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NEW INDICATORS OF BURNISHED SURFACE EVALUATION – REASONS OF APPLICATION

Daniel Toboła[1)], Piotr Rusek[1)], Kazimierz Czechowski[1)], Tatiana Miller[1)], Krzysztof Duda[2)]

1) Institute of Advanced Manufacturing Technology (IAMT), Wrocławska 37a, 30-011 Cracow, Poland (✉ daniel.tobola@ios.krakow.pl, +48 12 631 7251, *piotr.rusek@ios.krakow.pl, kazimierz.czechowski@ios.krakow.pl, tatiana.miller@ios.kralow.pl)*

2) AGH University of Science and Technology, Department of Measurement and Electronics, Al. Mickiewicza 30, 30-059 Cracow, Poland, (kduda@agh.edu.pl)

Abstract

Modern production technology requires new ways of surface examination and a special kind of surface profile parameters. Industrial quality inspection needs to be fast, reliable and inexpensive. In this paper it is shown how stochastic surface examination and its proper parameters could be a solution for many industrial problems not necessarily related with smoothing out a manufactured surface. Burnishing is a modern technology widely used in aircraft and automotive industries to the products as well as to process tools. It gives to the machined surface high smoothness, and good fatigue and wear resistance. Every burnished material behaves in a different manner. Process conditions strongly influence the final properties of any specific product. Optimum burnishing conditions should be preserved for any manufactured product. In this paper we deal with samples made of conventional tool steel – Sverker 21 (X153CrMoV12) and powder metallurgy (P/M) tool steel – Vanadis 6. Complete investigations of product properties are impossible to perform (because of constraints related to their cost, time, or lack of suitable equipment). Looking for a global, all-embracing quality indicator it was found that the correlation function and the frequency analysis of burnished surface give useful information for controlling the manufacturing process and evaluating the product quality. We propose three new indicators of burnishing surface quality. Their properties and usefulness are verified with the laboratory measurement of material samples made of the two mentioned kinds of tool steel.

Keywords: surface geometrical structure, slide diamond burnishing, correlation analysis, Discrete Fourier Transform.

1. Introduction

There are many factors which influence the final shape of surface profile. Roughness geometry forms are a result of a geometrically-kinematic representation of the tool point, relative vibrations of the tool and work-piece, plastic deformations and brittle destruction of surface irregularities which depend mostly on the machined materials and the nature of manufacturing processes [1–7].

It is well-known [8–10] that the surface geometry influences properties of manufactured items. Joint stiffness, sealing capacity, bearing, surface energy, wear, friction, fatigue resistance, electrical contact area, fracture, adhesion, plating and painting, reflectivity, liquid flow and much more depend on the three dimensional (3D) surface profile. There exist a lot of evidence and examples of proper applications given to the manufacturing methods employed to engineer matching surfaces [11–14]. Unfortunately, almost all of the evidence and our present knowledge of the subject have strong limitations. A weak repeatability of results, lack of suitable models and poor understanding of phenomena promote the situation of skill domination over the strong analytical formulation. As a result, a multitude of surface

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descriptive parameters and indicators exist. More than 40 different parameters describe the surface profile [1–3], but only a few of them can somewhat relate to the stochastic nature of surface topography with the peculiarity of upper layer of the products [15]. So far, the analytical results from probabilistic models do not permit to determine exactly relationships between the surface geometry and its properties, but some of the parameters are more suitable than the other ones.

Spectral methods (Fourier and wavelet transform [5–7, 15]) are also used for surface analysis. However, it is often desirable to obtain a single indicator as the final result.

Profile geometry is constituted as a consequence of variable conditions during manufacturing, so that it can be also used to determine pertinence of process conditions to functional behavior of the surface. That was the idea to employ key parameters to describe the surface function, especially for hard-to-determine properties of upper layers of the products.

In this paper we propose three new indicators of burnishing surface quality; two of them are defined with the cross-correlation function in the time and frequency domains. The practical usefulness of those indicators is verified experimentally, which is the main contribution of this paper.

In the following sections the experimental setup is firstly described, and then new indicators are defined and applied to laboratory measured surfaces. The obtained results are finally explained and related to physical phenomena.

