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ANALYSIS OF THE SBI AND SVI FUNCTIONAL INDICES IN HARD MACHINING

Abstract. *The functional requirements of precision machined parts can be expressed among others by topography parameters. In the automotive industry there is an increased need for the application of high-accuracy quantifying parameters. In this study wear resistance and the fluid retention ability-related 3D surface texture parameters are analyzed based on hard turning and grinding experiments. The less frequently applied functional parameters (Sbi and Svi) are compared to the high-accuracy volume parameters (Vmp and Vvv) to obtain information about the reliability of the former ones. It was found that the correlation between the two types of parameters are quite weak.*
Keywords: *hard machining; grinding; surface texture.*

1. INTRODUCTION

In several machining industrial application, the characterization of surface texture plays an important role in obtaining information about the functional properties and the functional operation performance of the components [1]. To increase production efficiency and therefore reduce costs, reliable control processes have to be applied. This can be reached by a high degree of precision and by ensuring the repeatability of the measurements [2]. In precision machining the need for this is increased due to the increased number of hardened components. In machining hardened surfaces grinding has been the dominant procedure for decades [3, 4]. Now, it can be substituted by e.g. hard turning, which is a more productive procedure and among certain circumstances the texture of the surfaces have the same quality as that of ground ones. Machining of hardened materials requires superhard tool materials [5] in order to reach the expected surface quality [6]. Hard turning results in a periodic surface topography, however, random topography is required, grinding has to be applied [7].

In this study some function-related 3D surface texture parameters of hard turned and ground surfaces are analyzed and compared for the two procedures. 3D texture characterization is necessary because of the increased need for exact analysis of the surfaces [8, 9] and they describe the state of the surface better that the 2D parameters [10]. The analyzed parameters are the volume parameters, peak material volume (*Vmp*) and valley void volume (*Vvv*) and the functional indices, surface bearing index (*Sbi*) and valley fluid retention index (*Svi*). They provide information about the surface peaks and through this the wear resistance and the surface valleys, and through this about the fluid-retention ability.

These tribology-related characteristics have a high importance in operation of contacting surfaces.

The functional indices were compared to the volume parameters when the latter were considered as basis due to their reliability.

The volume parameters *Vmp* and *Vvv* are exact 3D volume parameters and they measure the peak material volume and the valley void volume precisely. A lower *Vmp* value is more favorable from tribological point of view [11] and indicates higher wear resistance. Concerning the valley parameter, a higher *Vvv* indicates higher fluid-retention ability [12]. In the volume analysis the peak zone is defined as the upper 10% and the valley zone as the lower 20% of the topography.

The so-called functional indices are less frequently applied. They also characterize the wear resistance and fluid retention abilities of the surfaces [13]. The lower the surface bearing index, the higher its wear resistance, while the higher the valley fluid retention index, the better the fluid retention ability [14, 15]. It can be stated that the analyzed volume and functional parameters provide information about the same tribological properties. In the analysis the *Sbi* characterizes the upper 5% and the *Svi* characterizes the lower 20% of the topography.

2. METHODOLOGY

2.1 Experimental setup

In the experiments external cylindrical surfaces were machined by hard turning and infeed grinding. The machined material was 16MnCr5 case hardened steel used widely in the automotive industry. The hardness of the surfaces varied between 62 and 63 HRC. The carburizing was carried out at 900 °C for 8 h. The temperature of case hardening was 820 °C and its duration was 30 min. For the cooling oil was used. The chemical composition and the mechanical and physical properties are summarized in Tables 1 and 2.

The applied machine tools were a precision CNC lathe type Optiturn S600 and a universal cylindrical grinding machine type KE 250-04. In the hard turning experiment, the cutting speed and the feed rate were varied on four levels, the depth-of-cut was fixed. In the grinding experiment the infeed velocity and the workpiece revolution-per-minute (rpm) were varied on three levels, the allowance and the wheel rpm were fixed. In Table 3 the applied technological data and tool cutting specifications are summarized. Concerning the varied cutting parameters, full factorial designs of experiment were applied; all the varying parameter combinations were analyzed. This resulted in 16 setups (4*4) and 9 setups (3*3) in the cases of hard turning and grinding, respectively.

