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Surface Topography Modelling for Reduced Friction

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The aim of the present research was to investigate the possibility to design contact surfaces with reduced friction using surface roughness and topography analysis. For this purpose, different 100Cr6 plate samples with different surface topography were prepared. Using different grades and combinations of grinding and polishing samples with similar R_a values, but different R_{ku} and R_{sk} values were prepared. To evaluate influence of roughness parameters on friction and wear, dry and lubricated pin-on-disc tests were carried out under different contact conditions. Test results show that surfaces with high R_{ku} and negative R_{sk} values results in reduced friction.

To investigate the effect of surface topography on surface roughness parameters and consequently on friction, real roughness profiles were virtually altered to achieve virtually textured surfaces. Using NIST SMATS softgauge for calculation of surface roughness parameters, virtually altered roughness profiles were investigated in terms of texture size, shape and spacing, and their influence on surface roughness parameters, especially on skewness and kurtosis. Lower diameter, higher spacing and wedge-shaped dimples were found to reflect in higher R_{ku} and more negative R_{sk} parameters, which should lead to lower friction.

Keywords: surface topography, roughness parameters, friction, surface texturing

0 INTRODUCTION

Controlling the friction is becoming increasingly significant due to constant demands for improved reliability and effectiveness of mechanical parts and especially the reduction in frictional loses. In recent years surface texturing was introduced as a way of reducing friction. With employment of different patterns in the form of micro dimples or groves on the surface, reduction of friction can be obtained [1] to [13]. There are some texturing parameters like the shape of the dimples, their depth and width, their area density and orientation, which exert an influence on friction and wear. However, a lot of research work has been done in the field of surface texturing, while modification of surface topography by texturing is still mainly based on trial and error approach.

A possible way of designing surface texturing parameters, which would result in contact surfaces with lower friction, is by treating surface texturing as a controlled roughness. By knowing what kind of surface topography in terms of roughness parameters results in lower friction, we would be able to select proper surface texturing parameters. However, for this knowledge about the correlation between surface roughness and friction is essential.

Surface roughness and topography, which are used to characterize contact surfaces are described with surface roughness parameters. Unfortunately, standard surface roughness parameters normally used by designers do not describe contact surfaces sufficiently, with completely different surfaces showing similar or even the same values of standard roughness parameters and the other way round – similar surfaces having much different standard roughness parameters. In addition, different standards use different parameters. In practice most commonly used parameters for surface roughness description are R_a, R_q, and R_{max}.

Average surface roughness (R_a) gives a very good overall description of height variations, but does not give any information on the wavelength and it is not sensitive to small changes in profile. Root mean square deviation of the assessed profile (R_q) is more sensitive to deviations from the main line than R_a. However, there are also other roughness parameters defined by ISO 4287 standard, which give better surface description. R_{sk} is defined as skewness and is sensitive on occasional deep valleys or high

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peaks. Zero skewness reflects in symmetrical height distribution, while positive and negative skewness describe surfaces with high peaks or filled valleys, and with deep scratches or a lack of peaks, respectively. On the other hand, kurtosis (R_{ku}) describes the probability density sharpness of the profile. For surfaces with low peaks and low valleys, R_{ku} is less than 3, and more than 3 for surfaces with high peaks and low valleys [14]. The load bearing ratio, as well as the maximum contact pressure increase with the increase of skewness and kurtosis [15]. It was also observed that parameters R_k, R_{pk} and R_{vk} tend to have influence on coefficient of friction [16]. Parameters R_k, R_{pk} and R_{vk} are based on the bearing ration curve (Abbott-Firestone Curve) and are defined by the standard ISO13565-2. Core peak-to-valley height (R_k) give a numerical summary of the information contained in the bearing ratio curve based on the division of the curve into three regions. The upper region is defined as reduced peak height (R_{pk}), the middle region as core region (R_k) and the lower region as reduced valley depth (R_{vk}). When two surfaces rub together, the peak region usually gets worn out; the core region bears the load and has influence on the life of the product and valley region which acts as a lubricant reservoir.

