Current issues in uncertainty of dimensional tolerance metrology and the future development in the domain of tolerancing

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Abstract. Uncertainty is an integral part of measurement result. Moreover, any problem in the specification of tolerance or in the measurement phase of tolerance is related to uncertainty, but few methods and lack of experimental data are available to integrate this knowledge. In this work we present the current situation of uncertainty in GD & T, analyzing at the same time a future prospective and including some specific areas to be taken into consideration.

1. Introduction

Production environment involving Smart Manufacturing, Intelligent Factory, or Industry 4.0 stage and competition among the producers tend to not only produce low cost products, but also maintain high performance level. Especially with development of space and robotics industry, a keenly felt need is that special and highly advanced applications are necessary. Prerequisite of these significant advances in technology can be traced to improved dimensional metrology.

Today Geometric Dimensioning and Tolerancing (GD & T) or dimensional metrology is one of the main parts of manufacturing and quality control processes. On the one hand every measurement is only an estimate of the true value, on the other hand, uncertainty, according to standardized rules, identifies where the true value of measurement result is within a certain range.

We have already witnessed that the ISO 14253 standard provides clear guidance about the necessity in allowing for the uncertainty of the measuring device by reducing the size of the acceptance band. Thus, there is significant interest in having access to instruments with smaller measuring uncertainties – unfortunately these are usually more expensive to purchase, and may involve additional expenses such as special air-conditioned rooms or a longer measuring period [1].

Professor Richard Leach says “Metrology is not just a process of measurement that is applied to an end product. It should also be one of the considerations taken into account at the design stage. According to the Geometrical Product Specification (GPS) model, tolerancing and uncertainty issues should be taken into account during all stages of design, manufacture and testing. The most compelling reason is that it is often considerably more expensive to re-engineer a product at a later stage when it is found that it is difficult to measure, compared to designing it at the start with the needs of metrology in mind” (p. 14) [1].

2. Current issues in uncertainty of dimensional tolerance metrology
In the past, the measuring uncertainty has been unattended when ascertaining compliance with a specification, as long as the uncertainty was one tenth of the specification width. This procedure is no longer admissible [1].

Figure 1 shows the impact of the measuring uncertainty on the acceptable process tolerance. Machine C which might be highly precise and with high accuracy, coordinates measuring machine with measuring uncertainty 2.5 μm, achieving the 10:1 inspection ratio, but it would allow a process tolerance of only 20 μm. It also may need stable temperature conditions. Another machine is Machine A that could be an articulated arm measuring machine and its cost is ten times cheaper than previous Machine C, but which can barely meet a 3:1 inspection ratio.

![Figure 1. Impact of measurement uncertainty.](image)

| Machine       | Measuring uncertainty | Specified tolerance range | For production | For customer |
|---------------|------------------------|----------------------------|----------------|--------------|
| Machine A     | 7.5 μm                 | 25 μm                      | 10 μm          | High 40 µm   |
| Machine B     | 5 μm                   | 25 μm                      | 15 μm          | Average 35 µm|
| Machine C     | 2.5 μm                 | 25 μm                      | 20 μm          | Low 30 µm    |

The higher production costs, associated with producing components within this much reduced process tolerance of only 10 μm, may be acceptable if sufficient capital is available to purchase Machine C – it all depends on the actual circumstances of the job in hand, especially the value of the individual components, the number of items to be produced and the duration of the contract [1].

There are a lot of methods for evaluating and combining components of uncertainty. These standardized rules resulted in an ISO document [2-3]. Also, a lot of National Metrology Institutes (NMI) have their own guidelines for expression for uncertainty in measurement [4]. It is clear that uncertainty of measurement with fixed dimensional gages is not the same as with measuring instruments [5].

There are several contributors to the measurement uncertainty for an industrial length measurement [6]:

- the measurement equipment
- the application of the equipment
- the influence of the environment
- the influence of the device under test
- the repeatability of the measurement set-up
There are some main parameters that influence to workpiece measurement such as form error, roughness of the surface, shape (e.g. special uncertainties, if a radius of a partial arc should be measured), etc. Machine measurement has the repeatability of the machine, especially if positioning accuracy parameters are evaluated [6].

NMI has been working with estimating measurement uncertainty and has been developing this direction for a long time. Special emphasis has been placed on the uncertainties measurement involved in the dimensional calibrations gage blocks, gage wires, ring gages, gage balls, roundness standards, optical flats indexing tables, angle blocks, and sieves [7-8].