Table 1 – Physical and mechanical properties of 16MnCr5 [16]

Tensile strength	1158 MPa	**Elongation**	15 %
Yield strength	1034 MPa	**Specific heat**	500 J/kgK
Thermal conductivity	16 N/mK	**Melting temp.**	1370-1400 °C

Table 2 – Chemical composition of 16MnCr5 (DIN EN 10184:2008)

C	Si	Mn	Cr	S	P
0.14–0.19	<0.4	1.00–1.30	0.80–1.10	<0.035	<0.025

Table 3 – Cutting parameters cutting tools

Hard turning		Grinding	
depth-of-cut (a_p, mm)	0.05	allowance (*Z*, mm)	0.1
feed rate (*f*, mm/rev)	0.05; 0.1; 0.15; 0.2	wheel rpm (n_w, 1/min)	1400
cutting speed (v_c, m/min)	60; 90; 120; 150	infeed velocity (v_{fR}, mm/s)	0.007; 0.019; 0.03
CBN insert: CNGA 120408TA4 Tool holder: CLNR 2525M12		workpiece rpm (*n*, 1/min)	31.5; 63; 90
		Ceramic bound alumina wheel: KA32M5KE (diameter: 400 mm, width: 63 mm)	

2.2 Texture measurement and the analyzed parameters

The textures of the surfaces were scanned and analyzed by a 3D roughness tester equipment, type AltiSurf 520. An optical (chromatic confocal) sensor, type CL2, was used. The resolutions of the sensor in the x- and y-directions were 2 μm and in the z-direction 0.012 μm. The measurement range in z-direction was 0–300 μm. For the evaluation of the data λ_c = 0.25 mm cut-off and Gauss filter were applied according to the standard ISO 4288-1996. For the analysis of the parameters, the standards ISO 25178 and EUR 15178N were used. The evaluation area was 2 mm × 2 mm.

The analyzed functional parameters are defined based on the root mean square roughness value *Sq*, which is defined by Eq 1.

$$Sq = \sqrt{\frac{1}{\mathrm{MN}}\sum_{k=0}^{\mathrm{M}-1}\sum_{l=0}^{\mathrm{N}-1}[z(x_k, y_l)]^2}, \tag{1}$$

where M and N are the number of points scanned in x and y directions, and *z* is the height of a topography point.

The surface bearing index is defined by Eq 2 and the valley fluid retention index by Eq 3.

$$Sbi = \frac{Sq}{z_{0.05}}, \tag{2}$$

$$Svi = \frac{1}{Sq} \cdot \frac{V_v(h_{0.08})}{(M-1)(N-1)\delta x \delta y}, \tag{3}$$

where $z_{0.05}$ is the height from the top (highest peak point) of the surface to the line designating the 5% bearing area; $h_{0.8}$ is the height from the bottom (lowest valley point) of the surface to the line designating the 80% bearing area; V_v is the volume representing the void volume [17].

These functional and volume parameters are derived from the Abbott-Firestone curve. In Fig. 1 the z parameters and the topography zones and in Fig. 2 the definitions of the analyzed volume parameters are demonstrated.

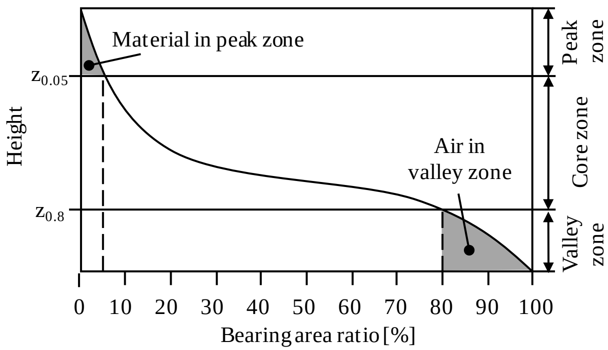


Figure 1 – Components of the *Sbi* and *Svi* indices and the topography zones [18]

