

Taking Dimensional Metrology to the Next Level

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Abstract

Traditionally, dimensional metrology has been viewed as just another area of measurement science and dimensional inspection has been considered a non-value-added quality control activity in the manufacturing community. Much effort has been focused on calibrating dimensional measurement equipment, yet very little effort has been expended on developing sound measurement processes that provide information that is useful beyond the simple acceptance and rejection of parts.

To take dimensional metrology to the next level and to unlock some of the enormous potential for savings for manufacturing industry that such a paradigm shift holds, it is necessary to see dimensional metrology not just as an area of measurement science, but as the information exchange format for geometrical properties of parts.

Once viewed in this light, several changes to the way dimensional metrology is applied become logical. Firstly, dimensional metrology shall primarily be applied earlier in the product development cycle than is the case today. This is to ensure that the specification that is developed properly reflects the true functional requirements. Secondly, more attention shall be paid to the measurement operator (the ordered set of operations) that defines the measurement and the changes in measured values that occur when the measurement operator (which is still not the guy that makes the measurement) is changed. Thirdly, product specifications shall be more precise by defining requirements in terms of well defined specification operators.

1. Introduction

The dimensional metrology field is made up of three sub-disciplines: Linear metrology is concerned with one-dimensional length measurements, angular metrology is concerned with the measurement of angles and geometrical metrology is concerned with multi-dimensional measurements, e.g. coordinates in 3-dimensional space.

Further, there are two basic approaches to dimensional metrology: Hard dimensional metrology, which is based on e.g. plug and ring gages for the evaluation of fits and geometrical measurements using surface plates and indicators and soft dimensional metrology which is based on computerized evaluation of sets of data point coordinates obtained by tactile, optical or other means using instruments such as coordinate measuring machines, form testers and surface texture measuring instruments.

Length metrology, angular metrology and hard metrology are mature areas with no conceptual developments in several decades, whereas geometrical metrology and soft dimensional metrology are rapidly developing areas. In the remainder of this paper, the former will be referred to as classical dimensional metrology and the latter as modern dimensional metrology.

2. Assumptions in Dimensional Metrology

Classical dimensional metrology is generally based on the unspoken assumption that the geometry and surface finish of the measurement object is so good that it adds only a negligible contribution to the measured value, compared to the tolerances being considered. As tolerances are reduced to the point where this assumption is no longer valid, considerable differences between results obtained using different methods will be evident, see figure 1.

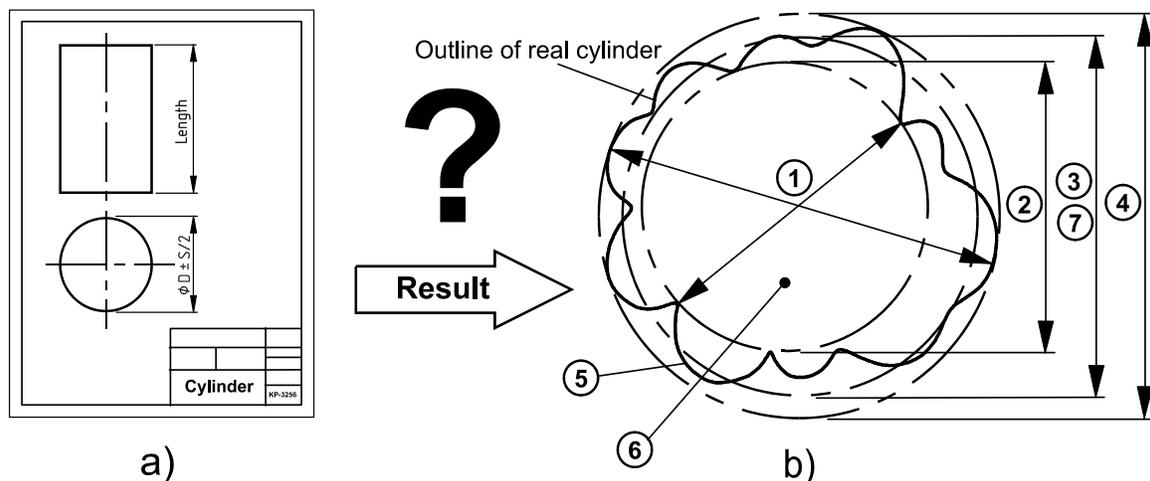


Figure 1: Variation in diameters measured using different methods.

In modern metrology choices have to be made both in sampling strategy and in what mathematical algorithms to apply to the collected data to get to the measured value. Because it is easy to apply different algorithms to the same data set, it is easy to detect that the different algorithms lead to different measured values. Therefore it is easier to realize that these choices are significant and that different part functions and geometry deviations require different algorithms for the measurement to provide relevant answers.

To bridge the gap between classical and modern dimensional metrology and to make it possible to compare dimensional metrology data obtained using different measurement processes, it will be necessary to develop unified interpretations such that a requirement to the geometry of a part will always mean the same to all the stakeholders and dimensional measurement results can always be sufficiently characterized for any qualified dimensional metrology laboratory to reproduce the result by reporting a known set of significant influence factors describing the measurement conditions in sufficient detail.

