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TRIBOLOGY AND TOPOGRAPHY OF HARD MACHINED SURFACES

Abstract. *In machining automotive industrial parts by hard machining procedures, the topographic characteristics of high accuracy surfaces have high importance. In this paper 2D and 3D surface roughness features of gear bores machined by hard turning and grinding are demonstrated. The 3D roughness parameters, which are considered as more exact than the 2D parameters, were compared to the 2D ones, which are used more widely in industrial practice. The analyzed machining procedure versions were ranked based on the topographic parameters determining the tribological (wear and oil-retention capability) characteristics of the different surfaces.*
Keywords: *hard turning; in-feed grinding; 3D surface roughness; tribology.*

1. INTRODUCTION

Due to the advancement of machining technology and the increasingly efficient machining procedures [1], the quality of the machined surfaces has to be described as exactly as possible. The grooves generated by the tool are different when the tool has a linear motion [2] or a rotating tool is applied [3]; these kinematic characteristics lead to different surface topography [4, 5]. Identical or almost identical roughness values can be reached by different machining procedures (e.g. hard turning and grinding); however, because of the different cutting characteristics the surface topography will also be different [6]. At the same time the cutting data, particularly the feed, significantly influence the roughness of the machined surface [7]. The potentially most accurate determination of roughness parameters is required by the diversity of machining procedures [8, 9], the high number of roughness influencing factors, and the comparability of roughness parameters of surfaces machinable by various procedures. In the automotive industry the efficient machining of hard surfaces has a high significance, thus hard machining procedures such as hard turning or grinding were compared in this study. These procedures or procedure versions differ from each other not only in the resulting surface topography, but also in other relevant factors such as economic issues of the machining procedures [10] or the impacts of the cooling and lubrication [11].

There are numerous machining procedures (use of dingle-point-tool or abrasive tool) for machining hard materials when high accuracy is required. The different procedures can result different surface topographies on the part. The working requirements of the parts can be different, thus the topography characteristics after machining should be analyzed [12, 13].

The lifetime of parts is significantly influenced by the irregularities of working surfaces (micro and macro geometrical errors). Contacting surfaces experience wear, but a suitable machining procedure and/or lubrication can decrease the extent of the wear. The wear of a surface with good oil-retention capability is slower. By analyzing the roughness parameters, conclusions about the tribological characteristics of the surfaces can be drawn [14, 15]. The experiments aimed to analyze the 2D and 3D roughness parameters by which the tribological properties can be characterized.

The core roughness depth (R_k) and the core height (S_k) are related to the lifetime of the surface. When two surfaces are in contact with each other during relative motion (working surfaces) part of the profile peaks will be sheared. The remaining layer is characterized by a relatively large bearing area and it is the part of the core zone of the surface. The reduced peak height (R_{pk}, S_{pk}) is the height of the layer worn in the initial wearing phase. The reduced valley depth (R_{vk}, S_{vk}) is the layer beneath the core zone and correlates with the oil-retention capability of the surface [16]. In terms of wear, lower reduced peak height values are favorable. At the same time, since these parameters are height and depth values, they do not provide information about the area (2D) or the volume (3D) of the peaks or valleys. This is why the peak material portion (M_{R1} in 2D and Sr1 in 3D) and the valley material portion (MR2 in 2d and Sr2 in 3D) have to be defined. By using the R_{pk}, R_{vk}, MR1 and MR2 values or the S_{pk}, Svk, Smr1 and Smr2 values the areas (2D parameters) of the peak (A1) and the valley zones (A2) and the volumes (3D parameters) of the peak (Sa1) and the valley zones (Sa2) can be obtained [17, 18]. The area or volume of the profile valleys provide relevant information about the oil-retention capability of a surface. The higher these values are, the more lubricant remains in the surface valleys.

The skewness (Rsk, Ssk) is the height distribution of profile points relative to the center line of the profile and provides information about the asymmetric nature of the surface points. Its value is positive if the heights of the peaks are higher than the depths of the valleys and negative when the depths of the valleys are higher. A surface is characterized by higher load bearing capacity and higher wear resistance if the skewness value is negative. The kurtosis (Rku, Sku) provides information about the peaky feature of a surface. When its value is relatively high (>3) a friction surface shows more intense wear. When its value is lower the surface shows higher wear resistance [19].

