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EVALUATION OF SEALING PERFORMANCE OF METAL GASKET USED IN DUAL PURPOSE METAL CASK CONSIDERING AGEING OF METAL GASKET UNDER LONG-TERM STORAGE

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ABSTRACT

A dual-purpose metal cask is sealed by bolting the lids with metal gaskets. However, the sealing performance is affected when the metal gasket is subjected to high temperatures for a long period; therefore, it is necessary to consider the aging effect of the metal gaskets. The residual linear load and total spring-back distance of a metal gasket might decrease due to the creep deformation of the outer jacket made of soft metal. To examine the compressive creep characteristics of an outer jacket made of heat-treated aluminum (A1050-O), compressive creep tests have been performed under various levels of stresses, temperatures, and loading durations. Based on these test results, we have proposed a creep constitutive model for numerical evaluation [1]. In the present study, the creep constitutive model was re-evaluated according to additional creep tests. To improve the numerical methodology for evaluating the sealing performance of the metal gasket subjected to aging over long-term usage, the compressive creep model of aluminum gaskets installed in the finite element method (FEM) code ABAQUS was also modified. A relaxation analysis was performed considering the actual overall gasket complex configuration to calculate the residual linear loads and total spring-back distance of the metal gasket. Moreover, we also metallographically examined the sample of the outer jacket used in the long-term sealing test and found that the specimen featured no remarkable growth in grain size.

INTRODUCTION

Although the dry interim storage of spent nuclear fuel in transport and storage metal casks has been licensed internationally to span a period of 40–60 years, extended periods may be necessary considering the uncertainties in future spent energy management strategies (e.g., the implementation of a sufficient reprocessing capacity and the establishment final repositories). The casks usually use metal gaskets, as shown in Fig.1, to ensure safety and steady sealing performance in the long term. Metal gaskets generally consist of a helical metal spring and inner and outer metal jackets. The outer jacket is made of a flexible metal material, such as aluminum or silver. In Japan, aluminum is adopted as the outer jackets for adhesion between the gasket and lids or cask body surface. During storage, the seal area of the cask lid systems is subjected to high temperatures due to the decay heat of the spent nuclear fuel; such temperature can accelerate aging, which can result in creep deformation of the outer jacket and a corresponding relaxation of the linear load of the gasket complex [1]. Therefore, it is important to evaluate the effect of the thermal aging on the load-deformation curve under high temperatures for long-term usage. As shown in Fig. 2, we tested two kinds of cask lid structure models: lid with a double metal gasket enveloped with aluminum and lid with a single metal gasket enveloped with silver for more than 19 years. In both models, the test temperature was maintained by electrical heaters installed in the cask cavities. The containment of the secondary lid was tested using a helium leak detector about twice a month. In a previous study, the containment performance has been demonstrated to be very reliable [2]. Moreover, we metallographically examined the sample of the outer jacket used in the long-term sealing test. Table 1 presents the comparison result of the metallographic sealability test of the outer jacket of the type-I model secondary lid gasket (based on a TN-24 cask design) after 19-year usage under a temperature of 140˚C. There was no remarkable growth in grain size in the aluminum gasket jacket.

To evaluate the sealing performance of metal gaskets used for a long period at high temperatures, understanding the creep characteristics of aluminum under high temperatures and compressive loading is important. In this study, the compressive creep characteristics were obtained by conducting compressive creep tests on aluminum under seven different temperatures and several stresses. To improve the numerical methodology for evaluating the sealing performance of metal gaskets subjected to aging over long-term usage, we modified the compressive creep model according to the results of the conducted compressive creep tests.

