

Gear Pump Seal Performance Analysis Incorporating Non-Linear Gasket Behavior

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Abstract:

Introduction: Gasket is a key sealing structure in industrial equipment, and its performance and reliability are increasingly required in modern industry. High performance gaskets have complex nonlinear behavior, and new numerical tools need to be developed to simulate their characteristics. This paper takes gear oil pump as the research object, analyzes the nonlinear behavior of gear oil pump gasket, reveals its loading and unloading characteristics, and provides a theoretical basis for the design of sealing elements. This research is helpful to deepen the understanding of gasket sealing mechanism and improve sealing performance and reliability.

Objectives: By studying the sealing performance and developing a new numerical calculation method, the sealing performance of gaskets can be accurately predicted and its nonlinear behavior can be fully considered.

Methods: Numerical simulation and finite element analysis were carried out on the research object. This article uses rubber based composite gaskets and incorporates their loading unloading curves into the numerical model to improve computational efficiency and convergence. The pump body, pump cover, and bolts adopt hexahedral and tetrahedral grids respectively, while the gasket adopts a single-layer grid. The boundary conditions include fixed constraints, bolt pre tightening force applied step by step, and internal pressure. The post-processing stage mainly analyzes the deformation, stress distribution, contact surface details of each component, as well as the closure and pressure characteristics of the gasket.

Results: Under the action of preloading force alone, the deformation of gasket is concentrated around the bolt hole. At the same time, when the internal pressure is applied, the total deformation of gasket is significantly increased, and the central area is obviously thickened. The normal pressure is higher when only the preload force is applied, and the minimum value is located outside the central region. When the internal pressure is applied at the same time, the normal pressure decreases significantly and the minimum position moves to the inside of the center. The distribution trend of total closure was the same in both cases, and the value decreased slightly.

Conclusions: Using a gear oil pump as a representative case, this study examines the non-linear behavior of seals. In particular, it investigates the mechanisms by which two key factors - bolt preload and internal pressure load - affect the sealing performance of these seals. The results show that the gaskets exhibit highly non-linear loading and unloading behavior.

Keywords: gear pump; seal performance; gasket; non-linear behavior.

INTRODUCTION

Gaskets are critical sealing structures in industrial plants, and with the development of modern industry, their performance and reliability are increasingly required. Due to the complex nonlinear behavior of high performance seals, there is an urgent need to develop new numerical calculation tools to simulate their properties. This paper takes the gear oil pump as a research object, incorporates the nonlinear behavior of the gasket into the analysis of the sealing performance of the gear oil pump, and reveals its loading and unloading operating characteristics through numerical calculation, to provide a theoretical basis for the design of sealing components. This study helps to deepen the understanding of the sealing mechanism of the gasket, improve the sealing performance and reliability, and promote the safe operation of industrial equipment.

Gaskets are the primary sealing structure for detachable joints in various industrial installations, including pressure vessels, process equipment, fluid and power machinery, and connecting pipelines. Its primary function is to prevent leakage of gases or liquids, thereby ensuring the integrity and safety of the entire system^[1-3]. As modern industry, particularly the chemical, petrochemical, thermal power generation and nuclear sectors, continues to expand and evolve, the demands on sealing have also increased. Industrial equipment is now being pushed to operate under conditions of high temperature, high pressure, high vacuum and significant temperature

differentials, while at the same time requiring greater scale. These trends have necessitated the continuous development of sealing technology, imposing stringent new requirements for sealing performance and reliability^[4, 5]. In response, gasket materials and design technology have undergone significant improvements, driving the overall development of industrial sealing.

The current high-performance gaskets are mostly multi-layer composite thin-layer structure, with complex loading and unloading behavior, reflecting a high degree of nonlinear characteristics^[6, 7]. Therefore, there is an urgent need to develop new numerical tools for simulating the nonlinear behavior of gasket seals, in order to deepen the understanding of scientists and engineers on the working characteristics of gaskets, so as to design sealing elements that take into account the economy and reliability.

Leakage is the unintentional flow of media within a confined space, primarily across the sealing surface - the interface between the internal and external environments. The primary cause of leakage is the presence of gaps in the mating surface. The pressure and concentration differentials across these gaps are the driving forces behind leakage. Factors such as the geometry and machining accuracy of the sealing surfaces can contribute to imperfect mating, resulting in gaps and subsequent leakage.

To reduce leakage, it is essential to optimize the degree of embedment between the contact surfaces. This reduces the area of the leakage channel and increases the resistance to leakage, ensuring that it exceeds the driving force. Applying compressive loads to the sealing surfaces creates compressive stresses that increase the degree of contact. If these stresses are sufficient to induce plastic deformation of the surface, they can effectively fill the gaps and block the leakage channels.

The gasket plays a key role in this process by utilizing its plastic deformation properties. It fills in the minute irregularities on the flange sealing surface, thereby improving the sealing effect. In flange sealing joints, the gasket is deformed under force, filling the micro-gaps and achieving a tight seal^[8].

Gasket failure is mainly manifested as penetration leakage, body material erosion and interface leakage of these three modes, the first two are mainly related to the physical and chemical properties of the gasket material itself, and the last one is related to the specific engineering design. Interface leakage is mainly gasket compression stress caused by insufficient, but also with the flange sealing surface roughness, equipment, thermal deformation, mechanical deformation, and vibration and other factors lead to the gasket and sealing surface between the fit is not tight closely related^[9].

OBJECTIVES

Gaskets play a critical role in structural assemblies, transmitting loads between adjacent components while maintaining a robust and secure seal. To fulfil these functions, gaskets are typically constructed from multiple layers of metal or synthetic modified rubber, which have a distinct dimensional characteristic - a small dimension in one direction compared to the others. As shown in Figure 1, the top and bottom surfaces of the cylindrical gasket are subjected to compressive forces, resulting in deformation. As a result, its thickness is compressed and decreases from the original h_0 to h_x .

As a result, gaskets exhibit complex loading and unloading characteristics with a significant degree of non-linearity. In practical applications, designers tend to prioritize the mechanical behavior of gaskets in the thickness direction, often neglecting that in-plane stiffness. Consequently, there is an urgent need to develop novel numerical calculation methods that can accurately predict the sealing performance of gaskets, taking into account their non-linear behavior in a comprehensive manner.

In this study, a gear oil pump is used as the focal research object to investigate its sealing performance. This gear pump operates by the intermeshing of two gears and is used to transport lubricating liquids, specifically those with a pressure not exceeding 2MPa and a temperature below 70°C. A schematic representation of its design is shown in Figure 2.

METHODS

Numerical modeling of the research object and finite element analysis are carried out, and the main flow of numerical modeling is shown in Figure 3. The left column of the figure describes the main steps of the numerical

analysis, which involves the modules of geometric modeling, material properties, mesh delineation, load application, solution, and post-processing of the results; whereas the right column gives the key settings of the relevant key steps.

