THE LASER TEXTURED SURFACES OF THE SILICON CARBIDE ANALYZED WITH THE BOOTSTRAPPED TRIBOLOGY MODEL

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Abstract

The surface layer properties of super-hard materials may be modified by a laser beam treatment and the regular texturization is one of possible approaches. The designed experiment was conducted based on two main controlled factors: the average diameter of cavities and the level of the blackening. The obtained dataset was processed with a response surface model for the coefficient of friction as the outcome. Typical statistical analysis of data with quantitative control factors bases on many theoretical assumptions, with the most important and the most influential one: the normality of random noises distributions. Such assumption is often used but rarely it is analyzed for its weakness and large uncertainty in results. The paper describes a non-parametric approach to the statistical analysis of the uncertainty. It releases us from the direct assumption of particular probability distributions. The bootstrap is formally the method based on random resampling with replacement from the source dataset. It allows to identify the whole distribution shape of raw data and related confidence intervals without additional assumptions about particular distribution. The paper presents the analysis processed for the practical case: original, commercially available rings for front sealing sintered from SiC with a texture modified by a laser beam and tested on tribological tester for changed properties. The paper contains notes on encountered difficulties and possible guidelines for similar analysis.

Keywords: Bootstrap, uncertainty, non-parametric approach, tribology, laser beam texturization

1. INTRODUCTION

The accessibility of materials with new properties decides on the development of engineering innovations. The first attempts to machine metals by the electrical discharge were made in the 1930s, however the origin of such approach dates back to 18th century, to John Priestley who discovered the erosive effect of the electrical discharge. In 1946 B.R. Lazarenko and N.I. Lazarenko patented industrial scale electro-spark maching tools. Since then, research into electrical erosion physics has focused on two areas: removal machining (EDM - Electro-Discharge Machining) and increment machining (ESA - Electro-Spark Alloying). The specific variant of ESA was developed: the electro-spark deposition (ESD) and has found recognition as a cheap method to transfer a material of an electrode onto the surface of machined material utilizing concentrated energy flux. It allows enhancing properties of the material surface layer.

The direction of a material transport depends on the polarity of electrodes: eroded material is transferred from the anode to the cathode and a new coating is formed on the surface of the cathode. Thus, in ESA/ESD machining process the electrode is anode and machined material is cathode. The ESA/ESD process is usually used to make a coating to protect new elements or recover worn elements. The robustness for wearing may be significantly enhanced by deposition of a material with greater hardness on the surface of machined element [1]. Unfortunately, an undesirable side effect of ESD is a surface with high roughness. The possible solution leading to the lower roughness is a specific point-localized melting induced by a high energy impulse of the laser beam (LBM - Laser Beam Machining). This melting changes microgeometrical and physical properties of a surface layer [1].

Two parameters controlling LBM process were investigated. The first factor was the cavity diameter and the second factor was the level of blackening. The outcome of the analyzed process was the average friction coefficient determined on the tribological tester. The experiment was planned and conducted according the response surface methodology (RSM) [2] being a branch of the design of experiment (DoE). Originally the appropriate RSM mathematical model was identified and analyzed using classic statistical methods [2].

The formal RSM model includes the specific additive random term describing 'noise factors'. The noise factors are the surrogate name for all uncontrolled process and environmental disturbances. The well-known parametric analysis and the least squares (LSQ) estimation assumes that the joined effect of noise factors is described by the normal distribution with the mean of zero value and the unknown variance. The remain part of the analysis procedure bases on this assumption and leads to the uncertainty of the obtained results described by *t* Student distribution [2]. Many observations supported especially by box-plots reveals that such assumption is poorly met [3, 4] and thus the description of the results uncertainty made by *t* Student distribution may be unreliable [5-8]. The solution of such problem are analytical procedures weakly related to the specific probabilistic distribution and under the common name 'non-parametric methods'. This set of methods includes among others solutions based on ranks e.g. Kruskal-Wallis ANOVA, solutions based on re-sampling e.g. Efron's bootstrap or the specific solution based on Wilkes's theorem i.e. Owen's empirical likelihood ratio. However both solutions, Efron's and Owen's base on an intensive numerical computations but Efron's solution is easy to implementation while Owen's rather not. The non-parametric methods are especially useful for the fuzzy approach which is very suitable for vague data, uncertain data or incomplete datasets.

The following sections will discuss and apply the bootstrap method to analyze differences between uncertainty of the model parameters obtained from the classic analysis (based on the weak assumption of the normality) and from the bootstrap (without the assumption of the normality).

