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Enhanced Reliability of Composite Pistons: A Study on Fretting Damage

Mechanics, Materials & Coatings

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ABSTRACT

Composite pistons, as critical components in high-power engines, rely on the structural integrity of the piston crown-skirt interface, which is subject to complex alternating loads during operation. Fretting wear and fatigue damage frequently occur at this interface due to high stress concentrations, posing significant risks to engine reliability and safety. Traditional finite element simulations combined with fatigue criteria often fail to capture the effects of actual surface roughness and the resulting stress variations on fretting behavior.

This study develops a semi-analytical elastoplastic contact model for the piston crown-skirt interface, integrating boundary element method (BEM) and finite element method (FEM). The model incorporates fast fourier transform (FFT) and the conjugate gradient method (CGM) to simulate the effects of actual surface roughness, preload forces, and taper angles on contact pressure, tangential stress, and slip zone distribution. Results indicate that increasing the preload force enhances contact pressure uniformity and reduces slip zones, thereby mitigating fretting damage. Conversely, larger taper angles cause uneven contact pressure distribution and expand slip zones, exacerbating fretting wear. Findings reveal that surface asperities significantly amplify stress concentrations, with maximum stresses located subsurface or near-surface depending on load conditions. Prolonged fretting exposure accelerates surface degradation, increasing the likelihood of fatigue crack initiation and propagation.

In conclusion, the proposed elastoplastic rough contact model provides a comprehensive understanding of the fretting contact behavior at the crown-skirt interface, offering valuable insights into mitigating fretting wear and optimizing composite piston design. These findings contribute to improving the durability and reliability of high-power diesel engines, ensuring safer and more efficient operations.

1 INTRODUCTION

The fretting contact phenomena at the piston crown-skirt joint are critical in determining the reliability of high-power diesel engines. Fretting damage manifests as wear and fatigue failure at the interface, leading to micro-cracks that remain undetected until catastrophic failure occurs. This failure mode is exacerbated by the increasing power density demands of modern engines, making fretting damage a dominant issue in piston reliability[1].

The piston crown-skirt joint—a critical structural component in composite pistons—experiences alternating high-temperature and high-pressure loads during operation. These operating conditions amplify stress concentrations at the joint interface, particularly at surface asperities, which significantly influence fretting behavior. Fretting damage emerges gradually, with fatigue-induced micro-cracks often concealed beneath the surface, making early detection difficult. The reliability and safety of high-power engines depend heavily on understanding and mitigating this damage mechanism.

Previous studies primarily relied on Finite Element Method (FEM) simulations to analyze fretting damage, focusing on idealized smooth surfaces. However, such approaches fail to accurately capture the effects of actual surface roughness and complex contact states under operating conditions. Surface roughness introduces localized stress variations and micro-slip zones, significantly impacting wear and fatigue characteristics. This gap in understanding necessitates advanced modeling techniques to address real surface conditions and improve fretting damage prediction.

This study introduces a semi-analytical Boundary Element Method (BEM) approach, combined with Fast Fourier Transform (FFT), to model the rough contact behavior at the piston crown-skirt interface. The elastoplastic fretting contact model incorporates surface asperities, pretension forces, and taper angles to evaluate their combined effects on contact pressure, slip zones, and crack propagation. By bridging the gap between theoretical modeling and practical applications, this research aims to enhance the reliability of composite pistons and inform the design of more durable engine components. The findings provide valuable insights into optimizing surface engineering and structural design for mitigating fretting damage in high-power diesel engines.

2 ELASTOPLASTIC FRETTING CONTACT MODEL

High-power marine diesel engine pistons typically feature a tapered profile on the skirt side of the crown-skirt joint to accommodate deformation of the piston crown. Under bolt pretension, the crown initially contacts the inner tapered surface of the skirt. During operation, thermal and mechanical loads deform the piston crown, causing it to contact the outer surface of the skirt taper. This study uses an equivalent elastoplastic rough surface model to analyze contact characteristics under normal and tangential loads, as illustrated in Fig. 1.

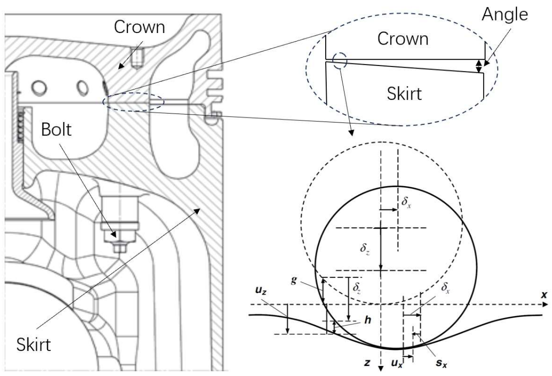


Figure 1. Contact model between the piston crown and skirt

2.1 Normal Contact Model

The geometric constraints of the contact gap between the two surfaces are described as

$$h = g + u_z - \delta_z \quad (1)$$

where g is the initial gap, u_z is the normal deformation comprising elastic and plastic components, and δ_z is the normal rigid-body displacement. In the contact and non-contact regions, the gap and normal contact pressure satisfy:

$$\begin{cases} h(i,j) = 0, p(i,j) > 0, (i,j) \in \Omega_c \\ h(i,j) > 0, p(i,j) = 0, (i,j) \notin \Omega_c \end{cases} \quad (2)$$