Other works are also available in dimensional metrology instrumentations’ uncertainty. In paper [5] the author discussed the lack of instrumentation uncertainty available in GD & T. Since that time, and especially during the last decades, a lot of papers related to instrumentation uncertainty have been published [9-11].

The influences on the overall measurement uncertainty and the machining accuracy may be grouped as follows [6]:

- definition of the process,
- process parameters,
- environment,
- handling of the workpiece,
- workpiece characteristics,
- machine performance.

According to ISO/TS 17450-2 there are many main determination factors on how well part functionality can be ensured with dimensional metrology data:

1. The correlation uncertainty, which gives a quantity information about correspondence between dimensional measurand definition and the part function.
2. The specification uncertainty which quantifies how equivocal the measurand definition is.
3. The measuring uncertainty, which deals with quantity information about quality of measurement of the measurand.

The last factor among two others has been developed within the last decade. Careful consideration of all these factors in specification development process has/provides enormous potential for savings in manufacturing industry.

Until now correlation and specification uncertainty have largely been ignored. Only a few papers [6] proposed some methods to estimate the form error and the associated uncertainty that caused by the measuring process. However, today we are reaching the point when form errors and surface texture are important and both uncertainties significances might be the same as the measurement uncertainty. 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 a surface texture should be considered or ignored in geometrical tolerances [12]. It means that control of correlations uncertainty is not possible with standardized specification language.

Taking dimensional metrology to the next level needs to enrich specification language. Consequently, it allows to unambiguously specify the wavelength domain at a design stage. In addition, it will require engineers at all points throughout the product development cycle to consider the ambiguities in measurement data definitions specifications and manage it to an appropriate level in order to ensure product functionality [12].

3. The future development in the domain of tolerancing

Today big manufacturing centers, especially among the NIM are situated in developed countries with well-equipped laboratories. They can carry out a lot of dimensional and geometric tolerance research and properly deal with uncertainty. However, with lack of experience and low financial support in developing countries’ researchers cannot access and share the knowledge of specific fields, like GD & T. So, sharing knowledge among researchers is another activity to developing specific uncertainty measurement in dimensional metrology.
One of the goals of this paper is to initiate future discussions in the area of GD & T and to offer a shared vision of examples in common resulting from a regular exchange of views. There is a good example of realization of collaboration and joining researchers, thus leading to the creation of Tolerancing Research Groups across the whole France. It was initiated in France in the 1970s in the ENS de Cachan, by Professors Pierre Bourdet and André Clément, among others [13].

In order to initiate discussions about the future development GD & T that will unite research groups in the domain of tolerancing, this paper takes as a successful case creation of TRG in France and according to [13] it has some objectives. It consist of:

- comparing points of view on common scientific problems;
- exchanging solutions;
- bringing forward new research themes to respond to the needs of industry and others;
- promoting research into tolerancing and dimensional metrology;
- developing research in developing countries and defending a certain school;
- taking the responses proposed to the problems of tolerancing and metrology known to the industry;
- proposing solutions to the normalization organizations;
- producing collected written work in this domain, to respond to the diverse expectations of young researchers, industrialists, teachers and students.

As mentioned above, the lack of tools that can allow collaborating, share research ideas and discuss to related topics in dimensional metrology, lead to improve collaborative tools for developing GD & T in developing countries. The CIRP CAT, which refers to the Scientific Technical Committee Design (STC Dn) of the International Academy for Production Engineering is a good example of providing a technical forum for researchers, industrial practitioners, and policy makers to exchange ideas, share research findings, and discuss the various issues on the fields of dimensional and geometrical tolerancing, dimensional metrology, uncertainty management and standardization [14]. The Open Academy is a complete resource of free high quality video courses, lectures educational materials. IPPOP (Integration of Product – Process – Organization for engineering Performance improvement) is a successful project to share expertise in a collaborative design approach and to ensure the traceability of the geometric specifications [13]. Another platform to connect the world of science and make research open to all is ResearchGate.com. However, it is clear that these resources have still lack of information in GD & T domain. So, the best method for collaboration and exchanging knowledge is organizing trainings/workshops and practicing methods of Geometric Tolerancing of Products with implementation.

4. Conclusion
The important recent developments and interest among researchers in dimensional metrology is a solid basis to initiate future discussions among research groups GD & T of and uncertainty of the measurement. It is also an opportunity to develop this activity among developing countries. Taking into account that uncertainty evaluation which is one of the integral components of every research activities, concerned with measurement in GD & T, it is critical that the approach to estimating uncertainty is well defined and unilaterally applied.

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