Statistical analysis of the quality of a technological process for the production of shafts for electric motors by roughness study

Kliment Georgiev
Technical University of Sofia, branch
Plovdiv
Faculty of Mechanical Engineering;
Department: Mechanical and
Instrument Engineering
Plovdiv, Bulgaria
k.georgiev@tu-plovdiv.bg

Abstract. **This paper presents a statistical analysis of the quality of a technological process by investigating the surface roughness of shafts for electric motors obtained during machining. Repeated measurements have been carried out using a portable roughness tester INSIZE ISR - C002 and the results are summarized. Statistical analysis is applied to analyse the accuracy, adjustability, and stability of technological process. The stability of the process is presented by investigating the correlation between the experimental and theoretical curve of the quality index. Accuracy evaluation is performed by calculating the accuracy coefficient. The adjustability analysis is evaluated by the relative position of the distribution curve of the obtained quality index with respect to the tolerance field.**

Keywords: analysis, quality, quality control, surface roughness, technological process, stability, accuracy, adjustability.

I. INTRODUCTION

With the development of technology, the quality requirements of the machined parts are increasing. The quest for defect-free production of quality workpieces leads to the need for in-depth technological process (TP) research and analysis.

Statistical analysis methods can solve many problems related to process quality. The three main tasks presented are some of the most important in process analysis:

- Process stability analysis;
- Process capability (accuracy) analysis;
- Analysis on process regulation (tuning);

The ability and regulation of the process is collectively called efficiency. The quality of a process is determined by its stability and efficiency.

A. Process stability analysis

Stability of the TP means preservation of the parameters of the distribution of deviations of the qualitative indicator according to a certain law for a sufficiently long time. The initial assessment of stability can be performed by means of point diagrams. In stable processes, the variance of the qualitative indicator is kept constant, and its meaning is either constant or changes in a regular manner. In unstable processes the variance changes randomly. Intermittent periods with qualitative or defective output are alternated. Stable processes are predictable, i.e. amenable to statistical control Fig. 1. Unstable processes are unpredictable, i.e. unsuitable for statistical control and quality regulation Fig. 2.

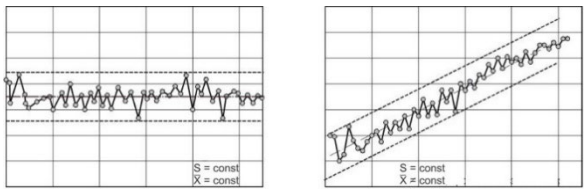

Fig. 1 Stable technological process

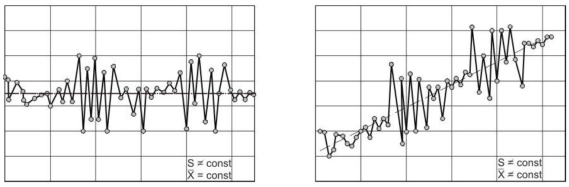

Fig. 2 Unstable technological process

Print ISSN 1691-5402
Online ISSN 2256-070X
https://doi.org/10.17770/etr2024vol3.8137

Process stability analysis is studied and evaluated using two approaches:

- By examining the correspondence between the experimental and theoretical qualitative indicator curve;
- By examining the histogram of the process;

The first approach is used less frequently when the process flow is not influenced by a dominant systematic factor that shifts the distribution, i.e. the average value of the qualitative indicator remains constant over time (stationary TP).

The second approach is more universal and is applied more often. It examines and analyses the average value of the qualitative indicator using the regression equation.

B. Statistical analysis of accuracy of a TP

This analysis applies only to proven stable processes. Accuracy is assessed by the accuracy factor.

If appropriate, the tolerance may be reduced. The other solution is to keep the tolerance but intensify the machining process by changing the mode parameters, which will increase productivity.

C. Tuning analysis of a TP

This is the third task of statistical analysis (the first for stability and the second for accuracy). Tunability is characterized by the relative position of the distribution curve or accuracy diagram with respect to the tolerance field.

Tuning is a process where the process system is brought into a state to produce a certain value of a quality metric. This value, which the output quality indicator should obtain at the beginning of operation after tuning, is called the working setpoint. It is defined differently for statistically stable and technologically stable processes.

Quality is a set of characteristics (indicators) of an object that determine its ability to satisfy certain or supposed needs. An object can be a product, an activity, a process, an organization, a person.

According to Mitra A. (2016) the aspects of the quality are three: Quality of conformance, Quality of Design and Quality of Performance (fig.3) [1].

Quality of conformance implies that a manufactured product or a service rendered must meet the standards selected in the design phase. This phase is concerned with the degree to which quality is controlled from the procurement of raw material to the shipment of finished goods [1].

Quality of performance is how a product functions or service performs when used. It measures the degree to which the product or service satisfies the user [1].