Using a tribological topography map the tribological characteristics of surfaces can be analyzed. The map includes the skewness and kurtosis values of the machined surfaces and they are placed in a coordinate system. From the tribological point of view a surface is ideal if the point of a surface characterized by these two parameters is located by lower kurtosis (close to 0) and also lower (negative) skewness values. In Fig. 1 an example for a tribological topography map is shown with points that belong to surfaces machined by the major procedures. Topographies of gear bore surfaces machined by hard turning, grinding and combined (turning and grinding in one clamping) experiments were compared based on roughness parameters which characterize the wear and the oil-retention capability. The differences of the 2D and 3D parameter values were also analyzed.

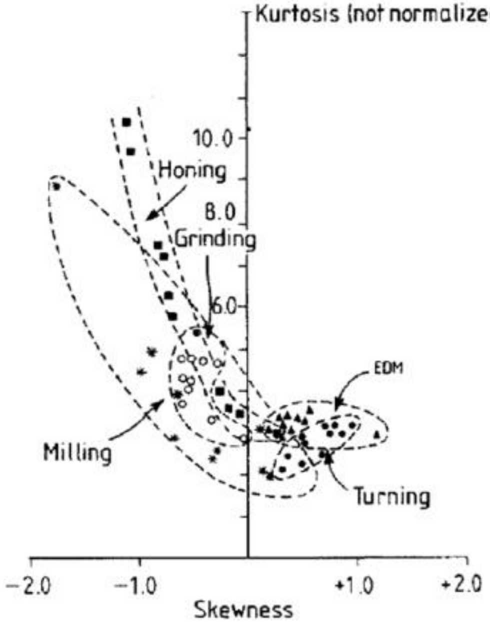


Figure 1 – Tribological topography map [20]

2. EXPERIMETNAL SETUP

In the experiments bores of gears were machined by hard turning when three different feeds were applied (T1, T2, T3), by infeed grinding (G1) and using a combination of hard turning and grinding (G2). The technological data of hard turning were:

- Feed (f): 0.1 mm/rev (T1), 0.2 mm/rev (T2), 0.3 mm/rev (T3)
- Depth of cut (a_p): 0.2 mm
- Workpiece rpm (n): 615 1/min

In the hard turning pass of the G2 combined operation the feed was set to 0.2 mm/rev when the other parameters were left unchanged.

Parameters of the infeed grinding:

- Feed (f): 0.01 mm/rev
- Wheel width (d): 34 mm
- Allowance (Z): 0.2 mm
- Workpiece rpm (n_w): 325 1/min
- Tool rpm (n_t): 20000 1/min

In the infeed grinding part of the G2 combined procedure operation the allowance was set to 0.05 mm when the other parameters were left unchanged.

The machining experiments were carried out on a machining center type EMAG VSC 400. In the machining experiment a Sandvik CCGW 09T308 NC2 type insert and an E25T-SCLCR 09-R type tool holder were used. The grinding operations were carried out using a bore grinding wheel type Norton 3AS80J8VET 01_36X37X13. The workpiece material was 20MnCr5, its hardness was 62–64 HRC. The length of the machined bore was 34 mm and its diameter was 88 mm.

The surface topography was analyzed by measuring 2D and 3D roughness parameters. In the 2D measurement 3 measurements were carried out per workpiece, located at 120° distance from each other. The measurement lengths were 4 mm. In the 3D measurements 2×2 mm areas were scanned. 0.8 mm cut-off and Gauss filter were applied in each measurement, which was carried out by using an inductive sensor. The number of scanned points was 4000 in the 2D and 1 million in the 3D measurement.

3. RESULTS AND DISCUSSION

Topographic characteristics of random (ground) and periodic (turned) surfaces (Fig. 2) were analyzed based on 2D and 3D roughness parameters.