2. Experimental

2.1. Work-piece materials

For our investigations we chose tool steels manufactured by the world's leading supplier of tooling materials – Uddeholm AB Company. The first one − Sverker 21 was Ledeburitic 12% Cr-steel (1.55 wt. % C, 0.3% Si, 0.4% Mn, 11.8% Cr, 0.8% Mo, 0.8% V) produced in the conventional metallurgical process. The second one was chromium-molybdenum-vanadium alloyed PM steel Vanadis 6 (2.10 wt. % C, 6.8% Cr, 0.4% Mn, 1.5% Mo, 1.0% Si, 5.4% V). Both are widely applied for cold working tools. The final macrohardness of both tool steels after the heat treatment was ~60 HRC.

2.2. Burnishing tool and machining process

Longitudinal turning of the bar probe (~ ø32x1000 mm) with a tool insert holder was performed first. Turning conditions were unified for all work-pieces, as shown in Table 1. CBN cutting inserts of commercial symbol NP-SNGA 120412GS2 MB730 according to Mitsubishi, were used.

Table 1. The specifications of turning conditions.

Parameter		Steel grade	
		Sverker 21	Vanadis 6
Speed v_c	m/min	100	150
Feed *f*	mm/rev.	0.16÷0.2	0.16÷0.18
Depth of cut *ap*	mm	0.2	

The surface roughness before burnishing was within the range: Ra = 0.74 ÷ 0.83 μm for Sverker 21, and Ra = 0.76 ÷ 0.84 μm for Vanadis 6, respectively, which was specified for the six measurements of a given sample. The above-mentioned range of the average surface roughness is for all samples. Turning improves the surface geometry, thus affecting the roughness.

The slide diamond burnishing process (Fig. 1) of our tool steels in the quenched state (~60 HRC) was carried out using diamond tools designed by us and currently produced by the Institute of Advanced Manufacturing Technology (IAMT) [16], with the tips made of diamond composites with ceramic bonding phase – Ti_3SiC_2 and the shape of spherical caps with the radius R = 1.5 mm.

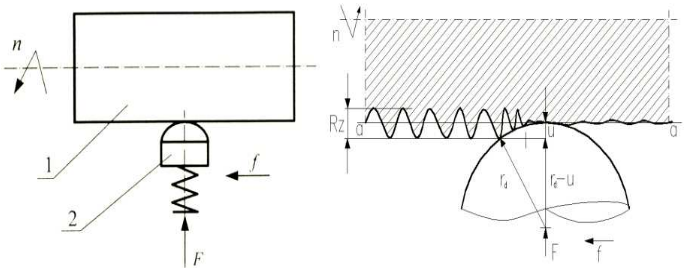

Fig. 1. The scheme of slide diamond burnishing: 1 – workpiece; 2 – burnishing tool; F – burnishing force; f – feed; n –workpiece rotation; r_d – radius of tool tip [17].

The experiments were carried out on a Mori Seiki NL2000SY CNC turning-milling centre, numerically controlled along five axes. The burnishing tool (Fig. 2) was fixed to the cutting head by means of a special fixture, which ensured the possibility of elastic clamping. The clamping force was recorded.

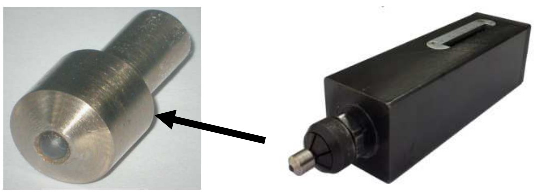

Fig. 2. The diamond burnisher with tool holder and working parts (spherical cups).

The selected input parameters for the burnishing process are shown in Table 2. Each time we applied only one burnishing pass i = 1. An oil mist made from the Castrol Hysol R oil was applied. The burnishing speed (v = 40 m/min) was constant. The burnishing process was implemented as a spring-loaded, which provided a constant force (normal force). Some literature references recommend using the same feed both for burnishing and turning processes [18–19]. In this case, the selection of technological parameters was the effect of our previous research results.

Table 2. The specifications of burnishing conditions.

Steel	**Burnishing force *F***	**Feed *f***
	N	mm/rev.
Sverker 21	80 ÷ 220	0.02
Vanadis 6	80 ÷ 200	

We have used a Hommel Tester T1000 apparatus for registration and determination of the surface geometry parameters. Roughness profilograms (discrete signals) were obtained. The surface layer parameters were measured before and after burnishing. 3D charts were recorded on a profilometer TOPO 01 produced by the IAMT.

