Journal of Research in Science and Engineering (JRSE)
ISSN: 1656-1996 Volume-7, Issue-4, April 2025
DOI: 10.53469/jrse.2025.07(04).05

High-Temperature Sealing Performance and Friction Resistance of C-Shaped Metal Sealing Rings

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Abstract: ***In addressing the challenges of high-temperature and high-pressure environments prevalent in offshore oilfield exploration, an extensive review was undertaken to examine the characteristics of a variety of sealing materials and structural configurations, assessing their viability at 350°C. Utilizing Ansys software, an in-depth study and analysis were conducted on the sealing performance and sliding friction resistance of C-shaped metal sealing rings. Additionally, the mechanical properties of these C-shaped metal sealing rings at 350°C were validated through a combination of software simulations and empirical testing. The findings indicate that C-shaped metal sealing rings are capable of fulfilling the requirements for both sliding and static sealing in a high-temperature environment of 350°C, thereby offering valuable insights for research endeavors in relevant domains.***

Keywords: High temperature, Sliding seal, C-shaped metal sealing rings, Frictional resistance**.**

1. Introduction

Crude oil is pivotal in the global economy, known as "liquid gold." Its effective exploitation and use are crucial for sustainable economic growth. However, during extraction, downhole tools face challenges like high pressure, temperature, and corrosiveness, making their safe and efficient operation critical. The sealing performance of these tools is key to ensuring stable operations and preventing risks. Sealing system failure can lead to environmental damage, resource loss, and endanger lives. Currently, conventional downhole tools use non-metallic materials like rubber for sealing, which are efficient within certain temperature ranges. In environments like offshore oil exploration, where temperatures often exceed 350℃, these materials fall short as their maximum operating temperature is around 327℃ [1-2]. Therefore, studying the sealing performance of C - ring metal seals at 350℃ is vital for solving high-temperature sealing issues and enhancing the reliability and safety of downhole tools.

2. Sealing Materials and Methods

In sealing technology, gasket materials are mainly divided into metallic and non-metallic categories. Non-metallic seals, like those made from rubber and plastic, are widely used in normal conditions due to their simplicity and practicality. However, they tend to age and fail in sealing at high temperatures of 350℃. In contrast, metallic elastic sealing materials are gaining attention for their good performance in high-temperature and high-pressure environments. Among them, metallic elastic sealing rings come in various cross-sectional shapes, such as W, O, C, U, and V types. As shown in references [3-6], studies have indicated that C-shaped metallic sealing rings exhibit better mobility stability, pressure-bearing capacity, and sealing performance in high-temperature and high-pressure conditions when sliding sealing is required, making them the preferred option for such working conditions.

3. The Structural Characteristics of the C-shaped Metal Seal Ring.

As shown in Figure 1, the C - shaped metal seal ring mainly consists of two parts: an inner helical spring and a metal cladding.

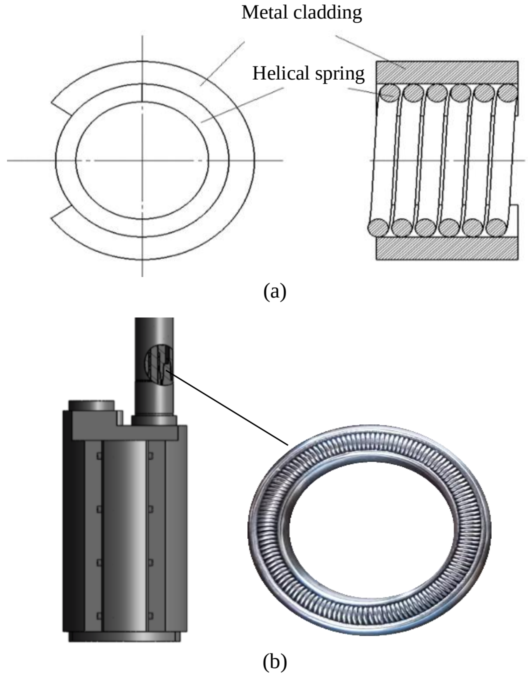

Figure 1: Structural schematic diagram (a) and physical diagram (b) of C - shaped metal seal ring

The cylindrical helical spring is made of Inconel X - 750, and the metal cladding is Inconel 718 [7], with specific properties shown in Table 1.