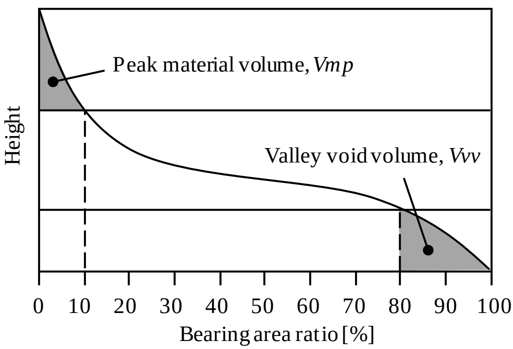
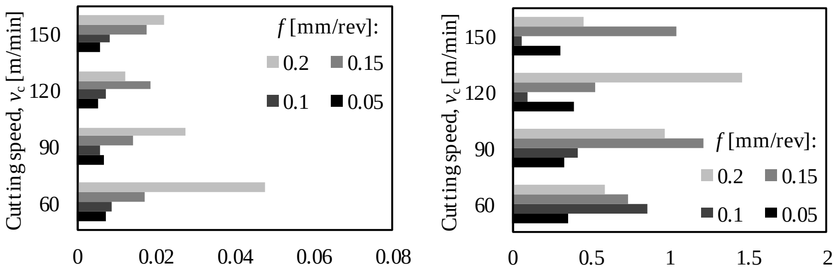


Figure 2 – Definitions of the analyzed volume parameters

3. RESULTS AND DISCUSSION

The peak material volume (*Vmp*) was compared to the surface bearing index (*Sbi*) for hard turning. It is demonstrated in Fig. 3 that the *Vvv* values show increase with the feed rate when 60 and 150 m/min cutting speed is applied. Such connection cannot be observed in the case of the *Sbi* parameter. At the same time, if only the lowest (0.05 mm/rev) and the highest (0.2 mm/rev) feed rates are considered, both the Vmp and the Sbi parameters increase with the feed rate. The two parameters theoretically are in connection with the same functional characteristics, the wear resistance and this connection can be observed in the analyzed setups, however the correlation is not obvious when all the setups are considered.



	60	90	120	150
0.2	0.0475	0.0276	0.0123	0.022
0.15	0.017	0.0144	0.0184	0.0176
0.1	0.0086	0.006	0.0074	0.0083
0.05	0.0071	0.007	0.0054	0.0059

Peak material volume, *Vmp* [ml/mm^3]

(a)

	60	90	120	150
0.2	0.585	0.9717	1.4642	0.4498
0.15	0.7387	1.222	0.5245	1.0401
0.1	0.8623	0.4155	0.0977	0.0567
0.05	0.3582	0.3253	0.3923	0.3038

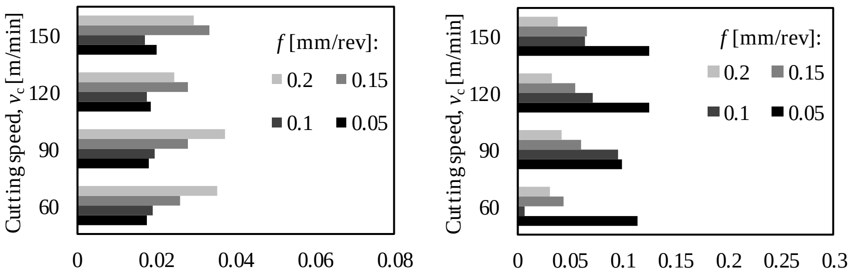
Surface bearing index, *Sbi* [-]

(b)

Figure 3 – (a) Peak material volume (*Vmp*) and (b) Surface bearing index (*Sbi*) parameter values of the hard turned surfaces

Analyzing the fluid retention ability based on the *Vvv* and the *Svi* parameters, contradictory results were obtained (Fig 4). The higher fluid retention ability theoretically is demonstrated by higher *Vvv* and higher *Svi* values. However, this cannot be observed from the data of the analyzed surfaces and the correlation between them is negative. It also can be observed that with the increase of the feed rate the *Vvv* values increase on 60 and 90 m/min cutting speeds and the *Svi* values decrease on 90 and 120 m/min. It can be observed from the diagrams (by neglecting some datapoints) that the increase in the *Vvv* show decrease in the *Svi* when the feed rate increases. The reason for this is the relatively high *Sq* values. While the valley volume increases the *Svi* value, the *Sq* decreases it. For example, in the case of *f*=0.05 mm/rev and v_c=60 m/min the *Vvv* divided by the *Sq*=0.155 μm results in 0.1148 ml/mm^3 *Svi* value or in the case of *f*=0.2 mm/rev, v_c=60 m/min and *Sq*=1.115 μm, the *Svi* equals to 0.0317 ml/mm^3. These *Vvv* and *Svi* values are placed in the first and fourth rows and first columns of the data tables in Fig 4 (The 0.001 and 0.003 differences of the calculated *Svi* values are resulted from the only four decimals). This result means that the values or their tendencies in the case of the *Svi* parameter do not inform uniformly or reliably about the same fluid retention ability due to the influencing effect of the incorporated *Sq* parameter. The comparison can be carried out only for surfaces whose *Sq* values are identical.