Therefore, the aim of the present research was to investigate surface topography of contact surfaces in terms of different surface roughness parameters and to correlate surface topography changes to friction. Furthermore, to investigate the possibility of using roughness parameters as design parameters for surface topography modification, real roughness profiles were virtually altered to achieve virtually textured surfaces and roughness parameters calculated using NIST Surface Metrology Algorithm Testing System (SMATS) softgauge [17]. Virtually altered roughness profiles were investigated in terms of influence of texture size and shape on skewness and kurtosis parameters.

1 EXPERIMENTAL

For the purpose of this investigation, 100Cr6 (AISI 52100) steel samples were used. Disc type steel samples with a diameter of 24 mm were prepared in terms of different average surface roughness. By using different grades of grinding and polishing results with R_a values from 0.02 to 0.49 μm, and different R_{ku} and R_{sk} values were obtained. With the use of different grain size and grinding parameters it is possible to obtain different surface roughness. Increasing grain size and depth of cut increased the grinding forces and surface roughness values [18].

All samples were first grounded under water for 10 min, using grinding paper Piano 120, force 250 N, and rotation speed of 300 rpm. Samples with average roughness R_a of about 0.5 mm were further grounded in water for 7 s with SiC paper and grain number 80, force 50 N and rotation speed of 150 rpm. On the other hand, smoothest surfaces with a surface roughness of about 0.02 mm were obtained with through two step polishing. They were first polished for 10 min with 9 mm DP-plan disc, using a force of 250 N and 150 rpm, and then subsequently polished for 10 min with 6 mm DP-plan disc, at 200 N force and 150 rpm. To prepare surfaces with similar R_a values but different R_{ku} and R_{sk} values, previously prepared samples with $R_a$values from 0.02 to 0.45 μm were used and treated afterwards with sandpapers or polishing pads to achieve desired roughness. Samples with higher R_a values were polished in order to remove high peaks on the surface, while polished samples were rubbed against sandpapers with different grain sizes to achieve groves on the smooth surface. Surface topography of all samples was randomly orientated.

Average surface roughness (R_a), root square (R_q), skewness (R_{sk}), kurtosis (R_{ku}), core peak-to-valley height (R_k), reduced peak height (R_{pk}) and reduced valley depth (R_{vk}) of prepared samples, measured on three different positions on the disc, with each incorporating 25 individual profiles, are shown in Table 1. The first four surface roughness parameters are according to ISO 4287 standard, while last three parameters are according to ISO 13565-2 standard. Samples tested under dry conditions are denoted with D and those under lubricated conditions as L. To investigate the influence of different roughness parameters on friction, regarding similar R_a values but different R_{sk} and R_{ku} values, we can mutually compare samples D1 and D2 with R_a in the range of ~0.11 μm, samples D3 to D5 (Ra ~0.16 μm), D6 and D7 (Ra ~0.47 μm), L1 and L2 (Ra ~0.02

µm), L3 and L4 (Ra ~0.13 µm), L5 and L6 (Ra ~0.16 µm), L7 and L8 (Ra ~0.44 µm) (Table 1),

Tribological testing under dry and lubricated sliding conditions was carried out on Pin on disc tribometer using a ball on disc contact. In order to concentrate all the wear and surface topography changes on the investigated steel discs polished Al_2O_3 ball (ϕ10 mm) was used as a counterpart. Tribological testing was then performed at 3 different sliding speeds (0.05, 0.1 and 0.2 m/s) and a normal load of 1 N, which corresponds to a nominal contact pressure of 0.56 GPa. All tests (dry and lubricated) were made at room temperature (23±2 °C) and the relative humidity of 50 ± 10%, with lubricated ones carried out under boundary lubrication conditions using pure PAO 8 oil (v_{40} = 46 mm²/s). During testing, coefficient of friction was monitored as a function of time and wear of contact surface measured after the test by means of topography analysis.

