

Preface

In Short

Geometric tolerances are increasingly being adopted in the design and manufacture of products, and awareness of their importance is now widespread.

This is not a book on geometric tolerances *per se*. A significant amount of literature work, including dedicated textbooks, is available that illustrates the main principles, definitions, and international standards related to geometric tolerances. Instead, this book explores the *impact* that geometric tolerances are having in specific areas of product development and manufacture, namely, product design, product quality inspection, and statistical process monitoring.

The book is structured as a collection of contributions from different authors, each highlighting one or more specific aspects related to the impact of geometric tolerances. New issues and also new opportunities are investigated.

From Dimensional to Geometric Quality Requirements

In the highly competitive scenario set by market globalization, it has become paramount for any company involved in product development to be able to reach the customer with appealing products in shorter times and with reduced costs. The capability of achieving and maintaining a consistently high level of *quality*, both of the final manufactured good and in the entire design and manufacturing process, is fundamental in achieving such a goal.

It is well known that the geometry of any manufactured product is characterized by variability with respect to its nominal counterpart: manufacturing-induced geometric variability is a long-established reality, which in turn affects functional performance and hence is tightly linked to quality. Acquiring a solid understanding of the geometric variation associated with a product has always been recog-

nized as a key strategic element for achieving a competitive advantage. Defining acceptable boundaries for geometric variation is a mission-critical task in product development: it means identifying the best trade-off between what is achievable by the manufacturing process, what is measurable with sufficient reliability and reproducibility at quality inspection and process monitoring, and what is necessary for guaranteeing acceptable functional performance.

In recent years, the push toward the realization of ever better performing, ever more energy-efficient, and ever more cost-effective products, the constant search for innovation, and the continuous efforts directed at achieving technological breakthroughs, including the race toward miniaturization, have given rise to an increasing need for understanding, measuring, and controlling geometric variability to a larger extent than was possible with traditional means. Geometric tolerances have been gradually introduced alongside traditional dimensional tolerances in technical drawings, with the goal of providing a more comprehensive way for defining allowable variation for a given product geometry. While with dimensional tolerances geometric variation is summarized in a few synthetic indicators associated with linear dimensions, with geometric tolerances it is possible to capture a wider range of variations related to shape, position, and orientation of geometric features; those variations can be handled in a more comprehensive manner, and it is possible to define more effective constraints to control allowable geometric variability.

Geometric tolerances are now widely recognized as a key strategic element when it comes to ensuring that a certain level of quality is met by the product, whether it is a complex assembly or a single part or even a simple geometric feature. As a consequence of that, geometric tolerances are now basically commonplace in technical drawings.

The transition from dimensional tolerances to a reality where geometric tolerances are increasingly being adopted alongside dimensional tolerances implies, at a conceptual level, that we are moving from a scenario where manufacturing-induced, allowable geometric variability is defined and inspected through the variations of a few linear dimensions to a scenario where allowable geometric variability is defined and kept under control in a more comprehensive manner, and a larger amount of information pertaining to the entire shape of the manufactured part is kept under consideration.

Impact on Design, Quality Inspection, and Statistical Process Monitoring

It is clear that the introduction of more comprehensive approaches for defining and handling geometric variability is having significant repercussions on all the aspects of product development. On one hand, geometric tolerances introduce a wider array of options to designers for specifying allowable geometric variation.

While this opens up more opportunities for the accurate capture of a designer's intent, at the same time it raises new issues. With more options to define the boundaries of what could be considered as acceptable geometry, more choices must be made on what, when, and how to use such new resources. In order to make these choices wisely and effectively, deeper investigations are needed, aimed at gaining a better understanding of the potentially numerous effects, either direct or indirect, that any constraint on the shape/position/orientation of a geometric element, such as a feature, a part, or an entire assembly, may have on functional performance, manufacturability, assemblability, and ultimately cost and time to market.

