

Development of Method of Prediction of Lifespan of Rubber Tubes in Oscillation-absorbing Sections of Automotive Engines in Extremely Low-temperature Environments

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ABSTRACT

A method of prediction of the lifespan of rubber air flow tubes that connect the air cleaner and the engine and absorb engine oscillation that will contribute to efficient development has been developed.

First, software was selected that would make it possible to numerically simulate the displacement behavior of rubber and the strain generated in the material, and an elastic-plastic CAE model was employed as an analytic model to enable simulation of the nonlinearity of rubber materials.

Tensile tests were then conducted in order to determine the stress-strain characteristics of the materials, and the results were reflected in CAE property data. S-N diagrams were formulated based on the results and results for number of cycles to fracture in unit bellows test pieces in response to repeated oscillation.

Study of the correlation between actual test results and CAE predictions (for bellows behavior and the position of cracks in the bellows) indicated a strong correlation, with a coefficient of determination of 0.92.

The developed method has provided an analytic technique for the prediction of the number of cycles to fracture in air flow tubes based on CAE stress values, making it possible to predict the lifespan of the products.

1. Introduction

Air flow tubes (AFT) (Fig. 2) fitted in automotive engine chambers (Fig. 1) fulfill the function of absorbing engine oscillation. The use environment for these AFT differs depending on the region of use and the vehicle model, and it is therefore necessary to develop AFT tailored to specific conditions. In addition, when acrylonitrile-butadiene rubber mixed with polyvinyl chloride (NBR/PVC), acrylic rubber (ACM), or epichlorohydrin rubber (ECO) is used as the AFT material, the glass transition temperature ranges from around -35°C to -45°C. This means that extremely low-temperature environments (-20°C to -35°C) do not correspond to the range for complete elasticity of the AFT.

Conventionally, CAE techniques have been employed in the super-elastic range in order to predict stiffness in relation to negative pressure in the engine. However, the material characteristics of rubber materials change in different temperature environments, and because there

is no clear method of prediction of the lifespan of the materials in relation to engine oscillation, examining the status of absorption of engine oscillation under different temperature conditions at the desk is not an easy task. Studies involving extremely low temperatures using CAE at the desk are particularly challenging because the super-elastic models used in conventional CAE are not able to accurately reproduce the behavior of rubber in extremely low-temperature environments.

A method of prediction of the lifespan of the bellows sections of the tubes under a variety of environmental conditions was therefore necessary for the efficient development of AFT.

Past research⁽¹⁾⁻⁽³⁾ had not discussed methods of lifespan prediction in extremely low-temperature environments; the present research therefore examined a new method, involving unit oscillation tests of the bellows sections of AFT in extremely low-temperature environments, and simulations using elastic-plastic models.

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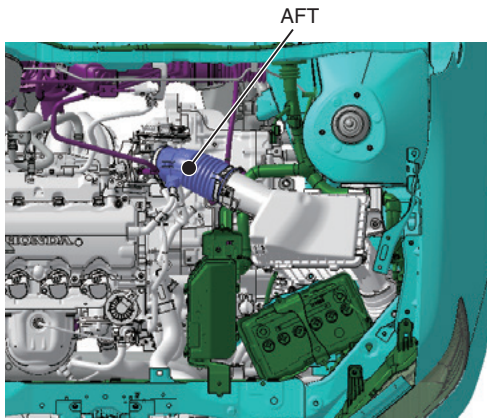


Fig. 1 Engine chamber

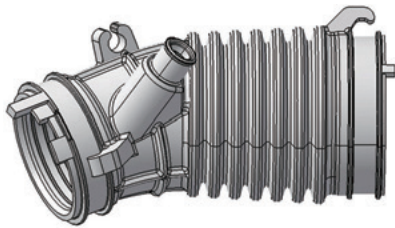


Fig. 2 AFT

2. Concept of Elastic-plastic Model

2.1. Concept of Selection

2.1.1. Selection of analysis methods

In order to accurately predict the lifespan of AFT, which are components that absorb engine oscillations, in extremely low-temperature environments, it is necessary to possess an accurate knowledge of the physical properties of rubber materials. When AFT absorb engine oscillations, their bellows sections deform, and strain is generated. Conventionally, when making judgments regarding the lifespan of materials, the relationship between strain and the number of cycles to fracture under a fixed environment (an ozone concentration of 50 pphm and a temperature of 40°C)⁽⁴⁾ has been used. However, because the stress generated by strain in rubber materials differs considerably⁽⁵⁾ depending on their shape and the temperature environment, it has not been possible to make judgments regarding lifespan based exclusively on strain.

