RESEARCH ARTICLE

An approach to evaluate the sealing performance of sealing structures based on multiscale contact analyses

Runliang Wang\textsuperscript{1}, Jianhua Liu\textsuperscript{1}, Feikai Zhang\textsuperscript{2} and Xiaoyu Ding\textsuperscript{1,}\textsuperscript{*}

\textsuperscript{1}Beijing Institute of Technology, School of Mechanical Engineering, 5 Zhongguancun Street, Haidian District, Beijing 100081, China and \textsuperscript{2}State Grid Corporation of China, China Electric Power Research Institute, 86 West Chang'an Street, Xicheng District, Beijing 100192, China

*Corresponding author. E-mail: xiaoyu.ding@bit.edu.cn

Abstract

The evaluation of sealing performance is important in the design stage and assembly process of sealing structures. To date, analyses of sealing structures have rarely quantitatively evaluated sealing performance: They tend to neglect microsurface topographic information or simplify rough surfaces. Herein, we propose a new and efficient simulation approach to analyse sealing performance based on a multiscale contact model. In this simulation approach, a new parameter, critical preload, is used as the index of sealing performance. The validity of the proposed index was verified using the case of a cone seal. The evolution of the contact characteristics during the assembly process, such as the real contact area, the distribution of contact pressure, and contact status, were studied in detail.

Keywords: critical preload; FEM; randomly rough surface; real contact area; sealing performance

1. Introduction

Seals play a vital role in guaranteeing the performance of many mechanical devices and are widely used in the pipelines of many engineering products, e.g. the transmission systems in spacecraft. The contact between sealing surfaces is the basis for the sealing mechanism. The failure of seals can have serious ramifications, such as energy loss, environmental pollution, and expensive replacement procedures.

Extensive research has been conducted on analysing the sealing performance of various sealing structures. The finite element method (FEM) has typically been used to analyse the contact width and contact pressure of various sealing structures at the macroscale (Table 1).

All of the simulation studies listed in Table 1 have a common limitation: They assume ideally smooth sealing surfaces. In real-world applications, sealing surfaces generated by a machining process are inevitably rough (Yastrebov et al., 2015). When two solids are squeezed together, they will generally not make contact everywhere within the nominal contact area (Persson et al., 2004), and the real contact area (RCA) is smaller than the nominal contact area. Noncontact areas could be the cause of leakage. Therefore, simulations based on ideally smooth surfaces cannot determine the real contact status of the sealing interface at the microscale; they can only evaluate sealing performance qualitatively.

Recently, researchers have taken microsurface topography into consideration when analysing sealing performance (Table 2). The leakage rate of an aviation seal (Liao et al., 2019) was calculated based on the assumption that there were isosceles triangle-shaped holes on the sealing interface. Haruyama...
Table 1: Summary of research analysing sealing performance of ideally smooth sealing surfaces.

| References                          | Sealing structures      | Method  | 2D/3D   | Index of sealing performance                      |
|-------------------------------------|-------------------------|---------|---------|--------------------------------------------------|
| (Puccio et al., 2006)              | Cone seals              | FEM     | 2D and 3D | Contact width, contact pressure                   |
| (Wen, 2006; Belforte et al., 2009) | Lip seals               | FEM     | 2D      | Contact width, contact pressure                   |
| (Krishna et al., 2007; Mathan & Siva Prasad, 2011; Nelson & Prasad, 2016; Luyt et al., 2017; Nelson et al., 2017) | Flange joints           | FEM     | 3D      | Contact pressure                                 |
| (Chen et al., 2018)                | Tubing and casing threaded connections | FEM     | 3D      | Contact pressure                                 |
| (Hu et al., 2017)                  | Compression packer      | FEM     | 3D      | Contact width, contact pressure                   |
| (Zhang & Hu, 2020)                 | Flat-to-sphere seals    | FEM     | 2D      | Contact pressure                                 |
| (Wang & Liu, 2015)                 | Steam turbine casing    | FEM     | 3D      | Contact pressure                                 |
| (Sui & Anderle, 2013; Zhou et al., 2014, 2017; Chen et al., 2016; Shuai et al., 2019) | O-ring                  | FEM     | 2D      | Contact pressure                                 |

Table 2: Summary of research on analysing sealing performance considering microsurface topography.

