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Statistical quality control in micro-manufacturing through multivariate μ-EWMA chart

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ABSTRACT

Micro-manufacturing processes are characterized by high process variability and an increased significance of measurement uncertainty in relation to tight tolerance specifications. Therefore, an approach that separates the superposition of measurement and manufacturing variation is demanded. A novel design for a quality control chart that makes it possible to monitor, control and extract measurement variation from manufacturing variation is proposed. Thus, a definite cause diagnosis on the approval or rejection of micro-components due to errors either in the measurement or in the manufacturing process is possible. The proposed multivariate μ-EWMA chart which is based on weighting each measurement data with its current measurement variation is discussed and benchmarked with traditional control charts.

1. Introduction

In order to guarantee stable processes, micro-manufacturing techniques must be controlled and continuously improved by an effective quality assurance. Up to now, there are no such production accompanying methods at hand as the statistical process control (SPC) applied in the macro-world is so far only adequate for non-varying series production with data that is based on a capable measurement instrument [1]. In contrast, micro-manufacturing processes are characterized by an uncertainty of geometric measurement results. The assumption valid for macro-dimensions saying that measurement devices are 10 times more precise than the given tolerance intervals does not hold true for micro-production. The measured data is always subject to a superposition of manufacturing process variation and measurement variation. Furthermore, Estler [2] detected that dimensional metrology in particular is always based on incomplete information and that, therefore, the result of a measurement represents a probability distribution. As a consequence, the superposition of manufacturing process variation and measurement variation renders the control of micro-manufacturing processes more difficult and requires new guidelines and tools.

The research challenge consists of the separation of manufacturing and measurement variation in order to control manufacturing processes and not a superposition of both processes. Finding a solution for this problem will allow for progress with regard to the effective control of micro-manufacturing processes and thus, the development of robust manufacturing processes.

2. State of the art

2.1. Measurement uncertainty and measurement variation

The main sources of information for quality assurance are dimension, shape, and position of workpiece properties. Multi-sensoric coordinate measuring machines (CMM) are widely used for the characterization of geometric features with regard to their flexibility and correlating versatile application options [3].

Regarding the determination of measurement uncertainty (MU) for micro-measurands, the experimental approach offers the most viable and flexible method for an industrial application. The estimation of task-specific CMM uncertainty using the experimental approach is based on the repeated measurement of one or more calibrated objects which resemble the actually measured workpieces. Calibration uncertainty u_C, the uncertainty of the repeated measurement u_P, the uncertainty from variations of workpiece features u_W and the absolute value of the systematic measurement error E Eq. (1) add to the uncertainty.

$$U = \sqrt{u_C^2 + u_P^2 + u_W^2} + |E| \quad (1)$$

Test series with workpieces machined from hardened steel X38 by means of micro-milling and laser ablation showed a great influence of MU resulting from repeated measurements of the same object u_P and from shape deviations u_W of the objects. This means, that a significant part of the experimental determination of MU for CMMs can be quantified through multiple measurements of the same object.

2.2. Quality control charts and measurement error

Up to now, mostly $\bar{x}$-Shewart quality control charts (QCC) or, in a few cases, advanced QCC designs such as EWMA (exponentially

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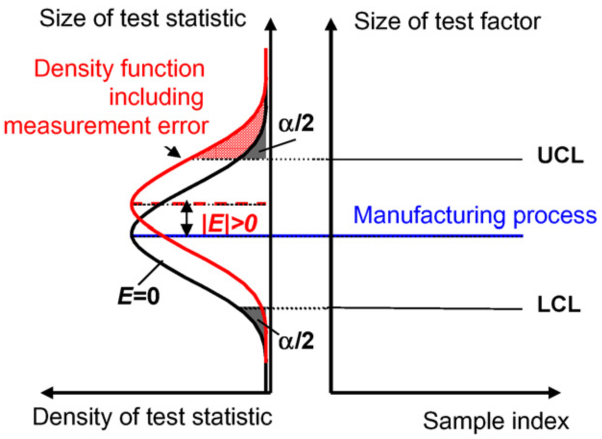

Fig. 1. Systematic measurement error E leads to a shift of the mean.

weighted moving average) or CUSUM (cumulated sum) charts have been used for the statistical process control of manufacturing technologies. In these cases, samples of workpieces are measured and the mean of the quality feature is plotted on a time scale to ascertain whether the manufacturing process is under control, i.e. whether or not it is kept within the control limits (between UCP = upper control limit and LCL = lower control limit). Values outside the CLs (confidence interval, α) refer to an out of control situation requiring the manufacturing process to be stopped and the cause of the out of control situation to be identified. When monitoring a micro-manufacturing process via standard QCCs, the following two errors and misinterpretations can occur (Figs. 1 and 2).