The setting of the gasket is the final important part of the whole numerical analysis process. From the mechanical point of view, in order to achieve its sealing performance, the essential role of the gasket is to transfer the force between the two parts that fit each other, and is usually in compression; at the same time, if the compression effect between the two parts is weakened due to the internal pressure and other factors, the gasket material will also reflect the corresponding unloading behavior and lead to an increase in thickness.

In practice, the gasket is made up of several layers of different materials, so the response of the gasket in the complex load-unload process is highly non-linear, which is reflected in the gasket:

The pressure behavior of the gasket is reflected in the closure of the gasket.

The starting point of gasket stress-relief is not fixed, so the gasket often has several different stress-relief paths.

The gasket material often has a permanent deformation behavior, i.e. even if there is no residual pressure at the end of the relief, or the pressure is very low, the gasket material may still retains some deformation.

In this paper, the gaskets are made of rubber matrix composites. As shown in Figure 4, the load-unload curve of the gasket is included in the numerical model, with the closure of the gasket as the horizontal coordinate and the pressure as the vertical coordinate. This approach takes into account the non-linear behavior of the gasket material and has advantages over just providing the intrinsic material properties. Specifically, it requires less computation and has superior convergence capabilities, allowing for more accurate and efficient simulations.

The pump body and cover are constructed from stainless steel, whereas the bolts are fabricated from structural steel. The specific physical properties of these two materials are comprehensively outlined in Table 1.

The research object was meticulously segmented into a high quality finite element analysis mesh, as shown in Figure 5. Specifically, the pump cover, gaskets and bolts have been segmented into a hexahedral-based mesh, prioritizing mesh quality and managing its quantity. Conversely, the more complex pump body was divided into a tetrahedral free mesh to account for its complexity. It is worth noting that the pump body has distinct fluid inlet and outlet apertures, resulting in a lack of symmetry throughout the three-dimensional assembly. Consequently, a comprehensive model is required for mesh partitioning and subsequent calculations.

The resultant information of meshing is counted and listed in Table 2.

Since the gasket has a minimal thickness, and the mechanical calculation of the gasket in the numerical model is based primarily on its load-unload curve rather than its inherent material properties, a single layer of mesh is sufficient for the gasket, as shown in Figure 6.

Unlike the meshes of other parts, the mesh cells of gasket do not have intermediate nodes in the thickness direction, but intermediate nodes can be set up on their edges parallel to each other on the top and bottom surfaces, as shown in Figure 7, which helps to adapt to a variety of complex and shaped geometries. Also, unlike other continuity cells, the intermediate positions of the gasket cells can be numerically integrated to accurately solve for their closure values.

The boundary conditions include constraints and loads. In terms of constraints, the mounting holes located at the base of the pump body are fixed. Regarding loads, considering the operating characteristics of the gear oil pump and the need for robustness of the numerical calculation, the application of bolt preload and pressure inside the pump is performed in three different steps, as shown in Table 3. Specifically, in step 1, the bolt preload is applied, which maintains its tensile effect throughout steps 2 and 3. Pressure is applied to the internal surfaces of the pump body and cover in step 3.

The post-processing phase primarily focuses on analyzing the deformation, stress distribution, and contact surface details of various structural components. Additionally, it specifically examines the closure and pressure characteristics of the gaskets.

RESULTS

Firstly, the deformation and equivalent stress distribution of the entire model without the gasket, derived from the final calculation, are thoroughly evaluated. The results are shown in Figure 8, where the deformation is magnified by a factor of 1200 for ease of observation. As shown in Figure 8(a), at the end of the calculation, the gear pump body and the pump cover are simultaneously affected by the bolt preload and the internal pressure. Due to the superior stiffness of the pump body and the restraining effect of the fixed restraints at the base, the overall deformation remains minimal. Conversely, the pump cover and bolt exhibit relatively significant deformation, particularly in the central region at the bottom of the pump cover, where a notable gap is observed.

Figure 8(b) shows the distribution of equivalent stress across the model. The results indicate that the pump body and cover experience minimal equivalent stress, with most regions experiencing less than 23MPa. The bolts, which are in a tensile state to provide the required preload, are subjected to higher equivalent stress. However, the stress remains well below the yield strength of their material.

The non-linear behavior of gaskets is the central theme of this study. A thorough investigation and characterization of the loading and unloading behavior of gasket under the combined influence of bolt preload and internal pressure is essential for designers to gain a deeper understanding of the operating dynamics of the gasket and ultimately improve its sealing performance and reliability. Figure 9 through 11 present a comparative analysis of the gasket behavior before and after compression, with particular emphasis on deformation, normal pressure, and total closure. Prior to compressive loading, corresponding to the first calculation step, the gasket is only influenced by the bolt preload. Conversely, after compressive loading, during the third calculation step, both bolt preload and internal pressure act simultaneously on the gasket. For ease of observation, the gasket deformation is exaggerated by a factor of 340 in Figures 9 to 11.

A comparison of Figure 9(a) and Figure 9(b) shows that under the influence of the preload force alone, the gasket undergoes significant deformation primarily around the upper and lower bolt holes, while the thickness variation in the other areas remains relatively small. The maximum deformation of the gasket is effectively contained within 0.005mm. However, with the additional application of internal pressure, the total deformation of the gasket experiences a sharp increase, reaching approximately 0.009mm, with a notable thickening observed in the central area.

Furthermore, as shown in Figure 10, when the gasket is subjected to the preload force alone, it experiences a higher normal compressive force, with the minimum value occurring on the outer periphery of the central region. Conversely, when both preload and internal pressure are applied simultaneously, the normal pressure within the gasket decreases significantly and the location of the minimum value shifts towards the inner side of the center section.

Figure 10(b) shows that although the minimum normal pressure of the gasket is less than 0.62 MPa, the normal pressure in the majority of regions exceeds the internal pressure value of 2 MPa. In particular, the area where the pressure exceeds 2 MPa effectively encompasses the annular region, ensuring that the sealing performance of the gasket is fully maintained.

With respect to the total closure, Figures 11(a) and 11(b) show a remarkable consistency in their distribution trends, with only minor differences in the numerical values. Overall, it can be observed that the total closure under the combined influence of preload and internal pressure is slightly reduced compared to that achieved under preload alone.

In addition to examining gasket deformation, normal pressure, and total closure, engineering practice often assesses seal performance by analyzing the state of contact between surfaces. Figures 12 and 13 show contour plots illustrating the distribution of penetration and gap on the contact surface between the gasket and the pump body, both before and after the application of internal pressure.