| References                          | Index of sealing performance | Surface type                      | Quantitative or qualitative |
|-------------------------------------|------------------------------|-----------------------------------|-----------------------------|
| (Liao et al., 2019)                 | Leakage rate                 | Surface with triangle grooves     | Quantitative                |
| (Haruyama et al., 2013)             | Contact width                | Simplified wavy surface           | Qualitative                 |
| (Wenk et al., 2016)                 | Contact pressure             | Measured rough surface            | Qualitative                 |
| (Yan et al., 2018)                  | RCA                          | Measured rough surface            | Qualitative                 |
| (Persson & Yang, 2008; Lorenz & Persson, 2009, 2010) | Leakage rate             | Measured rough surface            | Quantitative                |
| (Bottiglione et al., 2009)          | Leakage rate                 | Isotropic self-affine rough surface | Quantitative                |
| (Dapp et al., 2013)                 | Leakage rate                 | Numerically generated rough surface | Quantitative                |
| (Jianjun et al., 2018)              | Leakage rate                 | Numerically generated rough surface | Quantitative                |
| (Zhang et al., 2016)                | Leakage rate                 | Measured rough surface            | Quantitative                |
| This study                          | Critical preload             | Numerically generated rough surface | Quantitative                |

Figure 1: Main procedure of the approach.

et al. (2013) investigated the influence of surface roughness on sealing performance of a flange joint with a new metal gasket, where the surface roughness was simplified by using a sinusoidally wavy surface. These analyses have some limitations due to their incorporation of simplified rough surfaces. Research based on measured or numerically generated rough surfaces has also been conducted to analyse sealing performance more accurately. A multiscale FE model was developed based on measured surface roughness data of a lip seal (Wenk et al., 2016). Similarly, Yan et al. (2018) developed a multiscale contact model to analyse the change of the RCA of twin-ferrule pipeline fittings. The research on estimating the leakage rate of real rough surfaces provided a quantitative way to evaluate the sealing performance. Persson et al. (Persson & Yang, 2008; Lorenz & Persson, 2009) presented a theory of leakage rate for rough surfaces based on percolation theory and Persson’s contact mechanics theory (Persson, 2001). After that, the effective-medium theory of leakage rate for rubber seals was presented (Lorenz & Persson, 2010). Bottiglione et al. (2009) presented a theoretical approach to estimate the leakage rate based on critical path analysis and...
percolation theory. By combining Persson’s theory with a modified effective-medium solution of the Reynolds equation, the leakage rate was estimated (Dapp et al., 2013). A simplified rectangular leakage channel model for mechanical face seals (Jianjun et al., 2018) was proposed based on percolation theory. Zhang et al. (2016) also proposed a multiscale approach to calculate leakage channels and leak rates for metallic seals using measured surface topographies. Although these studies considered machining error of the sealing surface, most were still qualitative. Some quantitatively evaluated sealing performance according to the leakage rate, but calculating the leakage rate precisely is a time-consuming procedure and is thus difficult to apply in practical engineering situations.

In engineering situations, a more efficient simulation method is needed for the optimal design of sealing structures.

The simulation method should be able to quantitatively evaluate sealing performance and be implemented using existing simulation technology. Herein, we propose a new simulation approach to analyse the sealing performance of sealing structures based on a multiscale contact model. In this simulation approach, a new parameter, critical preload, is used as the index of sealing performance. Section 2 provides an overview of the proposed approach. Sections 3–6 detail the approach by applying it to a cone seal. The validity of the index is verified in Sections 7 and 8. Section 9 discusses how to comprehensively evaluate sealing performance, and Section 10 presents our conclusions. The approach proposed in this paper will be valuable for use in the design and assembly stage of sealing structures and thereby improve sealing performance.

2. Overview of the Approach

Figure 1 presents the main procedure of the approach proposed in this paper. The approach consists of the following three steps:

1) Multiscale modeling of sealing structures: A randomly rough surface is generated and filtered. The filtered rough surface is then added to the ideally smooth surface to generate a multiscale FE model. The material properties and boundary conditions are defined.
2) Contact analyses: Based on the generated FE model, the contact analyses on the sealing interfaces are conducted.
Sealing performance evaluation based on contact analyses

Through this step, the distribution of contact pressure and contact status of the sealing interface under different preloads can be calculated.

3) Quantitative evaluation of sealing performance: According to the contact status obtained from step 2, a sealing status judgment procedure is carried out to judge whether there is a leakage channel on the sealing interface. The relationship between the sealing status and preload can be obtained. The critical preload is proposed to quantitatively evaluate sealing performance.

Sections 3–6 present the proposed approach in detail by applying it to a cone seal as an example. Sections 7 and 8 investigate the effects of preload, surface anisotropy, and yield strength on sealing performance using this approach.