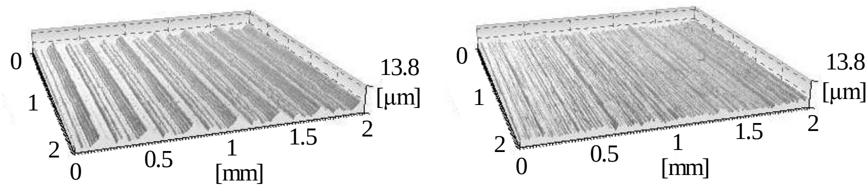
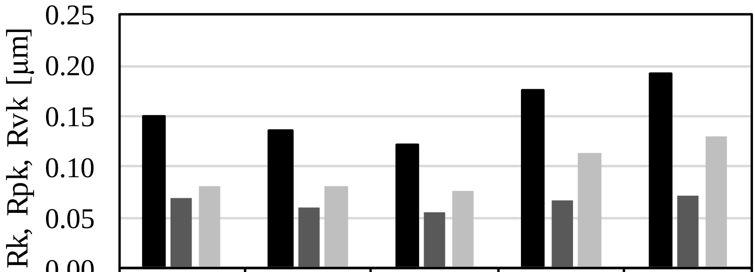


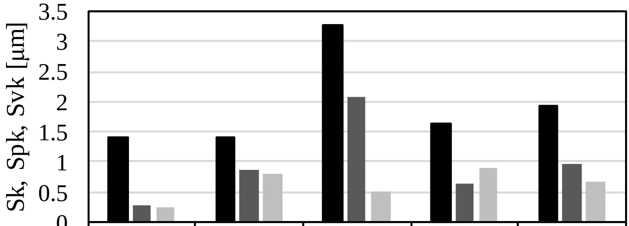
Figure 2 – Periodikus (a) és random (b) felületek (a T3 és G2 eljárásváltozatok)

In Figs. 2 and 3 the measured values of core roughness depth (2D), core height (3D), the reduced peak height and reduced valley depth are summarized. The core roughness depth (2D parameter Rk) varied from 0.12 and 0.19 μm. The core height (3D parameter Sk) varied from 1.39 to 3.27 μm. This means a difference of 3 orders of magnitude. The values of the 2D parameter of the hard turned surfaces showed a slight decrease and those of the 3D parameter a slight increase with the increase of feed. Compared to version G1, the 2D and 3D values of the ground surface machined in the combined version G2 were 10% and 20% higher, respectively. The values of the reduced peak height (Rpk and Spk) showed identical tendencies and similar rates. The values of the 2D parameter of the reduced valley depth (Rvk) showed similar rates; however, there were some deviations concerning the 3D parameter (Svk): the value of the surface machined by version T3 decreased compared to version T2 instead of the expected increase, and the value of version G2 decreased instead of increasing. In all, the 2D and 3D parameter values result in contradictory conclusions. Based on findings from the literature [21, 22], it can also be presumed in the present study that the results of 3D measurements are more exact than those of 2D measurements because the number of detected points is three orders of magnitude higher. Based on the 3D parameter, from a tribological point of view, it can be stated that the heights of the peaks that are worn in the initial phase of working is the most favorable (minimal) in version T1 (carried out by a feed of 0.1 mm/rev) and the least favorable in version T3 (0.3 mm/rev feed). Based on the depth of valley zone it can be concluded that the oil-retention capability is the most favorable in version G1 and similar in version T2.



	T1	T2	T3	G1	G2
Rk	0.1501	0.1366	0.1215	0.1748	0.1921
Rpk	0.0692	0.0586	0.0552	0.0660	0.0704
Rvk	0.0802	0.0811	0.0762	0.1124	0.1290

Figure 3 – Core roughness depth (Rk), reduced peak height (Rpk) and reduced valley depth (Rvk)