2.2 Tangential Contact Model

Tangential stresses q and slip follow Coulomb's friction law. The contact region is divided into stick Ω_{st} and slip Ω_{sl} zones:

$$\begin{cases} q = \sqrt{q_x^2 + q_y^2} \le \mu p, \sqrt{s_x^2 + s_y^2} = 0, (x,y) \in \Omega_{st} \\ q = \sqrt{q_x^2 + q_y^2} = \mu p, \sqrt{s_x^2 + s_y^2} \ge 0, (x,y) \in \Omega_{sl} \end{cases} \quad (3)$$

where μ is the friction coefficient, and s_x , s_y represents relative slip, and is calculated as:

$$\begin{bmatrix} s_x \\ s_y \end{bmatrix} = \begin{bmatrix} u_x \\ u_y \end{bmatrix} - \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix} \quad (4)$$

Here, u_x and u_y are deformations, δ_x and δ_y and are rigid-body displacements.

2.3 Influence Coefficients

Elastic deformation at a surface point due to normal pressure and tangential stresses is expressed using Boussinesq-Cerruti integrals:

$$\begin{aligned} u_x(x,y) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \big[& G_{xx}(x-x',y-y')q_x(x',y') \\ & + G_{xy}(x-x',y-y')q_y(x',y') \\ & + G_{xz}(x-x',y-y')p(x',y')\big]\,dx'dy' \\ & = G_{xx} * q_x + G_{xy} * q_y + G_{xz} * p \end{aligned}$$

$$u_y(x,y) = G_{yx} * q_x + G_{yy} * q_y + G_{yz} * p \quad (5)$$

$$u_z(x,y) = G_{zx} * q_x + G_{zy} * q_y + G_{zz} * p$$

Here, G_{mn} represents Green's functions, and $*$ denotes convolution. For detailed derivations, refer to the cited literature[2].

2.4 Stress Calculation

The stress is determined using the BEM-FEM coupling method, applying Von-Mises yield criteria and a bilinear kinematic hardening plasticity model. Contact pressures and tangential stresses from the BEM contact model serve as boundary conditions for FEM analysis.

3 NUMERICAL SOLUTION PROCEDURE

The BEM-FEM coupling integrates FFT and CGM to solve contact deformation and stress distribution iteratively[3]. The numerical procedure involves:

1. Initialization: Initialize contact pressure p and tangential stresses q.
2. Displacement Computation: Use FFT to calculate normal and tangential displacements.
3. Residual Update: Compute residuals r for normal and tangential contact conditions.
4. Conjugate Gradient Update: Adjust the conjugate gradient direction d based on residuals.
5. Step Size Calculation: Compute step size α using FFT.
6. Contact Pressure Update: Update p and q iteratively.
7. Constraint Enforcement: Enforce complementarity conditions and adjust pressures exceeding material hardness.

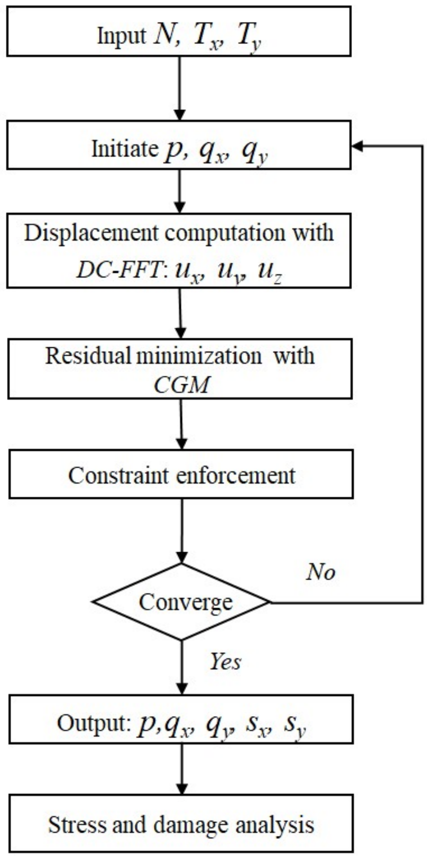
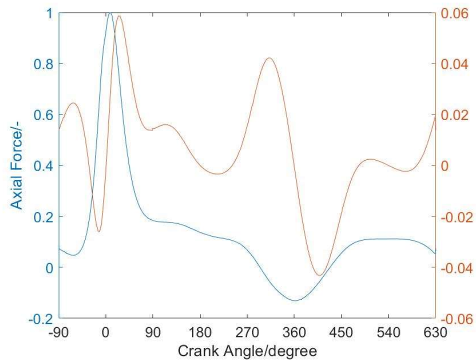


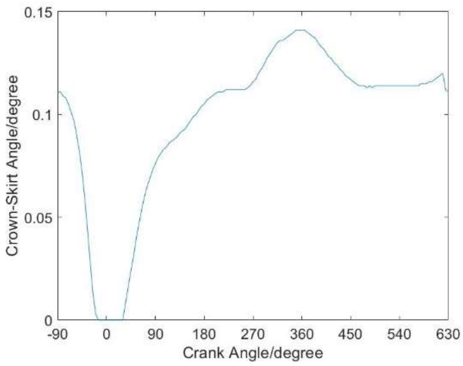
Figure 2. BEM-FEM coupling fretting contact solver procedure

