Specifications, operators and uncertainties

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Abstract: ISO/TS17450-2:2002 “Geometrical product specifications (GPS) – General Concepts – Part 2: Basic tenets, specifications, operators and uncertainties” is a new technical specification published by ISO TC 213 “Dimensional and geometrical product specifications and verification”. This document defines a number of new concepts that have the potential of revolutionizing how we think about specification and verification. It enhances the specification language by defining specifications as ordered sets of operations, a much richer language than the simplistic notion of tolerance zones. Additionally, it expands the concept of uncertainty from being something measurement related to being the universal currency for quantifying ambiguity in requirements, specifications and verifications.
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1. A VERY BRIEF HISTORY OF TOLERANCING

Tolerancing was initially brought about by the need for interchangeable parts in the late 1800s. Initially, only dimensional tolerances were used. This worked well because the workshop producing the parts was generally next door to the design office, so communication was easy and the capabilities of the machine tools at the time were such that it was relatively trivial to produce parts that were geometrically “perfect” compared to the tolerances of the day. If problems arose it was easy for the designer and the machinist to get together and solve the problem and decide how the parts were to be made in the future. In this way many of the important requirements were never written down, but became “tribal knowledge” within the company.

As tolerances kept shrinking, assemblability became an issue. Around 1920, Taylor describes the “Taylor principle” which defines the functional requirements for assembly. To this day, hard gauging is based on this criterion.

Around the time of World War II, various drafting standards emerged, defining graphical languages for geometrical tolerancing. These standards evolved and merged, leaving us today with two dialects of geometrical dimensioning and tolerancing, the ANSI/ASME Y14.5 and the ISO system, usually referred to as ISO 1101, for the number of the standard defining the tolerancing symbols. The two systems are conceptually similar in their current iteration, in that both are primarily designed to enable tolerancing for assemblability. There are differences, some of which are significant, in the detailed definitions of the specifications in the two systems, but the kinds of requirements that can be expressed with the two systems are the same.

1.1. The rate of change in requirements

It is important to realize that different tolerance attributes and different manufacturing inaccuracies have been shrinking at different rates. Dimensional tolerances and inaccuracies have been shrinking the fastest. Form, such as roundness, cylindricity, and flatness shrink at a much lower rate and surface texture such as roughness and waviness shrink little or not all.

Consequently, 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 and 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.

1.2. Changes in the ISO technical committee structure

Within the International Organization for Standardization, ISO, technical committees are established on an as-needed basis with little effort to coordinate the work of the committees. Because of this relatively loose planning structure, three different committees were working on issues relating to what we now call geometrical product specifications and verification. One committee defined drawing indications and the meaning of specifications; another committee covered measuring equipment and a third committee was dedicated to surface texture. In the early 1990s these three committees were combined into ISO TC 213 "Dimensional and geometrical product specifications and verification".

The work in TC 213 was based on the idea that the field of geometrical product specifications can be described as a matrix, where the rows are the various requirements and the columns are the various pieces that have to be in place to create a uniquely defined requirement and enable it to be verified with a traceable measurement. The latter is called a chain of standards and just as a physical chain is no stronger than its weakest link, a requirement is no better defined than the least unambiguous link in its chain of standards.

1.3. New realizations in the work of ISO TC 213

ISO TC 213 brought together the design community and the metrology community for the first time in the context of standardization. This enabled a unique dialogue where the design community could explain what they were trying to express with their requirements and the metrology community could explain what the gaps were in these requirements and where the inspector had to make decisions on issues that were not defined in the standards in order to verify parts.

Another interesting realization began to emerge in the work of ISO TC 213. The purpose of geometrical product specifications is to enable the designer to express functional requirements in technical product documentation. However, the only functional requirements that can be expressed precisely using the existing standards are the requirements related to assemblability.

Other functional requirements central to modern industry, such as resistance to wear, eliminating leakage and scuffing in dynamic, high-pressure, metal-to-metal seals and limitation of noise in roller bearings, cannot be expressed using standard geometrical product specifications. This is very significant as the surfaces involved in such interactions are the most expensive to produce, whereas the surfaces that "just have to fit" generally are fairly inexpensive to produce.

2. A NEW WAY TO DEFINE REQUIREMENTS

Geometrical requirements have historically been defined by zones. This works well for the function of fit to ensure assemblability, but does not lend itself well to the expression of other functional requirements.

In the field of surface texture it has always been customary to define each surface parameter in terms of the instrument used to measure it and the algorithms and settings of this instrument, since surface texture has no "natural" parameter, such as the diameter of a hole. The idea of expressing a measurement as a series of operations and to define a specification as a "recipe" for a measurement was first expressed by the now disbanded ISO TC 57 "Surface Texture". In the now withdrawn [ISO 4287-2:1984], the term "Ideal Operator" was used to describe the instrument, algorithm, settings, and measurement procedure that would yield the correct value according to the definition of a surface texture parameter.

Realizing the limited scope of current geometrical dimensioning and tolerancing standards and the potential held by the idea of expressing requirements in terms of operations, ISO TC 213 has been working on a new way of defining requirements. In this new approach, requirements are defined by operators, where each operator consists of an ordered set of operations, each of which is applied to a feature. The possible operations are:

- partition
- extraction
- filtration
- association
- collection
- construction
- evaluation

These operations are defined in [ISO/TS 17450-1:2001].

Making these seven operations available, each with its own set of selectable parameters, and allowing the recursive application of them in an operator, creates a very flexible and rich specification language.

