Feasibility Study on Neutron Diffraction Method for Evaluation of Residual Strain Distribution of Regenerative Cooled Combustion Chamber

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(Received May 7th, 2008)

The regenerative cooled combustion chamber of a cryogenic liquid rocket engine is exposed to a large temperature difference between the hot gas (about 3500K) and the liquid hydrogen (about 20K). This induces thermal stress, and strain is accumulated in the chamber wall throughout the cyclic firing tests. Evaluation of the stress and the strain distribution in a chamber wall is essential since chamber life is usually related to such stress and strain. In this study, the residual strain in a regenerative cooled combustion chamber wall was measured by applying the neutron diffraction method and the X-ray diffraction method. The measured data were compared with the numerical data by finite element analysis, and the feasibility of the neutron diffraction method for the regenerative cooled combustion chamber of a cryogenic liquid rocket engine was evaluated.

Key Words: Regenerative Cooled Combustion Chamber, Residual Strain, Neutron Diffraction Method, X-ray Diffraction Method, FEM Analysis

Nomenclature

- \(d\): d-spacing
- \(d_0\): d-spacing in stress free condition
- \(\lambda\): wavelength of neutron
- \(\varepsilon_r\): strain in radial direction
- \(\varepsilon_\theta\): strain in hoop direction
- (111): lattice plane (111)
- (220): lattice plane (220)

1. Introduction

The regenerative cooled combustion chamber of a cryogenic liquid rocket engine is exposed to a large temperature difference between the hot gas (about 3500K) and the liquid hydrogen (about 20K). This induces thermal stress, and strain is accumulated in a chamber wall throughout the cyclic firing tests. Evaluation of the stress and the strain distribution in a chamber wall is essential since chamber life is usually related to such stress and strain.

Cook et al. 1) surmised the life prediction method for the Space Shuttle Main Engine (SSME) based on creep-fatigue interaction. Murphy, Hannum and Quentmeyer et al. 2,4) conducted experimental testing using subscale combustion chamber and demonstrated several types of failure mode (creep-fatigue interaction, ductile rupture and blanching). Porowski et al. 5) attempted a simplified life prediction method using a rectangular beam model. Anderson, Riccius and Arya et al improved analytical life prediction model such as a elasto-plastic flow model based on FEM analysis. 5,8)

To improve the chamber life prediction method, many types of experimental data are essential. However, the experimental data are currently limited to observing cross-section after cutting the chamber or measuring inner surface geometry. Therefore, the effective nondestructive inspection techniques are needed to obtain the experimental data for comparison with the corresponding numerical data. The primary objective of the present study was to establish a method to obtain experimental data on strain nondestructively.

In this study, the measurement of residual strain in a regenerative cooled combustion chamber wall was attempted by applying the neutron diffraction method and X-ray diffraction method. In the tests, a chamber specimen which had been subjected to cyclic firing tests was used. Furthermore, two-dimensional nonlinear and inelastic FEM analysis was conducted to calculate the residual stress and strain in the chamber. The model used in the analysis had the same channel geometry as that of the specimens. After measurements and analyses, the measured data were compared with the numerical data, and the feasibility of the neutron and X-ray diffraction methods for the regenerative cooled combustion chamber of a cryogenic liquid rocket engine was evaluated.
2. Experimental procedure and equipment

2.1 Test specimen

In this study, a regenerative cooled combustion chamber which had been subjected to a total of 25 cyclic firing tests was selected as the combustion chamber specimen. Figure 1 shows the structure of the regenerative cooled combustion chamber. The material of the inner cylinder was copper alloy (OMC) and coolant channels were created by machining. The inner cylinder with coolant channels was then covered by the electroforming technique. Furthermore, the inner cylinder was reinforced by an external cylinder of nickel alloy (Inconel 718).

![Figure 1: Combustion chamber specimen](image)

Fig. 1. Combustion chamber specimen

![Figure 2: Structure of the regenerative cooled combustion chamber](image)

Fig. 2. Structure of the regenerative cooled combustion chamber

2.2 Experimental procedure and equipment

Measurements of residual strain by the neutron diffraction method were conducted using the experimental reactor and facility at the JRR-3 RESA of Japan Atomic Energy Agency (Fig. 3). Figure 4 shows the system components at JRR-3 RESA. The test specimen was set on a tri/axial movable stage above a rotating table, which made it possible to perform accurate positioning for strain measurements of the specimen. A neutron passed through the entrance slit (slit size: 3 mm × 1 mm or 2 mm × 1 mm) and irradiated the test specimen. The diffracted neutron from the specimen then passed through the 1 mm radial collimator and reached the one-dimensional detector. By using the one-dimensional detector, the diffraction angle which had the peak of diffraction intensity was determined. Figure 5 shows a schematic of the neutron diffraction method. Neutrons are scattered by a nuclear interaction with the nuclei of atoms. Two scattered waves from successive lattice planes were interfered, then the diffraction intensity peaks occur only under the special condition when the Bragg’s equation:

\[ 2d \sin \theta = \lambda \]  

(1)

is satisfied, where \( d \), \( \theta \) and \( \lambda \) denote the d-spacing of crystal grain, diffraction angle where the diffraction intensity has peak and wave length of neutron. From the diffraction angle \( \theta \) measured by the detector, the d-spacing \( d \) was calculated applying Bragg’s equation. Here, the wavelength of neutron (\( \lambda \)) was measured separately by using Ni powder (lattice constant: 0.35241 nm). Furthermore, the d-spacing of OMC in stress free condition \( d_{0} \) was measured separately from other specimen, and residual strain \( \epsilon \) was calculated by applying the equation as follows:

\[ \epsilon = \frac{\Delta d}{d_0} \]  

