

# PROCESS CONTROL ORIENTED GEOMETRIC PRODUCT SPECIFICATION AND DATA ANALYSIS

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**Abstract:** There is an increasing desire for an automatable milling process, which could optimize itself based on measurement data and adjust itself to the varying ambient conditions. However, the current ISO-tolerancing system is not suitable for the automated process control. Without the intervention of operators, who interpret the data and determine the correction factors, measurement data cannot be used for the process control. In this paper, a process control oriented geometric product specification, tightly connected with measurement results, is proposed. Experiments on milled cylindrical workpieces are carried out and the results show that, with the specification and its characteristic values, the process errors can be directly identified individually from the measurement results. It also shows the potential for automated process control by correcting these deviations through compensation function of the milling machine.

**Keywords:** Geometric product descriptions, Process control, Coordinate metrology, Measurement strategy

## 1. INTRODUCTION

Today's production is characterized by continuous decrease of product life cycles. Thus, industrial processes have to be controllable faster and have to comply with increasing demands for tolerances. The main task of process control is to guarantee a capable manufacturing process. Previous approaches, such as statistical process control (SPC), evaluate the process through sampling inspections of the products. However, a direct mapping between the process results (quality of the product) and the manufacturing process status (machine setting parameters, machine deviations, etc.) is lacking. The current mapping relies mainly on the knowledge of individual worker. **Figure 1** depicts the conventional quality control loop for manufacturing process [1]. Especially for complex production processes, like milling, a high order of knowledge of the process and its correlations as well as strategies for process control is required.

Recent progresses in metrology and geometric compensation of machine axes such as the multilateration with laser-tracking-interferometer enable traceable measurements of product features by machine integrated

probing systems using the machine coordinate system [2]. The machine integrated measurements can provide data for automated control loops without great loss of time for transportation to a measurement device, far away from the shop floor [3, 4]. To apply the data for automated process control the correlation between measurement results and control variables has to be established [1, 5].

However, current ISO-tolerance based on geometrical dimensioning and tolerancing (GD&T) is not capable of delivering unambiguous information (see section 2) about the direction of deviations [6]. The current tolerancing system is designed primarily to ensure the function of a product but not to control production processes [7]. In this paper, a process control oriented geometric product specification is proposed. With this specification the deviations of the milling process can be identified based on the measurement results, so that the measurement data could be used directly for process control and optimization.

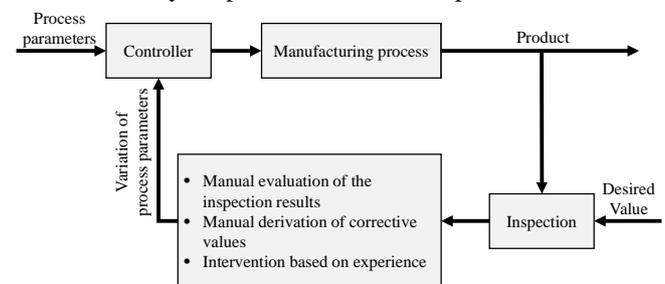


Figure 1: Conventional control loop for manufacturing processes

## 2. LIMITATIONS OF ISO-TOLERANCES FOR PROCESS CONTROL

The function of a product is determined by its geometry and material properties. Within the product development process, allowable geometrical deviations are nowadays described by the tolerancing system, which is determined by ISO-standards, such as ISO 8015, ISO 286 and ISO 1101. The ISO-tolerance bases on a nominal geometry and its allowable variation. The nominal geometry is determined as mathematically ideal elements in the design phase. The allowable variation from the ideal geometry is presented by a volume, in which the geometrical deviations through manufacturing or other reasons are tolerable. The application of ISO-tolerances to design a product or to

inspect the function and quality of workpieces has been approved over decades [7,8,9,10]. However, the use of ISO-tolerances is insufficient in consideration of automated process control, since they cannot describe adequately the actual geometry deviations from the manufacturing process, so that the process errors can hardly be reflected from the inspection results in a direct way.

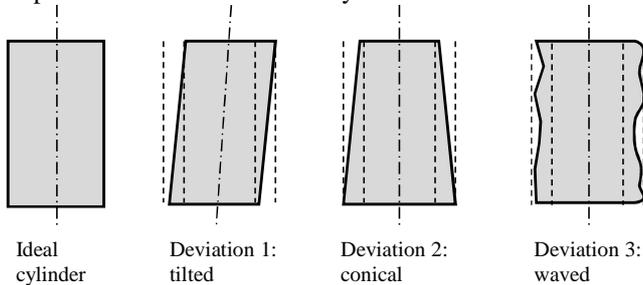


Figure 2: Limitation of ISO-tolerances using the example of cylindrical form

As can be seen from **Figure 2**, the deviations result obviously from different process errors. However, they are characterized by the same cylindrical value according to ISO-tolerance. Thus, the ISO-tolerance is ambiguous to evaluate the product quality and to control the manufacturing processes.

