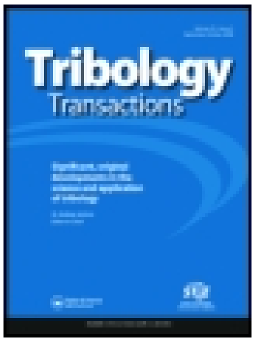

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Use of the Roughness Parameters S_{sk} and S_{ku} to Control Friction—A Method for Designing Surface Texturing

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ABSTRACT
The aim of this work was to show that with the use of the surface roughness parameters S_{sk} and S_{ku} we can predict tribological behavior of contact surfaces and use these parameters to plan surface texturing. This article presents a continuation of our research on virtual texturing and experimental work on surface textures in the form of channels. For this investigation, steel samples were laser surface textured in the shape of dimples with different spacings between the dimples and different dimple depths. The experimental results confirmed that the parameters S_{sk} and S_{ku} can be used to design the surface texturing, where a higher value of S_{ku} and more negative S_{sk} lead to lower friction.

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Surface roughness; roughness parameters; surface texturing; friction

Introduction

The constant demands to control friction losses and decrease the wear of machine components are becoming increasingly significant as they lead to an improved reliability and better performance of mechanical parts. Friction reduction can be achieved in many ways, including changing the element's geometry, using surface coatings, using antifriction additives, improving the surface roughness, or generating a specific surface structure, known as surface texturing. Although all of these methods can lead to an improvement in the tribological behavior of contact surfaces, the easiest way without changing the geometry is by changing the surface roughness. In this way, the lubrication mechanism can be changed from boundary to elstohydrodynamic lubrication, leading to more favorable tribological behavior (Suh, et al. *(1)*; Hu and Dean *(2)*; Santner, et al. *(3)*; Meine, et al. *(4)*; Sedlaček, et al. *(5)*, *(6)*). On the other hand, the surface topography can also be changed in a very controllable way by implementing different patterns in the form of microdimples or grooves on the sliding surface, also known as surface texturing. Well-defined textures can then, (1) in the case of a dry sliding contact and boundary lubrication, act as microtraps for wear particles (Varenberg, et al. *(7)*; Yamakiri, et al. *(8)*); (2) act as microreservoirs that enable the retention and supply of lubricants into the contact; (3) in conditions of mixed and hydrodynamic lubrication, act as microbearings and thereby improve the tribological properties of the contact (Hamilton, et al. *(9)*). In hydrodynamic lubrication, where textures act as microhydrodynamic bearings, theoretical studies and modeling enable us to study the effect and optimization of surface texturing parameters in order to improve the tribological properties of contact surfaces (Etsion and Halperin *(10)*; Zhu, et al. *(11)*; Podgornik, et al. *(12)*; Etsion *(13)*; Brizmer, et al. *(14)*; Etsion, et al. *(15)*). The importance of the dimple aspect ratio (λ) when judging the accuracy of the Reynolds equation was highlighted in Dobrica and Fillon *(16)*. It was also shown experimentally (Henry, et al. *(17)*) that surface textures are load dependent. At low loads, a friction reduction up to 30% in textured thrust bearings was reported, whereas for heavy loads, their performance is equivalent or even lower than that of an untextured planar bearings.

On the other hand, the effect of surface texturing in the starved, boundary, and mixed lubrication regimes still lacks some fundamental understanding, with the optimization of the surface texturing still more or less based on a trial-and-error approach (Ibatan and Uddin Chowdhury *(18)*). Though some studies have shown that the influential parameters are the depth-to-diameter ratio (Shinkarenko, et al. *(19)*) and the density of the edges perpendicular to the sliding direction, others (Braun, et al. *(20)*) have shown that they are insufficient and suggest the dimple size and the number of dimple edges in the contact as the most influential parameters.