4 WORKING LOAD ANALYSIS

During piston operation, the combustion pressure, inertia forces, and lateral forces act on the piston, while the friction between the piston and cylinder liner is neglected. The inertia and lateral forces are determined through piston dynamics calculations, while the axial force is derived by combining combustion pressure and inertia forces. The non-dimensional forces are shown in Fig. 3(a), where the crank angle of 0° corresponds to the top dead center (TDC). The crown-skirt joint angle varies cyclically under these alternating loads. Finite element analysis of the coupled thermal-mechanical behavior of the piston reveals the angle variation over time, as shown in Fig. 3(b). At TDC, the axial load is at its maximum, and the crown-skirt joint angle reaches its minimum of 0°. The angle variation trend is inversely related to the axial force.



(a) Piston Force



(b) Piston Crown-Skirt Angle

Figure 3. Piston Force and Crown-Skirt Angle Variation

5 FRETTING BEHAVIOR ANALYSIS

5.1 Model Inputs

The material model parameters, coefficient of friction, and surface roughness used in this model was provided in the Table 1.

Table 1. Main input parameters

Item	value
Elastic modular of crown/ GPa	212
Poisson's ratio of crown/ -	0.3
Elastic modular of skirt/ GPa	180
Poisson's ratio of skirt/ -	0.3
Friction coefficient/ -	0.2
Surface Roughness Ra / μ m	1.6

5.2 Contact State Evolution Under Piston Working Loads

Utilizing the established elastoplastic fretting contact model, this study examines the contact behavior of the piston crown-skirt joint under realistic operational loads. The analysis focuses on two significant crank angles: 0° (Top Dead Center, TDC) and 315°, which are associated with the maximum axial and lateral forces, respectively. The research examines a 2 mm × 2 mm area adjacent to the bolt hole, which is susceptible to fretting damage as a result of localized stress concentrations. The identification of this contact region was informed by a macro-scale contact analysis of the piston crown and skirt, as well as field testing as in Fig. 4.

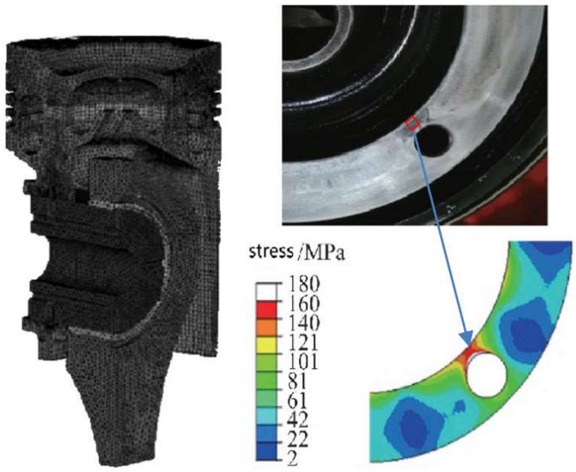
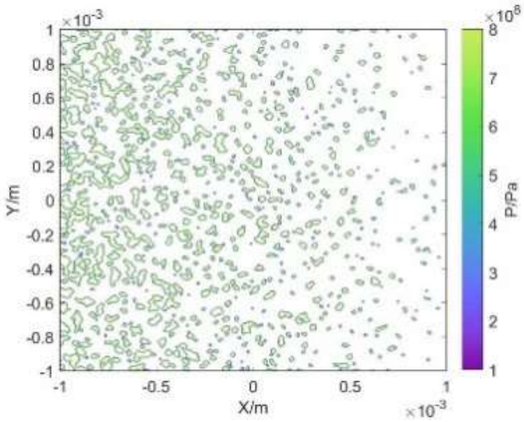
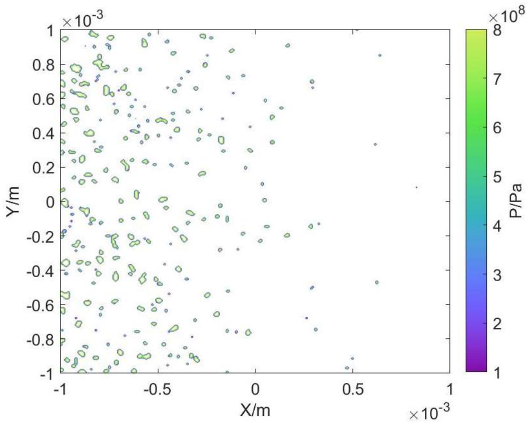


