Study of the influence of surface roughness parameters on the frictional characteristics of materials

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Abstract. The study of surface roughness parameters and their correlation with coefficient of friction (COF) is of great importance for metal-mechanic applications. Evidence suggests that $R_a$ (surface roughness average) is not directly related to COF under sliding conditions. In this study, the relation between surface roughness parameters, namely $R_a$, $R_t$ (maximum height of the profile), $\Delta a$ (mean slope of the profile), and COF, as well as their interactions, were particularly studied. The materials were of an aluminium alloy Al A380. Samples were chemically attacked to modify their surface roughness characteristics. Six different conditions were tested: Al A380 with the surface attacked with an alkaline substance for 0, 2.5, 5, 15, 30 and 60 min. The value of COF was determined using a T-05 block-on-ring tribotester, and surface roughness data was obtained using an optical 3D surface measurement system. MathWorks MATLAB software was used to process the data. Results show that $\Delta a$ has a strong positive correlation with COF during sliding conditions, whereas both $R_a$ and $R_t$ may vary without directly affecting COF, contrary to the commonly used industry standard.

1. Introduction
When analysing a surface, there are many roughness parameters available used to describe its different characteristics. For instance, Gadelmawla et al [1], has described at least 59 different roughness parameters. The most universally used, for quality control, is the Roughness Average ($R_a$), which is defined as the average absolute deviation of the roughness irregularities from the mean line over one sampling length [1]. This parameter can give a suitable general description of height variations but is not sensible to small changes in the profile. This can result in two surfaces with a very different profile but very similar $R_a$, thus when $R_a$ and Coefficient of Friction (COF) are compared, there is no strict correlation to be found [2]. Different individual parameters have been analysed, such as $R_{max}$ or $R_t$ (defined as the distance between the highest peak and the lowest valley over the assessment length of the surface) [3] which was reported as the most significant parameter during sliding wear under lubricated conditions. Nevertheless, recent studies suggest that hybrid parameters (which result from a combination of amplitude and spacing) [4] can be well related to COF. One of these hybrid parameters, $\Delta a$, is defined as the average of the slopes between each two consecutive points in the assessment length, and has been found to explain COF’s variations more closely [2].
Chemical machining is one of the oldest micromachining technologies. Chemical etching uses a strong acidic or alkaline chemical solution [5, 6], and may be applied to modify the surface roughness characteristics in products for several purposes [5, 7–10]. For the particular application of this study, aluminium alloy Al A380 components were chemically etched in order to study its effect on different surface roughness characteristics and their correlation to COF.

2. Materials and methods

Blocks of Al A380 measuring 15.75 x 10 x 6.35mm were prepared. Secondly, an alkaline substance was used to perform a chemical attack on the blocks. In order to compare the results, varying times of chemical attack were used. The chemical attack consisted on introducing the specimens into the alkaline substance during different time intervals to generate changes on the surfaces of the specimens; the time intervals of the chemical attack were 0, 2.5, 5, 15, 30 and 60min.

Tribological testing of the samples under dry conditions was performed with a T-05 block-on-ring tribotester, as shown in figure 1. Figure 1(a) shows a schematic of the equipment used and figure 1(b) focuses in the zone in which materials are tested, showing the block on ring configuration. The tribosystem consists on a stationary block in contact with a ring, as shown in figure 1(c). In this test, the ring rotates at a certain speed and simultaneously, a load is applied into the block. The Frictional Force of each test is recorded by the equipment, and dividing this value by the applied force the value of COF can be obtained. Prior to performing the tests, the surface roughness was measured with an optical three-dimensional measuring system to confirm that all the initial roughness average were similar (2.15µm) for all the block materials. The materials of the block and ring samples were Al A380 and an AISI D2 steel (cold work steel), respectively. All tests were performed at room temperature (25°C), with a load of 490N, rotating speed of 20rpm for 30s. The data obtained by the tests was processed by MathWorks MATLAB 2016 software, specifically to calculate the $\Delta a$, $R_t$ and $R_a$ parameters. It is very important to mention that for each of the parameters five runs were performed in accordance to the Dixon methodology that ensures a level of confidence of 95%.

Figure 1. Block-on-ring tribotester: (a) Schematic representation of the equipment. (b) Testing zone. (c) Block and ring specimens.
The formulas used to calculate \( R_a \), \( R_t \) and \( \Delta a \) are shown in equations (1), (2) and (3), respectively.

\[
R_a = \frac{1}{n} \sum_{i=1}^{n} |y_i| \\
\text{(1)}
\]

\[
R_t = R_p + R_v \\
\text{(2)}
\]

\[
\Delta a = \frac{1}{n-1} \sum_{i=1}^{n-1} \frac{\delta y_i}{\delta x_i} \\
\text{(3)}
\]

Where \( y_i \) is the vertical position, \( R_p \) is the highest peak and \( R_v \) is the depth of the lowest valley, all in relation to the horizontal line; \( n \) is the number of data taken, \( \delta y_i \) is the difference between consecutive vertical coordinates, and \( \delta x_i \) is the difference between consecutive horizontal coordinates.