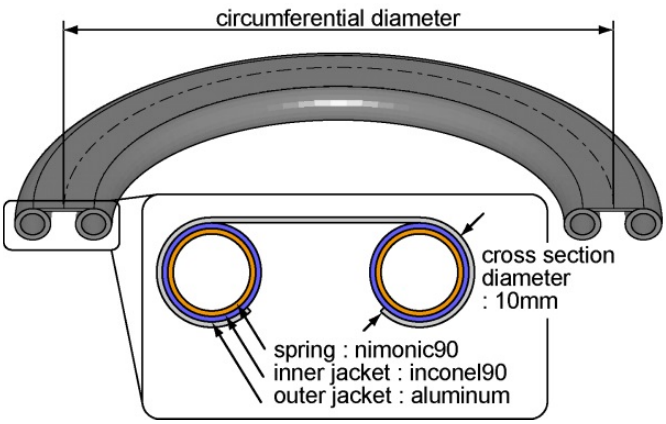


Fig. 1. Overview of a metal gasket

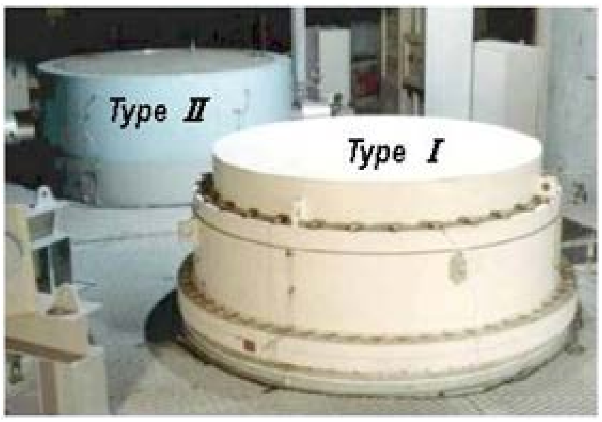
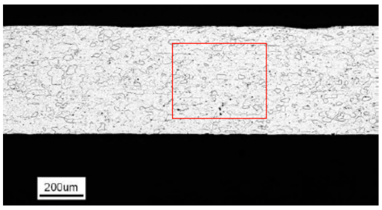
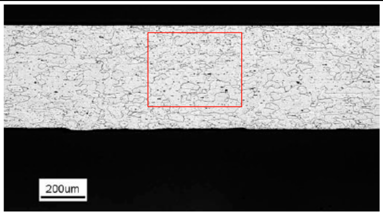
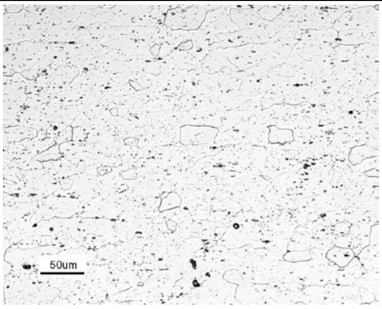
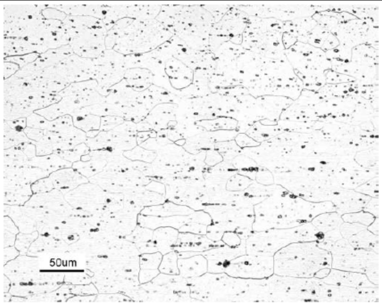


Fig. 2. Photograph of test models [2]

Table 1. Metallographical examination results of the outer gasket jacket

Magnification	Before Test	Test After 19 Years
×50		
×200		

To improve the numerical methodology for the sealing performance evaluation, we modified the compressive creep model of aluminum gaskets installed in the finite element method (FEM) code ABAQUS [1]. Moreover, to gain the representative data for the sealing performance of the gaskets used at high temperatures, the Central Research Institute of Electric Power Industry (CRIEPI) carried out relaxation tests using the test flanges for a metal gasket having an aluminum outer jacket with a full-scale cross-sectional diameter but a much smaller outer diameter at three different temperatures of 20˚C, 160˚C, and 190˚C under static conditions over longer periods of time and investigated the applicability of the modified FEM-based numerical methodology for evaluating the sealing performance of aged aluminum gasket.

1. COMPRESSIVE CREEP CHARACTERISTICS

It is important to sufficiently understand the creep characteristics of outer jackets in order to evaluate the sealing performance of the gasket used for a long term at high temperatures. In this chapter, the compressive creep tests to obtain the creep characteristics of the aluminum used as outer jacket are described. According to the test results, the existing FEM-based numerical methodology for evaluating the sealing performance of the gasket complex considering the creep characteristics [1] was modified.