Both in the wear resistance and the fluid retention ability no clear effects can be observed based on the cutting speed values.



	60	90	120	150
0.2	0.0354	0.0373	0.0245	0.0296
0.15	0.026	0.0281	0.0279	0.0334
0.1	0.0193	0.0196	0.0175	0.017
0.05	0.0178	0.018	0.0188	0.0199

Valley void volume, *Vvv* [ml/mm^3]

(a)

	60	90	120	150
0.2	0.0318	0.0419	0.0328	0.0392
0.15	0.0439	0.0612	0.0558	0.0653
0.1	0.0068	0.0964	0.0723	0.0649
0.05	0.1151	0.0996	0.1249	0.1258

Valley fluid retention index, *Svi* [-]

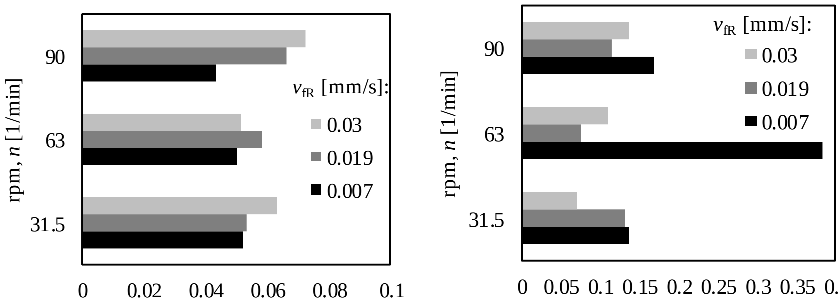
(b)

Figure 4 – (a) Valley void volume (*Vvv*) and (b) Valley fluid retention index (*Svi*) parameter values of the hard turned surfaces

In the grinding experiments the infeed velocity and the workpiece rpm were varied. The *Vmp* and *Sbi* values of the machined surfaces are demonstrated in Fig. 5. Clear tendencies cannot be observed when all the feed rates are considered. However, if neglecting the 0.019 mm/s infeed velocity, it can be stated that by the infeed velocity the *Vmp* value increases and the *Sbi* value decreases. The reason for this contradiction is similar to that between the *Vvv* and *Svi* parameters of hard turning. The *Sq* increases the *Sbi* and the $h_{0.05}$ peak zone height decreases it.

Concerning the fluid retention ability, no clear tendencies can be observed. The *Vvv* shows no unequivocal increase with both the infeed velocity and the rpm. Concerning the *Svi* parameter, it increases with the infeed velocity in the cases of 31.5 and 63 1/min rpm levels (Fig. 6). The reason for these contradictory results is the same as in the case of hard turning: the influencing effect of the scale of the *Sq* parameter.

To obtain quantitative information about the connections between the volume parameters and the functional indices, coefficients of determination were calculated. This parameter provides information about the strengths of the correlation of two variables if linear connection is supposed.



	31.5	63	90
0.03	0.0629	0.0514	0.0723
0.019	0.053	0.0582	0.0662
0.007	0.0519	0.0504	0.0434

Peak material volume, *Vmp* [ml/mm³]

	31.5	63	90
0.03	0.0711	0.1094	0.1377
0.019	0.1327	0.0738	0.1147
0.007	0.1376	0.384	0.1678

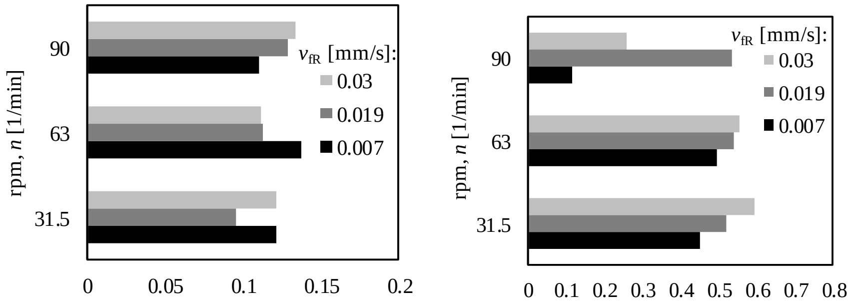
Surface bearing index, *Sbi* [-]

