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Optimization of Metal Skeleton of Fishbone Gasket and Performance Test

Zhou Xianjun, Li Jianhua and Chen Chunlei

Keywords: fishbone gasket, metal skeleton, orthogonal optimization, mechanical property, leakage rate.

ABSTRACT

With the continuous improvement of sealing performance requirements of modern mechanical equipment, many conventional gaskets have been unable to meet their working requirements. In this paper, a new type of fishbone gasket was studied. Firstly, ANSYS finite element analysis software and orthogonal optimization were used to simulate the mechanical properties of its metal skeleton, and the optimal combination of skeleton parameters was obtained. After optimization, the compression rate of the metal skeleton increased by 10.26% and the springback rate increased by 26.98% on the original basis. Compression springback tests were carried out on universal seals testing equipment under different loads and temperatures. Data analysis showed that gasket performance was relatively stable in the test temperature range. Gasket and flange were basically compacted after gasket surface stress exceeded 40 MPa, and the lower limit of bolt preload could be determined accordingly. Gaskets had excellent sealing performance, and self-sealing structure enabled them to maintain the standard leakage rate at lower assembly stress.

LITERATURE REVIEWS

Research status of gasket performance

Flange seal has always been a difficult problem for heat exchanger designers, operators and maintenance personnel. Sealing gasket is an important part of flange bolt connection system. Its performance directly affects the sealing reliability of flange connection system. Therefore, many researchers have studied the gasket sealing principle deeply and found that the compression rate under a certain load and the springback rate during unloading were important indexes to measure the gasket sealing performance.

Li Jun (2015) had studied the sealing performance and compression springback performance of flexible graphite wave-tooth composite gasket. He had found that the number of changing wave teeth had little effect on the springback rate of the gasket by numerical simulation. Then, the negative exponential relationship between gasket leakage rate and gasket assembly stress was obtained through the test data, and the proportional coefficient had decreased and tended to be stable with the increase of gasket assembly stress.

Liu Shulin et al. (2017) had obtained the optimal horizontal parameters by orthogonal test on the structure parameters of the metal graphite winding gasket, and analyzed and obtained that the angle of the steel strip itself, the ratio of winding tightness and the winding force of the steel strip were more significant among the factors affecting the sealing performance. At the same time, the structure and processing parameters of metal graphite wound gasket had direct influence on the properties of the gasket.

Wu Shuji (2012) had designed bimetallic self-sealing gasket by improving the structure of wave-tooth composite gasket. The most important advantage of this kind of sealing gasket was that it had the property of self-sealing.

Liu Wei (2017) had analyzed the failed metal tooth gasket and found that the local stress of gasket was concentrated due to the limitation of processing technology during the gasket processing, and the bolt force was uneven due to the improper bolt tightening method during the gasket assembly operation, and the brittle fatigue fracture of shim had reached the failure due to the joint action of gasket compression load and high temperature load during the equipment operation.

Through cyclic loading and unloading, Zheng Xiaotao et al. (2016) had studied the effect of temperature on the compression springback performance of flexible graphite metal wave-tooth composite gasket. According to the experimental results, the compression modulus of the wave-tooth composite gasket had increased with the increase of the loading rate at high temperature. As the number of

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College of Mechanical and Electronic Engineering, China University of Petroleum (East China), No. 66, Changjiang West Road, Huangdao District, Qingdao 266580, Shandong, China.

cyclic compression increased, the compression modulus of gasket had decreased gradually, but it was always higher than that of the first compression; With the increase of the number of cycles, the maximum amount of gasket compression had increased gradually, showing a more obvious ratchet effect.

Gu Boqin et al. (2000) had carried out compression springback test and high-temperature creep and sealing test on stainless steel skeleton flexible graphite wound gasket. Through the analysis of test data, it could be seen that with the increase of test temperature and gasket assembly stress, the compression amount of stainless steel skeleton flexible graphite wound gasket increased, and the springback rate of the gasket had decreased with the increase of temperature. Under the action of assembly stress, the gasket would creep at room temperature, and the creep variable had increased with the increase of temperature. The leakage rate had a negative exponential relation with the assembly stress of gasket and a positive exponential relation with the test temperature.

