Development of an Algorithm Based on 3D Surface Roughness for Engine Cylinder Head Sealing Analysis

Heloísa Colli Moreira
Giuseppe Pintaúde
Technological Federal University of Paraná

ABSTRACT

Adhesion between rough surfaces plays a critical role in the sealing of mechanical systems, directly impacting the efficiency and durability of engines. In this study, we investigated the adhesion between the cylinder head and its cover in an engine, joined by a silicon adhesive. We applied Persson's contact mechanics theory, which describes the relationship between roughness and adhesion through the spectral distribution of surface heights. The surfaces were characterized using optical interferometry, a 3D analysis technique that provides high-precision topographic data. Computational modeling was implemented in MATLAB to estimate the real contact area and evaluate percolation under operational conditions. The results provided a quantitative analysis of the effect of surface topography on adhesion and its influence on sealing performance, contributing to optimizations in engine design.

INTRODUCTION

In the automotive industry, the assembly of engine components represents a relevant technical challenge, especially when it involves dissimilar materials. Traditional joining solutions, such as bolting and welding, are still widely used but present significant limitations. [1] These methods introduce internal stresses in the parts, require strict assembly tolerances, and increase the overall system weight.

As an alternative, adhesive bonding has gained ground, as it allows the joining of different materials without introducing significant stress or excessive mass. [1] Moreover, adhesives perform well in sealing applications and can accommodate small geometric imperfections. However, this technique still faces important challenges, such as low resistance to extreme thermal variations and a high sensitivity to surface condition. For effective adhesion and reliable sealing, the surface must be properly prepared, exhibiting characteristics that favor both mechanical anchoring and adequate wettability by the adhesive.[2]

Traditionally, surface roughness has been evaluated using the Ra parameter, which represents the arithmetic average of surface height variations along a profile. Previous studies have shown a correlation between Ra and the mechanical and sealing performance of bonded joints. [3] In general, intermediate values of surface roughness promote better performance: high values hinder the adhesive's ability to penetrate valleys, leading to the formation of preferential flow paths and sealing failure; conversely, very low roughness provides insufficient mechanical anchoring, compromising adhesion and favoring delamination under mechanical stress.[2]

Despite its widespread use, the Ra parameter has critical limitations. It does not capture information about the spatial distribution of asperities and cannot differentiate between surfaces with distinct textures but identical average roughness. [3] This limits its ability to predict the functional performance of adhesive joints. In response, several authors have proposed multiscale surface analysis, employing parameters derived from the surface power spectral density (PSD). [2,4] This approach enables surface characterization based on its structure over different wavelength ranges, offering greater sensitivity to features relevant to adhesion, such as rms slope ξ, fractal dimension, and spectral energy distribution.

Additionally, recent studies indicate that the sealing performance of bonded rough surfaces is strongly linked to the percolation of the contact area, as well as to the formation of flow channels during both assembly and operation.[5] Thus, the study of surface roughness through the lens of elastic contact mechanics and fluid dynamics in complex interfaces provides a promising theoretical framework to understand and optimize the performance of bonded joints in automotive engines. In the context of sealing, a fundamental aspect is the percolation of the real contact area: this refers to the point at which the contacting regions form a continuous network that blocks the flow of fluid through the interface.[6]

The objective of this study is to present the computational implementation of a methodology for analyzing contact area percolation in the sealing system formed between an engine block and a valve cover, joined by a silicone based adhesive. The analysis is divided into two phases: (i) the assembly phase, when the silicone is still in a fluid state; and (ii) the operational phase, when the cured silicone is subjected to internal oil pressure. This work focuses on the simulation of the first phase, during assembly.

THEORY

Both surfaces in contact exhibit anisotropic roughness, which requires an approach that considers the directional behavior of asperities. Therefore, a theoretical model developed by Persson [5] was integrated: the fluid squeeze-out theory, which describes the evolution of contact during the assembly stage from the surface roughness data.

SURFACE ROUGHNESS CHARACTERIZATION - Surface roughness characterization is performed using the power spectral density $C(q)$, which contains all the relevant statistical information about the topography. The PSD describes how roughness energy is distributed over different wavelengths (represented by q) and is obtained through the Fourier transform of the autocorrelation function of surface height $h(x,y)$. Long wavelengths (low q) represent broad ondulations, while short wavelengths (high q) represent fine asperities.

$$C(q) = \frac{1}{(2\pi)^2} \int \langle h(x)h(0) \rangle e^{-iq\cdot x} d^2x \tag{1}$$