A new approach to designing surface texturing would be to treat the surface texturing as an ordered roughness. The roughness of a surface is usually described by the so-called roughness parameters. To be able to predict tribological behavior, knowing the correlations between the roughness parameters and the friction is essential.

Two of the most commonly used standard surface roughness parameters for an evaluation of the surface roughness are R_a and R_q. Unfortunately, these two parameters do not describe the contact surfaces sufficiently well. It was shown how two completely different surfaces can show similar, or even the same, values of the standard roughness parameters and vice versa—similar surfaces have much different standard

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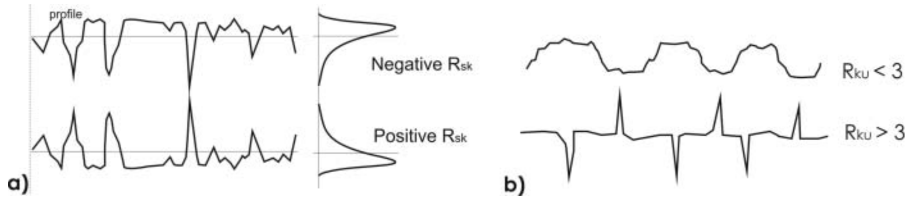

Figure 1. Schematic presentation of roughness profiles for (a) positive and negative skewness (R_{sk}) and (b) kurtosis lower and higher than 3.

roughness parameters (Sedlaček, et al. *(6)*). The average surface roughness (R_a) gives a very good overall description of the height variations, but it does not provide any information about the waviness, and it is not sensitive to small changes in the profile height. The root mean square deviation of the assessed profile (R_q) is more sensitive to deviations from the main line than R_a, but it still does not provide a satisfactory description of the surface roughness. A non-Gaussian distribution of the roughness profile is described using the parameter R_{sk} (skewness) and is sensitive to occasional deep valleys or high peaks in the profile because it measures the symmetry of the variation in a profile about its mean line. A symmetrical height distribution is reflected in zero skewness, whereas positive skewnesses such as turned surfaces have fairly high spikes that protrude above a flatter average. Negative skewnesses such as porous surfaces, on the other hand, have fairly deep valleys in a smoother plateau (Fig. 1). On the other hand, kurtosis (R_{ku}) describes the probability density sharpness of the profile. Surfaces with relatively few high peaks and low valleys are reflected in a kurtosis of less than 3, whereas a kurtosis value of more than 3 indicates many high peaks and low valleys (Gadelmawla, et al. *(21)*; Fig. 1). When the roughness parameters are related to a 2D profile they are denoted by the capital letter *R*, and when they describe a 3D surface they are denoted by the capital letter *S*.

The influence of roughness parameters on tribological behavior was studied by a number of researchers, with some focusing on dry contacts (Michalski and Pawlus *(22)*; Tayebi and Polycarpou *(23)*; Liu, et al. *(24)*; Komvopoulos *(25)*) and others on lubricated contacts (Wang, et al. *(26)*; Jeng *(27)*; Kang, et al. *(28)*; Menezes, et al. *(29)*–*(31)*; Maatta, et al. *(32)*; Hu and Dean *(33)*; Lundberg *(34)*; Wieleba *(35)*). In Michalski and Pawlus *(22)* it was shown that in dry contacts, surfaces with a high R_{ku} value and a positive R_{sk} value should result in a lower static coefficient of friction when compared to surfaces with a Gaussian distribution ($R_{ku} = 3$, $R_{sk} = 0$). On the other hand, at high R_{ku} values, the static coefficient of friction would decrease with reduced load, whereas increase in R_{sk} values would result in an increased static coefficient of friction. By increasing R_{ku} from 2 to 10, the static coefficient of friction should be decreased by a factor of about 6 (Tayebi and Polycarpou *(23)*), mainly due to an increased contact area (Sedlaček, et al. *(36)*). Surfaces with positive R_{sk} show good adhesion resistance and negative R_{sk} leads to lower values and larger force deviations from the Gaussian distribution (Komvopoulos *(25)*).