In recent years, other tolerancing methods have been developed to improve the suitability of tolerances in process control, for instance, the vectorial dimensioning and tolerancing (VD&T) [11]. Compared to the conventional GD&T, the VD&T defines a workpiece as a set of the substitute features (plane, pair of planes, cylinder, cone, etc.). Each feature is mathematically represented by a location vector, an orientation unit vector and, when applicable, a tolerated size. In comparison with the ISO-tolerance, the VD&T has the advantages of specifying the functional requirements, especially for clearance fits. In the case of cylindricity, it could be used to distinguish between “conical deviation” and other irregular deviations [12].

### 3 PROCESS ORIENTED GEOMETRIC PRODUCT SPECIFICATION

#### 3.1 DEMANDS AND INFLUENCING FACTORS

Numerous variables in the milling process, like geometric machine errors, temperature fluctuations and the cutting force, influence the geometric product quantities. These influencing factors can be divided whether they are arising during milling or if they already exist at static machine condition. All these influencing factors result in quality defects (deviation from the ideal geometry) of the produced workpieces. To implement automated process control loops, the geometric deviations have to be described unambiguously with their dimension, position and orientation. Besides, the indication of certain process deviations in an early stage as well as the method of determining appropriate control variable to correct the deviations are essential.

On milling processes there are only few variables which can be influenced in an automated control loop: the position and orientation of the tool and the workpiece, the tool state, compensation of the machine axes, the feed rate and the cutting speed.

#### 3.2 CONCEPT OF GEOMETRIC PRODUCT SPECIFICATION

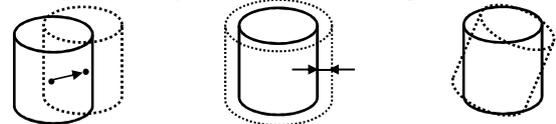
The Concept of the process control oriented geometric product specification consists of two principal parts, an order-based descriptive system and indicators of specific process errors. The former describes the general deviations of produced workpiece; the latter indicates certain process errors from measurement results.

Deviations between the nominal geometry and the manufactured geometry can be described by a classification system with different orders. The German standard DIN 4760 divides the shape deviation into 6 orders: form deviations (1), waviness (2) and roughness (3-6). On this basis, an order-based system is developed to describe the geometric deviations of workpieces, which is the basis of the developed process control oriented geometric product specification. In **Figure 3**, the geometric specification is illustrated on a cylindrical element as an example.

Position deviations include the -1, 0 and 1 orders of deviations. Order -1 indicates positioning deviations of the center of gravity of the manufacturing feature in relation to the reference system of the workpiece. The geometric deviations of several elements (distance between two planes) as well as dimensional deviations of a single element (for instance the diameters of a bore) are described by order 0. The positional deviations of an element, such as tilt of a plane or the axis of a bore, are defined by order 1. Low frequency form deviations like convex or concave curvature of surfaces or deviations of cylindrical shapes are described by order 2. Higher orders deviations include waviness, roughness and local defects on the surface like chatter marks.

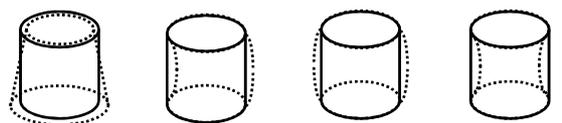
#### Position deviations

**-1 order:** center of gravity      **0 order:** geometrical deviations      **1 order:** positional deviations



#### Form deviations (2 order):

conical deviation      banana-shaped deviation      barrel-shaped deviation      pincushion-shaped deviation



#### Surface deviations (3, 4 and higher order):

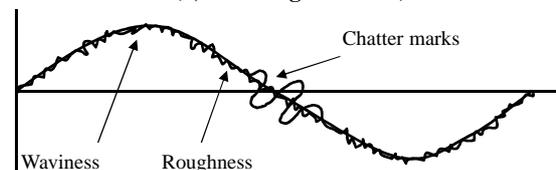


Figure 3: Geometric deviations of cylindrical element

Deviations on the orders can be caused by different process errors, for example:

- (order -1) mounting error of the workpieces,
- (order 0) wrong tool diameter,
- (order 1) positioning error, perpendicularity deviation of z-axis
- (order 2) deviation of machine axes, inappropriate tool length,
- (higher orders), inappropriate feed rate, temporary vibrations.

