Finite Element Analysis of the O-ring Squeezed into the Sealing Clearance Based on ABAQUS

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ABSTRACT

Aimed at the phenomenon of the rubber O-ring material squeezed into the sealing clearance occurred practically in the engineering application, in this paper, ABAQUS was utilized to establish the axisymmetric model of the O-ring to describe the generation mechanisms of this phenomenon and the clearance biting defect caused by the squeezed phenomenon. After analyzing the core factors related to the squeezed phenomenon, the method of finite element was raised to prove the theory that improving the hardness of the sealing O-ring may work on developing the reliability of the O-ring. The final curve graph Von Mises ranged after the change of the medium pressure shows that choosing the proper hardness of the rubber O-ring in different pressure condition will develop the sealing liability which provides the strong basis to the selection of the rubber O-ring in practical application process.

INTRODUCTION

O-ring is widely used in hydraulic systems because of its simple structure, easy installation features and so on. The clearance is closed by the compression deformation of the O-ring mounted in the groove under the action of the pressure of the sealed medium, which reach the purpose of sealing [1]. For static sealing, it can absolutely achieve leak-free seal under the correct premise of the groove design, O-ring selection, installation and application. However, in practical engineering application, it often occurs that the O-ring damage due to clearance bites, which causing the leakage [2]. When the working pressure is more than 10MPa by using retainer to protect the O-ring in a general application [3], although it can prevent the occurrence of an O-ring “clearance bite” phenomenon, but it will increase the friction of the sealing device. Domestic scholars qualitatively put forward that
changing the hardness of O-rings reduce possibility of which an O-ring is squeezed into the sealing clearance under the fluid pressure when the pressure is higher and the clearance is larger\cite{4}. If we can quantitatively analyze the relationship between the material hardness and the pressure on the working medium, it will provide a high reference value in the selection process of O-ring in the aspect of material hardness.

MODEL

Establishing a Geometric Model

As Figure 1 shows a typical static sealing structure in hydraulic system, O-ring size: $19 \times 2.65$ (international standard ISO 3601/1), the specific structure parameters are shown in Table 1:

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Figure1.png}
\caption{The typical static plane sealing structure.}
\end{figure}

\begin{table}[h]
\centering
\caption{Sealing Structure Parameters.}
\begin{tabular}{|c|c|c|c|c|}
\hline
Structural Parameters & diameter & width & depth & chamfer \\
\hline
Value (mm) & 11.4 & 3.8 & 2 & 0.6 \\
\hline
\end{tabular}
\end{table}

1.2 Establishing Material Models

Rubber material is highly composite material with geometric nonlinearity and material nonlinearity. The strain energy density function derived by Rivlin \cite{5} is widely recognized rubber basic model, and he put that strain energy density is expressed as the invariant of deformation tensor in series form:

$$W = \sum_{i+j=1}^{N} C_{ij} (I_1 - 3)^i (I_2 - 3)^j$$

(1)

Where $C_{ij}$ is the Rivlin coefficient.

The equation (1) will be further simplified, let $N = 1$, then Rivlin model can be simplified as the following formula:

$$W = C_{10} (I_1 - 3) + C_{01} (I_2 - 3)$$

(2)

In ABAQUS software, choose Mooney-Rivlin model to characterize the ultra-elastic properties of incompressible rubber-like materials. Using the different parameters of material mode to represent different hardness of materials\cite{6}, namely, by changing the value of $C_{10}$ and $C_{01}$ to acquire the hardness of materials, the density of the rubber material is set up 1.0g/cm$^3$. 

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SET LOAD AND BOUNDARY CONDITIONS

In the finite element analysis of ABAQUS software to establish a two-dimensional axisymmetric finite element model of the rubber O-ring material, because of the elastic modulus of sealing groove and sealing surface in a steel material is millions of times than a rubber material’s, so sealing groove and sealing surface is partly set up rigid body in the analysis. The Poisson's ratio of rubber material close to 0.5 and is considered the incompressible material, so incompressible behavior of it is simulated by CAX4H—mixed mesh cells with the shape of an arbitrary quadrilateral when the model carries on the grid division in ABAQUS software.

The process of plane static seal in working condition for the rubber O-ring is analyzed mainly consists of two steps:

(1) Simulating the installation process of O-ring, given the amount of compression, and ensure a certain degree of sealing clearance.

(2) According to the working process of the medium pressure, pressure load is put in the compression side of the O-ring.

THE CALCULATION RESULTS AND ANALYSIS

Evaluating the properties of the rubber O-ring mainly has two parameters about Von Mises and contact pressure[7]. Von Mises mainly reflects the different size between main stresses on the cross section of O-ring in working condition. In the same conditions, the greater the Von Mises and the more uneven Von Mises distribution, the more obvious of the stress relaxation behavior of rubber materials which cause the loss of stiffness, so the more prone to cracking for the O-ring in high stress areas[8]. In working condition, it is a necessary condition for O-ring to ensure good sealing effect that maximum contact pressure is greater than or equal to the pressure of sealed medium, so the size of the contact pressure reflects the strength of the O-ring sealing ability[9].