The research under discussion therefore focused on the relationship between stress and temperature, and elucidated the relationship between stress and number of cycles to fracture.

2.1.2. Reason for selection of elastic-plastic model

Figure 3 shows the relationship between stress and strain for a standard rubber test piece in a tensile test. The amount of engine oscillation was controlled through the engine mount system. The results show that the amount of strain

produced in the AFT was 50% or less. The super-elastic models used in conventional CAE studying rubber materials use curves with two inflection points, like the curve shown in Fig. 3, as modeling parameters. However, the range in which AFT manufactured from the rubber material providing the analytic parameters are normally used is the area bounded by the broken line in Fig. 3, close to the first inflection point. The characteristics of the stress-strain curve for this inflection point are approximated by the stress-strain curve for an elastic-plastic body shown in Fig. 4. The present research therefore focused on the range in which strain was 50% or less, and considered that an elastic-plastic model using an elastic model for the stress-strain characteristic of rubber in the elastic range and a plastic model for the stress-strain characteristic of resin in the plastic range would be an appropriate choice as a rubber material model making it possible to accurately reproduce the material's nonlinearity.

2.2. Identification of Stress-strain Curves for Elastic-plastic Model

Rubber test pieces shaped as thin rectangles rather than dumbbells (Fig. 5) were employed to determine stress-strain curves to be used for elastic-plastic models in extremely low-temperature environments. When tests are conducted using dumbbell-shaped test pieces, the cross-sectional area of the neck section changes as shown in Fig. 6 close to the glass transition temperature, and the stress distribution becomes distorted, leading to deviations in tensile stress. The use of thin rectangular test pieces makes it easy to calculate the cross-sectional area for each displacement, and to calculate

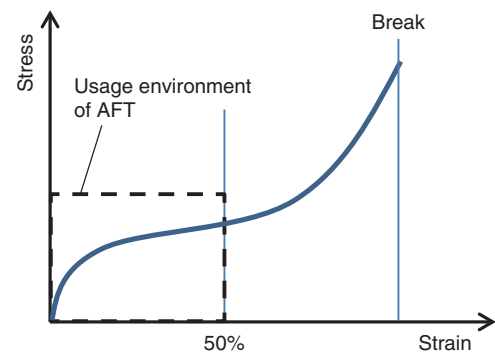


Fig. 3 Stress-strain curve for rubber

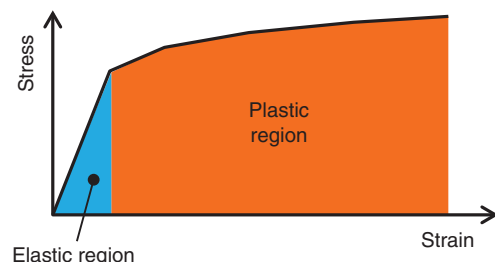


Fig. 4 Elastic-plastic model

the necessary true stress for the analysis. A low tensile speed of 12.5 mm/min was employed in order to control the generation of heat. The circles in Fig. 9 show the stress-strain curves for different temperatures obtained from tests.

2.3. Correlation between Test and CAE Figures

CAE was conducted using Abaqus for CATIA V5.

The elastic-plastic model employed to reproduce the stress-strain characteristics of the rubber material using CAE used physical property parameters for the material in the

elastic and plastic ranges. For the purposes of correlation, JIS tensile tests (Fig. 7) and tests modeling these using CAE (Fig. 8) were conducted, and the results for temperatures between -25°C and -35°C were obtained, as shown in Fig. 9.