3. Geometrical Model of a Cone Seal
A cone seal is a type of static sealing structure that is widely used in aircraft engine pipelines (Fig. 2). The seal consists of three parts: cone part 1, cone part 2, and nut. The sealing zone formed through the contact of the two conical surfaces prevents fluid leakage.

4. Multiscale Modeling of the Cone Seal
4.1 Generation of randomly rough surfaces with prescribed parameters
Extensive research has been conducted on methods to generate randomly rough surfaces (Whitehouse et al., 1970; Patir, 1978; Hu & Tonder, 1992; Wu, 2000; Manesh et al., 2010; Liao et al., 2018; Watson et al., 2020). The method used to generate such surfaces in this study is based on the numerical procedure proposed by Patir (1978) and further improved by Manesh et al. (2010). This method can be used to generate a rough surface with prescribed height distribution function and autocorrelation function (ACF). For the proposed approach, an exponential ACF that has the form described by equation (1) is adopted as follows:

\[
R(x, y) = \sigma^2 \exp \left\{ -2.3 \cdot \left[ \left( \frac{x}{\beta_x} \right)^2 + \left( \frac{y}{\beta_y} \right)^2 \right]^{1/2} \right\}.
\] (1)

Here, \( \sigma \) is the root-mean-square (RMS) roughness of the surface and is set at 1 \( \mu \)m. \( \beta_x \) and \( \beta_y \) are the correlation lengths in the \( x \) (circumferential) and \( y \) (radial) directions, respectively. The same value of \( \beta_x \) and \( \beta_y \) means that the surface is isotropic. Otherwise, surfaces generated with different \( \beta_x \) and \( \beta_y \) are anisotropic. The surface height matrix \( h \) can be generated...
Table 3: Statistical parameters of generated rough surfaces.

| Surface number | Average roughness, Ra (μm) | RMS roughness* (μm) | Skewness* | Kurtosis* |
|----------------|-----------------------------|----------------------|-----------|-----------|
| 1              | Original                    | 0.7907               | 0.9918    | 0.0062    | 3.0305    |
|                | Filtered                    | 0.6830               | 0.8589    | 0.0041    | 3.0866    |
| 2              | Original                    | 0.7894               | 0.9890    | 0.0031    | 2.9985    |
|                | Filtered                    | 0.6846               | 0.8584    | 0.0020    | 3.0136    |
| 3              | Original                    | 0.7879               | 0.9856    | −0.0054   | 2.9729    |
|                | Filtered                    | 0.6787               | 0.8520    | −0.0052   | 3.0041    |

*The RMS roughness, skewness, and kurtosis are input parameters when generating the rough surfaces. The RMS roughness is set to 1 μm. For rough surfaces with Gaussian distribution, the values of skewness and kurtosis are 0 and 3, respectively.

Table 4: Nayak parameters and related parameters.

| Surface number | Nayak parameter | RMS slope | RMS curvature | Average asperity radius of curvature (μm) |
|----------------|-----------------|-----------|---------------|------------------------------------------|
| 1              | Original        | 9.9021    | 0.0957        | 0.0289                                   | 23.0314                                  |
|                | Filtered        | 2.9982    | 0.0742        | 0.0110                                   | 60.2788                                  |
| 2              | Original        | 9.5841    | 0.0960        | 0.0286                                   | 23.2137                                  |
|                | Filtered        | 2.9405    | 0.0749        | 0.0111                                   | 59.7520                                  |
| 3              | Original        | 9.6720    | 0.0959        | 0.0288                                   | 23.0873                                  |
|                | Filtered        | 2.9421    | 0.0743        | 0.0110                                   | 60.1758                                  |

Figure 7: Generation of the rough cone.

According to equation (2) as follows:

\[ h_{k, j} = \sum_{i=1}^{N} \sum_{l=1}^{M} k_{i,j;i+l,j+l}; \quad i = 1, 2, ..., N; \quad j = 1, 2, ..., M \]  

(2)

Here, \( \eta \) is a Gaussian distribution with zero mean value and unit standard deviation. The convolution coefficient \( k \) in equation (3) can be determined through a system of \( n \times m \) nonlinear equations. Here, the nonlinear conjugate gradient method is applied to solve the equations as follows:

\[ R_{p,q} = E(h_{j,i}h_{p,j+q}) = \sum_{k=1}^{n-p} \sum_{l=1}^{m-q} k_{i,j+l,q+l}; \quad p = 1, 2, ..., (n-1); \quad q = 1, 2, ..., (m-1) \]  

(3)

Considering storage space and calculation time, surfaces with 217 × 397 points were generated to represent part of the sealing interface. The horizontal gap between two adjacent points was about 8 μm. Figure 3a presents the surface topography of the generated isotropic surfaces.