3. Results and discussion

Figure 2 depicts the representative 3-D images of the surface of the block materials showing the \( R_a \) and COF values obtained by the analyses. It can be noted that for samples attacked for 0-30min there are no significant variations in \( R_a \), however COF values are very different. This demonstrates that indeed this parameter does not possess a direct correlation to the frictional behaviour of the samples.

![Figure 2](image)

**Figure 2.** Representative 3-D surface images of the chemical etching test with their respective \( R_a \) and COF.

Table 1 presents the average COF values along with \( R_a \), \( R_t \) and \( \Delta a \). Results show that the samples with 30min of chemical attack presented the highest values in COF and \( R_a \), which were an increase of 121% and only 6% compared to the non-attacked samples, respectively. It is also noticeable that the samples with 30min of chemical attack presented the maximum increase on the \( \Delta a \) values, which was a 21%, in comparison with the non-attacked samples. Chemical attack for longer time (60min) resulted in a polishing effect of the surface lowering all surface roughness parameters and COF.
Table 1. Parameters obtained in the tests.

| Time of attack (min) | $R_a$ (µm) | $\Delta a$ (mrad) | $R_t$ (µm) | COF | COF Increment (%) |
|---------------------|------------|------------------|------------|-----|-------------------|
| 0                   | 2.15       | 95               | 8.65       | 0.071 | -                 |
| 2.5                 | 2.15       | 108              | 9.26       | 0.087 | 22.42             |
| 5.0                 | 2.11       | 105              | 8.60       | 0.116 | 63.45             |
| 15                  | 2.19       | 95               | 8.86       | 0.070 | -1.60             |
| 30                  | 2.28       | 115              | 9.50       | 0.157 | 121.09            |
| 60                  | 1.61       | 96               | 7.66       | 0.057 | -19.56            |

Figure 3 shows the COF in relation to the $R_a$; it can be noticed that, even though the values of $R_a$ are very similar, the results for COF vary greatly particularly for chemical attack in the range of 0-30 min. Also, similar COF is presented in the samples with very different $R_a$ values (chemical attack for 60 min); therefore, no apparent correlation is evident. According to some studies, two surfaces can have the same $R_a$, but different frictional characteristics; this can occur because the single parameter of roughness average does not sufficiently describe the topography of the surface, since it is purely sensitive to the height deviation from the main profile. Therefore, there is no apparent correlation of the $R_a$ with the behavior of the COF [1–4], similar to the results obtained by our study.

Figure 3. Relation between $R_a$ and COF. It can be noted that no strict correlation can be established.

Figure 4 presents the relation between the COF and the $\Delta a$ parameter, measured in mrad. A marked tendency is shown: in general, as the $\Delta a$ parameter increases, the COF also increases, marking a positive correlation between both of them. Some studies have obtained a similar tendency of $\Delta a$ and COF and concluded that this correlation is the closest between the COF and any other roughness parameters [2, 3, 5–10]. In accordance to Gadelmawla et al. [9], this correlation can be explained because the mechanical properties of friction, elastic contact, fatigue crack initiation and hydrodynamic lubrication effect are affected by the variations in the multiple slopes described by the $\Delta a$ parameter.
Figure 4. Relation between $\Delta a$ and COF.

Figure 5 shows the interaction between $R_t$ and COF suggesting that there is a positive correlation. This is consistent with the study by Koura & Omar [10] and Menezes & Kailas [6], where a general trend to increase COF along with the increase of the $R_t$ parameter was found. Figure 6 shows a contour map of the relation between $R_a$, $R_t$, and COF. Here, it is shown that if either $R_a$ or $R_t$ is high a higher COF can be obtained.

In Figure 7 a contour map of the relation among $\Delta a$, $R_t$, and COF is shown. A gradual increase in COF can be observed for $\Delta a$ for all values of $R_t$; however, it is also evident that different values of $R_a$ may provide similar COF. In figure 8 no apparent correlation between the roughness parameters of $R_t$ and $\Delta a$ was found. In this case a lower COF can be achieved with lower values of $R_t$. 

Figure 5. Relation between $R_t$ and COF.  
Figure 6. Relation between $R_a$, $R_t$, and COF.
4. Conclusions
In this study, aluminium alloy Al A380 samples were chemically attacked to modify their surface roughness characteristics. It was determined that there is not a direct correlation between COF and Ra. However, a direct correlation between COF and the Δa parameter was found. Therefore, it may be assumed that if a high value of Δa is obtained a high COF value will be achieved. The results showed that the amplitude parameters do not significantly determine the variations in COF; however slope parameters have a more direct impact. A chemical attack with an alkaline substance for 30min increased Δa by 21% causing a 121.09% increase in the COF. It is not advisable to perform a chemical attack for very long periods of time because this may result in a decrease in Ra (that could be an industry requirement), Δa and COF.

5. References
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