Communicating Functional Requirements with GD&T

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Abstract

GD&T is a language with words, syntax and grammar. However, even if you know the words, syntax and grammar, you may not be able to meaningfully explain your functional requirements with this language.

The task of the designer is to translate functional requirements into geometrical requirements by using GD&T. This is a complex task because there rarely is a one-to-one relationship between functional requirements and geometrical requirements. Further, a significant limitation in the current editions of the GD&T language is that the only function it expresses well is the function of fit for the purposes of assembly.

More complex functional requirements are usually determined based on practical experiments, but there are no provisions in the GD&T language for documenting in the requirements what settings were used on the measurement equipment (e.g. filters and point density) to arrive at the measurement data that was used to determine the requirements.

An additional problem is that most CAD systems tend to lead the designer towards using dimensional tolerancing as the primary tolerancing and only add GD&T as an afterthought. When tolerancing is done in this manner is usually leads to significantly reduced tolerances and therefore more expensive parts.

The cost of bad design is substantial. For example, the automotive PPAP (Purchased Part Approval Process) can be viewed as recognition that the engineering drawings do not fully express the functional requirements. The incremental cost that this process adds to a product can be attributed to poorly expressed functional requirements.

The paper discusses some of the limitations in current GD&T, some good and bad practices for applying GD&T as some of the extensions to the GD&T language that will be necessary in order to enable designers to more clearly express complex functional requirements.

1. Introduction

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.

2. 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.

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

3. Developments in Dimensional and Geometrical Metrology

A significant divergence has taken place between the fields of dimensional and geometrical metrology, to the point where they are almost two separate fields.

Dimensional metrology is primarily based on "hard" gages, e.g. gage blocks, ring gages and plug gages. It is characterized by the assumption that artifacts have very little form error and very good surface texture. This is a good assumption for gage blocks, but not for the finest grades of e.g. ring gages. The field of dimensional metrology is very mature and primarily limited by the gage makers’ ability to manufacture artifacts with negligible form error. A problem with dimensional metrology based on hard gage is that the accuracy attainable on gage grade artifacts does not carry over to typical production parts, because the definitions of size and distance become "fuzzy" in the presence of significant form error and surface texture. It may be possible to measure the distance between two points on a part with very high accuracy, but this distance may be meaningless relative to the function of the part, if it is not known where these points are relative to the peaks and valleys of the surfaces.

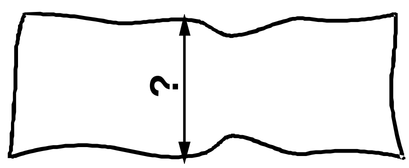

Figure 1: The definition of a distance becomes uncertain in the presence of form error and surface texture.

The field of geometrical (or “soft”) metrology has undergone revolutionary change in the last two decades, primarily due to the development of computerized measuring equipment. As computing power has increased and become more affordable, developments in sensor technology has allowed for the collection of ever denser data sets for the computers to manipulate. Using the results of these measurements, metrologists have realized that the results of geometrical measurements depend heavily on the sensor technology used, the data density and the filters applied. The question of how accurately one can measure the diameter or the roundness of the feature has become mostly a question of how well one can define "diameter" and "roundness". It has also become clear that different definitions of these parameters are needed to provide functional correlation for different workpiece functions.

Unfortunately, metrologists do not tend to be very precise when they talk about general concepts such as roundness. In a ring gage calibration laboratory "roundness" is usually the range of diameters measured in the ring gage. In a CMM laboratory "roundness" is usually the radius variations of a relatively sparse, unfiltered dataset relative to a least squares circle. Finally, in a form laboratory "roundness" includes details about the data density, the probe radius, the filter applied in the reference circle used. Yet, if all these laboratories were each asked to report the roundness of a part to a product development team trying to determine the proper tolerance, they would each report "their" value as the "roundness" of the part. In each case, if the product development team put the number they received from the laboratory on a drawing using the standard GD&T roundness symbol without further explanation, it would mean something entirely different than the value they received from the laboratory.