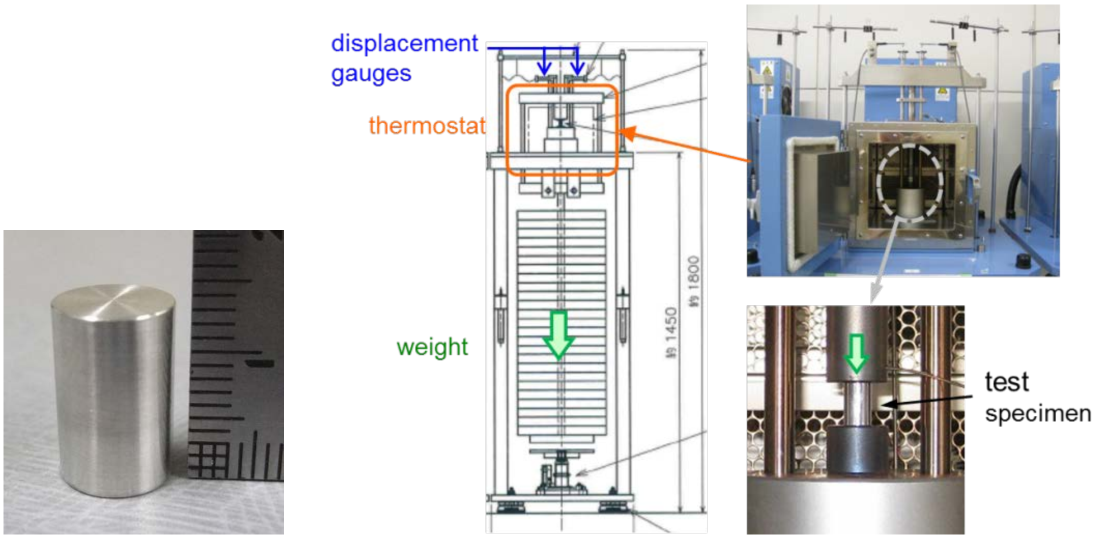
1.1 Compressive Creep Tests of Aluminum Material

(1) Test Specimen and Test Equipment

To evaluate the relaxation characteristics of the metal gasket complex, high-temperature compressive creep tests were executed using a 99.5% pure aluminum (A1050-O) heat-treated. The test specimen was columnar-shaped, with a diameter of 9 mm and height of 13.5 mm. The test equipment comprised displacement gauges, thermostat (max 250°C), and weights (300–3000 N), and could subject the test specimen to stresses at a high temperature. The thermostat temperature was adjusted by a PID control system within ±3°C, referring to the Japanese material standard JIS Z 2271 [3]. The creep strain of the test specimen was measured as compressive deformation by displacement gauges. The test specimen and the test equipment are shown in Fig. 3.

(2) Creep Test Condition

The creep tests were performed under seven different temperatures (140°C–200°C) and three different applied stresses. Using proof stress $\sigma_{0.2}$ and ultimate strength σ_u gained in the tensile tests at each temperature, the applied stresses were determined as $0.8 \times \sigma_{0.2}$, $\sigma_{0.2}$, and $0.5 \times (\sigma_{0.2} + \sigma_u)$. The temperatures and applied stresses of the creep tests are presented in Table 2. The creep tests were continued until holding time, over 1000 hours.



Test Specimen   Test Equipment

Fig. 3. Test specimen and test equipment of compressive creep test

Table 2. Temperature and applied stresses in the creep tests

Material	Temperature (°C)	Applied Stress (MPa)	Test Number	Target Heating Time
Aluminum A1050-O	140	21, 26, 34	1 for each stress	Over 1000 h
	150	20, 25, 33		
	160	19, 24, 31		
	170	18, 23, 30		
	180	17, 22, 28		
	190	17, 21, 28		
	200	17, 21, 26		

(3) Creep Test Result

The creep strain curves at 140°C and 200°C obtained in the creep tests are indicated by the solid lines in Fig. 4. Under the same condition, the creep strain curves showed repeatability and increased slowly with time. According to the curves, the strain hardening creep equation can be expressed as follows [4]:

$$\dot{\varepsilon}_c = C_1 \cdot e^{C_2 \cdot \sigma_t} \cdot \varepsilon_c^{C_3} \cdot e^{-C_4/T}$$

where $\dot{\varepsilon}_c$ is creep strain rate (/hour), ε_c is creep strain (-), and σ_t is true stress (N/mm^2). According to the test results, the coefficients in the above equation were obtained as follows:

$$C_1 = 7.423\times10^7, C_2 = 0.479, C_3 = -0.947, C_4 = 1.693\times10^4$$

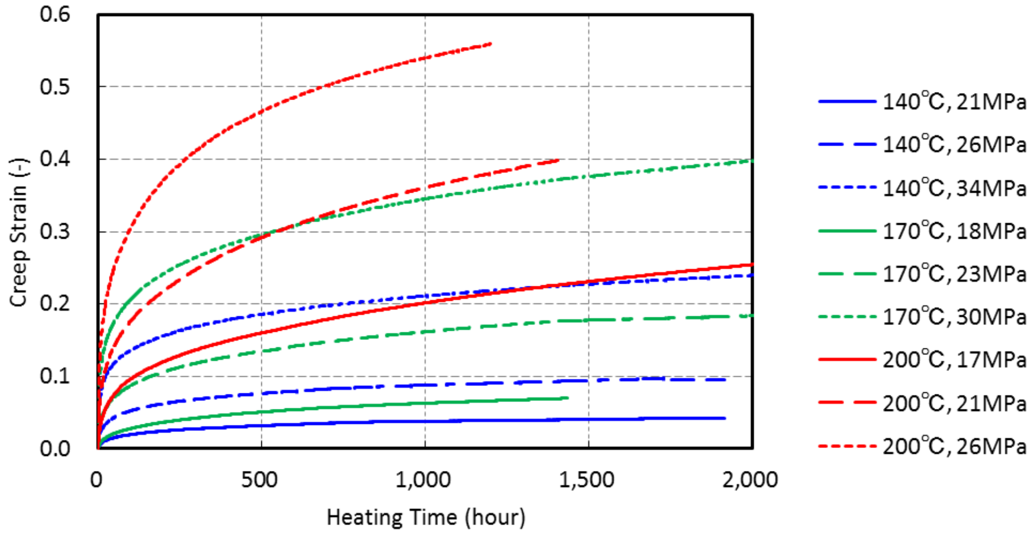


Fig. 4. Compressive creep tests results at 140°C, 170°C, and 200°C under various applied stresses for aluminum material

1.2 Applicability of Creep Model

The proposed creep model was developed in the user subroutine of ABAQUS® software. A 2D axisymmetric nonlinear finite element model of the columnar test specimen (9 mm diameter, 13.5 mm height) was used to investigate the creep strain under a certain temperature over extended periods, as shown in Fig. 5. Figure 6 shows the validation results of the proposed equation for creep strain evolutions at 140°C, 170°C, and 200°C. The estimated creep strains agree well with the experimental values.

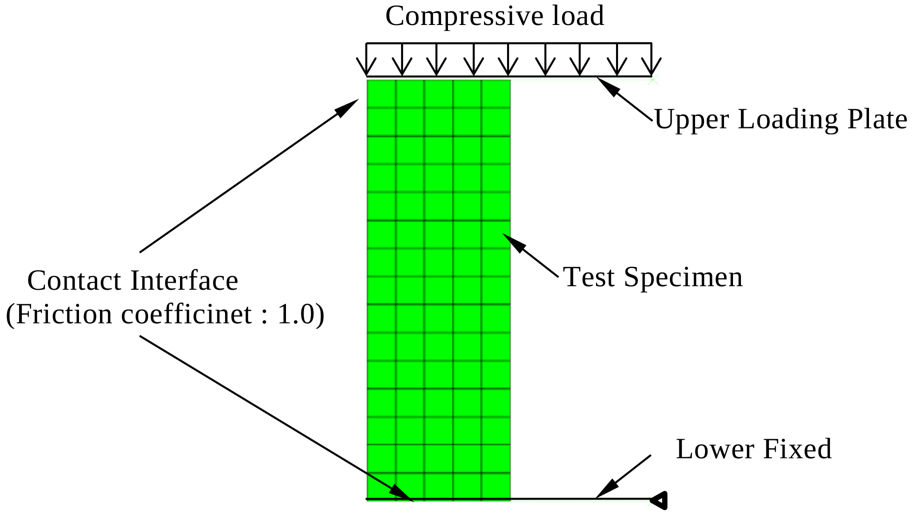


Fig. 5. 2D axisymmetric nonlinear finite element model of the cylinder test specimen