In contrast to dry contacts, it was shown that in lubricated contacts negative skewness results in lower friction. In Wang, et al. *(26)*, it was shown, using computer modeling, that skewness and kurtosis have a great effect on the contact parameters such as area ratio, load ratio, and maximum pressure, which increase with an increase in skewness and kurtosis in mixed lubrication. In Sedlaček, et al. *(5)*, *(6)* it was experimentally shown that negative skewness and high values of kurtosis result in lower friction. The same was shown in Jeng *(27)*, where lower friction and better scuffing resistance were reported when parameter S_{sk} decreased from 0.1 to −1.1. Additionally, it was shown in Kang, et al. *(28)* that surfaces with extreme negative S_{sk} values (approximately −4.7 or lower) may yield significant differences in contact pressure and lubricant film thickness. In Menezes, et al. *(29)*–*(31)* a greater influence of directionality of the surfaces was noted and in Wieleba *(35)* it was reported that the average slope of the profile Δ_α means that peak spacing (S_m) and core roughness depth R_k have an influence on friction.

As reported in Sedlaček, et al. *(5)*, *(6)*, a change in surface topographies, reflected in more favorable roughness parameters, will also lead to favorable tribological properties. In Sedlaček, et al. *(5)*, *(6)* was shown that plateau-like topographies with small cavities that supply lubricant into the contact, similar to surface texturing, reflected a higher kurtosis (S_{ku}) and a more negative skewness (S_{sk}), which resulted in lower friction. With the idea that surface texturing could be treated as ordered roughness, those findings were further used in the design of surface textures (Sedlaček, et al. *(36)*). By altering the 2D virtual roughness profiles, the influence of texture size and shape on the surface roughness parameters was investigated, particularly with respect to skewness and kurtosis. It was found that a smaller width, larger spacing, and wedge-shaped profile of the channels resulted in higher R_{ku} and more negative R_{sk} parameters, which should result in lower friction in the boundary and mixed lubrication regimes. These findings were confirmed experimentally using surface textures in the form of channels (Sedlaček, et al. *(37)*). It was shown that a smaller width and a larger spacing resulted in a higher R_{ku} and a more negative R_{sk} and, consequently, in lower friction. The effect of texture shape was further investigated in Scaraggi, et al. *(38)*. It was shown that a microwedge and/or microstep tend to yield thicker lubricating films, thus confirming the theoretical findings based on an analysis of the roughness parameters, predicting a wedge-like profile of the dimple as the most suitable shape.

In the present study, the aim was to further confirm the suitability of skewness and kurtosis for designing surface texturing and to extend their use into the field of dimple surface texturing. As shown in Fig. 2, when expanding a 2D roughness profile (Fig. 2a) into 3D space in just one direction, the 2D profile will be converted into a surface with grooves (Fig. 2b). However, if the extension is made in two directions, the 2D profile will be converted into a surface with dimples (Fig. 2c). Detailed virtual texturing was made for the case of channels (Sedlaček, et al.

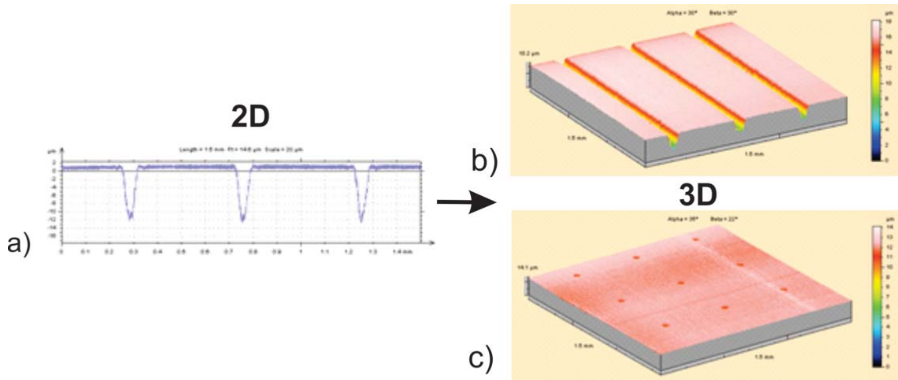

Figure 2. Transformation of the 2D profile (a) into 3D space; (b) in one (y) direction and (c) in two (x–y) directions.