To ensure surface smoothness at the small scale, high-frequency signals were removed through a wave-filtering process based on wavelet decomposition (Zhang et al., 2016). Figure 3b presents the 3D rough surface after wave filtering. As shown in Fig. 4, the original surface contains many sharp peaks; this is because the cutoff wavelength (Fig. 5) is so short that a microscale peak only consists of two or three elements. The cutoff wavelength increased significantly after filtering (Fig. 5), making the surface smoother at the small scale (Fig. 4). The shortest wavelength after filtering is about 10 times the smallest element size. A microscale peak consists of 8–10 elements for the filtered surfaces in Fig. 4. As shown in Table 4, the average asperity radius of curvature increases from 23 to 60 μm. Considering the computing costs in ANAYS, a decrease in the element size...
Sealing performance evaluation based on contact analyses

Figure 8: Modifying procedure of the coordinates: \( r_{\text{new},ij}, \theta_{\text{new},ij}, \text{and } z_{\text{new},ij} \) represent the coordinates after modification, and \( \alpha \) is the cone angle.

Figure 9: Multiscale FE model of the cone seal.

Table 5: Mechanical properties of the cone parts.

| Material  | Young’s modulus (MPa) | Poisson’s ratio | Yield strength (MPa) | Tangent modulus (MPa) |
|-----------|-----------------------|----------------|----------------------|-----------------------|
| GH1139    | 209 800               | 0.298          | 345                  | 881.696               |
where $\alpha$ represents the cone angle. The conical surface was discretized into $217 \times 397$ points. The coordinates of the points located in the theoretical cone can be modified according to the corresponding element in matrix $h$. Before beginning the modifying procedure, $h$ should be subtracted from the maximum of $h$ to ensure that there is no excessive penetration before the loading process, as shown in equation (6). The modifying process followed the rules shown in equation (7). Figure 8 shows how a point was modified according to the surface height.

$$h = h - \max(h)$$

$$r_{new, ij} = r_{ij} - h_{ij} \cos \frac{\alpha}{2}$$

$$\theta_{new, ij} = \theta_{ij}$$

$$z_{new, ij} = z_{ij} + h_{ij} \sin \frac{\alpha}{2}$$

With the rough cone, a multiscale FE model containing both macro structural characteristics and surface roughness of the cone seals was established in the commercial HyperMesh FE modeling software (Fig. 9). To reduce the required storage space and solution time, meshes far away from the contact surface had much larger sizes than meshes near the contact surface. The threaded part of cone 1 was not modeled. The element types of cone part 1 and cone part 2 were both hexahedral element SOLID185 with eight nodes. With regard to the sealing interface, the contact pair was established to investigate the contact behavior between two surfaces. The element TARGET170 was selected to represent the target surface, and element CONTACT173 was selected for the rough contact surface. The coefficient of friction between the two cones was defined as 0.1. The augmented Lagrange method was applied in the contact process. The multiscale FE model of the conical seal contained about 940,000 elements. The material for the two cones was a nickel-based superalloy; Table 5 provides the mechanical properties. The bilinear isotropic hardening model was used in the FE model to simulate the deformation of elastic-plastic materials. Figure 9a presents the boundary conditions of the multiscale model. To simulate the supporting effect that the nut provided to cone part 2, nodes on the bottom of cone part 2 were restrained from movement in the $x$, $y$, and $z$ directions. The preloads can be calculated through the sum of axial forces on these fixed nodes. Since it is part of the entire cone seal, symmetry constraints were applied to the left end and right end surfaces of cone part 1 and cone part 2 to restrict displacement along the circumference. An axial displacement was applied on the top surface of cone part 1 to simulate the preload produced by nut rotation during the assembly process.

The FE solving process was implemented in the ANSYS commercial software. The entire analysis used one static load step, which contained 200 substeps. The preconditioned conjugate gradient solver was used to accelerate the convergence.
process. Considering the effect of structural deformation on stiffness during the loading process, the large deformation effect was turned on to model real-world effects. Both the force and the displacement convergence criterion were adopted in the solving process.

