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Krzysztof ZAK[1*]

AREAL FIELD AND FRACTAL BASED CHARACTERIZATION OF HARD SURFACES PRODUCED BY DIFFERENT MACHINING OPERATIONS

The purpose of this study is to compare four surface textures produced by hard turning operations with CBN cutting tools, grinding operations using conventional ceramic and CBN wheels, and ball burnishing using Si_3N_4 ceramic ball with the Sa parameter of about 0.2 μm. These surfaces are characterized by standardized area field (3D) roughness parameters and non-standardized fractal dimensions. A new approach to the characterization of surface topographies using area-scale fractal analysis is proposed. In particular, some important correlations between surface texture parameters and fractal dimensions are determined and discussed.

1. INTRODUCTION

Among innovative machining processes precision machining of hardened steels (45-60 HRC) using CBN cutting tools has been ranked as an alternative to grinding. However, its effective industrial implementation requires a deeper knowledge of surface functionality which depends on the surface geometrical structure described by 2D and 3D surface roughness parameters. In this study four surface textures produced by hard turning operations with CBN cutting tools, grinding operations using electro-corundum Al_2O_3 and CBN wheels, and ball burnishing using Si_3N_4 ceramic ball with the Sa parameter of about 0.2 μm are characterized and compared, using a number of standardized areal (3D) roughness parameters as well as other non-standardized characteristics such as fractal dimension. A new approach to the characterization of surface topographies using S-roughness parameters, the vectorized micro-valley networks generated on the machined surface and area-scale fractal analysis is proposed [1],[2],[3],[4]. In particular, this characterization method allows establishing functional properties of surface textures generated by various machining operations.

The objective of this study is a comprehensive characterization and comparison of surface textures of representative hard turned, and differently ground and honed surfaces, using a number of standardized 3D roughness parameters as well as 2D and 3D fractal dimensions. Among 3D roughness parameters a set of 12 S-parameters and 13 V-parameters

[1] Faculty of Mechanical Engineering, Opole University of Technology, Opole, Poland
[*] E-mail: k.zak@po.opole.pl

specified in ISO 25178 Standard [5] was used in the comparison of four surface textures. The reference Sa roughness parameter is about 0.2 μm.

2. EXPERIMENTAL DETAILS

2.1. MACHINING TESTS

The workpiece material was an alloy 41Cr4 steel hardened to 57±1 HRC. The specimens with initial roughness of 0.42 μm Sa produced by turning were finished by precision turning, grinding and burnishing in order to reduce surface roughness to a comparable value of the Sa parameter of about 0.2 μm. In particular, this low value of Sa roughness parameter was obtained using a very low feed and depth of cut in turning and grinding operations and a very low feed (lower than the feed rate of 0.1 mm/rev in initial turning operation) in ball-burnishing operation.

Turning and ball burnishing operations were performed on Okuma Genos L200E-M CNC lathe and grinding operations on conventional cylindrical grinding machines. Machining conditions for the machining operations are selected as follows:

1. Hard turning (HT) using CBN TNGA 160408 S01030 chamfered insert with cutting speed of v_c=150 m/min, feed rate of f=0.06 mm/rev and depth of cut of a_p=0.15 mm.
2. Cylindrical grinding using electro-corundum (Al_2O_3) (GR-CW), 350×25×127 32A grinding wheel with grinding speed of v_c=11.9 m/s, in-feed of a_e=0.025 mm, cross-feed of f_a=3.5 mm/rev.
3. Cylindrical grinding using INTER DIAMENT B107 K100 SV grinding wheel (GR-CBNW) with grinding speed of v_c=36 m/s, in-feed of a_e=0.025 mm, cross-feed of f_a=1.6 mm/rev.
4. Ball Burnishing (BB) was performed, using a special burnishing tool equipped with Si_3N_4 ceramic ball of 12 mm diameter, as shown in Fig. 1a. The burnishing speed of 25 m/min and burnishing feed (f_b) of 0.075 mm/rev were selected. The burnishing feed f_b was lower than the turning feed f_t. The burnishing load was executed by compressed spring (Fig. 1a) and the tool correction of 0.25 mm which was programmed in the CNC control system.

a) b)