2.3. Proposed indicators of burnishing surface quality

From the surface measurement we obtain two discrete signals containing N samples each (traverse length lt = 4.8 mm). We denote the turning signal by $y_n^{(t)}$ and burnishing signal by $y_n^{(b)}$. The subscript n refers to the sample index, and n = 0,1,2,...,N–1. The mean value of signals $y_n^{(t)}$ and $y_n^{(b)}$ is zero. Based on signals $y_n^{(t)}$ and $y_n^{(b)}$ (roughness profiles for turned and burnished surfaces, respectively) we define the following indicators for surface evaluation:

a) Coefficient K – smoothing out indicator.
   The coefficient K is the ratio of mean values obtained from the absolute values of burnishing and turning signals:

$$K = \frac{\bar{y}_n^{(b)}}{\bar{y}_n^{(t)}}, \quad \bar{y}_n^{(t)} = \frac{1}{N}\sum_{n=0}^{N-1} | y_n^{(t)} |, \quad \bar{y}_n^{(b)} = \frac{1}{N}\sum_{n=0}^{N-1} | y_n^{(b)} |. \tag{1}$$

   For determining the percentage changes in surface smoothing we applied the coefficient K', which is defined as a difference between 1 and the K coefficient value:

$$K' = (1 - K)\cdot 100\ (\%). \tag{2}$$

   The inverse of K is similar to the well-known K_{Ra} factor [1–3, 20]. For this study we chose K instead of K_{Ra} for easier comparison with the rest of proposed indicators. We have the burnishing signal in the nominator of (1), because we prefer to look for the minimum value of indicator, and also we do not want to divide by small values.

b) Correlation coefficient C_1 – time domain indicator.
   The correlation coefficient C_1 is the maximum value of unbiased estimate of the cross-correlation function:

$$C_1 = \max_m \{c_m\}, \tag{3}$$

   which is defined for real valued signals (*i.e.* not complex) as:

$$c_m = \frac{1}{(N - |m|)} \begin{cases} \sum_{n=0}^{N-m-1} y_{n+m}^{(t)} y_n^{(b)} & m \geq 0 \\ c_{-m} & m < 0 \end{cases}. \tag{4}$$

   It is known that for a high $|m|$ the estimate c_m becomes not reliable and for that reason C_1 is searched in a narrowed range of m (in the implementation $|m| < 0.2\cdot N$ was set).

c) Correlation coefficient C_2 – frequency domain indicator
   The correlation coefficient C_2 is defined in the frequency domain as the amplitude of main frequency of unbiased estimate of the cross-correlation function c_m (4). The spectrum is computed with the Discrete Fourier Transform (DFT) with the rectangular window and the signal is extended by appending the vector of samples with zeros to obtain the required length [21, 22] (*e.g.* for measurement signals with the length N = 10000 samples we append zeros to obtain the length 2^{16} = 65536 samples, and then compute the DFT). In a number of cases the correlation coefficients C_1 and C_2 have the same value, however C_2 is expected to be more robust against some measurement disturbances (*e.g.* drift is located close to the DC component in the spectrum and thus have a little impact on C_2).

The highest theoretical value of all defined above indicators occurs for $y_n^{(t)} = y_n^{(b)}$ (*i.e.*, no burnishing). For that case $K = 1$, and the value of C_1 is $C_1 = \frac{1}{N}\sum_{n=0}^{N-1}(y_n^{(t)})^2$ and $C_2 \le C_1$ with the equality for $y_n^{(t)}$ being a single sinusoid. If the surface after burnishing is ideally flat (*i.e.*, the constant function), then the indicators K, C_1, and C_2 are zero. Note however, that above mathematical bounds of indicator values are not likely to be obtained for laboratory samples. In practice, the best surface for a given application may be the one having a predefined value of the indicator – not necessarily the smallest possible one.

3. Results

Figures 3–6 depict the exemplary turning and burnishing signals measured in the laboratory for steel Vanadis 6 (Figs. 3–4) and steel Sverker 21 (Figs. 5–6). From top to bottom the subplots show: the measured signals (turning $y_n^{(t)}$ and burnishing $y_n^{(b)}$), the unbiased estimate of cross-correlation function (4) with the maximum value (*i.e.*, C_1 indicator) marked by "x", and the DFT amplitude spectrum of c_m with the maximum value (*i.e.*, C_2 indicator) denoted by "x". The value of C_2 is also shown in the middle subplots by the line parallel to OX axis. OX axes are scaled in millimeters for the measurement signals and correlation function c_m, and in 1/mm for the spatial frequency in bottom subplots. The indicators K, C_1, and C_2 are given in the figure capture.