Based on Fig. 3, the range up to a strain of 2% was considered the elastic range, with that from this point onwards considered the plastic range. The elastic range was defined using the initial modulus of elasticity and Young's modulus, and the plastic range was defined using data from a table of results for true stress against plastic strain at multiple points. For the elastic-plastic model input values, values from CAE analyses were compared with test values for stress-strain characteristics for different materials and different temperatures, and correlations were verified via parameter fitting. Figure 9(a) shows stress-strain curves for NBR/PVC at different temperatures based on tensile test results and CAE analyses. Figure 9(b) shows the correlation between the test stress figures and CAE stress analysis results for different materials and different temperatures at various levels of strain in tensile tests. This study of the correlation between test and CAE results shows a strong correlation, with a coefficient of determination of 0.99.

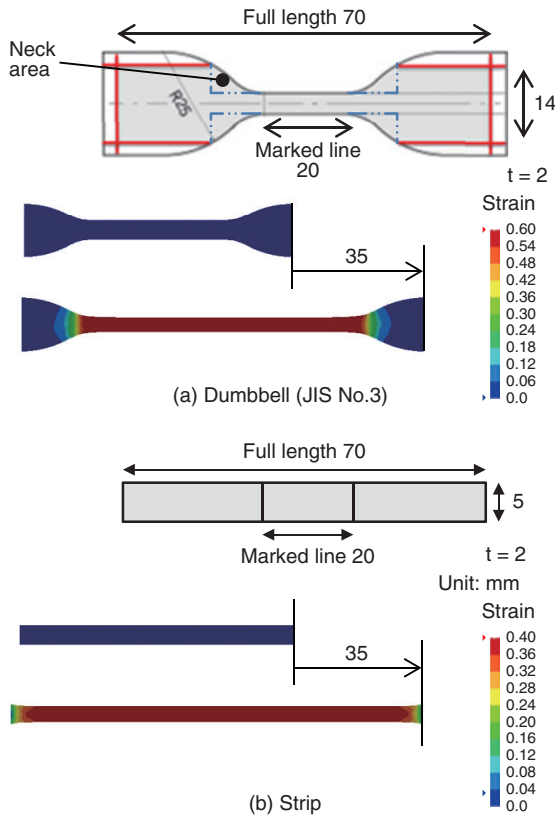


Fig. 5 Test piece

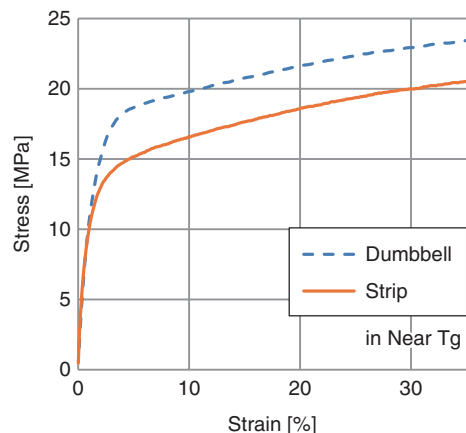


Fig. 6 Difference in stress

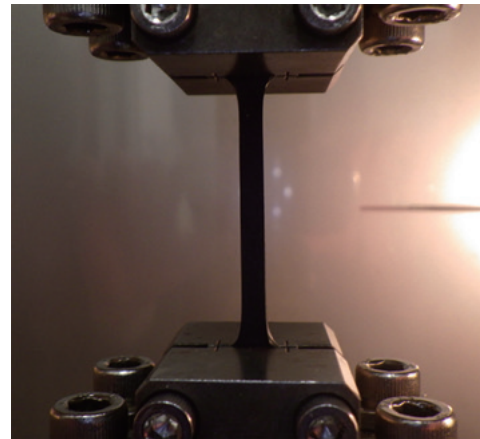


Fig. 7 JIS tensile test

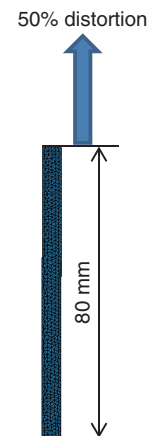
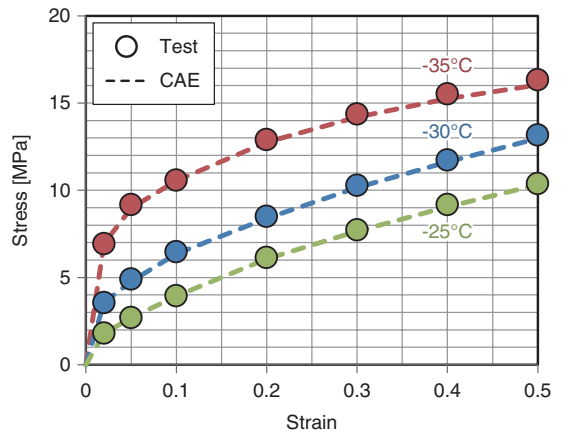
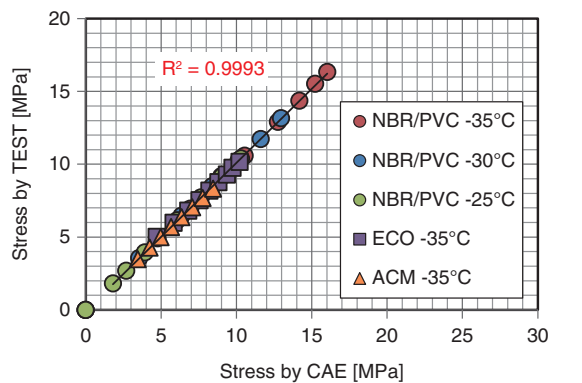


Fig. 8 JIS tensile test (CAE)



(a) Stress-Strain Curve



(b) Correlation between CAE and test results for each material

Fig. 9 Results of tensile test

3. Test Method