In 1999, the Material Testing Institute of Stuttgart University in Germany had carried out a project study on MTM bolted flange connection, and the compression and springback tests were carried out on graphite filled winding gaskets used in grooves and graphite filled winding gaskets with metal rings. The test results of H. Kockelmann (2000) and Roos Eberhard (2002) showed that the most important dimension parameter for the winding gasket used in the groove was the radial clearance size between the outside diameter of the gasket and the groove. With a metal ring winding gasket to prevent excessive gasket stress, spacer width was best 10 mm or less.

Research status of bolt flange connection performance and gasket test

The performance research of bolted flange joint was usually carried out by numerical simulation and experimental research. The finite element method was used in the papers of Dong Zhi et al. (2015), Chen Sunyi (2016), Wang Qing (2011) and other literatures. Lin Guojun (2015), Luo Congren (2013), Abid (2006), Nagata and Sawa et al. (2008) also used ANSYS finite element analysis software for analysis. On the basis of the room temperature test, A. Bagergui et al. (1989) had designed and established a gasket high temperature leakage test device, and proposed a set of gasket high temperature sealing performance test method. In China, Wen Weiping (2016), Sang Cong et al. (2016), Yu Jianliaing (2013) and others have started to carry out the high temperature sealing performance research work of gasket. An Yuansheng et al. (2016) and Ma Xiang (2015), from the fluid seal research center of East China University of Science and Technology, had carried out an in-depth study on the requirements of nuclear seals the testing equipment, which could detect seal compression and springback, high temperature creep, sealing performance, stress relaxation and other functions had been designed successfully.

In summary, there are many factors affecting the performance of bolt flange. For the compression springback performance of gasket, the performance of self-sealing and stress compensation is very important. The structure type of fishbone gasket determines that it has self-sealing performance and stress compensation ability, and the mechanical and sealing performance can be further improved by optimizing its structural parameters by means of numerical simulation and test. Therefore, the research content of this paper was carried out.

THE BRIEF INTRODUCTION OF FISHBONE GASKET

A new type of fishbone gasket was taken as the researcch target, and its mechanical and sealing properties were studied in this paper. The structure of fishbone gasket was mainly composed of metal skeleton, nonmetallic coating and reinforcement ring, as shown in Figure 2-1. The section shape of metal skeleton seal part was like fish skeleton, with multi-layer coaxial arc teeth facing the sealing medium up and down, and flexible graphite or polytetrafluoroethylene (PTFE) could be selected as nonmetallic coating. The central section and outboard of skeleton was reinforcement ring, the outer reinforcement ring could be added as the case may be, this simulation study had no outer reinforcement ring. The research of Zhao Jingwei (2015) showed that fishbone gasket could directly replace other traditional sealing gasket of similar structure, such as Metal graphite wound gaskets and Corrugated composite gasket with the same outer diameter, inner diameter and thickness, etc.

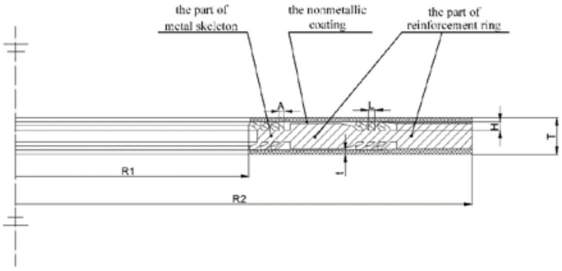


Figure 2-1 Basic structure brief diagram of fishbone gasket

The important structure of the metel skeleton sealing surface of the fishbone gasket was the fishbone arc tooth structure facing the sealing medium, which made it have the self-sealing function. The reasearch of Justin Zhao (2014) showed that at the top of the structure, it was semi-circular arc in contact with the upper and lower flange surface, so it was not easy to damage the dense flange cover and had good elasticity.

COMPRESSION SPRINGBACK ANALYSIS OF FISHBONE GASKET SKELETON

Due to the numerical simulation of graphite materials was very difficult, and when the thickness and density of graphite layer were certain, the gasket performance mainly depended on the performance of the skeleton, so the finite element analysis was mainly carried out on the metal skeleton.

