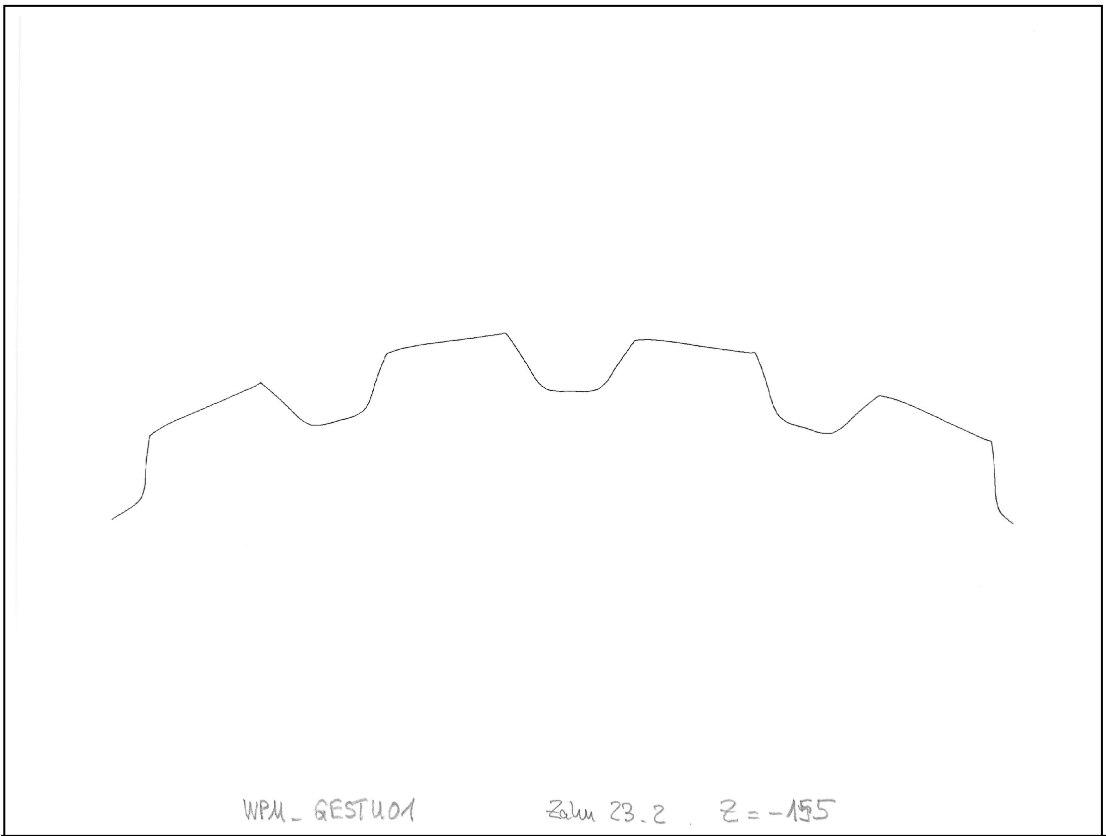
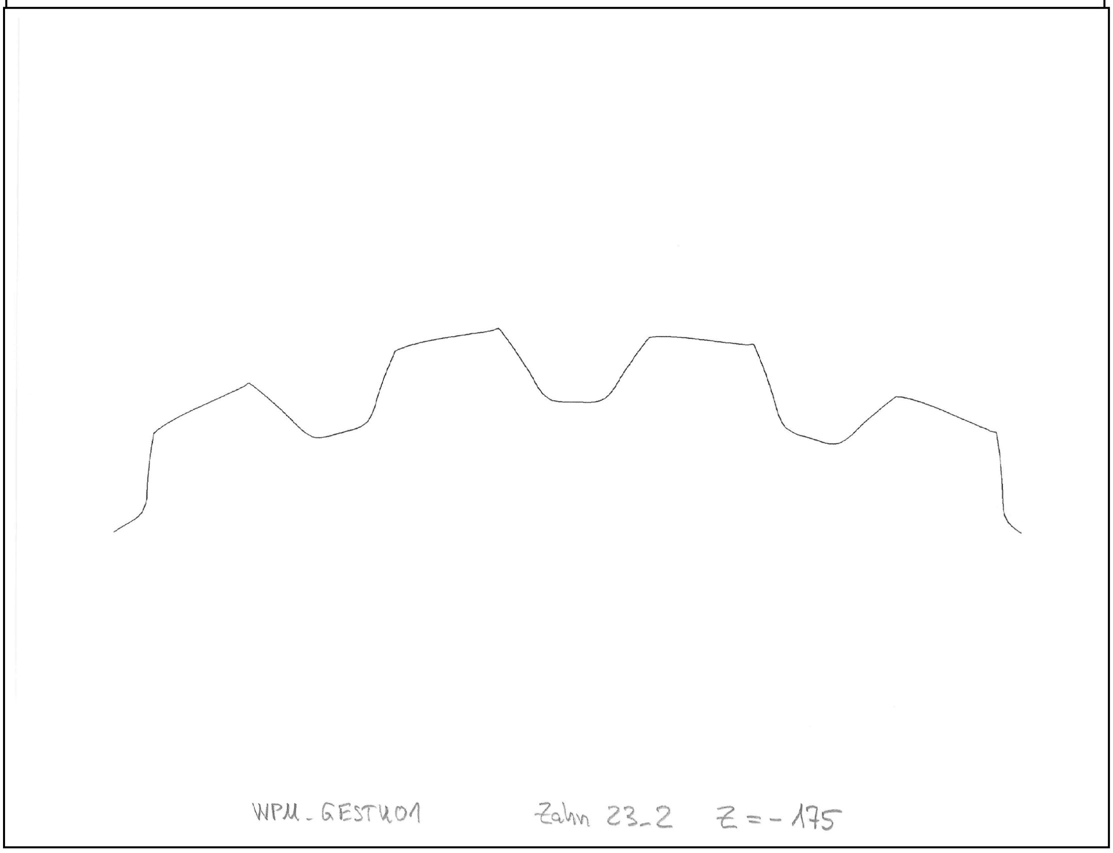
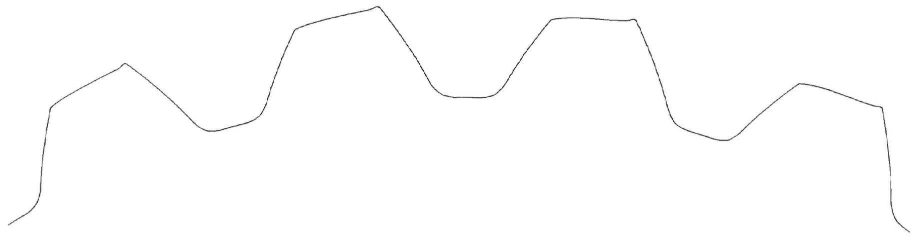
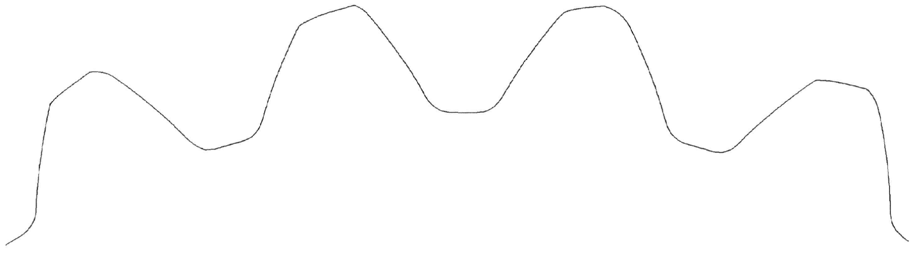