A comparison between Figure 12(a) and Figure 12(b) shows that prior to the application of internal pressure - when under the influence of bolt preload alone - the penetration across the contact surface exhibits a more uniform distribution. In particular, the minimum penetration value occurs at the outer periphery of the central section. However, following the application of internal pressure, the two contacting surfaces appear to have separated slightly and the region where the minimum penetration value is observed shifts towards the inner part of the central region.

Turning to Figure 13, the gap distribution remains largely unchanged before and after the application of internal pressure. At each location on the contact surface, the gap amount is less than zero, indicating close contact. In particular, the absolute value of the gap near the bolt holes is significant, indicating that the pump body surface penetrates deeply into the softer seal material under the preload force of the bolts, resulting in a seamless contact between the two surfaces.

DISCUSSION

Despite its seemingly insignificant appearance, the gasket plays a key role in the static sealing process of bolted flanges and similar structural features in equipment^[10-12]. However, due to its thinness and highly nonlinear nature, the gasket is often overlooked in existing research, which focuses primarily on the overall mechanical behavior of the structure and the associated properties of the contact surfaces^[13, 14].

In this study, we comprehensively consider the non-linear mechanical properties of the gasket by introducing its load-unload curves. In addition, the behavior and sealing performance of the gasket in a gear pump under different loading conditions are studied in detail. In particular, when the gasket is subjected to bolt preload alone, it experiences an almost uniform pressure distribution that reflects its loading behavior. Under these conditions, both the pressure and sealing distributions remain essentially uniform, ensuring robust sealing performance.

However, when both bolt preload and internal pressure are applied, the directions of these forces basically align, resulting in a more pronounced repulsive effect. As a result, the gasket experiences a degree of relief, resulting in reduced normal pressure and sealing effect. In addition, the internal pressure also induces deformation in the main structure, increasing the separation between the contact surfaces. This in turn alters the distribution characteristics of gasket normal pressure, total closure and surface penetration, potentially leading to the creation of weak areas and the risk of leakage.

CONCLUSION

Using a gear oil pump as a representative case, this study examines the non-linear behavior of seals. In particular, it investigates the mechanisms by which two key factors - bolt preload and internal pressure load - affect the sealing performance of these seals. To this end, a numerical model incorporating a gasket computational element type is established and finite element analysis is carried out.

The results show that the gaskets exhibit highly non-linear loading and unloading behavior. Furthermore, the numerical calculation method introduced in this study provides a valuable tool for gaining more intuitive and accurate insights into the mechanical behavior during the design process of static seals incorporating gaskets. This, in turn, provides improved guidance for design, ensuring more robust and effective sealing solutions.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Hehui Zhang: Writing— original draft, Data curation, Conceptualization, Data curation. **Kang Li:** Software, Investigation, Writing— review and editing. **Yutong Zong:** Formal analysis, Validation, Data curation, Visualization. **Qingsong Zuo:** Resources, Project administration, Supervision.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ACKNOWLEDGEMENTS

This research is supported by the Natural Science Foundation of Hunan Province, China, (2023JJ50240).

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Figure 1. Compression of gasket under pressure.

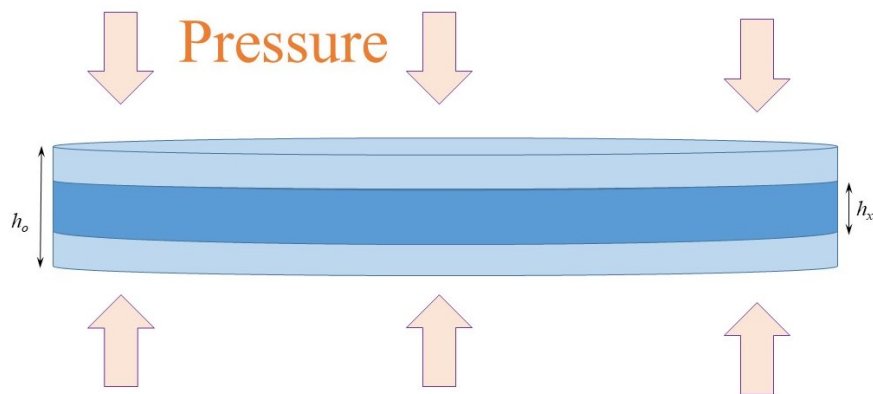


Figure 2. Schematic structure of the gear oil pump

1-pump cover, 2-bolt, 3-gasket, 4-pump body, 5-nut, 6-master shaft, 7-follower shaft, 8-follower gear, 9-master gear, 10-rivet, 11-intake port.

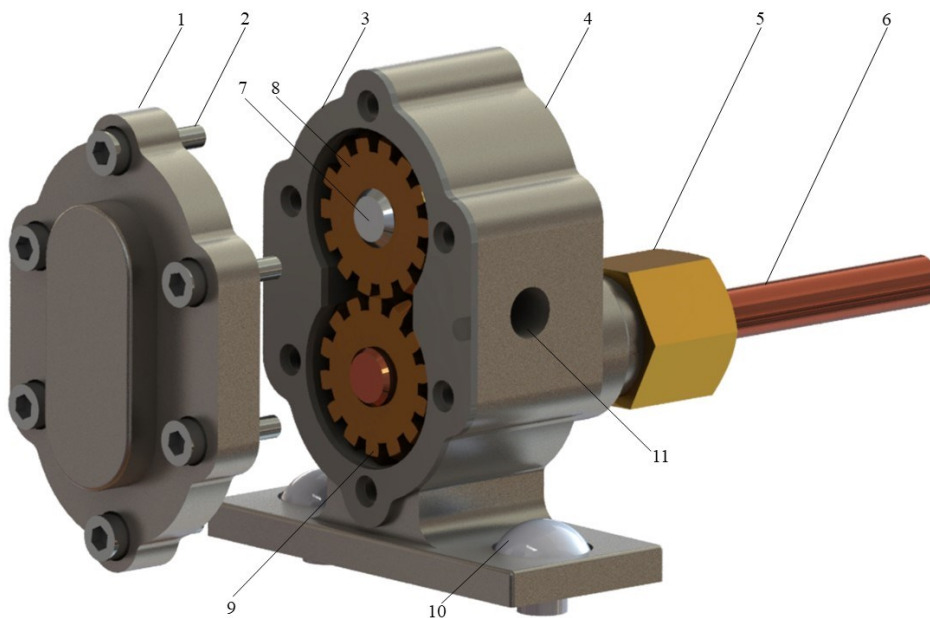


Figure 3. Flowchart of numerical modeling.

