The Effect of the Surface Roughness Profile on Micropitting

The roughness profile of metal-to-metal contacting parts is one of the most important characteristics in making mechanical systems more durable and energy efficient.

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A WIDE CHOICE OF SURFACE ROUGHNESS PARAMETERS IS AVAILABLE TO CHARACTERIZE components such as gears or bearings, with the goal of predicting the performance of such metal-to-metal contacting parts. Commonly in industry, the roughness average \( (R_a) \) or the mean peak-to-valley height \( (R_{z (DIN)}) \) is chosen to calculate the specific film thickness ratio for both superfinished and honed surfaces. However, these two surface roughness parameters fail to adequately predict the performance properties of surfaces that are superfinished or surfaces that are honed. In this paper, a superfinished surface is defined as a planarized surface having a \( \leq 0.25 \ \mu m R_a \). A honed surface is not considered to be planarized, even with a finish of \( \leq 0.25 \ \mu m R_a \). Thus, one is falsely led to predict that a planarized surface or a honed surface, having an equivalent \( R_a \) or \( R_z \), will perform similarly. Experimentally, an isotropic planarized surface delivers superior performance. The following discussion utilizes another roughness parameter, \( 3 \sigma_{50} \), to further explain this phenomenon.

INTRODUCTION

The roughness profile of metal-to-metal contacting parts is one of the most important characteristics in making mechanical systems more durable and energy efficient. Unquestionably, it is the interaction of the peak asperities from ground or honed surfaces that contributes to the degree of friction, high operating temperatures, deteriorated lubrication, and system failure [1]. Lubricant films attempt to keep such interactions to a minimum, but under high loads and low speeds peak asperity contact still occurs. The surface roughness profile may be defined as any parameter that is used to characterize the topographical features of a given surface. However, several parameters are used commonly. Table 1 represents a few of the most prominent surface roughness parameters in use by industry and academia today in addition to all parameters cited throughout this discussion.

Two parameters most commonly chosen to characterize the surface texture are the roughness average, \( R_a \), and the mean peak-to-valley height \( R_{z (DIN)} \). Yet, it is evident that surfaces having an identical \( R_a \) can have completely different characteristics (as illustrated in Figure 1) [2].

For well over a decade, many companies, universities, and research organizations carried out concerted investigations of gear and bearing micropitting. Recently these investigations have taken on even more urgency with the growth of wind turbine size and exponential growth in the number of megawatt wind turbines in service. Due to the extremely high load and low speed operation of the input stage of wind turbines, micropitting has become an epidemic problem and is now recognized as a failure indicator that can lead to premature gear and bearing failure.

Prior to this epidemic problem in the wind turbine industry, micropitting was often assumed to be self-arresting and not a failure mechanism in gearboxes. Researchers seem to be in universal agreement that micropitting is initiated by peak asperity interactions of the metal-to-metal contacting surfaces whereby high subsurface stresses arise [3] [4]. However, they pay little or no attention to the method used to generate the surface or the specific topographical features of the final surface. For example, ISO/TR 15144:2010 uses the effective composite arithmetic mean roughness to calculate the local specific lubricant film thickness [5]:

Equation 1:

\[ R_e = 0.5 \ (R_{a1} + R_{a2}) \]

where \( R_e \) is effective composite arithmetic roughness.
mean roughness value;
\( R_a \) is arithmetic mean roughness value of pinion;
\( R_a \) is arithmetic mean roughness value of wheel.

Although the technical report states explicitly, “At present \( R_a \) is used, but other aspects such as \( R_z \) or skewness have been observed to have significant effects which could be reflected in the finishing process applied,” in practice the roughness profile of the surface is ignored.