Tabel 1: Parameters of C - shaped metal seal ring material

Material grade	Modulus of elasticity/MPa	Poisson's ratio	Yield strength/MPa	Strain hardening exponent/MPa	R_{∞}/MPa	b/MPa
Inconel X-750	$2.14x10^5$	0.3	1223	$5.25x10^3$	190	300
Inconel 718	$2.14x10^5$	0.3	1150	$4.0x10^3$	150	240

4. Sealing Performance Analysis

4.1 Establish the Geometric Model for Finite Element Analysis.

A 3D axisymmetric model of the C-shaped metal seal ring, piston rod, and seal chamber was created with refined meshing. The model has 298,702 elements and 1,066,580 nodes (see Figure 2). To simulate real conditions, the piston rod and seal chamber are treated as rigid bodies, ignoring their deformation, to enhance the relevance and effectiveness of the analysis.

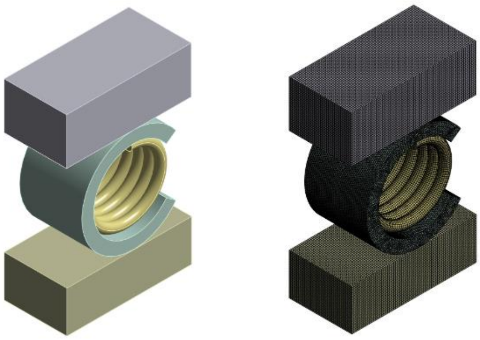

Figure 2: Sealing structure model and grid division

The structural parameters of the model are shown in Table 2.

Tabel 2: Basic parameters of Resilient Metal C Ring

C-ring ID/mm	C-ring OD/mm	Coating thickness/mm	Free height /mm	Wire diameter /mm	Number of coils
12.42	19.08	0.38	3.33	0.3	134

4.2 Stress Analysis Under Different Interference Fits

In the simulation, contact settings were applied to the piston chamber, C-ring, coating, and helical spring. The piston chamber and C-ring, as well as the coating and helical spring, were defined as no-separation contact, and the C-ring and piston rod also maintained no-separation contact. Subsequently, interference fit was used as a variable parameter, with simulations conducted in 0.005 mm increments until the maximum stress was reached. Using finite element analysis software, the model was built and solved (Figure 3), yielding results on stress distribution and displacement changes under different interference fits, as shown in Figure 4.

Figure 3: Finite element analysis of C - shaped metal seal ring

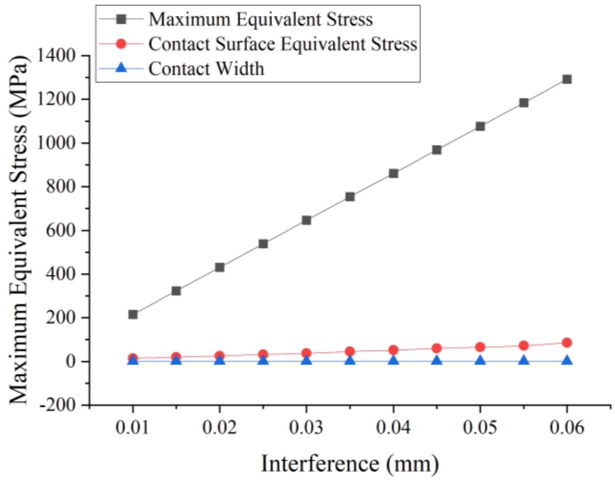

Figure 4: Different equivalent stress and contact area under different interference amounts

Finite element analysis reveals a rapid rise in the C - ring seal's maximum equivalent stress with increasing interference fit. At 0.06 mm interference, the stress reaches 1291.6 MPa, slightly exceeding the material's yield strength, indicating the seal is near its mechanical limit. In contrast, the contact region's stress increases moderately from 14.3 MPa to 84.6 MPa. The stable contact width of 0.31 mm throughout the simulation highlights the design's stability. Results show the C - ring seal can withstand 40 MPa working pressure at an interference fit of 0.035 mm or more.

4.3 Analysis of Frictional Resistance in a Pressure Field.

In the study of the actual working conditions of C - shaped metal seal rings, the encountered friction mainly comes from two key mechanisms: one is the interfacial friction caused by the contact stress distribution; the other is the extra resistance generated by the deformation of the C - ring under pressure. As shown in Figure 5, these two effects together make up the main friction sources of the seal ring during operation.