Z = -135


WPM_GESTU01
Zahn 23.2
Z = -155

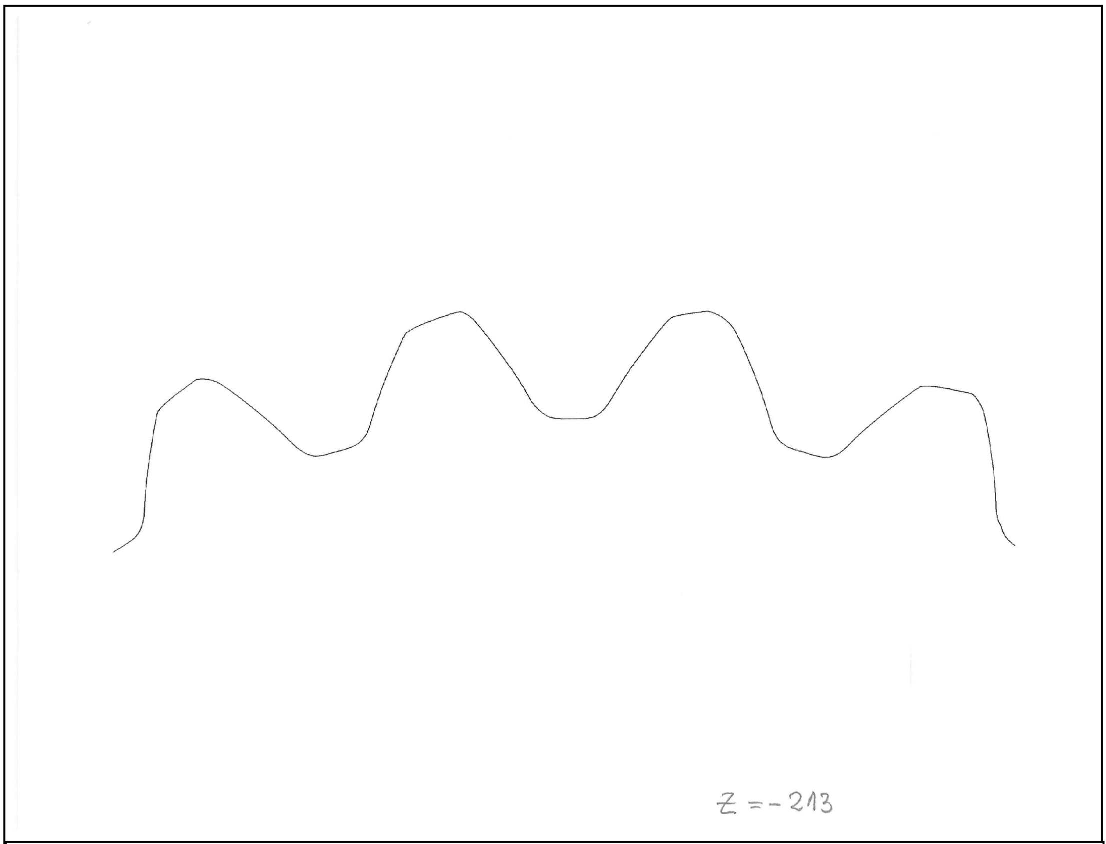

WPM_GESTU01
Zahn 23_2
Z = -175

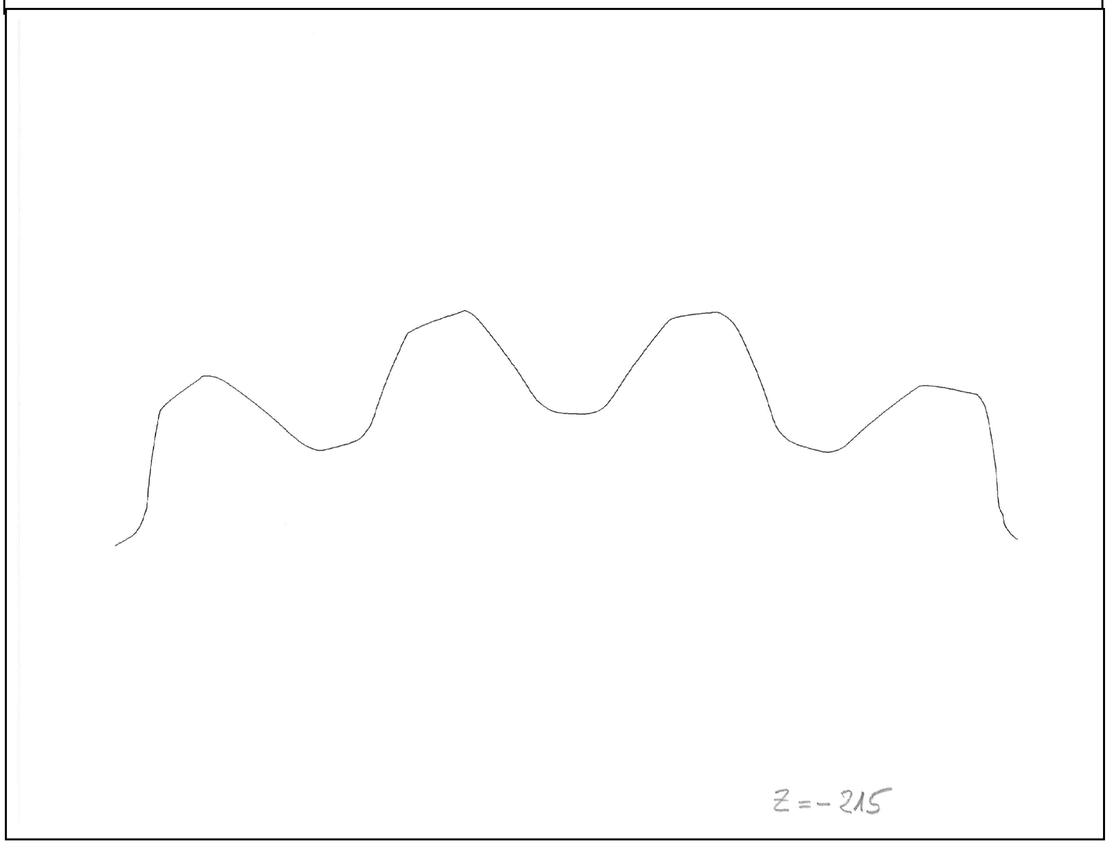


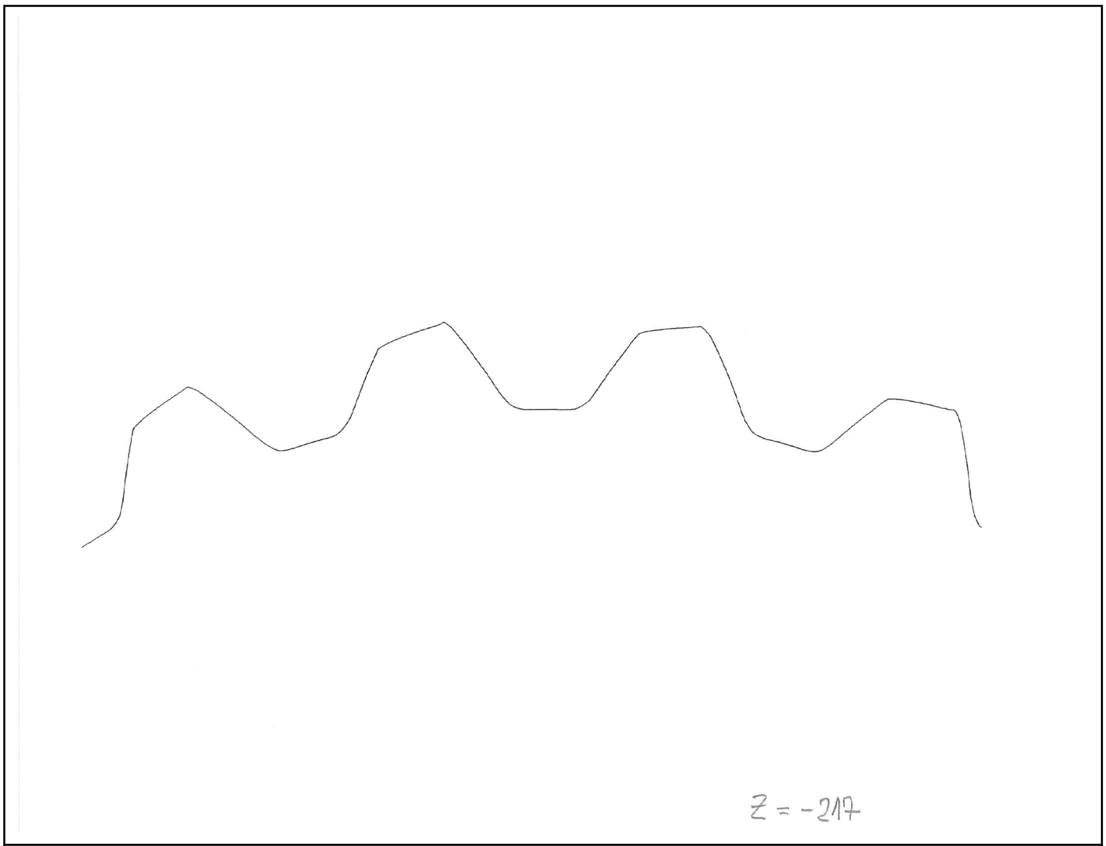
Z = - 195

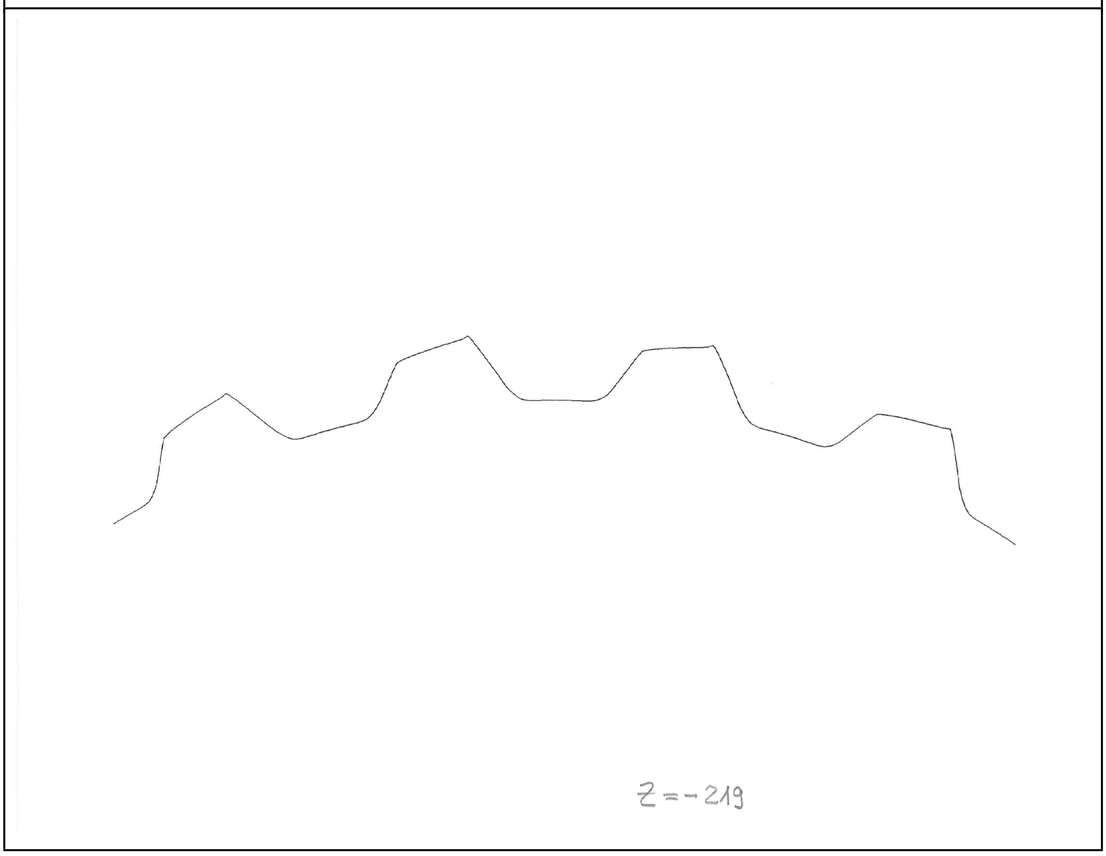


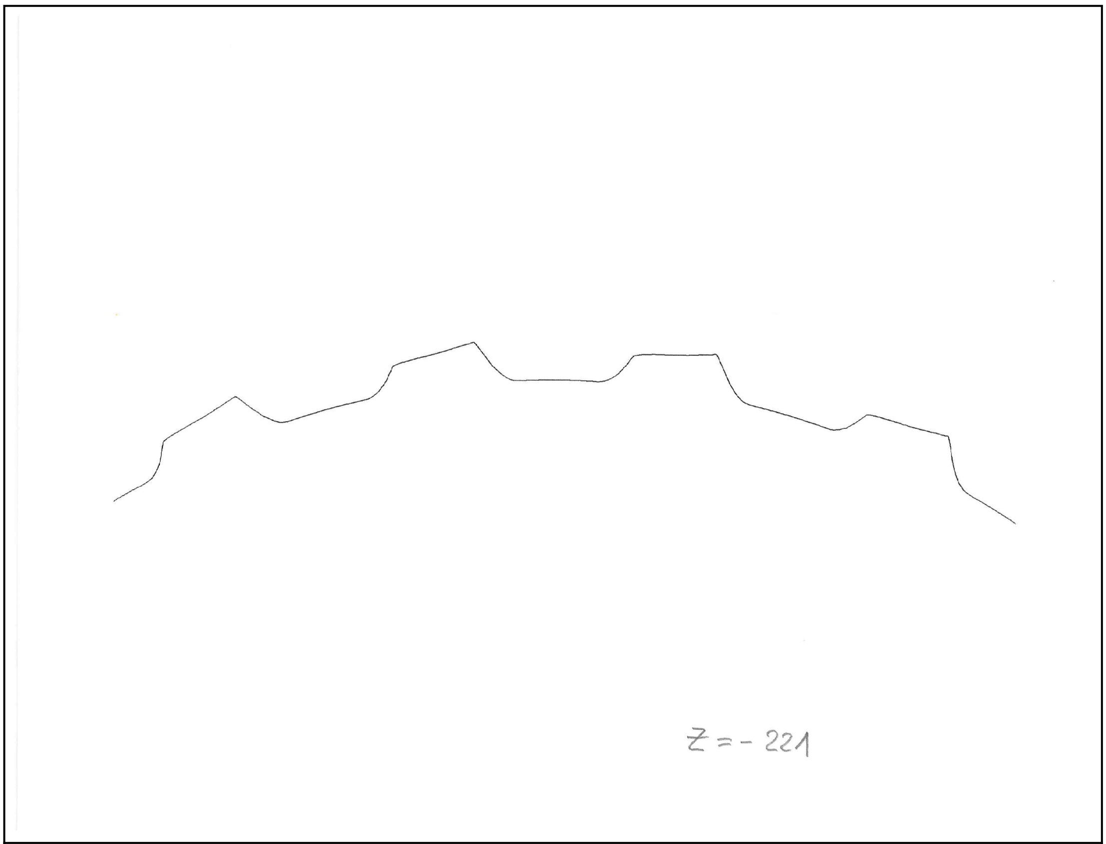
Z = - 211

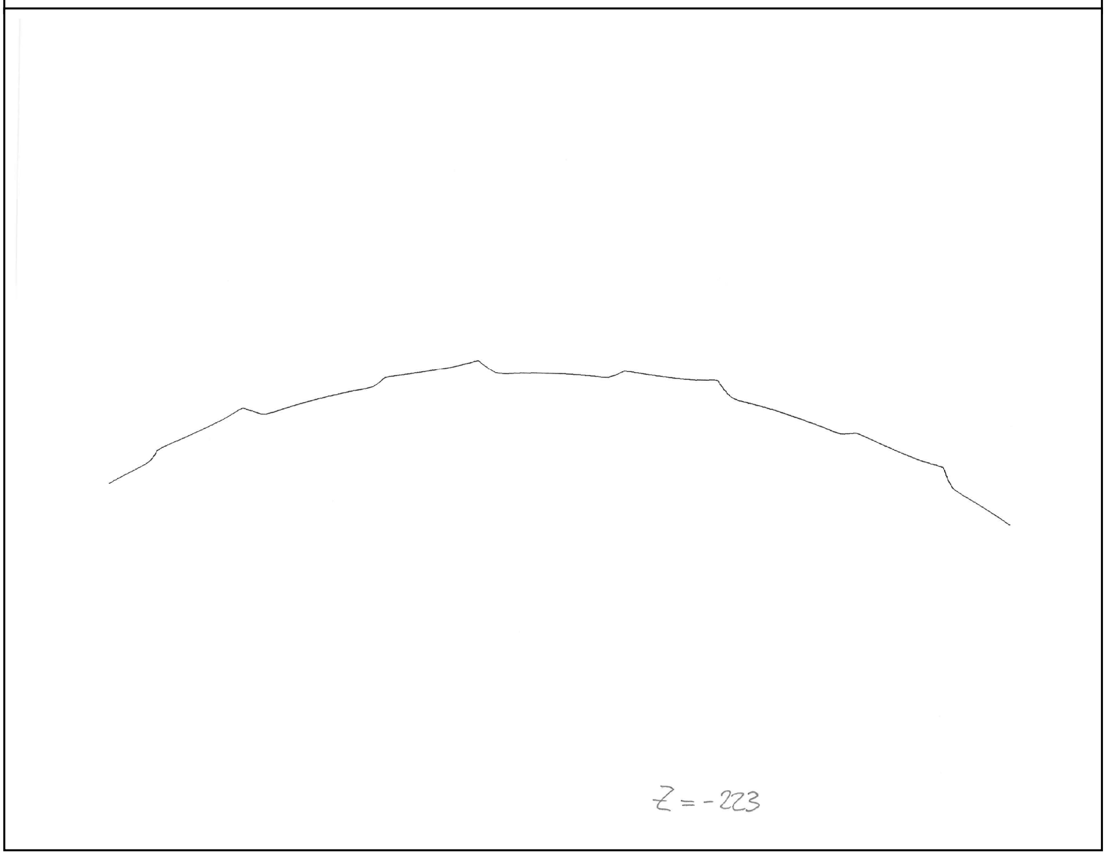

Z = - 213


Z = - 215


Z = -217


Z = -219


Z = - 221

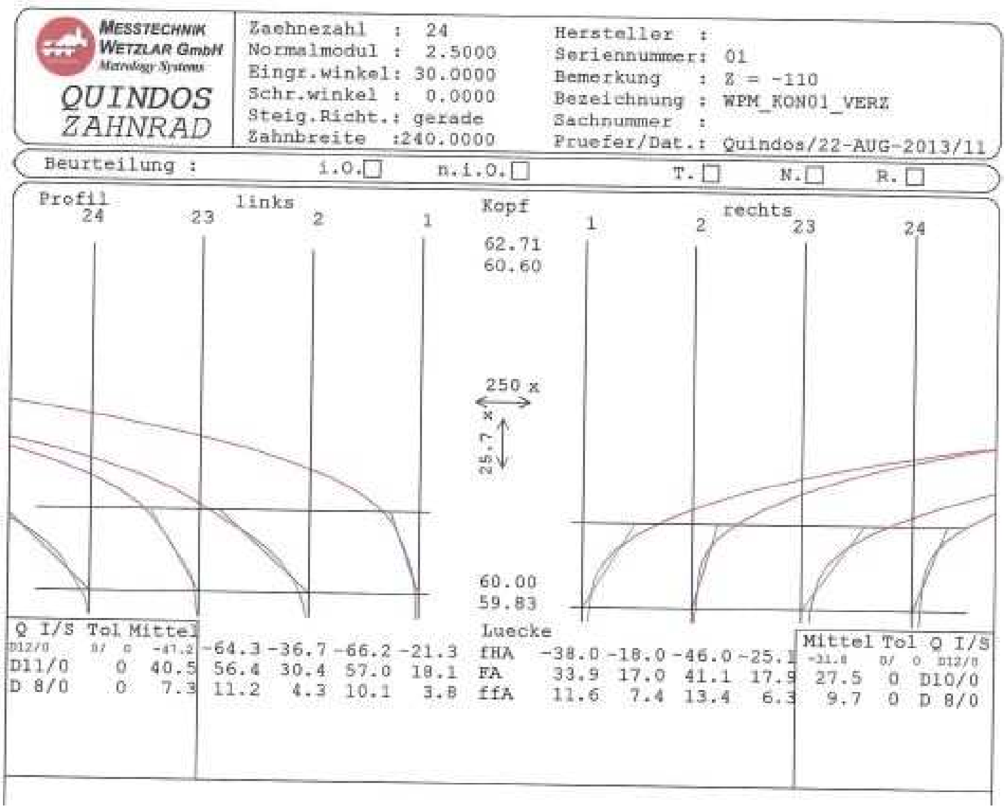

Z = - 223

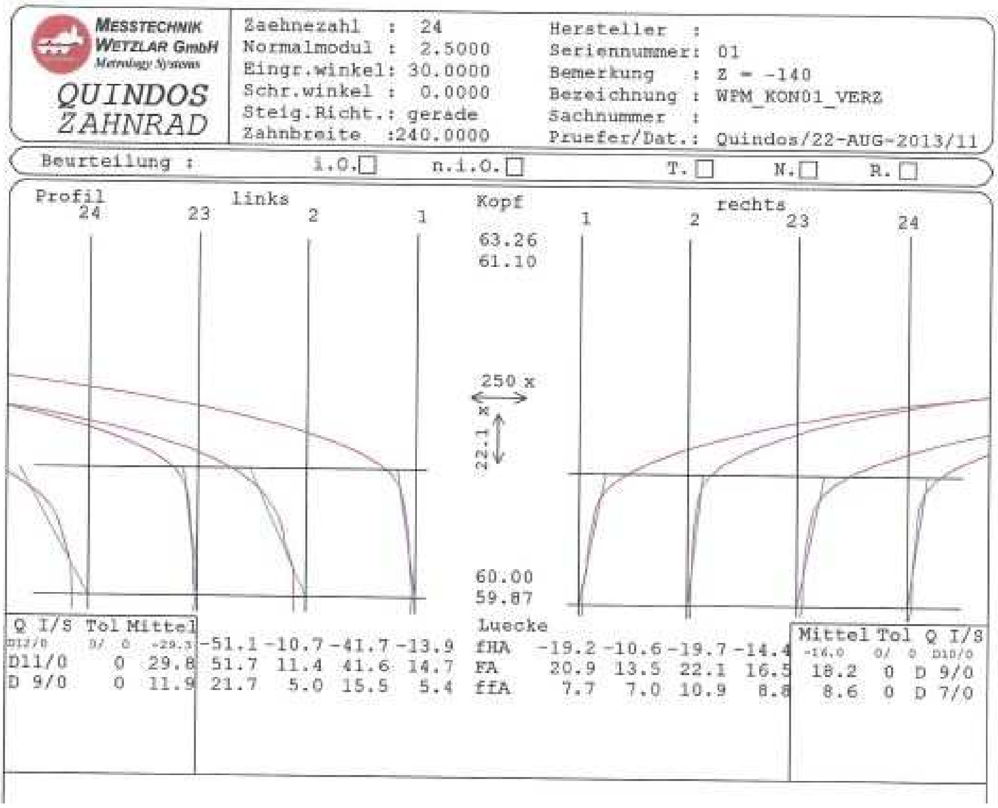
Appendix 2: Gear Measurement Results of rolling samples with special geometry

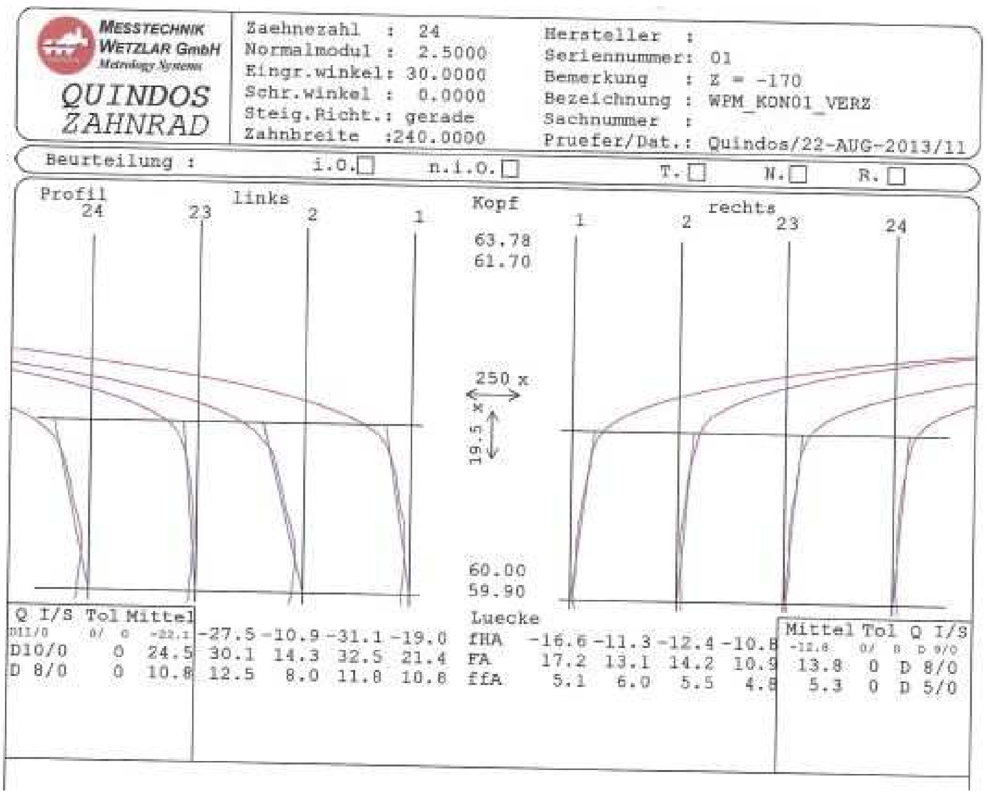
Conical Sample Gear Measurements The following selection of DIN 3960 conform measurement results being derived from a conical probe sample represents a subset of charts outlining the special characteristics behavior analyzed in chapter 5. The following measurements have been executed:

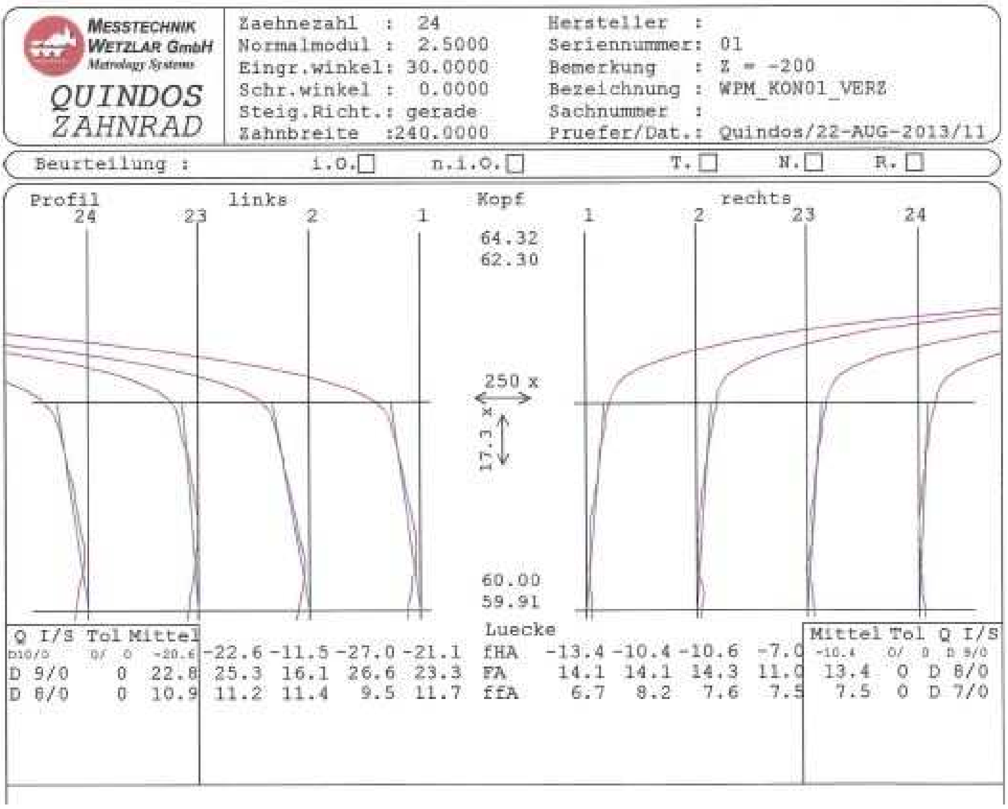
- Pitch and runout measurements in Z-sections at -Z= 230, 228, 200, 170, 140, 110, 80 and 60 mm
- Flank direction error measurements in tooth gap 1,2 ; 23,24 ; 10,11 and 12,13 at the nominal diameter of 59,6mm
- Profile measurements in tooth gap 1,2 ; 23,24 at Z-sections = -228, -200, -170, -140, -110 (at Z-sections lower than -110mm no gear measurement could be determined due to missing regular gear geometry after sample rolling)

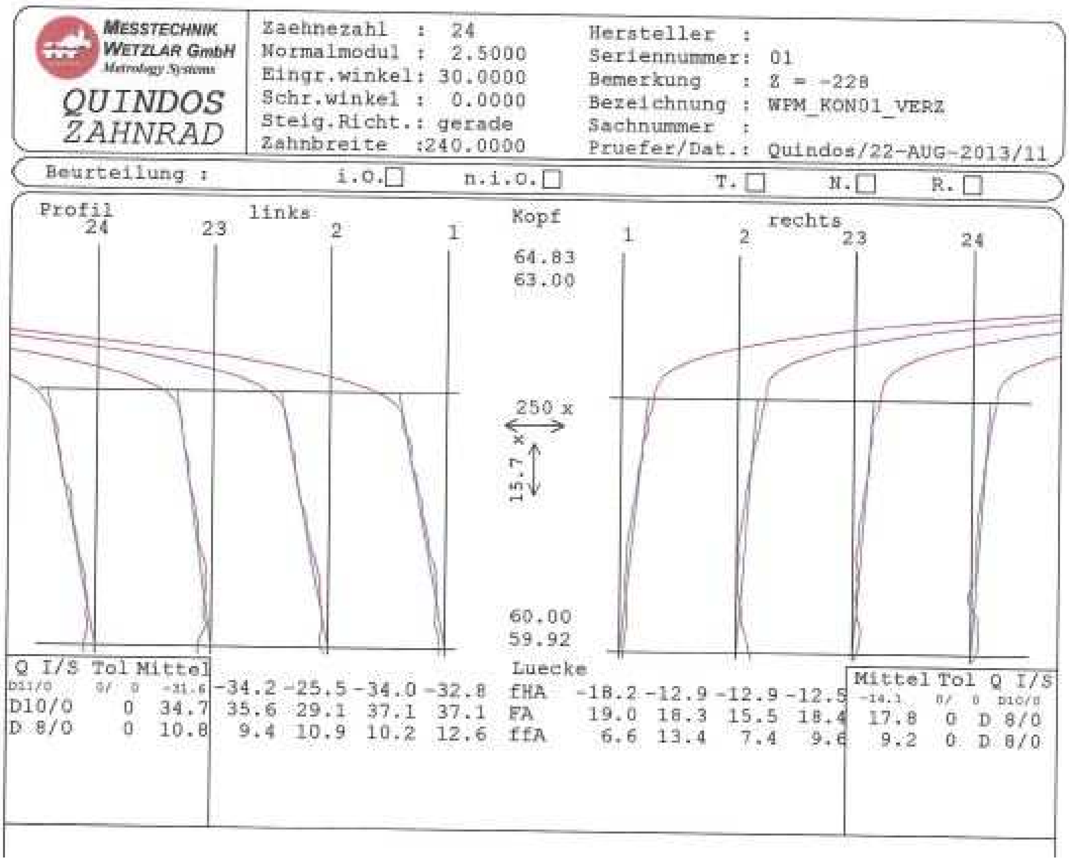
<u>Characteristic Charts:</u>




MESSTECHNIK WETZLAR GmbH
Metrology Systems
QUINDOS ZAHNRAD
Zaehnezahl : 24
Normalmodul : 2.5000
Eingr.winkel: 30.0000
Schr.winkel : 0.0000
Steig.Richt.: gerade
Zahnbreite :240.0000
Hersteller :
Seriennummer: 01
Bemerkung : Z = -140
Bezeichnung : WPM_KON01_VERZ
Sachnummer :
Pruefer/Dat.: Quindos/22-AUG-2013/11
Beurteilung : i.O. n.i.O. T. N. R.
Profil links 24 23 2 1
Kopf 63.26 61.10
rechts 1 2 23 24
250 x
22.1 x
60.00 59.87
Q I/S Tol Mittel
D12/0 0/ 0 -29.3
D11/0 0 29.8
D 9/0 0 11.9
-51.1 -10.7 -41.7 -13.9
51.7 11.4 41.6 14.7
21.7 5.0 15.5 5.4
Luecke
fHA -19.2 -10.6 -19.7 -14.4
FA 20.9 13.5 22.1 16.5
ffA 7.7 7.0 10.9 8.8
Mittel Tol Q I/S
-16.0 0/ 0 D10/0
18.2 0 D 9/0
8.6 0 D 7/0


MESSTECHNIK WETZLAR GmbH
Metrology Systems
QUINDOS ZAHNRAD
Zaehnezahl : 24
Normalmodul : 2.5000
Eingr.winkel: 30.0000
Schr.winkel : 0.0000
Steig.Richt.: gerade
Zahnbreite :240.0000
Hersteller :
Seriennummer: 01
Bemerkung : Z = -170
Bezeichnung : WPM_KON01_VERZ
Sachnummer :
Pruefer/Dat.: Quindos/22-AUG-2013/11
Beurteilung : i.O. n.i.O. T. N. R.
Profil links 24 23 2 1
Kopf 63.78 61.70
rechts 1 2 23 24
250 x
19.5 x
60.00 59.90
Q I/S Tol Mittel
D11/0 0/ 0 -22.1
D10/0 0 24.5
D 8/0 0 10.8
-27.5 -10.9 -31.1 -19.0
30.1 14.3 32.5 21.4
12.5 8.0 11.8 10.8
Luecke
fHA -16.6 -11.3 -12.4 -10.8
FA 17.2 13.1 14.2 10.9
ffA 5.1 6.0 5.5 4.8
Mittel Tol Q I/S
-12.8 0/ 0 D 9/0
13.8 0 D 8/0
5.3 0 D 5/0


MESSTECHNIK WETZLAR GmbH
Metrology Systems
QUINDOS ZAHNRAD
Zaehnezahl : 24
Normalmodul : 2.5000
Eingr.winkel: 30.0000
Schr.winkel : 0.0000
Steig.Richt.: gerade
Zahnbreite :240.0000
Hersteller :
Seriennummer: 01
Bemerkung : Z = -200
Bezeichnung : WPM_KON01_VERZ
Sachnummer :
Pruefer/Dat.: Quindos/22-AUG-2013/11
Beurteilung : i.O. n.i.O. T. N. R.
Profil links Kopf rechts
24 23 2 1 1 2 23 24
64.32
62.30
250 x
17.3 x
60.00
59.91
Q I/S Tol Mittel
Luecke
Mittel Tol Q I/S
-22.6 -11.5 -27.0 -21.1 fHA -13.4 -10.4 -10.6 -7.0
D 9/0 0 22.8 25.3 16.1 26.6 23.3 FA 14.1 14.1 14.3 11.0 13.4 0 D 8/0
D 8/0 0 10.9 11.2 11.4 9.5 11.7 ffA 6.7 8.2 7.6 7.5 7.5 0 D 7/0


MESSTECHNIK WETZLAR GmbH
Metrology Systems
QUINDOS ZAHNRAD
Zaehnezahl : 24
Normalmodul : 2.5000
Eingr.winkel: 30.0000
Schr.winkel : 0.0000
Steig.Richt.: gerade
Zahnbreite :240.0000
Hersteller :
Seriennummer: 01
Bemerkung : Z = -228
Bezeichnung : WPM_KON01_VERZ
Sachnummer :
Pruefer/Dat.: Quindos/22-AUG-2013/11
Beurteilung : i.O. n.i.O. T. N. R.
Profil links Kopf rechts
24 23 2 1 1 2 23 24
64.83
63.00
250 x
15.7 x
60.00
59.92
Q I/S Tol Mittel
Luecke
Mittel Tol Q I/S
-34.2 -25.5 -34.0 -32.8 fHA -18.2 -12.9 -12.9 -12.5
D10/0 0 34.7 35.6 29.1 37.1 37.1 FA 19.0 18.3 15.5 18.4 17.8 0 D 8/0
D 8/0 0 10.8 9.4 10.9 10.2 12.6 ffA 6.6 13.4 7.4 9.6 9.2 0 D 8/0

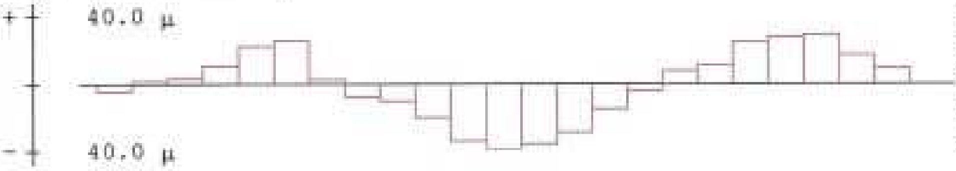
MESSTECHNIK WETZLAR GmbH
Metrology Systems

QUINDOS ZAHNRAD

Zaehnezahl	: 24	Hersteller	:
Normalmodul	: 2.5000	Seriennummer	: 01
Eingr.winkel	: 30.0000	Bemerkung	: Z = -228
Schr.winkel	: 0.0000	Bezeichnung	: WPM_KON01_VERZ
Steig.Richt.	: gerade	Sachnummer	:
Zahnbreite	:240.0000	Pruefer/Dat.	: Quindos/22-AUG-2013/11

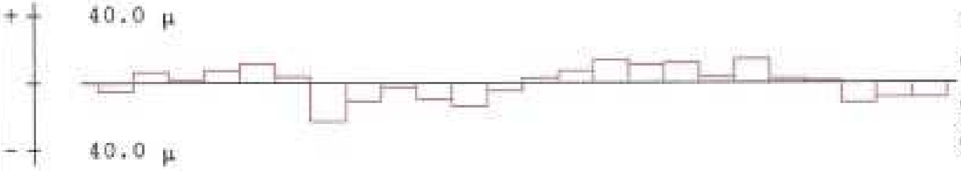
Beurteilung : i.O.☐ n.i.O.☐ T.☐ N.☐ R.☐

Fpi (linke Flanke) - eFr



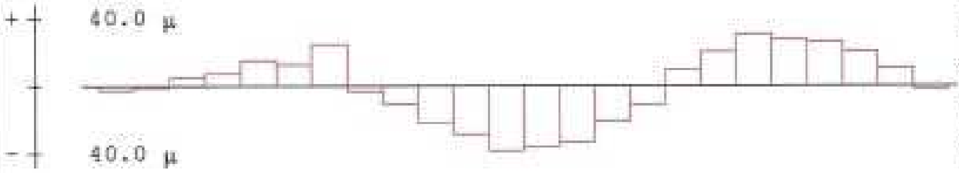
	Fp	fu
Ist	67.1	26.1
Qua.	D 9	D10
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke) - eFr



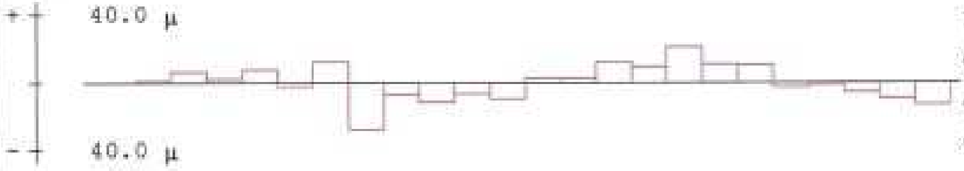
	Rp	fp
Ist	36.5	22.6
Qua.		D10
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke) - eFr



	Fp	fu
Ist	68.6	39.8
Qua.	D 9	D10
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke) - eFr



	Rp	fp
Ist	48.4	27.7
Qua.		D10
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri - eFr

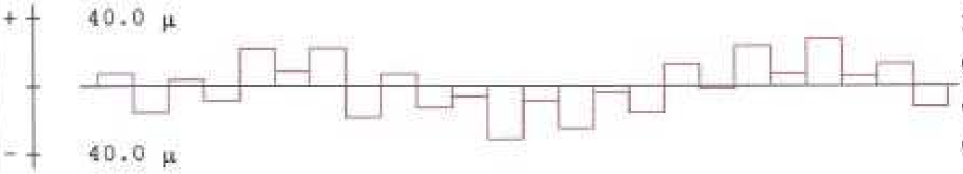
	Fr
Ist	25.2
Qua.	D 7
Tol.	0.0
Qua.	D 0

Exzentrizitaet 0.0213 X 0.0107 Y -0.0185

MESSTECHNIK WETZLAR GmbH Metrology Systems QUINDOS ZAHNRAD	Zaehnezahl : 24 Normalmodul : 2.5000 Eingr.winkel: 30.0000 Schr.winkel : 0.0000 Steig.Richt.: gerade Zahnbreite :240.0000	Hersteller : Seriennummer: 01 Bemerkung : Z = -110 Bezeichnung : WPM_KON01_VERZ Sachnummer : Pruefer/Dat.: Quindos/22-AUG-2013/11

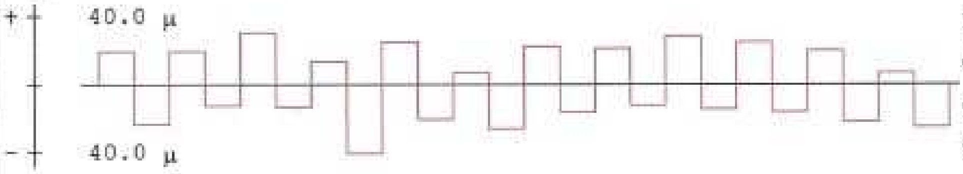
Beurteilung : i.O.☐ n.i.O.☐ T.☐ N.☐ R.☐

Fpi (linke Flanke) - eFr



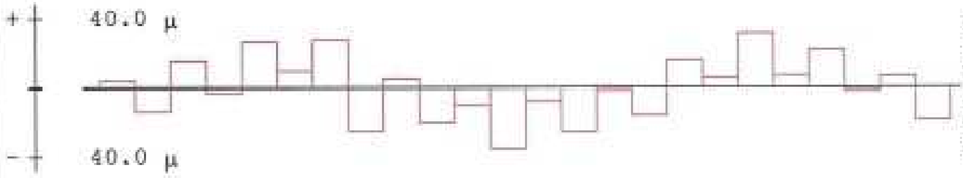
	Fp	fu
Ist	59.2	66.0
Qua.	D 9	D12
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke) - eFr



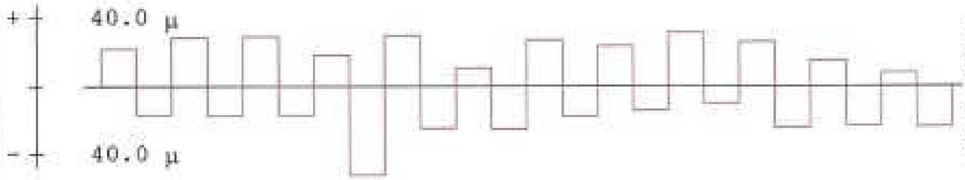
	Rp	fp
Ist	71.4	40.7
Qua.		D11
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke) - eFr



	Fp	fu
Ist	66.1	81.7
Qua.	D 9	D12
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke) - eFr



	Rp	fp
Ist	83.4	52.2
Qua.		D12
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri - eFr

	Fr
Ist	13.6
Qua.	D 5
Tol.	0.0
Qua.	D 0

Exzentrizitaet 0.0055 X 0.0039 Y -0.0038

Stepped Sample Gear Measurements The following selection of DIN 3960 conform measurement results being derived from a stepped probe sample represents a subset of charts outlining the special characteristics behavior analyzed in chapter 5. The following measurements have been executed:

- Pitch and runout measurements in 8 levels of Z-sections following the sample steps
- Flank direction error measurements in tooth gap 1,2 ; 23,24 in 8 levels of Z-sections and at the related nominal diameters per step
- Profile measurements in tooth gap 1,2 ; 23,24 at Z-sections = -212, -195, -175, -155, -135 (at Z-sections lower than -135mm no gear measurement could be determined due to missing regular gear geometry after sample rolling)