(36)), whereby analogously it should also apply to the dimples. However, in the case of dimples, even lower values of S_{sk} and a higher S_{ku} should be obtained. Therefore, the main aim of this research was to confirm that parameters S_{ku} and S_{sk} are appropriate for planning surface texturing, which will result in lower friction.

Experimental

Laser surface texturing

In order to confirm the theoretical findings (Sedlaček, et al. *(36)*), prepolished 100Cr6 steel plates (100Cr6, $S_a = 0.02$ mm, 850 HV) were laser surface textured in the form of dimples. To produce the textures, an Nd-YAG laser with a maximum laser power of 12.8 W, wavelength of 1,064 nm, pulse duration on the order of nanoseconds, and frequency of 15 kHz was used. By changing the laser's parameters, microdimples with different spacings and depths were obtained. The depths of the dimples were varied by changing the number of laser pulses and keeping the diameter of the dimples constant at 60 μm. Figure 3 presents the denotations, 2D profiles, and area density (r) of the various samples included in this investigation. The samples are denoted according to the spacings between the dimples and the depth of the dimples. By keeping the depth of the dimples constant, the spacings between the dimples were varied from 125 μm (sample E1) to 250 μm (sample E2) and 500 μm (sample E3). For the other set of samples the spacings between the dimples were fixed at 250 μm and the depth of the dimples was varied. The textured sample with a dimple depth of 5 μm was denoted D2, textured sample with a dimple depth of 11 μm as E2, and textured sample with a dimple depth of 20 μm as F2.

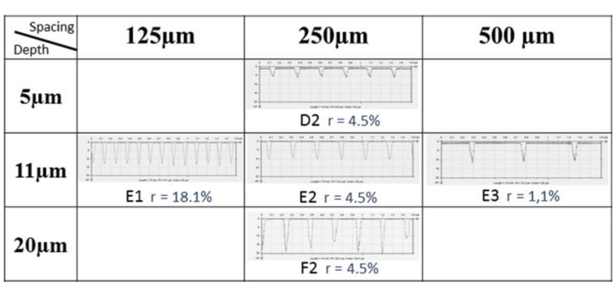

Figure 3. Denotation of the samples according to the spacing and depth of the dimples.

For comparison, sample A3, textured with channels of the same spacing (500 μm), depth (11 μm), and width of the textures (60 μm) as sample E3, was used. Details about sample A3 can be found in Sedlaček, et al. *(37)*. For comparison purposes, an untextured ground sample (G) with an average roughness S_a of about 0.08 μm was also used in this investigation.

Roughness measurement

Measurement of the 3D topography and the associated roughness parameters was performed prior to the tribological tests using a stylus profilometer. Before the measurement, the surfaces of all of the textured samples were repolished using a very low force in order to remove the bumps around the dimples that were caused by the vaporized material after the laser texturing. The surface evaluation area was 4.8 $\times$ 4.8 mm^2, with a sampling interval of 10 μm and a measurement speed of 0.05 mm/s. Prior to calculation of the three-dimensional roughness parameters, Gaussian filtering was used with 0.8-mm cutoff lengths.