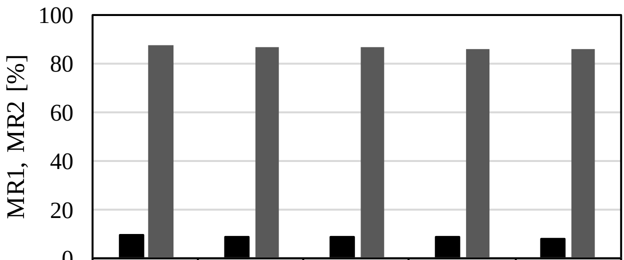


	T1	T2	T3	G1	G2
Sk	1.3894	1.4031	3.2711	1.6234	1.9393
Spk	0.2736	0.8694	2.0832	0.6383	0.9717
Svk	0.2278	0.8157	0.4934	0.8846	0.6536

■ Sk ■ Spk ■ Svk

Figure 4 – Core height (Sk), reduced peak height (Spk)
and reduced valley depth (Svk)

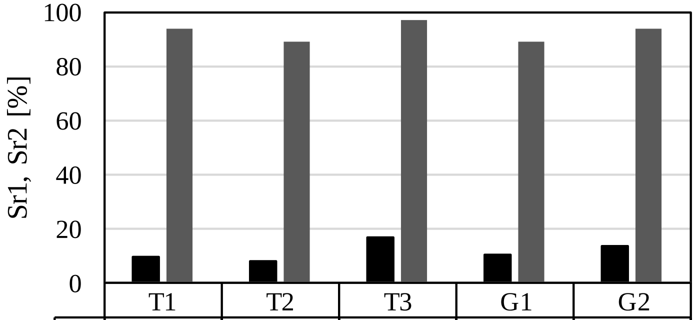
The peak and valley material portions are summarized in Figs. 4 and 5. MR1 and MR2 are the 2D, Sr1 and Sr2 are the 3D parameters that are required to calculate the areas and volumes of the peak and valley zones. It is shown in the figures that there is only a minimal difference between the analyzed versions: version T3 shows a slight outlying in the Sr1 and Sr2 values. The differences between the 2D values are negligible (e.g. there is only 1.2% difference between the maximum and minimum MR1 values).



	T1	T2	T3	G1	G2
MR1	9.0332	8.3372	8.8164	8.1586	7.8682
MR2	87.2010	86.2872	86.4789	85.5753	85.5016

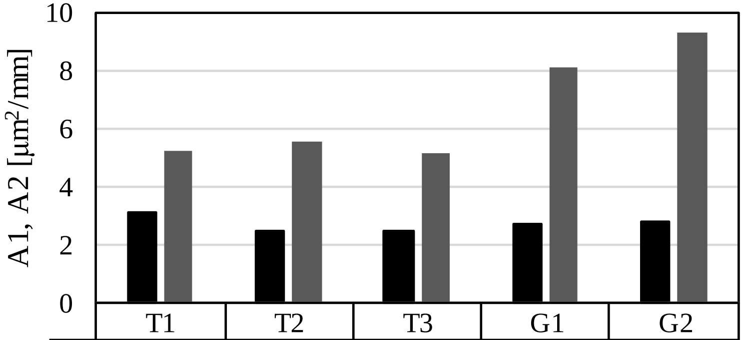
■ MR1 ■ MR2

Figure 5 – Peak material portion (MR1) and valley
material portion (MR2) 2D roughness parameter values



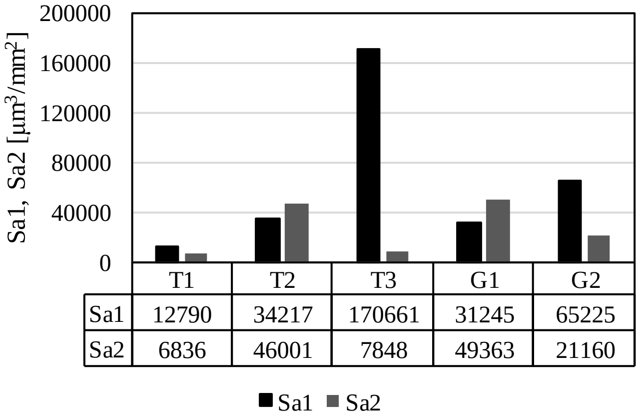
	T1	T2	T3	G1	G2
Sr1	9.348	7.8715	16.3844	9.97	13.425
Sr2	93.998	88.7215	96.8187	88.84	93.525