Figure 4. Macro contact analysis



(a) Crank angle 0°

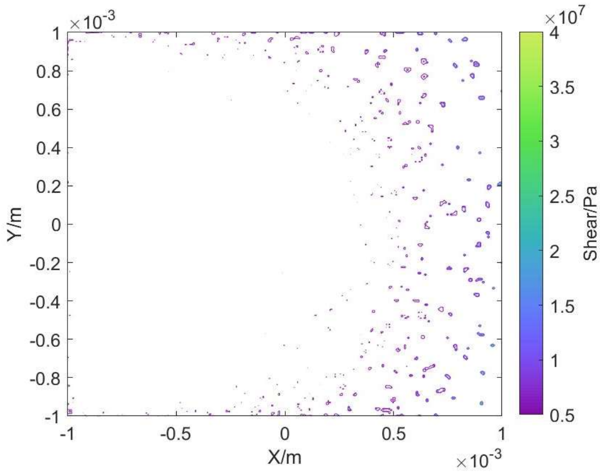


(b) Crank angle 315°

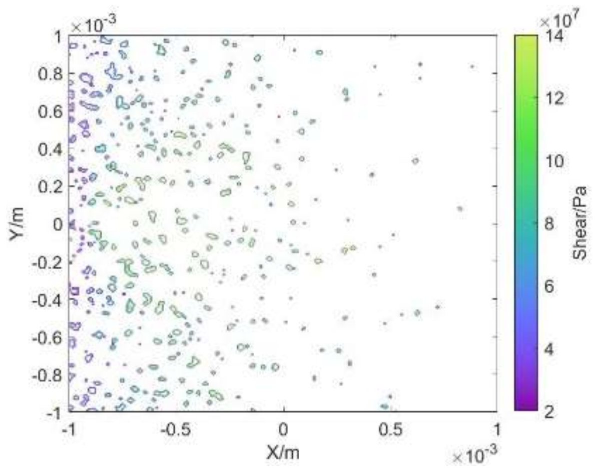
Figure 5. Normal Pressure Comparison

At TDC (0° crank angle), the axial force is at its maximum, resulting in elevated normal contact pressure over a wider surface area. In contrast, the tangential load remains minimal, leading to reduced shear stresses and negligible slip zones. Figure 5a illustrates that the normal pressure is uniformly distributed across the contact surface at this stage.

At a crank angle of 315°, lateral forces dominate while axial forces significantly decrease. Consequently, as shown in Figure 5b, the contact pressure becomes concentrated in smaller regions on the left side of the contact interface. The diminished normal force facilitates slip across the interface, especially on the right-hand side.



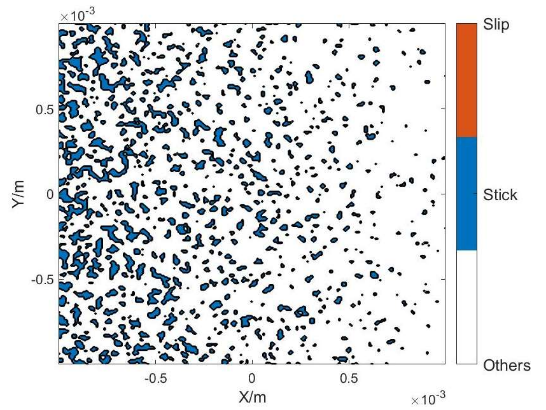
(a) Crank angle 0°



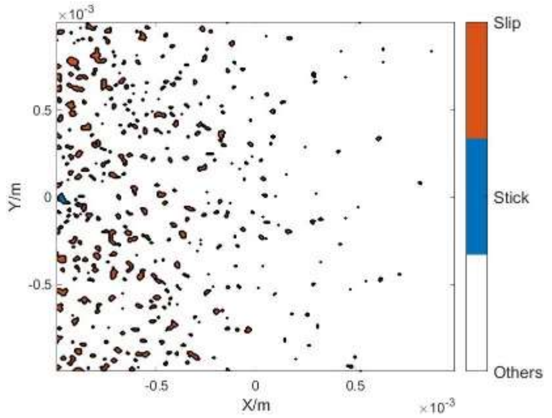
(b) Crank angle 315°

Figure 6. Tangential Stress Comparison

Figure 6 compares tangential stress distributions for the two crank angles. At TDC, tangential stress is minimal due to the limited lateral forces. However, at 315°, tangential stress increases substantially, exceeding the frictional limits in several regions and resulting in extensive slip zones (Figure 7b). This phenomenon underscores the higher susceptibility to fretting wear during the downward stroke.



(a) Crank angle 0°

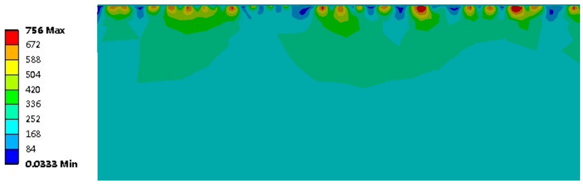


(b) Crank angle 315°

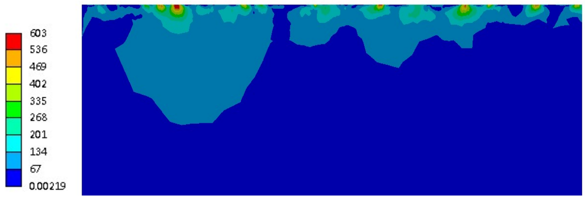
Figure 7. Stick-Slip Zone Comparison

When considering the effect of surface roughness, the stress distribution becomes significantly non-uniform, as stress concentrations are observed at surface asperities in Figure 8. These asperities amplify the local stress, with the maximum Von-Mises stress often located slightly below the surface, referred to as the subsurface region. This subsurface stress peak is attributed to the interaction between normal and tangential loads, combined with the elastic-plastic deformation behavior of the rough contact surface.