Tribological tests

In order to evaluate the frictional behavior, reciprocating sliding tests using a flat-on-flat contact were conducted (Fig. 4). As

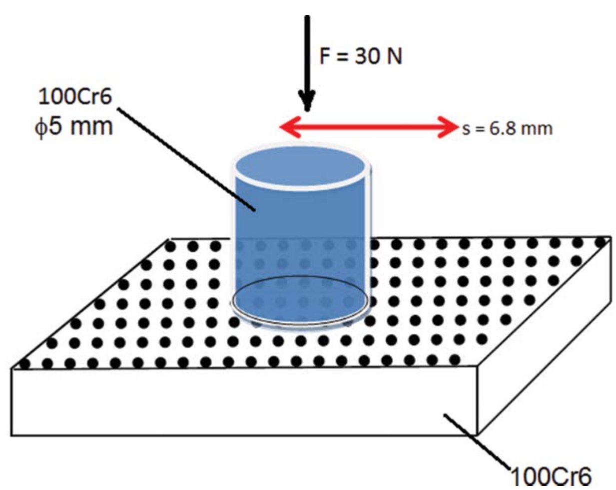

Figure 4. Schematic illustration of the contact between the pin and textured sample.

a counterpart to the textured surfaces, a 100Cr6 steel flat-ended pin with a diameter of 5 mm (flat contact of approximately 20 mm^2) was used. The surface of the flat-ended pin was leveled and polished before each sliding test to ensure proper alignment with the textured surface and to diminish the effect of the counterpart's roughness (Podgornik, et al. *(12)*). Tests were made at sliding speeds of 0.005, 0.05, 0.1, 0.2, and 0.3 m/s, where the flat-ended pin was loaded against a surface-textured disc using a normal load of 30 N, corresponding to a nominal contact pressure of 1.52 MPa. For all tests the contact was immersed into pure poly-alpha-olefin oil (PAO 8; $\nu_{40} = 46\ mm^2/s$) and the total sliding distance was ~100 m. The environmental conditions were also kept constant ($T = 23 \pm 2°C$; relative humidity $= 50 \pm 10\%$). For each of the contact conditions at least three repetitions were made to ensure proper repeatability. During testing, the coefficient of friction was monitored as a function of time.

Results

Roughness measurement

The values of the surface roughness parameters S_a, S_q, S_{sk}, and S_{ku} for the laser surface textured and machined samples are shown in Fig. 5. S_a, S_q, and S_{sk} values are plotted on the primary vertical axis and S_{ku} on the secondary axis so the trends are visible. It is clear that with an increase in the spacings (E1 → E2 → E3) the values of the parameters S_a and S_q become smaller, the parameter S_{sk} more negative, and the parameter S_{ku} higher (Fig. 5a). A more negative skewness and higher kurtosis were also achieved by reducing the depth of the dimples (F2 → E2 → D2; Fig. 5b). The lowest value for S_{sk} and the highest for S_{ku} were recorded for the sample E3, whereas the lowest values for the parameters S_a and S_q among all textured samples were recorded for sample D2.

With an increased spacing between the dimples, the area density also changed from 18.1 to 4.5 and 1.1%, respectively. The area density for the samples with different dimple depths (F2, E2, D2) remained constant at 4.5%. These findings are in good agreement with our previous work on virtual texturing (Sedlaček, et al. *(36)*) and experimental research (Sedlaček, et al. *(37)*) focused on the effects of the channel widths and spacings. However, in the case of the dimples, the values of S_{sk} are even more negative and S_{ku} even higher than for samples with the channels.

Tribological tests

The influence of the spacing between the dimples is presented in Fig. 6, where the coefficient of friction is plotted for five different sliding speeds; that is, 0.005, 0.05, 0.1, 0.2, and 0.3 m/s. It is clear that with an increased spacing between the dimples the coefficient of friction becomes lower, which is more evident at lower sliding speeds. By increasing the spacing from 125 to 500 μm (E1 → E3), S_{sk} was reduced by 4.3 times and S_{ku} increased by almost nine times (Fig. 5), which also resulted in an ~25% reduction in the coefficient of friction for sliding speeds below 0.1 m/s (Fig. 6). When the sliding speed is higher than 0.1 m/s the difference in the friction for samples E1 and E2 is almost negligible. However, in the case of sample E3 with the largest spacing and the most negative value of the parameter S_{sk} and the highest S_{ku}, the lowest coefficient of friction is maintained even at higher sliding speeds. Any kind of surface texture can be considered as irregularities or ordered microroughness that can obstruct sliding. If the spacing between the individual texturing features is increased, the number of these obstructions will decrease. This explains why the samples with wider spacings between the dimples exhibit a lower friction.