Figure 7 depicts mean values of the proposed burnishing surface quality indicators as a function of burnishing force F. For each value of F mean values of K, K', C_1, and C_2 were computed from 12 measurements taken on different material samples. The exact mean values and standard deviations are given in Table 3.

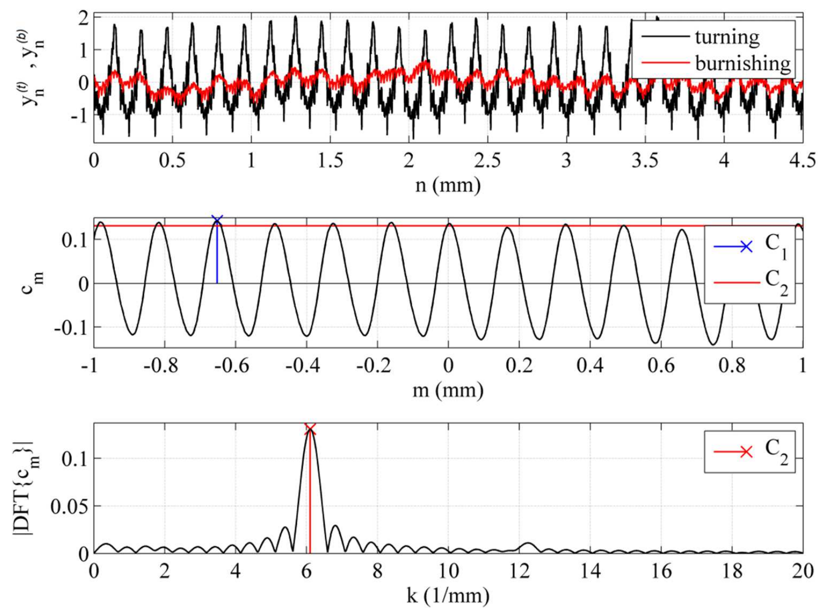

Fig. 3. The results for turned and burnished (F = 160 N, f = 0.02 mm/rev.) Vanadis 6 tool steel: the measured signals (top), the cross-correlation function with marked value of C_1 = 0.142 (middle) and the DFT amplitude spectrum with denoted value of C_2 = 0.131 (bottom).

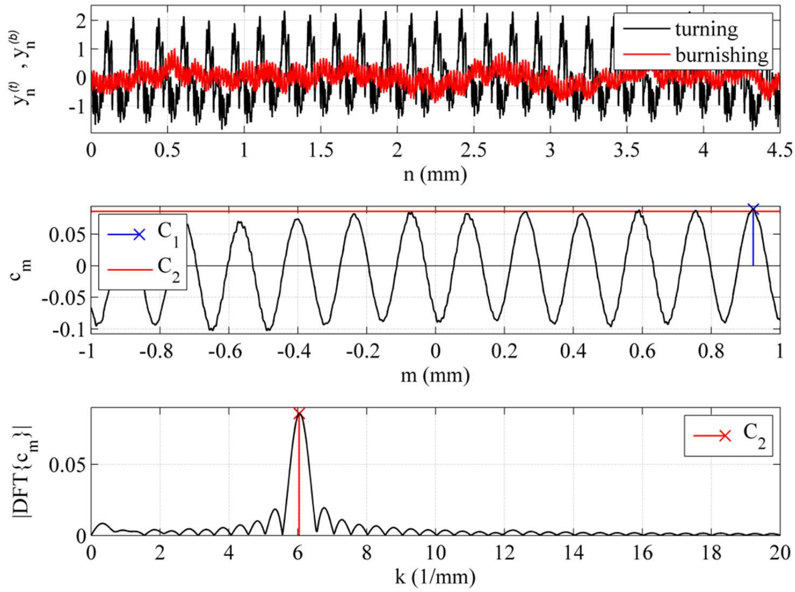

Fig. 4. The results for turned and burnished (F = 180 N, f = 0.02 mm/rev.) Vanadis 6 tool steel: the measured signals (top), the cross-correlation function with marked value of C_1 = 0.089 (middle) and the DFT amplitude spectrum with denoted value of C_2 = 0.085 (bottom).