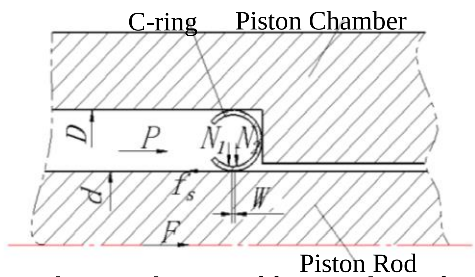

Figure 5: Schematic diagram of force analysis of C - shaped metal seal ring

Physical meanings of the symbols are as follows:

P —— Internal pressure of the piston chamber

N_1 —— Pressure exerted by the C - ring on the piston rod due to P

N_2 —— Rebound force of the C - ring

fs —— Frictional resistance between the C-ring and the piston rod

F —— Axial thrust of the piston rod generated by P

W —— Contact width between the C-ring and the piston rod

D —— Inner diameter of the piston chamber

d —— Outer diameter of the piston rod

The model was subjected to pressure fields of 0, 10, 20, 30, 40, and 50 MPa, with a metallic friction coefficient set at 0.1 for simulation calculations [8]. The results showed a dynamic relationship between frictional resistance and pressure (Figure 6), revealing the C - ring seal's frictional characteristics under different pressures.

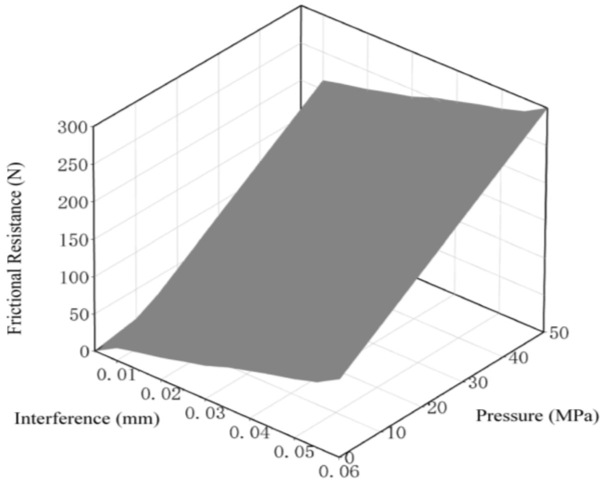

Figure 6: Variation of friction resistance at different pressure stages under different interference amounts

From the data in the figure, when the interference fit is 0.01 mm and the pressure 0 MPa, the frictional resistance of the C - ring seal is minimal at 17 N. Conversely, at an interference fit of 0.06 mm and pressure of 50 MPa, the resistance peaks at 300 N.

4.4 Sealing Performance Analysis under Temperature Field

A finite - element model was subjected to a 350℃ temperature field for simulation [9], yielding data presented in Figure7.

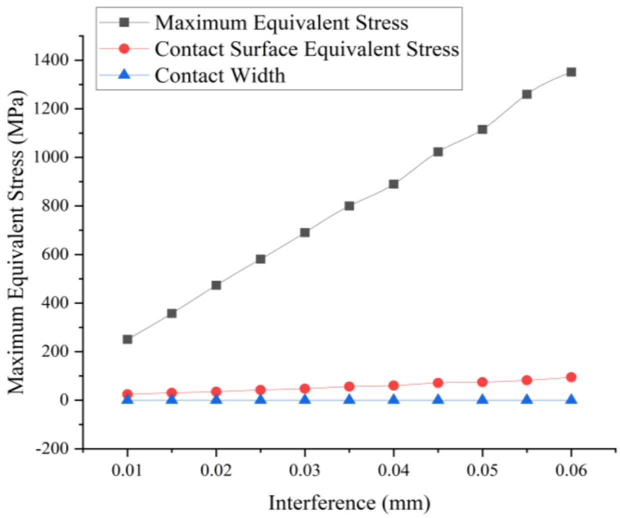

Figure 7: Equivalent stress and contact area of different interference amounts at 350℃

As shown in the figure, when the interference fit is set at 0.05 mm, the maximum equivalent stress reaches 1115 MPa, indicating a significant increase in contact stress compared to ambient temperature. Despite the high mechanical load, the contact width remains stable at 0.31 mm.

4.5 Experimental Analysis

In this study, downhole switch tools were tested with 11 seal rod diameters and 11 interference fit levels to analyze frictional resistance and sealing performance.