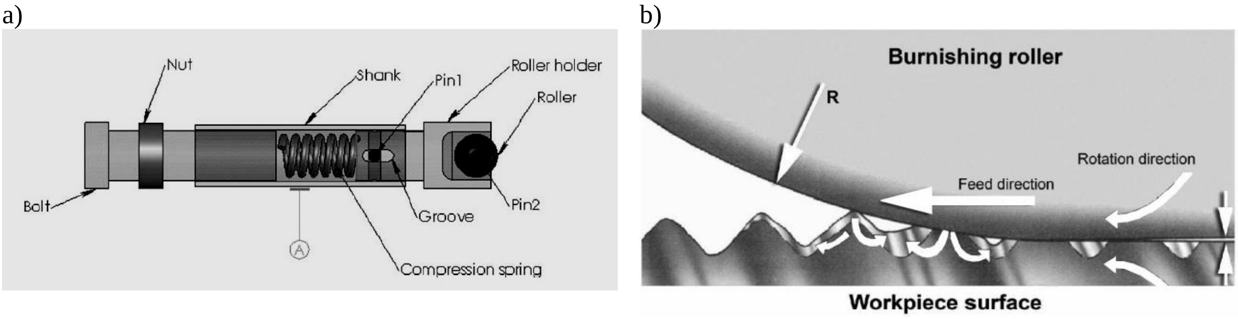


Fig. 1. Construction of burnishing tool with spring loading used (a) and (b) scheme of surface flattening by burnishing action [6]

Burnishing was performed with supplying a small amount of a BP Energol CS 100 machine mineral oil with the viscosity of 100 mm^2/s at 40°C, produced by BP Lubricants UK Ltd. The reduction of initial roughness of the turned surface by the burnishing ball is shown in Fig. 1b.

2.2. MEASUREMENTS OF 3D SURFACE ROUGHNESS

Surface topographies were measured by means of the stylus method using a TOPO-01P contact profilometer. 3D roughness parameters were determined and surface topographies were visualized using a Digital Surf, Mountains®Map package. In addition, specialized software Surfract was used to determine the relative area-scale relations and the fractal dimensions for different rough surfaces textures. Four specimens with surface textures produced by CBN cutting tools, ceramic and CBN grinding wheels and ball burnishing were examined and visualized using different measuring methods and software.

The characterization of surface topographies was based on four groups of parameters, including: a) standardized 3D surface roughness parameters divided into five groups: height, amplitude, horizontal, hybrid and functional [7],[8] and b) 2D and 3D fractal dimensions. It should be noted that only stylus measurements were performed and topographies of each of the four surfaces were generated using 200 different surface profiles obtained within selected area of 2.4 mm×2.4 mm (the micrometric table displacement of 12 μm for each profile record).

3. EXPERIMENTAL RESULTS AND DISCUSSION

Representative surface topographies obtained in hard turning (HT), grinding (GR-CW and GR-CBN) and burnishing (BB) operations performed are shown after magnification in Figs. 2a-d. It should be noted that, in general, all these operations can be classified as precision machining, because the maximum height Rz <2 μm [9].

For the surface textures shown in Fig. 2 the measured values of Sa range between 0.20 and 0.24 μm. In addition, values of Sz parameter increase from 1.47 μm for ball burnishing to 3.86 μm for grinding with Al_2O_3 wheel (GR-CW), which suggests different structures of surface topographies and consequently different functional properties.

Fig. 3 presents the shapes of 3D BAC’s (bearing area curves) and associated ADF (amplitude density function) curves obtained for the turned, ground and burnished surfaces. In particular, hard turned surface (1) has positive skew Ssk=0.24 but finish ground (2 and 3) and burnished (4) surfaces have negative skew Ssk - (-0.31) for GR-CW versus (-0.48) for GR-CBNW and (-0.53) for BB. Moreover, Fig. 3b suggests that hard turning and grinding produced topographies with diametrically different ADF shapes which can result in various bearing and contact properties. It can then reasoned that the superior bearing properties (Ssk=-0.53) can be achieved after ball burnishing (BAC #4 in Fig. 3a). Additionally, values of the areal material ratio Smr(c), the inverse areal material ratio Sdc(mr) and the peak extreme height Sxp are given in Fig. 3a.

