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Process-oriented tolerancing using the extended stream of variation model

José V. Abellán-Nebot [a,*], Jian Liu [b], F. Romero Subirón [a]

[a] Department of Industrial Systems Engineering and Design, Universitat Jaume I, Av. Sos Baynat s/n, Castellon 12071, Spain
[b] Department of Systems and Industrial Engineering, University of Arizona, Tucson, AZ 85718, United States

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ABSTRACT

Current works on process-oriented tolerancing for multi-station manufacturing processes (MMPs) have been mainly focused on allocating fixture tolerances to ensure part quality specifications at a minimum manufacturing cost. Some works have also included fixture maintenance policies into the tolerance allocation problem since they are related to both manufacturing cost and final part quality. However, there is a lack of incorporation of other factors that lead to increase of manufacturing cost and degrade of product quality, such as cutting-tool wear and machine-tool thermal state. The allocation of the admissible values of these process variables may be critical due to their impact on cutting-tool replacement and quality loss costs. In this paper, the process-oriented tolerancing is expanded based on the recently developed extended stream of variation (SoV) model which explicitly represents the influence of machining process variables in the variation propagation along MMPs. In addition, the probability distribution functions (pdf) for some machining process variables are analyzed, and a procedure to derive part quality constraints according to GD&T specifications is also shown. With this modeling capability extension, a complete process-oriented tolerancing can be conducted, reaching a real minimum manufacturing cost. In order to demonstrate the advantage of the proposed methodology over a conventional method, a case study is analyzed in detail.

1. Introduction

Machining operations are inherently imperfect in fabricating parts. This is due to the numerous process variables that affect the final quality of products, such as machine-tool thermal expansion, cutting-tool wear, fixture error, etc. The inherent variability of machining processes requires to specify dimensional and geometrical tolerances on raw and machined surfaces to ensure final product functionality. Product tolerancing defines the variability allowed for each key variable that characterizes the functional requirements of the product, named the key product characteristics (KPCs). There are two basic directions in tolerancing research: (a) tolerance analysis and (b) tolerance synthesis [1]. Tolerance analysis predicts the variation of the final product given the tolerance of each part using a mathematical model of tolerance accumulation such as the worst case model or the root square sum [2, Chapter 9]. Tolerance synthesis, or tolerancing, focuses on assigning tolerance specifications to individual manufacturing features on a part to ensure product functionality and minimize manufacturing cost. In the literature, the traditional tolerancing approach is *product-oriented*. It mainly focuses on assigning tolerance to product variables, such as dimensions of final product and parts. However, this approach only considers limited *a priori* knowledge about manufacturing capabilities and manufacturing costs of specific operations, and does not explicitly specify the allowable variability of the process variables, such as those related to tooling variations due to wear, thermal distortions or manufacturing accuracy. Recently, the *process-oriented tolerancing* approach was proposed by Ding et al. [3]. This approach is essentially a tolerance transfer method where the quality specification of the final product is ensured by optimally assigning tolerances of process variables throughout the manufacturing process.

In a multi-station manufacturing process (MMP), the process variables, also referred as key control characteristics (KCCs), are the root causes of the process faults that negatively impact on the KPCs. These KCCs define the working condition of the tools (machine-tools, fixtures and cutting-tools) that are used to fabricate a part. In the process-oriented tolerancing approach, the incorporation of KCCs into tolerance models leads to the integration of tolerancing with process maintenance and operation strategies. As a result, a more comprehensive function cost can be considered to find out the optimal tolerance allocation that

* Corresponding author. Tel.: +34 964 728186; fax: +34 964 728170.
E-mail addresses: abellan@uji.es (J.V. Abellán-Nebot), jianliu@sie.arizona.edu (J. Liu), fromero@uji.es (F.R. Subirón).

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minimizes the total manufacturing cost. The main challenge of process-oriented tolerancing is the definition of a mathematical model that describes the effect of KCC variations on the KPCs in a station of a MMP. Such effects on KPC variations may be propagated to downstream stations and accumulated to the final product. Recently, this type of variation propagation in MMPs has been successfully modeled by applying the stream of variation (SoV) modeling [4]. The SoV modeling is a systematic methodology to derive the KPC–KCC relationship based on engineering domain knowledge on the product/process design [5]. Based on SoV models, many quality improvement activities have been conducted on MMPs, such as process diagnosis [6], sensor placement for in-process inspection [7,8], quality prediction [9–11] and dimensional quality control [12,13]. However, only few works have been focused on process-oriented tolerancing [3,14–16]. In this specific field, Ding et al. [3] applied the process-oriented tolerancing approach to allocate product and process tolerances in a multi-station assembly process (MAP). The KCCs modeled were the variability of fixture locators caused by their degradation. Considering reciprocal functions as cost-tolerance functions, the optimal tolerance of KCCs with the minimum manufacturing cost was allocated by solving a constrained optimization problem. Similar problem was described by Chen et al. [14], who expanded Ding's work to integrate the process-oriented tolerancing with the fixture maintenance planning. Tool fabrication cost, fixture maintenance cost and quality loss functions were considered together to optimize the process tolerance allocation and the frequency of fixture maintenance operations in MAPs. The main goal of this work was to present an integrated method to analyze maintenance operations and process design together with the resulting assembly quality. These two works established the fundamentals of process-oriented tolerancing through the use of the SoV model. However, their works were focused on MAPs, where only fixture-induced variations are of interest for tolerance allocating purposes.