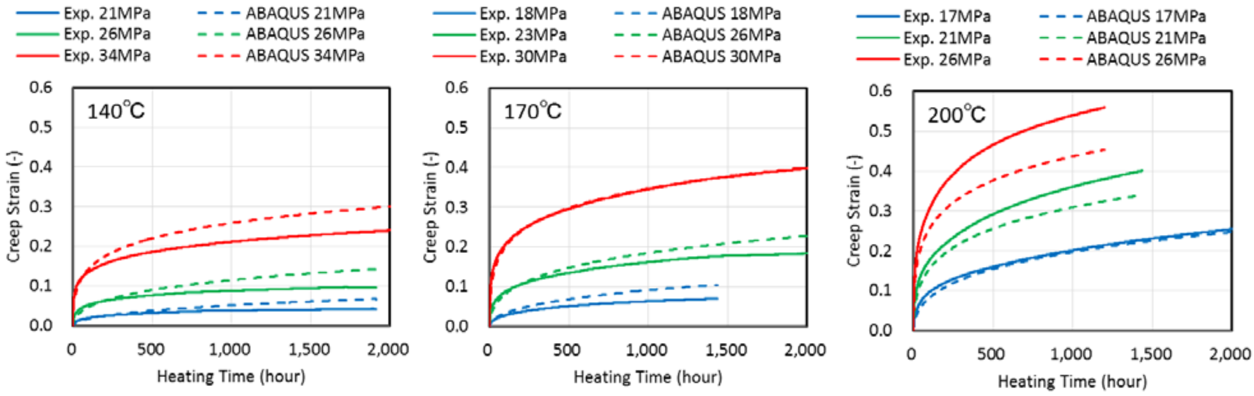


Fig. 6. Validation results of the proposed equation for creep strain evolutions

2. APPLICABILITY OF NUMERICAL METHODOLOGY

In this chapter, the numerical methodology for determining the sealing performance of the aged metal gasket. The numerical methodology involves calculating the representative data of the sealing performance, such as residual linear load and spring-back distance, based on the relaxation of the metal gasket complex under compressive load and heat. The applicability of the numerical method was confirmed by a comparison of the calculated representative data and the relaxation test results conducted by CRIEPI. Moreover, the linear load and spring-back distance of a gasket used for 60 years were evaluated using the proposed numerical methodology.

(1) Relaxation Tests of Aluminum Gaskets

To obtain the representative data for the sealing performance of the gaskets used at high temperature, CRIEPI carried out relaxation tests using a metal gasket with an aluminum outer jacket. Figure 7 shows the relaxation test setup. The gaskets used in these tests had a double O-ring with a full-scale cross-sectional diameter but smaller circumferential diameter. The gasket set in a 1/10-scale flange model was loaded with compressive deformation to the design value, 1.1 mm, and heated at 160°C for 1067 h and 190°C for 85 h. In the tests, representative data, such as the relationship between the gasket linear load and deformation, residual linear load after heating (Y_2), residual linear load with a leak rate of over 10^{-8} Pa·m^3/s (Y_1) during load relieving,

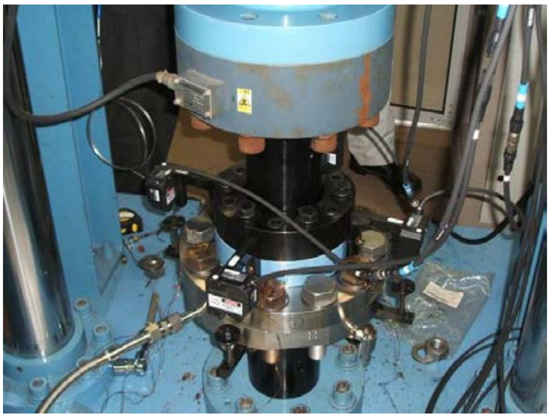


Fig. 7. The relaxation test using aluminum gasket

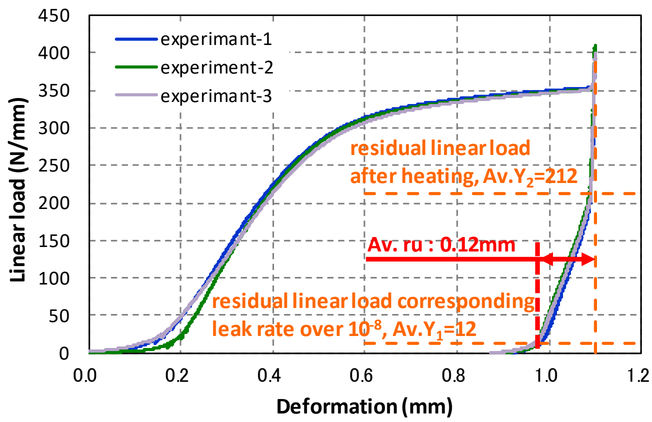


Fig. 8. Measured representative data in the relaxation tests at 160°C for 1076h

and effective spring-back distance (r_u) from maximum deformation up to a leak rate of over 10^{-8} Pa・m^3/s, were measured as illustrated in Fig. 8. The residual linear load decreased to 212 N/mm from 350 N/mm due to the relaxation of the heated gasket complex. Measurements of Y_1 and r_u were 12 N/mm and 0.12 mm, respectively. Thus, the threshold value of the residual linear load Y_1 to maintain sealing performance was determined to be 12 N/mm.