The way the product or the service satisfies the customer is a function of both quality of design and quality of conformance [1].

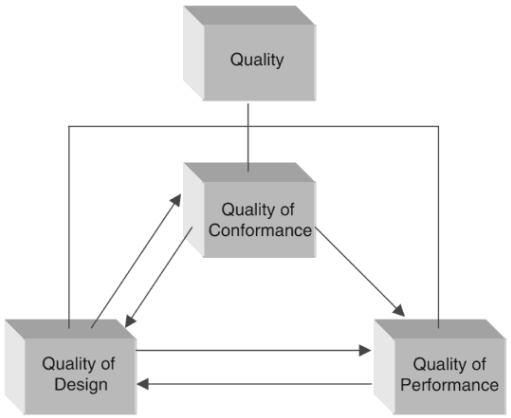

Fig. 3 The aspects of quality [1]

In this paper, an analysis of a technological process is presented and its stability, accuracy and tunability are investigated. The parameter used for quality assessment is surface roughness.

II. MATHERIALS AND METHODS

A. Matherials

The details used for the experimental studies are presented in Fig. 4. All experiments were conducted in a laboratory environment under controlled temperature and humidity conditions. The measuring instrument was pre-calibrated before the measurements were started.

The shaft is processed in two operations. The first machining is on the long side with a back saddle support. The machine is a DMG CLX350 with the following cutting modes:

- Rough machining: Vc = 115m/min, a = 1.5mm, F = 0.25 mm/rev;
- Fine machining: Vc = 200m/min, a = 0.5mm, F = 0.15 mm/rev;

The second processing is carried out on a Mazak Qtn 200 MSY. The basis of this machining is on the short side of the workpiece to the two-stand in the following cutting modes:

- Rough machining: Vc = 100m/min, a = 1.5mm, F = 0.24 mm/rev;
- Fine machining: Vc = 185m/min, a = 0.4 mm, F = 0.15 mm/rev;

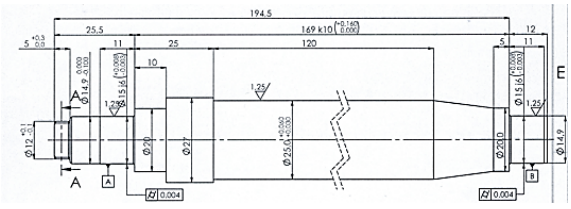

Fig 4. Measured detail

B. Methods

The technological process for manufacturing shafts for electric motors is evaluated by statistical analysis of the qualitative parameter roughness. Stability, accuracy, and process tuning analysis have been applied in the evaluation of the technological process. Statistical analysis using X and R control charts was used to evaluate the process.

The SPC is a basic statistical tool for verifying the conformity of technical requirements of products. Even in robust manufacturing processes, quality characteristics are associated with randomness due to the presence of uncontrollable (or difficult/costly to control) input variables [2].

Gejdos P. (2015) says that the control charts are the most frequently used tool in the statistical regulation of processes. According to him they allow us more accurate distinguishing of random from symmetric causes of the fluctuations in the value of a mark of quality. Control charts facilitate regulation and improvement in the quality of the technological process [3].

Process capability analysis is an important tool in the DMAIC (Define, Measure, Analyze, Improve and Control) process, with application in both the analyze and improve steps [4].

According to Oakland J. (2007) the basis of the theory of statistical process control is differentiation of the causes of variation during the operation of any process. Certain variations belong to the category of chance or random variations, about which little may be done, other than to revise the process [5]. Fig. 5 shows a schematic control chart.

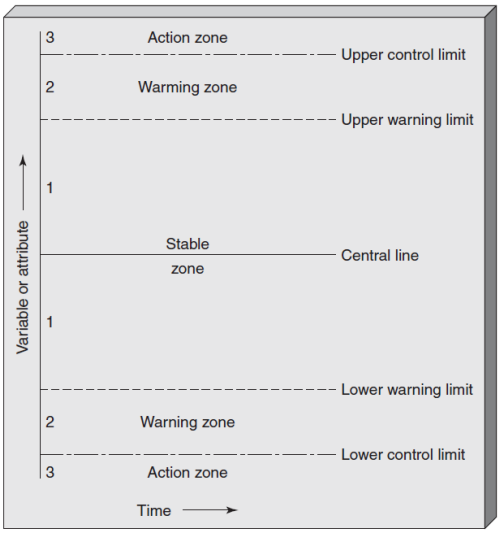

Fig 5. Schematic control chart [5]

When Control charts are applied, it is assumed that the behavior of the process could be characterized by the level or one or several qualitative values. These values are also known as regulated values. Control charts are used in monitoring processes and when ascertaining the need for corrections or changes in the process, to achieve a better mean value of the process or to reduce variability in the process. In control charts, the horizontal axis contains the times when statistical sampling of regulated values took place, and the vertical axis contains calculated values of the appropriate sample characteristics [3].