Similarly, novel problems are raised at quality inspection. As quality is now related to a more comprehensive and complex representation of geometric variation – especially when compared with what could be previously achieved by looking only at linear dimensions, *i.e.*, with dimensional tolerances – it is clear that quality inspection needs to react accordingly, and traditional approaches may not be capable of successfully supporting novel requirements. It goes without saying that verifying whether a linear dimension is in tolerance or not is definitely simpler than, for example, verifying that the deviation of a free-form surface with respect to its nominal counterpart is within the specifications. The latter problem implies the existence of a solid background of solutions for solving not-so-straightforward issues, such as how to measure the actual geometry and how to assess from measurement data if the feature variation is confined within acceptable boundaries. Countless other examples could be made to testify how this conceptual transition from dimensional requirements to geometric requirements is raising significant issues, while at the same time providing the opportunity to explore new promising ground.

A similar scenario is faced by researchers operating in statistical process monitoring. Once more, how can monitoring solutions evolve so that they can handle the geometric variability associated with an entire surface, starting from traditional approaches where monitoring relies on the variations of a few synthetic indicators, such as those obtainable from a set of linear dimensions? Again, new issues appear alongside new opportunities to explore promising paths toward the development of innovative solutions.

Approach of the Book

It cannot be denied that a thorough investigation of the impact of the conceptual transition from dimensional requirements to geometric requirements is a daunting task, given the multitude of domains that characterize the complex and multifaceted process known as product development. Producing a textbook which is comprehensive enough, while at the same time achieving significant depth of detail, is close to unfeasible. The effects of introducing a potentially more effective set of constraints on geometric variability into product development are numerous, and

delve deep into the process, affecting design, manufacturing process planning, quality inspection, and process monitoring activities in lots of direct and indirect ways.

This book chooses to deal with such complexity by collecting separate testimonies from different authors, each contribution concerning one or more specific issues that are deemed relevant within one of the subject areas listed earlier as product design, product quality inspection, and statistical process monitoring.

Manufacturing plays a central role in all the contributions: since geometric variability is induced by the process, manufacturing-related aspects cannot be ignored when dealing with any problem related to geometric variation. The manufacturing process, with its central importance, permeates the entirety of this book.

The contributions include original research, current literature reviews, and/or industrial practice experiences related to one of the subject areas listed above. This approach is intended to provide a significant breadth of views, while by no means attempting to achieve completeness. The hope is that a collection of significantly disparate topics covering such a wide range of subjects within product development may prove inspirational for researchers pursuing original research in one of the areas identified.

Reading Guide

The book is divided into three sections, each collecting contributions related to one of the subject areas:

- Part I: impact on product design;
- Part II: impact on product quality inspection;
- Part III: impact on statistical process monitoring.

In the following, a brief overview of the structure and contents of the book is presented. This is meant to provide an overall conceptual framework that allows the chapters to be placed in their correct context, and it also works as a reference guide, or gateway, for taking the reader toward the section he or she may be more interested in, for further reading.

Part I – Impact on Product Design

In this part of the book some key aspects related to the transition to geometric requirements are analyzed through the study of the introduction of *geometric tolerances* in product design. Geometric tolerances provide a multitude of new options for designers to specify allowable geometric variation. However, a competent and proficient use of such options implies a deeper understanding of the relationships among geometric variation, functional performance, and manufacturing and assembly processes. The principal new issues that are raised from the viewpoint of a product designer are related to *tolerance analysis* (i.e., understand-

ing how given tolerances affect functional performance) and – consequently – *tolerance synthesis* (i.e., creating tolerances to be applied to a given geometry). The problem of tolerance synthesis is further divided into the problem of *tolerance specification* (i.e., what tolerances to adopt, where to place them, and how to identify proper reference datums) and *tolerance allocation* (i.e., what values to assign to defined tolerances).