In case of a systematic measurement error (Fig. 1), the measured value consists of the real value plus/minus the systematic measurement error E (Eq. (1)). In contrast, the CLs are calculated on the basis of the original density function. Thus, when plotting the samples mean on a traditional QCC, samples of the mean will frequently fall outside the CL only due to the systematic measurement error. The cause of the out of control situation will wrongly be sought within the manufacturing process but not within the measurement process as should be the case. In statistical terms, the false alarm probability of first order increases.

The second misuse of traditional QCCs can occur in case of a random measurement error (u_P and/or u_W of Eq. ((1)) quantified by repeated measurements of the same object (Fig. 2). Thus, the calculated CLs are too large as they include both manufacturing and measurement variation. In contrast to the case of systematic measurement error, an out of control situation of the manufacturing process can be hardly identified as the CLs are too large and the false alarm probability of second-order increases (=out of control case is not identified).

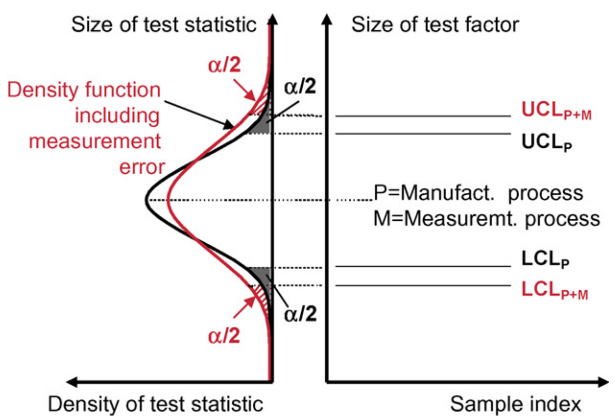

Fig. 2. A random measurement error (u_P and/or u_W) leads to an increase of measurement variation.

Although this issue is of paramount importance for process control in industry, there are only a few contributions to be found in the literature which deal with the effect of measurement errors on the usage and informational value of QCCs. All models suggested by the literature are based on the assumption that the observed measurement result Y is derived from adding a measurement error ε to an actual quality characteristic X (i.e. the real diameter of a drill):

$$Y = X + \varepsilon \tag{2}$$

however, measurement error ε is always assumed to be constant and the MU U according to Eq. (1) is not taken into consideration. That is, there is no recommendation on how to separate the random measurement error u_P and/or u_W from the manufacturing process.

2.3. *Identified deficits*

As in micro-manufacturing the MU is in the same range as the specified tolerances, a decision on approval or rejection of the measured object with regard to its operability is very difficult to make. One significant factor for the experimental determination of the MU for CMMs is measurement variation, which can be quantified by performing repetitive measurements of the same measurement object. The measured data of different components is always subject to a superposition of manufacturing variation and measurement variation. Up to now, not even state-of-the-art QCCs allow for the separation of manufacturing and measurement variation and, thus, do not provide for a definite cause diagnosis in case of malfunctions in the manufacturing or the measurement process.

Therefore, for the effective monitoring and controlling of micro-manufacturing processes with tolerances in the sub-micrometer range to be ensured, measurement variation must be monitored continuously and measurement and manufacturing variation must be separated. Thus, our focus is on achieving the continuous monitoring, controlling and separation of measurement and manufacturing variation in a simple and reliable manner.

3. Sugggested approach

3.1. *Multivariate μ-EWMA chart*

The identification of a systematic measurement error E should be quantified by means of measuring standards or calibrated objects which resemble the actually measured workpieces. Afterwards, the value of the systematic measurement error E needs to be compensated when calculating the CLs of the QCC. In order to cover the case of a drift of the measurement system away from zero bias, we recommend well-repeated measurements of the calibrated object in certain time intervals and the comparison between the arithmetic mean of the measurements and the true value. The handling of the random and time-varying measurement error, in turn, is more difficult. Therefore, a multivariate μ-EWMA QCC consisting of two charts was developed in order to

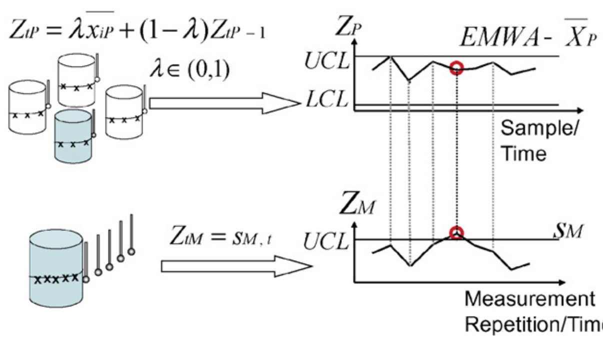

Fig. 3. Approach to the multivariate μ-EWMA chart.