Structure Optimization and Sealing Performance of Double Corrugated Self-Sealing Composite Gasket

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Abstract. A self-sealing nickel-titanium (NiTi) alloy double corrugated composite gasket was designed. The number of corrugation (5-7), the amplitude of corrugated (0.2-0.4 mm), the thickness of corrugated skeleton (0.5-1.0 mm) and the seam width (0.2-0.4 mm) of the composite gasket were selected to design a four-factor and three-level experimental scheme by orthogonal experimental method. The ANSYS finite element software was used to study its compression resilience and sealing performance. The statistica software was used to process the data by multi-factor analysis of variance. The results showed that the corrugated number was the most significant factor affecting the resilience rate, and the slot width was the most significant factor affecting the compression rate. The optimal scheme for the resilience performance was obtained. The sealing performances of self-sealing composite gasket and common corrugated composite gasket were compared. The results showed that self-sealing composite gasket had better sealing performance.

1. Introduction
The corrugated metal composite gasket is a new type of sealing gasket which was developed on the basis of corrugated metal gasket. It is a composite gasket which comprises the skeleton material of corrugated metal plate, and the upper and lower covering layer of flexible graphite or polytetrafluoroethylene [1]. This kind of gasket has good resilience of corrugated metal plate, and it also has high melting point, corrosion resistance and sealing performance. This gasket is widely used in petrochemical industries [2].

Self-sealing composite gasket is a new type of gasket and there is a narrow gap in the skeleton material. The gap will be pressed by bolt pre-tightening force. The medium will enter the gap of the pressing. The medium pressure in the gap will act on the flange and gasket contact surface in reverse so as to form the self-sealing effect. With the increase of the medium pressure, the self-sealing effect will be better [3]. A bi-metallic self-sealing composite gasket was introduced by Gao et al. This kind of gasket was used to solve the sealing problem of large-diameter flange connection [4]. The bimetal self-sealed wave tooth gasket based on the orthogonal test method was designed by Zhou et al. The finite element method was used to study the compression and resilience property [5].
Self-sealing gasket has good sealing performance, but its compression resilience is general. NiTi shape memory alloy material has excellent superelastic effect, good damping performance and corrosion resistance characteristics. Gasket skeleton made of NiTi alloy material can compensate the gap of flange connection caused by the reduction of preload and reduce the leakage rate of sealing connection [6]. The relationship between the compression-resilience property of NiTi alloy and ambient temperature was studied by Lu et al. The experimental results showed that the compression-resilience property of NiTi alloy depended on ambient temperature. When the compression stress was higher than a certain level, the compression and the recovery coefficient had little change at the completion temperature of austenite transformation. With the decrease of temperature, the residual strain of NiTi alloy increased [7]. Zhou et al. investigated leakage rate of sealing connection structure changing with preload, medium pressure and temperature. The results showed that the NiTi alloy had the characteristics of hyperelasticity under compression load. The resilience rate of samples under different compression stresses is more than 99%.

The NiTi alloy double corrugated self-sealing composite gasket was designed in this paper. The compression-resilience of the composite gasket was studied by using ANSYS finite element software. The sealing characteristics of the self-sealing composite gasket and the conventional corrugated composite gasket were compared.

2. Research contents and methods
The specific type of NiTi double corrugated self-sealing composite gasket designed in this paper was shown in Figure 1. It was mainly composed of four parts. The middle is H-type slotted stainless steel plate. The upper and lower were NiTi corrugated skeletons. The outer surface of the corrugated skeleton was composed of flexible graphite with a certain thickness. Among them, the H-type stainless steel plate was composed of two metal plates superposition welded into a whole structure, with a narrow gap left in the middle. The NiTi corrugated skeleton was bonded to the upper and lower parts of the H-type stainless steel plate, and the graphite was bonded to the NiTi corrugated skeleton. When the gasket was at work, the NiTi corrugated skeleton and H-type metal plate was pressed by the flange contacts the flexible graphite. The flexible graphite provided the main compression amount and improved the sealing performance. NiTi alloy corrugated skeleton can compensate the gap of flange connection caused by the reduction of preload, enhance the sealing effect and reduce the leakage rate of flange connection due to its hyperelasticity. When the H-type slotted stainless steel plate was under operating conditions, the medium pressure entered into the gap and caused the gasket to press against the flange surface. The attached pressure stress was formed and the sealing performance was improved.

Figure 1. Structure of NiTi double corrugated self-sealing composite gasket.

