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CIRP-1866; No. of Pages 23
ARTICLE IN PRESS

CIRP Annals - Manufacturing Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Tolerancing: Managing uncertainty from conceptual design to final product

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ARTICLE INFO

Keywords:
Design
Tolerancing
Uncertainty

ABSTRACT

Variability is unavoidable in the realization of products. While design must specify ideal geometry, it shall also describe limits of variability (tolerances) that must be met in order to maintain proper product function. Although tolerancing is a mature field, new manufacturing processes and design methodologies are creating new avenues of research, and modelling standards must also evolve to support these processes. In addition, the study of uncertainty has produced widely-accepted methods of quantifying variability, and modern tolerancing tools should support these methods. The challenges introduced by new processes and design methodologies continue to make tolerancing research a fertile and productive area.

1. Introduction

Uncertainty is ubiquitous in any engineering system, at all stages of product development and throughout the product life cycle. This presence of uncertainty incurs risks – to the product performance, to process scheduling, to market acceptance, or to the business itself. To mitigate these risks, strategies that bound design variables and their associated uncertainty are employed. These related concepts-uncertainty, risk, and tolerances-create the landscape within which many engineering design activities are performed. In the classic geometrical domain, uncertainty appears as dimensional variability, risk relates to non-conformance, and tolerances are used to limit the allowable variability.

The rising demand for high reliability, robustness and safety of complex engineering systems, such as automobiles and aircraft, requires engineers to understand and manage various uncertainties during the design process. Such uncertainties include anticipated manufacturing variation, imperfect numerical approximations, imprecise estimates of loading, and limited prototypes on which to perform testing. These uncertainties, if incorrectly managed, could lead to significant design bias, costly maintenance, even catastrophic consequences, especially for multidisciplinary systems. Therefore, it has become imperative to identify the sources of uncertainty and quantify the impact of multiple types of uncertainties in multidisciplinary systems design [12,225,248,293,294].

Examples of uncertainty include manufacturing imprecision, variations in product usage, and geometric variability; all of these are subject to imperfections and incomplete information. Such uncertainty has a significant impact on product performance. The ability to evaluate and improve product performance where several types of uncertainty are present is very important to avoid warranty returns and scraps [60].

V. Srinivasan identified two axioms underlying his discussion of computational metrology [280,281]. These are:

1) *The axiom of manufacturing imprecision*: "All manufacturing processes are inherently imprecise and produce parts that vary."
2) *The axiom of measurement uncertainty*: "No measurement can be absolutely accurate and with every measurement there is some finite uncertainty about the measured attribute or measured value."

Due to the imprecision associated with manufacturing process; it is not possible to repeatably produce the product's theoretical dimensions. This results in a degradation of the product performance. In order to ensure the desired behavior and the

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https://doi.org/10.1016/j.cirp.2018.05.009
0007-8506/© 2018 Published by Elsevier Ltd on behalf of CIRP.

performance of the engineering system in spite of uncertainty, the component features are assigned tolerance limits within which the characteristic of the feature – i.e. situation and intrinsic characteristic – lies. This activity is referred to as “tolerancing”. Further, the inability to determine the true value of actual part characteristics influences the ability to properly characterize manufacturing processes. To manage the rate of out-tolerance products and to evaluate the impact of component tolerances on product performance, designers need to simulate the influences of uncertainty with respect to the functional requirements.

1.1. History of tolerancing

The development of tolerancing can be traced back to the end of the 19th century or the beginning of the 20th century through the need for more precisely engineered components to be assembled interchangeably [99,47,131,240]. Since 1905, the “Taylor Principle” or “envelope requirement” which is based on the hard gauging practice, allowed the development of a function-oriented approach for assembly, thus enabling the foundations for a scientific approach to tolerancing [287]. Subsequently, the military and manufacturing sectors encouraged the development of standards addressing limits and fits, technical drawings, subcontracting documents, and also gave more consideration to manufacturing operations and the control of workpiece variability in the practices of the design and engineering offices [130].

A geometric model for tolerancing was developed by S. Parker in 1938 through the development of tolerances of location and tolerance zones [230]. Parker’s work is seen as the foundation of geometric tolerancing and has paved the way for new concepts such as the principle of the maximum material condition developed by Chevrolet in 1940 [64]. At the same time, efforts to standardize the graphical symbolism of tolerancing for technical drawing led to the GD&T (Geometric Dimensioning and Tolerancing) system through the development of American standards MIL-STD-8 (1949), ASA-Y14.5 (1957), USASI Y14.5 (1966), ANSI Y14.5 (1973), ANSI Y14.5M (1982), ASME Y14.5M (1994) [27], and ASME Y14.5 (2009) [24]. Similarly, international tolerancing standards (ISO) have also evolved from the ISO system of limits and fits ISO/R 286 (1962) and standards for technical drawing and geometrical tolerancing ISO/R 1101 (1969) to a new system of standards for Geometrical Product Specifications (GPS) which are now being developed in the different working groups of ISO/TC 213 [222].