2. MATERIALS

Commercially available rings (diameter 37mm, internal diameter 26.5 mm, thickness 8 mm) for front sealing sintered from SiC were textured by a laser beam. Regularly gridded crater-shaped cavities appeared after texturization (**Figure 1).**

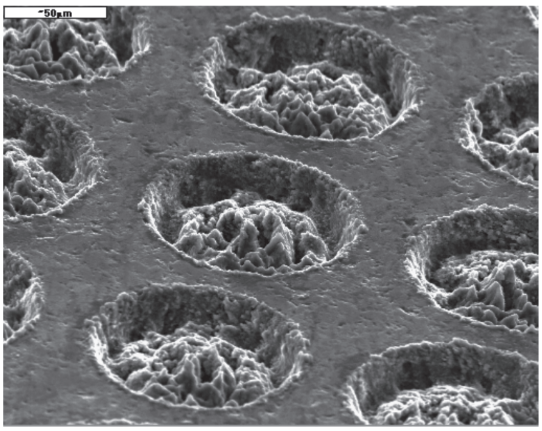

Figure 1 The texturized surface at 500x magnification

The rough surface was treated by means of lapping and superfinishing. This process led to obtain flat and hard areas allowing to transfer normal loads. Hydrodynamic forces were generated by neighboring cavities during a liquid lubrication and such surfaces may be used in sliding friction pairs. Ring surfaces texturized by

LBM were investigated on the tribological tester T-01M. The coefficient of a friction was measured as an outcome. The stem of the tester was replaced with a specifically cut bearing ball.

The central composite experimental design was used to plan the whole experiment. Two factors (the cavity diameter and the level of the blackening) were used at 5 levels each. The experimental design included 9 different treatments and 5 replication in the center treatment to evaluate the pure error i.e. the realization of the random term. The outcome dataset included 13 values of the friction coefficient mean.

3. METHODS

3.1. Boostrap approach

The bootstrap method [9] bases on processing of the dataset iteratively re-sampled from the original raw dataset. The idea of the method is presented in **Figure 2**.

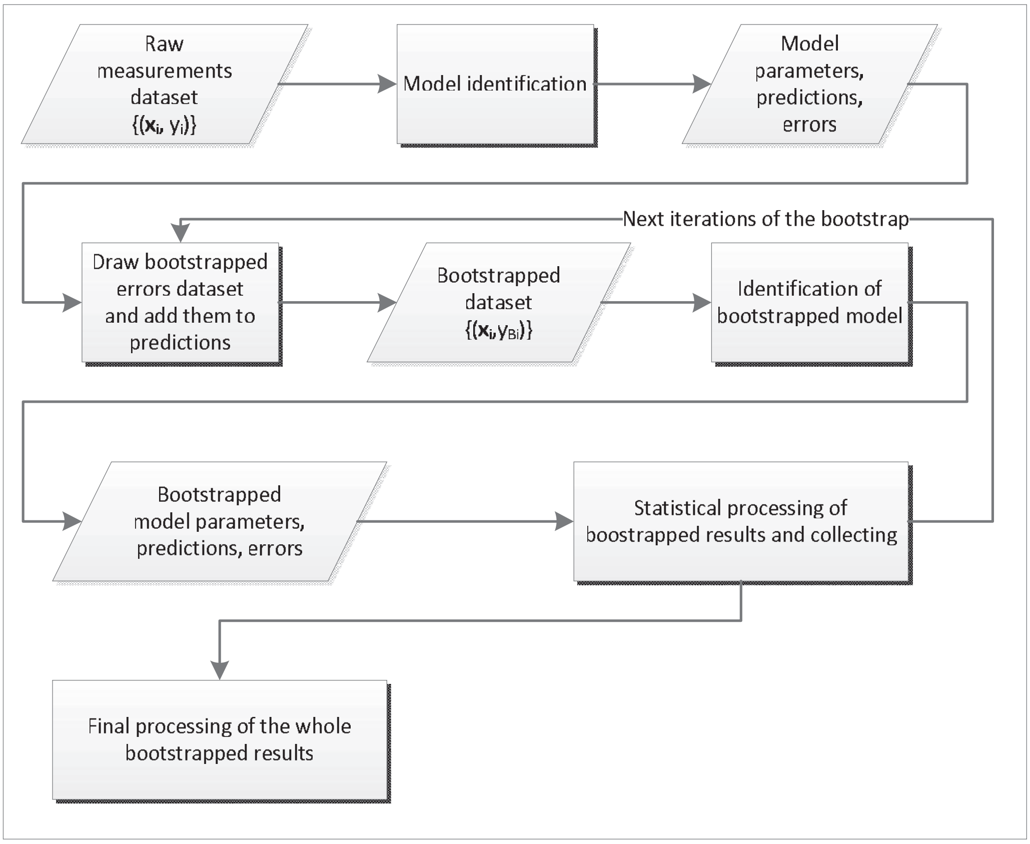

Figure 2 The scheme of the bootstrap method based on residuals

The key issue in the bootstrap is to make a proper identification of the random term built into the analyzed process. The main assumption of the bootstrap is focused on this term: its realizations should be independent and identically distributed (acronym i.i.d). In the designed experiment where a model is built according to the assumed cause-and-effect relationship, usually an error of the model (difference between prediction and measurement) is treated as a realization of i.i.d term.

