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The cross-correlation function in assessment of surface topography shaping by hybrid milling and burnishing

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In world literature much attention is devoted not only to the conscious surface shaping, but also to many problems that can be encountered during surface measurement. The development of surface metrology tries to respond to many industrial needs and keep up with sophisticated production techniques. Nevertheless the estimation and comparison of surfaces after several successive treatments is still complicated. For this purpose, the authors proposed the use of a correlation function to evaluate milled and then burnished surfaces, which is an alternative instrument to the parametric evaluation of the surface topography. This method can directly give an answer, whether the technological process has been carried out as expected. The measurements were carried out using a multi-sensor AltiSurf A520 instrument, manufactured by Altimet, according to its own developed methodology.

KEYWORDS: *surface metrology, hybrid manufacturing, correlation function*

Introduction

Each manufactured product must meet certain technological specification and allow for economical production. In industrial reality, this translates into shortening the production time, balancing production lines and better use of resources [1, 2].

For the production of very demanding and responsible parts (in the automotive, energy, medical industry, etc.), specific solutions are used to combine various manufacturing techniques within a single position (so-called hybrid production) [3, 4]. Then, it is extremely important to determine the state of the surface geometrical structure (SGP) [5] and to establish quality control procedures for critical elements. The control process and creation of measurement procedures pose a serious challenge when the manufactured part must have SGP specific properties. It should also be remembered that in relation to machining with hybrid methods (which is the result of many tasks), the measurement procedures should be properly understood and extremely carefully prepared.

In recent years, many authors have dealt with the problem of creating a new quality in processes related to the surface metrology. The literature clearly emphasizes that limiting oneself to conventional methods of 2D roughness analysis and parametric 3D roughness assessment can lead to erroneous conclusions. 2D and 3D surface roughness parameters may not be sufficient to characterize a given surface feature [6–7]. Separate issues are also the need to create measurement standards and to simplify methods that can be applied in industry [8].

Considering the fact that in the world literature the scope of research on non-parametric SGP assessment is still expanding, the authors attempted a nonparametric assessment of milled and burnished surface, using cross-correlation to record the morphological changes occurring in samples.

Cross-correlation is a measure of the similarity of two data series displaced in relation to each other. It is determined by the formula:

$$C(\tau) = \int f^*(t)g(t + \tau)dt \quad (1)$$

where: f^* – complex coupling of the signal f , $g(t + \tau)$ – shifted signal g , t – time, τ – shift.

Given that surface measurements are two-dimensional and discrete, cross-correlation can be calculated using the following equation:

$$C(k, l) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} S_1(m, n) S_2^*(m - k, n - l) \quad (2)$$

$$\begin{cases} -(W - 1) \leq k \leq M - 1 \\ -(V - 1) \leq l \leq N - 1 \end{cases}$$

where: S_1 and S_2 – matrices (dimensions $m \times n$ and $w \times v$, respectively), including surface measurements; S_2^* – complex coupling; k and l – shifts in both directions.

Research material

Experimental work was carried out on samples of 42CrMo4 steel, tempered to hardness 35 ± 2 HRC. The samples were milled on a DMG DMU 60 monoBLOCK machining center with a spindle axis tilted by 15° . Milling was performed using a torus head (WNT R1000G.42.6.M16.IK) with six cutting inserts with a diameter of $d_p = 10$ mm (RD.X1003 MOT – WTN1205). In tab. I, the machining parameters are given.

The tests were carried out for four drilling cases during milling: $f_{wf} = 0.7$ mm, $f_{wf} = 0.5$ mm, $f_{wf} = 0.3$ mm, $f_{wf} = 0.1$ mm. Immediately after milling, selected samples were subject to burnishing using a single-ball hydrostatic tool with a bellow actuator [9], terminated with a ball of ZrO₂ ceramic with a diameter of $d_k = 10$ mm. The burnishing velocity v_n was 8 m/min and the transverse burnishing feed $f_{wn} = 0.12$ mm. Burnishing was carried out with a force F_n equal to 800 N. Each of the burned fields was 11 mm wide.

TABLE I. List of milling technological parameters adopted in the experimental research plan

Milling speed v_c [m/min]	Depth of milled layer a_p [mm]	Feed per blade f_z [mm]	Milling cross feed f_{wf} [mm]
110	0.5	0.1	0.7
			0.5
			0.3
			0.1

Measurement methodology

SGP measurements on $2 \text{ mm} \times 2 \text{ mm}$ fields were carried out with the use of the Altisurf A520 Altimeturf topography surface measuring machine from Altimet with a CL1 confocal sensor with a working range up to $130 \mu\text{m}$ and vertical resolution of 8 nm . The assumed scan resolution along the X axis was $0.47 \mu\text{m}$ and along the Y axis – $5 \mu\text{m}$. The collected point clouds were developed in the AltiMap PREMIUM 6.2 software. For each surface analysis, the following methodology was used:

- determination of a threshold value to remove incorrectly collected surface points,
- leveling the surface (mean plane approximated by the method of least squares),
- surface leveling (with mean plane),
- determination of selected values of topographic parameters according to ISO 25178 and cross-correlation function.