For isotropic surfaces, such as those obtained through sandblasting, the PSD depends only on the magnitude $q=|q|$. However, for anisotropic surfaces, as in the present study, the PSD also varies with direction and is better described as $C(q,\theta)$. An important characteristic of surfaces described by their PSD is the fractal behavior often found in machined or cast components. These surfaces follow a power-law decay of the form:

$$C(q) \sim q^{-2(1+H)} \tag{2}$$

Where H is the Hurst exponent, directly related to the fractal dimension $Df=3-H$. Surfaces with H between 0.7 and 1 are classified as self-affine, meaning they maintain their statistical structure across scales when the vertical axis is properly rescaled. Other parameters can be derived from the PSD, such as the root mean square roughness, also written as h_{rms}:

$$Sq = 2\pi \int_{q_0}^{q_1} qC(q)dq \tag{3}$$

and the rms slope:

$$\xi = 2\pi \int_{q_0}^{q_1} q^3C(q)dq \tag{4}$$

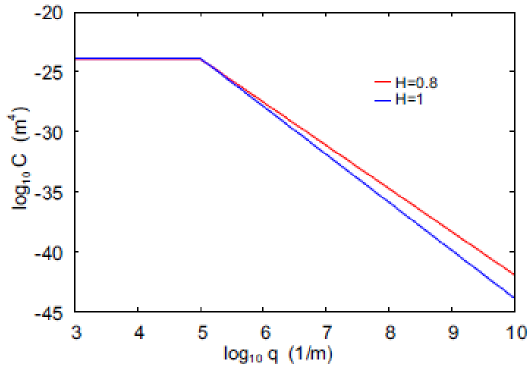

Figure 1. Example of power spectral densities with different Hurst exponents, from Persson [6]

While h_{rms} is mainly influenced by long-wavelength components, the rms slope ξ is dominated by high-frequency components, making it more representative for analyzing contact and sealing behavior.

SILICONE FLOW DURING ASSEMBLY - During assembly, the silicone adhesive is compressed between the engine block and valve cover, leading to fluid squeeze-out. To model this behavior, the adhesive is treated as a fluid flowing through the interconnected voids formed by non-contact regions of the surface. These form a complex network of channels with an effective hydraulic conductivity σ_{eff}, which depends on the local separation between the surfaces. Persson [5] developed a model for this fluid flow using classical lubrication theory for flow between parallel plates and mass conservation, extended through the Bruggeman effective medium theory to handle surface heterogeneity. Persson's contact mechanics theory provides a framework by relating the real contact area and distribution of interfacial separations to the applied pressure and surface roughness characteristics, such as the PSD of the surfaces, and the relation of the contact area and the nominal pressure is given by:

$$\frac{A}{A_0} = f\left(\frac{p}{E^*\xi}\right) \tag{5}$$

Where E^* is the effective elastic modulus and ξ is the rms slope. By integrating these relationships, the model predicts the time-dependent behavior of the interfacial separation and the extent of fluid squeeze-out during the assembly process. This information is crucial for understanding the initial conditions that affect the subsequent performance of the adhesive joint, particularly in terms of sealing effectiveness and resistance to leakage.

MATERIALS AND METHODS

For this work we investigated the system composed of a cylinder head and a cylinder head cover, both from the same model of internal combustion engine of a popular car. The cylinder head is made of aluminum with an iron enriched alloy with an elastic modulus of 75 GPa and Poisson coefficient of 0.33 as elastic properties and a milled surface finish. The cover is made of a fiber glass reinforced polymer with an elastic modulus of 10 GPa and Poisson coefficient of 0.30. These two materials are joined with silicone adhesive and screws with an interfacial contact pressure estimated to be 4 MPa. For this part of the study the influence of silicone in the interface is not considered.

DATA ACQUISITION – For implementing the theory it was necessary to acquire the matrix containing the height information of each surface, for that we used a Taylor Hobson Talysurf CCI Lite M12-3993-03 white light interferometer and 20x objective lens. After acquisition, the raw topographic data from both surfaces were processed and organized into square height matrices of size 1024×1024 points using MountainsMap software. Basic filters were applied to the data to level the surface, remove form errors, fill-in eventual non measured points and threshold the background noise respectively, this is an important step since it facilitates the posterior steps. Surface height parameters were also calculated in this step to provide validation for the later numerical implementation.

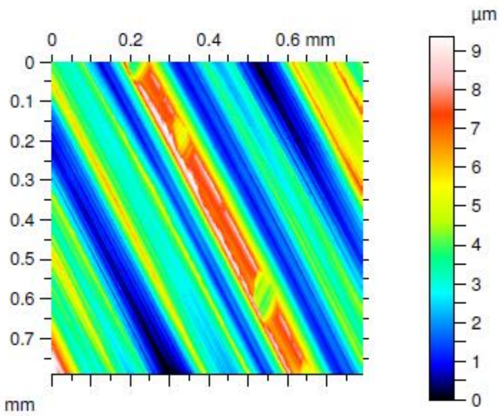

Figure 2. Milled surface for the aluminum cylinder head obteined from interferometry technique.