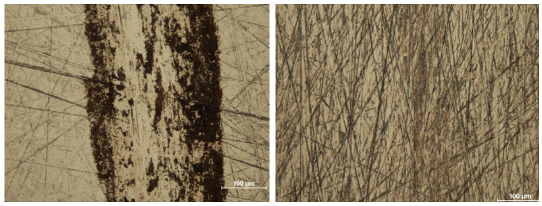
Table 1. *Values of surface roughness parameters for different samples*

	R_a	R_q	R_{sk}	R_{ku}	R_k	R_{pk}	R_{vk}
D1	0.11	0.20	-1.74	24.42	0.266	0.18	0.22
D2	0.12	0.16	-1.44	12.55	0.345	0.14	0.25
D3	0.15	0.23	-2.51	16.02	0.348	0.13	0.47
D4	0.16	0.23	-0.86	6.977	0.436	0.17	0.36
D5	0.16	0.21	-0.38	4.240	0.488	0.18	0.27
D6	0.49	0.74	-1.33	10.80	1.360	0.81	1.44
D7	0.45	0.59	-0.90	5.341	1.334	0.40	0.88
L1	0.02	0.02	0.25	3.075	0.071	0.02	0.01
L2	0.04	0.05	-1.37	16.63	0.132	0.03	0.05
L3	0.12	0.17	-0.27	9.310	0.352	0.07	0.26
L4	0.13	0.19	-1.67	12.21	0.304	0.18	0.32
L5	0.16	0.21	-0.38	4.240	0.488	0.17	0.27
L6	0.16	0.26	-3.11	23.20	0.342	0.17	0.53
L7	0.44	0.6	-1.32	10.29	1.002	0.65	1.41
L8	0.45	0.59	-0.90	5.341	1.334	0.40	0.88

2 RESULTS AND DISCUSSION

2.1 Dry Sliding

For all tests made under dry sliding conditions, a combination of plastic deformation and abrasion was found as the main wear mechanism (Fig. 1a), resulting in a complete change in surface topography. Consequently, wear volume and sliding distance, when steady state friction conditions are reached displayed a very high degree of scattering, as shown in Table 2.



a) *b)*

Fig. 1. *Topography change after; a) dry, b) lubricated sliding test*

However, when comparing samples D1 and D2, with sample D1 having much higher R_{ku} value at similar average roughness, the coefficient of friction tends to be lower for sample D1. A comparison of samples D3, D4 and D5 which have similar R_a and R_q values, but different R_{sk} and R_{ku}, shows that surface with the lowest skewness and the highest kurtosis (D3) also results in the lowest friction. Furthermore, for sample D3 friction is almost independent of the sliding speed, while for samples D4 and D5 friction is reduced with increase in sliding speed. Also the sliding distance to steady-state conditions is the shortest for sample D3, which is true for all sliding speeds.

Table 2. *Coefficient of friction and sliding distance to steady state conditions for dry sliding*

	Coefficient of friction [m/s]			Sliding distance to steady state conditions [m/s]		
	0.05	0.1	0.2	0.05	0.1	0.2
D1	0.89	0.92	0.91	34	50	38
D2	0.96	0.93	0.93	49	28	38
D3	0.89	0.90	0.89	31	29	16
D4	0.94	0.89	0.86	37	39	30
D5	0.99	0.97	0.92	39	30	33
D6	0.82	0.85	0.87	35	39	42
D7	0.84	0.63	0.66	40	24	34

When comparing samples D6 and D7, which have the highest R_a and R_q values between all D samples, lower friction and shortest sliding distance to steady state condition were obtained for sample D7, which displays smaller values of R_{sk} and R_{ku} parameters. For sample D6 sliding speed has a very minor effect on friction, while for sample D7 increase in sliding speed results in reduced friction.

However, experimental results show that for dry sliding in general coefficient of friction is lower when roughness is high, and it gets reduced with increase in sliding speed. Furthermore, for surfaces with high value of R_{ku} and more negative R_{sk} parameter, friction also tends to be lower.

Under dry sliding high degree of wear and change in surface topography limits a proper comparison and correlation between surface roughness and tribological properties of contact surfaces.

2.2 Lubricated Sliding

Under lubricated sliding original topography of the contact surfaces was preserved during the test (Fig. 1b), with higher sliding speed generally resulting in lower friction. The coefficient of friction and sliding distance to steady state conditions for lubricated testing are summarized in Table 3.