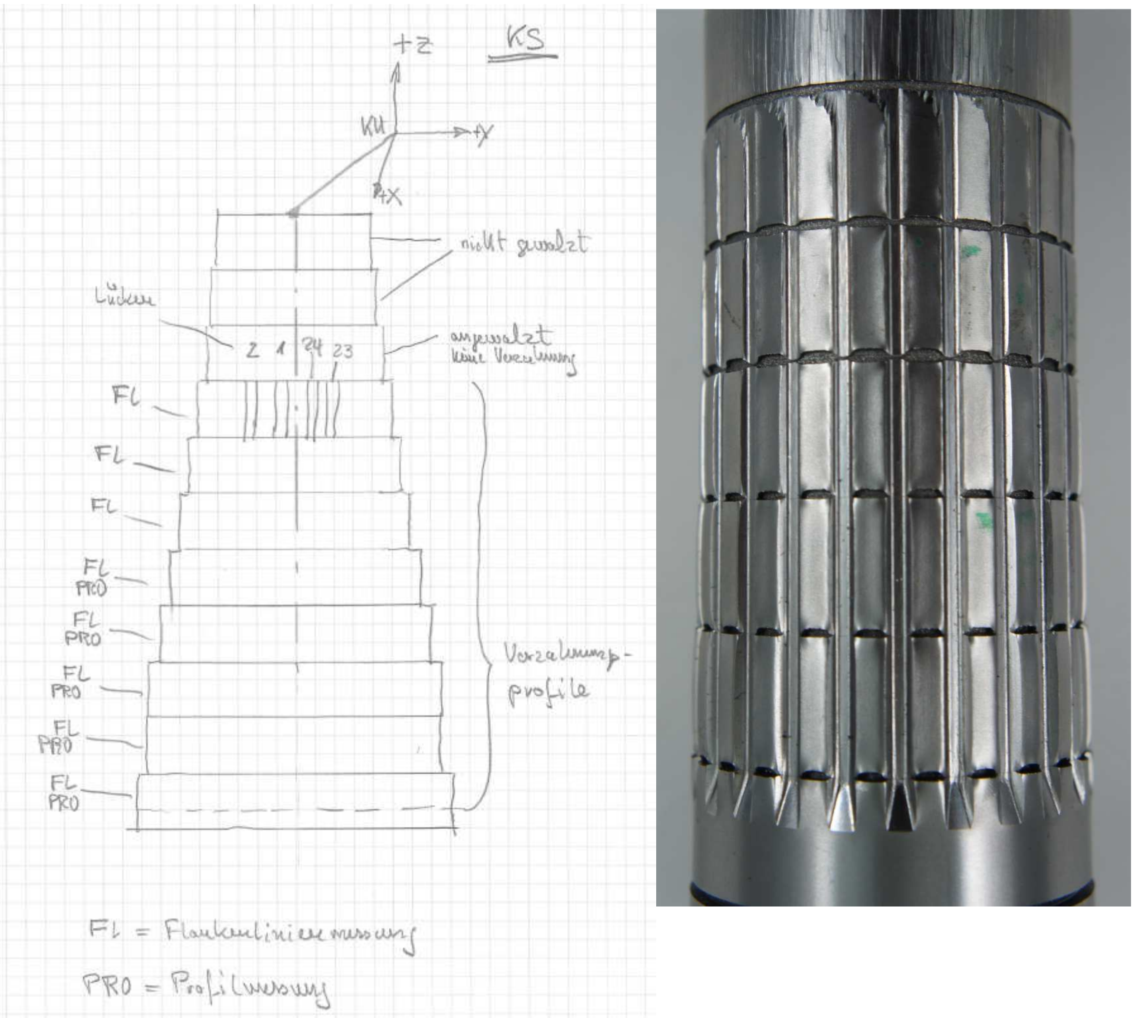
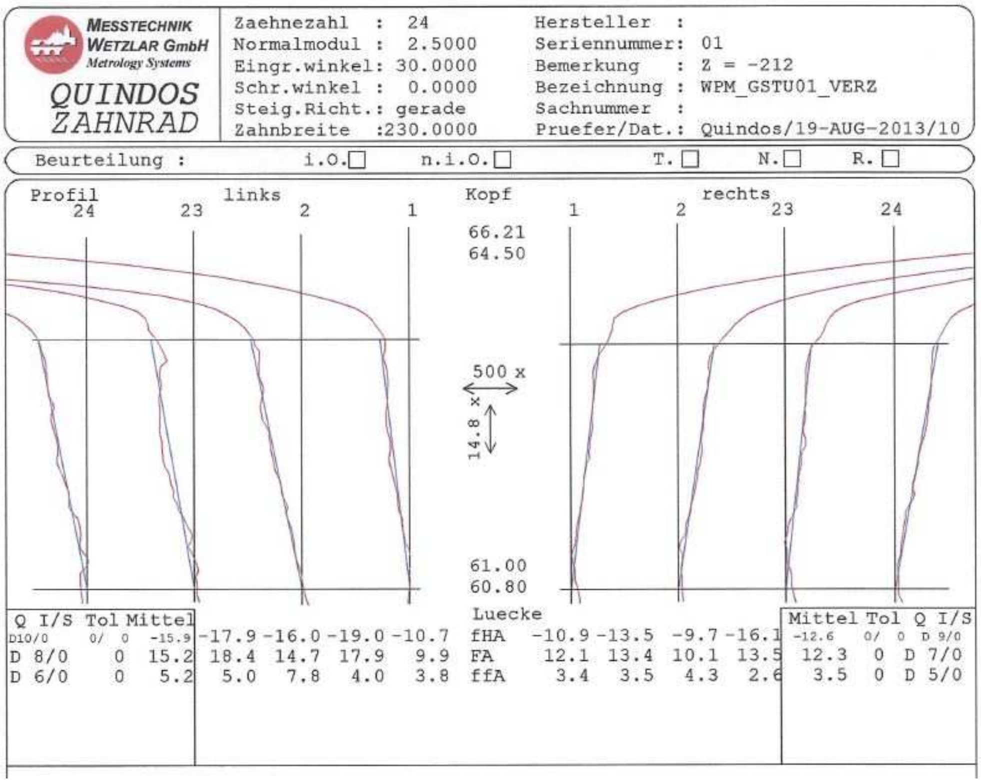
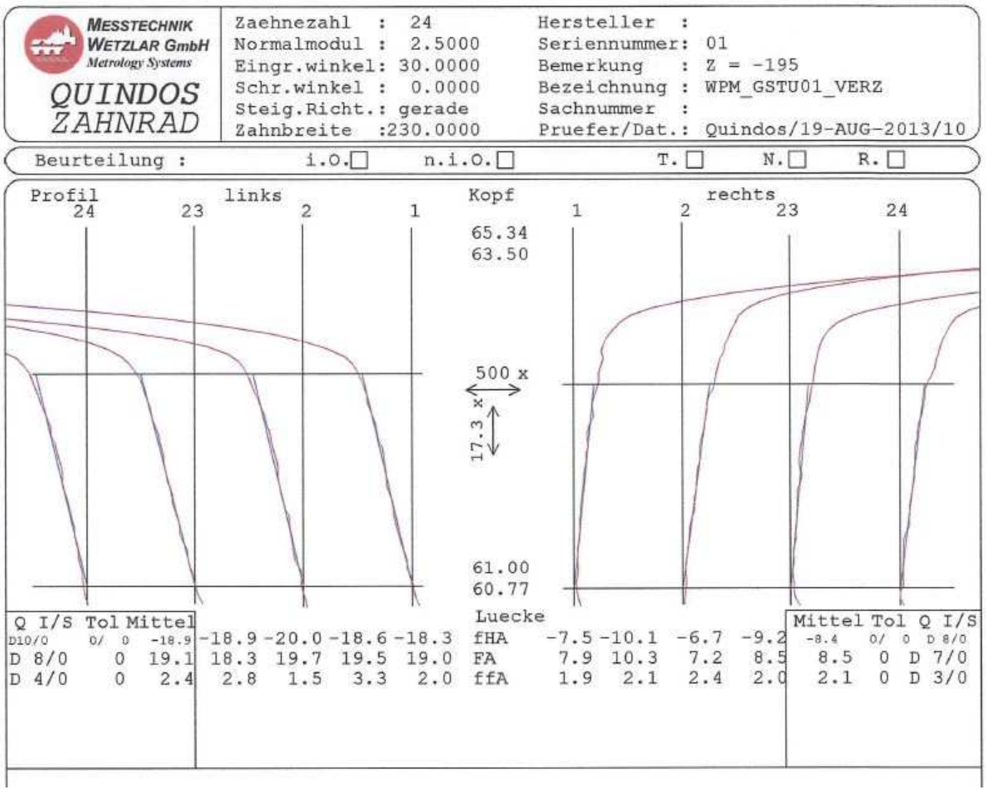


Figure 143 Stepped Sample Drawing

Characteristic Charts:



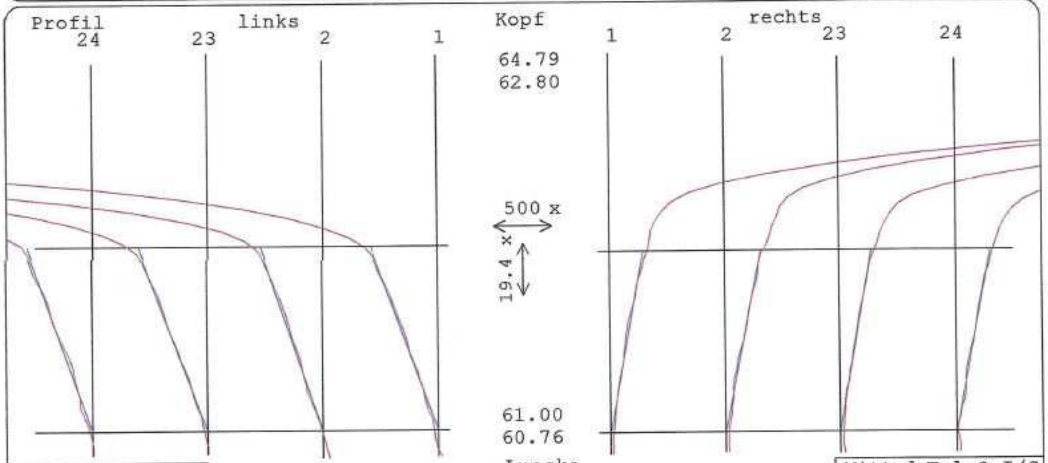


MESSTECHNIK WETZLAR GmbH Metrology Systems

QUINDOS ZAHNRAD

Zaehnezahl : 24	Hersteller :
Normalmodul : 2.5000	Seriennummer: 01
Eingr.winkel: 30.0000	Bemerkung : Z = -175
Schr.winkel : 0.0000	Bezeichnung : WPM_GSTU01_VERZ
Steig.Richt.: gerade	Sachnummer :
Zahnbreite :230.0000	Pruefer/Dat.: Quindos/19-AUG-2013/10

Beurteilung : i.O.☐ n.i.O.☐ T.☐ N.☐ R.☐



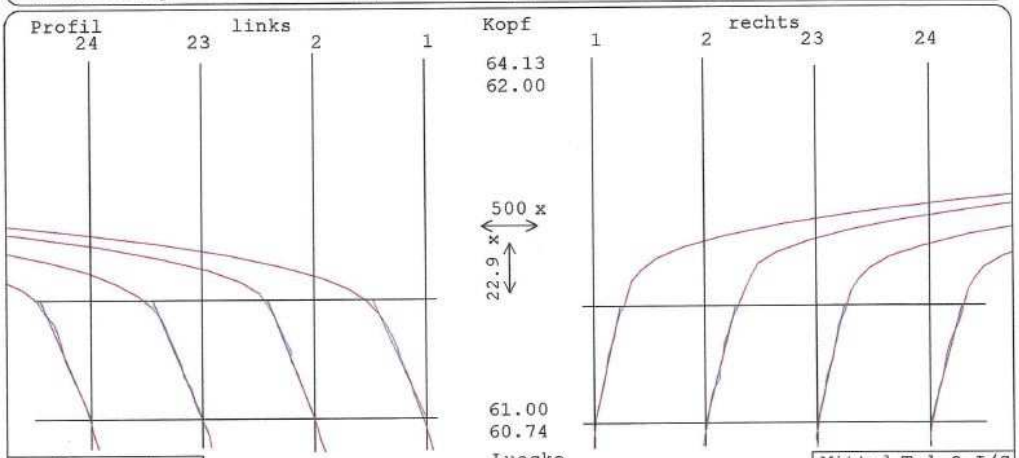
Q I/S	Tol	Mittel	24	23	2	1	Luecke	1	2	23	24	Mittel	Tol	Q I/S
D10/0	0/ 0	-23.1	-22.9	-24.1	-21.7	-23.6	fHA	-11.5	-12.6	-11.2	-12.0	-11.8	0/ 0	D 9/0
D 9/0	0	22.8	21.3	22.9	22.6	24.4	FA	10.6	11.2	10.7	12.0	11.1	0	D 7/0
D 4/0	0	2.7	2.6	2.1	2.7	3.2	ffA	1.6	1.7	1.5	1.5	1.6	0	D 2/0

MESSTECHNIK WETZLAR GmbH Metrology Systems

QUINDOS ZAHNRAD

Zaehnezahl : 24	Hersteller :
Normalmodul : 2.5000	Seriennummer: 01
Eingr.winkel: 30.0000	Bemerkung : Z = -155
Schr.winkel : 0.0000	Bezeichnung : WPM_GSTU01_VERZ
Steig.Richt.: gerade	Sachnummer :
Zahnbreite :230.0000	Pruefer/Dat.: Quindos/19-AUG-2013/10

Beurteilung : i.O.☐ n.i.O.☐ T.☐ N.☐ R.☐



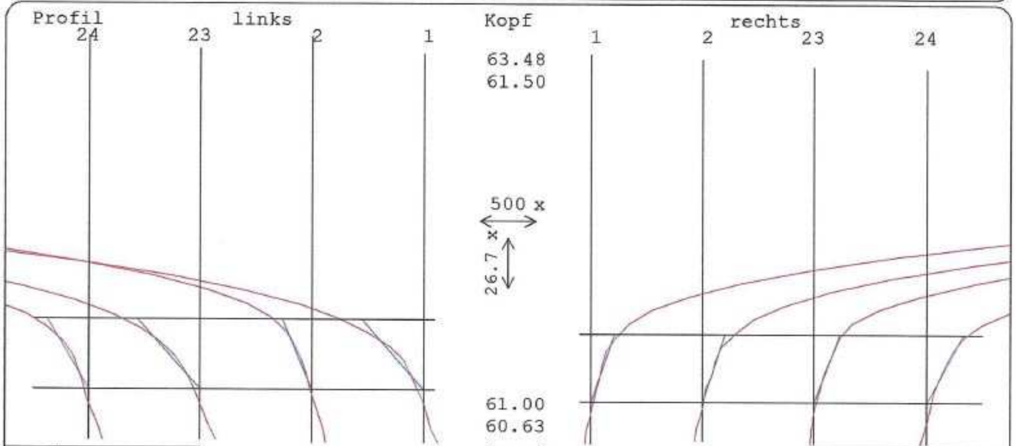
Q I/S	Tol	Mittel	24	23	2	1	Luecke	1	2	23	24	Mittel	Tol	Q I/S
D10/0	0/ 0	-17.9	-17.9	-17.9	-16.6	-19.1	fHA	-9.5	-11.0	-9.8	-11.6	-10.5	0/ 0	D 8/0
D 8/0	0	17.7	18.1	16.4	16.5	19.7	FA	8.4	10.0	8.9	10.1	9.3	0	D 7/0
D 4/0	0	2.4	2.4	1.8	1.9	3.4	ffA	0.7	1.7	1.1	1.3	1.2	0	D 2/0

MESSTECHNIK WETZLAR GmbH
Metrology Systems

QUINDOS ZAHNRAD

Zaehnezahl	: 24	Hersteller	:
Normalmodul	: 2.5000	Seriennummer	: 01
Eingr.winkel	: 30.0000	Bemerkung	: Z = -135
Schr.winkel	: 0.0000	Bezeichnung	: WPM_GSTU01_VERZ
Steig.Richt.	: gerade	Sachnummer	:
Zahnbreite	:230.0000	Pruefer/Dat.	: Quindos/19-AUG-2013/10

Beurteilung : i.O.☐ n.i.O.☐ T.☐ N.☐ R.☐



Q I/S	Tol	Mittel	24	23	2	1	Luecke	1	2	23	24	Mittel	Tol	Q I/S
D10/0	0/ 0	-17.6	-14.9	-22.6	-10.5	-22.2	fHA	-8.5	-7.9	-9.3	-13.0	-9.7	0/ 0	D 9/0
D 8/0	0	14.3	12.3	18.1	8.5	18.2	FA	7.2	6.3	7.3	10.5	7.8	0	D 7/0
D 5/0	0	3.0	2.8	3.2	1.3	4.6	ffA	1.9	0.8	0.6	1.1	1.1	0	D 2/0

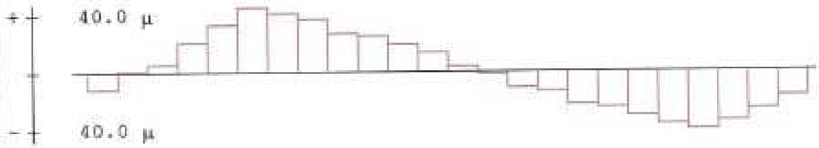
MESSTECHNIK WETZLAR GmbH
Metrology Systems

QUINDOS
ZAHNRAD

Zaehnezahl : 24	Hersteller :
Normalmodul : 2.5000	Seriennummer: 01
Eingr.winkel: 30.0000	Bemerkung : Z = -212
Schr.winkel : 0.0000	Bezeichnung : WPM_GSTU01_VERZ
Steig.Richt.: gerade	Sachnummer :
Zahnbreite :230.0000	Pruefer/Dat.: Quindos/16-AUG-2013/10

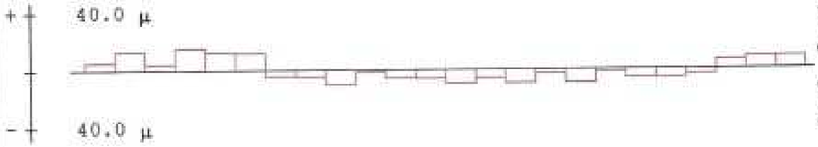
Beurteilung : i.O.☐ n.i.O.☐ T.☐ N.☐ R.☐

Fpi (linke Flanke)



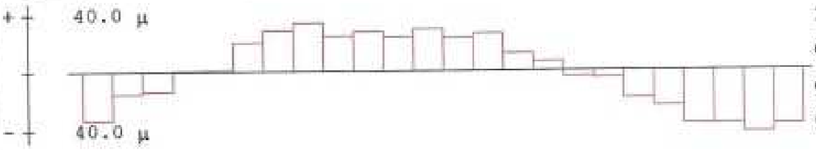
	Fp	fu
Ist	86.0	16.2
Qua.	D10	D 8
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke)



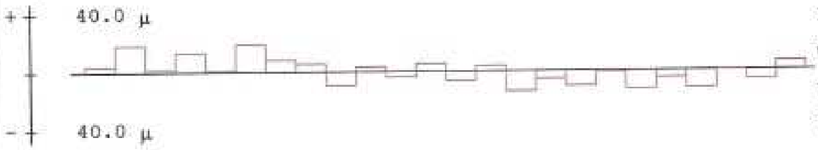
	Rp	fp
Ist	25.4	15.2
Qua.		D 9
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke)



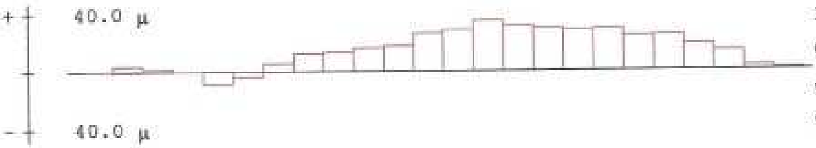
	Fp	fu
Ist	76.2	18.3
Qua.	D10	D 9
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke)



	Rp	fp
Ist	33.2	19.0
Qua.		D 9
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri

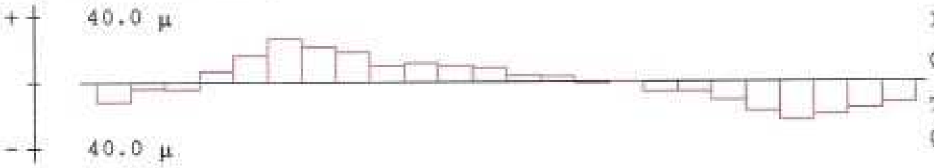


	Fr
Ist	43.4
Qua.	D 9
Tol.	0.0
Qua.	D 0

MESSTECHNIK WETZLAR GmbH Metrology Systems QUINDOS ZAHNRAD		
	Zaehnezahl : 24	Hersteller :
	Normalmodul : 2.5000	Seriennummer: 01
	Eingr.winkel: 30.0000	Bemerkung : Z = -212
	Schr.winkel : 0.0000	Bezeichnung : WPM_GSTU01_VERZ
	Steig.Richt.: gerade	Sachnummer :
	Zahnbreite :230.0000	Pruefer/Dat.: Quindos/16-AUG-2013/10

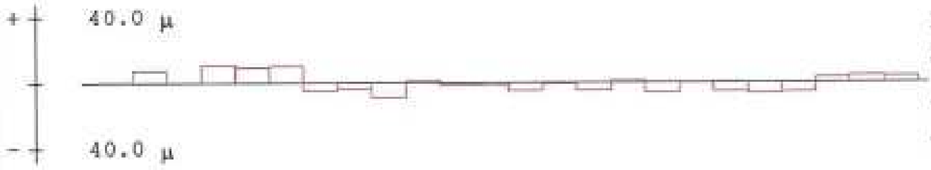
Beurteilung : i.O.☐ n.i.O.☐ T.☐ N.☐ R.☐

Fpi (linke Flanke) - eFr



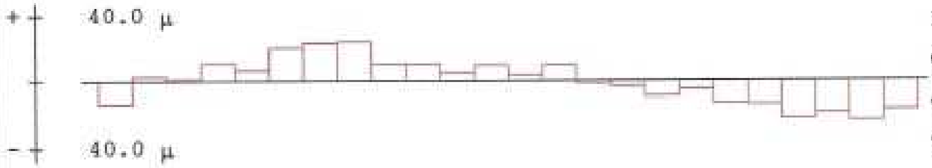
	Fp	fu
Ist	49.8	14.9
Qua.	D 8	D 8
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke) - eFr



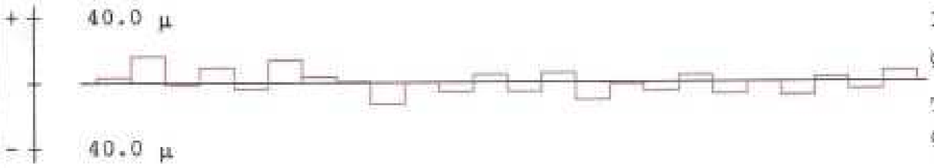
	Rp	fp
Ist	19.3	11.1
Qua.		D 8
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke) - eFr



	Fp	fu
Ist	47.1	17.9
Qua.	D 8	D 8
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke) - eFr



	Rp	fp
Ist	29.5	16.1
Qua.		D 9
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri - eFr

	Fr
Ist	12.1
Qua.	D 5
Tol.	0.0
Qua.	D 0

Exzentrizitaet 0.0171 X -0.0139 Y 0.0101

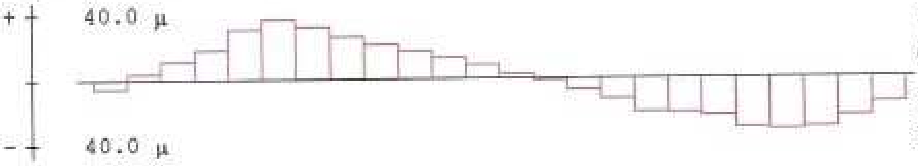
MESSTECHNIK WETZLAR GmbH
Metrology Systems

QUINDOS ZAHNRAD

Zaehnezahl :	24	Hersteller :	
Normalmodul :	2.5000	Seriennummer:	01
Eingr.winkel:	30.0000	Bemerkung :	Z = -195
Schr.winkel :	0.0000	Bezeichnung :	WPM_GSTU01_VERZ
Steig.Richt.:	gerade	Sachnummer :	
Zahnbreite :	230.0000	Pruefer/Dat.:	Quindos/16-AUG-2013/10

Beurteilung : i.O.☐ n.i.O.☐ T.☐ N.☐ R.☐

Fpi (linke Flanke)

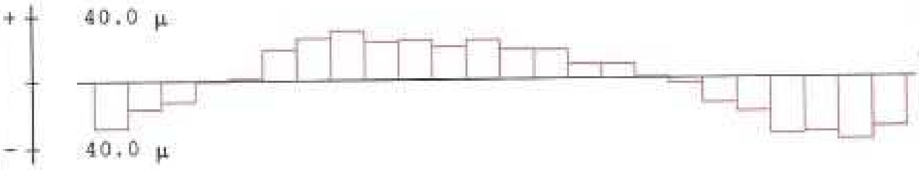


	Fp	fu
Ist	68.8	10.7
Qua.	D 9	D 7
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke)

	Rp	fp
Ist	20.8	12.6
Qua.		D 8
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke)

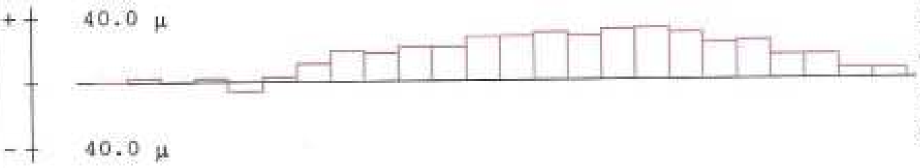


	Fp	fu
Ist	67.3	15.8
Qua.	D 9	D 8
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke)

	Rp	fp
Ist	31.2	17.5
Qua.		D 9
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri



	Fr
Ist	37.3
Qua.	D 8
Tol.	0.0
Qua.	D 0

MESSTECHNIK WETZLAR GmbH Metrology Systems

QUINDOS ZAHNRAD

Zaehnezahl	: 24	Hersteller	:
Normalmodul	: 2.5000	Seriennummer	: 01
Eingr.winkel	: 30.0000	Bemerkung	: Z = -195
Schr.winkel	: 0.0000	Bezeichnung	: WPM_GSTU01_VERZ
Steig.Richt.	: gerade	Sachnummer	:
Zahnbreite	:230.0000	Pruefer/Dat.	: Quindos/16-AUG-2013/10

Beurteilung : i.O.☐ n.i.O.☐ T.☐ N.☐ R.☐

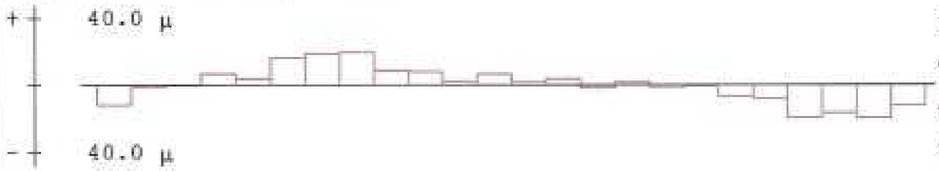
Fpi (linke Flanke) - eFr

	Fp	fu
Ist	38.6	9.5
Qua.	D 8	D 7
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke) - eFr