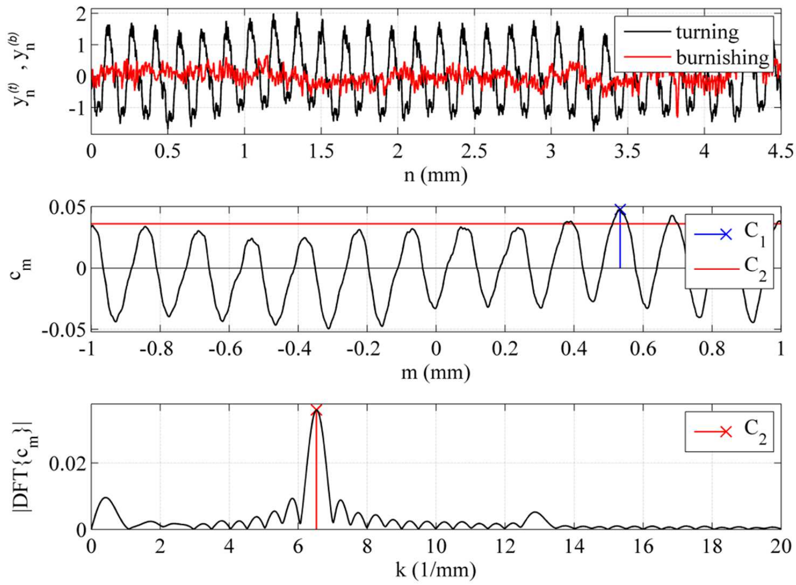

Fig. 5. The results for turned and burnished (F = 180 N, f = 0.02 mm/rev.) Sverker 21 tool steel: the measured signals (top), the cross-correlation function with marked value of C_1 = 0.048 (middle) and the DFT amplitude spectrum with denoted value of C_2 = 0.036 (bottom).

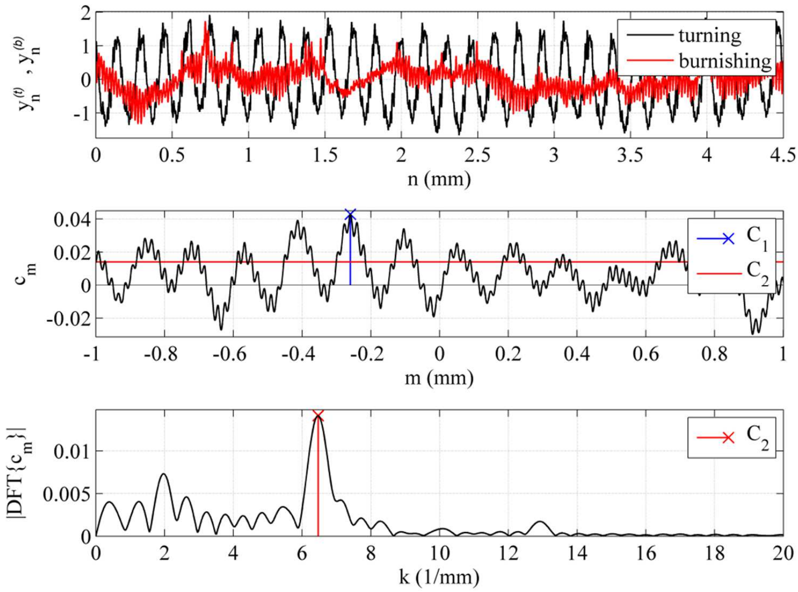

Fig. 6. The results for turned and burnished (F = 200 N, f = 0.02 mm/rev.) Sverker 21 tool steel: the measured signals (top), the cross-correlation function with marked value of C_1 = 0.043 (middle) and the DFT amplitude spectrum with denoted value of C_2 = 0.014 (bottom).