The geometric structure, load and displacement of fishbone gasket all met the axisymmetric conditions, and its grid could be divided on any meridian plane. Therefore, the two-dimensional axisymmetric simplified model was used for finite element analysis to study its mechanical properties. According to the study of Zhou Xianjun et al. (2015), the properties of skeleton materials were defined as elastic modulus was 2.05 $\times 10^5$ MPa, Poisson's ratio was 0.3, bilinear kinematic Hardending bilinear follow-up strengthening yield strength was 235 MPa, tangent modulus was 6100MPa. After many simulations and attempts, when the stress reached 40MPa, the stress would rise in a straight line after continuous loading, indicating that the reinforcing ring had began to contact and bear pressure. Therefore, 45MPa was determined as the pressure of compression test in the finite element analysis, and the springback rate of the gasket was tested by unloading after the compression was completed.

The parameters of the gasket were shown in Table 3-1, and its simulation model of metal skeleton was eastablished as shown in Fig 3-1. The compression state and contact stress of gasket skeleton model were shown in Fig 3-2 and 3-3. According to the simulation results, the compression rate of metal skeleton was 3.9%, and the springback rate was 10.6%.

Table3-1 Dimensions of fishbone gaskets

Pitch	0.7mm
Tooth thickness	0.5mm
Tooth height	1.05mm
The thickness of graphite coating	0.5mm
Inner diameter (D_1)	310mm
Outer diameter (D_2)	363mm
The thickness of gasket (H)	4.6mm

Under the action of load, the curved tooth structure of the skeleton of the fishbone gasket deformed to the center of the gasket, while the oblique teeth of both sides bent and deformed downward, resulting in contact stress with the upper and lower flanges. Multiple sealing surfaces were formed in the working process of the fishbone gasket, thus playing a good sealing function. Because the internal pressure was not applied, the self-sealing structure of the gasket had not yet worked, so the deformation of the inner tooth was large but the contact stress was low.

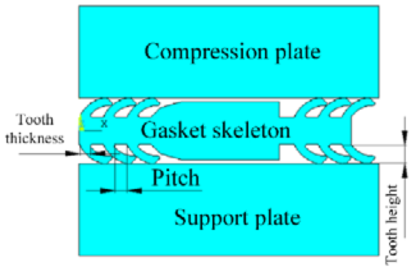


Fig 3-1 ANSYS model of fishbone gasket

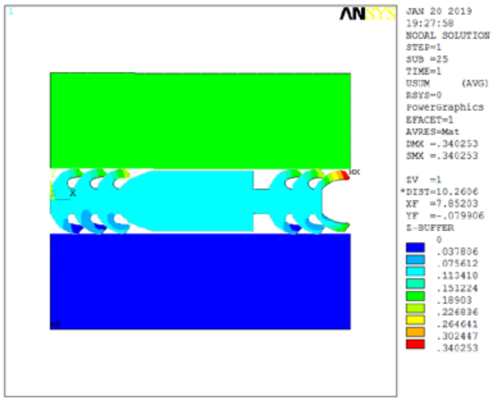


Fig 3-2 Compression state of fishbone gasket skeleton

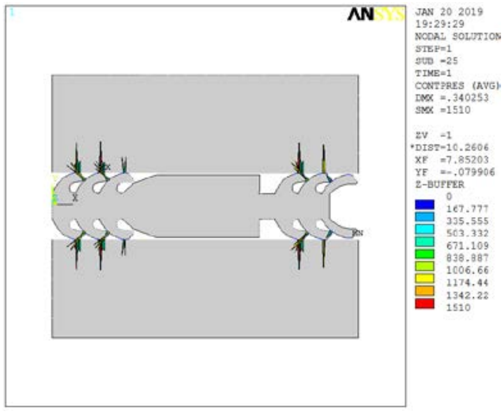


Fig 3-3 Contact stress of fishbone gasket skeleton under compression

Selection of structural parameters and orthogonal design of fishbone gasket

The metal skeleton of fishbone gasket was the main factor affecting its compression springback performance. According to the existing metal skeleton structure of gasket, the three main structural parameters of tooth height, tooth thickness and pitch were extracted as the research objects. As shown in Fig 3-1, the structural parameters were properly selected, combined with ANSYS software, orthogonal test method and the papers of Chen Qing et al. (2003,2014,2016), Teng Jiazhuang et al. (2016), Qiao Tianxing (2015), the compression springback characteristics were studied. The factor level was shown in Table 3-2.