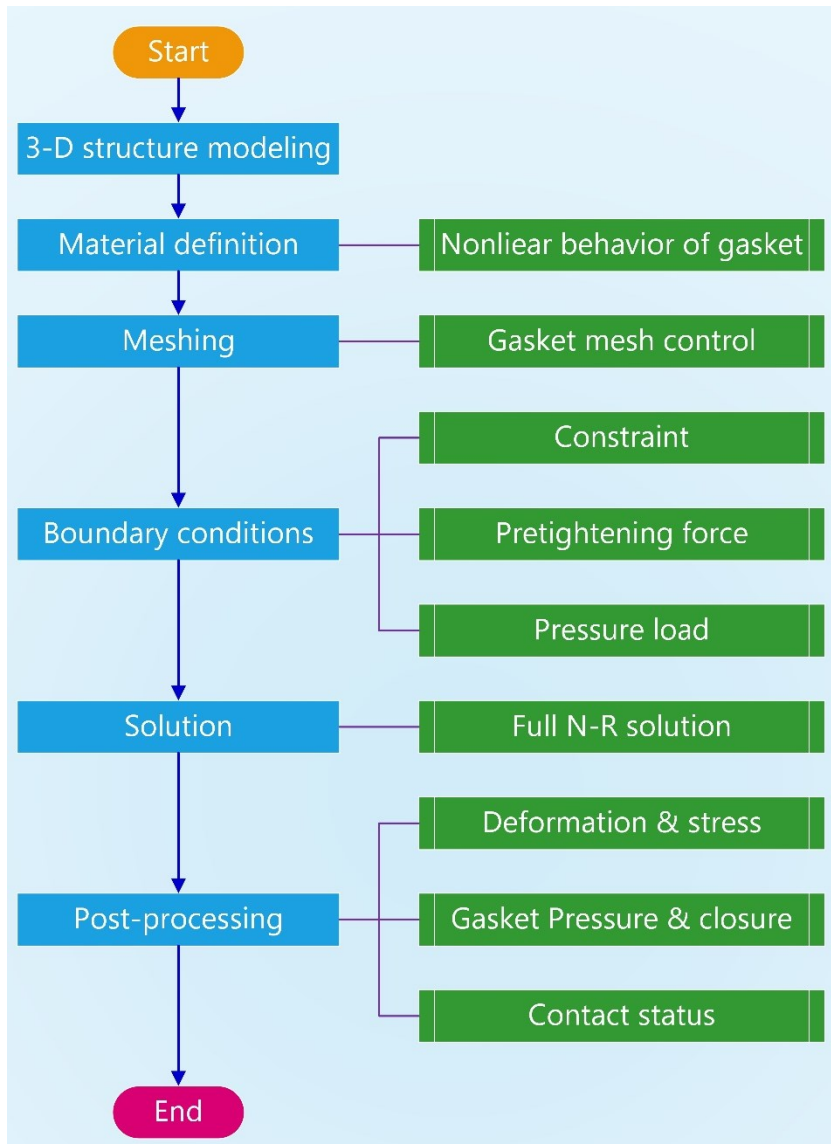


Figure. 4 Loading-unloading curves of gasket material.

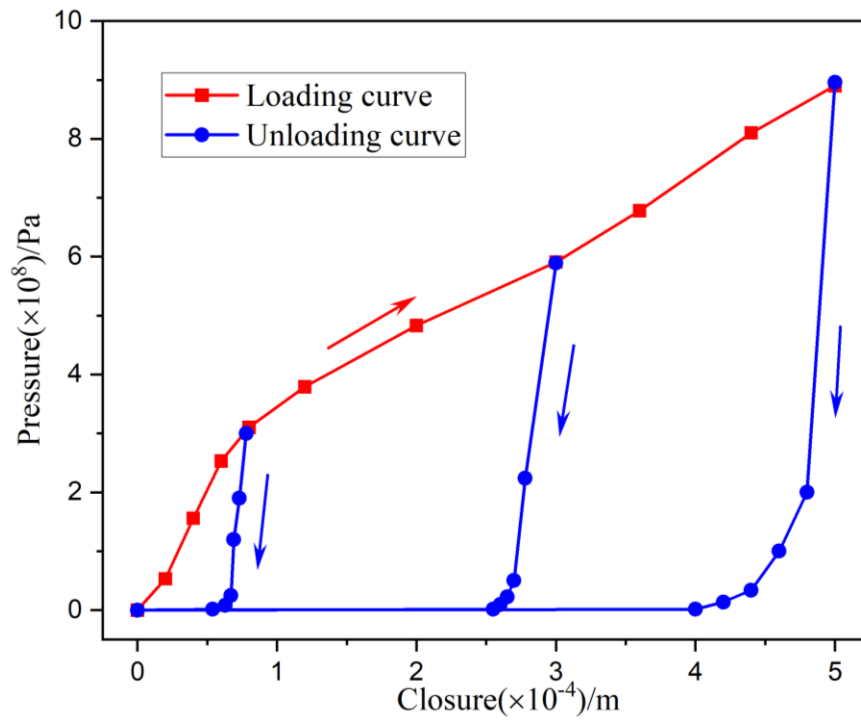


Figure 5. Finite element analysis mesh of the whole model.

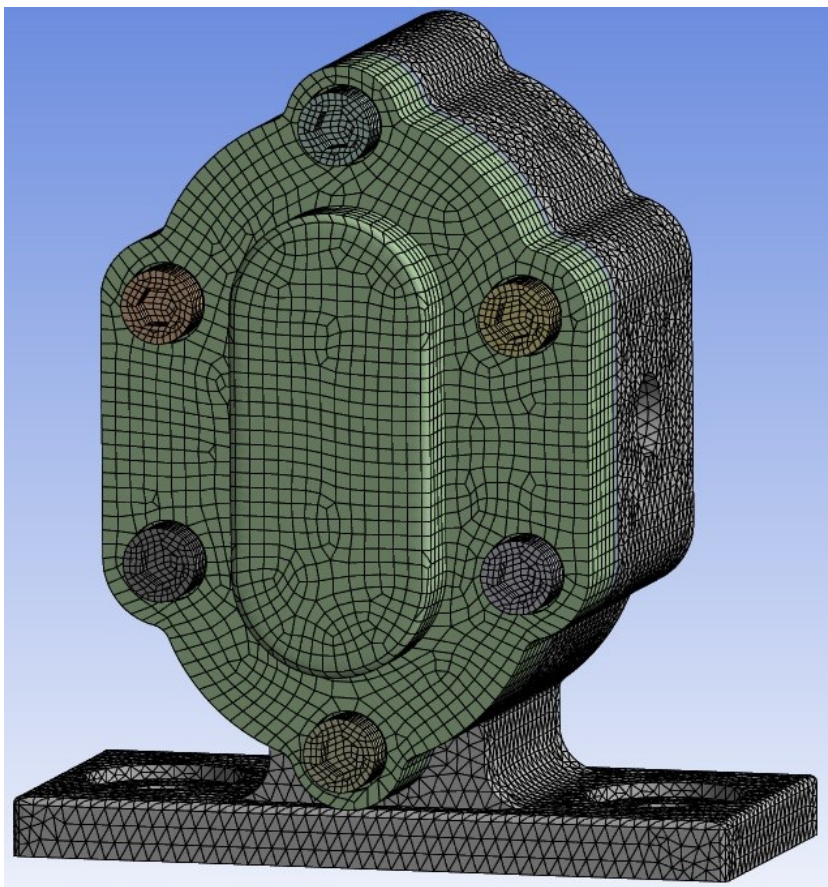


Figure 6 Mesh of the gasket.