5. Multiscale Contact Analyses

5.1 Distribution of contact pressure

During the assembly process of the cone seal, the rotation of the nut will cause a displacement of cone part 1 downward in the axial direction. The continuous downward displacement of cone part 1 will cause mutual compression between the two cones, which can result in the deformation of the asperities located on the sealing surfaces. The contact between the two cones is key to achieve the sealing mechanism of the cone seals. The contact status, which is closely related to the RCA, has a significant effect on the sealing properties of the cone seals. Due to the containing of both structural parameters and surface roughness, the distribution of contact pressure on the sealing interface is nonuniform (Fig. 10).

5.2 RCA

During the assembly process, higher asperities engage in contact earlier. Then, these asperities are squeezed, causing a decrease in the asperity heights. As the height of these

---

**Figure 11:** Evolution of the contact status (the white area represents the contact area).

**Figure 12:** Relationship between RCA and preload.

**Figure 13:** Relationship between slipping distance and preload.
asperities decreases, other asperities with lower height have the opportunity to engage in contact with the opposite side. Figure 11 presents the distribution of the contact status of the simulation results after being processed in the MATLAB software. It is evident that the contact area is smaller than the nominal area, and it increases with increasing preload. The RCA, which is defined as contact area/nominal area, has a significant effect on sealing performance of the cone seals. A common understanding is that a larger RCA means better sealing capabilities under the same conditions. Figure 12 presents the relationship between RCA and preload. The sudden high-speed increase in RCA at the end of the curve is due to slippage between the two cones. The RCA under normal loading was smaller than the RCA under combined normal and tangential loading (Wang et al., 2020). As shown in Fig. 13, slippage remains stable in the initial stage, but suddenly increases when the preload is about 14 000 N. Compared with Fig. 12, the position where the slope of the RCA-preload curve increases quickly is exactly the position where slippage suddenly increases. The slipping phenomenon in this structure accelerates the evolution of the RCA and thus facilitates the formation of the contact interface.

6. Quantitative Evaluation of Sealing Performance

The function of the sealing structure is to prevent leakage of liquid between the interfaces. It is necessary to analyse the contact status of the sealing interface to determine whether there is a leakage channel. Figure 14 presents a schematic illustration of the leakage channels under increasing preload. The black areas provide the basis for the presence of leakage channels. It can be seen from Fig. 14 that at the beginning of the assembly (at small preload), only a small area is in contact, which means that the leakage channel must exist. As the preload increases, the RCA increases and the leakage channels would finally disappear. There is a critical preload during this process, at which point the leakage channel just disappears. In another word, the sealing status changes from leak to sealing at this point. Based on the contact status matrix (shown in Fig. 15), a sealing status judgment procedure is carried out to judge whether there is a leakage channel under the current contact status and output the critical preload. Taking the current model as an example, which has the material properties described in Table 3 and 1-μm RMS roughness, the critical preload is about 15 000 N. The critical preload is an effective index to quantitatively evaluate sealing performance of seals. A smaller critical preload means that the sealing structure would achieve sealing more easily. To some extent, the smaller the critical preload, the better the design of the sealing structure.

7. Effects of Surface Anisotropy on Sealing Performance

In engineering applications, some machining methods, e.g. turning, produce surfaces with anisotropic properties. Researchers usually use the parameter \( \gamma \) to indicate the degree of anisotropic properties via \( \gamma = \beta_x/\beta_y \). Figure 16 compares isotropic and anisotropic rough surfaces. The anisotropic surface has a striped shape while the isotropic surface is uniform in the \( x \) and \( y \) directions. Figure 17 presents the contact status of the surfaces. Under the same preload, the contact status presents obvious striped characteristics for \( \gamma = 1/5 \). Other simulations with \( \gamma = 1/2, 1/3, \) and \( 1/4 \) were also conducted. Figure 18 shows the effects of anisotropy on the evolution of the RCA. The smaller \( \gamma \) results in a greater RCA under the same preload. Figure 19 shows the critical preload required for the structures with different anisotropy to achieve sealing. Structures with smaller \( \gamma \) need smaller critical preloads. Taking the critical preload as the index of sealing performance, the sealing performance of a structure with smaller \( \gamma \) is better than that of a structure with larger \( \gamma \). It should be noted that the effects of anisotropy on sealing performance in our model are not significant. This is mainly because the critical preload appears at the slippage stage (see Figs 18 and 19). The difference in the critical preload axis, which is mapped from the difference in the RCA axis, is not obvious.
Figure 16: Numerically generated rough surfaces with different $1/\gamma$.

Figure 17: Contact status under different preloads for structures with different $1/\gamma$ (the white areas correspond to contact areas).
due to the relatively large slope of the RCA–preload curve at the slippage stage.