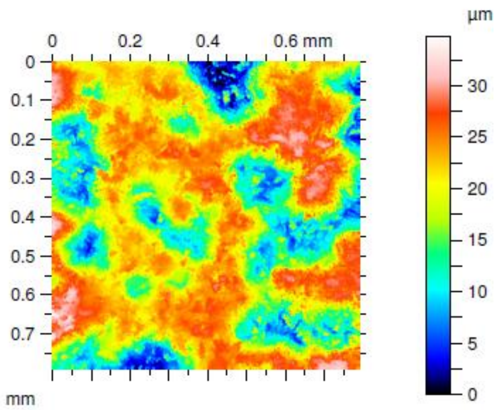

Figure 3. Surface of the polymer valve cover obteined from interferometry technique.

NUMERICAL IMPLEMENTATION – The theoretical model implementation was caried out using MATLAB, based on the experimental surface data obtained via interferometry. The height matrices of both the cylinder head and polymer cover were imported into MATLAB environment for spectral and contact analysis.

A two-dimensional Fast Fourier Transform (2D FFT) was applied to each height matrix, with appropriate normalization to preserve the surface's total energy. From the Fourier-transformed data, the power spectral density (PSD) $C(q_x, q_y)$ was obtained in its full anisotropic form. Additionally, an angular averaging was performed to compute the radial PSD $C(q)$, which simplifies the interpretation by condensing directional data into a function of the wavevector magnitude.

The Hurst exponent H was estimated from the log-log slope of the radial PSD in its linear fit approximation. The root-mean-square roughness and the root-mean-square slope were extracted directly from the PSD according to the equations presented before (3 and 4).

Each surface was analyzed individually in contact with a rigid flat counter face and the influence of the silicone in the contact was not included in this part of the analysis. The non-adhesive elastic contact model proposed by Persson was applied to estimate the real contact area fraction A/A_0 as a function of the nominal contact pressure, according to the equation (5). This analytical relationship provides a simple and efficient way to estimate the evolution of contact area with pressure, enabling rapid assessments of sealing potential and onset percolation.

For a given operating pressure, a binary contact map was generated. Each surface was classified as "in contact" or "not in contact" based on a threshold height criterion, selected to match the calculated contact area fraction. This binarization allows for visualization and further topological analysis of the interface.

To determine whether a fluid-tight seal was formed under a given pressure condition, a percolation analysis was performed. The binary contact map was processed using a function in MATLAB, which identifies all connected contact clusters. A cluster was considered percolating if it connected opposite edges of the sample in either the x or y-direction. The absence of a percolating cluster indicates that the interface contains open fluid channels, allowing for potential leakage. Conversely, the presence of a continuous contact path across the surface suggests that fluid flow is blocked, i.e., a sealing condition has been achieved.

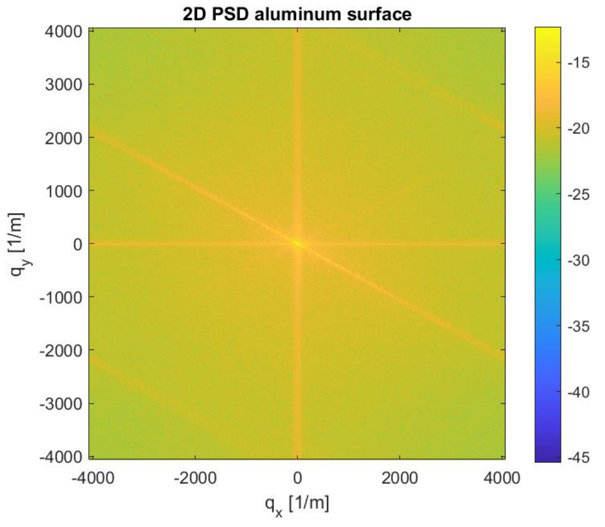

Figure 4. 2D power spectrum density for the aluminum cylinder head, generated in MATLAB