At 315° crank angle, the combination of reduced normal pressure and increased tangential loads further enhances shear stress near the surface. This condition results in higher Von-Mises stresses at or close to the surface layer, shifting the maximum stress location from the subsurface to the near-surface region. The stress concentration at asperities under these conditions suggests a higher risk of surface-level material damage, such as micro-crack initiation or fretting wear.



(a) Crank angle 0°



(b) Crank angle 315°

Figure 8. Von-Mises Stress Comparison

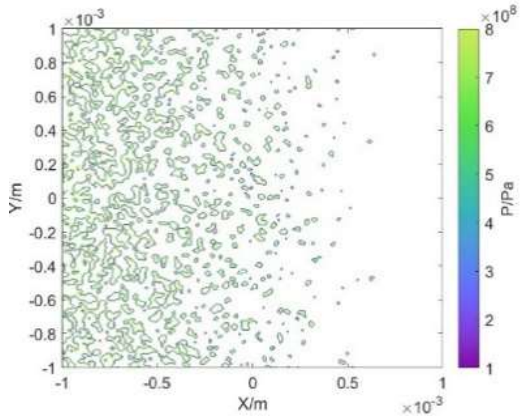
5.3 Effect of Pretension Force and Taper Angle

The influence of pretension force and taper angle on the contact characteristics of the piston crown-skirt joint was investigated under rough surface conditions. This analysis evaluates the effects of these parameters on contact pressure distribution, tangential stress, and stick-slip behavior, providing a scientific basis for optimizing joint design and mitigating fretting damage.

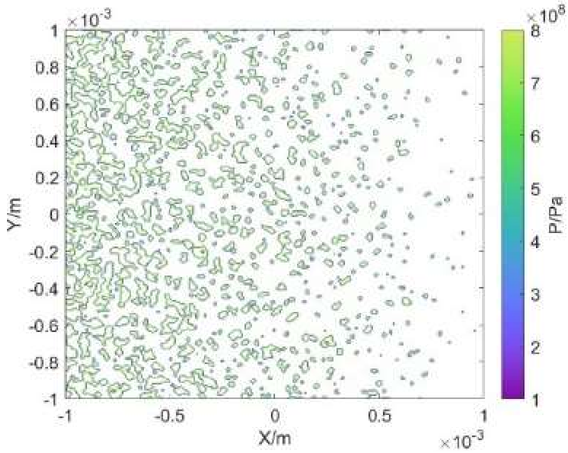
5.3.1 Effect of Taper Angle

The taper angle of the crown-skirt joint is a key parameter influencing contact pressure distribution and stick-slip behavior. Simulations were performed for taper angles of 0.25°, 0.15°, and 0°, using a normal load of 500 N and a tangential load of 35 N. The following observations were made:

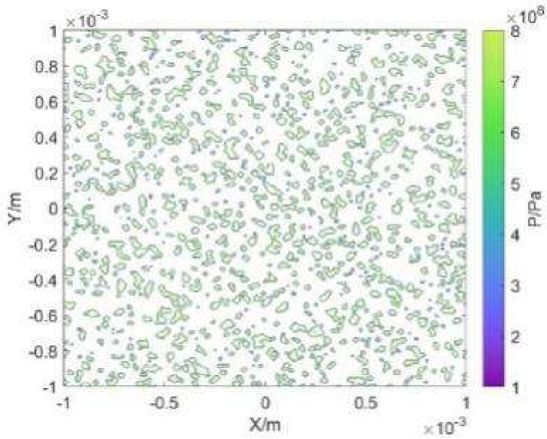
At a taper angle of 0.25°, the contact pressure is concentrated on the left side of the interface, leaving the right side under low pressure, as shown in Figure 9a. This uneven distribution results in extensive slip zones, increasing the likelihood of fretting damage. Reducing the taper angle to 0.15° improves the contact pressure distribution, expanding the contact area and reducing the extent of slip zones (Figure 9b). However, small slip zones persist near the far-right edge of the interface. For an ideal flat surface (0° taper angle), the contact pressure is distributed uniformly across the interface, effectively eliminating slip zones (Figure 9c). This uniform distribution minimizes stress concentrations and significantly reduces fretting wear risks.