3.1. Extremely Low-temperature Unit Oscillation Test on Bellows

These tests were conducted in order to obtain accurate information regarding changes in the shape of the bellows section of the AFT and the number of cycles to fracture. As shown in Fig. 10, straight rubber tubes with three folds in the bellows section were produced, and these test pieces were subjected to unit oscillation tests at extremely low temperatures using a servo pulser with a low-temperature thermostat bath (the EHF-LV010KI-A04SP manufactured by Shimadzu Corporation, shown in Fig. 11).

In order to study the behavior of the test pieces and the number of cycles to fracture in different directions, the test pieces were vibrated and tested while fixed in a number of different positions, as shown in Fig. 12: Vertically (0°), with tensile and compression loads applied in an up-down direction [Fig. 12(a)]; horizontally (90°), with a shearing load applied in a left-right direction [Fig. 12(b)]; and diagonally (45°), with a composite tensile, compressive, and shearing load applied [Fig. 12(c)]. Tests in these directions were also conducted at different temperatures

in order to study the temperature-dependence of behavior and number of cycles to fracture in each direction. These tests were conducted separately for NBR/PVC, ACM, and ECO as materials. Engine oscillation behavior during actual acceleration and braking were measured, and a trapezoid wave with a plateau period was employed in the tests as shown in Fig. 13 in order to simulate this behavior.