The vast majority of dimensional metrology applied in manufacturing industry is classical metrology. As mentioned, this creates problems as tolerances are reduced. On the other hand, modern metrology is far from mature. Although sophisticated equipment such as coordinate measuring machines, form testers and surface finish measuring instruments exist, there is only limited standardization for sampling strategies and evaluation algorithms and few users of these types of equipment have the necessary background to use them to their full potential. Most user training is limited to operating the software and does not include discussions of how to make metrologically sound measurements.

Taking dimensional metrology to the next level will require a shift from classical dimensional metrology to modern dimensional metrology as well as a significantly more mature set of standards for how to characterize the measurement process used to obtain dimensional metrology data, e.g. what sampling strategy was used, what filtering was applied and what measurands definition was applied. It will also require more know-how on the user level of the metrology involved in operating modern measurement equipment.

3. Controlling Function

It is a basic tenet of industrial manufacturing that one can control the functional properties of mechanical parts by controlling the geometry as well as the material properties of the parts. If one also accepts that the core of any language for exchanging information about part geometry is dimensional metrology data, one arrives at the conclusion that dimensional metrology and requirements to part geometry are only means to ensure part function.

While this is also true for other areas of metrology, dimensional metrology is distinct in two areas: The transfer functions that translate between geometry and function, e.g. the relationship between bearing geometry and bearing noise and lifetime, are vastly more diverse and complex than the similar functions encountered in other areas of metrology and the minute details of the definition of a dimensional measurand have a significantly larger influence on the measured value than in other areas of metrology.

There are 3 factors that determine how well part functionality can be ensured with dimensional metrology data, see ISO/TS 17450-2:

1. The correlation uncertainty, which quantifies how well a dimensional measurand definition correlates with the part function.
2. The specification uncertainty which quantifies how ambiguous the measurand definition is.
3. The measuring uncertainty, which quantifies how well the measurand has been measured.

Until now the first two have largely been ignored and only within the last decade has some consideration been paid to the measuring uncertainty. However, it is only when all three are deliberately considered in the specification development process that the enormous potential for savings in manufacturing industry can be realized.

It is interesting to note that the relative importance of the three uncertainties change with the relationship between dimensional, form and surface texture deviations in the manufactured parts. When form errors and surface texture are insignificant compared to the dimensional tolerances, only the measuring uncertainty matters. But when form errors and surface texture are significant, the correlation uncertainty and the specification uncertainty become more significant, often to the point of completely overshadowing the measuring uncertainty.

Taking dimensional metrology to the next level will require a better understanding of the correlation between the function of a part and its geometrical attributes. It will also require a language that allows for the expression of more precise and unambiguous specifications that are truly correlated to part function. Finally, it will require engineers at all points throughout the product development cycle to consider the ambiguities in measurement data definitions (descriptions of the measurand) and specifications and manage these ambiguities to an appropriate level to ensure product functionality.

4. The Rate of Change in Manufacturing Capabilities

The relative magnitude of dimensional, form and texture capabilities in manufacturing are converging, i.e. the finest dimensional tolerances are no longer much larger than the amplitudes found in form, such as roundness, cylindricity, and flatness and surface texture, such as roughness and waviness. Therefore there is an urgent need to improve the possibilities for describing and specifying measurands for dimensions and form that are unambiguous in the presence of significant form and surface texture, i.e. have specifications with low specification uncertainty.