For a comparison, the ground sample G with lower values of the parameters S_a and S_q than the surface-textured samples was also tested. Figure 6 indicates that the coefficient of friction for this sample is considerably higher, indicating that the parameters S_a and S_q are not the most dominant roughness parameters for the tribological behavior of the contact surfaces for the presented contact conditions. As was shown in previous

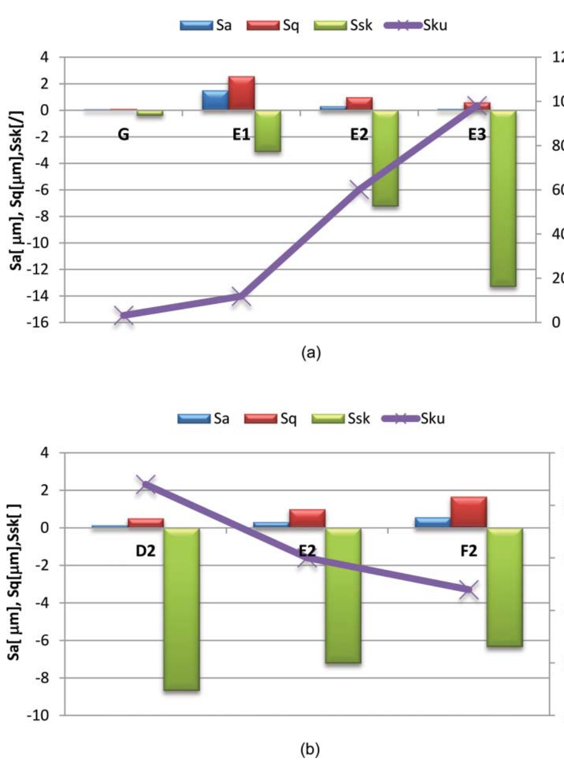

Figure 5. Surface roughness parameters S_a, S_q, S_{ku}, and S_{sk} for samples (a) G, E1, E2, and E3; (b) D2, E2, and F2.

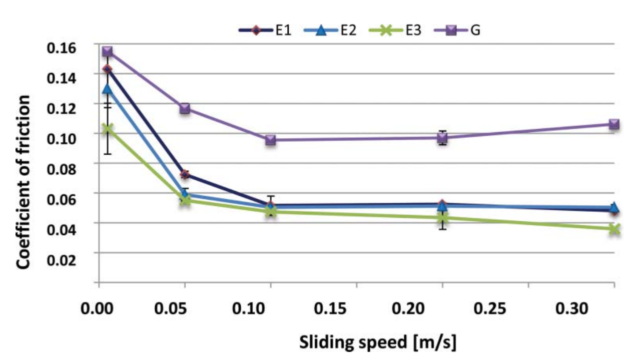

Figure 6. Influence of sliding speed and spacing between the dimples on the coefficient of friction in a lubricated sliding contact.