Fig. 10 Unit body bellows test piece

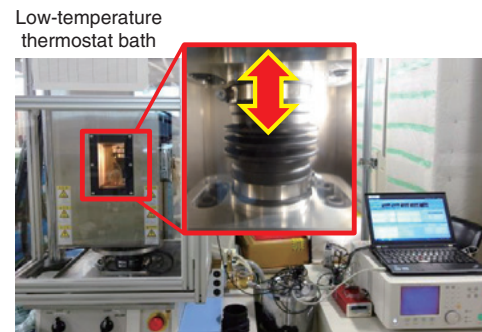


Fig. 11 Strength-testing apparatus

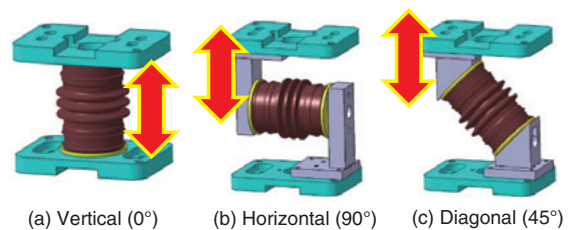


Fig. 12 Direction of oscillation

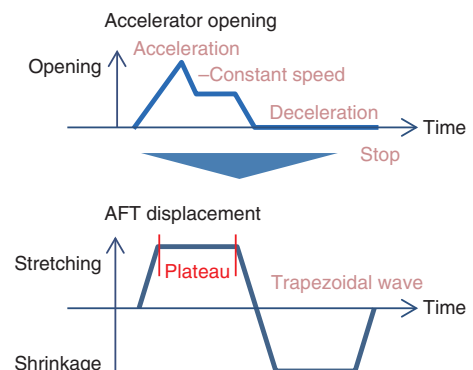


Fig. 13 Waveform for oscillation test

3.2. Extremely Low-temperature Oscillation Tests on AFT Products

Oscillation tests (Fig. 14) were also conducted in extremely low-temperature environments in order to study the correlation of test and CAE results for complex product shapes (Fig. 2).

The tests were conducted at -35°C , using sine waves of a frequency of 2 Hz. The amplitude and direction of the waves were set to generate the maximum displacement in engine oscillation.

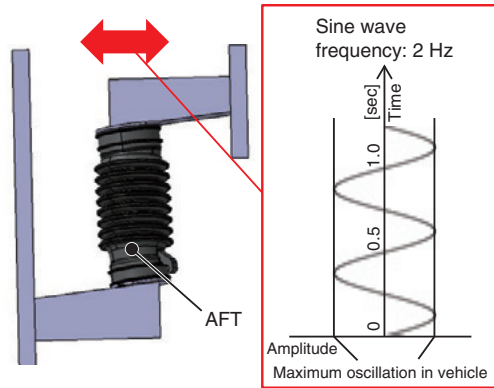


Fig. 14 Strength-testing apparatus for actual AFT

4. Test Results and Considerations

4.1. Test Results

Using unit bellows test pieces, repeated oscillation tests of the bellows were conducted at extremely low temperatures for the three displacement directions described above. Figure 15 shows results for the number of cycles to fracture of the AFT.

Figure 16 shows photographs of the positions of the fractures following each oscillation test.

4.2. CAE Analysis Results

Figure 16 shows the results of CAE analyses of von Mises stress (the maximum generated stress) generated in the bellows in response to a forced displacement input to the unit bellows test pieces for the same three displacement directions as discussed in Section 4.1. Figure 16 shows contour diagrams of the stress generated under each oscillation condition.

4.3. Considerations

In the test results, the order of the directions of oscillation in terms of the number of cycles to fracture, from lowest to highest, was diagonal direction [Fig. 12(c)], followed by up-down direction [Fig. 12(a)], and left-right direction [Fig. 12(b)]. In the CAE results, the order of the directions of oscillation in terms of stress values, from highest to lowest, was diagonal direction, up-down direction, and left-right direction; the higher the stress values,

the lower the number of cycles to fracture. In addition, the positions of the fractures for each oscillation direction in Fig. 16 correspond to the positions of maximum stress and fracture from CAE results for maximum stress.

Figure 18(a) shows an S-N diagram that plots the relationship between the generated stress in CAE analyses and the number of cycles to fracture in actual tests based on the results shown in Figs. 15 and 17. As this diagram shows,