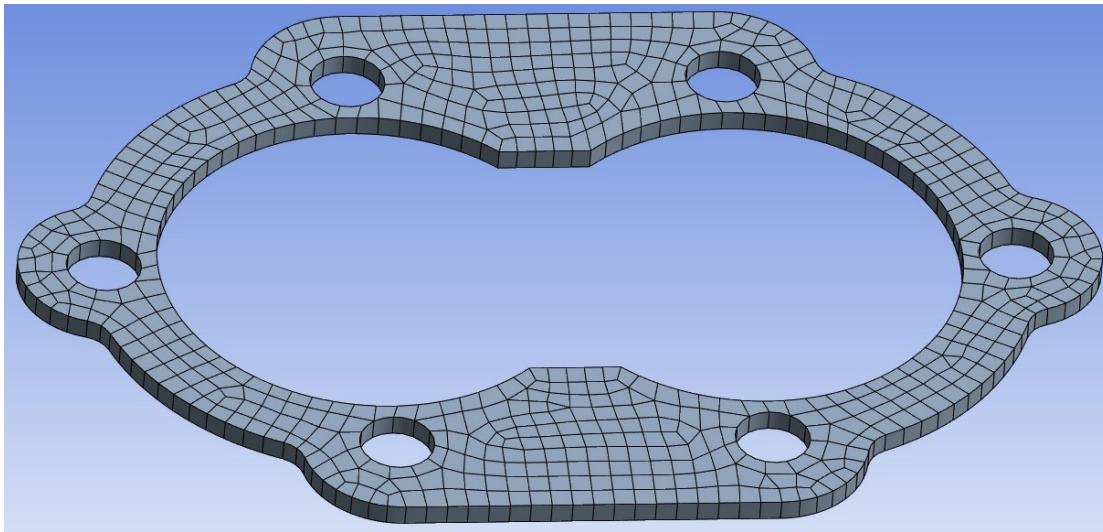


Figure 7. Schematic diagram of gasket element.

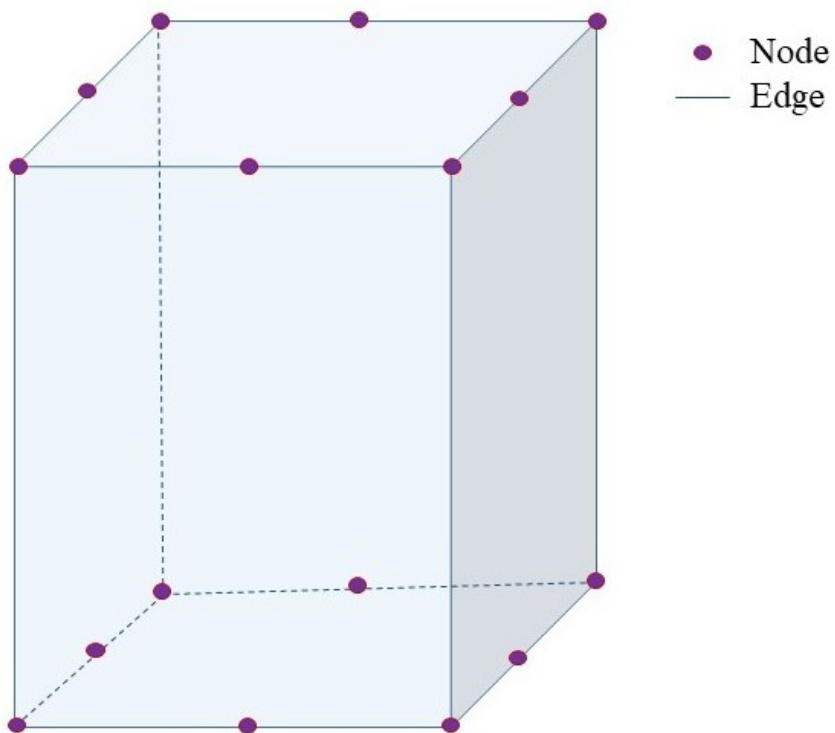
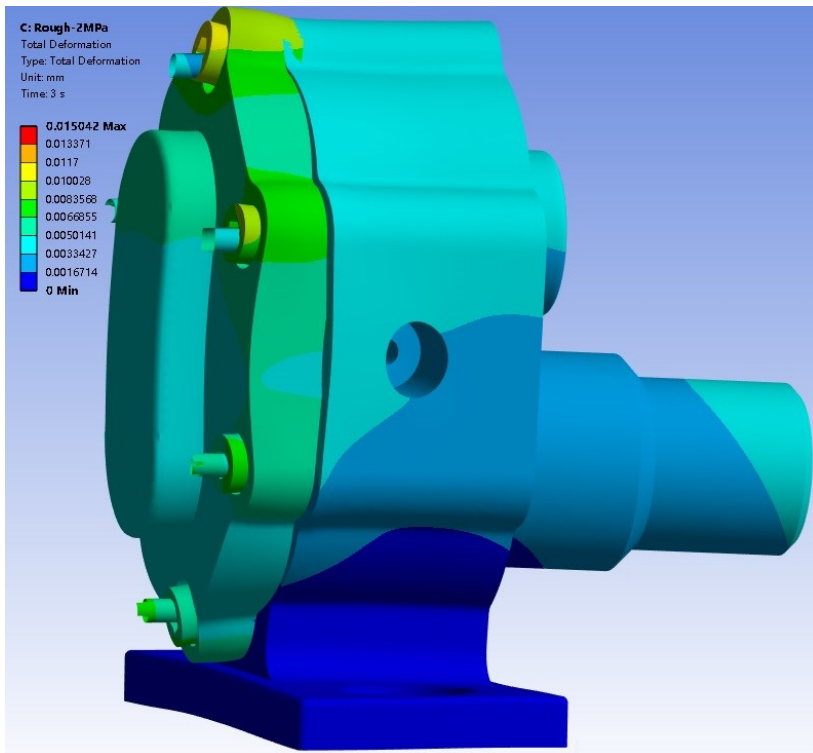
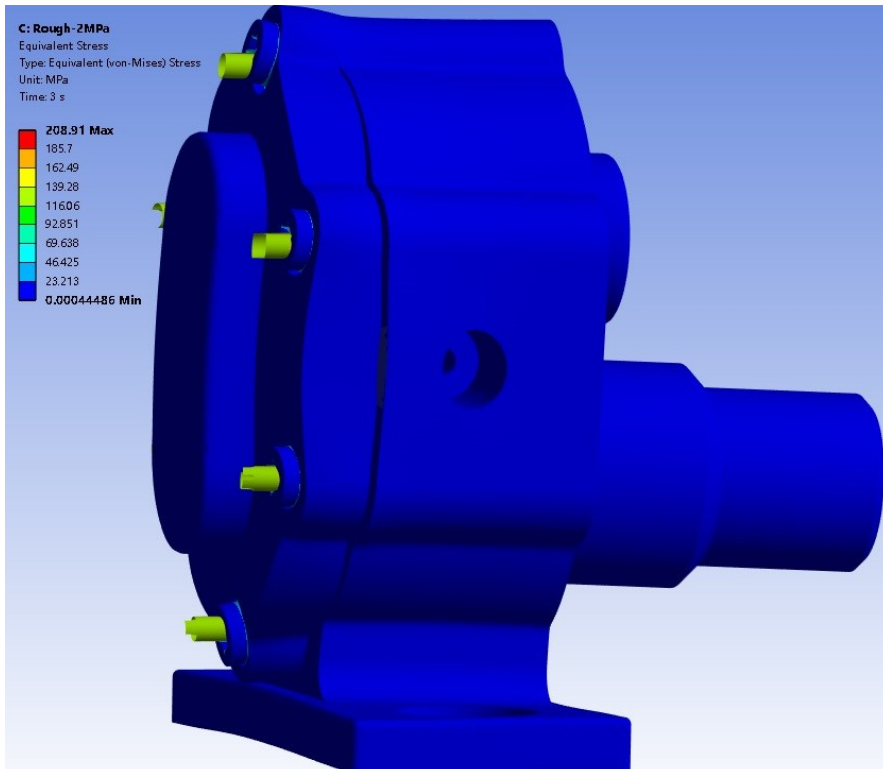