The parameter \( R_a \) is used repeatedly with little consideration of the actual topographical features or surface texture of the polished surface in the 2004 patent Polished Gear Surfaces [6]. In this pivotal patent, gears having different surface roughnesses were generated by radically different techniques (hobbed and shaved, ground, honed, fine grit honed, physicochemically polished, and electrochemically polished). Although the patent acknowledges that each surface has a different roughness profile, only the \( R_a \) is used to predict contact fatigue life, wear resistance, and performance. While the authors correctly conclude the macroscopic correlation of reduced surface roughness and stress reduction, the specification ignores the microscopic intricacies of the nature of the surface roughness and the resulting variations in the magnitude of stress reduction by the surface roughness generation technique.

The planarized surface is that generated by chemically accelerated vibratory finishing (henceforward referred to as superfinishing). Figure 2 summarizes the process of superfinishing on an “as-ground” or “as-honed” surface. Depicted in scanning electron microscope images and profilometer traces, the superfinishing process removes the peaks resulting in a planarized surface. The planarized surface has no sharp peak asperities, hence, even if two planarized surfaces
come in contact, the subsurface stresses are significantly less than those generated by surfaces having sharp peak asperity interaction. Eventually, even the valleys disappear as the superfinishing process continues leaving a planarized, micro-textured surface. In general, on different surfaces with an equivalent Ra and Rz, the planarized surface will give superior performance to that of a ground surface or honed surface since the latter has peak asperities (Figure 3). The optimum surface is that surface where the valleys also have been completely removed.

Figure 4 illustrates ground or honed surfaces brought into contact (top) versus two planarized surfaces brought into contact. The film thickness required to separate the planarized surfaces is much less than that required to separate the ground or honed random surfaces.

Recently, the performance of honed gears with an average 0.25 mm Rz were compared to superfinished gears with an average 0.04 mmRz [7]. The superfinished gears lasted 2,000 hours with no indication of micropitting while the honed gears showed micropitting after only 150 hours. One can argue that a gear with a smoother (honed) surface should outperform a gear with a rougher surface. However, a 0.25 mm Rz planarized surface devoid of stress raisers (peak asperities) should outperform a honed 0.25 mm Rz surface.

A BETTER PARAMETER TO CHARACTERIZE THE PLANARIZED SURFACE

The specific film thickness ratio, \( \lambda \), is a dimensionless parameter commonly used to predict or define the degree of separation between two contacting and lubricated surfaces. The degree of separation may range from full-contact or boundary lubrication to full-separation or hydrodynamic (full fluid) lubrication. Specifically, refers to the minimum lubricant film thickness divided by the composite surface roughness of the mating surfaces (equation 2).

Equation 2: \( \lambda = \frac{\text{Minimum film thickness, } H}{\text{Composite surface roughness, } S} \)

Historically, there were several derived methods of determining the composite surface roughness. Examples are shown in Equations 3 through 5.
Equation 3: \[ S = (R_{a1}^2 + R_{a2}^2)^{0.5} \]
Equation 4: \[ S = 0.5 (R_{a1} + R_{a2}) \]
Equation 5: \[ S = (R_{q1}^2 + R_{q2}^2)^{0.5} \]

Occasionally, \( R_a \) is substituted in the preceding formulas with \( R_z \) [5]. Consequently, the \( \lambda \)-ratio, associated with the lubrication regime, is dependent on how the composite surface roughness is calculated. Thus, the \( \lambda \)-ratio may vary widely. See examples in Table 2.

Conway-Jones and Eastman suggest that the best definition of the Lambda Ratio, where sliding and rolling contact occurs (gears, for instance), is better stated by the arithmetic summation of the heights of the peak asperities [13].

This is represented by Equation 6, where \( e_s \) and \( e_b \) are the heights of the asperities on the respective surfaces “s” and “b.” The numerator, \( h_{min} \), is the minimum film thickness required for full hydrodynamic lubrication under the operating conditions. The authors state that this \( \lambda \)-ratio correlates more closely to actual test data. Alternatively, the equation may be expressed by Equation 7.

In addition, the authors propose the calculation of the composite surface roughness according to Equation 8.