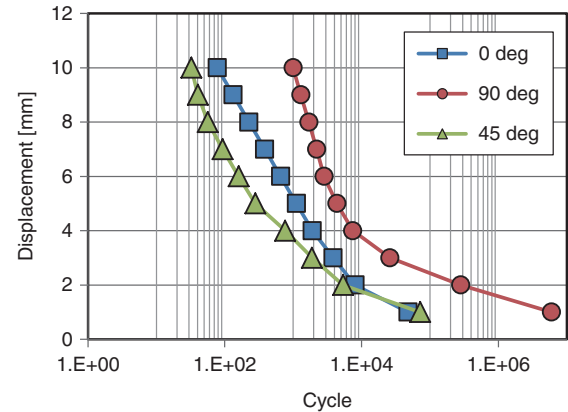


Fig. 15 Results of oscillation test

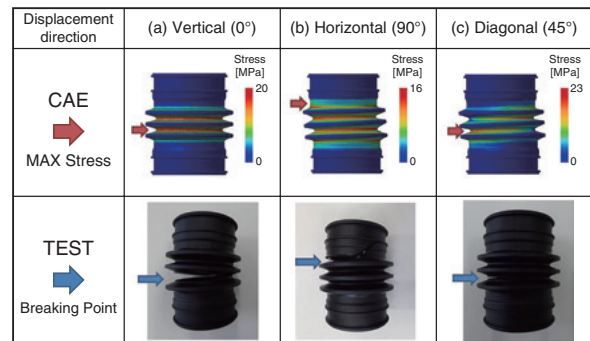


Fig. 16 Comparison between oscillation test results for test and CAE

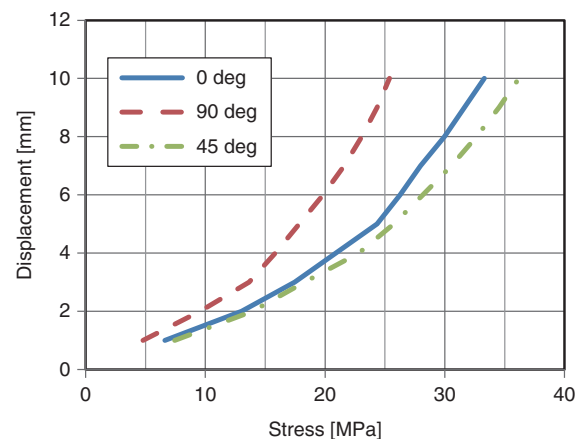
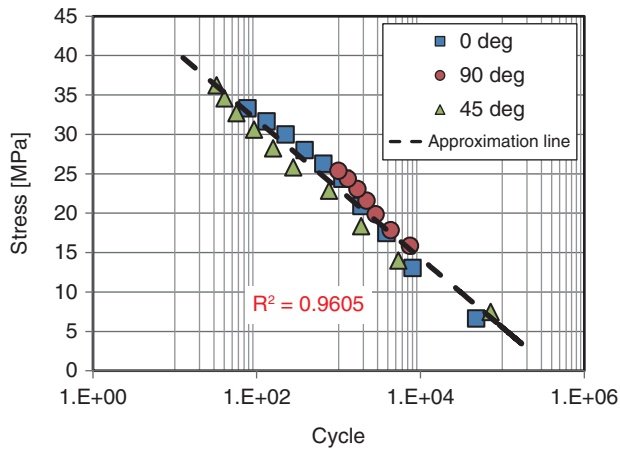


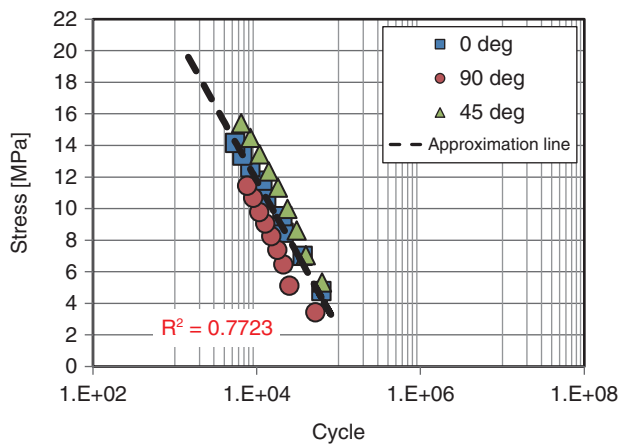
Fig. 17 CAE results

there is a strong correlation between stress and the number of cycles to fracture, with a coefficient of determination of 0.96.

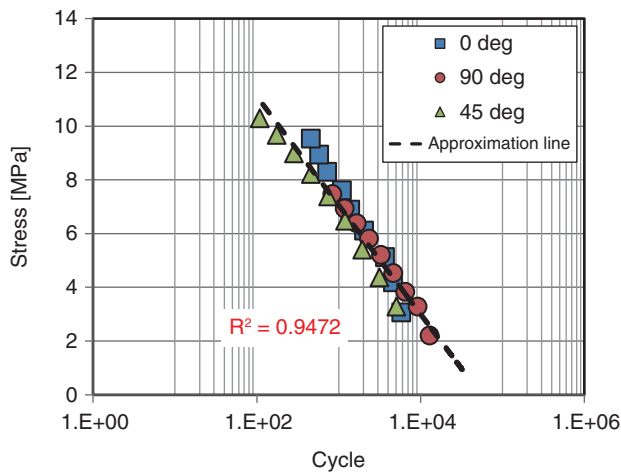
The results of plotting lifespan curves for each of the other materials [Figs. 18(b) and (c)] are considered to



(a) Results for NBR/PVC



(b) Results for ACM



(c) Results for ECO

Fig. 18 Stress and number of cycles to fracture for each material

demonstrate the potential to predict the lifespan of AFT in relation to oscillation based on the number of cycles to fracture of the material, as determined by the calculation of stress values using CAE.