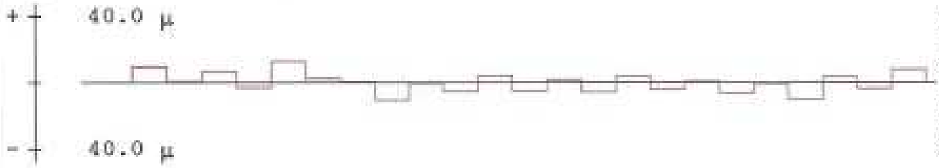
	Rp	fp
Ist	18.8	10.1
Qua.		D 8
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke) - eFr



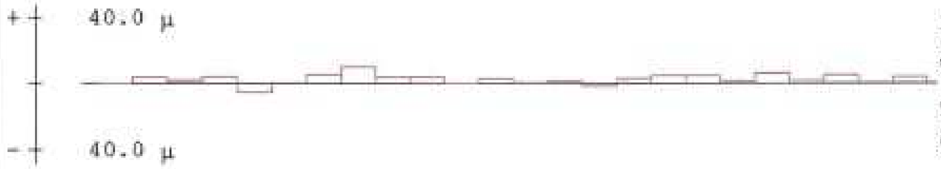
	Fp	fu
Ist	38.6	15.6
Qua.	D 8	D 8
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke) - eFr



	Rp	fp
Ist	23.5	12.8
Qua.		D 8
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri - eFr



	Fr
Ist	15.1
Qua.	D 6
Tol.	0.0
Qua.	D 0

Exzentrizitaet 0.0156 X -0.0136 Y 0.0077

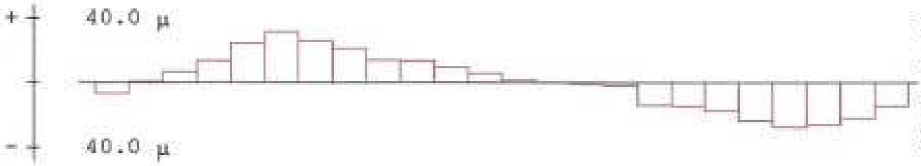
MESSTECHNIK WETZLAR GmbH
Metrology Systems

QUINDOS ZAHNRAD

Zaehnezahl :	24	Hersteller :	
Normalmodul :	2.5000	Seriennummer:	01
Eingr.winkel:	30.0000	Bemerkung :	Z = -175
Schr.winkel :	0.0000	Bezeichnung :	WPM_GSTU01_VERZ
Steig.Richt.:	gerade	Sachnummer :	
Zahnbreite :	230.0000	Pruefer/Dat.:	Quindos/16-AUG-2013/10

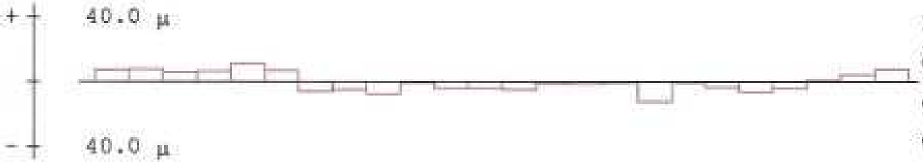
Beurteilung : i.O.☐ n.i.O.☐ T.☐ N.☐ R.☐

Fpi (linke Flanke)



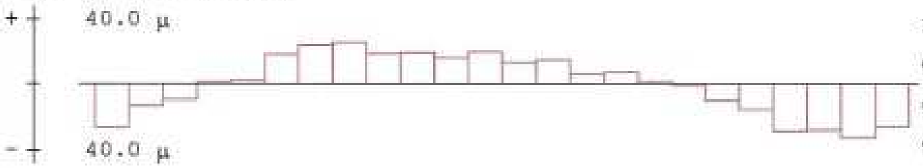
	Fp	fu
Ist	59.3	12.6
Qua.	D 9	D 8
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke)



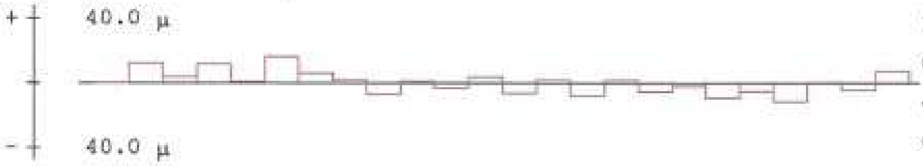
	Rp	fp
Ist	22.9	12.1
Qua.		D 8
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke)



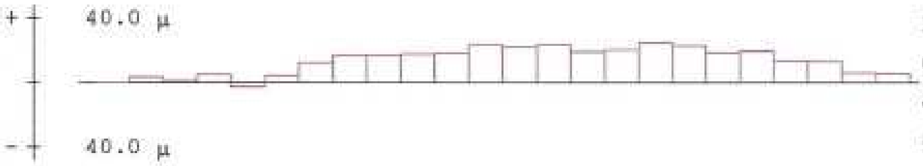
	Fp	fu
Ist	58.1	15.6
Qua.	D 9	D 8
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke)



	Rp	fp
Ist	28.0	16.2
Qua.		D 9
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri



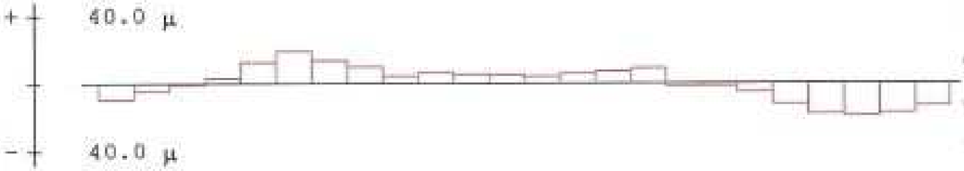
	Fr
Ist	27.4
Qua.	D 7
Tol.	0.0
Qua.	D 0

MESSTECHNIK WETZLAR GmbH
Metrology Systems
QUINDOS ZAHNRAD

Zaehnezahl	: 24	Hersteller	:
Normalmodul	: 2.5000	Seriennummer:	01
Eingr.winkel:	30.0000	Bemerkung	: Z = -175
Schr.winkel	: 0.0000	Bezeichnung	: WPM_GSTU01_VERZ
Steig.Richt.:	gerade	Sachnummer	:
Zahnbreite	:230.0000	Pruefer/Dat.:	Quindos/16-AUG-2013/10

Beurteilung : i.O.☐ n.i.O.☐ T.☐ N.☐ R.☐

Fpi (linke Flanke) - eFr



	Fp	fu
Ist	38.2	12.3
Qua.	D 8	D 8
Tol.	0.0	0.0
Qua.	D 0	D 0

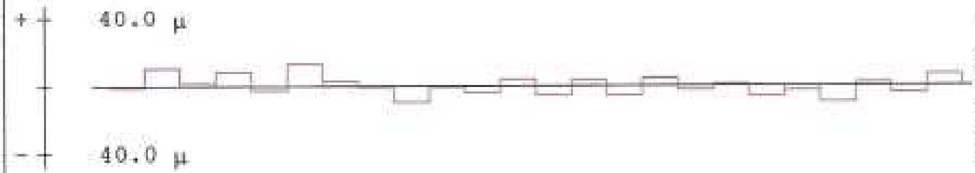
fpi (linke Flanke) - eFr

	Rp	fp
Ist	19.9	10.6
Qua.		D 8
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke) - eFr

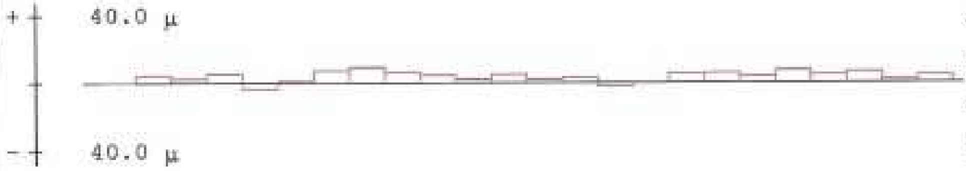
	Fp	fu
Ist	38.0	15.6
Qua.	D 8	D 8
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke) - eFr



	Rp	fp
Ist	22.5	12.9
Qua.		D 8
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri - eFr



	Fr
Ist	12.6
Qua.	D 5
Tol.	0.0
Qua.	D 0

Exzentrizitaet 0.0110 X -0.0099 Y 0.0046

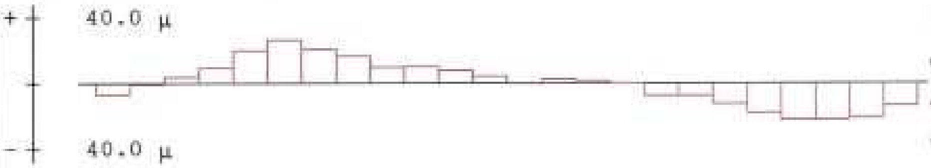
MESSTECHNIK WETZLAR GmbH Metrology Systems

QUINDOS ZAHNRAD

Zaehnezahl : 24	Hersteller :
Normalmodul : 2.5000	Seriennummer: 01
Eingr.winkel: 30.0000	Bemerkung : Z = -155
Schr.winkel : 0.0000	Bezeichnung : WPM_GSTU01_VERZ
Steig.Richt.: gerade	Sachnummer :
Zahnbreite :230.0000	Pruefer/Dat.: Quindos/16-AUG-2013/10

Beurteilung : i.O. ☐ n.i.O. ☐ T. ☐ M. ☐ R. ☐

Fpi (linke Flanke)

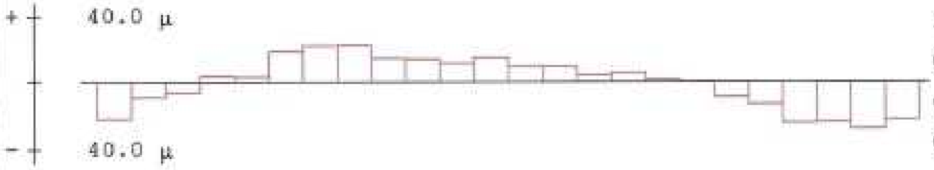


	Fp	fu
Ist	49.0	12.3
Qua.	D 8	D 8
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke)

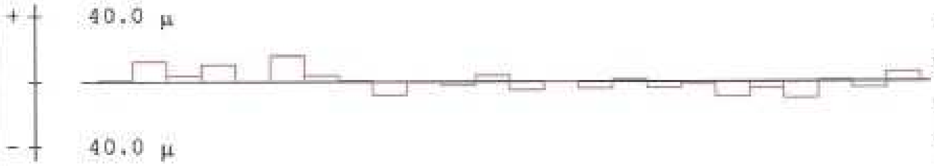
	Rp	fp
Ist	18.1	10.7
Qua.		D 8
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke)



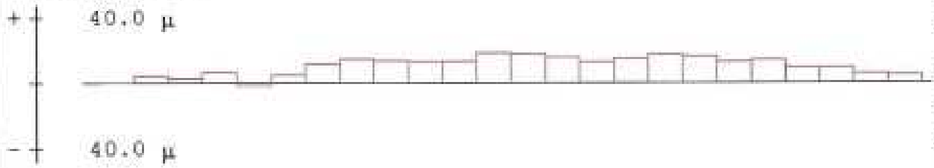
	Fp	fu
Ist	49.8	15.7
Qua.	D 8	D 8
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke)



	Rp	fp
Ist	25.6	15.3
Qua.		D 9
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri



	Fr
Ist	19.8
Qua.	D 6
Tol.	0.0
Qua.	D 0

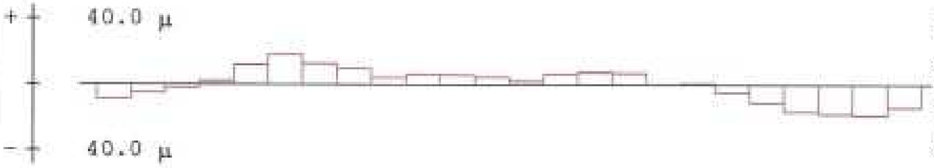
MESSTECHNIK WETZLAR GmbH Metrology Systems

QUINDOS ZAHNRAD

Zaehnezahl :	24	Hersteller :	
Normalmodul :	2.5000	Seriennummer:	01
Eingr.winkel:	30.0000	Bemerkung :	Z = -155
Schr.winkel :	0.0000	Bezeichnung :	WPM_G5TU01_VERZ
Steig.Richt.:	gerade	Sachnummer :	
Zahnbreite	:230.0000	Pruefer/Dat.:	Quindos/16-AUG-2013/10

Beurteilung : i.O.☐ n.i.O.☐ T.☐ N.☐ R.☐

Fpi (linke Flanke) - eFr

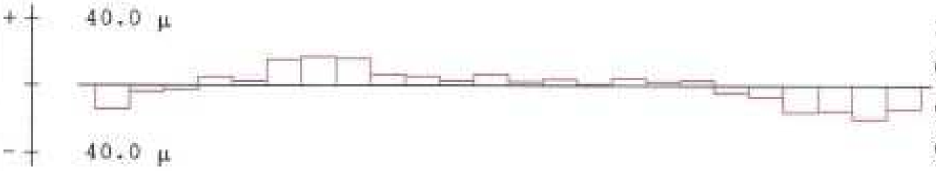


	Fp	fu
Ist	36.8	11.8
Qua.	D 8	D 7
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke) - eFr

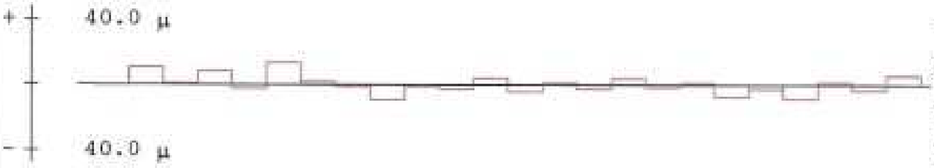
	Rp	fp
Ist	16.5	9.9
Qua.		D 7
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke) - eFr



	Fp	fu
Ist	36.3	15.7
Qua.	D 8	D 8
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke) - eFr



	Rp	fp
Ist	22.6	13.2
Qua.		D 8
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri - eFr

	Fr
Ist	11.5
Qua.	D 5
Tol.	0.0
Qua.	D 0

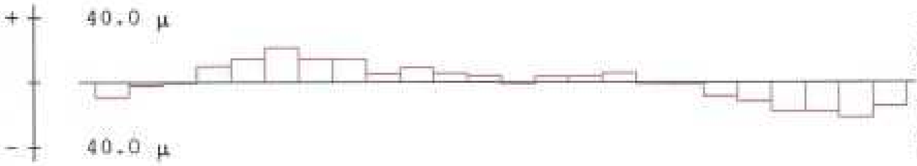
Exzentrizitaet 0.0072 X -0.0069 Y 0.0023

MESSTECHNIK WETZLAR GmbH
Metrology Systems
QUINDOS ZAHNRAD

Zaehnezahl	: 24	Hersteller	:
Normalmodul	: 2.5000	Seriennummer:	01
Eingr.winkel:	30.0000	Bemerkung	: Z = -135
Schr.winkel	: 0.0000	Bezeichnung	: WPM_GSTU01_VERZ
Steig.Richt.:	gerade	Sachnummer	:
Zahnbreite	:230.0000	Pruefer/Dat.:	Quindos/16-AUG-2013/10

Beurteilung : i.O. ☐ n.i.O. ☐ T. ☐ N. ☐ R. ☐

Fpi (linke Flanke)

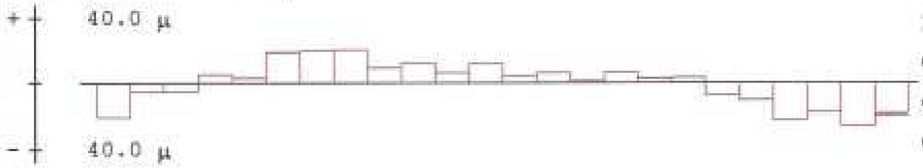


	Fp	fu
Ist	43.1	14.0
Qua.	D 8	D 8
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke)

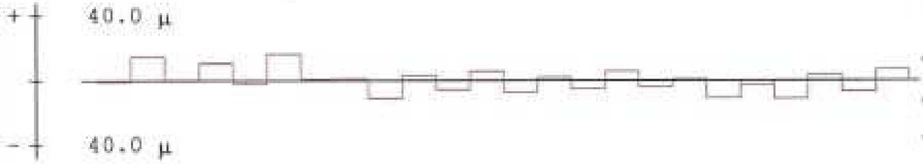
	Rp	fp
Ist	19.0	10.3
Qua.		D 8
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke)



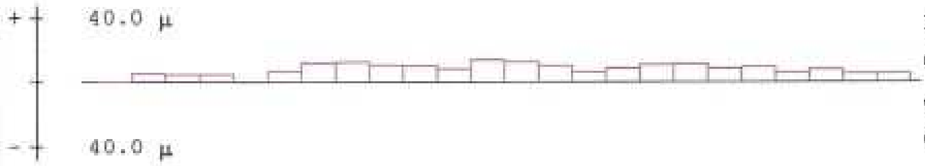
	Fp	fu
Ist	45.7	18.0
Qua.	D 8	D 8
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke)



	Rp	fp
Ist	27.3	16.0
Qua.		D 9
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri



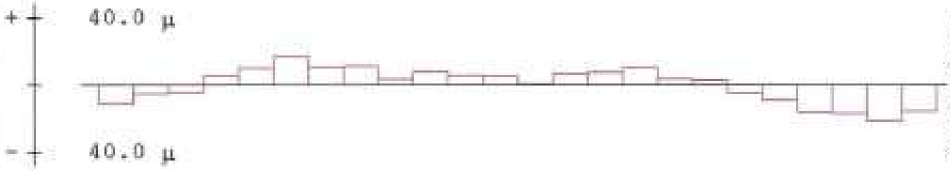
	Fr
Ist	13.9
Qua.	D 5
Tol.	0.0
Qua.	D 0

MESSTECHNIK WETZLAR GmbH
Metrology Systems
QUINDOS ZAHNRAD

Zaehnezahl :	24	Hersteller :	
Normalmodul :	2.5000	Seriennummer:	01
Eingr.winkel:	30.0000	Bemerkung :	Z = -135
Schr.winkel :	0.0000	Bezeichnung :	WPM_GSTU01_VERZ
Steig.Richt.:	gerade	Sachnummer :	
Zahnbreite :	230.0000	Pruefer/Dat.:	Quindos/16-AUG-2013/10

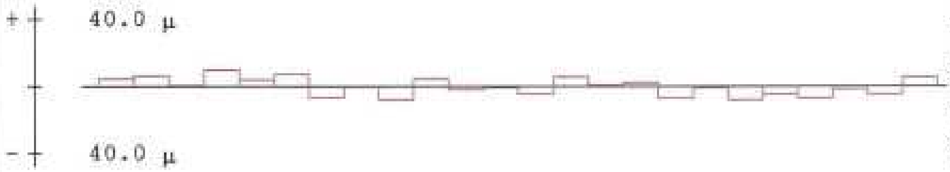
Beurteilung : i.O.☐ n.i.O.☐ T.☐ N.☐ R.☐

Fpi (linke Flanke) - eFr



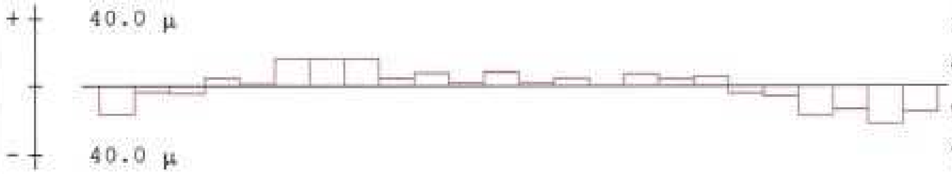
	Fp	fu
Ist	38.7	13.7
Qua.	D 8	D 8
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke) - eFr



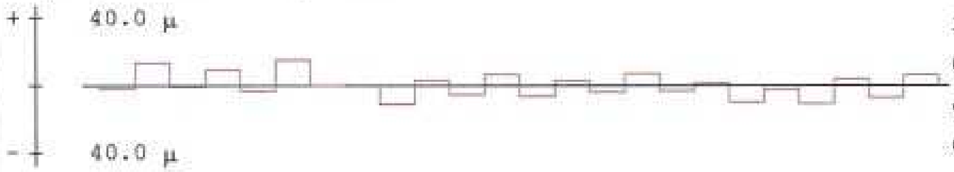
	Rp	fp
Ist	17.6	9.9
Qua.		D 7
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke) - eFr



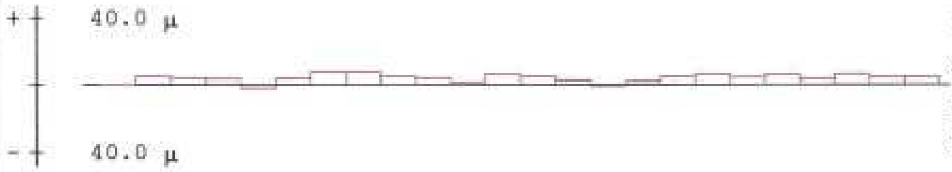
	Fp	fu
Ist	37.5	18.1
Qua.	D 8	D 9
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke) - eFr



	Rp	fp
Ist	26.4	14.9
Qua.		D 9
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri - eFr



	Fr
Ist	10.0
Qua.	D 5
Tol.	0.0
Qua.	D 0

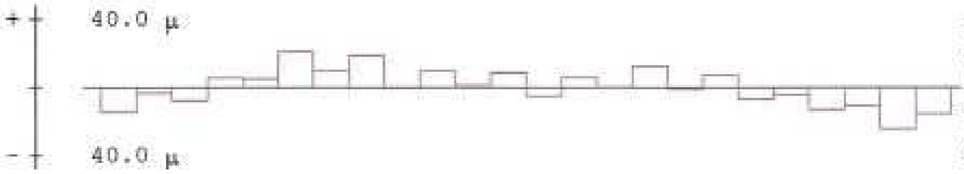
Exzentrizitaet 0.0039 X -0.0039 Y 0.0002

MESSTECHNIK WETZLAR GmbH
Metrology Systems
QUINDOS ZAHNRAD

Zaehnezahl	: 24	Hersteller	:
Normalmodul	: 2.5000	Seriennummer:	01
Eingr.winkel:	30.0000	Bemerkung	: Z = -115
Schr.winkel	: 0.0000	Bezeichnung	: WPM_GSTU01_VERZ
Steig.Richt.:	gerade	Sachnummer	:
Zahnbreite	:230.0000	Pruefer/Dat.:	Quindos/16-AUG-2013/10

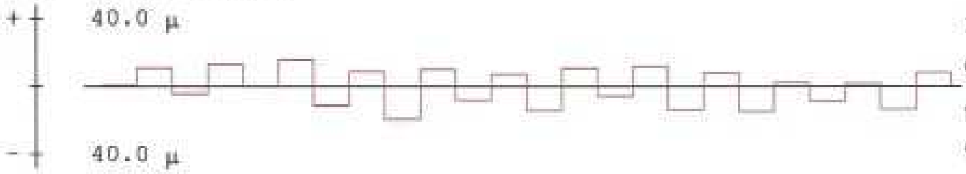
Beurteilung : i.O.☐ n.i.O.☐ T.☐ N.☐ R.☐

Fpi (linke Flanke)



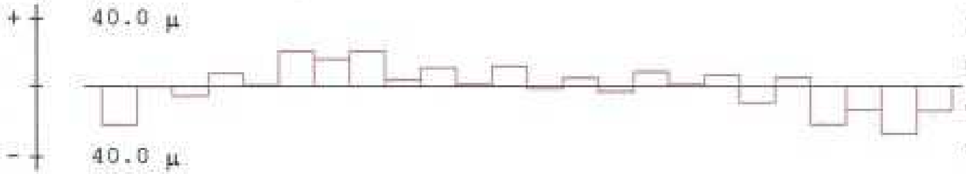
	Fp	fu
Ist	45.1	29.2
Qua.	D 8	D10
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke)



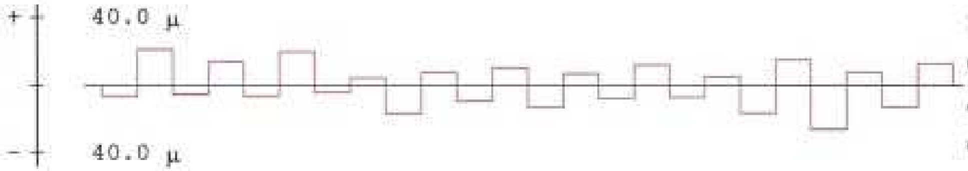
	Rp	fp
Ist	34.8	19.0
Qua.		D 9
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke)



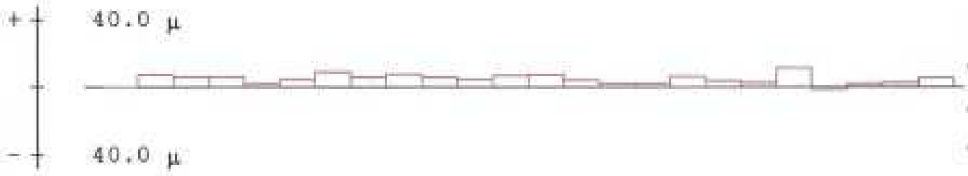
	Fp	fu
Ist	47.4	41.3
Qua.	D 8	D11
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke)



	Rp	fp
Ist	47.3	26.4
Qua.		D10
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri



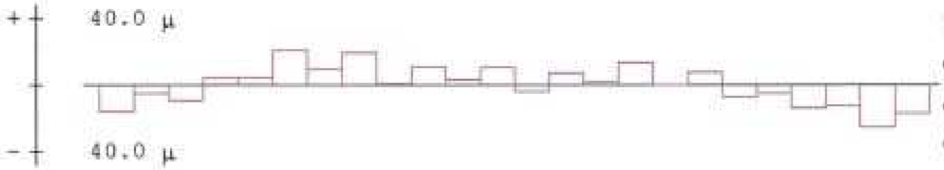
	Fr
Ist	13.0
Qua.	D 5
Tol.	0.0
Qua.	D 0

MESSTECHNIK WETZLAR GmbH
Metrology Systems
QUINDOS ZAHNRAD

Zaehnezahl	: 24	Hersteller	:
Normalmodul	: 2.5000	Seriennummer	: 01
Eingr.winkel	: 30.0000	Bemerkung	: Z = -115
Schr.winkel	: 0.0000	Bezeichnung	: WPM_GSTU01_VERZ
Steig.Richt.	: gerade	Sachnummer	:
Zahnbreite	:230.0000	Pruefer/Dat.	: Quindos/16-AUG-2013/10