a) Sa=0.21µm, Sz=1.56 µm b) Sa=0.21µm, Sz=3.86 µm

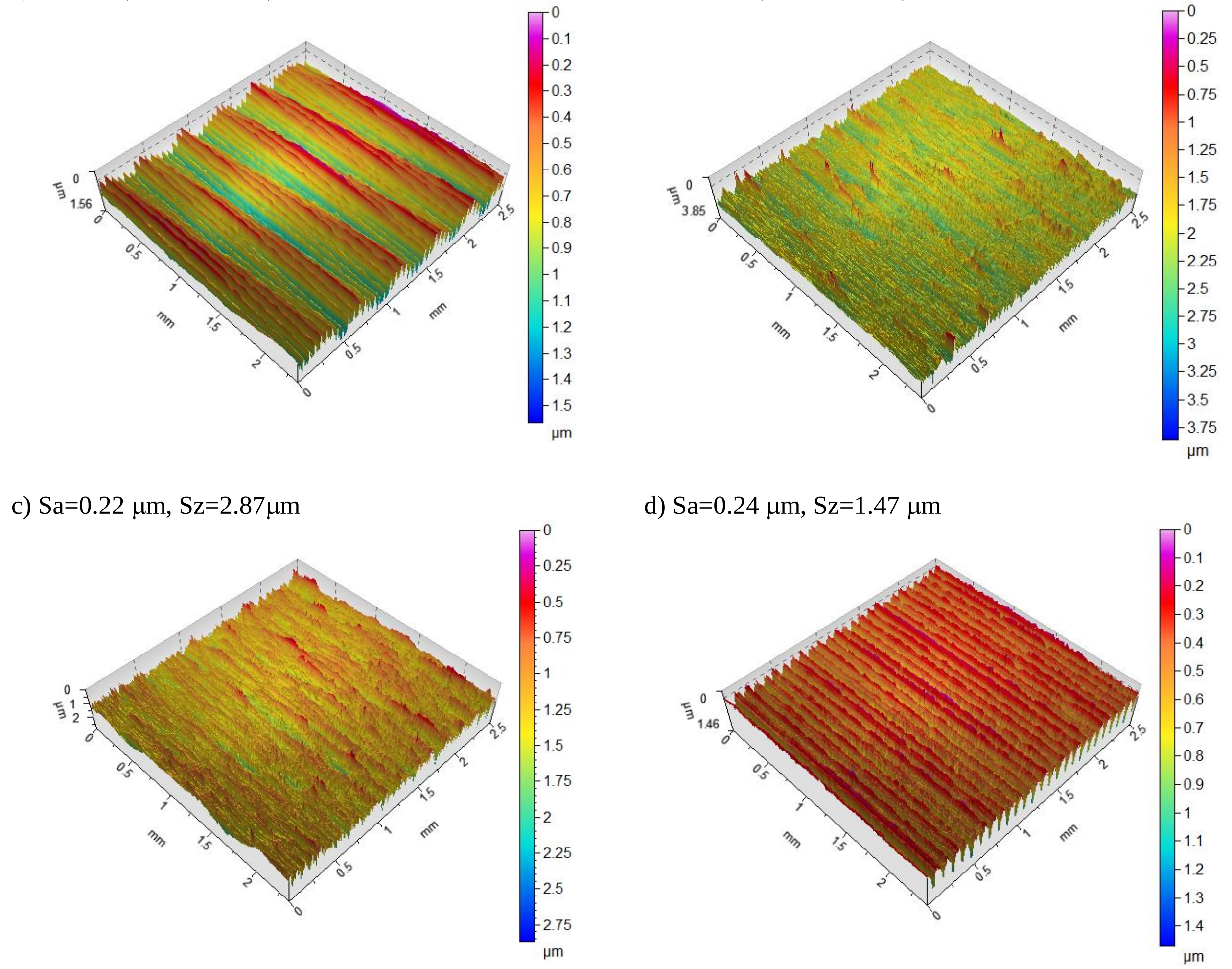


Fig. 2. Surface textures produced by HT (a), grinding using Al_2O_3 (b) and CBN (c) wheel and ball burnishing (d)

a) 1-Sdc=0.66 µm, Sxp=0.44 µm, 2-Sdc=1.97 µm, Sxp=0.60 µm, 3-Sdc=1.13 µm, Sxp=0.65µm, 4-Sdc=0.62 µm, Sxp=0.62 µm

b) 1- Ssk=0.24, Sku=2.56; 2- Ssk=-0.31, Sku=5.41, 3-Ssk=-0.48, Sku=3.70, 4-Ssk=-0.53, Sku=2.02