To build the control charts X, it is necessary to calculate: upper control limit (UCL), lower control limit (LCL) and center line (CL)[6, 7].

X chart is used to reflect changes in the average values of a process. To construct an X chart, it is necessary to draw its center line (CL). This is achieved by collecting the sample data and calculating the mean of $\bar{x}$ [8, 9].

$$\bar{x} = \frac{x_1+x_2+x_3+x_n}{k} \quad (1)$$

$$CL = \bar{x} \quad (2)$$

To calculate the upper and lower control limits, the following formulas are used:

$$UCL = \bar{x} + z\sigma_{\bar{x}} \quad (3)$$

$$LCL = \bar{x} - z\sigma_{\bar{x}} \quad (4),$$

where:
$\bar{x}$ - average value of the sample;
z – standard normal variable equal to 2 for 95.44% confidence interval and 3 for 99.73% [10];

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}} \quad (5),$$

where:
σ – process standard deviation;
n – number of tests per sample.

Since σ is usually unknown, we must replace it with an estimate. Most frequently the use of as an estimate of σ, which is the sample standard deviation (s) [4].

Process capability ratio is a frequently used way to express process capability. There are many ways to express process capability and one of them is in terms of the process capability ratio (PCR) C_p, which for a quality characteristic with both upper and lower specification limits (USL, LSL) is [4]. USL stands for Upper specification limit, that can be also called Upper Tolerance limit. The same goes to LSL, which is Lower Specification limit, which is also known as Lower Tolerance Limit:

$$C_P = \frac{USL-LSL}{6\sigma} \quad (6)$$

According to Montgomery D. C (2009) the 6σ spread of the process is the basic definition of process capability. Since σ is usually unknown, we must replace it with an estimate. Most frequently the use of
as an estimate of σ, resulting in an estimate $\widehat{C_p}$ of C_p is "s", so [4]:

$$\hat{\sigma} = s \quad (7)$$

Based on the above, we arrive at the formula for calculating the precision factor $\widehat{C_p}$ by the following formula:

$$\widehat{C_p} = \frac{USL-LSL}{6\hat{\sigma}} \quad (8)$$

The analysis of the process setup can be represented by calculating the coefficient C_{pk}:

$$C_{pk} = \min(C_{pu}, C_{pl}) \quad (9),$$

where:

$$C_{pu} = \frac{USL-\mu}{3\sigma} \quad (10)$$

$$C_{pl} = \frac{\mu-LSL}{3\sigma} \quad (11)$$

According to what is written above σ is usually unknown and we can replace it with (s), μ or c $\bar{x}$.

III. Results and Discussion

The experiments were conducted in a laboratory environment under controlled conditions of temperature and humidity. Twenty shafts were measured, and each shaft was measured three times. According to the submitted technical documentation, the nominal prescribed roughness was Ra = 1.25 μm with USL = 2.25 μm and LSL = 1 μm. The results of the shaft roughness measurements are presented in Table 1. The same results The standard deviation is calculated using the formula (12):

$$s = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}} \quad (12)$$

For the data presented in Table 1, the value of the standard deviation is:

$$s = 0{,}0229\text{mm} \quad (12)$$

The X chart is constructed using formulas (3) and (4) to calculate the UCL and LCL, replacing σ by the value of s as described above. The confidence interval was chosen to be 3σ, respectively 3s, hence:

$$UCL = \bar{x} + zs \quad (13)$$

$$LCL = \bar{x} - zs \quad (14)$$

were used for the statistical analyses.

Table 1 Measurement Data

№	Surface Roughness, μm			Average
	1	*2*	*3*	$\bar{x}$
1	2.023	2.051	2.068	2.05
2	2.076	2.063	2.083	2.07
3	2.114	2.049	2.109	2.09
4	2.077	2.064	2.106	2.08
5	1.996	2.018	2.019	2.01
6	2.059	2.055	2.046	2.05
7	2.072	2.012	2.021	2.04
8	2.061	2.043	2.037	2.05
9	2.061	2.054	2.049	2.05
10	2.063	2.068	2.007	2.05
11	2.034	2.063	2.078	2.06
12	2.086	2.073	2.095	2.08
13	2.123	2.061	2.121	2.10
14	2.082	2.075	2.128	2.10
15	2.005	2.025	2.028	2.02
16	2.069	2.068	2.056	2.06
17	2.083	2.023	2.035	2.05
18	2.075	2.052	2.052	2.06
19	2.085	2.065	2.066	2.07
20	2.073	2.085	2.025	2.06
Total average				2.06

After substituting the data in formula (13) and (14), the following results are obtained:

$$UCL = 2.06 + 3 \times 0.0229 \quad (13)$$

$$UCL = 2.128\ \mu\text{m};$$

$$LCL = 2.06 - 3 \times 0.0229 \quad (14)$$

$$LCL = 1.991\ \mu\text{m};$$

The value of $\bar{x}$ is taken as the central line. The histogram in Figure 6 graphically presents the results of the study.