(a) Taper 0.25°



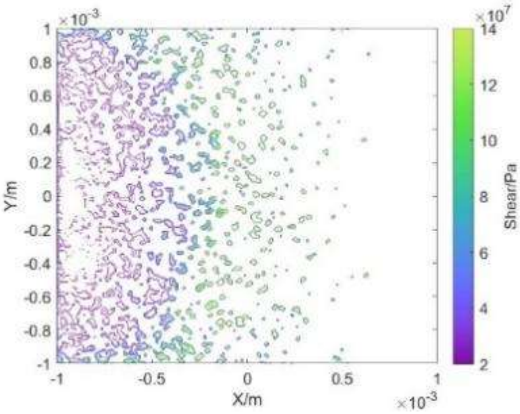
(b) Taper 0.15°



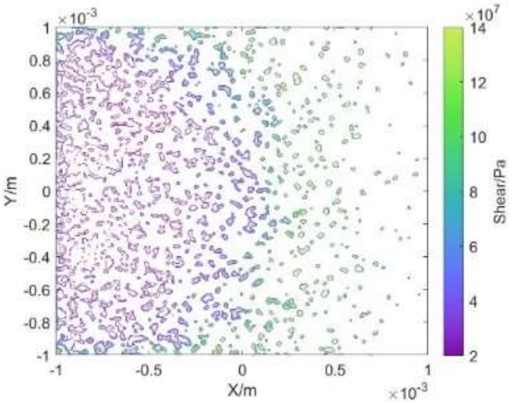
(c) Taper 0°

Figure 9. Normal Pressure Comparison by Taper Angle

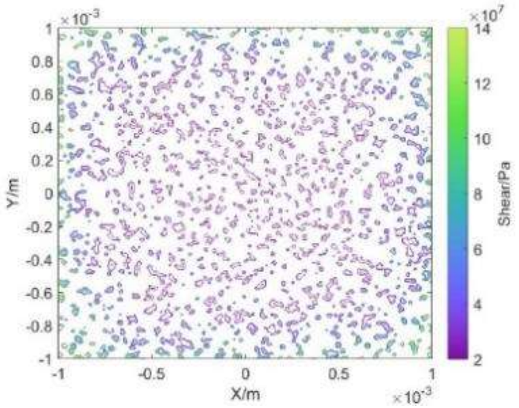
As the taper angle decreases, tangential stress concentrations diminish, and the stick regions become more dominant. Figures 10 and 11 illustrate that the reduction in taper angle leads to improved contact, with minimal slip zones observed for the flat surface (0° taper angle).



(a) Taper 0.25°

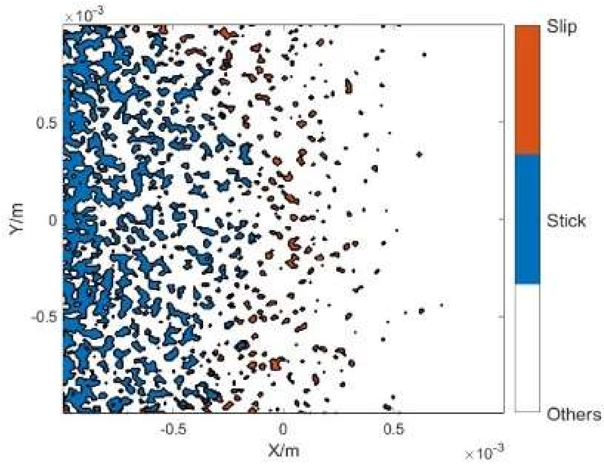


(b) Taper 0.15°

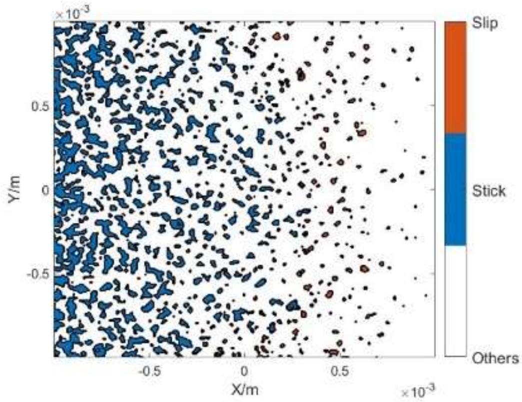


(c) Taper 0°

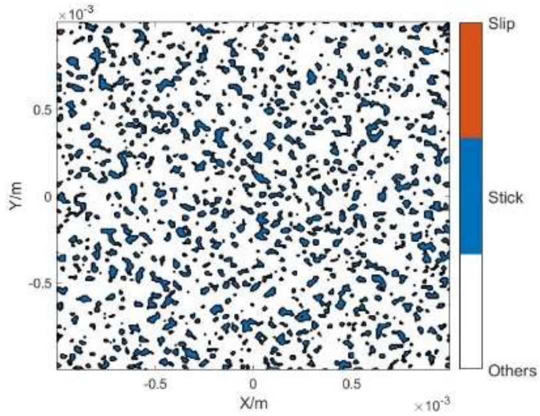
Figure 10. Tangential Stress Comparison by Taper Angle



(a) Taper 0.25°



(b) Taper 0.15°



(c) Taper 0°

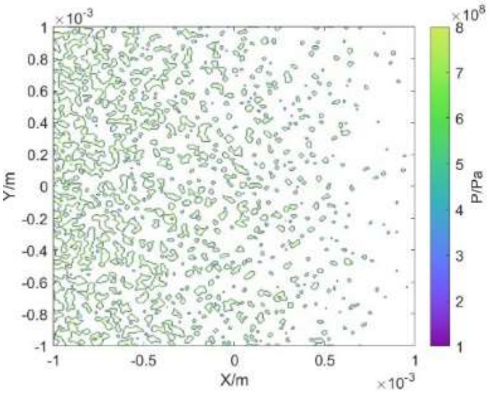
Figure 11. Stick-Slip Zone Comparison by Taper Angle

Decreasing the taper angle improves contact and reduces slip zones, thereby enhancing fretting resistance. While an ideal flat surface (0° taper) offers the best performance, slight taper angles (e.g., 0.15°) may be necessary to accommodate manufacturing tolerances and thermal deformation without significantly compromising performance.