According to the factor-level table of Chang Zhaoguang (2009), the orthogonal test of three factors and three levels was determined, and the orthogonal table L9 (3^4) was selected. According to the orthogonal test table, the head of table was designed as Table 3-3.

Table 3-2 Levels of metal skeleton factors for fishbone gaskets

factor \ level	1	2	3
Tooth height (mm)	0.95	1.05	1.15
Tooth thickness (mm)	0.4	0.5	0.6
Pitch (mm)	0.6	0.7	0.8

Table 3-3 Header of orthogonal test form

Column number	1	2	3
Factor	Tooth height (A)	Tooth thickness (B)	Pitch (C)

Experimental study on orthogonal simulation of metal skeleton structure of fishbone gasket

According to the results of the numerical simulation, the most important factors affecting the compression rate and springback rate were found out, the influence degree of each factor on the compression rate and springback rate was determined, and the optimal horizontal combination was selected. The simulation results were as shown in Table 3-4, and the results processed by orthogonal intuitive method were shown in Table 3-5.

Table 3-4 Table of simulation test results of metal skeleton compression springback

Factor \ Test No.	Tooth height	Tooth thickness	Pitch	Compression rate	Springback rate
1	A1	B1	C1	3.16%	11.40%
2	A1	B2	C2	2.70%	10.20%
3	A1	B3	C3	6.02%	9.22%
4	A2	B1	C2	3.75%	11.80%
5	A2	B2	C3	4.30%	13.46%
6	A2	B3	C1	2.92%	11.21%
7	A3	B1	C3	3.36%	11.57%
8	A3	B2	C1	3.69%	11.28%
9	A3	B3	C2	3.38%	10.65%

Table 3-5 Results of data processing by visual method

Level	Compression rate%			Springback rate%		
	Tooth height	Tooth thickness	Pitch	Tooth height	Tooth thickness	Pitch
K_{i1}	3.960	3.423	3.273	10.273	11.590	11.297
K_{i2}	3.673	3.563	3.277	12.157	11.647	10.883
K_{i3}	3.477	4.123	4.560	11.167	10.360	11.417
R	0.483	0.700	1.287	1.884	1.287	0.534
Better level	A1	B3	C3	A2	B2	C3
Primary and secondary factors	3	2	1	1	2	3

From the processing results, it could be seen that the compression rate of metal skeleton met certain operating conditions and the springback rate was maintained well. The main factors affecting the compression rate were pitch, tooth thickness, tooth height and in turn, and the main factors affecting springback rate were tooth height tooth thickness, and pitch in turn. The optimum programme of compression rate was A1B3C3, that was, the tooth height was 0.95 mm, the tooth thickness was 0.4 mm, and the pitch was 0.8 mm. The optimum programme of springback rate was A2B2C3, that was, the tooth height was 1.05 mm, the tooth thickness was 0.5 mm, and the pitch was 0.8 mm. In the gasket standard, the compression rate is confined within a certain range. When the compression rate index was met, the higher springback rate made the gasket more adaptable to the fluctuation of pressure and temperature, and improved the sealing performance of the gasket. So the springback rate was more important compared with the compression rate. Therefore, the structural parameters were selected as A2B2C3, that was, tooth height 1.05 mm, tooth thickness 0.5 mm, pitch 0.8 mm.

Compared with the results of the structural parameters of the original gasket, the compression rate of the metal skeleton increased by 10.26% and the springback rate increased by 26.98% after the optimization of the parameters.

COMPRESSION SPRINGBACK TEST OF FISHBONE GASKET AT DIFFERENT TEMPERATURES

The solid fishbone gasket was processed with the optimized parameters. The metal skeleton of the gasket was 304 stainless steel and the nonmetallic coating was flexible graphite. The compression springback performance of the gasket was studied at different temperatures. The curve of the compression springback performance of the fishbone gasket was drawn by using the test data, and the relationship of changing with temperature between the compression springback performance of the gasket and the temperature was studied by Qiu Xingqi et al.(2001), Shang Qingjun et al.(2003) and Zhou Xianjun et al.(2003).