Equation 6: \[ \lambda = \frac{h_{min}}{e_s + e_b} \]
Equation 7: \[ \lambda = \frac{h_{min}}{R_z} \]
Equation 8: \[ S = 3\sigma_{50} + 3\sigma_{50} \]

In the three following topographical scenarios, the authors calculate various \( R \) parameters from optically measured histograms of peak heights. The parameter \( R_z \) is defined as the standard deviation of the height distribution. Therefore, in the histogram of heights, one can multiply \( R_q \) by three to obtain the \( 3\sigma \) value. This value is then multiplied by two to approximate two contacting surfaces.

For the bearing ratio, \( t_b \) the \( 3\sigma_{50} \) value is calculated by only taking into account to between 0.13% and 50%. The very highest peaks (\( t_b \) roughly less than 0.13%) on a gear or bearing surface are quickly cleaved or worn away during the run-in period and, thus; do not affect surface wear significantly. Likewise, a \( t_b \) greater than 50%, the material has little or no effect on surface wear and fatigue. Again, the \( 3\sigma_{50} \) value is doubled to approximate two contacting surfaces.

Afterward, for illustrative purposes, the mean line of the histogram
of peak heights is aligned with the line that corresponds to a tp of 50%. The values of 3σ (Rq) and 3σ50 are calculated and compared beneath the illustrations. In Figure 5, the 3σ of the histogram of heights (left) approximates the 3σ50 of the micron depth vs. bearing area. The values are relatively close since the ground surface approximates a normal distribution of peaks and valleys on the surface. To obtain full film lubrication for mating surfaces having the same roughness, Ra, see Table 3. To obtain full film lubrication for mating surfaces having the same roughness, see Table 4.

In this case, Rq underestimates the thickness of the film required to achieve full film lubrication. The reason is that a first polishing of the ground surface in the previous example introduced raised areas results in a positive skew, Rsk (Figure 6). Certain difficult bearing alloys and high-carbide alloys display this characteristic feature during the initial stages of superfinishing. Areas of raised peaks, plateaus, or nodules

![Figure 9: Three-dimensional topographical representations of a ground, polished and superfinished surface. (Courtesy of The Timken Company)](image)

![Figure 10: Correlation between Rpm and 3σ50.](image)
may appear on the surface. To obtain full film lubrication for mating surfaces having the same roughness, see Table 5.

In this case, $R_q$ greatly overestimates the thickness of the film to obtain full film lubrication. The $R_{sk}$ is negative as it is for superfinished surfaces where mostly valleys and very few peaks are present (Figure 7).

**EXPERIMENT — AN IN SITU CASE STUDY**

A through-hardened high-grade alloy steel specimen having an initial ground surface finish of a 0.8 mm $R_a$ was planarized. The $R_m$, $R_u$, and $3 \sigma_{50}$ were measured periodically during the planarization process. The theoretical separation film thickness was calculated using the parameters $R_q$ and $3 \sigma_{50}$. The results, plotted in Figure 8, show that the minimum film thickness required to obtain full film lubrication decreases much more rapidly when calculated using $3 \sigma_{50}$ versus when calculated using the $R_q$. This occurs because the surface has been planarized with the removal of the peak asperities. Thus, when a ground part is superfinished to a 0.23 $\mu$m $R_a$, it requires a much thinner lubricant film than that predicted from the calculation of $R_q$. As the $R_u$ gets very low, the film thickness will be the same no matter what parameter is used to calculate it. In Figure 8, it is evident that the film thickness required for full film lubrication for a planarized surface having a 0.5 $\mu$m $R_a$ is the same as a ground surface having a $R_u$ equal to approximately 0.22 mm.

Thus, a planarized surface having a 0.25 $\mu$m $R_a$ will yield superior performance to a honed/polished surface having a 0.25 $\mu$m $R_a$ surface. Figure 9 emphasizes that superfinished surfaces will require a thinner lubricating film to keep them separated than mated ground-to-ground surfaces, mated polished-to-polished surfaces, and even mated superfinished-to-polished surfaces.