investigations (Sedlaček, et al. *(5)*, *(36)*, *(37)*), the roughness parameters S_{sk} and S_{ku} have a much stronger influence on the tribological behavior of the contact surfaces. Under the boundary lubrication regime the textures act as lubricant reservoirs, but their density must be kept low to obtain a plateau-like topography with small cavities that supply lubricant into the contact. This kind of surface displays negative values of the skewness parameter and high values of kurtosis. The untextured sample G, on the other hand, has a negative but very small value of S_{sk} and an S_{ku} value just above 3 (Fig. 5). Comparing the untextured sample G with the textured sample E3, which has the nearest value to the average roughness parameter S_a but a much more negative S_{sk} and a higher S_{ku}, it becomes clear that the parameters S_{sk} and S_{ku} have a dominant influence on the coefficient of friction under the contact conditions being studied. Sample E3, as well as all of the other textured samples, exhibits a significantly lower friction than sample G, although it has higher S_a and S_q values. However, as shown in Sedlaček, et al. *(37)*, the wrong selection of texturing parameters, resulting in unfavorable S_{sk} and S_{ku} parameters, can lead to worsened tribological properties.

The influence of dimple depth on the coefficient of friction is shown in Fig. 7. It is clear that by increasing the dimple depth from 5 to 20 μm (D2 $\rightarrow$ E2 $\rightarrow$ F2) the coefficient of friction also increases. By analyzing the roughness parameters we can see that samples with a smaller dimple depth result in a more negative S_{sk} value and a higher value of the S_{ku} parameter (Fig. 5) and, consequently, a lower coefficient of friction. Sample D2, with the smallest depth, resulting in the most negative S_{sk} and the highest S_{ku}, exhibits up to 32% less friction than sample F2, with a less negative S_{sk} value and a much lower value of the S_{ku} parameter. The difference in the coefficient of friction between the samples with different dimple depths is visible for all sliding speeds, except for the lowest sliding speed, as shown in Fig. 7. For the lowest sliding speed (0.005 m/s) the difference in the frictional behavior for the different dimple depths is negligible, indicating that hydrodynamic effects cannot be established at such a low sliding speed. When the sliding speed is increased, the difference between the samples becomes apparent, such that samples with a smaller dimple depth have a lower coefficient of friction. The advantage of shallower dimples can be explained by the smaller volume, which is more easily filled with oil in order to build hydrodynamic pressure and separate the contacting surfaces. The increase in the coefficient of friction observed with an increased dimple depth is in good agreement with the findings in Scaraggi, et al. *(38)*, who focused on an investigation of the optimal dimple depth. The optimal dimple depth can also be determined with the use of roughness parameters. As shown in Sedlaček, et al. *(36)*, an increase in dimple depth results in increased S_a and S_q values and decreased S_{sk} and S_{ku} values. However, untextured surfaces show even lower values for the S_{sk} and S_{ku} parameters and, consequently, a higher coefficient of friction.

Figure 7 shows that, with the exception of the lowest sliding speed, the sliding speed has almost no influence on the coefficient of friction for dimple-textured surfaces with different dimple depths. Again, a lower coefficient of friction is achieved with the sample that possesses the lowest S_{sk} and the highest S_{ku} values. This confirms the finding that a negative S_{sk} and a high S_{ku} can be used for planning surface texturing for the boundary as well as the hydrodynamic lubrication regime.

If we compare the roughness parameters and the tribological behavior of sample G produced by grinding, the textured sample A3 with channels (details can be found in Sedlaček, et al. *(37)*), and the textured sample E3 with dimples that are dimensionally comparable to channels, we can see that sample E3 has the lowest S_{sk} and the highest S_{ku}, resulting in the lowest friction (Figs. 8a and 8b). Furthermore, surface texturing moves the mixed lubrication regime toward lower sliding speeds and enhances the effects in the hydrodynamic lubrication regime. The same was also observed for samples D2, E2, and F2. The comparison of ground and textured sample also confirmed that the parameters S_a and S_q are not the most dominant ones in terms of the friction behavior of the contact surfaces.