Gasket skeleton was referenced on metal tooth gasket size standard JB/T88-2014. The inner and outer diameters of gasket skeleton were 149 mm and 105 mm, respectively. The thickness of the intermediate stainless steel plate was 2 mm. The height of the inner and outer rings on the edge of the metal plate was 3 mm. The thickness of the graphite layer was 0.1-0.5mm higher than the wave crest of NiTi alloy. The length of the corrugated skeleton was 18 mm. The corrugated number $N$, corrugated amplitude $H$, corrugated skeleton thickness $T$ and seam width $C$ of the gasket were selected as the research objects. The orthogonal experiment method was adopted to design the four-factor and three-level test scheme. The specific parameters were shown in Table 1. The ANSYS was used to simulate the compression-resilience of gasket. The statistica multi-factor variance analysis was conducted with the orthogonal experimental results. The effect of each factor on the compression-resilience was further
investigated. At the same time, based on optimization results of the orthogonal experimental, the ANSYS simulation was used to analyze the sealing characteristics of the self-sealing composite gasket.

Table 1. Factor level table.

| Factors                  | Corrugated Number $N$ | Corrugated amplitude $H/\text{mm}$ | Skeleton thickness $t/\text{mm}$ | Seam width $C/\text{mm}$ |
|--------------------------|-----------------------|-----------------------------------|---------------------------------|--------------------------|
| The level of             |                       |                                   |                                 |                          |
| 1                        | 5                     | 0.2                               | 0.5                             | 0.2                      |
| 2                        | 6                     | 0.3                               | 0.8                             | 0.3                      |
| 3                        | 7                     | 0.4                               | 1.0                             | 0.4                      |

3. Relationship between structural parameters and compression-resilience property

3.1. Orthogonal experimental design

According to Table 1, 9 groups of orthogonal experiments were designed, as shown in Table 2. Since the NiTi double corrugated self-sealing composite gasket generally only bears axial load and was circular in structure, the effect of bolt load was ignored and the composite gasket was set as an axisymmetric model. For the flange connection structure, the stress is transmitted from the flange end face when the gasket is at work. In order to simulate the real stress condition of the corrugated composite gasket, contact analysis for the corrugated crest was established. The upper and lower elastic plates were used to exert pressure on the metal skeleton. The load and Y-axis displacement constraints were applied to the upper plate. The lower plate was set as the fixed constraint.

Quadrilateral was mainly used for grid division. The grid size was 0.05 mm. The grid division of the overall model of gasket was shown in Figure 2. When the compression-resilience property was analyzed, the load application was mainly divided into three steps, namely initial boundary application, loading to 60 MPa and unloading to 0 MPa. The material parameters of NiTi alloy were obtain in reference [8].

According to the formula of software output of the axial deformation and compression resilience, the compression rate and resilience rate of the gasket were obtained. The compression rate $C$ and resilience rate $R$ were shown in the formula (1) and (2).

$$C = \frac{T_2}{T_1} \times 100\% \quad (1)$$

$$R = \frac{T_1 - T_2}{T_1} \times 100\% \quad (2)$$

In the formula, $T_1$ was the compression amount under the total load of 60 MPa, mm; $T_2$ was the compression amount returned to 0 MPa, mm; $T$ is the initial thickness of the gasket, mm.

Figure 2. Finite element model of composite gasket.
Table 2. Orthogonal test results.

| Number | Number of wavelets N/unit | Corrugated amplitude H/mm | Corrugated skeleton thickness t/mm | Seam width C/mm | Compression ratio / % | Resilient rate / % |
|--------|---------------------------|---------------------------|----------------------------------|-----------------|----------------------|-------------------|
| 1      | A₁                        | B₁                        | C₃                               | D₂              | 7.70%                | 55.03%            |
| 2      | A₂                        | B₁                        | C₁                               | D₁              | 7.76%                | 58.50%            |
| 3      | A₃                        | B₁                        | C₂                               | D₃              | 9.30%                | 51.88%            |
| 4      | A₁                        | B₂                        | C₂                               | D₁              | 7.01%                | 50.22%            |
| 5      | A₂                        | B₂                        | C₃                               | D₃              | 8.61%                | 60.82%            |
| 6      | A₃                        | B₂                        | C₁                               | D₂              | 8.91%                | 52.44%            |
| 7      | A₁                        | B₁                        | C₁                               | D₃              | 11.80%               | 44.42%            |
| 8      | A₂                        | B₃                        | C₂                               | D₂              | 7.65%                | 54.86%            |
| 9      | A₃                        | B₃                        | C₃                               | D₁              | 5.42%                | 58.43%            |

3.2. Analysis of compression resilience of gasket

The orthogonal experimental results were shown in Table 2. It can be seen from the table that the compression rate of the self-sealing composite gasket was about 9% and the resilience rate was greater than 44% which were higher than that of the conventional corrugated composite gasket. The Multi-factor analysis of variance was shown in Table 2. The analysis results were shown in Table 3. The relationship between gasket skeleton parameters and compression and resilient rate were shown in Figure 3 and Figure 4, respectively.