Figure 8. Deformation and stress distribution contours of the whole model: (a) Deformation; (b) Equivalent stress.

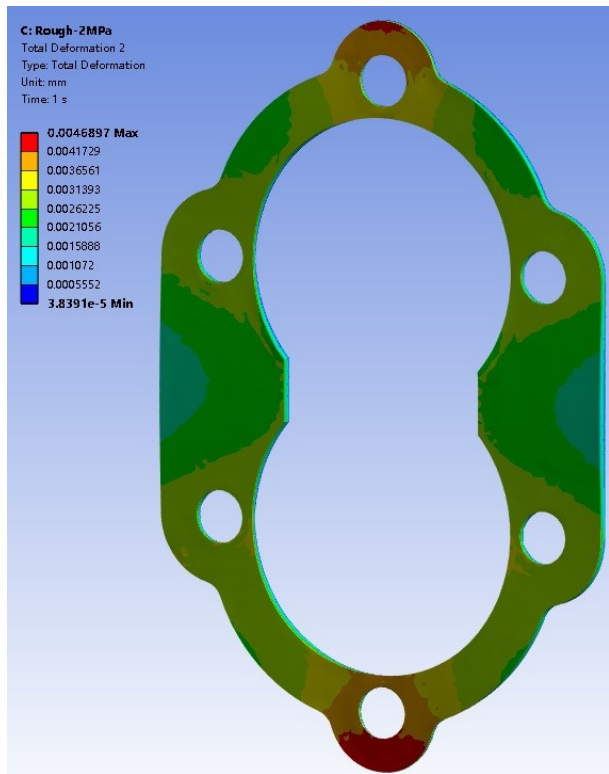


(a)

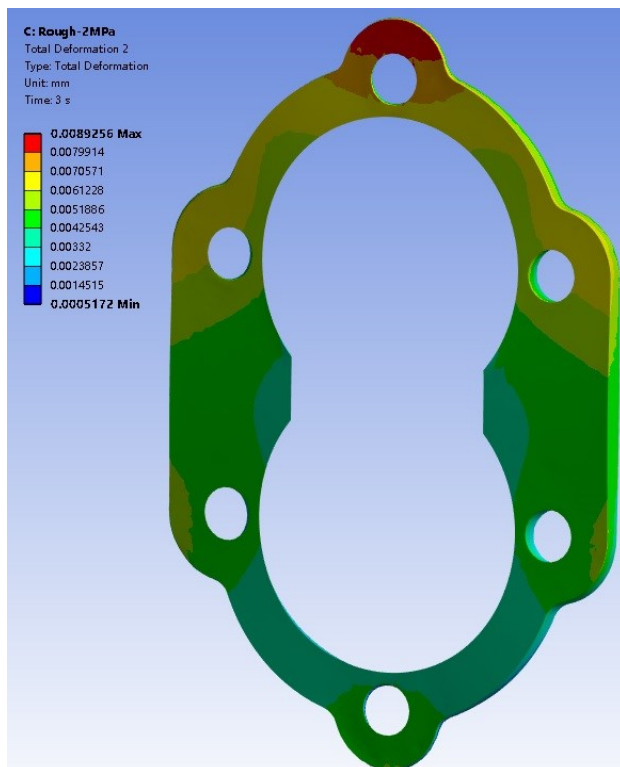


(b)

Figure 9. Deformation distribution contours of the gasket: (a) Before pressure load; (b) After pressure load.

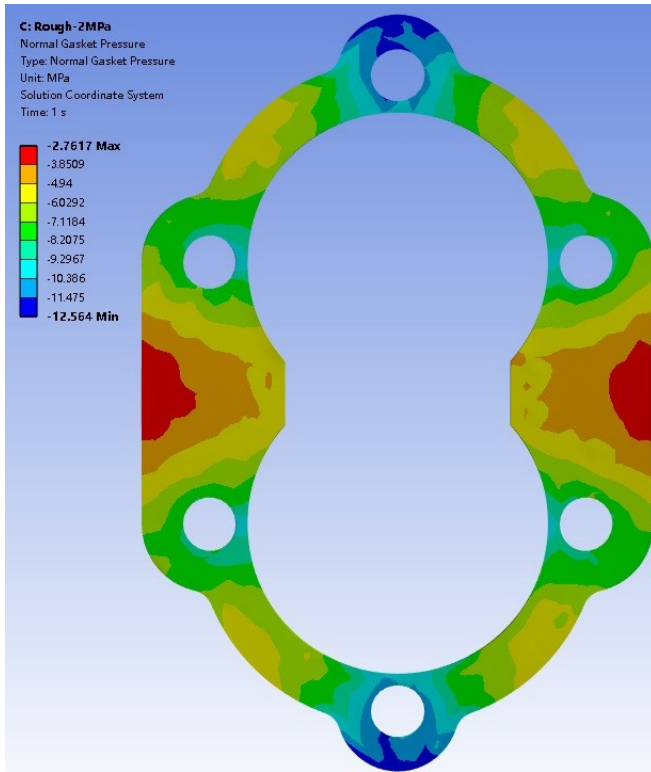


(a)