Table 3. *Coefficient of friction and sliding distance to steady state conditions for lubricated sliding*

	Coefficient of friction [m/s]			Sliding distance to steady state conditions [m/s]		
	0.05	0.1	0.2	0.05	0.1	0.2
L1	0.11	0.09	0.08	8	15	21
L2	0.09	0.08	0.07	17	16	8
L3	0.14	0.14	0.14	19	16	13
L4	0.14	0.13	0.12	17	9	5
L5	0.15	0.15	0.14	28	20	16
L6	0.10	0.10	0.10	23	11	6
L7	0.14	0.14	0.13	31	23	6
L8	0.16	0.14	0.14	22	18	9

In the case of smooth surfaces (samples L1 and L2), sample L2 gave lower friction although its average roughness (R_a) was higher than for L1. However, while sample L1 has positive skewness and kurtosis around 3, L2 has negative skewness and very high kurtosis. Besides the lower friction sample L2 also shows a reduction in the sliding distance to steady-state conditions with sliding speed as compared to sample L1 where it increases as shown in Table 3. For samples with R_a values around 0.12 μm (L3 and L4) similar friction was observed although L4 displays higher R_{ku} value and more negative R_{sk} than sample L3. On the other hand, the difference in R_{sk} and R_{ku} roughness parameters has an influence on sliding distance when steady state conditions are reached. Sample L4 with higher R_{ku} and more negative R_{sk} shows drastically shorter sliding distances, as shown in Table 3

When comparing samples with R_a values of about 0.16 μm (L5 and L6), effect of parameter R_{ku} and R_{sk} is even more pronounced. Higher R_{ku} and more negative R_{sk} values measured for sample L6 result in lower friction. Furthermore, when comparing coefficient of friction for sample L6 and samples L3 and L4, it can be seen that sample L6 shows lower friction and shorter sliding distance to steady state conditions although displaying higher R_a values. In the case of the roughest samples (L7 and L8), with R_a values ~0.45 μm, similar tendencies were observed, with higher R_{ku} and more negative R_{sk} values leading to lower friction. On the other hand, for very rough surfaces sliding distance to steady state condition tends to increase with an increase in R_{sk} and R_{ku} parameters (L7). Interesting results were observed when comparing samples L3 and L7. Although sample L7 shows much higher average surface roughness, it has similar R_{sk} and R_{ku} value and consequently gives similar friction under lubricated sliding. However, as expected, sliding distance to steady state condition is shorter for the smoother surface (sample L3).

It can be also noticed that all samples which resulted in lower friction (L2, L4, L6 and L7) show lower values of R_{vk} regarding to the mutually compared samples (Table 1).

Taking a look at the nature of surface roughness parameters R_{ku} and R_{sk}, it can be seen that negative R_{sk} describes surfaces with deep scratches or lackness of peaks, and parameter R_{ku}, greater than 3, surfaces with high peaks and low valleys. By combining those two descriptions, we end up with smooth surface containing deep valleys. If we treat surface texturing as ordered roughness, those deep valleys can be treated as micro-dimples. With an implementation of micro dimples a ordered surface, which should reflect in lower friction, is obtained. The main idea of surface texturing is that textures act either as micro-traps for capturing wear debris or as micro-reservoirs which enhance lubrication. When comparing experimental results with the idea of surface texturing some correlations can be observed. Under dry sliding higher values of parameter R_{ku} and more negative values of parameter R_{sk} led to lower friction, indicating that deep valleys act as wear particle traps. The same tendency was observed under lubricated sliding, where greater R_{ku} and more negative R_{sk} values give lower friction and shorten the sliding distance to steady-state condition. In this case it can be assumed that deep valleys act as micro reservoirs, which enhance lubrication. Accordingly, a general conclusion can be drawn, that is that R_{ku} and R_{sk} have an influence on friction and could therefore be used as a guideline for designing surface topography with reduced friction.

3 MODELLING

To investigate the effect of surface texturing on surface roughness parameters and to analyse the possibility of using roughness parameters for designing contact surfaces, the real roughness profile was virtually altered to achieve virtually textured surfaces. Using NIST SMATS [17] softgauge for the calculation of surface roughness parameters, virtually altered roughness profiles were investigated in terms of the effect of texture size and shape on surface roughness parameters, especially on skewness and kurtosis.