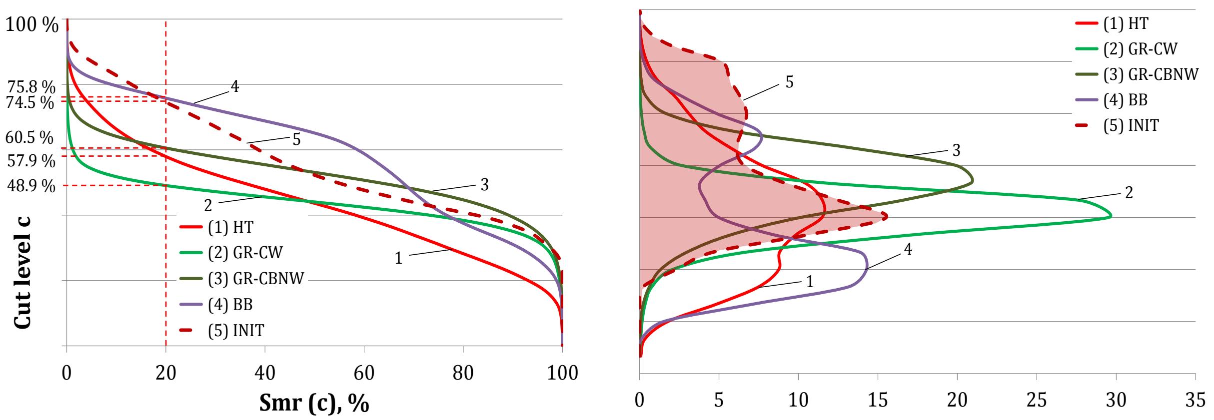


Fig. 3. 3D BAC shapes (a) and ADF distributions (b) for turned (1), ground (2 and 3) and ball burnishing (4) surfaces, 5-initial hard turned surface