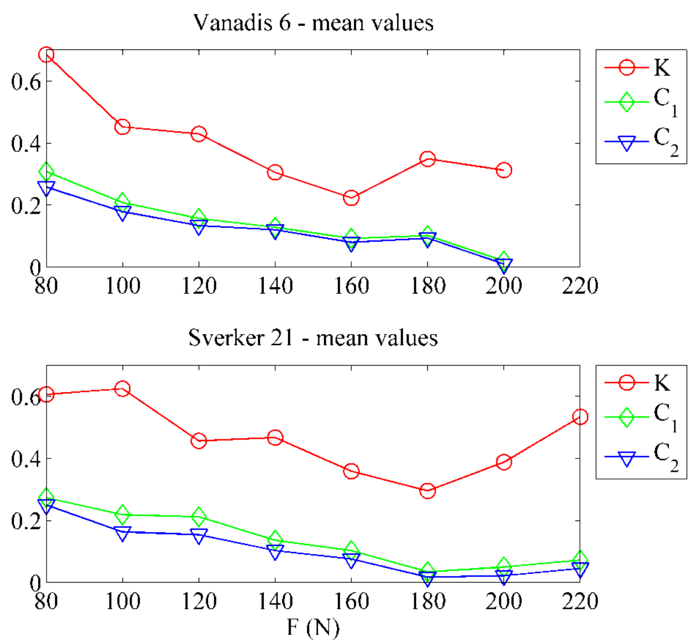

Fig. 7. The proposed burnishing surface quality indicators as a function of burnishing force F: Vanadis 6 (top) and steel Sverker 21 (bottom).

Table 3. The mean values (depicted in Fig. 7) and standard deviations of the proposed burnishing surface quality indicators.

	Vanadis 6							Sverker 21						
	K		K'	C_1		C_2		K		K'	C_1		C_2	
	mean	std	mean	mean	std	mean	std	mean	std	mean	mean	std	mean	std
F = 80 N	0.686	0.044	31.4	0.308	0.031	0.259	0.031	0.606	0.023	39.4	0.274	0.070	0.250	0.089
F = 100 N	0.452	0.079	54.8	0.208	0.094	0.179	0.100	0.625	0.046	37.5	0.219	0.044	0.164	0.047
F = 120 N	0.430	0.061	57.0	0.157	0.042	0.134	0.036	0.456	0.055	54.4	0.212	0.057	0.155	0.035
F = 140 N	0.306	0.038	69.4	0.128	0.024	0.120	0.024	0.467	0.099	53.3	0.136	0.026	0.103	0.015
F = 160 N	0.223	0.031	77.7	0.093	0.064	0.080	0.062	0.359	0.041	64.1	0.103	0.034	0.076	0.033
F = 180 N	0.349	0.013	65.1	0.102	0.010	0.093	0.008	0.296	0.064	70.4	0.035	0.010	0.018	0.008
F = 200 N	0.313	0.025	68.7	0.020	0.004	0.010	0.004	0.388	0.055	61.2	0.050	0.015	0.022	0.008
F = 220 N	–	–	–	–	–	–	–	0.534	0.018	46.6	0.073	0.021	0.046	0.012

Independently three dimensional (3D) surface patterns of the same turned and burnished material samples were examined. The results are shown in Fig. 8 (samples made of Vanadis 6 PM steel were analyzed) upon the optimal burnishing tool pressure conditions (F = 160 N) and precarious ones (F = 200 N).

Changing the burnishing force leads to significant changes in the resulting state of surface geometrical structure. The progress of burnishing process is accompanied by plastic deformation of surface irregularities. The changes in the surface geometrical structure as a function of pressure F were analyzed using the K factor. The maximum $K = f(F)$ dependence was observed for wrought steel Sverker 21 and PM steel Vanadis 6 (180 N and 160 N, respectively). Analogous results can be obtained using the well-known factor K_{Ra}.

This, however, is not sufficient to establish changes in the state of turned surface caused by burnishing, occurred in conditions different to the turning process (much less tool movement). This may be accompanied with adverse changes in the surface layer, especially the surface integrity. Even observation with 3D techniques (Fig. 8) does not help. We cannot find any significant difference between the records obtained from two very different manufacturing conditions (F = 160 N and F = 200 N) – even areal material ratio distribution does not change significantly.

Therefore, concurrent observations of the same signal were performed using the proposed indicators C_1 and C_2. This enabled additional clarification of the observations with regard to changes of the surface state, consisting of removal of the previous, turned, surface state structure and formation of the new, burnished state. An increase in the burnishing force F is accompanied by a decline in the value of coefficients C_1, and C_2. In the proximity of optimal values of burnishing force guaranteeing the highest smoothing of surface, the largest reduction in the values of coefficients C_1 and C_2 occurs. A further reduction of C_1 and C_2, below a certain limit value may be dangerous, because excessive surface transformation in brittle hard tool materials may be accompanied with micro-cracking of the burnished surface, resulting from exceeding the optimum processing conditions – Fig. 9.