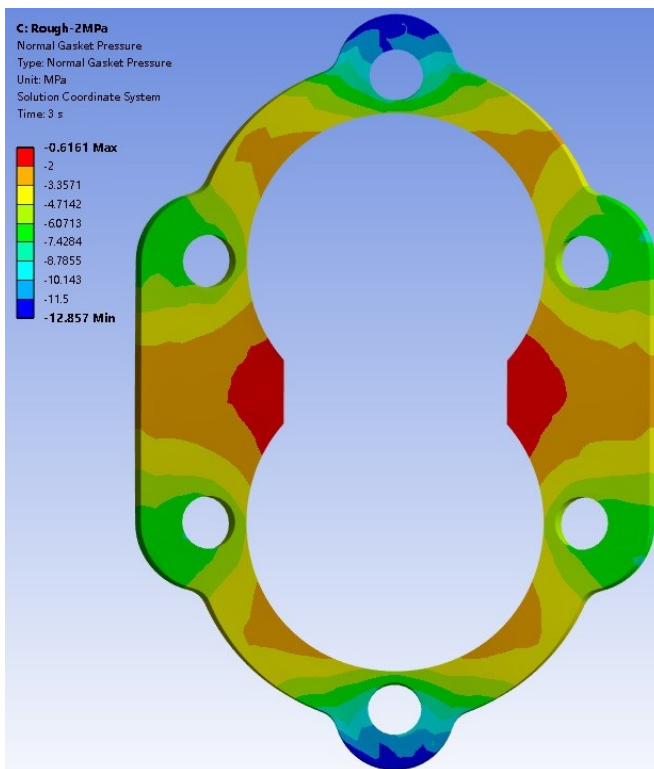


(b)

Figure 10. Normal gasket pressure distribution contours: (a) Before pressure load; (b) After pressure load.

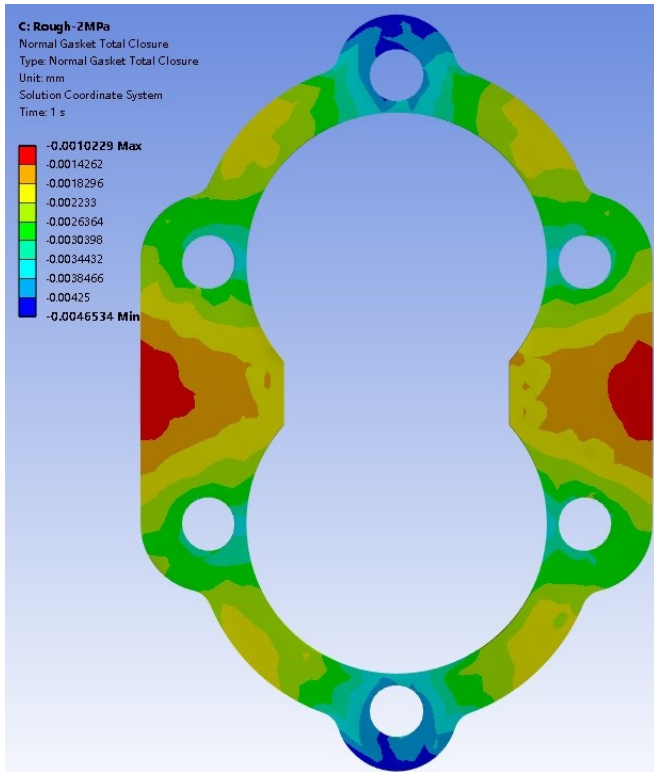


(a)

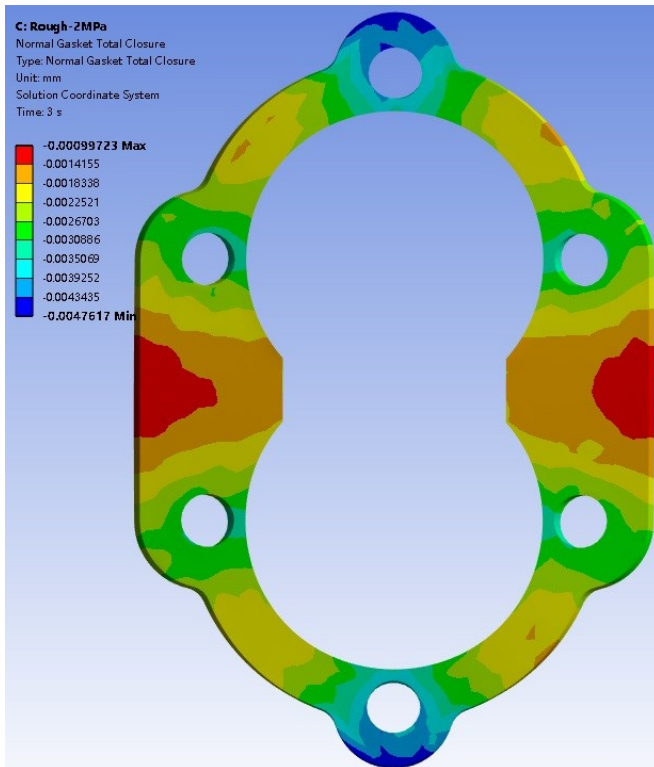


(b)

Figure 11. Normal gasket total closure distribution contours: (a) Before pressure load; (b) After pressure load.

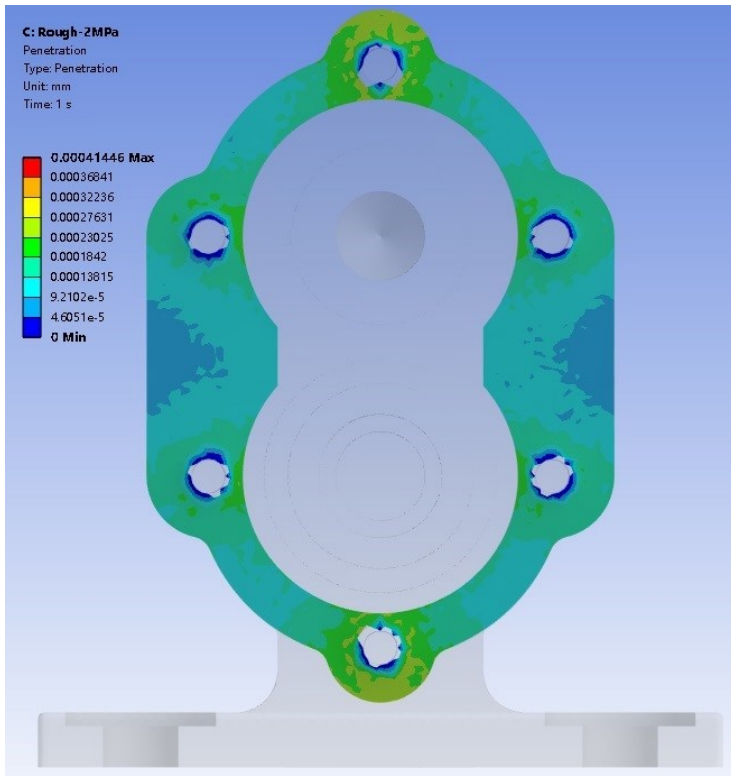


(a)