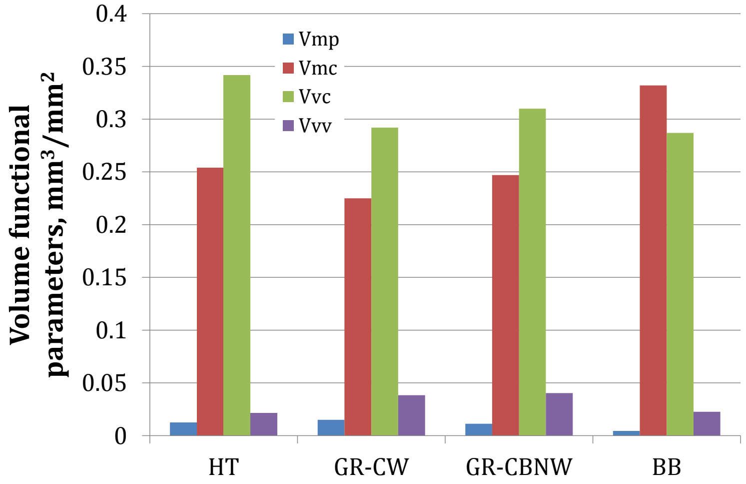


Fig. 4. Functional volumetric parameters for different finishing operations

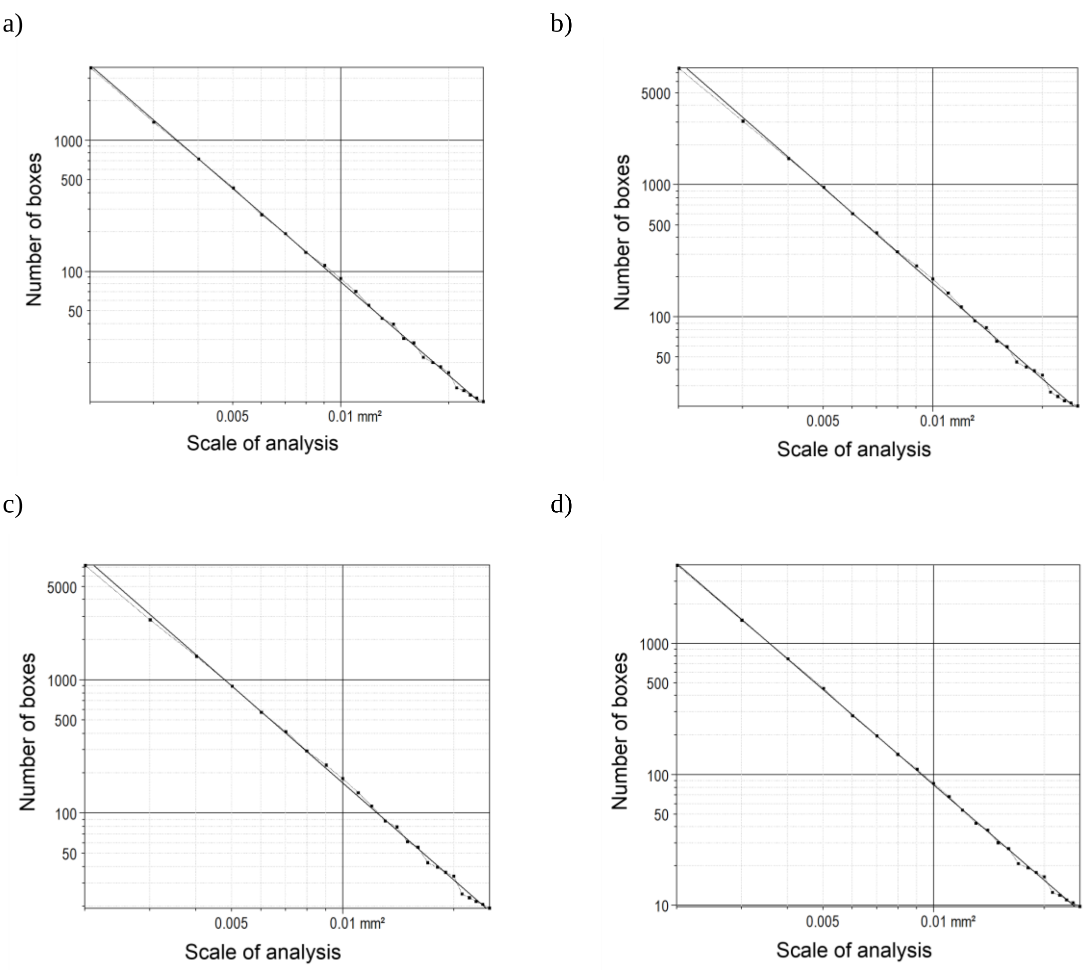


Fig. 5. Structure fractal functions obtained for four machining operations: a) hard turning, b) conventional grinding, c) CBN grinding and d) ball burnishing

The changes of the volume functional parameter (Vmp and Vvv) are shown in Fig. 4. In this study, the functional analysis of the 3D BAC's is based on the four volume parameters including the peak material volume (Vmp), the core material volume (Vmc), the core void volume (Vvc) and the valley void volume (Vvv) parameters. [10],[11]. Their values obtained for the four machined surfaces are as follows (in order HT/GR-CW/GR-CBNW/BB): Vmp=0.0125/0.0150/0.0112/0.0045 $\mu m^3/\mu m^2$; Vmc=0.254/0.225/0.247/0.332 $\mu m^3/\mu m^2$; Vvc=0.342/0.292/0.310/0.287 $\mu m^3/\mu m^2$; Vvv=0.0213/0.0383/0.0403/0.0226 $\mu m^3/\mu m^2$. For example, higher values of Vvv=0.0383 and 0.0403 $\mu m^3/\mu m^2$ suggest better fluid retention ability of ground surfaces (for turned surface Vvv=0.0213 $\mu m^3/\mu m^2$).