(a) (b)

Figure 5 – (a) Peak material volume (*Vmp*) and (b) Surface bearing index (*Sbi*) parameter values of the ground surfaces

The coefficient of determination is calculated from the linear correlation coefficient; the former is the square of the latter. The connection is considered as extremely strong if $0.81 \leq R^2 < 1$; strong, if $0.49 \leq R^2 < 0.81$; medium, if $0.16 \leq R^2 < 0.49$; weak, if $0.04 \leq R^2 < 0.16$ and extremely weak, if $R^2 < 0.04$.

In the cases of the hard turned surfaces there is a positive weak correlation between the *Vmp* and the *Sbi* parameters and a negative medium correlation between the *Vvv* and the *Svi* parameters. In the cases of the ground surfaces there is a weak correlation between the *Vmp* and the *Sbi* parameters and an extremely weak correlation between the *Vvv* and the *Svi* parameters.



	31.5	63	90
0.03	0.1216	0.112	0.134
0.019	0.0951	0.1126	0.1293
0.007	0.121	0.137	0.1097

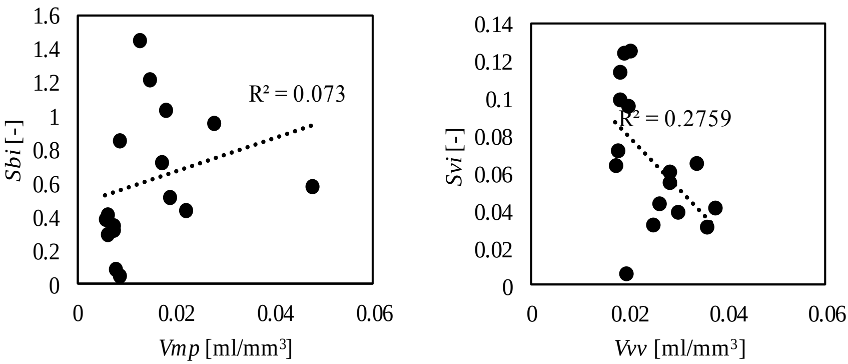
Valley void volume, *Vvv* [ml/mm³]

	31.5	63	90
0.03	0.596	0.5528	0.2572
0.019	0.5192	0.5382	0.5354
0.007	0.4496	0.4938	0.1138

Valley fluid retention index, *Svi* [-]

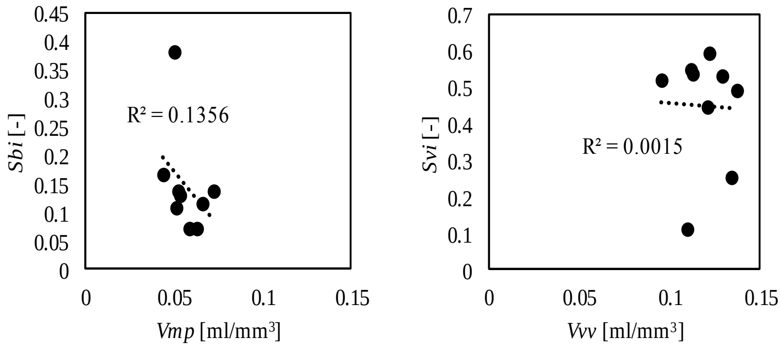
(a) (b)

Figure 6 – (a) Valley void volume (*Vvv*) and (b) Valley fluid retention index (*Svi*) parameter values of the ground surfaces



(a) (b)

Figure 7 – Connection between the (a) *Vmp* and *Sbi* parameters and the (b) *Vvv* and *Svi* parameters of the hard turned surfaces



(a) (b)

Figure 8 – Connection between the (a) *Vmp* and *Sbi* parameters and the (b) *Vvv* and *Svi* parameters of the ground surfaces

The connections between the data points and the values of the coefficients of determination are demonstrated in Figs. 7 and 8 for hard turning and grinding, respectively.