8. Effects of Yield Strength on Sealing Performance

As shown in Fig. 20, yield strength ($\sigma_s$) has a significant effect on the relationship between force and deformation because it determines when the material begins to deform plastically. To investigate the effects of yield strength on sealing performance, models with different yield strengths were established to analyse the contact behaviors. Table 6 provides the mechanical parameters of the materials used in this section.

Figure 21 shows the effect of yield strength on RCA. The RCA decreases with increasing yield strength. This is mainly because models with smaller yield strength yield plastically earlier. Figure 22 shows that models with smaller yield strength need a smaller critical preload to achieve sealing. Taking the critical preload as the index of sealing performance, models with smaller yield strength have better sealing performance.

9. Comprehensively Evaluating Sealing Performance

The evaluation of sealing performance should usually be based on multiple parameters, and the proposed index of sealing performance, critical preload, is just one parameter among them. For example, the strength of the structure is another important parameter that should be taken into account. According to the simulation results presented in Section 8, a decrease in yield strength could cause a decrease in critical preload, i.e. improved sealing performance. However, this decrease in yield strength would reduce the allowable stress of the entire sealing structure and thus cause a decrease in the reliability of the sealing structure. Therefore, the critical preload should be used in combination with other indices and their working requirements to comprehensively evaluate the performance of a specific sealing structure. This is the direction of our research group.

Table 6: Mechanical parameters of different materials.

| Material   | Young’s modulus (MPa) | Poisson’s ratio | Yield strength (MPa) | Tangent modulus (MPa) |
|------------|-----------------------|-----------------|----------------------|-----------------------|
| GH1139     | 209800                | 0.298           | 345                  | 881.696               |
| Material 1 | 209800                | 0.298           | 200                  | 881.696               |
| Material 2 | 209800                | 0.298           | 300                  | 881.696               |
| Material 3 | 209800                | 0.298           | 400                  | 881.696               |
| Material 4 | 209800                | 0.298           | 500                  | 881.696               |
Sealing performance evaluation based on contact analyses

10. Conclusions

With the goal of quantitatively evaluating sealing performance, a simulation approach was proposed based on a multiscale elastic–plastic FE contact analysis. The critical preload, calculated from the contact status, was used as the index of sealing performance. The validity of this approach was verified by applying it to a cone seal. The combined normal load and tangential load on the conical sealing interface during the assembly process were simulated by applying an axial displacement on the top surface of the cone seal. The evolution of the RCA with preload was studied in detail. Slippage between sealing surfaces accelerated the evolution of the RCA and thus facilitated the formation of the sealing interface. Taking the critical preload as the evaluation index, the effects of surface anisotropy and yield strength on sealing performance of the cone seals were investigated in detail. Structures with smaller $\gamma$ had a better sealing performance; sealing performance increased with decreasing yield strength. The critical preload should be used in combination with other indices and their working requirements to comprehensively evaluate the performance of a specific sealing structure.

Acknowledgment

This work was supported by the National Natural Science Foundation of China (grant numbers 51975055 and 51935003).

Conflict of interest statement

None declared.

References

Belforte, G., Conte, M., Bertetto, A. M., Mazza, L., & Visconte, C. (2009). Experimental and numerical evaluation of contact pressure in pneumatic seals. Tribology International, 42(1), 169–175. https://doi.org/10.1016/j.triboint.2008.04.010.

Bottiglione, F., Carbone, G., Mangialardi, L., & Mantriota, G. (2009). Leakage mechanism in flat seals. Journal of Applied Physics, 106(10), 104902. https://doi.org/10.1063/1.3254187.

Chen, Z., Liu, T., & Li, J. (2016). The effect of the O-ring on the end face deformation of mechanical seals based on numerical simulation. Tribology International, 97, 278–287. https://doi.org/10.1016/j.triboint.2016.01.038.

Chen, W., Di, Q., Zhang, H., Chen, F., & Wang, W. (2018). The sealing mechanism of tubing and casing premium threaded connections under complex loads. Journal of Petroleum Science and Engineering, 171, 724–730. https://doi.org/10.1016/j.petrol.2018.07.079.

Dapp, W. B., Lücke, A., Persson, B., & Müser, M. (2013). Self-affine elastic contacts: Percolation and leakage.

Haruyama, S., Nurhadiyanto, D., Choiron, M. A., & Kaminishi, K. (2013). Influence of surface roughness on leakage of new metal gasket. International Journal of Pressure Vessels and Piping, 111–112, 146–154. https://doi.org/10.1016/j.ijpvp.2013.06.004.