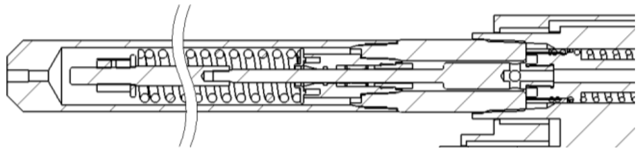

Figure 8: Friction resistance and sealing performance test

Test results are shown in the figure below:

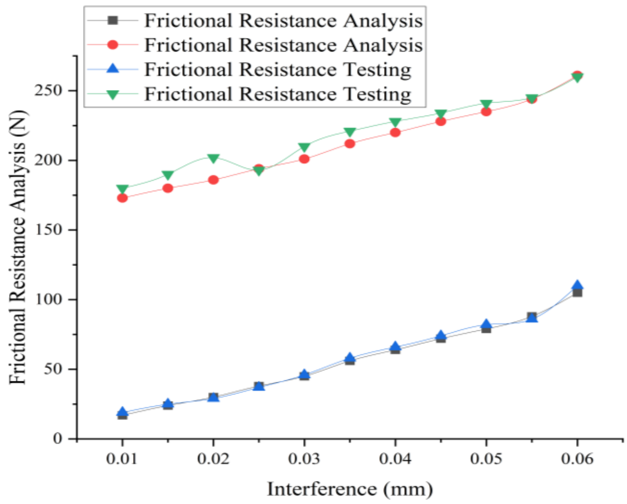

Figure 9: Friction resistance analysis and test data

Compared with simulation results, experimental data shows some numerical deviations but similar overall trend curves. The simulation effectively predicts the variation trends of frictional resistance and sealing performance with interference fit, aligning well with experimental expectations.

The designed switch tool has a shut-off pressure of 40 MPa. The sealing performance at this pressure for different interference fits is shown in the figure below.

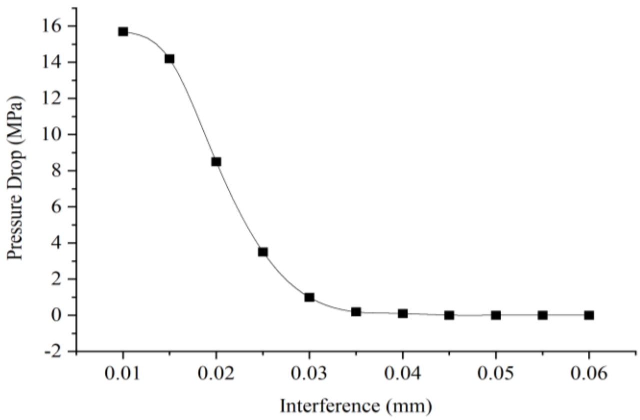

Figure 10: Pressure drop of 40MPa pressure test with different interference

Results show that when the interference fit is less than 0.03

mm, the pressure drop decreases rapidly and the leakage increases significantly. However, when the interference fit reaches and exceeds 0.035 mm, the sealing performance standard is met, ensuring suitability for practical applications.

Based on the above theoretical analysis, this experiment selected an interference fit of 0.045 mm for high-temperature performance verification tests in actual product applications. The procedure involved heating the switch tool in a high-temperature furnace to 350℃, maintaining this temperature for two hours, and then conducting a series of tests, as shown in Figure 11.

Figure 11: High temperature experiment

In the experiment, pressure was first applied to the piston chamber to move the piston rod to the specified position. Then, the pressure was increased to exceed the preset value of 40 MPa [10]. After reaching this pressure level, it was maintained for 15 minutes, during which pressure data was continuously monitored and recorded.

The experimental results indicate that during the pressure - increasing process, the pressure rises steadily, driving the piston rod to move smoothly to the target position. After the piston rod is in place, the required pressure can be successfully maintained. The experimental data is shown in Table 3.

Table 3: Pressure-holding test of piston cavity

Times	Initial pressure/ MPa	Pressure holding time/Min	Final pressure/MPa	note
1	40.5	15	40.5	
2	41	15	41	
3	41.8	15	41.7	pressure drop0.1MPa
4	41.5	15	41.5	
5	40.7	15	40.7	

After five complete pressure loading and holding tests, the maximum pressure drop in the piston chamber is 0.1 MPa, meeting the technical requirements. The experimental results basically match the simulation expectations.

5. Conclusion

1) This paper first widely and deeply researched various sealing materials and forms. Results show non-metallic sealing materials can't meet the required sealing performance standards in high-temperature environments of 350℃. Metallic elastic materials can maintain good properties in high temperatures. After studying metallic elastic seals with different cross-sectional shapes, it is concluded that the C - shaped metal seal structure has significant advantages and feasibility in high-temperature and high-pressure applications where sliding sealing is required.

2) Based on theoretical analysis, this paper uses Ansys for finite element simulation to study the sealing performance and frictional resistance of C - shaped metal seal rings under different interference fits. Experiments confirm that the C - shaped metal seal ring can effectively function as a sliding seal element in high - temperature environments up to 350℃, meeting sealing requirements.

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