Characteristic values are developed for each order. For instance, the following characteristic values are defined to describe the cylindrical element:

- Mean diameter of the bore
- Position of the smallest diameter
- Position of the biggest diameter
- Variation of the diameter along the cylinder axis
- Position of cylinder axis at its intersection point with the neighboring plane
- Projection of the cylinder axis
- Angle between two opposite surface lines
- Order of the dominating waves of low frequency in the Fourier spectrum (circle profiles, surface lines along the axis)
- Roughness values

It should be emphasized that all these characteristic values are closely related to the measurement strategy. Dependent on the cylindricity of the bore, the diameter can vary along the bore axis. If the bore has a constant diameter along its axis, its deviation to the nominal diameter can be corrected by the tool diameter. Additional deviations like conical cylindricity are caused by e.g. an angular deviation between tool axis and rotary spindle axis. To get this kind of information, errors must be determined by a set of characteristic values. For example, to evaluate the position of the axis, other deviations like the tilt of the axis and the position and form of the neighboring plane have to be considered. If the machine's z-axis is tilted, in view of metrology, the position of cylinder axis is only detectable by determining the intersecting point of the cylinder axis with the neighboring plane. If this plane shows a significant angular deviation, too, the intersecting point can deviate. To avoid this, the nominal position and orientation according to the reference system should be used to determine the intersecting point.

Furthermore, the indicators are developed within the process control oriented geometric product specification, since certain geometrical deviations are caused by specific process errors. Thus, indicators can be developed to indicate potential process errors from the measurement results in an early stage. Here are some examples:

- The same size but different sign of interior and exterior diameters indicate the use of wrong tool or the false setting of tool diameter in NC program.
- The Amplitude of second order component in Fourier spectrum indicates the elliptic deviation of bores and as the cause the perpendicularity deviation of x- and y-axis.

- The tilt of bore axis with parallel surface lines indicates the deviation of clamping of workpiece or the bias of z-axis.
- The one sided inclined side lines of cylinder indicates the form deviation of z-axis.

#### 4. VALIDATION

For the validation of developed specification, a set of experiments was performed to check whether geometric deviations are identifiable unambiguously and can be traced to control variables. Therefore, workpieces were manufactured on milling machine with forced process errors, such as using tool with wrong diameter, inappropriate feed rate and cutting speed, over compensated machine axes, positional errors of workpieces, and so on. These process errors are exerted separately, that means only one error is added each time. Then the manufactured workpieces are measured and evaluated to determine whether the process errors can be identified by the developed geometric product specification. Results show that the process errors, which are not identifiable by ISO-tolerance, can be indicated. On the basis of a few specific examples, it shall be illustrated further.

As the first example, the process with perpendicularity deviation of machine coordinates system is shown. With the overcompensation of the milling machine, a very slight perpendicularity deviation of 50  $\mu\text{rad}$  is exerted on the machine's x- and y-axis. Then, the workpieces manufactured with perpendicularity deviation (with p.d.) and without perpendicularity deviation (without p.d.) are measured and compared. As it can be seen from **Figure 4**, a geometric deviation (oval) is simulated and validated with measurement results for the perpendicularity deviation.

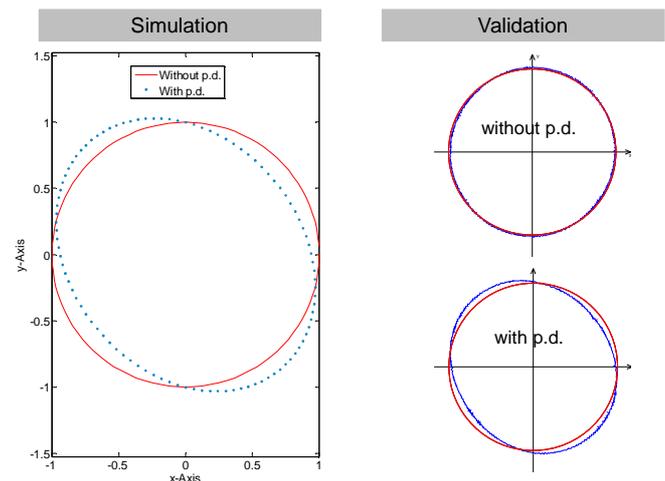


Figure 4: Simulation and validation of perpendicularity deviation

If the perpendicularity deviation between x- and y-axis is slight enough ( $\leq 25 \mu\text{rad}$ ) and occurs with other process errors, the ISO-tolerance is not capable of indicating this error. The diameters of the cylinder are identical and roundness values are almost the same (0.0086 for without

p.d. and 0.0089 for with p.d.), since the perpendicularity deviation is relatively small (top half of **Figure 5**).

