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Tolerance analysis in manufacturing using process capability ratio with measurement uncertainty

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ABSTRACT

Tolerance analysis provides valuable information regarding performance of manufacturing process. It allows determining the maximum possible variation of a quality feature in production. Previous researches have focused on application of tolerance analysis to the design of mechanical assemblies. In this paper, a new statistical analysis was applied to manufactured products to assess achieved tolerances when the process is known while using capability ratio and expanded uncertainty. The analysis has benefits for process planning, determining actual precision limits, process optimization, troubleshoot malfunctioning existing part. The capability measure is based on a number of measurements performed on part's quality variable. Since the ratio relies on measurements, elimination of any possible error has notable negative impact on results. Therefore, measurement uncertainty was used in combination with process capability ratio to determine conformity and nonconformity to requirements for quality characteristic of a population of workpieces. A case study of sheared billets was described where proposed technique was implemented. The use of ratio was addressed to draw conclusions about non-conforming billet's weight expressed in parts per million (ppm) associated with measurement uncertainty and tolerance limits. The results showed significant reduction of conformance zone due to the measurement uncertainty.

1. Introduction

Each manufacturing operation creates a feature that is subjected to variations. If manufacturing technology for a part is known, there is a limit to the minimum achievable variation that the quality feature under consideration cannot become better than that level. The limits vary from one manufacturing process to another, and is inherently difficult to predict them. For a particular manufacturing method, it is primarily controlled with intervention of machine operator during the production stage. The operator changes parameters (input variables) on machine tool and by quality characteristic's inspection, the optimum values are found. Therefore, process performance is left to operator experience. Depending on the complexity of the process, this traditional way of optimization can be time consuming and costly to manufacturers.

In order to address this problem, optimization techniques have been developed to balance a trade-off between machine workability, production time, surface quality and dimensional accuracy. Several experimental designs and optimization methods such as Taguchi, full factorial, gray relational, fractional factorial, artificial neural network (ANN), fuzzy logic and genetic algorithm (GA) were introduced for optimizing operating parameters in manufacturing processes. The procedure is also highly dependent on identification of the critical parameters and functional relationship between the parameters and part quality characteristics. For some manufacturing methods such as metal-based additive manufacturing where material undergoes complicated physical deformation, it is difficult to find critical-to-quality process variables and relate them to part quality [1].

Although the knowledge of process, operator skills and the optimization techniques are effective, there should be a method for the above-mentioned improving efforts in order to provide lower bounds on process yields with respect to allocated tolerances at engineering drawings. Therefore, if a tolerance analysis can be developed to measure the actual process performance (achievable tolerances) for manufacturing precision products, there is a potential to improve systematically process efficiency by decreasing development efforts and productions costs.

Since quality improvement attempts deal with variability and the only way to describe this, is in statistical terms, statistical methods have central role in tolerance analysis. Every aspect of manufacturing

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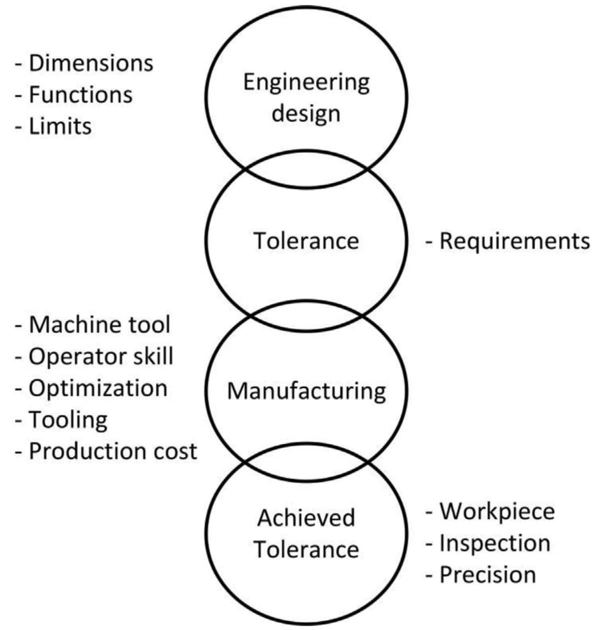

Fig. 1. Effect of tolerances on design and production.

business is significantly influenced by the limits in engineering design as well as production level. Tolerance analysis of manufactured parts checks the conformity of process to specified values, or to assist in modifying the process until the desired values are obtained (Fig. 1).