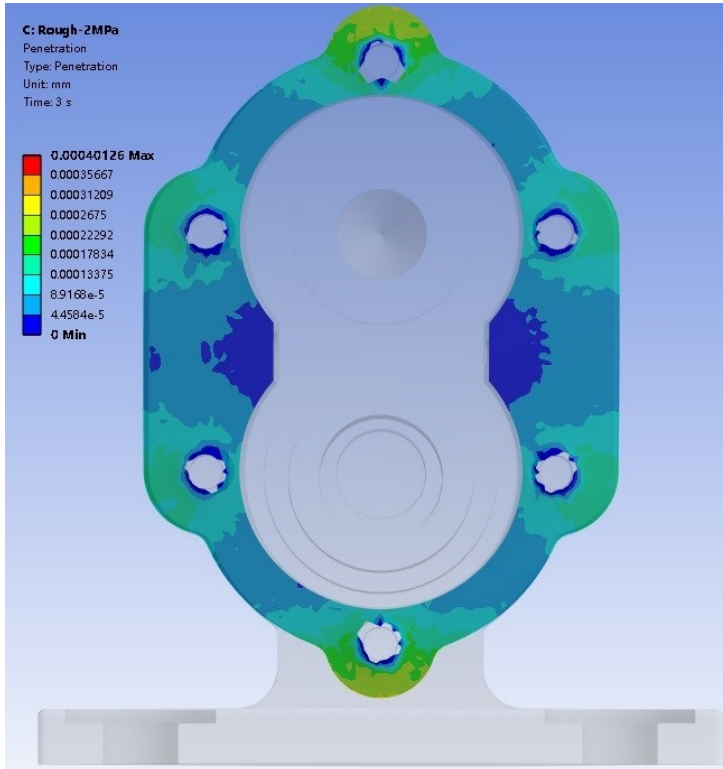


(b)

Figure 12. Penetration distribution contours on the contact surface: (a) Before pressure load; (b) After pressure load.

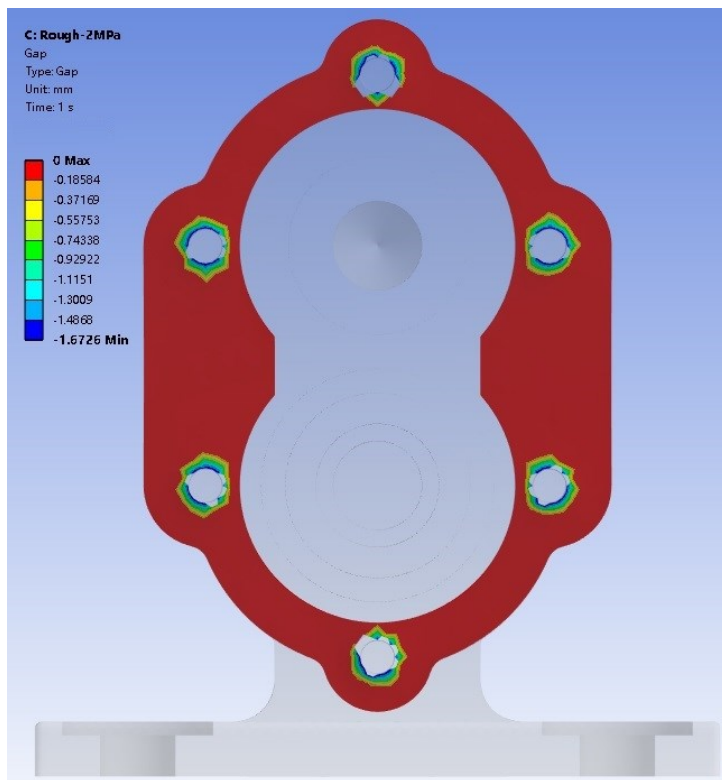


(a)

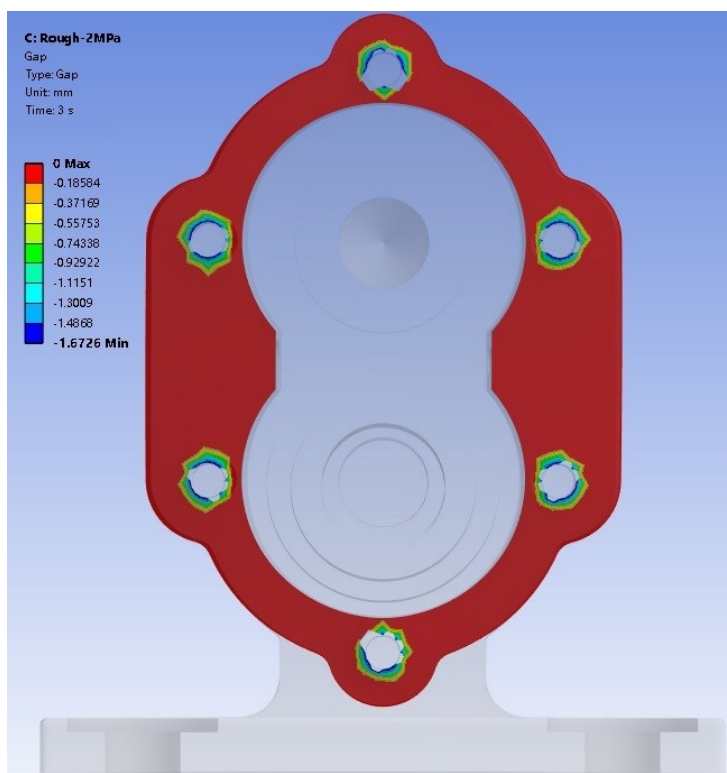


(b)

Figure 13. Gap distribution contours on the contact surface: (a) Before pressure load; (b) After pressure load.



(a)



(b)

Table 1. Physical properties of the material.

Material	Density (kg/m ³)	Young' s Modulus(GPa)	Poison' s ratia	Tensile Yield Strength(MPa)	Tensile Ultimate Strength(MPa)
Stainless steel	7930	190	0.26	205	450
Structural steel	7850	200	0.30	250	460

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Table 3 Load setup.

Step No.	Pretightening force	Inner pressure
1	2560N for each bolt	None
2	Lock	None
3	Lock	2.0MPa on the inner surfaces of pump