(2) Model Description of Relaxation Analysis

In the relaxation analysis, a nonlinear 2D axisymmetric model was used, as illustrated in Fig. 9. Outer and inner jackets, upper and lower flanges, and spring were modeled using an isotropic material, rigid body, and equivalent ring pipe, respectively. The maximum deformation of the gasket complex was set to the design value, 1.1 mm, which corresponds to that in the relaxation tests.

(3) Analysis Procedure and Material Description

Table 3 presents the analytical procedure of the simulation of an actual gasket loading process. This procedure is divided into four main loading steps: to reproduce compressive loading, bolts tightening, heating, and heat holding. The material properties and stress-strain curves used in the analysis are depicted in Fig. 10. Nimonic spring was described with an equivalent toroidal tube and considered as an equivalent elastic–plastic material. Inconel 600 inner jacket was considered as an elastic–plastic material. The aluminum outer jacket was considered as a visco–plastic material. According to the analysis results, Y_2 (the residual linear load of gasket) after Step 3 and r_u (spring-back distance, see Fig. 8) at Y_1, 12 N/mm, during Step 4 were evaluated.

(4) Relaxation Analysis Results

Figure 11 illustrates the relationship between the deformation and linear load of the gasket, considering the analytical and experimental results. The analytically obtained maximum linear load Y_{20} and Y_2 values agree well with the experimental results. The analytically obtained linear load increased more rapidly than the experimental results at the early stage. This difference is

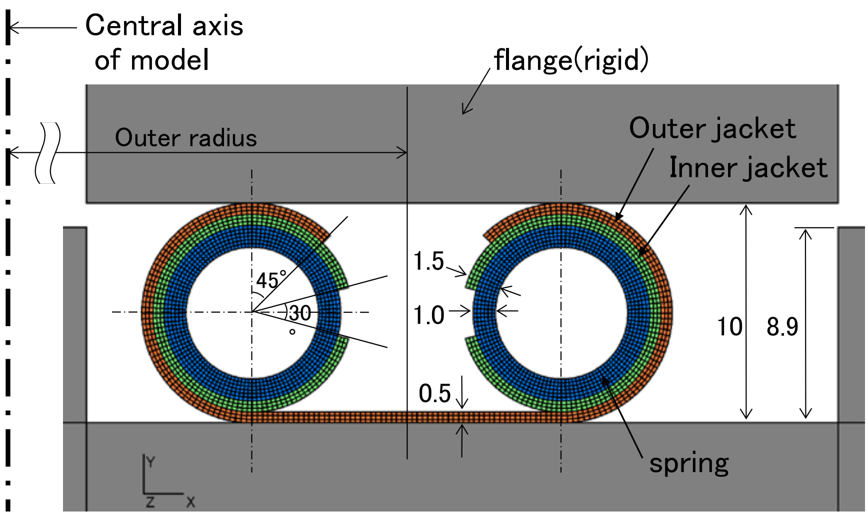
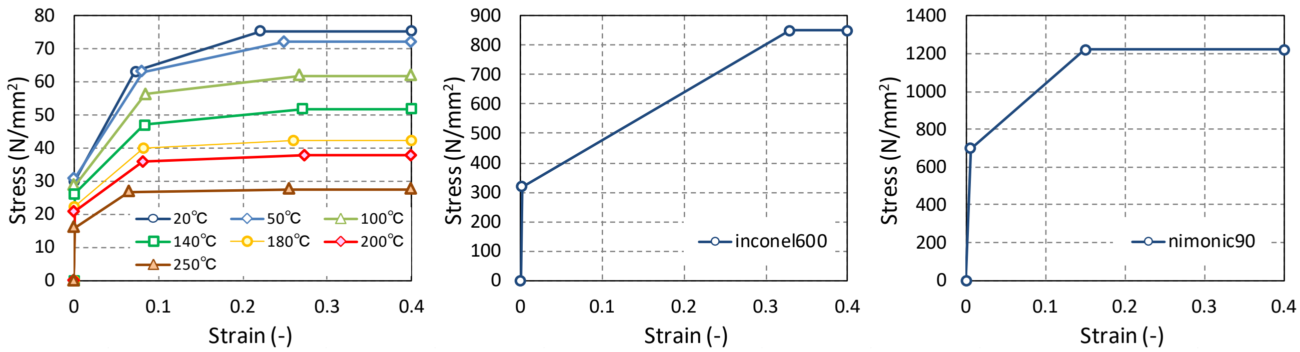