2.1. Expressing functional requirements

As discussed above, current geometrical product specifications can only express the function of fit in a precise manner. To enable the discussion of how well a specification expresses a functional requirement, ISO TC 213 has developed a new set of concepts and an associated terminology. [ISO/TS 17450-2:2002] defines this terminology.

Correlation uncertainty is one of these concepts. The correlation uncertainty quantifies how well the specification expresses the functional requirements. If there is good correlation between the true functional requirements and the requirements expressed by the specification, then the correlation uncertainty is low. If the correlation is poor, the correlation uncertainty is high.

Specification uncertainty is another one of these concepts. The specification uncertainty quantifies the ambiguity in the requirements set out by the specification. Specification uncertainty is usually caused by poor definitions in standards and other requirement documents. Examples of issues that can cause specification uncertainty are:

- undefined or poorly defined filtering requirements
- poor definition of the direction in which the requirement applies
- poor definition of the boundaries of the feature to which the requirement applies

It is possible to have a well-defined requirement – a requirement with low specification uncertainty – that does not express the true functional requirement and thus, has a high correlation uncertainty.

2.2. Verifying parts against a specification

A specification defined as an ordered set of operations can be thought of as a virtual measurement instruction, where each operation and the parameters defining that operation are steps in the measuring process. Through the so-called duality principle defined in [ISO/TS 17450-1:2001] the verification (measurement) can mirror the specification operation for operation. The method uncertainty is low if the chosen verification process mirrors the specification well, and high if it does not. The method uncertainty is part of the measurement uncertainty. The other part of the measurement uncertainty is the implementation uncertainty. To reach a low measurement uncertainty you not only have to have accurate instruments, a good environment, a trained operator etc., you also have to make sure that what your process measures is indeed what the specification requires.

3. CONSEQUENCES FOR MANAGING PRODUCT GEOMETRY

Within ISO TC 213 there is a strong expectation that current zone-based tolerancing systems can be redefined into the operator-based system with little or no change to the meaning of the requirements. However, when the zone-based tolerances are translated, it will become obvious that some information is missing – that the specification is uncertain.

This problem is well known in the metrology community. Every time an inspector measures a part, he or she has to make some decisions about how to make the measurement due to lack of information in the specification. What is less well known is that when experiments are performed to determine the appropriate tolerances in a specification, similar decisions are made. It is rare that these decisions – the measurement details – are communicated in the technical product documentation or even to the designer. Without this information in the technical product documentation, the specification is at best incomplete, i.e. uncertain, or misleading.

3.1. Determining tolerances and functional requirements

For simple workpiece functions, such as fit, the proper tolerances can be determined using relatively simple theoretical tools such as stack-up analysis. Thus there is rarely much prototype work involved in determining these tolerances and the designer can have a high degree of certainty that the tolerance values are proper for the application. However, as mentioned above, these are the least expensive parts to produce.

For more complex workpiece functions, including all dynamic interfaces, it is impossible to determine the proper tolerances without some amount of prototyping work. In the classic prototyping process, parts are first measured and then run in the application and the range of measured values for the parts that worked become the tolerance. In this case, it is imperative that the details of the measurement process and instrument settings are communicated as part of the product specification, otherwise the prototyping work is wasted and the tolerance is meaningless. Note that these workpiece functions are the most expensive to realize and the most critical for product performance, reliability, and longevity.

3.2. Communicating functional requirements

The operator-based system provides a much richer and more precise language for communicating geometrical product requirements than the zone-based system. It will still be possible to communicate simple functions, such as fit, without paying too much attention to the new possibilities offered. But for a designer to take advantage of the richness of the new language and be precise in his or her requirements, it will be necessary for the designer to know and understand what the various operations do and how they affect the values for attributes specified.

The advantages offered to the designer who understands the details of the operator-based system are immense. If a specification does not exactly describe the true functional requirements, the consequence is that the tolerance has to be tightened to ensure that all parts that are accepted will function correctly. This means that some parts that may function correctly will have to be rejected and some manufacturing processes that could yield functional parts will have to be replaced, generally by more expensive processes. In short, the correlation uncertainty makes the product more expensive.

A similar situation arises for the designer whose specification is in principle related to the functional requirement, but is also ambiguous. In this case, the tolerance will have to be set at the value that ensures functional parts using the most permissive interpretation of the specification. If part verification is subsequently performed using a more restrictive interpretation of the specification, functional parts may be scrapped and adequate manufacturing processes may be rejected in favor of more expensive processes.

4. CONCLUSIONS

The evolving operator-based system for product specifications allows for much more precise descriptions of the functional requirements for complex workpiece functions such as dynamic interfaces, while still enabling designers to describe simple functions, such as fit using a language that is no more complex than the current geometrical dimensioning and tolerancing system.

The operator-based system enables designers to precisely and unambiguously express tolerances and requirements that have been determined based on part measurements and prototyping work.

A designer dismissing the detailed definition of a requirement as "measurement details" will be a liability to his or her company's profitability and future. A designer embracing this new, richer language will help his or her company prosper. The extra effort it takes in the design phase to understand the operator-based system and apply precise, functional requirements is insignificant compared to the immense potential savings in the manufacturing and support phase of the product lifecycle.

REFERENCES

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[ISO/TS 17450-2:2002] "Geometrical product specifications (GPS) – General Concepts – Part 2: Basic tenets, specifications, operators and uncertainties."