4. The State of the GD&T Language

The issues discussed above have been well known in the metrology community for at least a decade. However, no substantial developments have taken place to extend the GD&T language to allow a designer or product development team to express in a drawing which definition of "diameter", "roundness", etc. applies for each particular toleranced part feature, based on the function of that feature. This shortcoming in the language makes it impossible to express functional requirements precisely and forces designers to use tighter tolerances than what is necessary to compensate for the limitations of a language that is overly simplistic.

It is possible to use notes in drawings to compensate for these shortcomings, but this not only defies the purpose of having a symbol language for GD&T, it also carries the potential of miscommunication and ambiguity, if the designer does not know exactly which parameters are important to specify or relies on the terminology and settings offered by his particular brand and model of measuring equipment.

It can be argued that the vast majority of part features are toleranced to ensure assemblability and that this problem only applies to very few features and tolerances. However, this misses the very significant point that the expensive features to manufacture of a part or a design are those which have functions beyond simple assemblability. These are also the features that determine the perceived value, the "quality" and the durability of the part or design and therefore are the features that determine the price that can be charged for the part. Finally, these are the tight tolerances, and the cost of manufacturing a feature typically doubles when the tolerance is halved. Experience shows that 5 % of the tolerances for a part are responsible for 90 % of its cost. These are the tolerances that are difficult or impossible to express accurately with the current GD&T language and these are the tolerances that therefore are tighter than they need to be, making the parts more difficult and expensive to produce than they need to be.

5. Application of GD&T

For all its shortcomings, GD&T is still a very powerful language. However, there is very little guidance available on the proper use of GD&T. Most GD&T training tends to focus on the grammar and syntax of GD&T rather than its application. There are no GD&T “creative writing” classes available. Too many draftsmen see GD&T as a secondary tolerancing system to be applied after dimensional tolerances have been applied to a drawing - and only in special cases. CAD systems also tend to guide users in this direction, because it is fairly easy for a CAD system to ensure that all dimensions are toleranced, but it is hard for a CAD system to offer constructive advice on applying GD&T.

The result is that most drawings have two sets of tolerancing, dimensional and GD&T, and that these are not related to each other, so those features toleranced with dimensions can "float” relative to the datum system and the features toleranced relative to the datums.

A drawing that is properly toleranced with GD&T will have very few dimensional tolerances and all of these will apply to features of size.

6. Recognizing GD&T and Metrology Problems

The root cause that allows these issues to persist is that they are rarely recognized as GD&T issues or metrology issues. They are usually perceived as being process control issues or product reliability issues, where the produced parts change without the shop floor gages being able to detect the change.

The automotive industry has instituted the PPAP (Production Part Approval Process). In essence this process requires that a supplier submits a production sample for approval. These sample parts are functionally tested and if they are approved, the supplier is prohibited from changing the manufacturing process without the customer’s approval. This is a tacit recognition that the requirements expressed by the tolerances in the drawings alone are not sufficient to ensure functionality of the parts.

With a more precise application of GD&T and an extension of the GD&T language to allow for the specification of the wavelength content to be considered, it would be easier to determine the proper shop floor metrology requirements to keep workpiece function under control.

With better communication between R&D laboratories and product development teams, the teams would be aware of the details of the data they use to base their GD&T requirements on and the better equipped to communicate this information in their product drawings.

7. Conclusion

Substantial savings are available for manufacturing industry. To realize these savings, it is necessary to employ more sophisticated geometrical metrology early in the product development cycle. It is also necessary to extend the GD&T language so the results of these product development measurements can be properly documented in the product specification.

Further savings are available for companies that are willing to consciously employ GD&T as the primary tolerancing language, rather than an afterthought on top of traditional dimensional tolerancing. To realize these savings it is necessary for designers and product development teams to have an understanding of GD&T that goes beyond the basic grammar and syntax of the language.

Companies that embrace these two changes to how product requirements are determined and communicated will be able to substantially reduce their manufacturing cost, while improving the quality, reliability, and durability of their products. While the cost of implementing these changes may be substantial, it is minuscule compared to the potential savings.