Test conditions and equipment

Using 300T high temperature universal seal testing equipment, the compression springback test of fishbone gasket was carried out at room temperature, 125 ℃, 257 ℃ and 360 ℃ respectively. The No.1 test was loaded with 5 MPa, 15 MPa, 25 MPa, 35 MPa, 45 MPa to load cyclically, the loading curve was shown in Fig 4-1, the test was directly loaded to the maximum stress of 45MPa, the loading curve was as shown in Fig 4-2, and the test conditions were shown in Table 4-1 below.

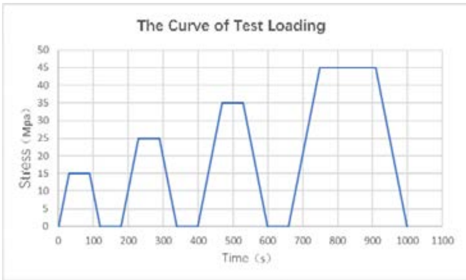


Fig 4-1 Room temperature loading curve

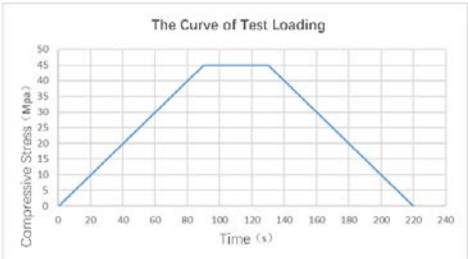


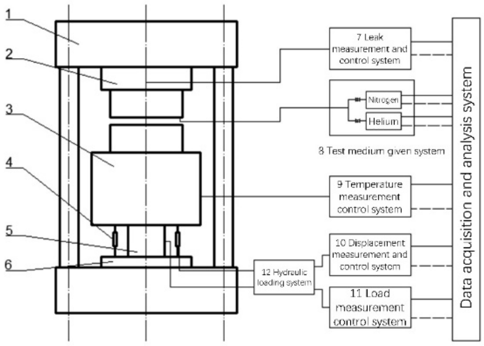
Fig 4-2 High temperature loading curve

The 300T high temperature universal seal testing equipment was used in the test, as shown in Fig 4-3 and 4-4. The device mainly includes press machine, simulated flange, test system, displacement sensor, load sensor, servo cylinder, oil cell and oil pump, electric control cabinet, test control system and computer. After setting the corresponding test program and parameters, the equipment automatically run and collectd and calculated the relevant data of gasket.

Table 4-1 Test data processing table

Test No.	Ambient temperature （℃）	Loading rate （MPa/s)	Unloading rate （MPa/s）	Heating up （℃/min）	Initial stress （MPa）	Ultimate stress （MPa）
1	Room temperature	0.5	0.5	5	1	45
2	125	0.5	0.5	5	1	45
3	257	0.5	0.5	5	1	45

4	360	0.5	0.5	5	1	45



1.Press machine 2. Simulated flange 3. Test unit 4. Displacement sensor 5. Load sensor 6. Servo cylinder

Fig 4-3 System diagram

Fig 4-4 Physical chart of equipment

Analysis of the test results of fishbone gasket

Fig 4-5 was the compression springback curve of gasket drawn according to the test data at room temperature, the abscissa was the strain of gasket under load, and the ordinates was gasket stress.