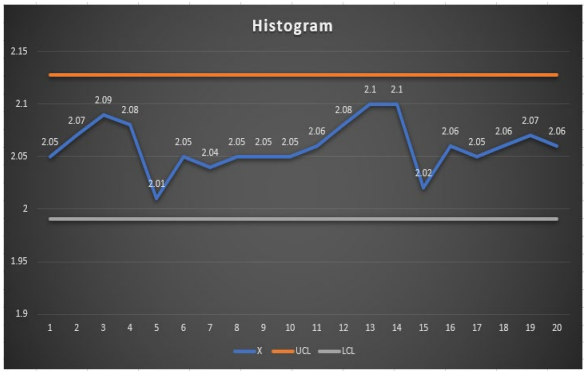

Fig 6. Histogram

The plot in Fig. 6 shows the distribution of the value of$\bar{x}$ versus the upper and lower bounds. Although all the values of $\bar{x}$ are outside the tolerances, the process does not cross the control limits.

The calculation of the accuracy coefficient was carried out using formula (8).

$$\widehat{C_p} = \frac{2{,}25-1}{6\times 0{,}0229} \quad (8)$$

$$\widehat{C_p} = 9{,}1$$

According to the standard used, the values of the resulting accuracy factor C_p must be greater than 1.67 to satisfy the process accuracy conditions. The resulting value for the coefficient C_p = 9,1, which is greater than the 1.67 that is specified in the standard.

The estimation of the tunability of the technological process was made by using the coefficient C_{pk}, formula (9). Calculate the values of the criteria in the upper limit deviation (C_{pu}) (10) and the value of the criteria in the lower limit deviation (C_{pl}) (11), The criteria then require the minimum value obtained to be assumed to be selected.

$$C_{pu} = \frac{2{,}25-2{,}06}{3\times 0{,}0229} \quad (10)$$

$$C_{pu} = 2{,}76$$

$$C_{pl} = \frac{2{,}06-1}{3\times 0{,}0229} \quad (11)$$

$$C_{pl} = 15{,}43$$

It follows from the calculations that for the coefficient C_{pk} must be chosen the value of $C_{pu} = 2{,}76$, which is the minimum. The value adopted for $C_{pk} = 2{,}76$ is greater than that recommended in the criterion ($C_{pk} > 1{,}67$).

IV. CONCLUSIONS

1. The process is set, and no upper or lower control limit crossing is observed.
2. The calculated process accuracy factor C_p = 9,1 indicates that the process is accurate.
3. The process tuning evaluation factor $C_{pu} = 2{,}76$ indicates that the process is well tuned.
4. The set nominal roughness is not met, but nevertheless the measurement data and statistical analysis show that the process is set, accurate and adjustable.

AKNOWLEDGEMENTS

The author/s would like to thank the Research and Development Sector at the Technical University of Sofia for the financial support."

REFERENCES

[1] Mitra, A. (2016). *Fundamentals of quality control and improvement*. John Wiley & Sons.

[2] Hristov, M. H. (2023, September). SPC as an Instrument for Implementation and MSA as an Instrument for Evaluation of Non-Linear Object Based Temperature Compensation into Shop Floor CMM. In *2023 15th Electrical Engineering Faculty Conference (BulEF)* (pp. 1-9). IEEE.

[3] Gejdoš, P. (2015). Continuous quality improvement by statistical process control. *Procedia Economics and Finance*, *34*, 565-572.

[4] Montgomery D. C., Introduction to Statistical Quality Control, Sixth Edition, Copyright 2009 by John Wiley & Sons, Inc., ISBN 978-0-470-16992-6

[5] Oakland, J., & Oakland, J. S. (2007). *Statistical process control*. Routledge.

[6] H.R. Radev, "Metrologiya i izmervatelna tehnika", vol. II, S., Softtreyd, 2010, ISBN: 978-954-334-093-4

[7] Дюкенджиев Г., Р.Йорданов, Контрол и управление на качеството, София., Софттрейд, 2002.

[8] Statistical process control (SPC), Reference manual, Copyright 1992, Chrysler Corporation, Ford Motor Company, and General Motors Corporation

[9] Allen T., Introduction to Engineering Statistics and Lean Six Sigma, Statistical Quality Control and Design of Experiments and Systems, Third Edition Springer-Verlag London Limited 2006, ISBN 978-1-4471-7420-2 (eBook), https://doi.org/10.1007/978-1-4471-7420-2

[10] Qiu P., Introduction to Statistical Process Control, 2014 by Taylor & Francis Group, LLC, ISBN-13: 978-1-4822-2041-4 (eBook - PDF)