Hu, Y. Z., & Tonder, K. (1992). Simulation of 3-D random rough surface by 2-D digital filter and Fourier analysis. International Journal of Machine Tools and Manufacture, 32(1), 83–90. https://doi.org/10.1016/0890-6955(92)90064-N.

Hu, G., Zhang, P., Wang, G., Zhang, M., & Li, M. (2017). The influence of rubber material on sealing performance of packing element in compression packer. Journal of Natural Gas Science and Engineering, 38, 120–138. https://doi.org/10.1016/j.jngse.2016.12.027.

Jianjun, S., Chenbo, M., Jianhua, L., & Qiuping, Y. (2018). A leakage channel model for sealing interface of mechanical face seals based on percolation theory. Tribology International, 118, 108–119. https://doi.org/10.1016/j.triboint.2017.09.013.

Krishna, M. M., Shunmugam, M. S., & Prasad, N. S. (2007). A study on the sealing performance of bolted flange joints with gaskets using finite element analysis. International Journal of Pressure Vessels and Piping, 84(6), 349–357.

Liao, D., Shao, W., Tang, J., & Li, J. (2018). An improved rough surface modeling method based on linear transformation technique. Tribology International, 119, 786–794. https://doi.org/10.1016/j.triboint.2017.12.008.

Liao, B., Sun, B., Li, Y., Yan, M., Ren, Y., Feng, Q., Yang, D., & Zhou, K. (2019). Sealing reliability modeling of aviation seal based on interval uncertainty method and multidimensional response surface. Chinese Journal of Aeronautics, 32(9), 2188–2198. https://doi.org/10.1016/j.cja.2019.01.019.
Patir, N. (1978). A numerical procedure for random generation of random surfaces of significance in their contact. *Journal of Physics: Condensed Matter*, 15(8), S840–S861. https://doi.org/10.1088/0953-8984/15/1/S21.

Perronson, B. N. J. (2001). Theory of rubber friction and contact mechanics. *The Journal of Chemical Physics*, 115(8), 3840–3861. https://doi.org/10.1063/1.1388626.

Lorenz, B., & Perrsonson, B. N. J. (2010). Leak rate of seals: Effective-medium theory and comparison with experiment. *The European Physical Journal E*, 31(2), 159–167. https://doi.org/10.1140/epje/i2010-10558-6.

Luyt, P. C. B., Theron, N. J., & Pietra, F. (2017). Non-linear finite element modelling and analysis of the effect of gasket creep-relaxation on circular bolted flange connections. *International Journal of Pressure Vessels and Piping*, 150, 52–61. https://doi.org/10.1016/j.ijpvp.2016.12.001.

Manesh, K. K., Ramamoorthy, B., & Singaperumal, M. (2010). Numerical generation of anisotropic 3D non-Gaussian engineering surfaces with specified 3D surface roughness parameters. *Wear*, 268(11), 1371–1379. https://doi.org/10.1016/j.wear.2010.02.005.

Mathan, G., & Prasad, S. N. (2011). Studies on gasketed flange joints under bending with anisotropic Hill plasticity model for gasket. *International Journal of Pressure Vessels and Piping*, 88(11), 495–500. https://doi.org/10.1016/j.ijpvp.2011.07.010.

Nelson, N. R., & Prasad, S. N. (2016). Sealing behavior of twin gasketed flange joints. *International Journal of Pressure Vessels and Piping*, 138, 45–50. https://doi.org/10.1016/j.ijpvp.2016.01.001.

Nelson, N. R., Siva Prasad, N., & Sekhar, A. S. (2017). Studies on joint strength and sealing behavior of single and twin-gasketed flange joints. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, 232(4), 480–492. https://doi.org/10.1080/09544089177181598.

Patir, N. (1978). A numerical procedure for random generation of rough surfaces. *Wear*, 47(2), 263–277. https://doi.org/10.1016/0043-1648(78)90157-6.

Perronson, B. N. J. (2001). Theory of rubber friction and contact mechanics. *The Journal of Chemical Physics*, 115(8), 3840–3861. https://doi.org/10.1063/1.1388626.

Perronson, B. N. J., Albohr, O., Tartaglino, U., Volokitin, A. I., & Tosatti, E. (2004). On the nature of surface roughness with application to contact mechanics, sealing, rubber friction and adhesion. *Journal of Physics: Condensed Matter*, 17(1), R1–R62. https://doi.org/10.1088/0953-8984/17/1/R01.