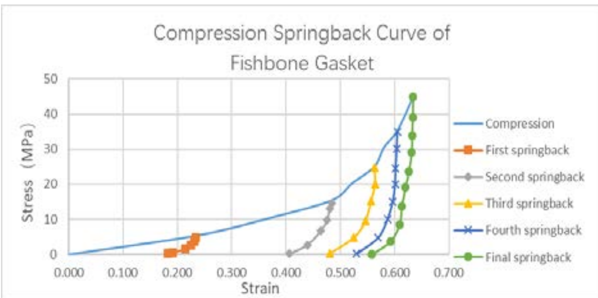


Fig 4-5 The curve of compression springback at room temperature

As shown in Fig 4-5, the curve showed nonlinear characteristics from the compression springback curve of fishbone gasket. Under initial loading, the stress of gasket changed little, the deformation changed greatly, and the slope of curve was small. With the increase of test stress, the deformation had increased gradually and the slope of curve had increased gradually. When the contact stress of gasket reached about 42MPa, the load had continued to increase, the curve rose sharply, the stress increased continuously, but the deformation changed little. It could be concluded that when the contact stress exceeded 42MPa, the basic compaction between gasket and flange could be obtained reinforcement ring bearing load of bolt and storing stress, the stress of the sealing part was basically unchanged. Therefore, when the pressure fluctuation occurs under the actual operating condition, the reinforcement ring could release or store part of the stress, thus enhancing the ability of the fishbone gasket to adapt to the pressure fluctuation.

The performance curve of fishbone gasket at four temperatures was shown in Fig 4-6.

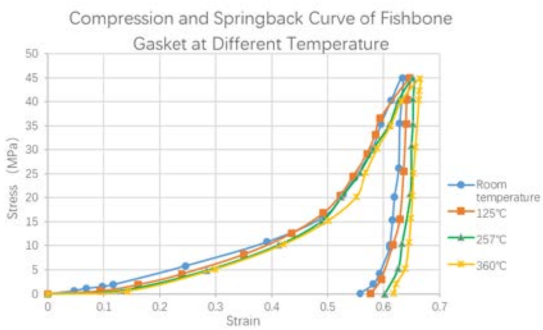


Fig 4-6 Compression springback of fishbone gasket at different temperatures

Fig 4-6 showed that the compression springback curve of fishbone gasket changed at different temperatures. It could be seen from the curve that with the increase of temperature, the compression rate had increased and the springback rate had decreased, the slope of the compression curve also had decreased gradually, and the slope of the springback curve had increased. On the whole, the performance of gasket was affected by temperature to a certain extent, but the performance was stable in the range of test temperature.

The comprehensive analysis showed that for the fishbone gasket in practical use, it was necessary to ensure the compaction of the gasket and flange, and the resulting contact stress was stable and could ensure the strong adaptability of the fishbone gasket. Taking the gasket studied as an example, the contact stress of the fishbone gasket should exceed 40 MPa when installed. After the value was larger than this, part of the fishbone was compressed and deformed, and the reinforcing ring had began to bear pressure. According to this, the lower limit of bolt preload could be determined.

EXPERIMENTAL STUDY ON SEALING PERFORMANCE OF FISHBONE GASKET

The sealing performance test of fishbone gasket at room temperature was tested by A, B test method. A, B test method was a very scientific and effective sealing testing method which was first studied and demonstrated by PVRC in the United States. The test is composed of two processes of A, B, usually A is carried out first and then. A test process was used to test the sealing performance of gasket installation process and different sealing media, and B test process was used to test the simulation of gasket working condition and the sealing performance under different assembly stress. After the B test was done, the more accurate performance parameters of the gasket could be obtained by analyzing the test data and the sealing performance of the test gasket was evaluated accurately and scientifically by Wang Xuewen et al.(1994). Under the test conditions, the medium pressure to be selected was 1.6 MPa, 3.2 MPa, 4.9 MPa, and the assembly stress of the gasket was 15 MPa, 25 MPa, 35 MPa and 45 MPa respectively.

The leakage rate curve measured by fishbone gasket at room temperature A and B test was shown in Fig 5-1, 5-2. According to the analysis of leakage rate curve, it could be seen that:

(1) In the A test part, as shown in Fig 5-1 under the same assembly stress, the leakage rate of fishbone gasket had increased gradually with the increase of nitrogen pressure, and the greater the nitrogen pressure was, the greater the leakage rate was. Under the assembly stress of 15MPa, the leakage rate was relatively high. Although the assembly stress of gasket had reached 25MPa, the sealing performance of gasket had tended to be stable, and the leakage rate curve was gradually smooth when the assembly stress had continued to increase. When the assembly stress had reached 35MPa, the leakage rate had tended to be stable, and the sealing performance of fishbone gasket had entered the best state.