The analysis of the perpendicularity deviation with Fourier-analysis provides interesting result (lower half of **Figure 5**). Especially the amplitude of second order (2 waves per revolution) is increasing significantly due to perpendicularity deviation. This offers an unambiguous way of identifying tiny oval distortions between the two machine axes. So far, however, it's still not possible to derive correction factors from the second order frequency because the intensity strongly relies on the amount of measured points and the superposition with other waves of different frequencies.

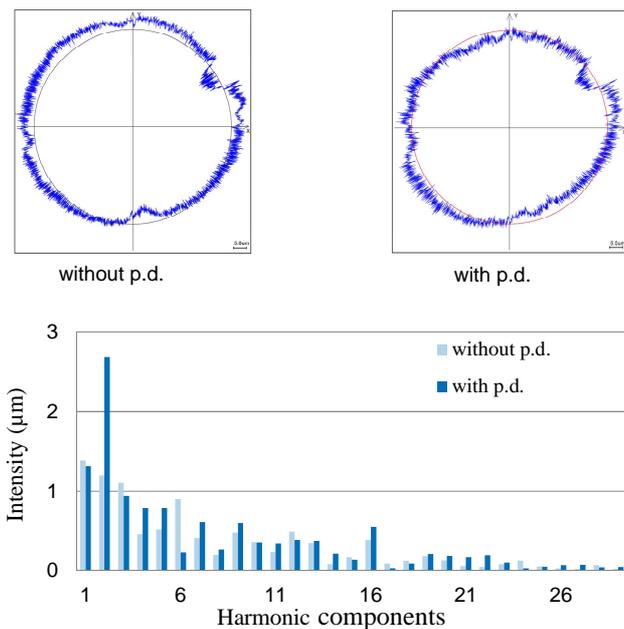


Figure 5: Results with Fourier-analysis

In the second example, the machine's z-axis has a form deviation along the x-direction (**Figure 6**). This error was generated by overcompensation of machine axes. Measurement data of the experiments on a milling machine validate the simulation results. Through the comparison of difference of the form deviations towards and backwards on the workpiece (material side), this process error can be identified.

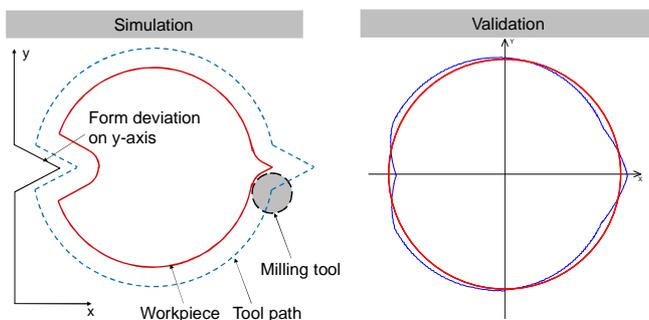


Figure 6: Simulation and validation of form deviation on y-axis along x-direction

Besides different machine's axes errors, other errors, such as wrong setting of milling tools, inappropriate clamping und positioning of workpieces, etc. were also simulated and validated with the developed geometric product specification. Experimental results show that the process errors can be directly identified from the measurement results using the developed geometric product specification and its characteristic values.

## 5. CONCLUSION

Nowadays an automated process control for milling is not possible without manually intervention, since the current ISO-tolerancing system is not capable of identifying the process errors from the measurement results. In this paper, a process control oriented geometric product specification is presented. It described the geometric deviations of workpieces with characteristic values of different orders. Experiments, in which several process errors are exerted separately, were conducted. Results show that process errors, which are not identifiable in ISO-tolerance, can be indicated with developed geometric product specification individually. Moreover, based on measured geometric deviations of workpieces, this knowledge is further used to correct the process with the compensation function of the machine using VCS (Volumetric Compensation System).

So far the experiments were carried out for single process error each time. In the next stage more experiments, which have several process errors simultaneously, will be designed and conducted to analyze the interaction of different process errors for the automated process control. Furthermore, the correlation between the measurement data and adjustment of process parameters will be built, so that the geometric product specification can be used directly for the manufacturing process control. It is expected that some combinations of errors may cause same or similar geometric deviations, so that it will be difficult to distinguish these error unambiguously. However, the objective of an automated process control can be still achieved, since the developed solution focuses on the correction of caused deviations through the compensation function of the machine, but not on the identification of every process error.

## 6. ACKNOWLEDGMENT

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