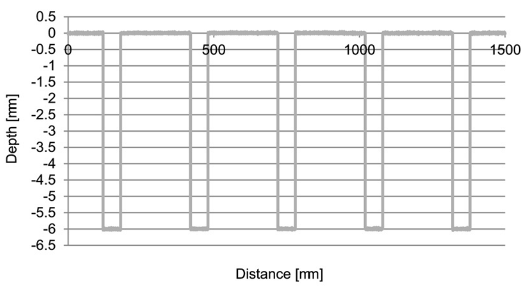


Fig. 2. *Example of virtually textured surface (diameter of dimples 0.06 mm, spacing 0.24 mm, depth 6 µm, rectangular shape)*

The real roughness profile was obtained using stylus profilometer. The polished sample with R_a value of 0.02 µm (R_q = 0.024 µm, R_{sk} = 0.24, R_{ku} = 3.07) was used as the origin profile. This profile was then virtually altered using Microsoft Excel to achieve virtually textured surfaces as shown in Fig. 2 and the influence of different spacing, and dimple diameter, shape and depth on the surface roughness parameters investigated. According to experimental results which emphasized R_{ku} and R_{sk} as the most influencing parameters, modelling was concentrated on finding texturing parameters, which would reflect in high R_{ku} and more negative R_{sk} values.

First, the effect of spacing between dimples was investigated. Rectangular dimples with a diameter of 0.12 µm and depth of 6 µm. were simulated by shifting down the original profile for the value of the dimple depth. This surface topography modelling showed that increase in spacing result in decreased R_a, R_q and R_{sk} values and increased R_{ku} value. For instance, if spacing is increased from 0.12 to 0.24 mm, R_{sk} will decrease and R_{ku} increase from -0.668 to -1.026, and from 1.492 to 3.028, respectively. With a further increase in spacing between dimples, R_a and R_q values are further decreased and R_{ku} further increased. However, for R_{sk} parameter an increase in spacing between dimples after initial reduction leads to increase in R_{sk} value, as shown in Fig. 3.

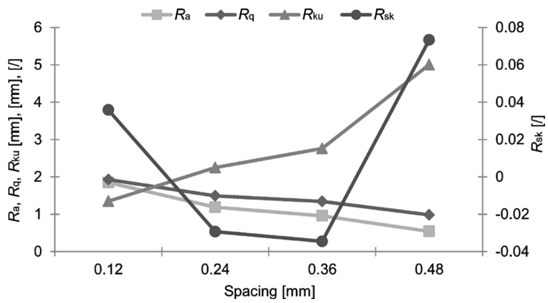


Fig. 3. *Surface roughness parameters in dependence of spacing between dimples (diameter of dimples 0.12mm, depth 6µm)*

Varying the depth of dimples was found to have very minor effect on the R_{sk} and R_{ku} parameter values. For the same diameter of 0.12 mm, changing the depth from 6 to 10 µm resulted in doubled R_a and R_q values, but almost equal values of R_{sk} and R_{ku} parameter. The same observations were found for smaller dimple diameters and larger dimple depths. Changing the diameter of dimples only slightly affects R_a, R_q and R_{ku} parameters, but has a considerable effect on R_{sk} value. A reduction in dimple diameter results in an only minor increase in R_a, R_q and R_{ku} values but a drastic increase in R_{sk}, as shown in Fig. 4.

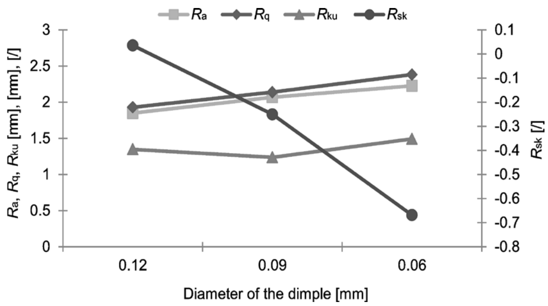


Fig. 4. *Surface roughness parameters in dependence of diameter of the dimples (spacing 0.12 mm, depth 6 µm)*