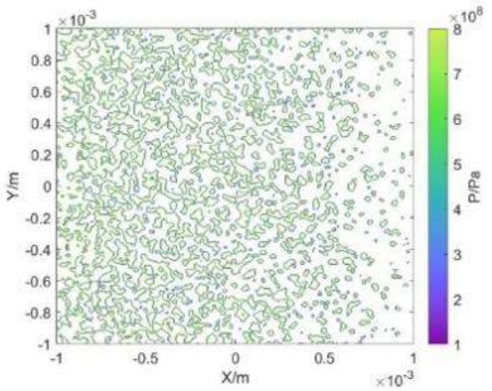
5.3.2 Effect of Pretension Force

The pretension force is another critical factor in determining the contact interface, as it directly affects the contact area, pressure distribution, and the extent of stick-slip zones. Numerical simulations were conducted for normal loads of 500 N, 1000 N, and 2000 N, combined with a tangential load of 35 N, under a taper angle of 0.15°. The results are summarized as follows:

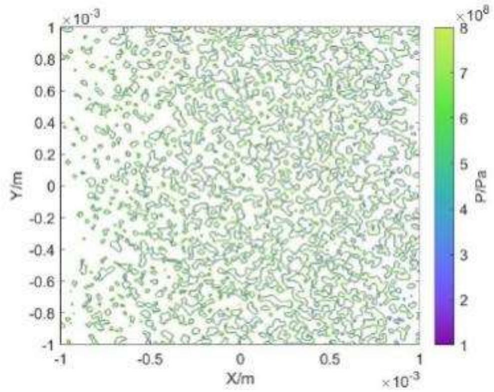
At a normal load of 500 N, the contact pressure is localized on the left side of the interface, with substantial areas on the right exhibiting low pressure. This uneven distribution leads to pronounced slip zones, as shown in Figure 12a. With an increase in pretension force to 1000 N, the contact area expands, resulting in a more uniform pressure distribution and a notable reduction in slip zones (Figure 12b). When the pretension force is further increased to 2000 N, the contact pressure approaches the material's elastic limit, inducing localized plastic deformation on the left side of the interface. Under this condition, slip zones are almost completely eliminated, achieving a near-stick contact state (Figure 12c).



(a) 500 N



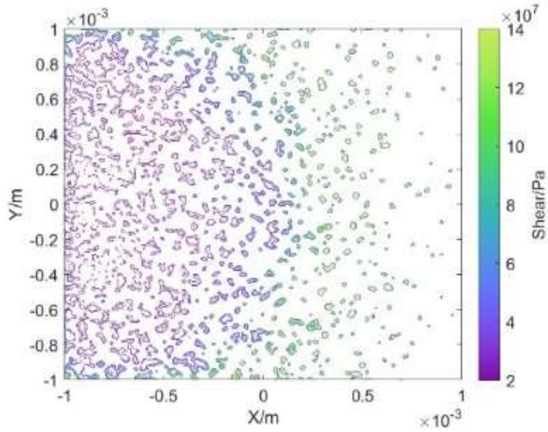
(b) 1000 N



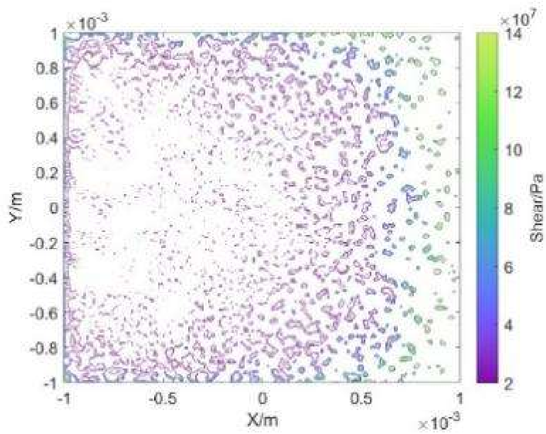
(c) 2000 N

Figure 12. Normal Pressure Comparison by Pretension Force

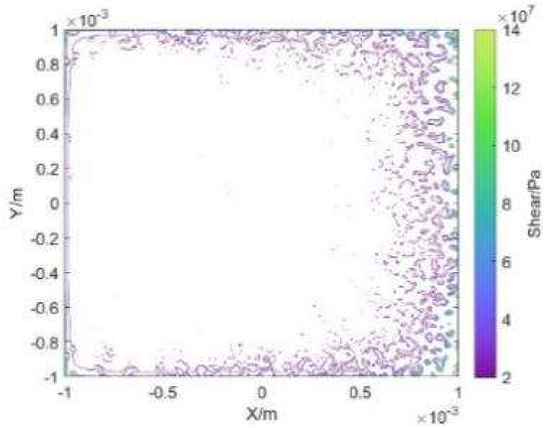
Higher pretension forces reduce tangential stress concentrations and minimize slip regions. As shown in Figures 13 and 14, the slip zones progressively decrease with increasing pretension force, and at 2000 N, the interface achieves a fully stick condition.