Given its core importance in product design, *geometric tolerance specification* was chosen as the main subject for Chapter 1. In this chapter, an overview of the principal and most widespread approaches for selecting the most appropriate types of geometric tolerances, identifying where to place them on part geometry, and identifying proper reference datums is presented. Geometric tolerance specification is discussed under a dual perspective: producing protocols/guidelines to be manually applied by designers, and developing formal representations/methods to be implemented in computer-aided tools. In the chapter, tolerance specification is not addressed as a stand-alone problem; instead it is discussed in the context of its deep interconnections with tolerance allocation and tolerance analysis. The relationships between product geometry variability, manufacturing process, and fulfillment of functional requirements are highlighted, and the opportunities available for product design improvement are discussed.

Already introduced as one of the key aspects of product design, and not only because of its strong ties with tolerance specification as investigated in the previous chapter, the problem of *geometric tolerance analysis* becomes the core subject of Chapter 2. The chapter chooses to specifically focus on one of the most interesting, complex, and industrially relevant issues of tolerance analysis: the study of *tolerance chains* and their effects on the functional performance of assembly products. An overview of some of the most widely known literature approaches is presented, and they are discussed both in terms of protocols/guidelines that can be derived for designers to adopt and in terms of development of computer-aided solutions. Specifying the correct amount of allowable geometric variability of mechanical parts or simple features is of vital importance, as it has relevant repercussions both in the manufacturing domain, as it may damage the assemblability of the parts, and from a purely functional standpoint, as the overall functional performance of the assembly product may be degraded, or entirely lost, owing to the combined effects of the tolerance stack-up.

Part II – Impact on Product Quality Inspection

This part is dedicated to analyzing how the conceptual transition to geometric requirements is affecting current industrial practice and scientific research in the domain of *product quality inspection*.

The adoption of a more comprehensive set of constraints on the shape of a product raises the bar in terms of precision and complexity for all the activities related to its inspection. Current solutions (measurement instruments, measurement techniques, data analysis, and processing approaches) are in constant need of upgrading to keep pace with the evolving design scenario.

Fundamental challenges are related to how to acquire and analyze geometric information more efficiently and effectively in order to cope with the increased requirements; new opportunities surface as well.

This part of the book addresses two main subjects in the field of inspection: geometry *measurement solutions* (i.e., measurement instruments and measurement processes) and *measured data analysis*. For both subjects, the selection of authored contributions was driven by the desire to highlight specific theoretical and applied subject areas that have recently attracted considerable interest, such as the inspection of microtopographic features, inspection through the adoption of sensor-fusion techniques, the development of innovative measurement process planning solutions, and the development of new formal representations for encoding a shape and its variations. *Shape (form)* and *shape error (form error)*, in particular, emerge as the central subject shared by most of the contributions presented in this part of the book.

In detail, Chapter 3 is about measurement instruments such as profilometers and 3D microscopes and their application to the assessment of form error on microtopographic surface features. The problem is attracting considerable interest owing to the increased production of items such as microelectromechanical systems, semiconductors, other types of micromanufactured goods, and also more standard-sized parts characterized by microtopographic surface features. As form error assessment becomes relevant for such products, several issues must be faced to make profilometers and 3D microscopes adequate – with their peculiar modes of measurement and performance features – for such quality inspection tasks.

In Chapter 4, the problem of measurement process planning is analyzed for coordinate measuring machines (CMMs) involved in form error assessment tasks. As constraints on variability of surface shape evolve toward more comprehensive solutions, it becomes increasingly necessary to ensure that inspection captures all the relevant aspects of a surface geometry: for point-based measurement, this implies denser point clouds and/or a more thought-out placement of measurement points themselves. Significant measurement process planning problems arise, as the requirement of a more detailed inspection clashes with measurement time and cost.

Chapter 5 explores some issues related to the analysis of measured data. The focus is again shifted toward microtopography, and problems related to the assessment of form error on a microtopographic surface feature are analyzed, starting from a cloud of points as can be obtained by means of a profilometer or 3D microscopes. Peculiar aspects include the fact that the point cloud may be potentially suboptimal for a given geometry, owing to it being generally acquired by means of raster scanning, and that the exact localization of the surface feature within the acquired surface region may not be known, thus implying the need for feature identification and alignment with a nominal reference, before the actual form error can be assessed.

