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A model- and simulation-based approach for tolerancing and verifying the functional capability of micro/nano-structured workpieces ☆

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The evaluation of functional features of manufactured workpieces is based on GO- and NO-GO-test results, which are obtained by comparing measured geometric characteristics with nominal dimensions and tolerances specified by the designer. These geometrical specifications are based on a tolerancing system, which was originally defined for the function *mating capability*. Against the background of upcoming lots of other new functions (like reduction of flow resistance, light absorption, reduction of friction, diffraction of light, self-cleaning or mass transmission) are to be realized with our products – particularly by micro- and nano scaled features. If the verification process will deliver the prediction of the achievable degree of functionality, the usability of a part can be assessed more accurately and in consequence quality and economics can be improved. So, a new principle for tolerancing and verifying turns out to be necessary. In this paper the fundamental deficit of the actual tolerancing and specification systems GPS and ASME Y14.5 is derived and the path for enlarging the system by preposing a functional model is shown. To verify the functional capability of the workpieces an approach based on simulations done with the parameterized mathematical–physical model of the function is suggested. Advantages of this approach will be discussed and demonstrated by examples with microstructured inking rolls, crankshafts and injection valves.

1. Introduction

The required function of a mechanical workpiece for serial production is “translated” by the designer into geometric specifications (quantitative dimensions and tolerances), which are for mechanical engineering mostly in accordance with the international tolerancing concept *Geometrical Product Specifications and Verification* (GPS) according to ISO 8015:2011 [1] or from the United States according to *Geometrical Dimensioning and Tolerancing* (GD&T) ASME Y14.5-2009 [2]. Using GPS, which was built up over several decades [3], geometric relationships can be considered as form, orientation, location and run-out tolerances. Tolerances according to the GPS principles and rules ISO 8015:2011 [1] have managed to formulate functions in a mathematical context with the aim to ensure the functional capability of a workpiece [4]. Thus, the functional capability *mating* of workpieces with deviations in form, orientation, location and run-out can be predicted, if a suitable measurement and evaluation strategy are considered [5].

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The increased demands and increased complexity of workpieces are met with ever lower, mostly linearly scaled-down, geometric tolerances, which are reduced every 50 years by a factor of 10 [6]. Currently geometrical tolerances have reached a level in the manufacturing process, where deviations of a few microns – which means the surface texture – are crucial for the decision about GO or NO-GO workpieces [7].

This "*law of reduction*" is neither useful nor economical in the long run. The technical committee ISO/TC 213 has responded to this situation, so that particular fundamental GPS standards are currently in a major process of change [8]. However, actual tolerancing systems almost describe the function *mating capability* (or *interchange ability* or *assemblability*) [9] – but *mating capability* is nowadays not the only function of workpieces. With the upcoming micro/nano-technologies other functional requirements like *reduction of flow resistance* (riblet structures [10]) *friction control* (cell structures [11]), *self cleaning* (hydrophobic surfaces [12]), *light absorption* (anti-reflection surfaces [13]), *diffraction of light* (micro lens arrays [14,15]), *mass transmission* (tri-helical structures [16,17]) and others ([18,19]) get dominating. So new add-ons and new modifications are permanently invented to be implemented into the system. And the system is of permanently increasing complexity. One can see the limit is reached, at which conventional mating oriented tolerancing concepts are sufficient for defining all geometric features adequately to new function-based requirements. In consequence the GPS- or ASME-based verification of the functionality of a workpiece is getting more and more time consuming and the results are of high uncertainty [20]. In consequence surface structures are evaluated faulty based on inappropriate geometric specifications in the verification process or based on unskilled or not enough well trained people who are often overburdened with the complexity of the tolerancing system.

Furthermore, functional microstructures have found their way from laboratory experiments into series production now [21–26], although GPS- or ASME-based tolerancing systems do not offer the potential for the verification of their functional capability. This underpins the need to analyse fundamental deficits of all steps of production (from engineering design via manufacturing to verification) and to provide a holistic approach assessing functional properties of workpieces regarding the entire production process chain. Without reduction of generality we look to GPS as one example and demonstrate the new approach referring to this system.

2. Deficits of the actual GPS-based process chain

In the fundamental GPS standard ISO 8015:2011 following basic assumptions for the reading of specifications from drawings are defined:

- Functional limitations: Functional limits are based on a complete experimental and/or theoretical investigation and known without any uncertainties.
- Tolerance limits: Tolerance limits correspond to the functional limits.
- Functional level of the workpiece: Within the tolerance limits a manufactured part works to 100%, outside to 0% (non-functional).

Specifications are concrete definitions, which must comply with a contractor. They are reviewed at delivery and approved by the client. The above assumptions are of fundamental importance for the specification and for subsequent manufacturing and verification. However, these assumptions apply in only very few cases in practice. For example, tolerance limits are closer defined for the purposes of safety thinking (distrust tolerance limits) than the functional limits. The restriction of tolerances on the part of the designer can cause to considerable difficulties and high process costs, especially when features are also associated with process capability requirements [27]. According to ISO 8015:2011 a specification of a workpiece is only complete, if all intended functions of the workpiece are described and controlled by GPS specifications. Hence the focus of specification is on the functionality and not on the manufacturability and measurability. However, in ISO 8015:2011 is also noted that a complete specification can be achieved only in a few cases, because many functions can described or controlled imperfectly or not at all with GPS specifications. This is a contradiction to the above assumptions.

Products have become more complex in terms of functional requirements and the related tolerances. GPS, as the *language of the engineer*, has become more precise concerning the specification of the function *mating capability*. However, for historical reasons, *mating capability* is the only function that is actually covered by the GPS system [28]. Thus, often *translation errors* occur, if other functional requirements are described and verified according to GPS. For example, the specified envelope condition of a shaft-hub joint is verified by minimum circumscribed and maximum inscribed regression algorithms [29]. This is suitable for the simple static case *mating*. But if also kinematic conditions have to be considered – as it is at the function *rolling* – first problems arise. The smoothness of a cylinder is toleranced by the operator roundness. As well known, the roundness of a cylindrical workpiece with Reuleaux polygonal form deviations should be measured at least with a 3-point measurement or a n-point form tester to determine the form deviation precisely. However, if the function of the cylinder (or sphere) is rolling between two plates or rings (like it is at rolling bearings), a 2-point measurement would be function-oriented (Fig. 1). Otherwise high deviations in roundness would be measured, although the workpiece fulfils its function. In this case the specified and measured values describe not everything. Also the type of form deviation has to be taken into account for this workpiece-function as described in [30].

Although the designer defined – based on a basic idea of a function – target characteristics of a workpiece, the actual functional properties of a workpiece are produced during the manufacturing process. The resulting deviations from the desired properties are especially in micro- and nanostructures of high and unpredictable complexity (extent of form deviations, types of form deviations, changing material properties, etc.). Nevertheless, according to