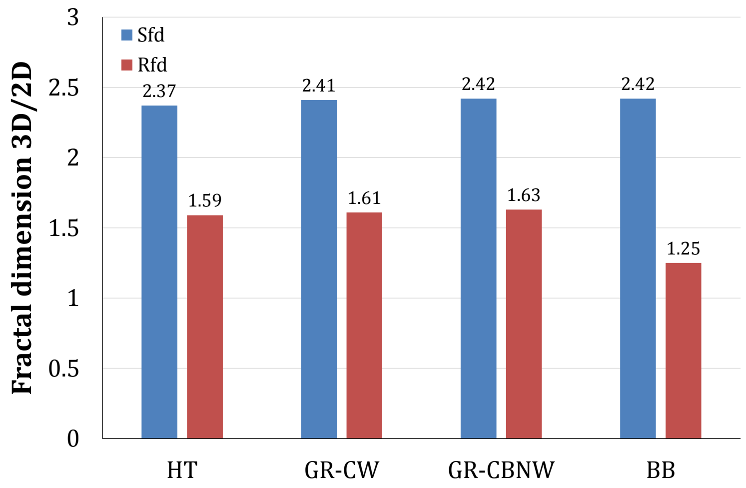
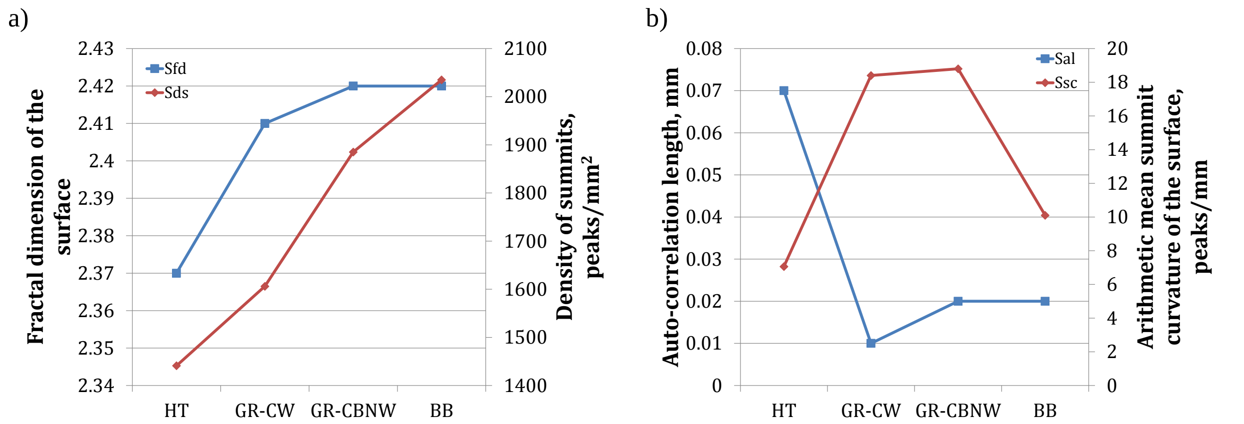


Fig. 6. Influence of machining operation on fractal dimension Sfd



Sfd: HT-2.37, GR-CW-2.41, GR-CBN-2.42, BB-2.42
Sds: HT-1441 $1/mm^2$, GR-CW-1605 $1/mm^2$, GR-CBNW- 1885 $1/mm^2$, BB-2006 $1/mm^2$
Sal: HT-0.07 mm, GR-CW-0.01 mm, GR-CBNW-0.02 mm,BB-0.02mm
Ssc: HT-7.06 1/mm, GR-CW-18.4 1/mm, GR-CBNW-18.8 1/mm, BB-10.1 1/mm

Fig. 7. Functional relationships between selected 3D S-parameters and fractal dimension

The fractal dimension concept enables to describe the complexity of engineering surfaces under the form of a single number. Fractal dimension may vary between the theoretical limits of 1 for a straight line and 2 for a space-filling curve. It should be noted that real machined surfaces are called multifractal because obviously they are formed by several different processes each with its characteristic topographical features [12]. Digital Surf, Mountains®Map software used [13] allows calculating the fractal dimension for the surface profile (2D) or real surface (3D) by means of the accounting method or morphological envelopes. In case of the accounting method applied in this study, the fractal dimension is determined by calculating the slope of the regression line which corresponds best to the ln$N$ versus lnε plot (where N is the number of boxes and ε is the size of a box) as shown for all generated topographies in Fig. 5.

The values of 3D fractal dimension Sfd determined by means of the accounting method are equal to 2.37, 2.42/2.42 and 2.42 for turned, ground and ball burnishing surfaces, as shown in Fig. 6. It should be noted that comparable values of 2.42 were determined for ground and burnished surfaces.

Functional relationships between fractal dimension Sfd and Sal, Ssc and Sds spatial and hybrid parameters are presented in Fig. 7. It can be noticed in Fig. 7a that the Sfd is strongly correlated with the density of summits (Sds) and Sfd=2.42 corresponds with the maximum value of Sds=2035 1/mm^2 determined for the burnishing surface. A quite good correlation was also obtained for the arithmetic summit curvature (Ssc) and the autocorrelation length Sal parameter which characterizes the texture anisotropy (Fig. 7b).