When comparing the textured samples A3 and E3, which have the same spacing, width, and depth of the textures, the

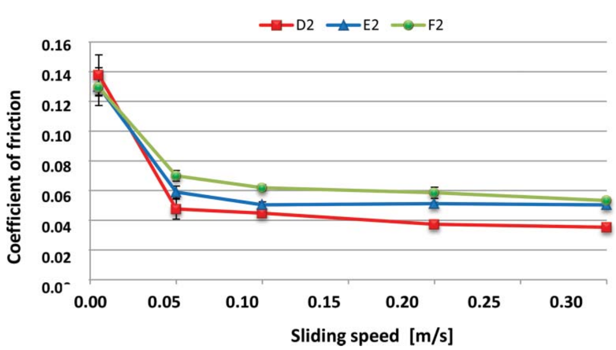

Figure 7. Influence of sliding speed and dimple depth on the coefficient of friction in a lubricated sliding contact.

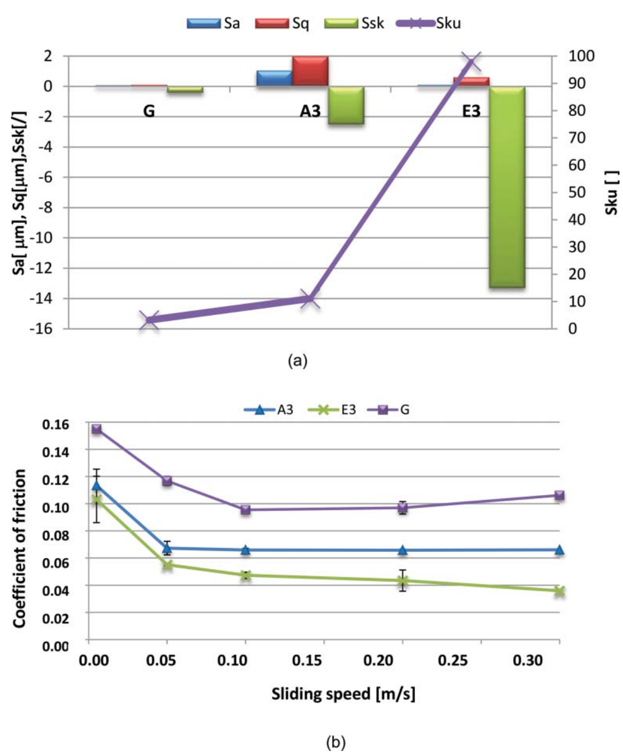

Figure 8. Effect of texture shape (G, ground; A3, channels; E3, dimples) on (a) the roughness parameters and (b) the coefficient of friction at different sliding speeds in a lubricated sliding contact.

only difference being that the A3 textures were in the form of channels and those of E3 were in the form of dimples, we can see that the dimples (E3) result in more favorable roughness parameters and, consequently, lower friction. The advantage of a dimple-textured surface is observed for all lubrication regimes, confirming the theoretical (Sedlaček, et al. *(36)*) and experimental findings (Sedlaček, et al. *(37)*) that the roughness parameters skewness and kurtosis can be used to design textured surfaces with the desired coefficient of friction. Use of dimples instead of channel texturing is also favorable because dimples are not orientation dependent as channels are. The friction tends to reduce when the parameter S_{ku} increases. However, the most dominant parameter is S_{sk} and the more negative it is the lower the friction we can expect.

Conclusions

The roughness parameters S_{sk} and S_{ku} can be used to plan the surface texturing in the boundary and mixed lubrication regimes. When the parameter S_{ku} is increasing and the parameter S_{sk} is becoming more negative, the coefficient of friction, in general, tends to become smaller.

Surface texturing that results in a larger S_{ku} and a more negative S_{sk} and is reflected in less friction is characterized by a wider spacing between the dimples and smaller dimple depths. With the correct choice of texturing parameters, giving a negative S_{sk} and a high S_{ku}, textured surfaces can result in a lower coefficient of friction and a reduced sensitivity of the contact to sliding speed. It was also shown that texturing in the form of dimples is reflected in a more negative S_{sk} and a high S_{ku} and, consequently, less friction.

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