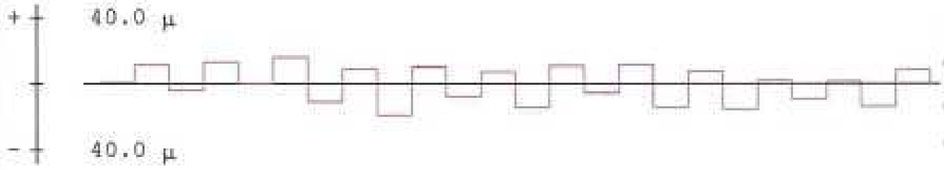
Beurteilung : i.O. ☐ n.i.O. ☐ T. ☐ N. ☐ R. ☐

Fpi (linke Flanke) - eFr



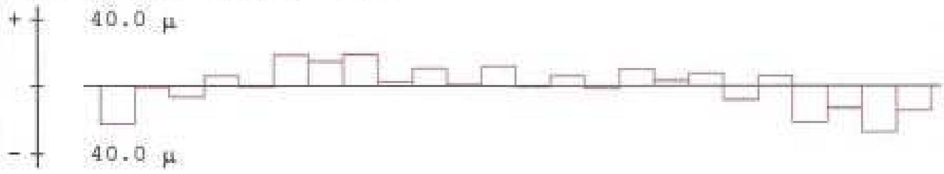
	Fp	fu
Ist	46.2	29.1
Qua.	D 8	D10
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke) - eFr



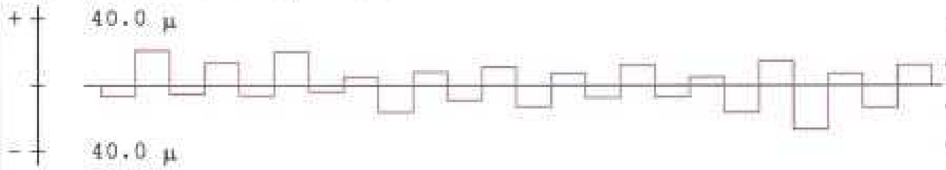
	Rp	fp
Ist	34.8	18.7
Qua.		D 9
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke) - eFr



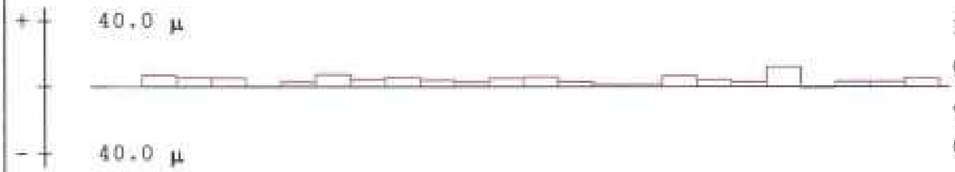
	Fp	fu
Ist	45.8	41.4
Qua.	D 8	D11
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke) - eFr



	Rp	fp
Ist	47.3	26.7
Qua.		D10
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri - eFr



	Fr
Ist	13.0
Qua.	D 5
Tol.	0.0
Qua.	D 0

Exzentrizitaet 0.0014 X -0.0007 Y -0.0012

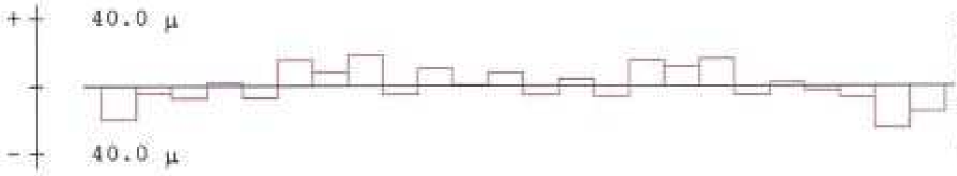
MESSTECHNIK WETZLAR GmbH
Metrology Systems

QUINDOS ZAHNRAD

Zaehnezahl	: 24	Hersteller	:
Normalmodul	: 2.5000	Seriennummer	: 01
Eingr.winkel	: 30.0000	Bemerkung	: Z = -95
Schr.winkel	: 0.0000	Bezeichnung	: WPM_GSTU01_VERZ
Steig.Richt.	: gerade	Sachnummer	:
Zahnbreite	:230.0000	Pruefer/Dat.	: Quindos/16-AUG-2013/10

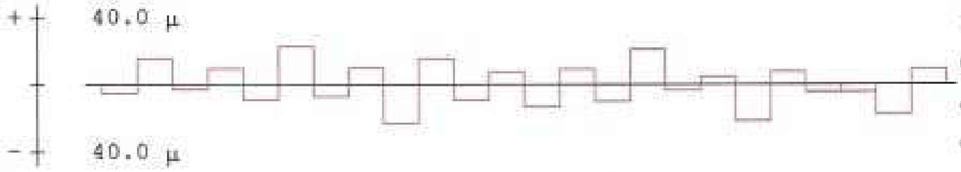
Beurteilung : i.O. ☐ n.i.O. ☐ T. ☐ N. ☐ R. ☐

Fpi (linke Flanke)



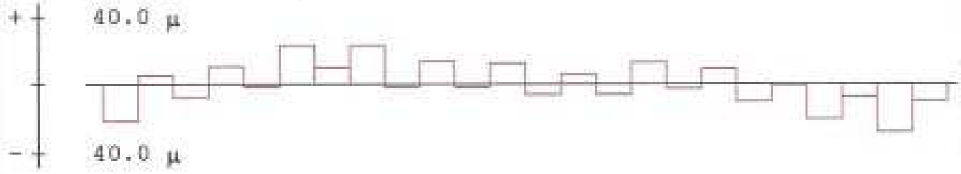
	Fp	fu
Ist	42.7	38.4
Qua.	D 8	D10
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke)



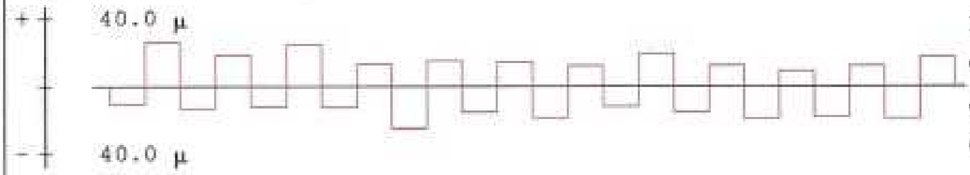
	Rp	fp
Ist	45.5	23.2
Qua.		D10
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke)



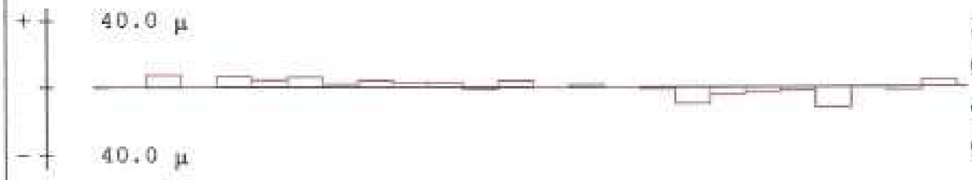
	Fp	fu
Ist	50.4	39.9
Qua.	D 9	D10
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke)



	Rp	fp
Ist	50.7	26.0
Qua.		D10
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri

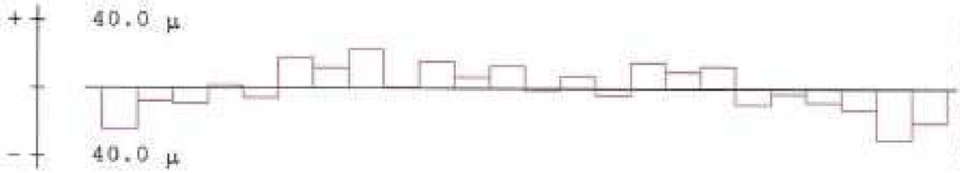


	Fr
Ist	19.5
Qua.	D 6
Tol.	0.0
Qua.	D 0

MESSTECHNIK WETZLAR GmbH Metrology Systems QUINDOS ZAHNRAD		
	Zaehnezahl : 24	Hersteller :
	Normalmodul : 2.5000	Seriennummer: 01
	Eingr.winkel: 30.0000	Bemerkung : Z = -95
	Schr.winkel : 0.0000	Bezeichnung : WPM_GSTU01_VERZ
	Steig.Richt.: gerade	Sachnummer :
	Zahnbreite :230.0000	Pruefer/Dat.: Quindos/16-AUG-2013/10

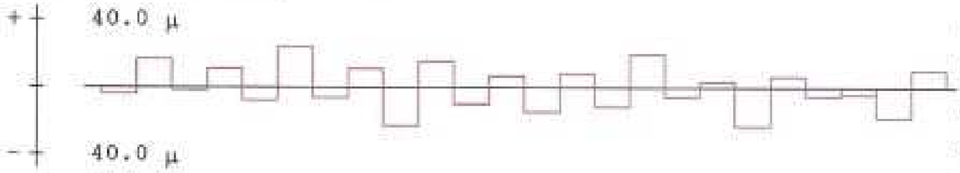
Beurteilung : i.O. ☐ n.i.O. ☐ T. ☐ N. ☐ R. ☐

Fpi (linke Flanke) - eFr



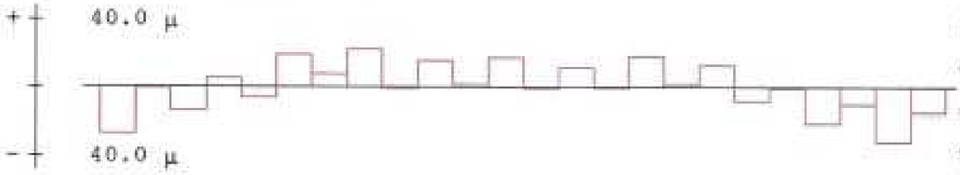
	Fp	fu
Ist	53.4	38.0
Qua.	D 9	D10
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke) - eFr



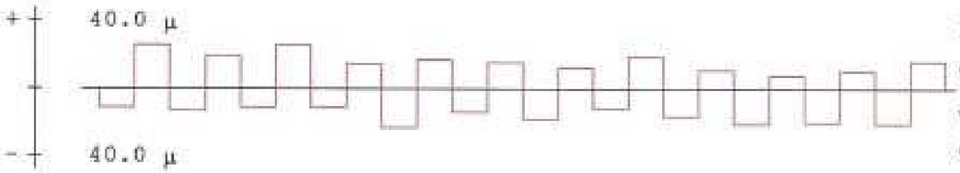
	Rp	fp
Ist	46.7	23.8
Qua.		D10
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke) - eFr



	Fp	fu
Ist	53.2	39.8
Qua.	D 9	D10
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke) - eFr



	Rp	fp
Ist	48.9	25.7
Qua.		D10
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri - eFr

	Fr
Ist	14.0
Qua.	D 5
Tol.	0.0
Qua.	D 0

Exzentrizitaet 0.0051 X 0.0010 Y -0.0050

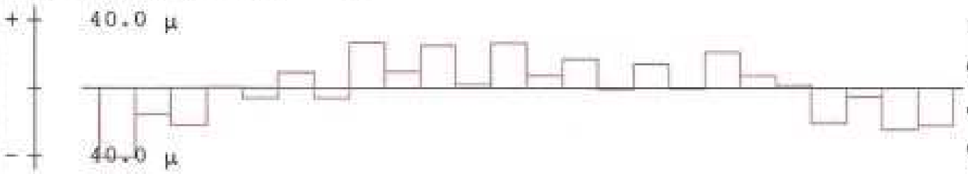
MESSTECHNIK WETZLAR GmbH
Metrology Systems

QUINDOS ZAHNRAD

Zaehnezahl :	24	Hersteller :	
Normalmodul :	2.5000	Seriennummer:	01
Eingr.winkel:	30.0000	Bemerkung :	Z = -75
Schr.winkel :	0.0000	Bezeichnung :	WPM_GSTU01_VERZ
Steig.Richt.:	gerade	Sachnummer :	
Zahnbreite :	230.0000	Pruefer/Dat.:	Quindos/16-AUG-2013/10

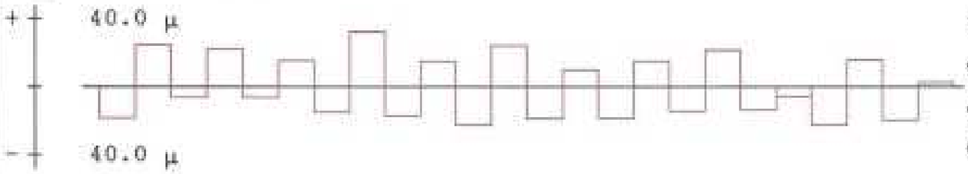
Beurteilung : i.O.☐ n.i.O.☐ T.☐ N.☐ R.☐

Fpi (linke Flanke) - eFr



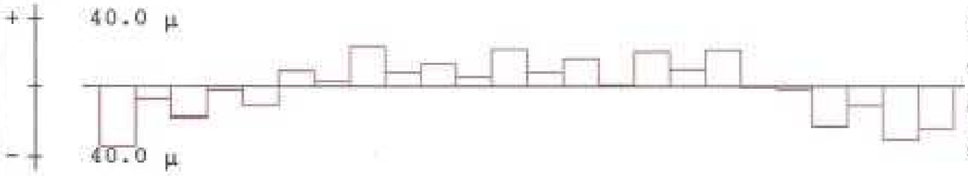
	Fp	fu
Ist	66.8	49.1
Qua.	D 9	D11
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke) - eFr



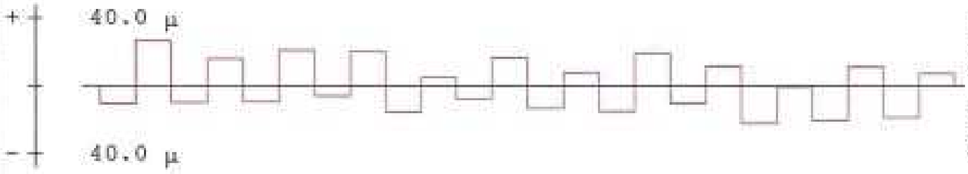
	Rp	fp
Ist	54.9	32.3
Qua.		D11
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke) - eFr



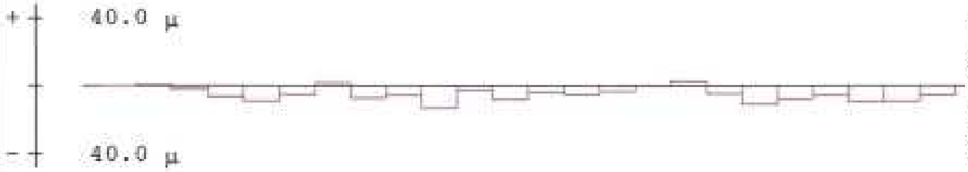
	Fp	fu
Ist	57.4	37.1
Qua.	D 9	D10
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke) - eFr



	Rp	fp
Ist	48.7	26.3
Qua.		D10
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri - eFr



	Fr
Ist	16.0
Qua.	D 6
Tol.	0.0
Qua.	D 0

Exzentrizitaet 0.0105 X 0.0017 Y -0.0103

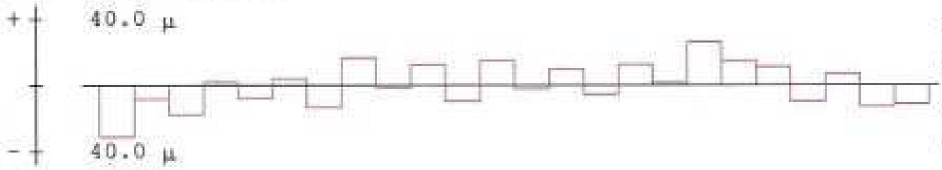
MESSTECHNIK WETZLAR GmbH
Metrology Systems

QUINDOS ZAHNRAD

Zaehnezahl :	24	Hersteller :	
Normalmodul :	2.5000	Seriennummer:	01
Eingr.winkel:	30.0000	Bemerkung :	Z = -75
Schr.winkel :	0.0000	Bezeichnung :	WPM_GSTU01_VERZ
Steig.Richt.:	gerade	Sachnummer :	
Zahnbreite :	230.0000	Pruefer/Dat.:	Quindos/16-AUG-2013/10

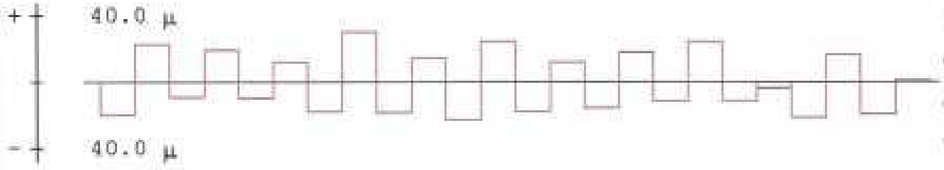
Beurteilung : i.O. ☐ n.i.O. ☐ T. ☐ N. ☐ R. ☐

Fpi (linke Flanke)



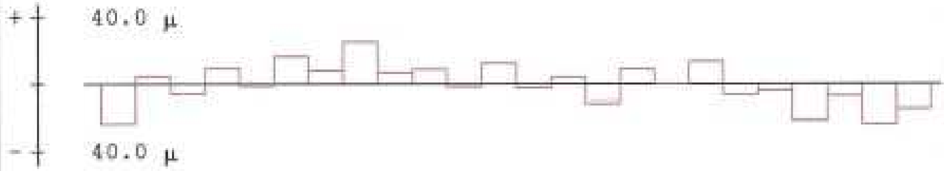
	Fp	fu
Ist	57.1	48.5
Qua.	D 9	D11
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (linke Flanke)



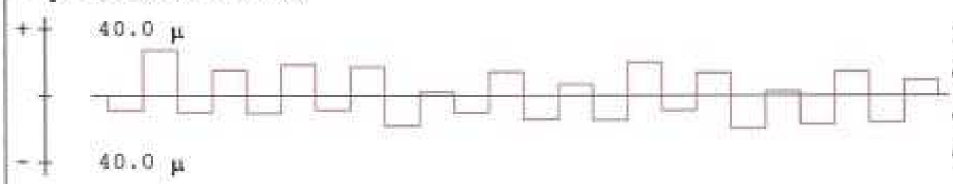
	Rp	fp
Ist	52.6	30.2
Qua.		D10
Tol.	0.0	0.0
Qua.		D 0

Fpi (rechte Flanke)



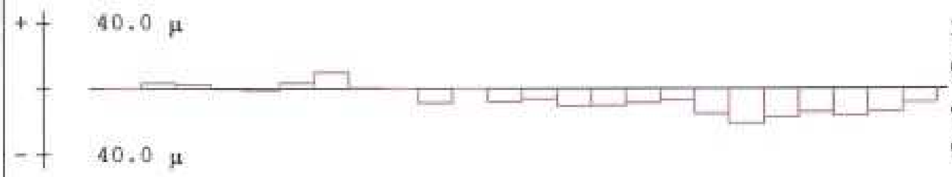
	Fp	fu
Ist	48.4	37.3
Qua.	D 8	D10
Tol.	0.0	0.0
Qua.	D 0	D 0

fpi (rechte Flanke)



	Rp	fp
Ist	46.9	27.2
Qua.		D10
Tol.	0.0	0.0
Qua.		D 0

Rundlauf Fri

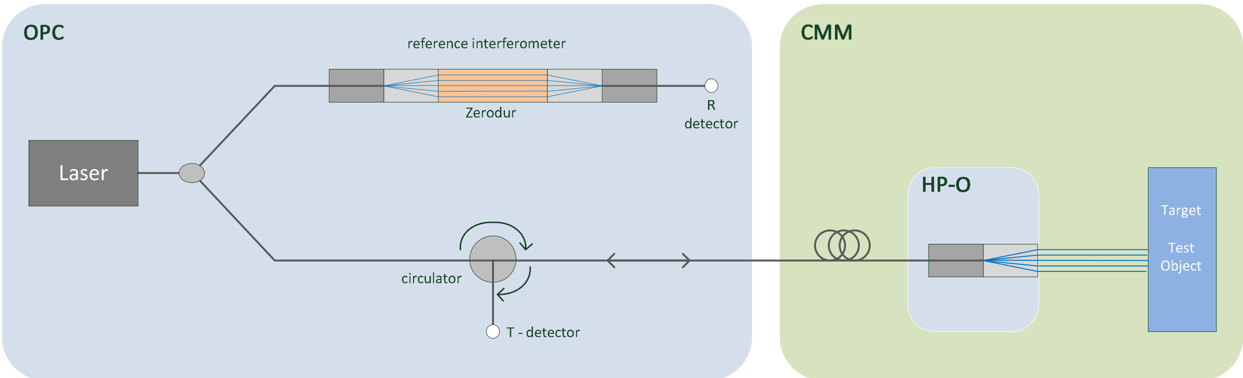


	Fr
Ist	31.1
Qua.	D 8
Tol.	0.0
Qua.	D 0

Appendix 3: HP-O physical principle

The Hexagon Manufacturing Intelligence HP-O optical sensor is a 1D-probing technology using unique laser based frequency-modulated interferometry in order to realize a highest accuracy non-contact measurement setup at high measurement speed. The details in this appendix outline the basic functional principles. The HP-O sensor technology is currently being used in Hexagon CMMs of highest accuracy classification but the addressable applications can be extended by design to In-Process Metrology Framework applications as well.

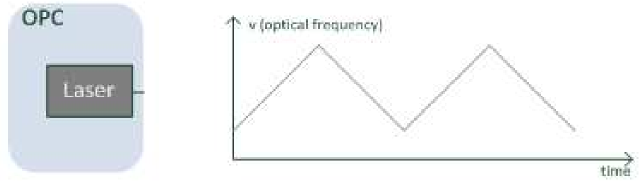
1. Measurement principle



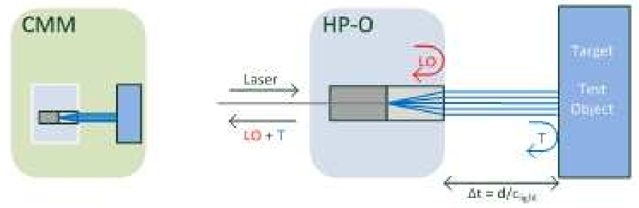
OPC Laser (tunanble)
reference intereferometer (calibrated distance in Zerodur)
detectors for reference (R) and target (T) signals

HP-O free-beam micro-optics

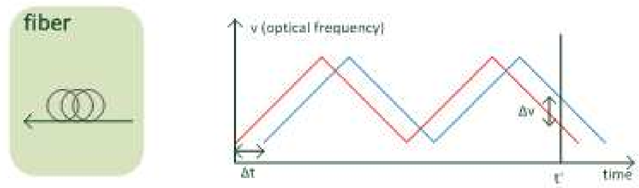
2. Signal Generation



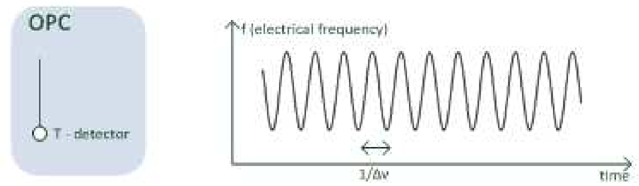
Laser tunes its wavelength
or optical frequency over time



HP-O splits light into LO (local oscillator) and target beam; received target signal T is delayed by Δt

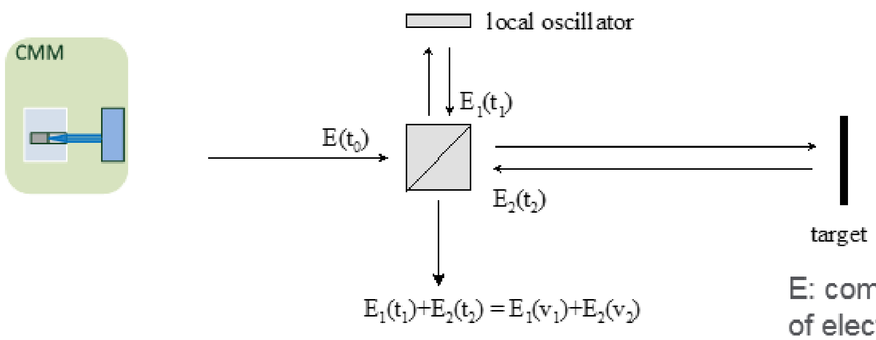


LO and delayed target signal T merge inside fiber with optical frequency difference Δν

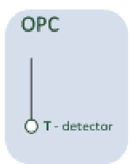


detector converts optical freqency difference Δν into electrical beat frequency f

3. Physical Description



E: complex amplitudes
of electro-magnectic fields



$$I = (E_1 + E_2)\cdot(E_1 + E_2)^*$$
$$I = E_1^{\,2} + E_2^{\,2} + 2E_1E_2 \cdot \cos(2\pi f t)$$

detected intensity at the
detector

4. Interference Formula

negligible contribution:

power collected from target

> -95 dB

interference "amplification"

+ 40 dB

$$I(t) = E_{LO}^2 + E_T^2 + 2\,E_{LO}E_T\cos\left(2\pi\underbrace{\left(\nu_{LO}(t) - \nu_T(t)\right)}_{\Delta\nu}\cdot t\right)$$

dominant contribution:

local oscillator, DC term (probe reflection)