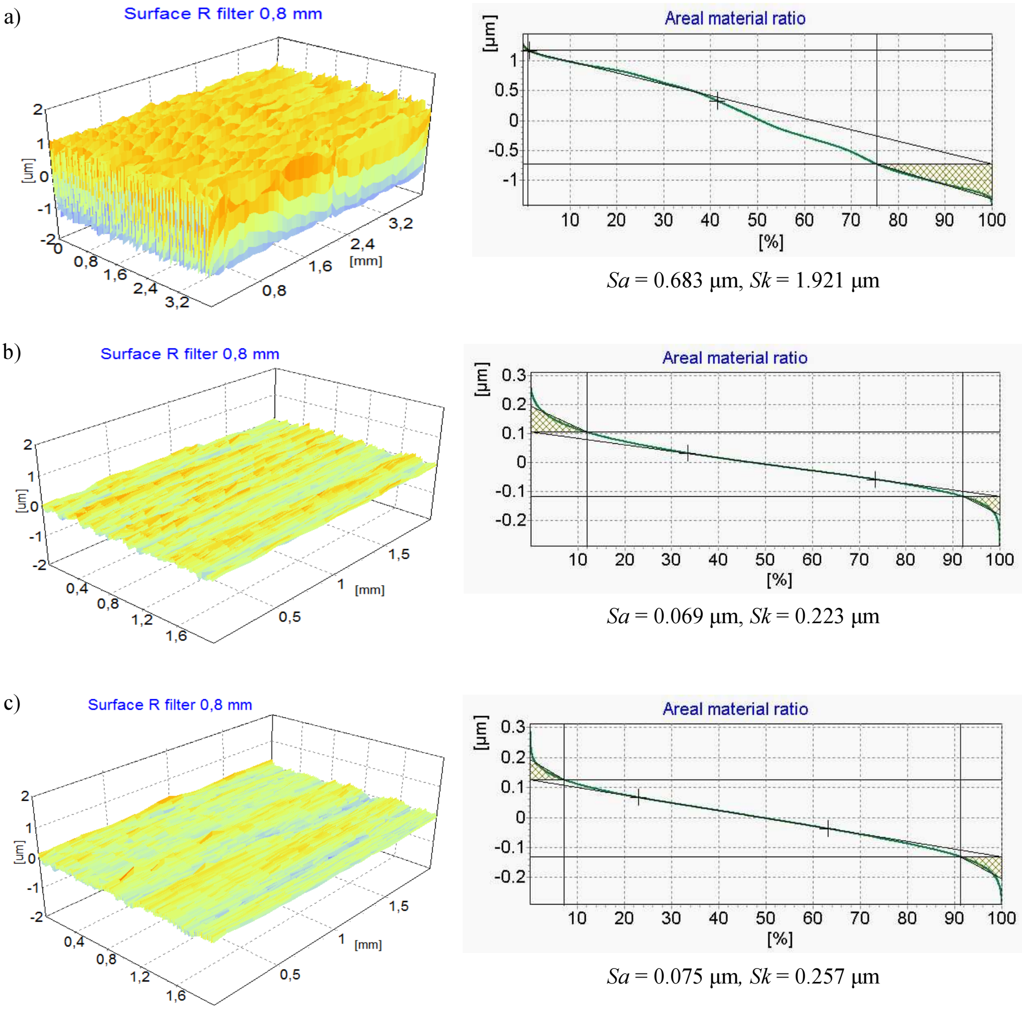

Fig. 8. The 3D surface roughness with areal material ratio for Vanadis 6 tool steels after: a) turning; b) burnishing (F = 160 N, f = 0.02 mm/rev.); c) burnishing (F = 200 N, f = 0.02 mm/rev.).

An increase in the value of coefficient C_1 above a certain limit value can also be a symptom of occurring other unfavorable changes (the effect of "copying" of previous surface roughness accompanying peeling of burnished surface): disintegration of the surface layer when accompanied with an increase in the coefficient C_2 value for the frequency corresponding to the feed rate of the procedure preceding burnishing (turning).

Both of the above-mentioned effects are observable in an indirect way (the measurement of coefficients C_1 and C_2) without a need for destructive testing of materials (*e.g.* metallographic or X-ray observations of transverse specimen sections).