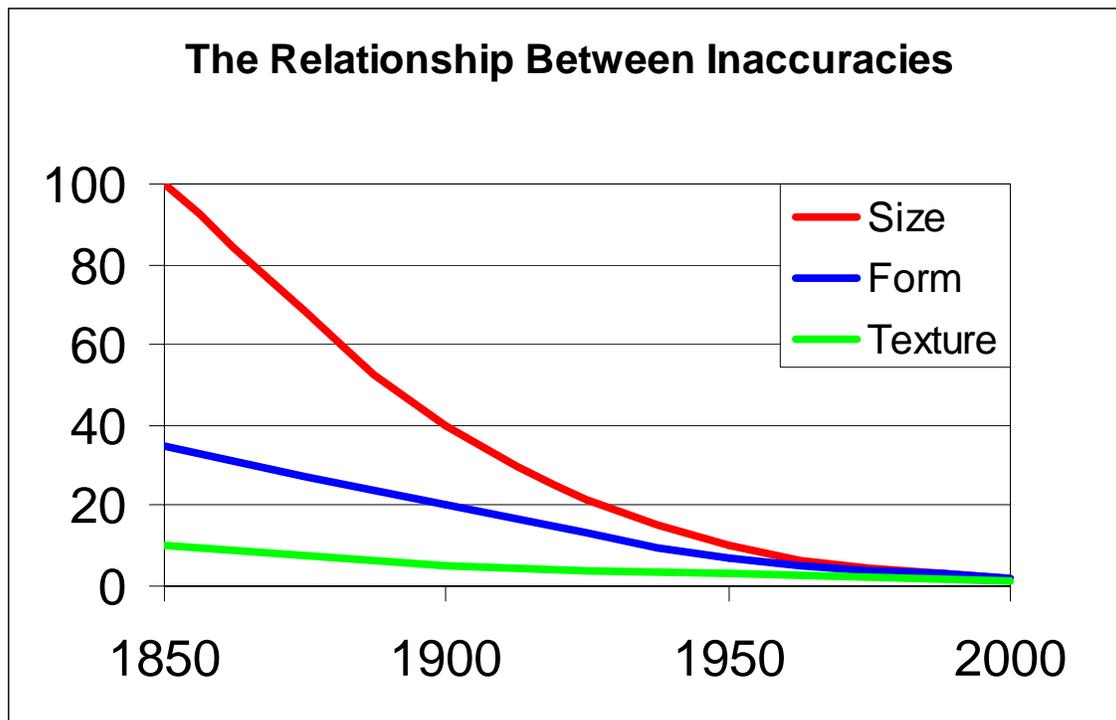


Figure 2: The rate of change in manufacturing capabilities.

Early manufacturing could be accomplished using only dimensional tolerancing, as form error and surface texture were usually inconsequential. By the time of World War II, dimensional tolerances had shrunk to a level where the form errors of typical manufacturing processes became significant. Geometrical dimensioning and tolerancing can be viewed as an answer to this problem, allowing the designer to communicate which form errors are acceptable and which are not.

We are now reaching the point where dimensional tolerances and form tolerances have shrunk to a level where surface texture is significant. This is the point where traditional, zone-based tolerancing becomes inadequate. It is impossible for a designer using the current system – be it the ISO 1101 or the ANSI/ASME Y14.5 dialect – to express to which extent surface texture should be considered or ignored in geometrical tolerances.

Similarly, it is impossible to express what range of “wavelengths” should be considered for form, orientation and location tolerances.

In other words, it is impossible to control the correlation uncertainty with the standardized specification language available to designers today.

Taking dimensional metrology to the next level will require a richer specification language that allows designers to unambiguously specify e.g. the wavelength domain and association criterion for requirements.

5. *The Right Measurement at the Right Time*

The value of metrology data is determined by the consequences of the decisions the data support. Correspondingly, the quality of a decision cannot be any better than the data it is based upon.

Therefore, the most important change in the way dimensional metrology is applied today is to move advanced geometrical metrology upstream in the product development cycle, where it can support the most significant decisions, i.e. the determination of the specifications used to ensure correct functionality and the design of the processes used to manufacture the parts, rather than downstream where it can only support process control of processes that may or may not be inherently capable and simple pass or fail decisions against a specification that may or may not be functionally relevant.

It is well recognized that decisions made early in the product development cycle has much more far-reaching consequences for the functionality, manufacturing cost, and quality of a product, than the decisions made later in the cycle. Yet, the decisions made early in the cycle are usually made with very little data and often this data is of dubious quality. The typical example is the design engineer who uses the un-calibrated caliper he keeps in his desk drawer to make measurements on prototype parts to determine critical tolerances.

The least of the problems in this scenario is that the caliper is not calibrated. A much more significant problem may be that the caliper is not a very accurate instrument. The fact that he does not document how he made the measurement may be even more significant and most significant of all is that he will have missed any form and surface texture information that may have influence the function of the prototype parts.

Taking dimensional metrology to the next level will require making detailed and well documented measurements of prototype parts early in the product development cycle to gather the necessary information to be able to develop specifications that are truly describing the functional requirements, i.e. have low correlation uncertainty and are unique, even in the presence of the expected form error and surface texture, i.e. have low specification uncertainty.

6. Conclusion

Substantial savings are available for manufacturing industry. To realize these savings, it is necessary to start thinking of dimensional metrology data as the information exchange format for geometrical properties of parts.

It is necessary improve the documentation of measurements, e.g. in terms of wavelength domain and association criterion for dimensional metrology data to effectively serve as this information exchange format. It will also be necessary to have a standardized language to express requirements precisely and unambiguously in the same terms as the metrology data, so the information gathered during the prototype phase can be accurately communicated in the product documentation.

Finally, and most importantly, it is necessary to shift the dimensional metrology effort from a pass/fail quality control and process control focus to an upstream effort that ensures more data based decisions in the design phase for a product and better defined data for these product specification decisions.

The savings from implementing these changes will come from:

- Fewer changes to the product specifications later in the product development cycle.
- Better decisions on what manufacturing equipment and environment will be necessary to produce the product.
- More flexibility in where the product is produced.
- Less need for process control measurement.
- More predictable product performance
- Better quality

7. References

1. ISO/TS 17450-2:2002 Geometrical product specifications (GPS) -- General concepts -- Part 2: Basic tenets, specifications, operators and uncertainties