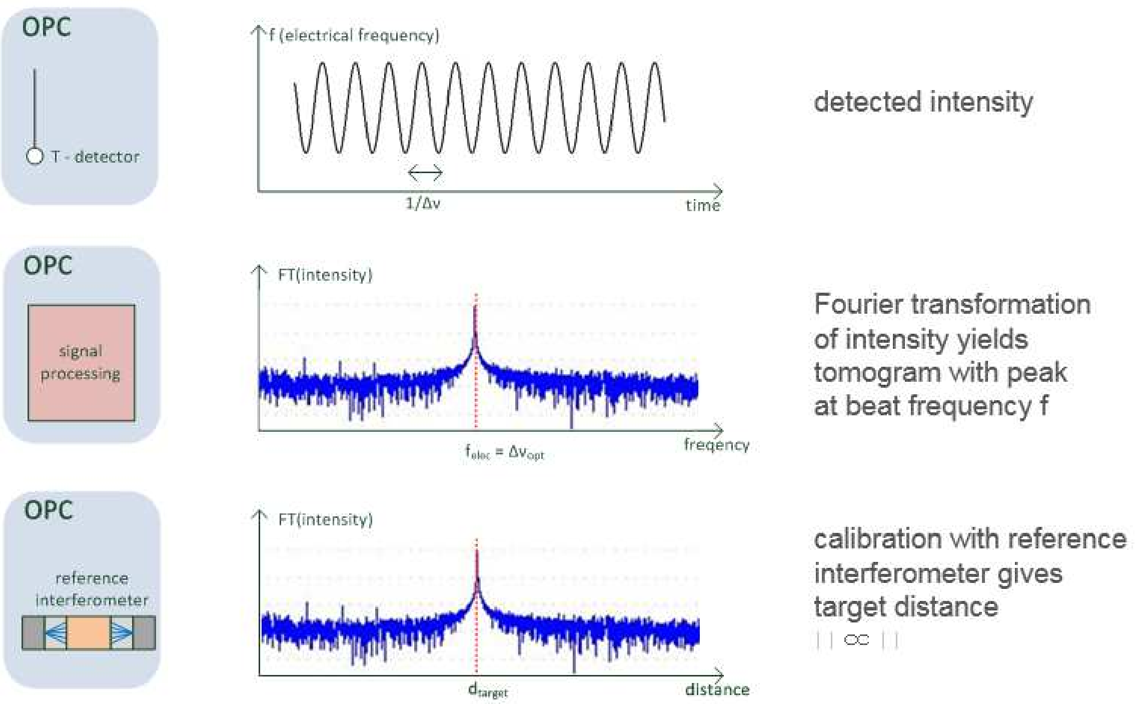
-20 dB

interference term:

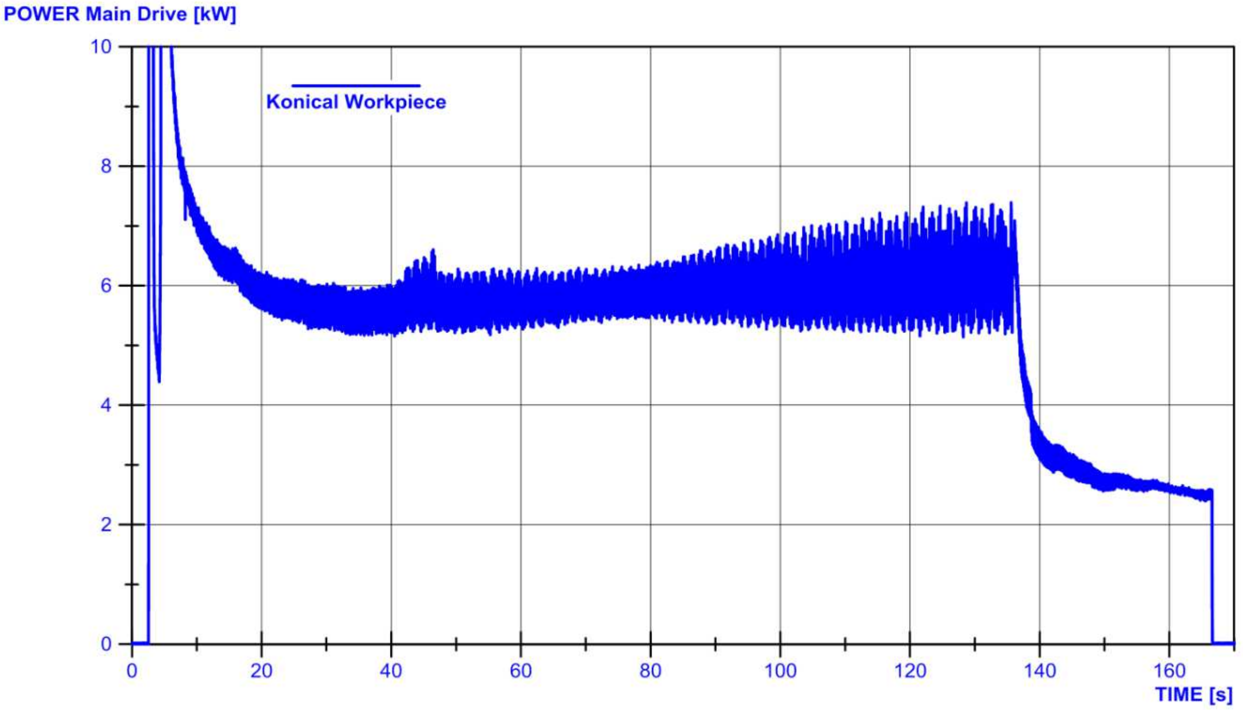
beat frequency

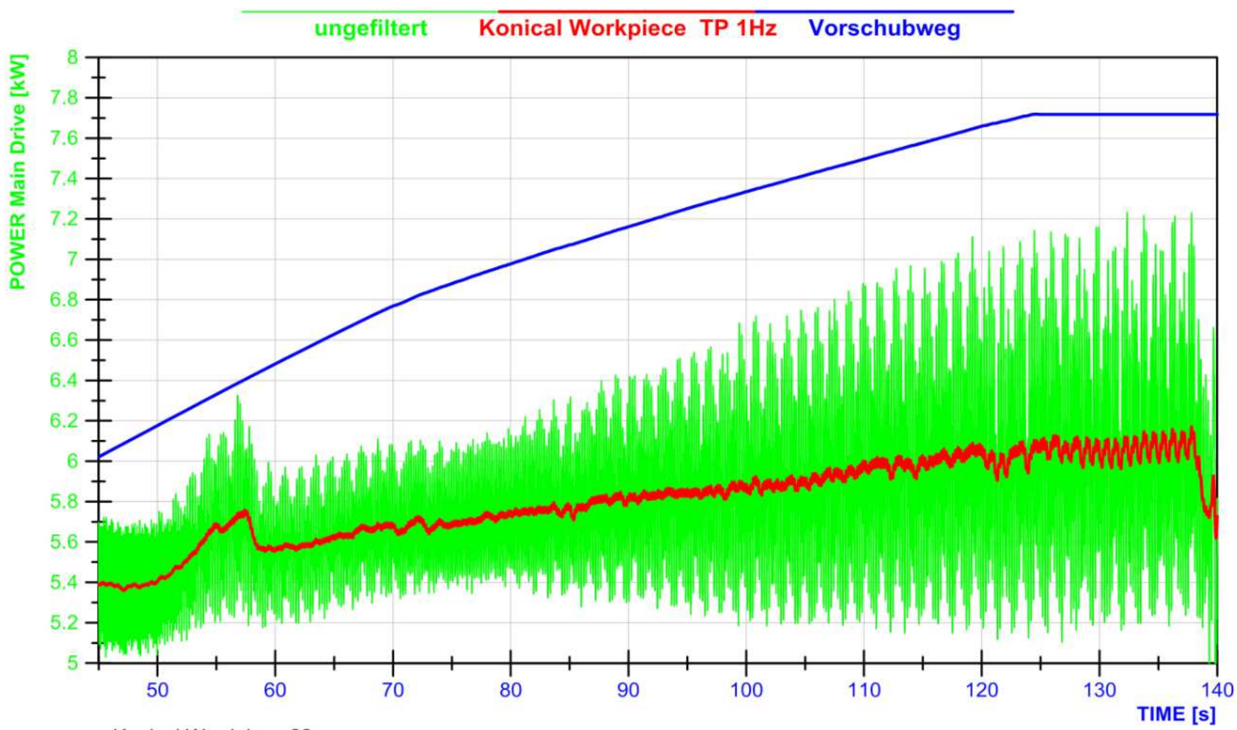
> -55 dB

5. Tomogram

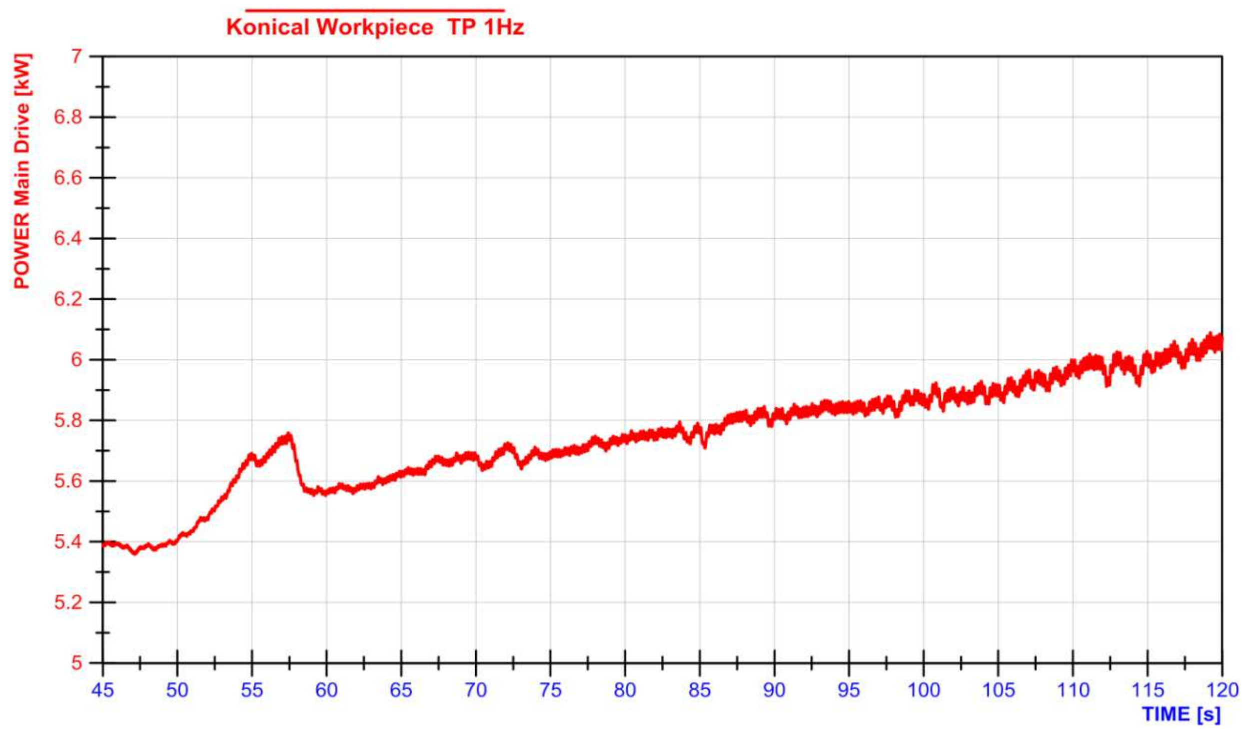


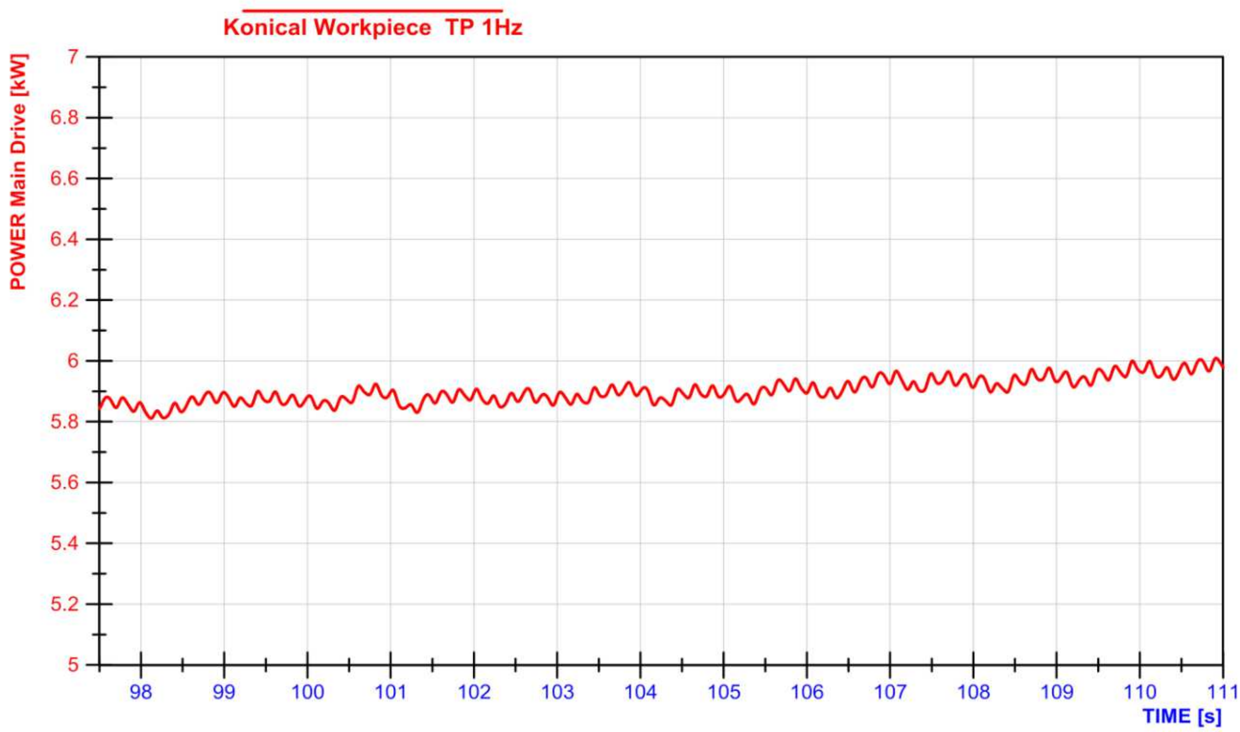
Appendix 4: Measurement Results Framework

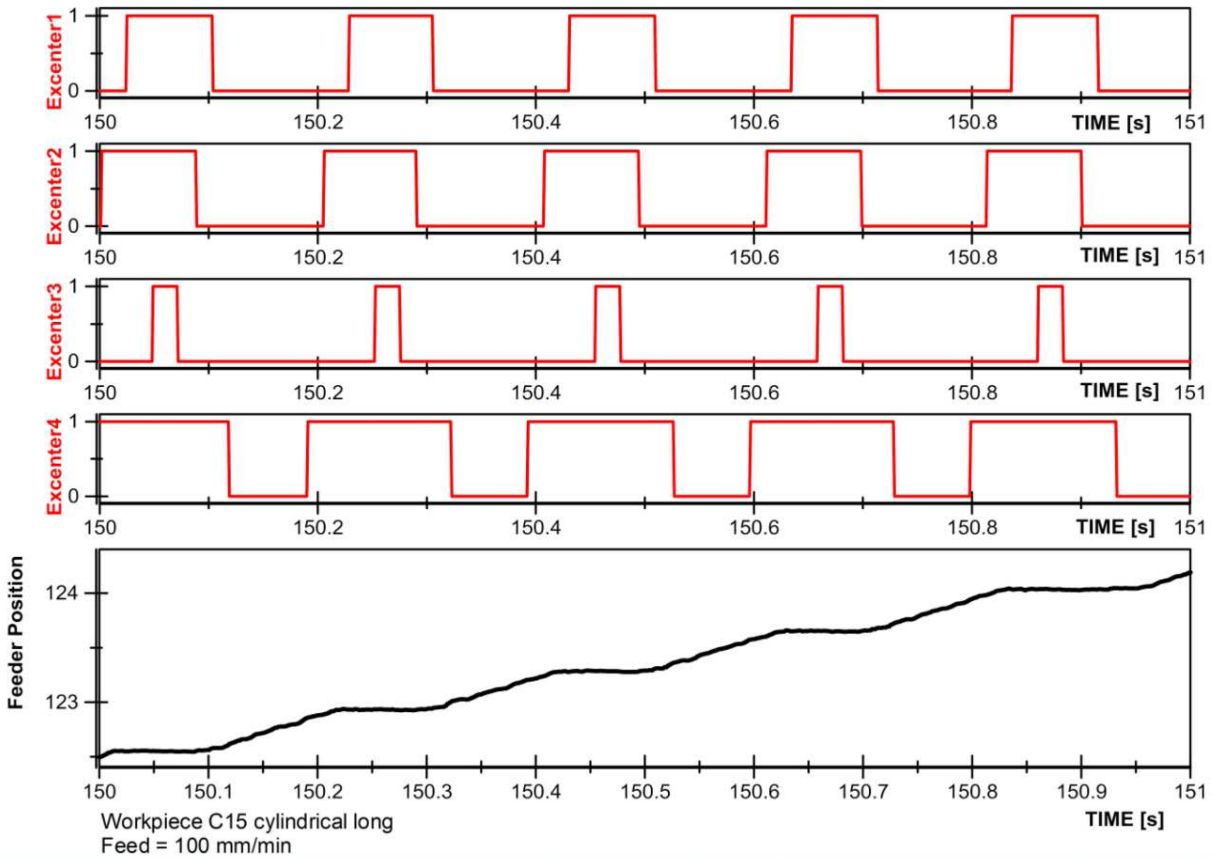


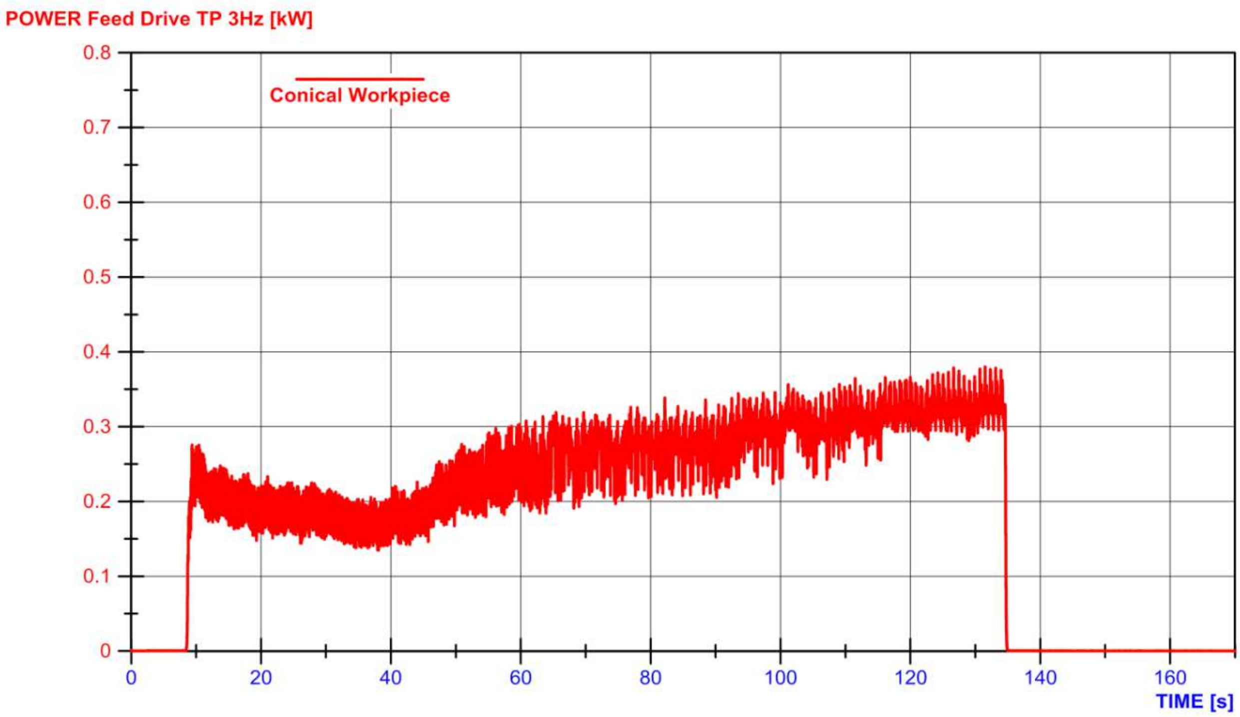


Konical Wordpiece 22

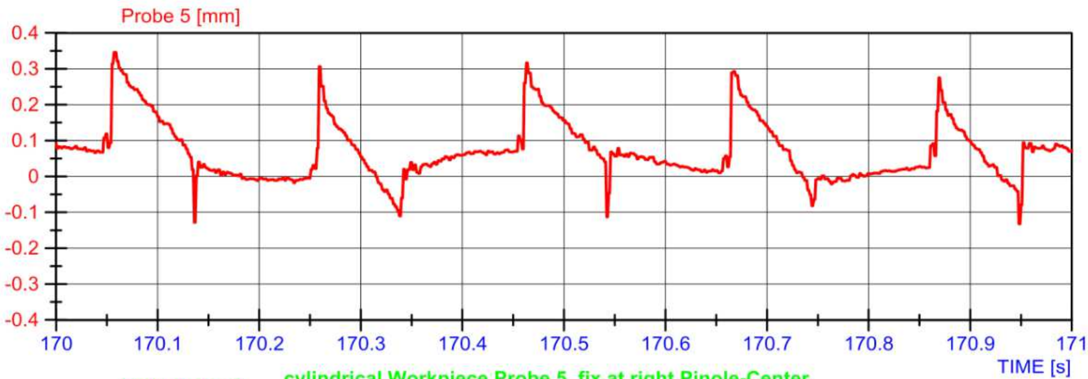

Konical Workpiece TP 1Hz
POWER Main Drive [kW]
7
6.8
6.6
6.4
6.2
6
5.8
5.6
5.4
5.2
5
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
TIME [s]


Konical Workpiece TP 1Hz
POWER Main Drive [kW]
7
6.8
6.6
6.4
6.2
6
5.8
5.6
5.4
5.2
5
98
99
100
101
102
103
104
105
106
107
108
109
110
111
TIME [s]

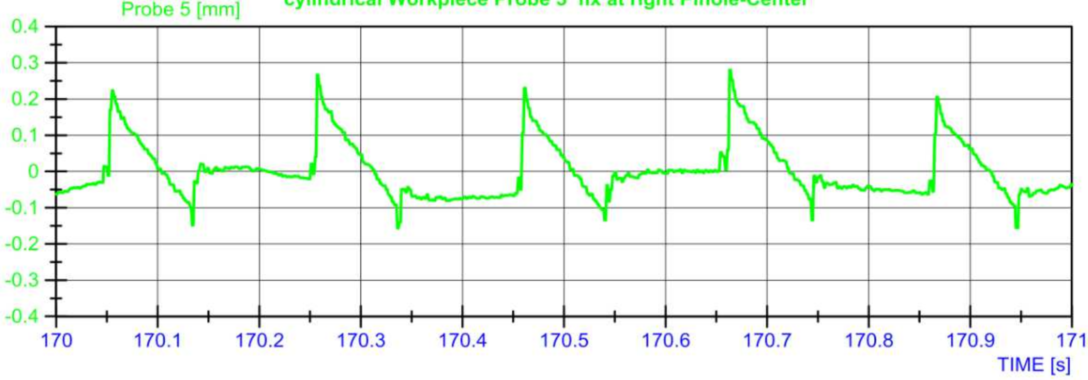

Excenter1
Excenter2
Excenter3
Excenter4
Feeder Position
TIME [s]
Workpiece C15 cylindrical long
Feed = 100 mm/min


POWER Feed Drive TP 3Hz [kW]
Conical Workpiece
TIME [s]

cylindrical Workpiece Probe 5 fix at front of tools

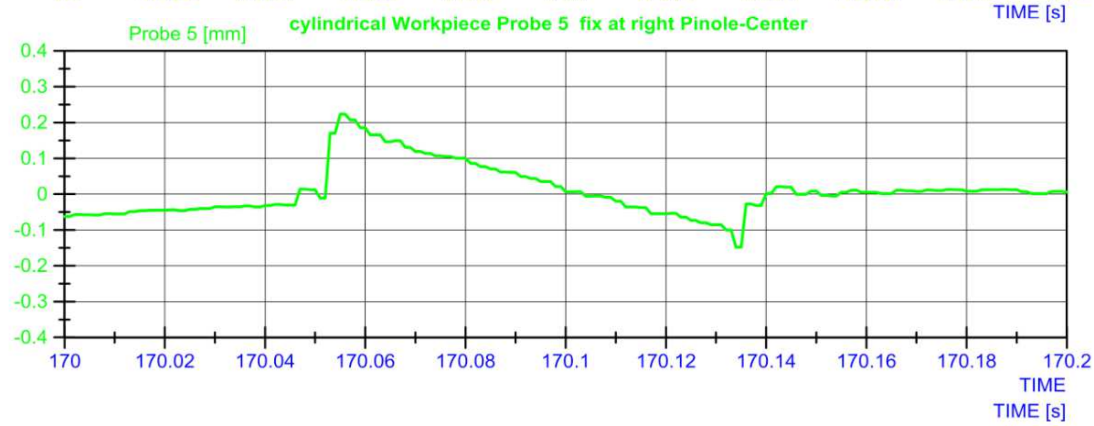


cylindrical Workpiece Probe 5 fix at right Pinole-Center



cylindrical Workpiece Probe 5 fix at front of tools

cylindrical Workpiece Probe 5 fix at right Pinole-Center



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129	Schmitt R., Körfer F., Sawodny O. et al	Virtuelle Messgeräte: Definition und Stand der Technik.	2008	pp. 298-310	TM Technisches Messen 75
130	Schmoeckel, D.,	Kaltwalzen von Verzahnungen durch Querwalzen	1983	pp. 75	Springer-Verl.
131	Schmoeckel, D.,	Kaltwalzen von Verzahnungen durch Querwalzen	1983	pp. 75	Springer-Verl.
132	Schmoeckel, D.; Hauk, pp.	Entwicklung eines kombinierten Drück-Walz-Verfahrens zur Herstellung von Zahnradvorformen	1996		VDI-Z Integrierte Produktion ; 138 , Special Blechbearbeitung ; 46-48, Aufsatz (Zeitschrift),
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134	Schmoeckel, D.; Hammerschmidt, E.	Uebersicht der Verfahrenstechnologie	1980	pp. 20	Ingenieur Digest
135	Schmoeckel, D.; Hammerschmidt, E.	Ermittlung des Einflusses der Maschinenkenngroessen	1983	pp. 43-48	Dt. Verb. f. Materialprüfung
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137	Schmoeckel, D.;Hauk, pp.,	Entwicklung eines kombinierten Drück-Walz-Verfahrens	1996		VDI-Z Integrierte Produktion
138	Schmoekel, D., Hammerschmidt, E.	UKD'88. 3. Umformtechnisches Kolloquium	1988		UKD'88. 3. colloquium on metal forming
139	Schöck, J.; Kammerer, M.	Verzahnungsherstellung durch Kaltfließpressen	1999	pp. 36-42	Umformtechnik