Fig. 9. Nonlinear 2D axisymmetric model used in the relaxation analysis

explained by the presence of a microscopic gap between the adjacent members of an actual gasket. By taking Y_1 value as 12 N/mm in the relaxation analysis, the spring-back distance r_u of the analytical result was evaluated as 0.11 mm, which is close to the experimental results. It is clear that the proposed numerical methodology could evaluate the sealing performance with sufficient accuracy. The numerical evaluation has the advantage of easy applicability to different configurations of metal gaskets and temperature conditions.

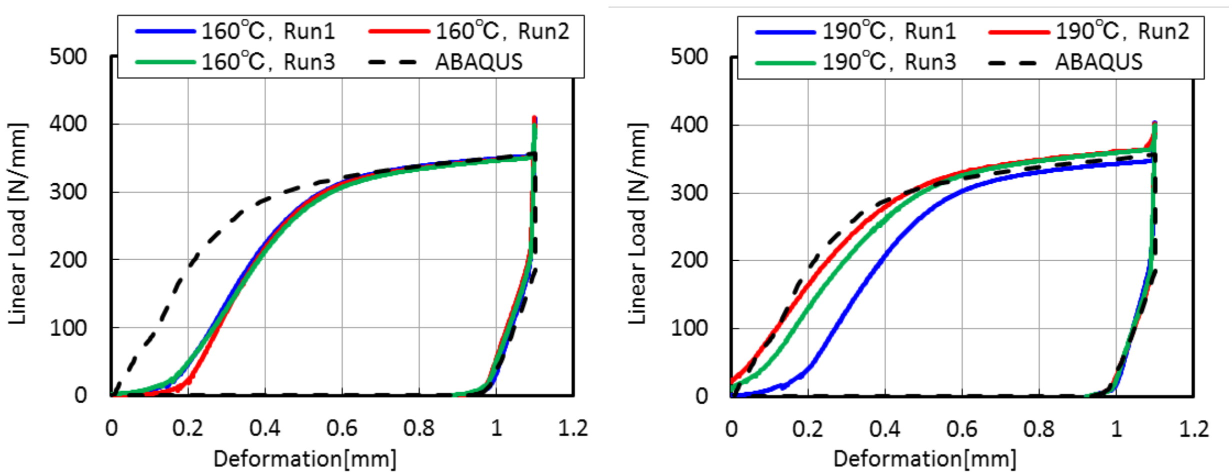
Table 3. Analytical Procedure

Step	Temperature	Process	Creep
Step 1	Constant (at R.T.)	Compressive loading	None
Step 2	Heating to test temperature	Considering thermal deformation and material temperature dependency	Considered
Step 3	160°C or 190°C constant	Heat holding period	Considered
Step 4	Temperature on the last time of Step 3 (Fig.8)	Unloading	None



Outer jacket　　Inner jacket　　Spring

Fig. 10. Stress-Strain relationship used in numerical model



160°C for 1067h　　190°C for 85h

Fig. 11. Relationship between deformation and linear load

CONCLUSION

In this study, we improved the numerical methodology for evaluating the sealing performance of a metal gasket subjected to aging over long-term usage. First, we performed a series of compressive creep tests with heat-treated aluminum specimen under high temperatures and proposed creep characteristics of aluminum used as an outer jacket material of the gasket. Using these creep characteristics, we modified the compressive creep model installed in the FEM code in a previous study, thereby improving the numerical method of sealing performance evaluation, and we compared the results of the modified model with relaxation test results, using small-scale gasket flanges with the full-scale diameter gaskets. The proposed improved numerical methodology was found to evaluate the sealing performance with sufficient accuracy.

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