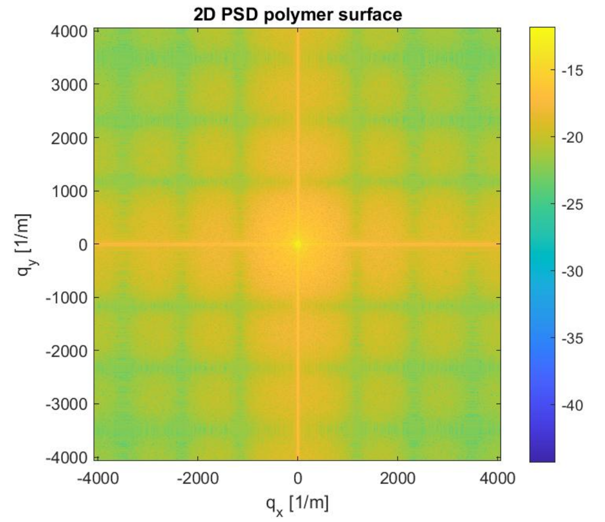

Figure 5. 2D power spectrum density for the polymer valve cover, generated in MATLAB

DISCUSSION

The interferometry measurements resulted in high-resolution topographic data for both the cylinder head and valve curve surfaces as shown in figures 2 and 3. From the height maps, the PSDs were computed and revealed distinct spectral behaviors (figures 4 and 5). The aluminum cylinder head, with a milled finish, exhibited a marked anisotropy, with higher energy concentration along the machining direction. The polymeric cover, although rougher in amplitude, showed a more isotropic texture. The radial PSDs shown in figures 6 and 7 followed clear power-law behavior in the intermediate q-range, indicating self-affine fractal behavior.

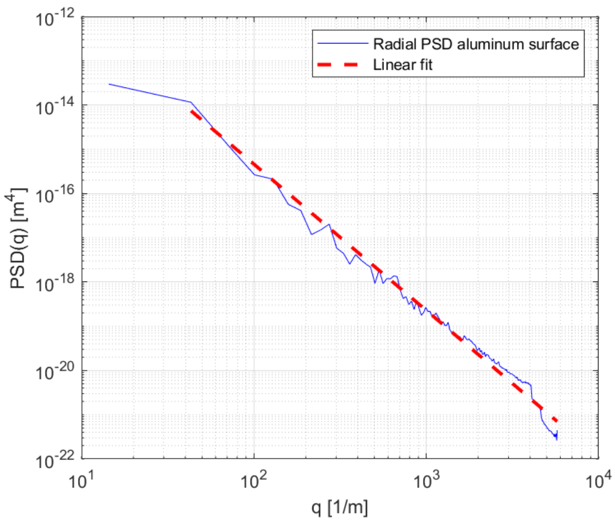

Figure 6. Radial power spectrum for the aluminum cylinder head with linear fit to estimated 0.653 Hurst exponent.

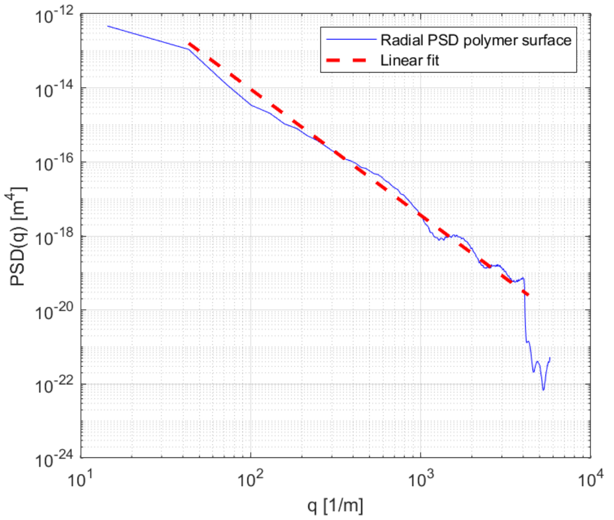

Figure 7. Radial power spectrum density for the polymer valve cover with linear fit to estimated 0.704 Hurst exponent.

The estimated Hurst exponents were 0.653 for the aluminum surface and 0.704 for the polymer surface. These values are within the typical range for engineering surfaces and confirm the fractal characteristic of the surfaces, which is crucial for applying Persson's contact mechanics theory. An important remark is that for the polymer surface the final portion of the radial PSD was excluded from the estimation of the Hurst exponent. This region showed abnormal fluctuations attributed to background noise, which significantly distorted the linear behavior expected in the log–log plot. Such noise is common when measuring polymeric surfaces with interferometry, due to their low reflectivity and diffuse scattering properties. Although additional image acquisition and preprocessing steps were performed to reduce these effects, the high-frequency range of the PSD remained notably affected and was therefore disregarded to ensure the reliability of the Hurst exponent estimation.

The rms roughness calculated from PSD is the same as the Sq parameter extracted from the MountainsMap software which is 1.81 μm for the aluminum surface and 6.51 μm for the polymer, this indicates that the data is being correctly managed.