The selection of rubber material with A60 shall hardness to ensure the sealing clearance under the premise of 0.1mm is respectively set up the medium pressure of 0MPa, 2MPa and 8MPa. Observing the section strain and the internal Von Mises distribution, the most obvious phenomenon of the O-ring squeezed into the sealing clearance appears when the pressure of sealed medium is 8MPa, as shown in Figure 2:

![Figure 2. Stress nephogram of medium pressure under the 0MPa.](image-url)
As can be seen from the figure, the pressure of sealed medium of O-ring in working condition increases from 0MPa to 8MPa, high stress area of the Von Mises inside the O-ring is gradually transferred to the chamfer section of sealing notch from the middle section. In the low-pressure conditions, the internal Von Mises stress distribute more uniform and locate in the central cross section of the O-ring with a larger area of dumbbell shape; in the high-pressure conditions, high stress areas reduce from internal distribution of cross section with larger areas to marginal distribution of the sealing notch with the small area. There are two main points of high stress with the point A of sealed surface and the point B of notch chamber, as shown in Figure 5.
In working process, the crack appeared in A and B high stress region, with the crack continuously extended, the force squeezed into the sealing clearance which is similar to dental occlusion caused damage of O-ring between A and B. Appearing clearance biting defect which lead to leak. The result of this process is conform to the practical engineering.

Using “s” to show the size of O-ring squeezed into the sealing clearance. As shown in Figure 5, when the rubber material hardness is shore hardness A60 and seal clearance is 0.1mm, changing the medium pressure from 1MPa to 10MPa, deriving the curve shown in Figure 6. When the medium pressure less than 1MPa, There is no the phenomenon of squeezed into the sealing clearance. When the medium pressure less than 8 MPa, the s which the size of O-ring squeezed into the sealing clearance is roughly a linear growth with the increase of the medium pressure. When the medium pressure more than 8 MPa, the growth rate was significantly lower.

![Figure 6. The curve of the Rubber material squeezed into the sealing clearance changing with medium pressure.](image)

We can see from figure 7, when the rubber material hardness is shore hardness A60, the medium pressure is 5 MPa, changing the sealing clearance, s and the sealing clearance also is roughly a linear growth.

So, through the finite element simulation, in the using process of the O-ring, the medium pressure and the seal clearance is approximately a linear growth relationship with the size of squeezed into the sealing clearance, which has a great influence on the squeezed phenomenon.

About the measures to solve the clearance biting defect, the reference generally suggest to selection high hardness materials. As shown in Figure 8, When the rubber material hardness is shore hardness A60, the medium pressure is 10MPa and the seal clearance is 0.1mm, the obvious squeezed phenomenon will appear and more concentrated areas of high stress. Using the finite element method to prove the effect of Hardness on the sealing performance in the same working condition. Changing the hardness of the material to shore A70 and Shore A80, we will gain the Von Mises stress distribution as shown in Figure 9 and Figure 10.
Figure 7. The curve of the Rubber material squeezed into the sealing clearance changing with seal clearance.

Figure 8. The Von Mises stress nephogram when rubber material hardness is shore A60.

Figure 9. The Von Mises stress nephogram when rubber material hardness is shore A70.
From the Figure can be seen, when the material hardness gradually changing from shore A60 to shore A80, the squeezed phenomenon is obviously improved, the stress distribution is uniformed than in shore A60, and high stress area be transferred from the edge part of O-ring to the internal section of O-ring, greatly reducing the possibility of clearance biting phenomenon. In a certain situation, changing the sealing material hardness can effectively inhibit the clearance biting phenomenon, so that can protect the sealing ring, and avoid the leakage caused by the damage of the sealing ring.

However, not the more high sealing material hardness, the more high system sealing reliability performance in the all cases.

The curve of the O-ring maximum contact stress changing with pressure in different hardness is shown in Figure 11. The Q1, Q2, Q3, Q4, Q5 respectively represent the corresponding curve of rubber material hardness is shore A60, A65, A70, A75, A80. As shown in the Figure, in the different hardness cases, the maximum contact stress were all higher than the medium pressure, that is the reliable seals in theory.

However, observing the curve of the maximum Von Mises stress changing with pressure in different hardness, as shown in Figure 12, we can see that the influence of hardness on the maximum Von Mises stress values is relatively obvious. In the other conditions remain unchanged, the maximum Von Mises stress of high hardness O-ring was significantly higher than that of low hardness material in the range of low pressure. The maximum Von Mises stress under different hardness was increased along with the sealed medium pressure, but the growth rate is not the same. In low hardness, the maximum Von Mises stress with the increasing pressure...
is grow faster; in high hardness material, the maximum Von Mises stress with the increasing pressure is grow slower. In the range of high pressure, the maximum Von Mises stress of high hardness O-ring was significantly less than that of low hardness material, which caused the possibility of cracking is lower, the permanent deformation caused by stress relaxation under a long time working is smaller, and the reliability of the O-ring is higher.

![Graph showing the relationship between medium pressure and maximum Von Mises stress](image)

**Figure 12.** The curve of the maximum Von Mises stress changing with pressure in different hardness.

**SUMMARY**

By using ABAQUS to analysis the O-ring with the finite element simulation, and combined with the engineering problems in practice, the following conclusions can be drawn:

(1) The O-ring clearance biting defect phenomenon is mainly due to the stress concentration appears at the o-ring pressing in the seal groove part and sealing surface contact part, the crack appears in the work process, and causing the material squeezed into the sealing clearance is damaged.

(2) Changing the material hardness of O-ring can effectively improve the reliability of the seal, not only reduced the size of O-ring squeezed into the sealing clearance, but also makes the stress distribution on the section of the O-ring is more uniform.

(3) In practical application, we should choose material hardness in reason according to the pressure condition, selecting low hardness material in the low pressure and high hardness material in the high pressure, it can effectively reduce the possibility of seal failure.

**REFERENCES**