As can be seen from Table 3, the influencing factors of the gasket resilience rate were the corrugated number > the skeleton thickness > the seam width > the corrugated amplitude. Figure 3 and Figure 4 showed that the resilience rate increased with the increase of corrugated skeleton thickness and decreased with the increase of seam width and corrugated amplitude. The compression rate decreased with the increase of corrugated skeleton thickness and increased with the increase of corrugated amplitude and seam width. The optimal framework parameter scheme for the resilience of NiTi double corrugated self-sealing composite gasket was A₂B₁C₃D₁. The corrugated number was 6, the corrugated amplitude was 0.2 mm, the skeleton thickness was 1.0 mm, and the seam width was 0.2 mm.

Table 3. The variance analysis between the resilience rate and skeleton parameters of gasket.

| The source                  | Type III Sum of squares | d₁ | The mean square | F         | P          |
|-----------------------------|-------------------------|----|-----------------|-----------|------------|
| Seam width                  | 0.003                   | 2  | 0.001           | 3.0×10⁷   | More significant |
| Corrugated Number           | 0.015                   | 2  | 0.007           | 1.8×10⁸   | More significant |
| Corrugated amplitude        | 0.001                   | 2  | 0.001           | 1.6×10⁷   | More significant |
| Skeleton thickness          | 0.011                   | 2  | 0.006           | 1.3×10⁸   | More significant |
| Error                       | 2×10⁻¹⁰                 | 6  | 4.2×10⁻¹¹       |           |            |
| Total                       | 4.460                   | 15 |                 |           |            |
| Correction of total         | 0.029                   | 14 |                 |           |            |
4. Analysis of gasket seal characteristics

The effective sealing width of the gasket was set to be equal to the radial width of the gasket during analysis. The lower surface of the flange connection was taken as the fixed load, and a 40 kN pretightening force was applied to the gasket. At the same time, applied a certain medium pressure at the sealing surface and gasket gap where the inner wall of the flange and gasket is not in contact with the gasket. In order to compare the sealing performance of NiTi double corrugated self-sealing composite gasket and traditional corrugated composite gasket.

The stresses of NiTi double corrugated self-sealing composite gasket and corrugated composite gasket at the medium pressure of 50 MPa were shown in Figure 5 and Figure 6, respectively. The maximum compressive stress of self-sealing gasket and corrugated composite was 61.9MPa and 31.0MPa, respectively. The overall contact compressive stress of the self-sealing composite gasket was greater than that of the corrugated composite gasket. Therefore, the NiTi double corrugated self-sealing composite gasket can provide better sealing performance for bolted flange connection.

Figure 3. Relation curve between gasket Skeleton parameters and resilience rate.

Figure 4. Relation curve between gasket skeleton parameters and compression rate.

Figure 5 Stress diagram of self-sealing gasket.

Figure 6 Stress diagram of corrugated gasket.

Figure 7 showed the relationship between maximum contact compressive stress of the crest and the medium pressure. The results showed that the contact compressive stress at the crest of the corrugated composite gasket decreased gradually with the increase of medium pressure. The contact compressive stress of self-sealing composite gasket increased with the increase of medium pressure. When the medium pressure is lower than 7 MPa, the contact compressive stress of the corrugated composite gasket was greater than that of the self-sealing composite gasket. When the medium pressure was greater than 7 MPa, the contact compressive stress of the self-sealing composite gasket was higher than that of the corrugated composite gasket. It can be indicated that the corrugated composite gasket had better sealing performance at low pressure level, and the self-sealing composite gasket can provide greater contact pressure and better sealing effect at high medium pressure.
5. Conclusion
The performance of compression resilience of NiTi double corrugated self-sealing composite gasket was analyzed. It showed that the resilience rate of the new gasket was over 44%, which was obviously better than the traditional metal composite gasket. The dimension parameters of self-sealing composite gasket were analyzed, and the optimal parameter scheme was $A_2B_1C_3D_1$. The sealing characteristics of gasket were investigated. When the medium pressure was greater than 7 MPa, the sealing performance of the self-sealing composite gasket was better than that of the conventional corrugated composite gasket.

![Figure 7. Relationship between gasket contact compressive stress and medium pressure.](image)

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