In Chapter 6, recent trends toward the development of multisensor measurement solutions are explored, and their role and applicability to inspection scenarios involving form error and geometric tolerances are discussed. The analysis is

concerned with both measurement instruments (*e.g.*, combinations of CMMs and vision systems) and data-fusion approaches, where measurement data from different sources must be either used sequentially (*e.g.*, coarser measurement solutions used for optimal planning of more accurate, but slower, measurement processes) or merged into a single representation of the acquired geometry.

Finally, Chapter 7 is about shape coding. The need to identify efficient and effective solutions for encoding a shape into mathematical terms is central to the field of form error assessment. In this chapter, statistical shape analysis techniques, originally developed for modeling the shape of biological objects in the natural sciences, are analyzed and discussed, with particular reference to Procrustes-based methods. Possible solutions are proposed for some of the relevant issues that are related to the application of such methods to the representation of the geometry of manufactured parts.

Part III – Impact on Statistical Process Monitoring

In this part of the book, methods and tools are presented for performing *statistical process monitoring* (also known as *statistical process control* – SPC – or *statistical quality monitoring*) when the quality requirements concern the geometry of the manufactured item. The viewpoint is the one typical of the quality or process engineer who wants to quickly detect any change in the manufacturing process from its in-control or target state, given that the changes are usually associated with deteriorated process performance (*i.e.*, increase of nonconforming percentage). Traditional approaches in this area focus on dimensional requirements only, given that the basic tool in SPC, *i.e.*, the control chart, assumes that the quality characteristic of interest can be modeled as a univariate or multivariate random variable. When product quality is related to geometry rather than dimensions, the traditional control chart cannot be easily used, unless a synthetic set of indicators are used to summarize all the information contained in the cloud of measured points.

Chapter 8 presents two approaches that, given their inner simplicity, can be assumed as representative of industrial practice. The first approach consists in summarizing the information provided by the cloud of measured points in one synthetic indicator, namely, the maximum deviation of the actual shape from the nominal or ideal one, and then monitoring this indicator over time with a univariate control chart. The second approach extends a tool developed by Boeing for monitoring the upper flange angle at many different locations and consists in computing a control region where the upper and lower control limits are k standard deviations from the sample mean at each location. According to this method, an alarm is issued when at least one point in the whole set of data observed in a profile exceeds the control limits.

The following two chapters, *i.e.*, Chapters 9 and 10, are aimed at showing more complex but more efficient solutions for statistical process monitoring of geometric tolerances. The first type of solution relies upon a parametric model of the profile/surface geometry and hence is referred to as a “model-based” solution. In particular, two different methods are presented, depending on the specific type of

model representing surface data (namely, linear regression with spatially correlated noise and principal component analysis). Chapter 10 shows a “model-free” approach where no model of the machined surface is assumed for the development of the monitoring strategy. In this case, the monitoring tool consists of a neural network operating in unsupervised mode to cluster the machined surfaces. Given a set of in-control surface data collected over a long period of time, the network is trained to detect any different patterns as representative of a different (and possibly) out-of-control state.

The performances of all three classes of approaches presented in the previous chapters of this part are compared in Chapter 11, where a real case study concerning roundness form errors of lathe-turned items is considered as a starting reference and different production scenarios are derived by slightly perturbing the case-study features. In this chapter, the best approaches in each production scenario are outlined in order to let the reader gain some insight into the advantages and disadvantages of the alternative solutions.

Milano, Italy
September, 2010

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Geometric Tolerances

Impact on Product Design, Quality Inspection and
Statistical Process Monitoring

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2011, XVIII, 336 p., Hardcover

ISBN: 978-1-84996-310-7