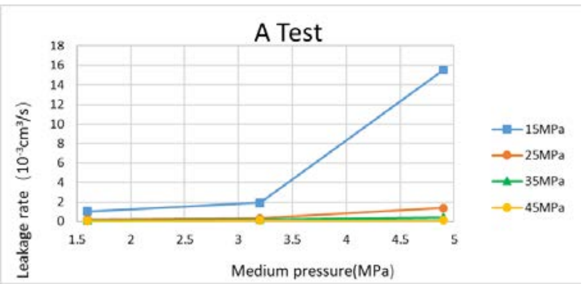


Fig 5-1 The curve of A test leakage rate

(2) In the B test part, as shown in Fig 5-2, under the same nitrogen pressure, the assembly stress of the gasket had decreased from 45 MPa to 25 MPa, and the leakage rate of the gasket had increased gradually with the decrease of the assembly stress of the gasket, but the tendency of the increase in leakage rate was not obvious, and it had increased obviously when the assembly stress decreased to 15 MPa.

From the analysis of the test data, the compactness of fishbone gasket reached T_3 (tight type) level (Cai Renliang (1997)), and the sealing performance was excellent. When the assembly stress of internal pressure 4.9MPa had decreased to 15MPa, the leakage rate had increased obviously, but the decrease of tightness could still reach T_2 (standard type) level. Compared with the need for assembly stress to reach 40MPa in the study of mechanical properties of skeleton, the leakage rate could be maintained when the assembly stress had reached 35MPa in the sealing performance test, which was related to the influence of sealing covering layer and self-sealing structure on the surface of gasket.

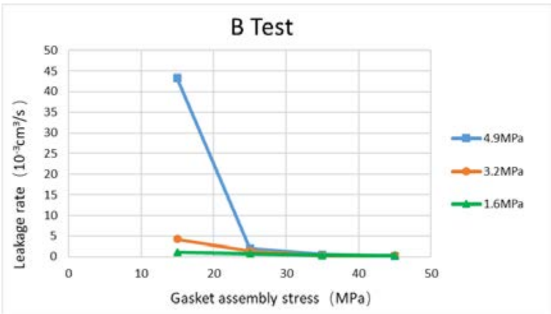


Fig 5-2 The curve of B test leakage rate

CONCLUSION

(1) Using the ANSYS finite element analysis software and the orthogonal test method, the parameters of the skeleton of the fishbone were optimized, and the optimal structural parameters were the tooth height of 1.05 mm, the tooth thickness of 0.5 mm and the pitch of 0.8 mm. The compression rate of the metal skeleton increased by 10.26% on the original basis and the springback rate was increased by 26.98% after the parameter optimization.

(2) According to the experimental results, the compression springback curve of fishbone gasket showed nonlinear characteristics, and the temperature affected the compression springback performance of fishbone gasket. In the same case, the compression rate had increased with the increase of temperature, and the springback rate had decreased with the increase of temperature, but the performance was stable in the range of test temperature. After the contact stress of the gasket was over 40MPa, the gasket and flange were basically compacted, and the reinforcement ring bore the load of bolt and stored the stress. The lower limit of bolt preload could be determined accordingly.

(3) Through the analysis and treatment of

fishbone gasket at room temperature A, B sealing test data could be determined that the sealing performance was excellent. The nitrogen leakage rate of gasket was affected by gasket load and nitrogen pressure. From the A test, it could be seen that the leakage rate of fishbone gasket had increased gradually with the increase of nitrogen pressure under the same assembly stress. After the assembly stress reached 35MPa, the sealing performance of fishbone gasket had tended to be stable, the leakage rate changed little, and the tightness had reached T_3 (tight type) level in the range of 0.064-$0.12\times10^{-3}cm^3/s$. From the B test, it could be seen that the leakage rate of the gasket had tended to be stable with the gasket under the same nitrogen pressure，the decrease of assembly stress had increased gradually. When the assembly stress was gradually unloaded, the external reinforcement ring of the metal skeleton of gasket could compensate for a certain stress loss. When the stress continued to decrease, the metal skeleton of gasket had its unique self-sealing structure of oblique tooth, which made the gasket leakage rate remain in a stable range when the assembly stress had decreased, but when the assembly stress had decreased to 15MPa, the leakage rate had increased obviously and the tightness had decreased to T_2 (standard type) level.

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