Figure 6 – Peak material portion (MR1) and valley material portion (MR2) 3D roughness parameter values



	T1	T2	T3	G1	G2
A1	3.1205	2.4445	2.4350	2.6972	2.7792
A2	5.1977	5.5650	5.1596	8.1290	9.3381

Figure 7 – Area of peak (A1) and valley zone (A2)



	T1	T2	T3	G1	G2
Sa1	12790	34217	170661	31245	65225
Sa2	6836	46001	7848	49363	21160

Figure 8 – Volume of peak (Sa1) and valley zone (Sa2)

In Figs. 6 and 7 the areas (2D) and volumes (3D) of peak and valley zones are demonstrated. Comparing the area to the volume data is inadequate because of their different dimensions. However, the comparison of the versions to each other is possible. The 2D parameters A1 and A2 are in line with the parameters Rpk and Rvk and the 3D parameters Sr1 and Sr2 with Spk and Svk. Here the higher accuracy of the 3D parameters can also be assumed. The values of the volume parameters reinforce the above statement that from the wear mechanism's point of view version T1 is the most favorable and from the oil-retention capability's point of view versions G1 and T2 are the most favorable.

Procedure version	Rsk	Rku
T1	0.162	2.108
T2	0.006	3.773
T3	0.770	2.887
G1	-0.047	3.582
G2	-0.014	3.344

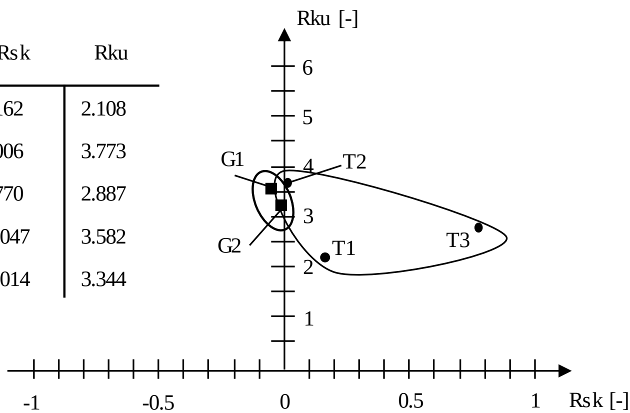


Figure 9 – Tribological topography map for the 2D parameters (skewness, kurtosis)

Procedure version	Ssk	Sku
T1	0.153	2.180
T2	0.003	3.735
T3	0.665	2.715
G1	-0.317	5.099
G2	0.468	3.279

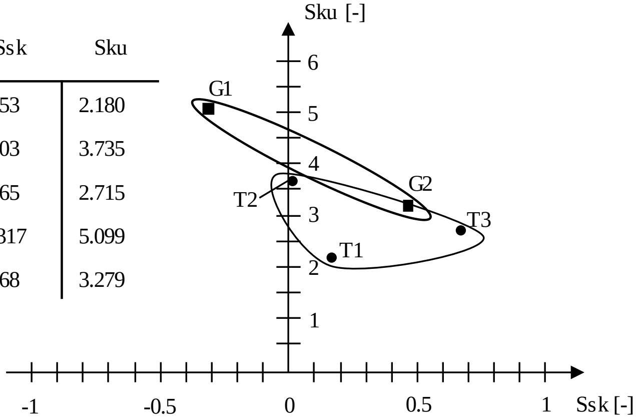


Figure 10 – Tribological topography map for the 3D parameters (skewness, kurtosis)

Based on the 2D (Fig. 8) and 3D (Fig. 9) parameters (skewness and kurtosis) the tribological topography maps of the versions were prepared. The locations of data points of the hard turning versions are in line with the published results. There is no significant difference between the 2D and 3D values. Based on the 2D parameters – considered less exact – the locations of data points of the two ground surfaces are in line with published results. However, for the 3D parameters one difference is experienced: the skewness (Ssk) of version G2 is higher than expected.