CONCLUSIONS

The findings of this study were obtained based on hard machining experiments and 3D texture analysis and valid for the material grade 16MnCr5 (HRC 62–63) and for the next cutting parameters: hard turning – a_p = 0.05 mm; v_c = 60 – 150 m/min; f = 0.05 – 02. mm/rev; infeed grinding – Z = 0.1 mm; n_w = 1400 1/min; v_{fR} = 0.007 – 0.03 mm/s; n = 31.5 – 90 1/min. The followings can be stated for the reliability of the surface bearing index (*Sbi*) and the valley fluid retention index (*Svi*) when the volume parameters peak material volume (*Vmp*) and valley void volume (*Vvv*) are considered as bases:

- In hard turning the correlation between the *Vmp* and *Sbi* parameters is positive and weak (R^2 = 0.073). Considerably connection can be observed only when the feed rate values are relatively far from each other.
- In hard turning the correlation between the *Vvv* and *Svi* parameters is negative and medium (R^2 = 0.2759). The reason for the negative correlation is the relatively strong influencing effect of the *Sq* parmeter incorporated in the formula of *Svi*.
- In grinding the correlation between the *Vmp* and *Sbi* and between the *Vvv* and *Svi* parameters are weak (R^2 = 0.1356) and extremely weak (R^2 =

0.0015), respectively. The reason for there is the relatively high influencing effect of the *Sq* parameter.

References: 1. *Whitehouse, D.J.:* Handbook of surface and nanometrology, Taylor & Francis, NY, 2011. **2.** *Deltombe, R., Kubiak, K.J., Bigerelle, M.:* How to select the most relevand 3D roughness parameters of a surface, Scanning 36, pp150-160, 2014. **3.** *Mamalis, A.G., Kundrak, J., Horvath, M.:* On a Novel Tool Life Relation for Precision Cutting Tools, Journal of Manufacturing Science and Engineering 127(2), pp.328-332, 2005. **4.** *Kundrak, J., Felho, Cs.:* 3D Roughness Parameters of Surfaces Face Milled by Special Tools, Manufacturing Technology 16(3), pp.532-538, 2016. **5.** *Zawada-Tomkiewicz, A.:* Analysis of surface roughness parameters achieved by hard turning with the use of PCBN tools, Estonian Journal of Engineering 17(1), pp.88-99, 2011. **6.** *Kundrak, J., Nagy, A., Markopoulos, A.P., Karkalos, N.E.:* Investigation of surface roughness on face milled parts with round insert in planes parallel to the feed at various cutting speeds, Cutting & Tools and Technological System 91, pp.87-96, 2019, pp.87–96. **7.** *Grzesik, W., Zak, K., Kiszka, P.:* Comparison of surface textures generated in hard turning and grinding operations, Procedia CIRP 13, pp.84–89, 2014. **8.** *Przestacki, D., Majchrowski, R., Marciniak-Podsadna, L.:* Experimental research of surface roughness and surface texture after laser cladding, Applied Surface Science 388, pp.420–423, 2016. **9.** *Kumar, R., Seetharamu, S., Kamaraj, M.:* Quantitative evaluation of 3D surface roughness parameters during cavitation exposure of 16Cr–5Ni hydro turbine steel, Wear 320, pp.16–24, 2014. **10.** *Aidibe, A., Nejad, M.K., Tahan, A., Jahazi, M., Cloutier, S.G.:* A proposition for new quality 3D indexes to measure surface roughness, Procedia CIRP 46, pp.327–330, 2016. **11.** *Letocha, A., Miller, T., Kalisz,* J.: Optimization of measurement and analysis parameters of burnishing surfaces, Mechanik 11, pp.1030-1034, 2017. **12.** *Grzesik, W., Zak, K., Kiszka, P.:* Comparison of surface textures generated in hard turning and grinding operations, Procedia CIRP 13, pp.84–89, 2014. **13.** *Yu Gazizova, M., Smirnov, N.A., Kudryashov, S.I., Chen, J., Ahmadeev, Y.H., Goncharov, I.Y., Shugurov, V.V., Prokopenko, N.A.:* Correlation of the tribological properties of LIPSS on TiN surface with 3D parameters of roughness, IOP Conf. Series: Materials Science and Engineering 1014, art no 012014, 2021. **14.** *Grzesik, W.:* Prediction of the functional performance of machined components based on surface topography: state of the art, Journal of Materials Engineering and Performance 25(10), pp.4460–4468, 2016. **15.** *Suh, A.Y., Polycarpou, A.A., Conry, T.F.:* Detailed surface roughness characterization of engineering surfaces undergoing tribological testing leading to scuffing, Wear 255, pp.556–568, 2003. **16.** Longhai Special Steel. Available online: https://www.steelss.com/Carbon-steel/16mncr5.html (accessed on 10/09/2022). **17.** *Georgescu, C., Cristea, G.C., Dima, C., Deleanu, L.:* Evaluating lubricating capacity of vegetal oils using Abbott-Firestone curve, IOP Conf. Series: Materials Science and Engineering 174, art no 012057, 2017. **18.** *Deleanu, L., Cantaragiu, A., Georgescu, C., Botan M.:* Influence of measurements on 3D roughness parameters, Mechanical Testing and Diagnosis 1, pp.42-53, 2011.