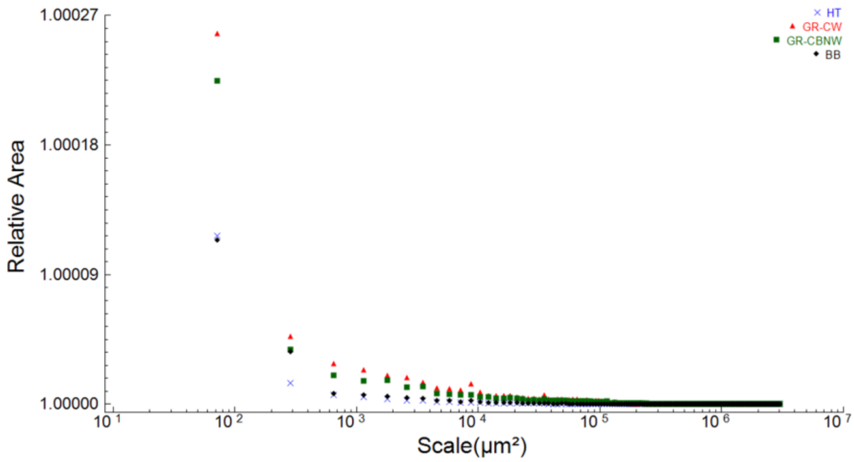


Fig. 8. Fractal-based comparison of surface textures using log(relative area)-log (scale) plot

a) Sa=0.21μm, Sz=1.56 μm

b) Rfd=1.58, Sfd=2.37

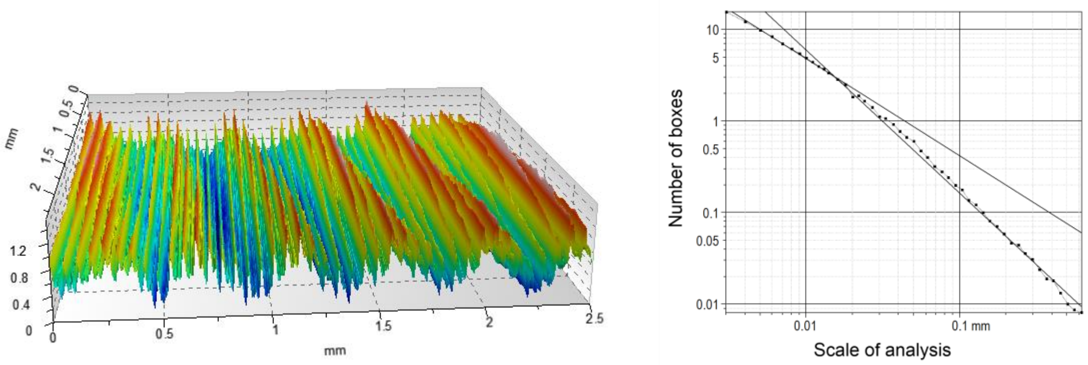


Fig. 9. Topography of turned surface (a) and corresponding fractal window (b)

Fig. 8 presents also corresponding relative area-scale graph obtained for all surface textures measured and analyzed. It can be seen in Fig. 8 that a good correlation between the values of the fractal dimension and the trends observed in the relative area-scale plot occurs at the scale 70 μm^2. Moreover, the fractal and the conventional roughness parameters demonstrate counterintuitive co-variances, i.e. greater fractal dimensions correspond to lower Rz values, greater summits density Sds correspond to higher complexities. In addition, the surface topographies produced by ceramic and CBN wheels correspond to distinctly greater relative areas and complexities than for turned and burnished surfaces.

Fig. 9 shows the topography of turned surface and corresponding fractal plot which confirm the above-mentioned recommendation concerning the analysis scale.

4. CONCLUSIONS

1. Turned surfaces finished by grinding or burnishing have topographies with better functional capabilities in comparison to the effects of precision hard cutting. In particular, such modified surfaces have better good bearing or locking properties depending on their engineering applications.
2. Ground and burnished surfaces are characterized by the ADF function with a symmetrical shape with a large kurtosis and/or a large skew. Ground hard surfaces are characterized by a large negative Ssk value and higher Vvv volumes can result in enhanced fluid retention abilities.
3. Hard turned and CBN ground textures have comparable Vmp and Spk parameters which can result in similar tribological properties. The best tribological performance of the burnished surface is caused by the minimum of both Vmp and Spk parameters.
4. The fractal dimension Sdf correlates well with the density of summits which can result in the decrease of the normal contact pressure. Also the wear rate decreases with increasing Sdf parameter.
5. Characterization of the surface topographies needs a careful scale analysis in order to determine appropriate area field parameters and their correlation with the fractal dimension.

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