SUMMARY

From a tribological point of view, wear resistance and oil-retention capability are determinant characteristics of machining industrial parts. Analyzing the surface topography of wearing parts is a critical research area. In this paper roughness characteristics of surfaces machined by hard turning, infeed grinding and using a combination were analyzed and compared. Based on the analyzed parameters the following order or ranking (most favorable comes first) was established between the studied versions:

- Reduced peak height, Spk (wear resistance), favored: low
  T1, G1, T2, G2, T3
- Volume of the peak zone, Sa1 (wear resistance), favored: low
  T1, G1, T2, G2, T3
- Skewness, Sks (wear resistance), favored: low
  G1, T2, T1, G2, T3
- Kurtosis, Sku (wear resistance), favored: <3

T1, T3, G2, T2, G1

- Reduced valley depth, Svk (oil-retention capability), favored: high
  G1, T2, G2, T3, T1
- Volume of valley zone, Sa2 (oil-retention capability), favored: high
  G1, T2, G2, T3, T1

Different orders are found for the parameters characterized by various tribological properties: based on the parameters Spk and Sa1 the orders of wear resistance are identical, but the skewness and kurtosis values are not in line with these orders. The reason for this is the different mathematical approaches. Because of this, the roughness parameters to be used have to be selected carefully and the results have to be interpreted with some reservation. The study pointed out that there can be significant differences between the 2D and 3D parameter values obtained by measuring the same surface and this may lead to controversial interpretation of the results.

The study can be extended to more experimental setups or to analyzing various grades of materials.

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ТРИБОЛОГІЯ І ТОПОГРАФІЯ ЖОРСТКО ОБРОБЛЕНИХ ПОВЕРХОНЬ

Анотація. *В автомобільній промисловості ефективна обробка твердих (загартованих) поверхонь має велике значення, тому в цьому дослідженні порівнювалися такі методи обробки, як жорстке точіння і шліфування. Ці процедури або версії процедур відрізняються один від одного не тільки результуючою топографією поверхні, але і іншими важливими факторами, такими як економічні проблеми, пов'язані з процедурами обробки або вплив охолодження і мастила. Різні процедури можуть призвести до різної топографії поверхні деталі. Робочі вимоги до деталей можуть бути різними, тому необхідно аналізувати топографічні характеристики після обробки. Аналізуючи параметри шорсткості, можна зробити висновки про трибологічні характеристики поверхонь. Експерименти були спрямовані на аналіз 2D і 3D параметрів шорсткості, за допомогою яких можна охарактеризувати трибологічні властивості. Використовуючи карту трибологічної топографії, можна проаналізувати трибологічні характеристики поверхонь. Карта включає в себе значення асиметрії та ексцесу оброблених поверхонь, і вони поміщені в систему координат. З трибологічної точки зору поверхня ідеальна, якщо точка поверхні, що характеризується цими двома параметрами, розташована з меншим ексцесом (близьким до 0), а також меншими (негативними) значеннями перекосу. Топографії поверхонь отворів зубчастих коліс, оброблених жорстким точінням, шліфуванням і комбінованим (точіння і шліфування за один затиск) експериментально порівнювалися на основі параметрів шорсткості, які характеризують знос і здатність утримувати мастило. Також були проаналізовані відмінності значень 2D і 3D параметрів. Для параметрів, що характеризуються різними трибологічними властивостями, знайдені різні порядки: для параметрів* S_{pk} *і* S_{a1} *порядки зносостійкості ідентичні, але значення асиметрії та ексцесу не відповідають цим порядкам. Причина цьому - різні математичні підходи. Через це параметри шорсткості, які будуть використовуватися, повинні бути ретельно обрані, щоб їхні результати були інтерпретувані з деякими застереженнями. Дослідження показало, що між значеннями 2D і 3D параметрів, отриманих при вимірюванні однієї і тієї ж поверхні, можуть бути значні відмінності, і це може привести до суперечливої інтерпретації результатів.*

Ключові слова: *жорстке точіння; врізне шліфування; тривимірна шорсткість поверхні; трибологія.*