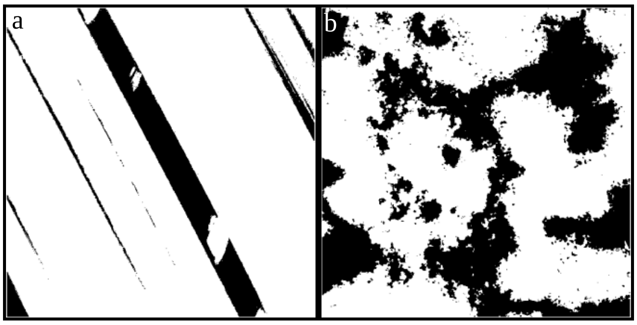

Figure 8. Binary contact maps for both surfaces (a) aluminum and (b) polymer.

Using Persson's model, the real contact area fraction A/A0 was estimated as a function of the nominal pressure. To analyze the fluid tightness potential, a binary contact map was generated and processed through cluster connectivity analysis. As shown in figure 8, at this pressure level the contact clusters do not yet percolate across the surface in all directions. Therefore, it is inferred that open fluid channels are still present. This result suggests that sufficient pressure is required not only to increase contact fraction but also to reach the percolation threshold, typically around 40–50% for isotropic surfaces and adjusted for anisotropic cases using:

$$\left(\frac{A}{A_0}\right)_{perc} = \frac{\gamma}{1+\gamma} \qquad (6)$$

where γ is the anisotropy parameter. The aluminum surface showed a preferential orientation that may delay percolation in one direction, emphasizing the need to evaluate sealing in both axes.

The results indicate that surface roughness characteristics, particularly slope and anisotropy, strongly influence the sealing performance. Despite relatively high pressures, regions of non-contact may persist, forming preferred leakage paths if percolation is not reached. In practical applications, this reinforces the importance of controlling surface finish and selecting adhesive properties that complement the mechanical interaction of the parts.

Although the silicone adhesive was not explicitly modeled in this stage, the squeeze-out behavior during assembly depends critically on the same pressure and roughness parameters. In future stages of this study, these results will support the time-dependent simulation of adhesive flow, incorporating fluid viscosity and curing dynamics to assess filling efficiency and potential void formation.

A relevant perspective for future development of this work is to model the cured silicone adhesive as a very thin O-ring, allowing the application of Persson's leakage theory in the second phase of the analysis. With this approach, it becomes possible to evaluate whether the non-contact paths identified during the first phase are actually sealed after curing, or if they remain open and potentially lead to leakage. Furthermore, the model may predict the fluid pressure required to induce lift-off at the interface, particularly important during engine operation, where oil pressure acts dynamically on the bonded joint.

Analyzing each surface individually, rather than as a combined roughness system, also offers important insights. This strategy helps to identify which is more susceptible to failure and under what conditions, whether due to insufficient adhesion caused by roughness, or due to fluid-induced lift-off. Ultimately, this could provide a deeper understanding of how surface failure initiates or at least allow the simulation of best and worst-case scenarios under realistic operating conditions. This is particularly relevant when the available surface data does not clearly indicate whether the differences in roughness alone are significant enough to determine sealing performance. By refining this approach, the model may contribute to predictive design strategies for more robust adhesive joints in automotive applications.

CONCLUSION

This study presented the first stage of a computational implementation based on Persson's theory of fluid squeeze-out between rough elastic surfaces. The system under analysis, comprising a cylinder head and a polymeric valve cover joined by a silicone adhesive, was experimentally characterized using white-light interferometry, and its surface roughness was quantified through spectral methods. From the acquired topographies, the power spectral densities were computed, allowing the extraction of key parameters such as rms roughness, rms slope, and the Hurst exponent.

A numerical model was implemented in MATLAB to simulate the contact area evolution and identify conditions under which percolation of the contact area occurs. The analysis confirmed that surface anisotropy plays a significant role in the percolation behavior and, therefore, in the sealing efficiency of the joint. The results also highlight the sensitivity of PSD-based roughness analysis to experimental noise, especially when dealing with low-reflectivity polymeric surfaces.

Although the influence of the adhesive was not yet incorporated in this stage, the results establish a solid foundation for simulating the second phase of the interface behavior, which will include the adhesive flow dynamics, the effect of internal pressure during engine operation and the combined surface roughness influence on the interface.

The developed model contributes to a better understanding of how surface roughness affects contact mechanics and sealing performance and opens the way for more accurate predictions of fluid retention and leakage in bonded joints of automotive components.

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