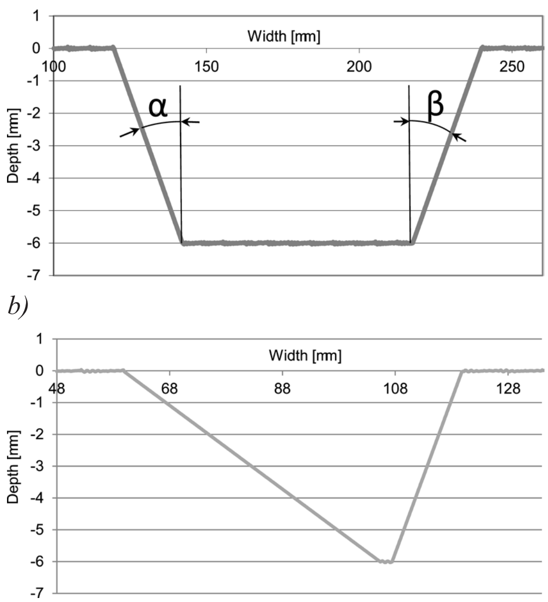


Fig. 5. *Profile of the dimple; a) α = β = 59° b) α = 82.4°, β = 24.7°*

Finally, the shape of the dimples was investigated, using dimples with a diameter of 0.12 mm and spacing of 0.12 mm. By changing the slope of the dimple walls (Fig. 5a), an increase in the slope angle was found to result in reduced values of R_a, R_q and R_{sk} parameters in increased values of R_{ku}. By shifting the bottom of the dimple to one side (α ≠ β, Fig. 5b) higher values of R_{ku} and more negative R_{sk} are obtained, as shown in Table 4. Such dimple shapes should also have good hydrodynamic effects. As can be seen from Table 4, the most suitable values of R_{ku} and R_{sk} parameter are obtained when angle α is close to 90º and β is very small, but not 0°.

By combining different dimple parameters, such as bigger spacing between dimples (0.36 mm), smaller diameter (60 µm) and wedge-shaped dimple (α = 82.4° and β = 24.7°), for which it has been found to increase R_{ku} and decrease R_{sk} values, very high values of R_{ku} (12.3) and negative R_{sk} (-2.7) can be obtained. Additionally, such texturing parameters also result in lower R_a and R_q values (0.44 and 0.92 µm, respectively). According to the experimental results, presented in this paper, such shape and spacing of the dimple should result in lower friction. However, these findings still need to be experimentally confirmed.

Table 4. *Roughness parameters vs. dimples wall angle (diameter 0.12 mm, depth 6 µm)*

	R_a	R_q	R_{ku}	R_{sk}
α=β=0°	1.85	1.93	1.35	0.03
α=β=59°	1.18	1.49	2.25	-0.04
α=β=75°	1.56	1.67	1.42	-0.26
α=β=83.7°	1.07	1.31	2.96	-1.05
α=85.4° β=14.6°	1.21	1.45	2.55	-0.86
α=86.2° β=14.6°	1.07	1.33	3.21	-1.05
α=83.7° β=0°	1.52	1.69	0.33	-1.69
α=86.3° β=0°	1.29	1.56	2.61	-0.77
α=86.9° β=0°	1.14	1.44	3.30	-0.99

α and β defined in Fig. 5a

5 CONCLUSIONS

Under dry sliding high wear rates and change in surface topography blurs the effect of surface roughness on friction. However, in general higher roughness of the contact surface and higher sliding speeds result in lower friction, with surfaces displaying higher kurtosis (R_{ku}) values and more negative skewness (R_{sk}) parameter often having an advantage.

For lubricated sliding contact kurtosis and skewness were found to be the most important roughness parameters in terms of tribological behaviour. The use of surfaces with higher kurtosis and more negative skewness always reflects in lower friction and shorter distance when steady-state condition has been reached, even if average roughness is not the same.

Plateau-like topography of contact surfaces with high kurtosis and more negative skewness and the effect of kurtosis and skewness on friction indicate that these parameters could be used as design parameters for surface topography modification and texturing aimed to reduce friction.

By surface topography modelling, surface texturing parameters which would result in greater kurtosis and more negative skewness parameter and consequently in lower friction in boundary lubrication can be defined. These parameters are lower diameter of the dimple, higher spacing between the dimples and wedge-like shape of the dimples.

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