It leads to the following algorithm: process a raw dataset, identify parameter of an assumed model, evaluates its errors and next iteratively randomly draw new errors dataset from the original errors dataset, add them to original predictions generating bootstrapped predictions, identify the bootstrapped model and process it further collecting obtained results. After a large number of iterations, collected results may be evaluated by statistical methods resulting in a whole distribution instead of the one number as in classic approach.

3.2. Predictive model

The predictive model was selected as a full-quadratic with additional two-way interaction. The model has the following formula:

$$y = \mu + A + B + AB + AA + BB \tag{1}$$

where: y_i - measured value of the average friction coefficient; μ - constant value; A - main (linear) effect the cavity diameter; B - main (linear) effect of the blackening; AB - two-way interaction of A and B factors; AA - quadratic term of A factor; BB - quadratic term of B factor.

4. RESULTS AND DISCUSSION

The analysis of the raw dataset and removing of the insignificant terms led to the base model presented in **Table 1**. The whole response surface is presented in **Figure 2**. The coefficients of the model are reported for coded factors i.e. scaled into range -1.414…1.414 to avoid undesirable numerical errors during calculations.

Table 1 Model parameters and their statistical significance for coded factors

	Parameter	Std. dev.
Constant	0.0915	0.0044
A	0.0040	0.0033
B	-0.0032	0.0034
AB	-0.0012	0.0044
AA	-0.0092	0.0034
BB	0.0086	0.0035

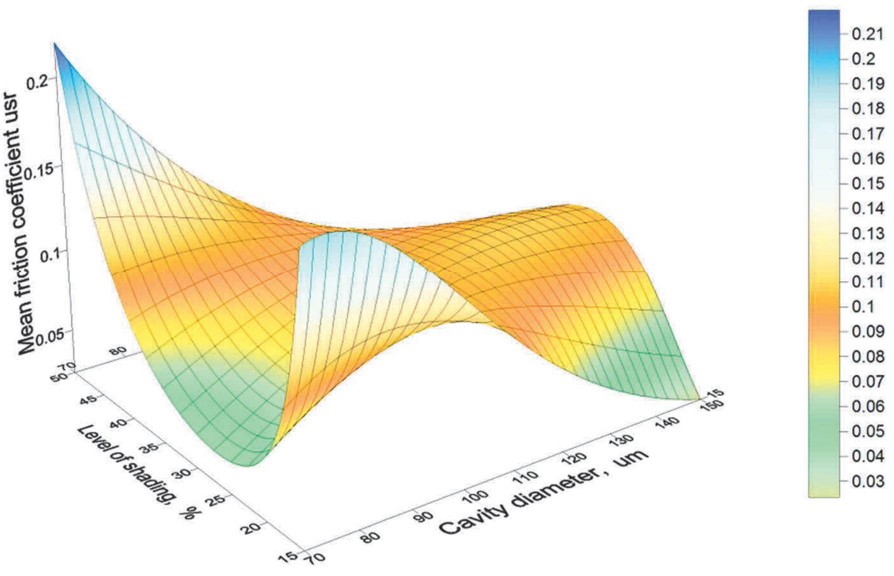

Figure 3 Response surface plot for the identified model

The bootstrap was performed for 10000 iterations, because such a number allows easy identification of bounds for 95% confidence interval (located at 250 and 9750 positions inside sorted dataset columns). The yielded statistics for the model constant and effects are presented in **Table 2** simultaneously with values obtained from classic parametric analysis. Tests of the normality were rejected for constant, B, AA and BB term. The terms for A and AB were not rejected however at very low p-Value: 0.077 and 0.76, respectively. It reveal that classic assumption of normality is usually not met and bootstrap based results and more reliable in this context.

Table 2 Comparison of the statistics of the model constant and parameters obtained from the classic analysis and the bootstrap simulation

Model term	Mean		-95%CI		+95%CI	
	classic	bootstrap	classic	bootstrap	classic	bootstrap
Constant	0.0915	0.0914	0.0793	0.0742	0.1037	0.1073
A	0.0040	0.0011	-0.0052	-0.0119	0.0131	0.0140
B	-0.0032	0.0001	-0.0187	-0.0122	0.0004	0.0117
AB	-0.0012	-0.0011	-0.0126	-0.0181	0.0061	0.0153
AA	-0.0092	-0.0092	-0.0010	-0.0222	0.0183	0.0029
BB	0.0086	0.0092	-0.0134	-0.0043	0.0111	0.0220

5. CONCLUSIONS

1) The bootstrap approach revealed that the normality assumption assumed in the classic approach is met in this data and cannot be set as a base for reliable statistical inference.
2) The yielded values obtained from the bootstrap approach are consistent with means obtained from the classic approach however bounds of the confidence intervals differ even up to 46%.
3) Further analysis should concentrate on more subtle non-parametric analytical techniques like Owen's empirical likelihood ratio to obtain more accurate bounds and regions of confidence.
4) Similar approach may be used in the other domains of materials science analysis where the normality assumptions is rather weakly satisfied e.g. 3D analysis based on SEM preparations [10], piezoelectric actuators [11, 12], vibrations in conical shells [13] or the powder metallurgy [14, 15].

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