Beginning in the late 1980, researchers began investigating methods for selecting tolerances at design level (tolerance requirements as seen in Fig. 1). As this research has progressed, it has been found that design and manufacturing are the most important issues for mechanical tolerance analysis in order to ensure competitive products. In 1988, Chase and Greenwood [2] published a document regarding common and advanced tolerance analysis for designers. They demonstrated that quality control techniques must be used to determine process capability in order to make advanced tolerance analysis and optimization methods available. In 1991, Kenneth et al. [3] reviewed applications of tolerance analysis for predicting the manufacturing effects on performance and quality control. It was discussed that Monte Carlo Simulation is capable for tolerance analysis of mechanical assemblies, for both nonlinear assembly functions and non-Normal distributions. Moreover, Nigam and Turner [4] discovered that the role of tolerance requirements is to indicate a choice of manufacturing technology and process parameters. Then it is statistical tolerance analysis that has to determine the effect of manufacturing process on the part precision, and associated specification limits has no more relevance at this stage. From studies conducted by Gerth and Hancock [5], the effectiveness of Monte Carlo Simulation was validated with actual production data to improve a complex process system that contains large number of variables. It was also shown that Monte Carlo and Root-sum-square (RSS) are the most common and reliable statistical methods available for tolerance analysis. In 2011, Fischer [6] published a document and discussed, that when assuming all component tolerances to be $\pm 1\sigma$, $\pm 2\sigma$, $\pm 3\sigma$, then the RSS assembly tolerance represents $\pm 1\sigma$, $\pm 2\sigma$, $\pm 3\sigma$ respectively.

Due to the simplicity and effectiveness, process capability ratios (C_p and C_{pk}) have been used to represent the ability of the process to manufacture products that consistently stays within the specification limits [7]. These numerical measures may quantify process potential and performance using suitable statistical methods. The ratios have received substantial attentions in engineering literature as well. Wu et al. [8] published a review of theory and practice on process capability ratios for quality assurance for years 2002–2008 at which applications of these ratios over a variety of processes and productions are discussed. Statistical tools are often used for tolerance analysis in manufacturing. In 2012, Barkallah et al. [9] developed a statistical method for simulation of 3D manufacturing tolerances of a milling process using small displacement torsors (SDT). In 2013, the quality control of injection-molded micro mechanical parts was explored using uncertainty measurement, quality control approach and measuring instrument capability ratios by Gasparin et al. [10]. Khodaygan and Movahhedy [11] used the concept of process capability to propose new functional process capability ratios for estimation of process performance expressed in nonconforming percentage and performed sensitivity analysis for optimization of process variables. Additionally, Singh [12] conducted a study for process capability analysis of fused deposition modelling (FDM). The results realized $\pm 4.5\sigma$ limit for dimensional accuracy of plastic component used in bio-medical applications. Recently, Kumar et al. [13] concluded that three dimensional printing as casting solution for non-ferrous alloys is capable ($C_p \geq 1.33$) of manufacturing components within $\pm 5\sigma$ limit with respect to dimensional accuracy. However, the effect of gauge measurement errors were not considered in capability calculations in the last two studies.

The aim of this study is to develop a simple tolerance analysis based on conventional process capability ratio. In particular, the analysis describes tolerances, which can be achieved when manufacturing technology is known. The paper will examine if reliable control limits can be established to adjust expectations for future production. The data for statistical analysis are from measurements performed on actual workpieces. Consequently, the sample data are affected by errors caused by measuring instrument, environment and workpieces. In this paper, the measurement uncertainty will be used and compared to tolerances calculated from process capability ratio to obtain reliable critical limits and confidence bounds. The conformity with a calculated tolerance will be proved when the complete measurement result (measurements including measurement uncertainty) falls within conformance zone of a workpiece characteristic according to ISO standard. The proposed method has several benefits for process decision-making and process optimization. There is no need to define functional relationships between quality characteristics and critical-to-quality variables. This paper provides a case study illustrating the achievements of the proposed method. The materials and tools used in the case study for sample production are presented in Section 2. In Section 3, the methodology and the basic concepts for both process capability ratio and measurement uncertainty along with their limits and requirements, are discussed. Section 4 explains results for conformity testing to use of process capability ratio. In addition, the calculations of measurement uncertainty for quality variables under consideration are obtained. In Section 5, tolerance analysis is described. The limits from the proposed method are validated with the tolerances obtained from worst case and RSS methods. A full description of tolerances with respect to measurement uncertainties for the case study are discussed.

2. Material and tools

For many years, shearing has demonstrated prominent cutting method, which is characterized by high speed and low material loss. The method has also received attention for high performance in various applications such as biomedical [14], optical MEMS [15], electrical motors [16], lithium-ion cell stacking [17] and billet shearing [18].

For precision manufacturing of micro metal parts in a micro cold former, it is important to maintain tight dimensional tolerances on cropped billets (Fig. 2) in order to control the volume of material at each forming operation; otherwise, the force distribution (F1 and F2 in Fig. 2) is impaired on the upper plate of former. Consequently, this will cause tool deflection, which introduces errors in geometry of final produced parts. To reduce this variability, a tolerance of 0.5–1% is generally recommended for weight of billets in solid forming [19].

A cropping tool with bar and cutoff holder was manufactured. The shearing tool primarily was developed to fabricate billets for precision manufacturing of micro metal parts using high performance transfer