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АНАЛІЗ ФУНКЦІОНАЛЬНИХ ПОКАЗНИКІВ SBI І SVI ПРИ ЖОРСТКІЙ МЕХАНІЧНІЙ ОБРОБЦІ

Анотація. *У цьому дослідженні деякі функціональні параметри тривимірної текстури поверхні точених та відшліфованих поверхонь аналізуються та порівнюються для двох процедур. Тривимірна характеристика текстур необхідна через збільшення потреби в точному аналізі* *поверхонь, і вони краще описують стан поверхні, ніж двовимірні параметри. Аналізованими параметрами є об'ємні параметри, піковий об'єм матеріалу (Vmp) та обсяг порожнеч у западинах (Vvv), а також функціональні індекси, індекс поверхневої несучої здатності (Sbi) та індекс утримання рідини в западинах (Svi). Вони надають інформацію про піки поверхні і, таким чином, про зносостійкість і западини поверхні, а також про здатність утримувати рідину. Ці пов'язані з трибологією характеристики, мають велике значення при експлуатації поверхонь, що контактують. Функціональні показники зіставлялися з об'ємними параметрами, коли останні бралися за основу через їх достовірність. В експериментах зовнішні циліндричні поверхні оброблялися точінням різцем із КНБ та шліфуванням з подачею. Оброблюваним матеріалом була цементована сталь, що широко використовується в автомобільній промисловості. Твердість поверхонь варіювалася від 62 до 63 HRC. Навуглерожування проводили при 900°C протягом 8 годин. Температура цементації 820 ° C, тривалість 30 хв. Для охолодження використовувалося масло. Текстури поверхонь були відскановані та проаналізовані за допомогою 3D-тестеру шорсткості типу AltiSurf 520. Використовувався оптичний (хроматичний конфокальний) датчик типу CL2. Результати дослідження були отримані на основі експериментів для наступних параметрів різання: жорстке точіння –* a_p *= 0,05 мм;* $v_к$ *= 60–150 м/хв; f = 0,05–0,2 мм/об; врізне шліфування – Z = 0,1 мм;* n_w *= 1400 1/хв;* v_{fR} *= 0,007–0,03 мм/с; n = 31,5–90 1/хв. Щодо надійності індексу несучої здатності поверхні (Sbi) та індексу утримування рідини у западині (Svi), коли об'ємні параметри пікового обсягу матеріалу (Vmp) та обсягу порожнин у западині (Vvv) розглядаються як базові, можна констатувати наступне: при жорсткому точінні, кореляція між параметрами Vmp та Sbi позитивна та слабка (*R^2 *= 0,073). Помітний зв'язок можна спостерігати лише тоді, коли значення швидкості подачі відносно далекі одне від одного. При жорсткому точінні кореляція між параметрами Vvv і Svi негативна і середня (*R^2 *= 0,2759). Причиною негативної кореляції є відносно сильний вплив параметра Sq, закладеного у формулу Svi. При шліфуванні кореляція між параметрами Vmp та Sbi та між параметрами Vvv та Svi слабка (*R^2 *= 0,1356) та вкрай слабка (*R^2 *= 0,0015) відповідно. Причиною є відносно високий ефект впливу параметра Sq.*

Ключові слова: *жорстка механічна обробка; шліфування, поверхнева текстура*.