5. Verification

In order to verify the validity of these lifespan curves, stress analyses and extremely low-temperature AFT oscillation tests (Fig. 14) were conducted using actual AFT product shapes (Fig. 2). Figure 19 shows a graph plotting results for the number of cycles to fracture of the AFT in actual oscillation tests against the predicted lifespan curve.

Figure 20 shows the correlation between the number of cycles to fracture in the extremely low-temperature unit bellows oscillation tests (Fig. 11) and the number of cycles to fracture estimated from CAE stress values [Fig. 18(a)]. There is a strong correlation between the results, with a coefficient of determination of 0.92.

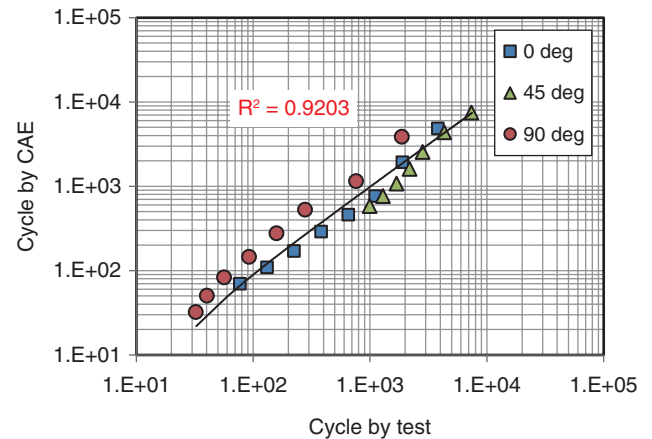


Fig. 19 Correlation between CAE and test for each material

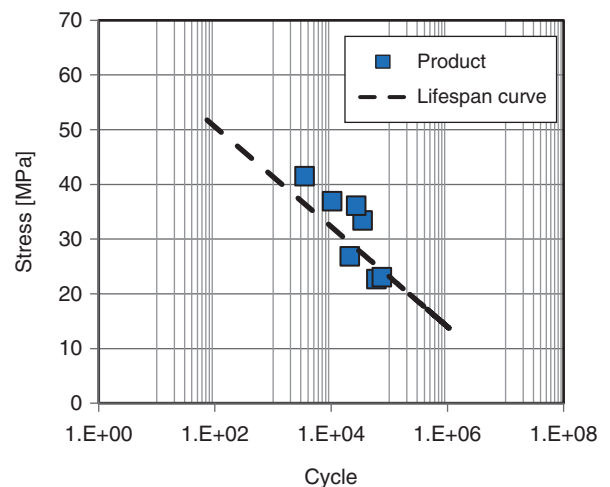


Fig. 20 Lifespan curve and test results

The results discussed above indicate that when considering the durability of AFT in relation to repeated oscillation in extremely low-temperature environments during the development process, it is possible to predict the number of cycles to fracture using lifespan curves for different materials plotting number of cycles to fracture against generated stress, based on the results of numerical analyses of stress conducted in advance for actual product shapes using CAE.

6. Conclusion

The research discussed in this paper realized a good correlation between predictions of the lifespan of bellows sections in AFT in extremely low-temperature environments and test results.

- (1) High-accuracy material characteristic curves were obtained by modifying the measurement method employed at extremely low temperatures;
- (2) Extremely low-temperature oscillation tests were conducted using unit bellows test pieces; and
- (3) S-N diagrams were generated using unit test and CAE results.

The results of this research have made it possible to predict the number of cycles to fracture for AFT from the results of numerical analyses of stress generation in AFT products (Fig. 2) using CAE.

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