The work in TC 213 is based on the idea that the field of geometrical product specifications can be described as a matrix: the rows are the various requirements and the columns are the various pieces that have to be in place to create an unambiguous specification. In this new approach, specifications are defined by an ordered set of operations, each of which is applied to a feature [167] according to Mathieu and Ballu [208], based on these ordered set of operations (or operators) the uncertainties links to tolerancing activities are developed in [169]. The idea of the GPS system is to guarantee and ensure mechanical product properties in terms of functionality, reliability and interchangeability.

Over the last 40 years, the confluence of industrial need, the rise of the CAx software, and the development of coordinate metrology has justified both significant research and an evolution of the tolerancing standards. The CIRP Seminar on Computer Aided Tolerancing (CAT) was conceived during the 1980s following the growing desire of the CIRP community to undertake cooperative projects on the topics of tolerancing and dimensioning of mechanical parts, the functional meaning of tolerances, uncertainty and standardization [132,232,314]. Two main needs were identified to be emerging at that time [313]: the integration of tolerancing procedures in the CAD/CAM environment, and the assessment of geometrical errors of Coordinate Measuring Machines (CMMs) and algorithms for analyzing workpiece data. These two areas were being researched extensively with most of those contributions being published at the CIRP Annals [241]. Meanwhile, in the field of Computer Aided Process Planning (CAPP), tolerance transfer and tolerance charting were being computerized in order to be integrated into CAD/CAM systems [115,117]. Bearing in mind the relevance that CAT was acquiring, the necessity to meet, share and discuss the developments of this field was manifest. In December 1989, in response to this need, Prof. R. D. Weill organized the first two-day Working Seminar on CAT in Jerusalem, Israel. Since then, the seminar has been held every two years, taking place 15 times worldwide and with over 600 papers published.

1.2. New challenges in tolerancing

The introduction of new manufacturing technologies has broadened the scope of both geometry and material attributes that a designer may specify. With this specification naturally comes the need for control of variability in these new attributes. As an example, new additive manufacturing processes can produce assemblies in as-built form, create complex lattice structures for support, and produce gradients in the density and composition of material throughout the workpiece. These potential workpiece attributes introduce challenges in the modelling of the workpiece’s nominal design, and until the nominal properties are defined, variability in these attributes is difficult to control. For example, consider the complex support structure in Fig. 1: both the explicit modelling of this geometry, and appropriate controls to the support shapes represent challenges to conventional tools and practice. However, there is a great opportunity to simultaneously consider control methods as the modelling methods are developed. If a particular representation is chosen to describe how material density changes throughout a part, this representation should accommodate the allowable variation in this density attribute.

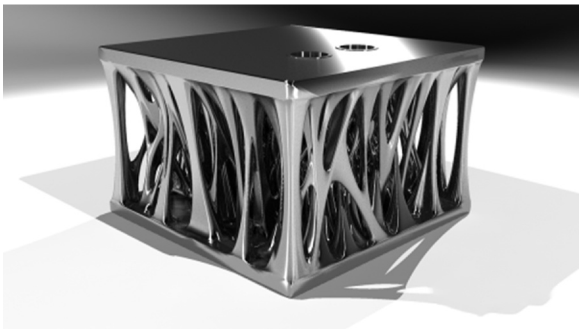

Fig. 1. Complex support structure.

In addition to broadening the domain of workpiece specification, the consistency and traceability of data throughout the product lifecycle is of increasing importance as enterprises rely more heavily on a digital representation of not only the workpiece, but the processes that produce, inspect, and maintain the product through-out its lifecycle. Current standards describe how the tolerances associated with features may be presented to a human user, as shown in Fig. 2, but do not require a specific underlying model or representation. The concept of a “digital thread” is that all product information is captured in a format that is usable by the design, manufacturing, and inspection activities of the product's lifecycle, and that the information is uniquely identifiable, so that the traceability of information may be maintained.

These new challenges (and others) are revisited in more detail in Chapter 7, where a framework for future research is proposed in the context of the information provided in the intervening Chapters.

Please cite this article in press as: Morse E, et al. Tolerancing: Managing uncertainty from conceptual design to final product. CIRP Annals - Manufacturing Technology (2018), https://doi.org/10.1016/j.cirp.2018.05.009