Perronson, B. N. J., & Yang, C. (2008). Theory of the leak-rate of seals. *Journal of Physics: Condensed Matter*, 20(31), 315011. https://doi.org/10.1088/0953-8984/20/31/315011.

Puccio, F. D., Ciulli, E., & Squarcini, R. (2006). Comparison of two sealing coupling geometries for a direct fuel injector. *Tribology International*, 39(8), 781–788.

Shuai, Z., Sier, D., Wenhu, Z., & Naizheng, K. (2019). Simulation and experiment on sealing mechanism with rigid-flexible combined seal groove in hub bearing. *Tribology International*, 136, 385–394. https://doi.org/10.1016/j.triboint.2019.04.005.

Sui, F. C., & Anderle, S. (2011). Optimization of contact pressure profile for performance improvement of a rotary elastomeric seal operating in abrasive drilling environment. *Wear*, 271(9), 2466–2470. https://doi.org/10.1016/j.wear.2011.02.021.

Wang, W., & Liu, Y. (2015). Analysis of the sealing performance and creep behavior of the inner casing of a 1000MW supercritical steam turbine under bolt relaxation. *Engineering Failure Analysis*, 57, 363–376. https://doi.org/10.1016/j.engfailana.2015.08.012.

Wang, X., An, B., Xu, Y., & Jackson, R. L. (2020). The effect of resolution on the deterministic finite element elastic-plastic rough surface contact under combined normal and tangential loading. *Tribology International*, 144, 106141. https://doi.org/10.1016/j.triboint.2019.106141.

Watson, M., Lewis, R., & Slatter, T. (2020). Improvements to the linear transform technique for generating randomly rough surfaces with symmetrical autocorrelation functions. *Tribology International*, 151, 106487. https://doi.org/10.1016/j.triboint.2020.106487.

Wen, J. C. Y. (2006). Simulation and experimentation on the contact width and pressure distribution of lip seals. *Tribology International*, 39, 915–920.

Wenk, J. F., Stephens, L. S., Lattime, S. B., & Weatherly, D. (2016). A multi-scale finite element contact model using measured surface roughness for a radial lip seal. *Tribology International*, 97, 288–301. https://doi.org/10.1016/j.triboint.2016.01.035.

Whitehouse, D. J., Archard, J. F., & Tabor, D. (1970). The properties of random surfaces of significance in their contact. *Proceedings of the Royal Society of London A. Mathematical and Physical Sciences*, 316(1524), 97–121. https://doi.org/10.1098/rspa.1970.0068.

Wu, J.-J. (2000). Simulation of rough surfaces with FFT. *Tribology International*, 33(1), 47–58. https://doi.org/10.1016/S0301-679X(00)00016-5.

Yan, Y., Zhai, J., Gao, P., & Han, Q. (2018). A multi-scale finite element contact model for seal and assembly of twin ferrule pipeline fittings. *Tribology International*, 125, 100–109. https://doi.org/10.1016/j.triboint.2018.04.028.

Yastrebov, V. A., Anciaux, G., & Molinari, J.-F. (2015). From infinitesimal to full contact between rough surfaces: Evolution of the contact area. *International Journal of Solids and Structures*, 52, 83–102. https://doi.org/10.1016/j.ijsolsstr.2014.09.019.

Zhang, F., Liu, J., Ding, X., & Yang, Z. (2016). An approach to calculate leak channels and leak rates between metallic sealing surfaces. *Journal of Tribology*, 139(1), 011708. https://doi.org/10.1115/1.4033887.

Zhang, J., & Hu, Y. (2020). Sealing performance and mechanical behavior of PEMFCs sealing system based on thermodynamic coupling. *International Journal of Hydrogen Energy*, 45(43), 23480–23489. https://doi.org/10.1016/j.ijhydene.2020.06.167.

Zhou, Y., Huang, Z., Tan, L., Ma, Y., Qiu, C., Zhang, F., Yuan, Y., Sun, C., & Guo, L. (2014). Cone bit bearing seal failure analysis based on the finite element analysis. *Engineering Failure Analysis*, 45, 292–299. https://doi.org/10.1016/j.engfailanal.2014.07.007.

Zhou, C., Zheng, J., Gu, C., Zhao, Y., & Liu, P. (2017). Sealing performance analysis of rubber O-ring in high-pressure gaseous hydrogen based on finite element method. *International Journal of Hydrogen Energy*, 42(16), 11996–12004. https://doi.org/10.1016/j.ijhydene.2017.03.039.