140	Sheljaskow, pp.	Kaltwalzen von Innenverzahnungen	1983	pp. 116-121	Forschungsgesellschaft
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147	Stöbener D., Beekhuis B.	Application of an in situ measuring system for the compensation of wall thickness variations during turning of thin-walled rings	2013	pp. 511-514	CIRP Annals - manufacturing Technology 62/I
148	Swinkels, Bastiaan Lucas	High-accuracy absolute distance metrology	2006		Dissertation Technische Universiteit Delft
149	Tuzinsky W., Scheuerich R.	In-line dimensional measurement of long and flat products.	2009	pp. 70-71	MPT International (2)
150	Uematsu, Seizo; Houser, Donald R.	A study on reducing gear tooth profile error	2005	pp. 34-39	Gear Technology
151	Volkov, M.;Korotkov, A	Thread-Rolling Worm Shafts	1970	pp. 90-92	W+B
152	Vrana J.	Grundlagen und Anwendungen der aktiven Thermographie mit elektromagnetischer Anregung.	2008		Dissertation, Naturwissenschaftliche-Technische Fakultät III der Universität des Saarlandes, Saarbrücken
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155	Weckenmann A., Gawande B.	Koordinatenmesstechnik – Flexible Messstrategien für Maß, Form und Lage	1999		1. Auflage Karl Hanser, München
156	Weckenmann A., Weickmann J., Hartmann W.	Multi-component fringe projection sensors: assistance system for short and Inspection processes	2008	pp. 1-13	Metrology's Impact on Business NCSL. International Workshop and Symposium
157	Weickmann J., Weckenmann A., Brenner PF.	Automatic, task-sensitive and simulation-based optimization of fringe projection measurements.	2010	pp. 439-443	Key Engin Mater 437
158	Wendt K., Franke M., Steinbrenner I.	M3D3 - High Accuracy Measurement of Large Complex 3D-Objects Using Tracking Interferometry	2011		NimTech International Workshop – Advances in Coordinate Measurement Techniques for Industrial App. , Braunschweig, Germany, February 22, 2011
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160	Zhongxue Gan, Qing Tang	Laser Stripe Sensor Calibration, Visual Sensing and its Applications: Advanced Topics in Science and Technology in China, Vol. 0	2011	pp. 41-91	Springer Berlin
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Appendix 6: List of Standards

Nr.	Standard	Description
ST 1	DIN ISO 14	Keilwellen-Verbindungen mit geraden Flanken und Innenzentrierung; Maße, Toleranzen, Prüfung; Identisch mit ISO 14
ST 2	DIN 0867	Bezugsprofile für Evolventenverzahnungen an Stirnrädern (Zylinderrädern) für den allgemeinen Maschinenbau und den Schwermaschinenbau
ST 3	DIN 0868	Allgemeine Begriffe und Bestimmungsgrößen für Zahnräder, Zahnradpaare und Zahnradgetriebe
ST 4	DIN 1319 -1	Grundlagen der Meßtechnik - Teil 1: Grundbegriffe
ST 5	DIN 3960	Begriffe und Bestimmungsgrößen für Stirnräder (Zylinderräder) und Stirnradpaare (Zylinderradpaare) mit Evolventenverzahnung; Zusammenstellung der Gleichungen
ST 6	DIN 3961	Toleranzen für Stirnradverzahnungen
ST 7	DIN 3962 - 1	Toleranzen für Stirnradverzahnungen; Toleranzen für Abweichungen einzelner Bestimmungsgrößen
ST 8	DIN 3963	Toleranzen für Stirnradverzahnungen; Toleranzen für Wälzabweichungen
ST 9	DIN 8580	Fertigungsverfahren - Begriffe, Einteilung
ST 10	DIN 5480 ff.	Keilwellenverbindungen
ST 11	DIN 8583	Umformverfahren
ST12	DIN 332	Zentrierbohrungen
ST 13	VDI 3200	Fließkurven metallischer Werkstoffe; Grundlagen
ST 14	VDI 2617	Messunsichheit, Koordinatenmessen
ST15	VDI 2612	Anforderungen Messgeräte
ST 16	DIN 1101	Durchmesser und Rundheit
ST 17	DIN EN ISO10360	Prüfung für Koordinatenmessgeräte

Politechnika Krakowska

Wydział Mechaniczny

Wewnątrzprocesowy system pomiarowy do kontroli parametrów procesowych oraz wymiarowych produktu

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Streszczenie rozprawy doktorskiej

Opracowane przez

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Kraków, 2016

0. WSTĘP

Ocena jakości komponentów oraz systemów w warunkach przemysłowych wymaga kosztownych oraz czasochłonnych procesów mających na celu kontrolę produkcji tych wyrobów, która przyczynia się do poprawy ich wydajności oraz jakości, z punktu widzenia ich właściwości funkcjonalnych. W tym kontekście, przykładowymi kryteriami, które powinny być oceniane w ramach takiej kontroli są: dopuszczalne obciążenia, prognozowane zużycie oraz trwałość, sprawność mechaniczna czy oddziaływania zakłócające występujące w procesie.

Ponieważ wymagania jakościowe stopniowo się zwiększają, będąc przy okazji nieproporcjonalnie oddziaływane przez okresowe niedobory surowców, procesy wytwarzania muszą spełniać stawiane im wymagania. W celu zapewnienia zgodności z nawet najwęższymi obszarami tolerancji geometrycznej oraz chcąc osiągać coraz większy wzrost efektywności produktów, wytwarzanie musi bazować na zaawansowanych pętlach kontroli jakości połączonych ze sprzężeniem zwrotnym do procesów produkcyjnych, jak dzieje się np. w przypadku produkcji układów napędowych.

Współrzędnościowe maszyny pomiarowe (WMP) są wykorzystywane w systemach zapewniania jakości wybranych cech oraz właściwości części i ich połączeń, a w szczególności do kontroli zautomatyzowanych procesów produkcyjnych. Rozważając proces produkcyjny jako całość, WMP razem z pozostałymi urządzeniami pomiarowymi są w niego wplecione jako swego rodzaju czujniki, w tzw. pętlach kontroli jakości, które umożliwiają stabilizację procesów produkcyjnych. Idealnym rozwiązaniem jest **zastosowanie pętli kontroli jakości wewnątrz procesu produkcyjnego**, umożliwiając w ten sposób jego **regulację w czasie zbliżonym do rzeczywistego**.

Obecnie, w praktyce przemysłowej analiza oceny wydajności jest głównie napędzana przez techniczną i ekonomiczną ocenę technologii współrzędnościowych, nakierunkowanych na konkretne obszary zastosowań. Z obserwacji autora wynika, że w środowiskach zorientowanych na produkcję można wyróżnić dodatkowe funkcje WMP, które mogą stanowić wspomagające narzędzie w poprawieniu konkurencyjności firmy, a co za tym idzie mogą wpłynąć na decyzję o zakupie danego rozwiązania oraz o ew. ekspansji rynkowej przedsiębiorstwa. Są to:

- Poprawiona dokładność oraz precyzja,
- Poprawiona przepustowość całego procesu, a nie tylko przepustowość pomiarowa,
- Niezawodność, wytrzymałość, krótkie przestoje (MTBF, MTTR),
- Integracja procesu pomiarowego w procesie produkcyjnym,
- Tolerowanie oraz ocena nakierunkowane na konkretne zadania pełnione przez części,
- Zwiększona ilość informacji niesionych przez wyniki pomiarów, zależność kształt kontra chropowatość,
- Elastyczny wybór czujników.

Opracowania przedstawione w ramach tej pracy doktorskiej mają na celu sprawdzenie możliwości wprowadzenia nowego podejścia do kontroli jakości, zadając pytanie czy możliwe będzie w przyszłości połączenie kontroli parametrów procesu wytwarzania oraz geometrii produktu, wykonywanej w czasie trwania procesu w precyzyjnej produkcji masowej, i na podstawie tych parametrów wyznaczenie lub oszacowanie parametrów jakościowych wytwarzanego produktu?

1. ANALIZA STANU WIEDZY Z ZAKRESU PORUSZANEGO W PRACY

Wszechstronne zastosowanie nowoczesnych technik pomiarowych stosowanych w warunkach produkcyjnych wyznacza główny obszar zastosowań metrologii współrzędnościowej.

Techniki pomiarowe stosowane w warunkach produkcyjnych: Ze względu na rosnące wymagania odnośnie dokładności wytwarzania, metrologia współrzędnościowa znajduje szeroki obszar zastosowań w systemach produkcyjnych. Obserwując poczynania niektórych przedsiębiorstw ze środowiska produkcyjnego, można zauważyć rosnącą tendencję do integracji WMP w zautomatyzowanych, elastycznych liniach produkcyjnych. Tendencja ta została również zauważona przez ośrodki badawcze, które coraz częściej podejmują w tym kierunku badania oraz angażują się w projekty badawcze zorientowane na zastosowania przemysłowe WMP.

Inne ważne zastosowania metrologii obejmują:

Ocenę jakości: Postępujący wzrost wydajności towarów, rozproszone globalnie procesy produkcyjne oraz wymagania odnośnie zamienności części powodują konieczność stosowania bardzo wąskich zakresów tolerancji. Naciski na redukcję kosztów i zwiększanie konkurencyjności oraz wzmocnione prawodawstwo międzynarodowe związane z odpowiedzialnością za jakość produktów są widoczne w serii norm związanych z Systemami Zarządzania Jakością. Zapewnienie jakość przed, w trakcie oraz po obróbce detalu jest integralną częścią linii produkcyjnych. Mając na uwadze fakt, że tam gdzie to tylko możliwe oraz opłacalne, wykorzystuje się zautomatyzowane systemy wytwarzania, konieczność stosowania systemów kompleksowego zapewniania jakości jest tym bardziej widoczna. Wyzwanie stanowi niedrogi, szybki oraz niezawodny system kontroli procesu wytwarzania umieszczony np. wewnątrz obrabiarki, który powinien zostać oparty o zastosowanie metod metrologii współrzędnościowej.

Sterowanie procesem: Z zastosowaniem kontroli wyrywkowej oraz z uwzględnieniem niepewności realizowanych pomiarów możliwe jest szybkie wykrycie błędów produkcji w czasie trwania procesu wytwarzania. Kluczowym wymaganiem jest znajomość odpowiednich granic błędów wymiaru, kształtu oraz pozycji sprawdzanych obiektów. Bazując na zebranych zestawach parametrów geometrycznych można ustalić wartości parametrów korygujących i zastosować je w rozpatrywanym procesie. Celem takiego postępowania jest polepszenie jakości procesu wytwarzania lub jego optymalizacja. Wynikiem może być ograniczenie ilości produktów niezgodnych lub wymagających poprawek, a co jest z tym związane ograniczenie kosztów produkcji. Z tego względu, szybka, dokładna oraz zintegrowana z procesem produkcyjnym kontrola właściwości geometrycznych wyrobów została przez Autora zidentyfikowana jako główne wymaganie dotyczące zapewnienia efektywności WMP.

Kontrola Wewnątrzprocesowa (In-Process Control): Metrologia wewnątrzprocesowa stanowi najwyższy stopień integracji technik pomiarowych z maszynami produkcyjnymi. Dotyczy ona nie tylko pomiaru parametrów procesu, ale również pomiaru wyrobów w czasie ich wytwarzania. Ten typ pomiarów stanowi duże wyzwanie ponieważ pomiary muszą zostać zrealizowane w czasie taktu produkcyjnego, a ich wyniki powinny być analizowane w sposób niemalże automatyczny. Kolejnym problemem związanym z tego typu podejściem jest zagadnienie analizy niepewności pomiaru. Przy wspomnianych trudnościach, kontrola wewnątrzprocesowa, jeżeli jest stosowana w profesjonalny sposób, umożliwia jednakże najszybszy czas reakcji na rozregulowania jakości procesu.

WMP przyszłości wyłaniająca się z powyższych rozważań (a ogólnie ujmując z rozważań zaprezentowanych w omawianej pracy doktorskiej) jest oparta na modelu procesu wykorzystanym do oceny opłacalności przyszłych generacji WMP, uwzględniającym przewidywane wymagania stawiane WMP w przyszłości oraz możliwe zmiany w jej obecnych funkcjach, a charakteryzuje się wykorzystaniem modułowej struktury różnych technik pomiarowych jako integralnej części kontroli procesu oraz opanowaniem zaawansowanych technik:

- Identyfikacji przyczynowości pomiędzy wymaganiami technicznymi opartymi na kontroli geometrii części, a ekonomiczną efektywnością wdrożonych WMP
- Analizy kosztów i korzyści oraz wrażliwości na podstawie przyszłych wymogów rynku uwzględniając systematyczne oraz niesystematyczne niepewności w kryteriach ewaluacji

Tym sposobem, całkowite koszty procesowe są ciągle redukowane, podczas gdy liczba kontroli geometrycznych w procesie pomiarowym wzrasta. Najważniejsze potencjalne skutki ciągłej poprawy efektywności CMM przedstawiono poniżej:

- Zwiększenie zawartości informacji niesionej przez wyniki pomiarów oraz obszaru zastosowań WMP poprzez wykorzystanie systemów multisensorycznych umożliwiających mierzenie wymiarów, kształtów, struktury oraz właściwości obszarów brzegowych komponentów
- Zmiana sposobu postrzegania geometrycznej kontroli jakości ze zorientowanej tylko na ocenę tolerancji produktów, na definiowanie kryteriów jakościowych dotyczących oceny późniejszych właściwości użytkowych
- **W przyszłości, opracowywanie zamkniętych pętli kontroli jakości wykorzystujących zasady metrologii wewnątrzprocesowej poprzez lepsze zrozumienie zależności przyczynowo-skutkowych w odchyłkach geometrycznych, co z kolei doprowadzi do wewnątrzprocesowej kontroli procesów wytwarzania**

Biorąc pod uwagę przedstawione powyżej stwierdzenia, dalsze dociekania przedstawione w tej pracy dotyczą systemu wykorzystującego założenia metrologii wewnątrzprocesowej opracowanego, w pierwszej kolejności dla specjalnego procesu wytwarzania kół zębatych (WPM120), ale którego obszar zastosowań może również zostać rozszerzony na inne procesy kształtowania poprzez analizę zidentyfikowanych kluczowych parametrów, specyfikacji oraz wymagań odnośnie oczekiwanej niepewności pomiarowej. Te rozważania połączone z analizą użyteczności odpowiednich czujników, takich jak czujniki stykowe, bezstykowe czy czujniki obszaru oraz zintegrowanie ich z systemem wytwarzania stanowią zakres prac zrealizowanych w ramach mojej rozprawy doktorskiej.

2. PLAN ROZPRAWY

<u>Wewnątrzprocesowy system pomiarowy do kontroli parametrów procesowych oraz wymiarowych produktu:</u>

3. CEL I ZAKRES PRACY

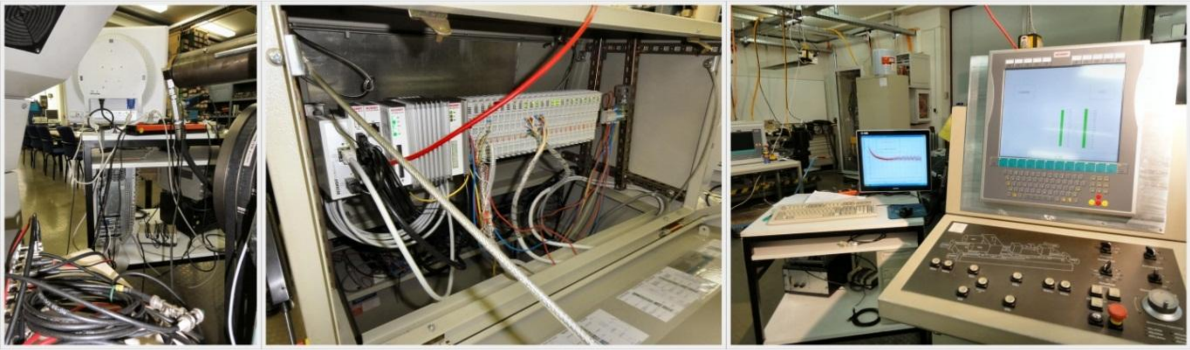
Główne cele realizowane w ramach zakresu pracy zostały podane w rozdziale "2. Plan rozprawy", a w jednym zdaniu mogą zostać opisane jako badania nad wyznaczeniem ram, warunków oraz procedur zastosowania metrologii wewnątrzprocesowej. Zakres pracy doktorskiej uformował się podczas trwających 6 lat badań własnych autora dotyczących specjalnego procesu formowania przekładni zębatych (WPM120). Nowe podejście do zagadnienia kontroli procesu wytwarzania kół zębatych oparte jest na analizie charakterystycznych geometrii wynikających z bezwiórowej obróbki kół zębatych z zastosowaniem narzędzi o uzębieniu wewnętrznym, które może zostać zaadaptowane do wykorzystania w innych procesach obróbki plastycznej, poprzez ocenę inherentnych i kluczowych dla danego procesu specyfikacji i wymagań oraz oczekiwanego rzędu niepewności pomiarowych.

4. TECHNICZNE ASPEKTY PRACY

W ocenie autora metodę wytwarzania kół zębatych wykorzystującą narzędzia walcujące z wewnętrznym uzębieniem można uznać za interesującą. Nawet jeśli otrzymywane w ten sposób produkty nie spełniają standardów przemysłowych, metoda ta posiada pewne unikalne zalety. Wynikają one przede wszystkim z faktu wchodzenia narzędzi w przedmiot obrabiany, co skutkuje większą kontrolą nad przedmiotem w procesie kształtowania. Dodatkowo, w przypadku wytwarzania dużych zębów metoda ta pozwala na uzyskanie jakości nieosiągalnej z zastosowaniem innych metod.

W pierwszej części pracy autor skupił się na wszechstronnej analizie pracy maszyny WPM120. Następnie przystąpiono do instalacji i testów czujników znajdujących się na wyposażeniu Instytutu Obróbki Plastycznej pod kątem ich przydatności w planowanych badaniach. Część czujników musiała zostać wymieniona. Testy przeprowadzono z użyciem standardowego systemu akwizycji danych, przez co należało liczyć się z występowaniem zakłóceń takich jak szumy lub przesłuch. Zwłaszcza w przypadku analogowego pomiaru pozycji może stanowić to poważny problem. Opisane czynności wymagały poświęcenia znacznej ilości czasu.

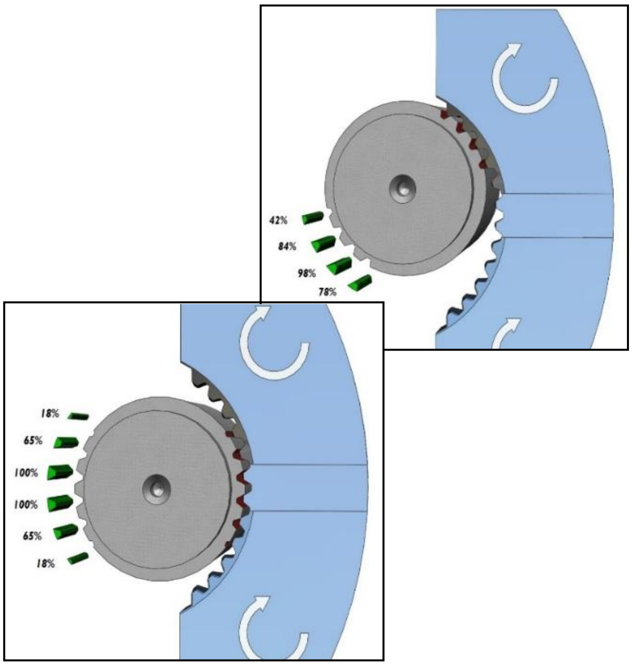
Wejścia cyfrowe, wykorzystywane m.in. przy pomiarze okresu, połączone były z zegarem systemowym, którego taktowanie ustawiono na 1 ms. Tak dobrana wartość wydaje się zasadna ponieważ może być z powodzeniem zastosowana w przypadku analogowych systemów akwizycyjnych oraz zważywszy, że jest to standardowa częstotliwość graniczna dla większości wbudowanych czujników. Dodatkowym argumentem przemawiającym za takim wyregulowaniem zegara jest maksymalna częstotliwość pracy narzędzia, która wynosi 3 cykle na sekundę (3 Hz).



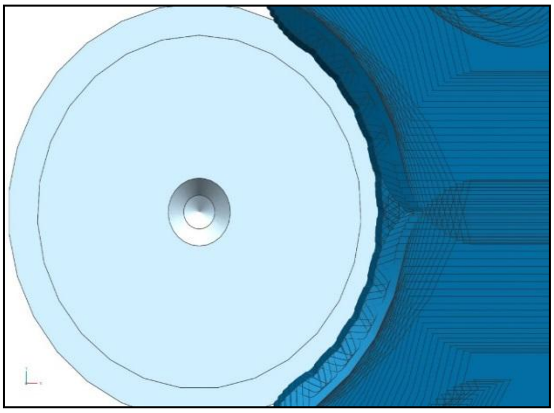
Rysunek 1

Akwizycja danych oraz ich analiza odbywają się z użyciem oprogramowania DIADEM 8.1. Obecnie trwają prace nad opracowaniem nowego systemu akwizycji danych.

Przed przystąpieniem do analizy danych procesowych wykonano analizę teoretyczną metody WPM, z uwzględnieniem kinematyki i charakterystyk procesu. Przy użyciu symulacji przeprowadzonych w środowisku CAD oszacowano istotne parametry wpływające na jakość procesu. Zmienność parametrów geometrycznych została oszacowana z zastosowaniem symulacji czynnego obszaru niestabilnego kształtowania części zębatych w trakcie procesu obróbki.

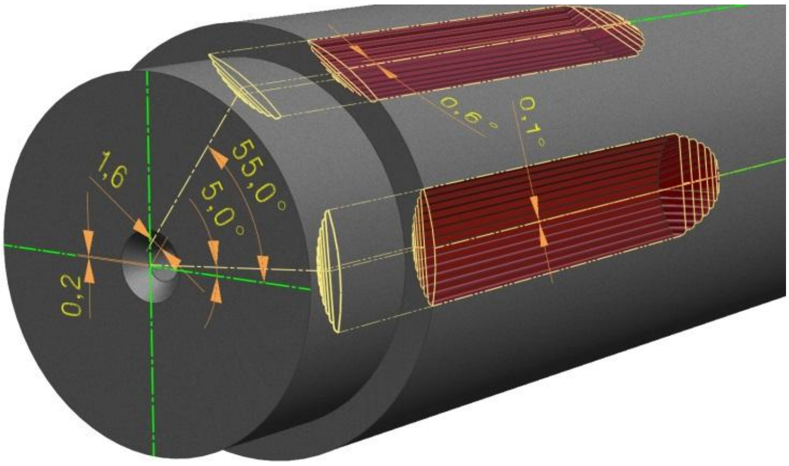


Rysunek 2 Nakładanie się pozycji narzędzi w kolejnych krokach procesu WPM



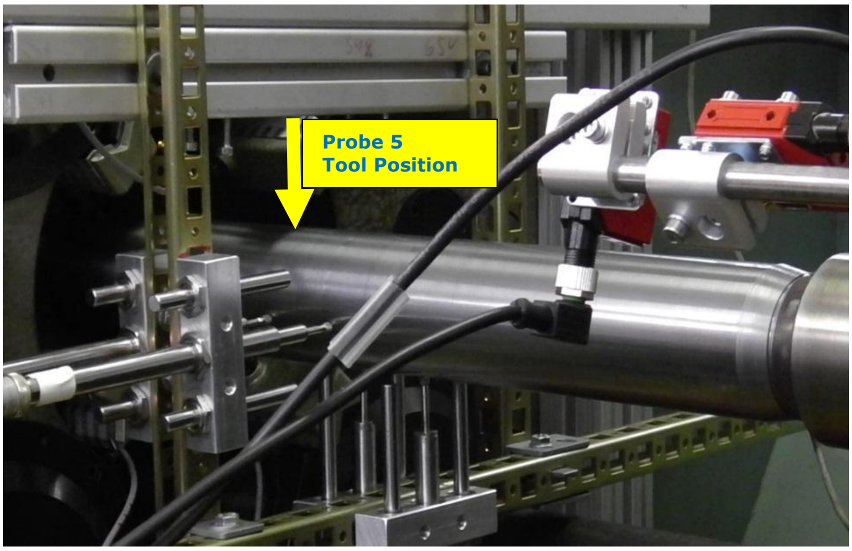
Rysunek 3 Czynny obszar niestabilnego kształtowania

Ocena procesu obróbki uzębienia z użyciem WPM, przyczyniła się do zaobserwowania pewnych zależności geometrycznych, które wpływają na geometrie wytwarzanego zęba.



Rysunek 4 Analiza przekroju poprzecznego

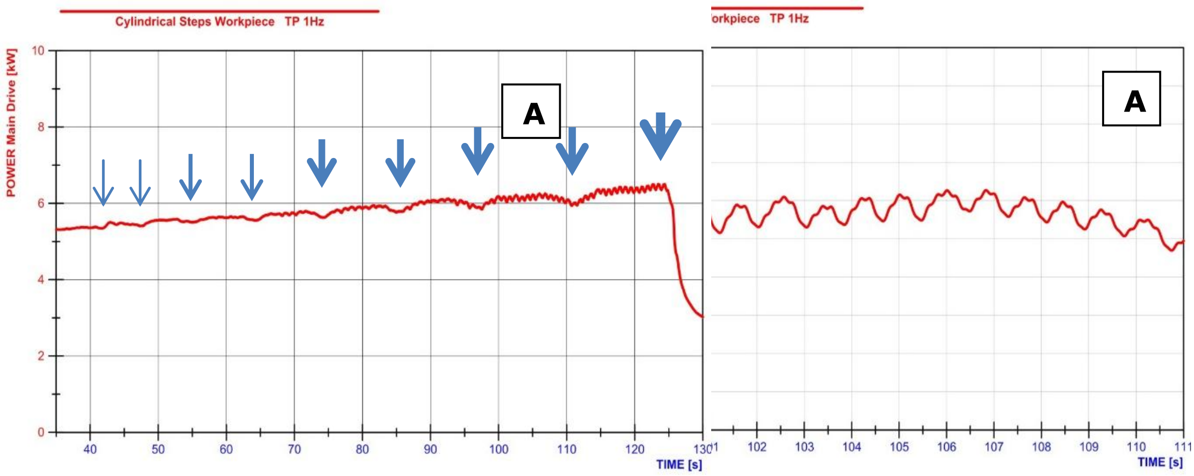
Aby potwierdzić czy proces został poprawnie zasymulowany jak również w celu określenia istotnych parametrów procesu które stanowiłyby podstawę dla “Koncepcji Wewnątrzprocesowej Kontroli Jakości ” przeprowadzono obróbkę dla próbek o kształcie stożkowym oraz stopniowym. Następnie poddano inspekcji geometrie otrzymanych wyrobów.