(a) 500 N

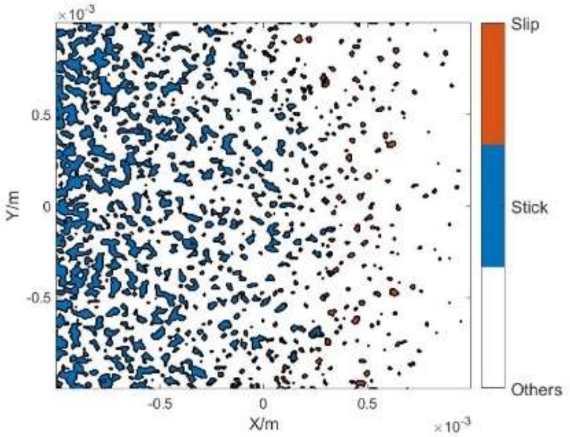


(b) 1000 N

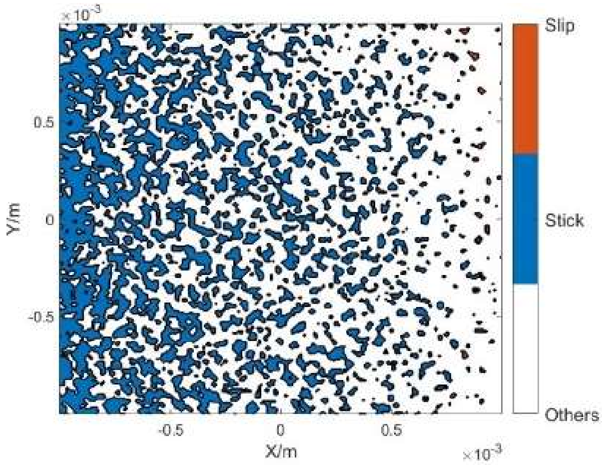


(c) 2000 N

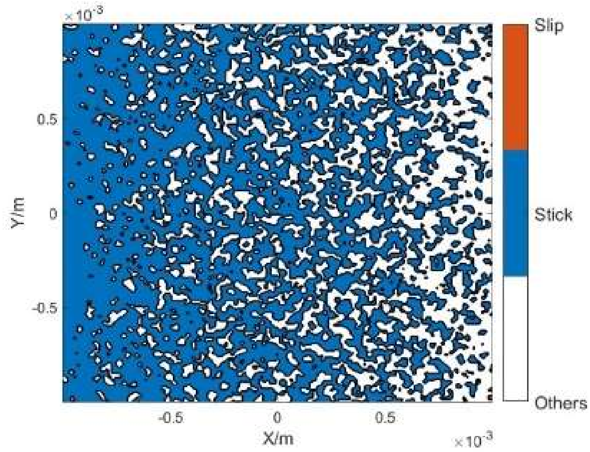
Figure 13. Tangential Stress Comparison by Pretension Force



(a) 500 N



(b) 1000 N



(c) 2000 N

Figure 14. Stick-Slip Zone Comparison by Pretension Force

Increasing pretension force significantly enhances the uniformity of contact pressure, reduces slip zones, and mitigates fretting damage risks. Excessively high pretension forces may lead to localized plastic deformation. Thus, careful optimization is required.

6 CONCLUSIONS

This study developed an elastoplastic fretting contact analysis model for the rough piston crown-skirt joint based on the BEM-FEM coupling method. The model accounts for rough surface asperities and material elastoplastic behavior. By integrating a semi-analytical BEM approach with Fast Fourier Transform (FFT) and the Conjugate Gradient Method (CGM), the contact pressure, tangential stress, and fretting contact characteristics of rough surfaces were simulated. The FEM model further evaluated the stress distribution under actual engine operating conditions.

The model was applied to analyze fretting contact behavior under realistic piston load spectra, providing insights into contact states during an engine cycle. The effects of pretension force and taper angle on contact characteristics were also investigated. Results indicate that taper angle significantly affects contact area and pressure distribution. Excessive taper increases uneven pressure distribution and slip zones, while reduced taper and higher pretension force increase contact area and reduce slip zones. Proper taper selection improves fretting contact states, mitigating fretting wear and fatigue risks. These findings provide a solid foundation for optimizing piston design and enhancing the reliability of composite pistons in diesel engines.

In this study, the loading history were discretized into multiple load steps and conducted a quasi-steady-state analysis to approximate the fretting behavior. Transient effects should be included in future study to allow for a more comprehensive evaluation of the cyclic sliding behavior.

7 REFERENCES

[1] Tang Yihu, Wu Limin; Liang Gang. Tribological Development of Piston Assembly in Marine Diesel Engines Based on Analysis and Experimental Verification. CIMAC World Congress on Combustion Engine, 29th, Vancouver, BC, CA.2019.

[2] Chen WW, Wang QJ. A numerical model for the point contact of dissimilar materials considering tangential tractions. MECHANICS OF MATERIALS. 2008;40(11):936-48.

[3] Polonsky I A, Keer L M. A numerical method for solving rough contact problems based on the multi-level multi-summation and conjugate gradient techniques[J]. Wear, 1999, 231(2): 206–219.