**A COMMON AND PRACTICAL PARAMETER FOR PROFILOMETRY**

Conway-Jones and Eastham [13] found, by measuring numerous processed surfaces, that $3 \sigma_{50}$ approximates $R_{pm}$. The $R_{pm}$ is the mean of the highest peaks above the average level on five measurement lengths. This observation was confirmed on superfinished surfaces (Figure 10). Hence, $R_{pm}$ is a much more meaningful surface measurement parameter for determining the quality of the superfinished surface compared to $R_a$ or $R_q$. The I-ratio may be defined by Equation 9:

$$\lambda = \frac{h_{\min}}{S} = \frac{h_{\min}}{R_1 + R_2} = \frac{h_{\min}}{R_{pm1} + R_{pm2}}$$

One marked and three random profilometer traces compiled on an actual ground production gear show an initial correlation between $R_{pm}$ and $3 \sigma_{50}$ on a planarized gear versus the same gear in the as received state (Figure 11 and Figure 12). Note the lack of correlation of these two parameters on the ground, non-planarized gear. Further evaluation and study may be required to fully understand this relationship.

The $R_{pm}$ is a readily available parameter on most profilometers. Importantly, $R_{pm}$ may be much less stylus tip radius-sensitive since the parameter calculates the mean of the five highest peaks [14] [15]. Stylus tip size is relatively independent of the peak measurement sensitivity versus the valleys where a larger tip diameter may prevent contact as shown in Figure 13 [16]. This would end the frustration of comparing $R_u$ data obtained with stylus having different tip sizes.

**CONCLUSIONS**

The preceding discussion yields several important and correlated conclusions. Altogether, these conclusions (numbered below) show that $3 \sigma_{50}$ and more practically $R_{pm}$ are better indicators of the nature...
of the surface roughness profile whether ground, honed, or superfinished. Moreover, the data reinforces the superiority of a planarized surface over a ground or honed surface.

1. Hertzian fatigue and consequently micropitting are directly correlated to the contacting peak asperities of two mating surfaces such as gears and bearings
2. The magnitude of \( R_a, R_z, \) and \( R_q \) are not indicative of the magnitude of peak asperities on the mating surfaces
3. There is no industry-wide agreement on the calculation of the composite surface roughness, \( S \)
   a. Profound effect on the defined lubrication regimes
   b. Some groups use \( R_a \) while others use \( R_z \)
   c. Even the simple algebra used varies widely
4. Conway-Jones and Eastham show
   a. That \( 3\sigma_{50} \) is a better variable to use in the calculation of the composite surface roughness, \( S \)
   b. Their calculation of \( S \) better characterizes the actual surface roughness profile
   c. That \( 3\sigma_{50} \) is a better predictor of the minimum film thickness required for full hydrodynamic lubrication
   d. Specimens of the same \( R_a, R_q \) are a less reliable indicator of the surface
   e. Calculation of \( R_q \) commonly overestimates, underestimates, or roughly approximates the minimum film thickness required for full hydrodynamic lubrication
   f. That \( 3\sigma_{50} \) approximates \( R_{pm} \), a common profilometer parameter
5. A REM case study on a steel specimen shows
   a. That as the roughness profile is lowered, the required minimum film thickness to obtain full film lubrication decreases much more rapidly using \( 3\sigma_{50} \) calculations, versus using \( R_q \) calculations
   b. A planarized surface having a 0.5 \( \mu m \) \( R_a \) requires the same film thickness as a ground surface having a \( R_a \) equal to approximately 0.22 \( \mu m \)
   c. A planarized surface is superior to a ground or honed surface having nearly identical \( R_q \) and/or \( R_a \) values
   d. The \( R_{pm} \), as Conway-Jones and Eastham conjectured, is a superior profilometer parameter to gauge the true surface roughness profile of a surface, whether ground, honed, or superfinished
   e. The \( R_{pm} \) is less sensitive to stylus tip size, eliminating variability in measurements of the same surface by different instruments.

BIBLIOGRAPHY


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