Rysunek 5 Stanowisko badawcze – Mimośrodowość przedmiotu obrabianego w odniesieniu do pozycji narzędzia

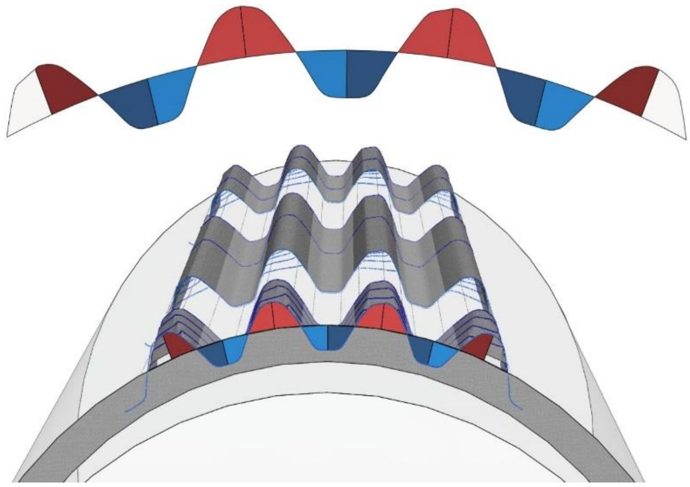
Wyniki eksperymentów opisanych powyżej posłużyły autorowi do wskazania które parametry procesu należy monitorować i zapisywać w celu późniejszego określenia korelacji. Próbki po procesie obróbki zostały zmierzone na maszynie współrzędnościowej zgodnie z wytycznymi normy DIN 3960 traktującej o pomiarach kół zębatych. Dodatkowo w wybranych przekrojach przeprowadzono pomiary z użyciem profilometru.

Wyniki pomiarów zostały poddane analizie pod kątem zgodności z wynikami symulacji, oraz przyczyniły się do lepszego zrozumienia zjawisk zachodzących w trakcie obróbki. Rozkład materiału ustalono poprzez porównanie w środowisku CAD otrzymanego profilu z profilem teoretycznym założonym w fazie projektowej.

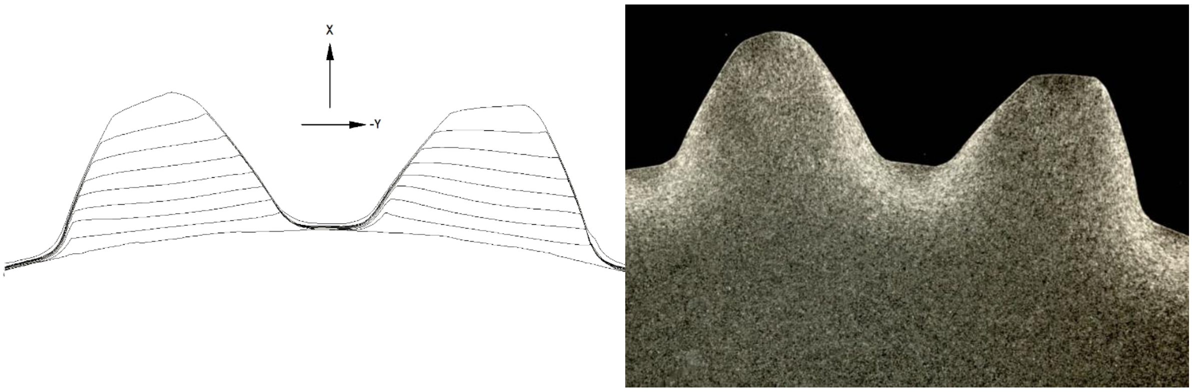


Rysunek 6 Pobór mocy napędu głównego

Ponadto w ramach projektu EVeQT – rządowego projektu badawczego dotyczącego zwiększenia efektywności produkcji kół zębatych – dokonano szeregu analiz metalograficznych, w celu określenia wpływu struktury materiału na zaburzenia w procesie kształtowania zębów.

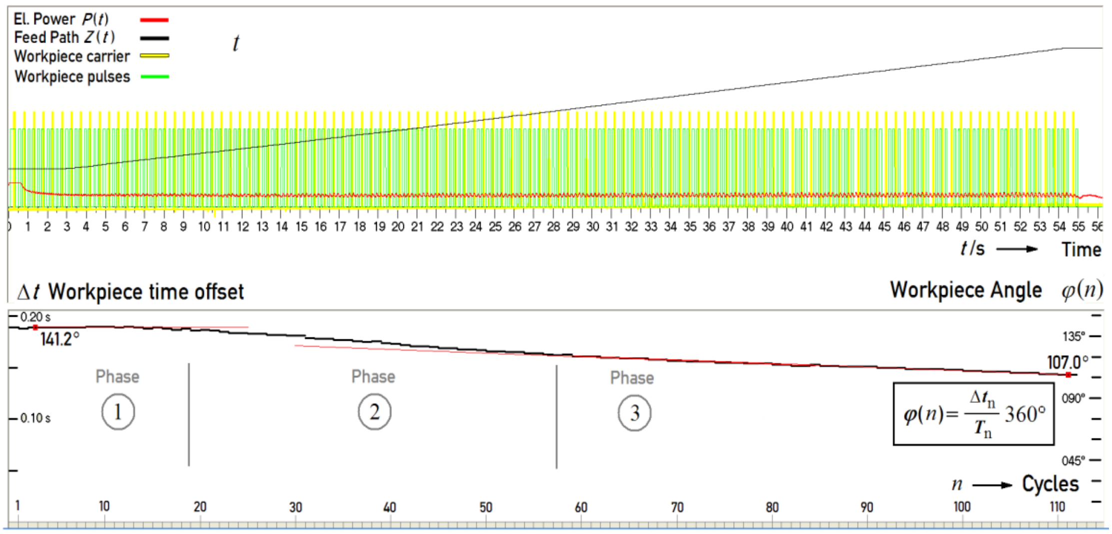


Rysunek 7 Materiał



Rysunek 8 Próbka stożkowa - zaobserwowana asymetria zębów oraz analiza metalograficzna

Przeprowadzano również szczegółową analizę sygnałów zapisanych przez czujniki w trakcie opisanych eksperymentów. Na ich podstawie ustalono charakterystyki specyficzne dla procesu WPM.



Rysunek 9 Analiza sygnałów cyklu walcowania WPM

Ze względu na wiek maszyny WPM120 (ponad 30 lat) należało na tym etapie rozważyć jakie kolejne kroki powinny zostać podjęte w ramach przygotowywania rozprawy doktorskiej. Podstawowe elementy maszyny takie jak silniki, hydraulika, przełączniki czy szafa sterująca są co prawda, z punktu widzenia obecnej technologii, przestarzałe, niemniej maszyna może z powodzeniem stanowić platformę badawczą dla Metrologii Wewnątrzprocesowej. Za równo autor jak również profesorowie Uniwersytetu w Darmstadt uznali modyfikację lub wymianę elementów funkcjonalnych urządzenia za zbyt kosztowną oraz długotrwałą.

Następny etap badań zakładał dogłębną analizę zasady działania narzędzi walcujących z wewnętrznym uzębieniem, określenie w jakim stopniu jakość otrzymywanych zębów zależy od właściwości procesu, a także jakie parametry procesowe należy modyfikować aby wpłynąć na geometrię otrzymywanego wyrobu. W tym celu zaproponowano i opracowano stanowisko badawcze (prototyp urządzenia o działaniu podobnym do WPM), finansowane w ramach badań przemysłowych objętych umową o poufności. Stanowisko powinno spełniać szereg wymogów aby mogło należycie przyczynić się do rozwinięcia koncepcji sformułowanej w ramach rozprawy doktorskiej:

- możliwość szybkiej zmiany ruchów narzędzia, kierunku ruchu obrotowego
- ruchy narzędzi powinny móc być wykonywane niezależnie za równo pod względem ich względnego położenia oraz prędkości względem siebie, ale również pozycji i prędkości bezwzględnej w relacji do przedmiotu obrabianego
- możliwość zmiany mimośrodowości, a zatem stopienia głębokości kształtowania przedmiotu obrabianego przez narzędzie
- możliwość mocowania przedmiotu obrabianego w pozycji obrotowej oraz manipulowania położeniem przedmiotu obrabianego w trakcie procesu z wykorzystaniem ruchów urządzenia, w momencie gdy narzędzie nie jest w stanie kontaktu z przedmiotem obrabianym
- możliwość przesuwania przedmiotu obrabianego w kierunku osiowym posuwu poprzez interakcję narzędzi

Bazując na wynikach badań oraz rezultatach uzyskanych na nowym stanowisku, sformułowano koncepcję podejścia metrologicznego opartego na wykorzystaniu różnorodnych czujników. Tak zdefiniowane podejście może zostać wykorzystane również w przypadku innego rodzaju maszyn.

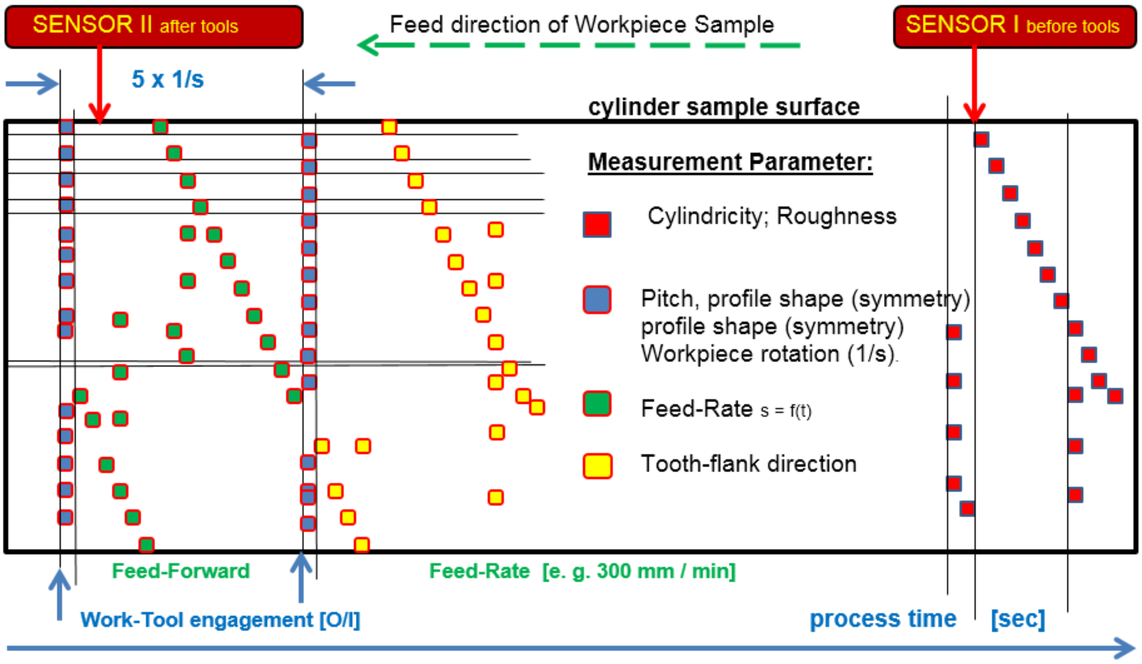
5. WYNIKI, WNIOSKI ORAZ KIERUNKI DALSZYCH BADAŃ

W odniesieniu do planowanego podejścia wykorzystującego założenia metrologii wewnątrzprocesowej, opierając się na charakterystyce procesu, sformułowano następujące wymogi (więcej szczegółów jest objętych umową o poufności):

- możliwość monitorowania w wysokiej rozdzielczości zużycia energii przez układ przeniesienia ruchu narzędzia
- możliwość śledzenia w czasie rzeczywistym pozycji każdej z części (połówek) narzędzia w czterowymiarowej przestrzeni (trzy współrzędne przestrzenne oraz informacja o czasie)
- możliwość śledzenia w czasie rzeczywistym pozycji głównej osi przedmiotu obrabianego w czterowymiarowej przestrzeni (trzy współrzędne przestrzenne oraz informacja o czasie)
- możliwość śledzenia osiowej pozycji przedmiotu obrabianego w kierunku posuwu

- możliwość kontrolowania kształtu zębów w obszarach niefunkcjonalnych w kilku przekrojach dwuwymiarowych względem przestrzeni kształtującej narzędzia
- możliwość przygotowania systemu odniesienia w celu zarządzania opóźnieniem oraz względnym położeniem w przestrzeni trójwymiarowej wykorzystywanych czujników

Na Rys. 10 przestawiono strategię pomiarową opracowaną z uwzględnieniem opisanych wytycznych:



Rysunek 10 Analiza sygnału cyklu walcowania WPM

Dalsze prace nad ulepszeniem systemu metrologii wewnątrz-procesowej w WPM powinny być ukierunkowane na lepsze zintegrowanie systemu z urządzeniem (z uwzględnieniem konstrukcji maszyny) oraz włączenie do systemu narzędzi monitorujących parametry opisujące stan powierzchni np. chropowatości, pęknięć w strukturze materiału lub jego utwardzania.

Jako holistyczny punkt wyjścia dla zastosowania systemów kontroli wewnątrz-procesowej, należy potraktować dane zebrane z czujników bezdotykowych w trakcie kontaktu narzędzia roboczego z przedmiotem obrabianym. Informacja o geometrii otrzymywanego wyrobu, analiza stanu jego powierzchni wraz z danymi na temat utwardzania materiału w wyniku obróbki, przyczynią się do powstania wszechstronnego systemu kontroli jakości dla metod walcujących.

Podsumowując główne rezultaty tej pracy, należy przyjąć co następuje:

1. W próbkach otrzymanych w wyniku walcowania WPM występują charakterystyczne deformacje geometryczne na powierzchni zębów wału,
2. Wspomniane deformacje występują zarówno w części funkcjonalnej jak i nie funkcjonalnej powierzchni zębów oraz, że zachodzi korelacja pomiędzy ich kształtem,
3. Możliwe jest wyznaczenie funkcji korelacji pomiędzy parametrami procesowymi a geometrycznymi otrzymywanych wałów oraz opracowanie systemu kontroli parametrów procesowych umożliwiającego monitorowanie zmian geometrii wytwarzanych części w pętli kontroli jakości on-line,
4. Większość charakterystycznych deformacji występuje na powierzchni walcowanych elementów, toteż możliwy jest ich pomiar z zastosowaniem odpowiednich czujników (bezstykowych), wykonywany w trakcie procesu wytwarzania bezpośrednio na walcarce,

Uwzględniając przytoczone powyżej stwierdzenia, stopień spadku jakości w procesie WPM, i dalej w wytwarzanym elemencie może zostać wyznaczony poprzez analizę przyczynowo-skutkową opartą na kontrolowaniu następujących parametrów:

1. Wstępne niestabilności oraz wady w obrębie układów mechanicznych walcarki lub jej układu napędowego,
2. Mimośrodowość osi walcowanego półfabrykatu spowodowana siłami procesowymi / momentem lub zainicjowana przez kontakt z narzędziem w strefie walcowania,
3. Deformacje i zniekształcenia półfabrykatu spowodowane siłami procesowymi / momentem.

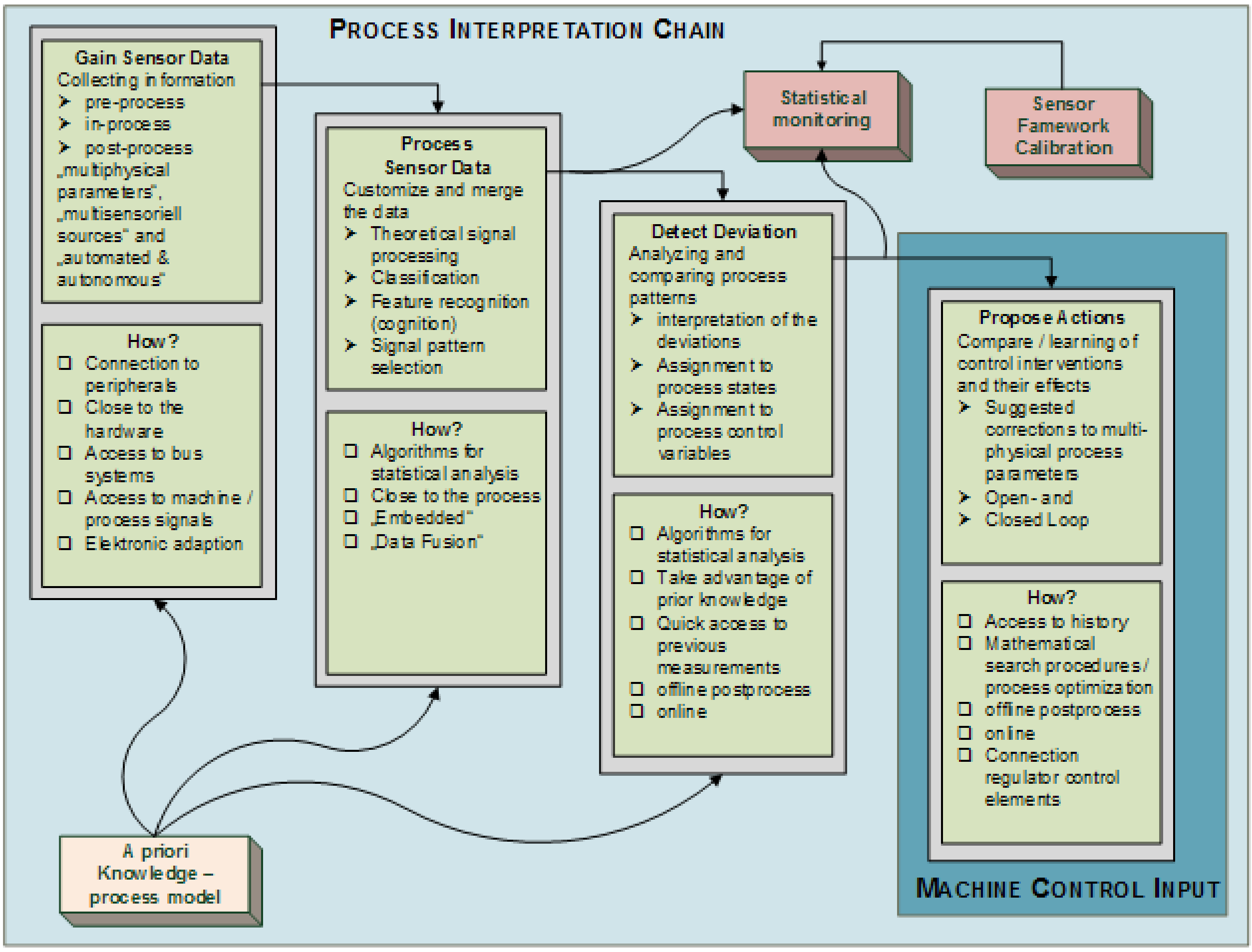
Podstawowymi wyzwaniami dotyczącymi zastosowania nowego podejścia metrologicznego opartego na metrologii wewnątrzprocesowej są:

- wykorzystanie systemu w warunkach produkcyjnych
- integracja systemu sensorów oraz zbieranie danych w czasie rzeczywistym
- wyznaczenie zależności pomiędzy różnorodnymi kombinacjami parametrów (oparte na metodach numerycznych lub eksperymentalnych)
- analiza i konsolidacja danych zebranych z zastosowaniem wielu czujników mierzących różne wielkości fizyczne
- konieczność opracowywania pętli kontroli jakośći pracujących w czasie rzeczywistym oraz analiza danych w oparciu o wyznaczone relacje między parametrami, mająca na celu zapewnienie stabilności procesu

Opierając się na wykonanych pracach można wskazać następujące kroki implementacji nowego podejścia opartego na kontroli wewnątrz-procesowej:

- wyznaczenie parametrów procesu opisujących różne wielkości fizyczne
- pomiar wyrobów otrzymanych z procesu w celu zdefiniowania modelu śladu obróbki oraz
- określenia jakości wyrobu (obszary funkcjonalne i niefunkcjonalne); określenia funkcji korelacji parametrów procesu
- walidacja opracowanej pętli kontroli jakości

Najważniejszym zagadnieniem związanym z implementacją omawianej koncepcji oprócz wymogu stosowania gamy czujników przeznaczonych do pomiaru różnorakich wielkości fizycznych staje się opracowanie specjalnego oprogramowania integrującego wszystkie wymagane informacje oraz zapewniającego kontrolę nad procesem w czasie rzeczywistym. Oprogramowanie powinno pozwalać na analizę w czasie rzeczywistym sygnałów procesowych oraz powstających w procesie odchyleń co umożliwiałoby modyfikację parametrów trwającego procesu, a także jego optymalizację. Dodatkowo, znajomość a priori wartości niektórych parametrów połączona ze statystyczną kontrolą parametrów oraz ich trendów powinna rozszerzyć możliwe zastosowanie tego podejścia w łańcuch interpretacyjny procesu, zaprezentowany schematycznie na rys. 11:



Rysunek 11 Schemat wymagań dotyczących oprogramowania obsługującego łańcuch interpretacyjny procesu

W celu stworzenia możliwości oddziaływania na proces, generowania wzorcowych danych dla zapewnienia spójności pomiarowej wyników oraz zapewnienia niezawodnego wykonania procesu, ostatecznym rozwiązaniem powinno być zbieranie wielowymiarowych parametrów procesu, wykonywanie pomiarów poprodukcyjnych dla próbek testowych w celu zidentyfikowania śladu obróbki; a następnie wykazanie i wyznaczenie zależności pomiędzy jakością części a parametrami procesu w celu walidacji opracowanego nowego podejścia opartego na kontroli wewnątrzprocesowej (IPCA).

Bazując na przeprowadzonych analizach oraz zależnościach odkrytych w ramach pracy doktorskiej, autor zidentyfikował następujące ryzyka związane z wdrażaniem w przyszłości systemów metrologii wewnątrz-procesowej:

- Trudność w opracowaniu metodyki wzorcowania czujników wykorzystywanych w systemach kontroli wewnątrz-procesowej w celu uzyskania wysokiej spójności pomiarowej
- Konieczność opracowania metod szacowania niepewności pomiarów wykonywanych z ich zastosowaniem
- Integracja zaawansowanych systemów metrologicznych w procesach obróbkowych
- Konieczność analizy stabilności pętli kontroli jakości opartych o systemy kontroli wewnątrz-procesowej
- Wymagana identyfikacja i analiza możliwych wpływów zakłócających (wpływy otoczenia, wibracje, itp.) występujących w tego typu systemach.

Przyszły sukces nowego podejścia do systemów kontroli jakości zintegrowanych z systemem wytwarzania jest możliwy do osiągnięcia jedynie gdy aspekty związane z systemem kontroli jakości będą traktowane na równi z zagadnieniami dotyczącymi samego procesu wytwarzania.

6. NOWOŚĆ I ORYGINALNOŚĆ ROZPRAWY DOKTORSKIEJ

Metrologia wewnątrz-procesowa jest niszową metodologią, której znaczenie jednak ciągle wzrasta ze względu na możliwość wykorzystywania jej do sterowania i kontroli zautomatyzowanymi procesami wytwarzania przy użyciu systemu zintegrowanych czujników.

Jeśli chodzi o procesy produkcyjne, takie jak obróbka skrawaniem oraz obróbka plastyczna, szczególnie procesy kształtowania kół zębatych o podwyższonej jakości, metrologia wewnątrz-procesowa nie była dotychczas wykorzystywana w taki sposób w jaki zostanie to przedstawione w opracowywanej pracy doktorskiej.

Biorąc pod uwagę np. wały wielowypustowe (DIN 5480) i wały zębate jako obiekty badań, części te są używane w jednostkach służących do przenoszenia momentu obrotowego z dodatkowym stopniem swobody w kierunku wzdłużnym. Wymagania przemysłu odnośnie jakości i dokładności wymiarowo kształtowych części, wynikające z rozwoju przemysłu samochodowego czy maszynowego stanowią nie lada wyzwanie dla technik wytwarzania kół zębatych. Oczywisty jest również fakt, że stosowanie procesów obróbki plastycznej pozwala zaoszczędzić zasoby materiałowe, a co za tym idzie, zmniejszyć koszty produkcji.

Zadania metrologiczne, które wymagają rozwiązania w przypadku kontroli wewnątrz-procesowej są powodowane głównie przez:

- Ruchy narzędzi skrawających lub formujących
- Stopnie swobody przedmiotu obrabianego podczas skrawania lub obróbki plastycznej
- Duże siły kształtowania / reakcji oraz związane z nimi odkształcenia przedmiotu obrabianego

Te składniki jakości reprezentowane głównie przez parametry systemu lub procesu wpływają na ostateczną dokładność i funkcjonalność detalu, poprzez wprowadzanie systematycznych i / lub przypadkowych błędów geometrycznych. Identyfikacja cech geometrycznych możliwa jest z wykorzystaniem techniki współrzędnościowej. Oprócz geometrii części, również tekstura materiałów i powierzchni, która jest m.in. wskaźnikiem osiągalnej długości funkcjonowania komponentu, jest bardzo podatna na zmiany wspomnianych parametrów.

Obserwując przedstawione wyniki analizy na urządzeniu WPM, błędy geometryczne wytworzonej próbki są głównie zależne od interakcji pomiędzy narzędziami a przedmiotem obrabianym w strefie ich styku, podczas gdy próbki są formowane. Jakiekolwiek rozregulowanie procesu może powodować błędy symetrii mierzonych parametrów kół zębatych, generując nierównomierne rozchodzenie się materiału w czasie procesu.

Szczegółowa analiza **złożonych współzależności** pomiędzy **narzędziami oraz przedmiotem obrabianym w trakcie procesu kształtowania kół zębatych WPM**, z wykorzystaniem narzędzi o uzębieniu wewnętrznym, poprzez akwizycję parametrów procesu w niemal rzeczywistym czasie, **stanowi oryginalność** opisywanej rozprawy doktorskiej. Ze względu na to, mierzone i analizowane parametry procesu muszą zostać podzielone na parametry lub odchyłki geometryczne oraz parametry technologiczne procesu. **Nowością pracy doktorskiej** jest **połączenie różnych technologii monitorowania procesu z zastosowaniem czujników wraz z prognozowaniem jakości procesu** za pomocą ustalenia korelacji otrzymanych wyników.

Rezultaty opisywanej rozprawy doktorskiej będą mogły zostać wykorzystane do:

1. Oceny procesu wytwarzania kół zębatych on-line (w czasie produkcji kół zębatych)
2. Ustalania parametrów stabilności procesu, oraz

3. Charakteryzowania procesów kształtowania na podstawie metod bazujących na wiedzy eksperckiej

Połączenie wielu rodzajów czujników (do pomiaru wymiarów oraz wartości parametrów procesu), w połączeniu z ewaluacją ich wyników w czasie rzeczywistym oraz związaną z tym oceną i prognozowaniem jakości na podstawie odkrytych reguł dotyczących ich współ-zależności w postaci systemu metrologicznego stanowi bardzo unikalny system w zakresie metrologii wewnątrz-procesowej.

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