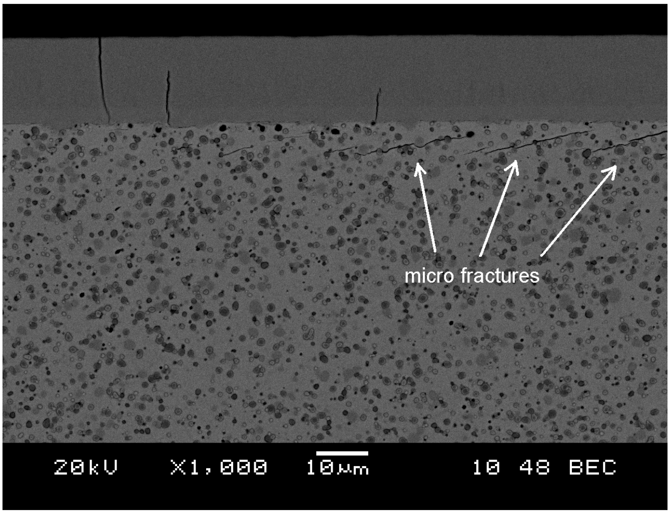

Fig. 9. Microcracks formed beneath the turned and burnished surface of Vanadis 6 tool steel and after the hard chromium coating was deposited as a final surface treatment process. The burnishing parameters: F = 180 N, f = 0.02 mm/rev. The picture taken with a JEOL JSM 6460 V digital scanning electron microscope.

There is a need for non-destructive analysis of the surface layer quality after complicated processes of surface treatment, especially the plastic surface treatment, in particular in high volume production environments or storage. Treatment consisting of cold work deformation of the surface introduces compressive stresses which, as confirmed by numerous, independently carried out research of national and international centers [14, 23–25], have a very beneficial effect on the performance of products. The level of stress and a way of their distribution may, however, be subjected to significant changes due to the existence of variable, random conditions of the manufacturing process, giving a large scatter of the performance of products. In some cases it may cause the occurrence of conditions causing disintegration of the surface layer, especially in the case of hard brittle materials – as tool materials described in the article.

In the absence of the possibility of introducing a direct rapid non-destructive measurement of the state of surface layer in the production environment, the authors propose an indirect method of assessment of the resulting surface, indicating adherence to or exceeding the limit of production regimes, by observing changes in the coefficients C_1 and C_2, resulting from changes in the geometric area, *i.e.*, analyzing a random function.

4. Conclusion

Selecting the burnishing conditions usually consists in observation of changing surface roughness, whose primary indicator used in industrial environments is the height parameter *Ra* (CLA – in the USA), *i.e.*, the mean deviation of roughness profile from the mean line. The greatest improvement of surface quality (maximum reduction of surface roughness) and corresponding manufacturing conditions are then considered as optimal and recommended for use in production. Not always the optimal conditions of smoothing the surfaces translate to a corresponding improvement in the functional properties of surface layer.

In some cases it can be observed that the surface integrity has already been breached and the random function analysis of its geometry can greatly assist in a better description of the surface and changes occurring in it. Loss of the surface integrity is caused by exceeding locally the strength of the surface layer and may lead to nucleation of a catastrophic crack in the burnished component. Such a situation is shown in Fig. 8, which shows how cracks are formed under the burnished surface, arising from exceeding the burnishing force. Such cracks are not visible on the surface and can, during service, initiate fatigue, penetrating into the depth and the surface of component, and diminishing the wear resistance of surface layer.

It may be observed that the values of proposed indicators coincident well with each other in presented experiments. This intentional redundancy confirms correctness of the measurement data. The proposed indicators have a similar meaning, but very different ways of obtaining (*i.e.*, computation algorithms), and are robust/sensitive to different measurement disturbances. For a reliable and precise description of the burnishing process all proposed indicators should be used simultaneously, and all of them must lay in predefined boundaries.

The analysis of random function indicators allows even a more complete assessment of the intermediate structural phenomena occurring in the top layer, which is reflected in the geometric surface state data. Thus, progressive processing of surface irregularities resulting from the applied burnishing will reduce the cross-correlation function and the component amplitude (in signal frequency analysis) resulting from turning – the machining applied prior to burnishing. The appearance of a periodic component in the signal – corresponding to the tool feed rate while burnishing – testifies the progressive processing of turned surface into the burnished surface.

Taking into account the elastic-plastic properties of a work-piece material (as in the case described in this paper, very brittle material Vanadis 6) – a strong tool interaction, *e.g.* a high burnishing tool tip pressure, can be dangerous to the integrity of surface layer and its functional properties. Adoption of the allowable limits: the correlation function C_1 and amplitudes of component frequencies of the harmonic analysis C_2 appropriate for the work-piece, allows an indirect control of the surface layer integrity in production conditions, and the methodology gives us hope of increasing the possibility of a future evaluation of the surface layer in an on-line mode.

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