Processing the results

Tabs. II and III present determined SGP parameters – average values of amplitude parameters and spatial parameters of reference milled samples (tab. II) and milled and then burnished samples with the force $F_n = 800$ N (tab. III).

TABLE II. The values of 3D surface roughness parameters of samples after milling

	Transverse feed during milling f_{wf}			
	0.7 mm	0.5 mm	0.3 mm	0.1 mm
Sq [μm]	4.880	3.337	1.823	0.626
Sz [μm]	24.500	21.100	16.900	9.920
Sa [μm]	4.115	2.857	1.623	0.474
Sal [mm]	0.197	0.165	0.110	0.042
Str	0.195	0.163	0.110	0.044

TABLE III. The values of 3D surface roughness parameters of samples after burnishing with the force $F_n = 800$ N

	Transverse feed during milling f_{wf}			
	0.7 mm	0.5 mm	0.3 mm	0.1 mm
Sq [μm]	0.628	0.342	0.304	0.283
Sz [μm]	9.757	7.570	7.543	6.663
Sa [μm]	0.537	0.273	0.234	0.226
Sal [mm]	0.282	0.206	0.159	0.304
Str	0.291	0.341	0.237	0.336

Fig. 1. Sq (a), Sa (b) and Str (c) parameter values for milled and milled and burnished samples with the force $F_n = 800$ N

Fig. 2. Isometric images of reference milled samples with transverse feed f_{wf} equal to: a) 0.7 mm, b) 0.5 mm, c) 0.3 mm, d) 0.1 mm

Fig. 3. Isometric images of burnished samples with a force $F_n = 800$ N after milling with a transverse feed f_{wf} equal to: a) 0.7 mm, b) 0.5 mm, c) 0.3 mm, d) 0.1 mm

Fig. 4. Correlation results of milled surfaces as well as milled and burnished: a) and c) cross-correlation of a milled sample with feed $f_{wf} = 0.7$ mm and milled with a feed $f_{wf} = 0.7$ mm and burnished with a force $F_n = 800$ N; b) and d) cross-correlation of the milled sample with feed $f_{wf} = 0.5$ mm and the milled sample with feed $f_{wf} = 0.5$ mm and burnished with the force $F_n = 800$ N

Fig. 5. Correlation results of milled surfaces as well as milled and burnished: a) and c) cross-correlation of a milled sample with feed $f_{wf} = 0.3$ mm and milled with a feed $f_{wf} = 0.3$ mm and burnished with a force $F_n = 800$ N; b) and d) cross-correlation of the milled sample with feed $f_{wf} = 0.1$ mm and the milled sample with feed $f_{wf} = 0.1$ mm and burnished with the force $F_n = 800$ N

Based on the results of the tests, it can be stated that there is a significant reduction in the amplitude values of roughness parameters Sq , Sa and Sz at burnishing with 800 N. The final effect of such process depends, among others, from the texture created at the milling stage. Fig. 1 compares the average values of parameters Sq , Sa and Str of milled, as well as milled and burnished samples with a force of 800 N.

The smallest values of Sq and Sa after burnishing were recorded in the case of a sample that had previously been milled with the lowest feed $f_{wf} = 0.1$ mm. Comparing the Sq and Sa values of reference samples, it can be seen that the most effective was machining consisting of burnishing of samples, which in the previous procedure were milled with a transverse feed of $f_{wf} = 0.5$ mm. In this case, the value of Sq decreased by 89.8%, and Sa – by 90.4%.

Values of Sal and Str parameters significantly increased after burnishing. An increase in the Str parameter value after the second treatment indicates a uniform structure of the surface.

Figs. 2 and 3 show isometric images of recorded surfaces.

To assess the degree of removal of marks left by the milling cutter, correlation of the corresponding surfaces after milling and burnishing was performed (figs. 4 and 5). Analyzing the obtained results, it can be stated that the marks left by the milling cutter are the least visible in the case of the sample which in the pre-burnishing machining was subjected to milling with a transverse feed of $f_{wf} = 0.3$ mm.

Summary

Combination of parametric assessment of the surface geometrical structure and nonparametric assessment is very important in the optimization of technological processes aiming at obtaining a surface that meets stringent requirements. Cross-correlation in SGP analysis can definitely be a good helper tool to optimize hybrid technological operations. First of all, however, it allows for observing changes in the surface texture that are the result of subsequent technological operations. At the same time, it should be borne in mind that in industrial practice, such tests (even though they are very much needed) can be burdensome. Therefore, it is worth working on improving the tools that would allow creating a virtual model and thus allow obtaining a model of the machined surface. To this end, the authors undertake further research not only on the creation of mathematical models to optimize machining, but also virtual models for simulations that facilitate the understanding of changes occurring in the material during machining combining milling and burnishing.

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