Process-oriented tolerancing has been less explored on machining systems, where unlike MAPs, a large number of process variables with different cost functions should be considered. In this field, Huang et al. [15] developed a tolerance allocation methodology considering as process variables the deviations of fixture locators and the generic deviation of the cutting-tool movements of the machine-tool at each station. This tolerance allocation problem seeks to maximize the variance of these process variables constrained to part quality specifications, assuming that all process variables are independent to each other and follow a normal distribution. Recently, Liu et al. [16] studied the use of the SoV model to determine optimal setup planning that ensures product quality with minimum cost, assuming that cost is inversely proportional to the necessary process precision. In their work, both fixture-induced and machining-induced deviations (considering the later as a generic cutting-tool path deviation) were treated as random process deviations.

Four main limitations can be identified in the previous research works. (i) The process variables considered in the machining systems are not comprehensive, and the tolerance allocation is conducted considering locator tolerances and generic cutting-tool path deviations. However, machine-tools present other process variables that influence on the cutting-tool path accuracy such as cutting-tool wear, thermal state of the spindle, etc. [17]. In fact, a recent research work [18] demonstrated that without considering these process variables in the SoV model, part quality prediction at the end of a MMP may result in important misleading conclusions. Therefore, a complete tolerance allocation requires the inclusion of additional process variables. (ii) The cost to be considered in the tolerance allocation problem should include not only fixture cost (both design and maintenance cost) but also other cost related to machining such as cutting-tool costs, thermal-control costs, etc. (iii) The process variables considered have been assumed to follow a normal distribution [15,16] for tolerance allocation purposes. However, other distributions closer to the real production system should be considered for process variables such as locators wear or cutting-tool wear. (iv) The part quality constraints should be considered as geometric dimensional and tolerancing (GD&T) specifications, instead of vectorial dimensioning and tolerancing (VD&T) specifications which are not used in industry, although they can be easily applied by using the SoV model.

In order to illustrate the limitations of current process-oriented tolerancing due to the neglection of specific machining-induced variations, an example of a two-station machining process shown in Fig. 1 is considered. At the first station, the dimension of the machined feature D_2 is deviated from its nominal value due to the locator tolerance, denoted by $\pm T_2$, and the machining-induced variations due to the cutting-tool wear, denoted by $\pm T_3$, and those induced by the spindle thermal expansion, denoted by $\pm T_4$. Thus, considering the worst case deviation, the tolerance of D_2 is defined by $T_1 = T_2 + T_3 + T_4$. The workpiece is then set up at station 2, where the dimension of the feature to be machined, D_3, will be deviated from nominal values in a similar way and thus, its final tolerance will be defined by $T_5 = T_6 + T_7 + T_8$. As a result, the KPC of this part defined by the dimension of the feature D_4 will depend on all previous fixture and machining-induced variations. Its tolerance will be defined as $T_{10} = T_1 + T_5 + T_9 = T_2 + T_3 + T_4 + T_6 + T_7 + T_8 + T_9$, which means that if machining-induced variations are not negligible with respect to fixture-induced variations, the achievable tolerance of this KPC depends on the variability of six different KCCs defined by the tolerances $\{T_2, T_3, T_4, T_6, T_7, T_8\}$. Note that the tolerance T_9 refers to the tolerance of the dimension D_1 (raw material) so it is not related to a fixture or machining-induced variation. Neglecting the machining-induced variations will result in allocating a higher tolerance value for fixture locators. However, if in reality machining-induced variations

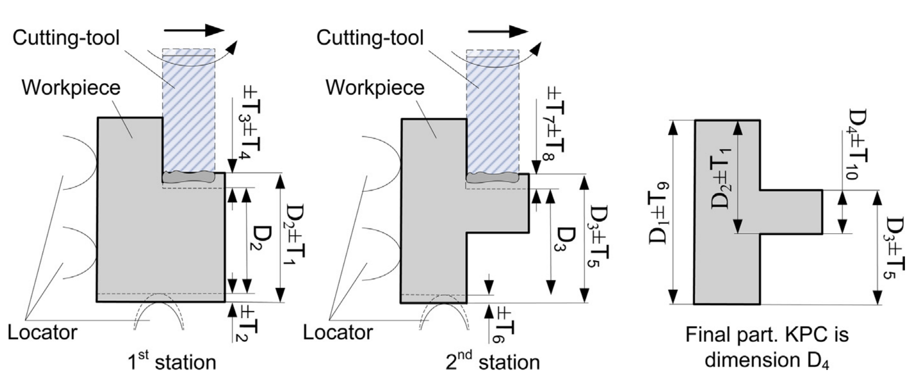

Fig. 1. Example of the influence of machining-induced variations on the tolerance allocation problem.