(2)

Where \( \Delta d \) denotes the difference between the d-spacing of OMC in under stress condition \( d_{1} \), and that in stress free condition \( d_{0} \).
3. Results and discussion

3.1. Confirmation tests for coolant channel positions

The high accuracy positioning of both the strain measurement position where the neutron was irradiated and the position at the coolant pass channels in the test specimen are essential for the precise measurement of strain. In this test, coolant channel positioning was conducted by measuring the diffraction intensity at each position. Figure 6 and Figure 7 show the measurement position and area in the cross section of the test specimen, respectively. The throat area in the combustion chamber specimen was selected as the area for strain measurement because the heat load condition there was the severest, resulting in accumulation of the strain. In addition, measurement positions were selected on lines ①-④ in Fig. 6. Here, regarding the diffraction intensity, its decrease in the coolant channels and its increase in the ribs and inner walls were predicted by the tests.

Figure 8 shows an example of change in the diffraction intensity with each position on line ①. The diffraction intensity in the ribs increased and that in coolant channels decreased on line ①. Thus, the decrease of diffraction intensity occurs when there is no portion of the specimen at the measurement position. The above mentioned phenomenon was also observed on lines ②-④. From the results, it was suggested that the positioning of coolant channels in the chamber specimen is possible by performing the measurement of diffraction intensity at certain positions in a chamber specimen.
3.2. Residual strain measurement test

The residual strain measurements of the hoop (\(\varepsilon_\theta\)) and radial (\(\varepsilon_r\)) directions were conducted based on the results of the confirmation tests for positions of coolant channels. Here, regarding the \(\varepsilon_\theta\) measurement, the residual strain of lattice plane (220) could not be measured in the preliminary test.

Figure 9(a) shows the relationship between the lattice plane and strain direction, and Figure 9(b) shows the strain measurement point in the specimen. Regarding the \(\varepsilon_r\), (111) measurement, the strain distribution in the hoop direction on the chamber wall was investigated at a distance of 0.5 mm between two rib parts (5 points). Regarding the \(\varepsilon_\theta\) (111) and \(\varepsilon_r\) (220), the strain distribution in radial direction on the rib was investigated at a distance of 0.5 mm distance the inner surface and a distance of 0.6 mm in other parts (a total of 6 points).

Furthermore, residual strain measurements obtained by the X-ray diffraction method were also conducted to investigate the strain on the surface of the specimen. Figure 10 shows the test equipment used in the X-ray diffraction method.

The results from the neutron and the X-ray diffraction method are shown below in section (3.3) together with the results of FEM analyses.

![Strain measurement direction](image)

**Fig. 9.** Relationship between lattice plane and strain measurement direction (a) and The strain measurement points in the specimen (b)

3.3. Comparison between the strain measurement results and FEM analyses

Two-dimensional nonlinear and inelastic FEM analysis was conducted to calculate the residual stress and strain under firing test conditions which were the same as those of the tests using the chamber specimen. The strain data calculated in the analysis were compared with the strain measurement data of the tests. The commercial FEA code/ABAQUS was used in the analysis. Figure 11 shows the FEM analysis model, which is geometrically the same as the chamber specimen. An 8-nodes isoparametric element was selected, and generalized plain strain condition was applied for this model. In addition, the contact problem between the inner and external cylinders was taken into consideration. Here, regarding z direction (chamber axis direction), thermal stress in internal cylinder might be induced by restraining of External cylinder under experimental test condition. However, it is considered that thermal stress in z direction was small because the chamber specimen used in the experimental tests had small length in z direction compared with an actual liquid rocket engine. Figure 12 shows the boundary conditions of temperature, pressure and heat transfer coefficients in the combustion gas and coolant (liquid hydrogen). Here, the combustion times in each of the 25 cycles were changed in accordance with the test results of the specimen. In addition, temperature dependence regarding the material and the secondary creep phenomenon were taken into consideration. Figure 13 shows an example of the temperature distribution in the chamber model at steady combustion.

Figure 14, 15 respectively show the residual strain distribution in the radial and hoop directions. Here, in Fig. 14, the data obtained by the neutron diffraction method at the surface point (r=0) were excluded because the measurement area at the surface point was reduced by half and accurate data could not be obtained for such surface points. Alternatively, the X-ray diffraction method was used to obtain the data at the surface points.

With regard to the \(\varepsilon_\theta\) in radial distribution in Fig. 14, the strain near the inner surface indicated tensile strain and that near the external cylinder indicated compressive strain. These results from the FEM analysis and the strain measurement tests indicate the same tendency. On the other hand, regarding the \(\varepsilon_r\) in the radial distribution, the strain from the FEM analysis indicates tensile strain and the test data indicates compressive strain near the external cylinder. These results indicate a different tendency. This
difference might be induced by the measurement point where the material is electroforming copper. An accurate $d_0$ was not obtained by using electroforming copper test pieces. Alternatively, the data for pure copper was used in calculating the strain.

In Fig. 15 of $\varepsilon$, both strain shown by the FEM analysis and that of the measurement tests indicate compressive strain. However, the absolute value of FEM analysis was about twice as large as the test data.

From the results, it is considered that the strain tendency (tensile or compressive) as shown by the FEM analysis and that of the test data correspond with each other. In addition, the applicability of the neutron diffraction method for a regenerative cooled combustion chamber was shown by the results. However, the absolute values were different from each other. The reason for this difference is not clear. A paucity of crystal grains in the measurement area and initial residual strain from the machining and electroforming might have affected the data accuracy. In addition, FEM analysis should be as sophisticated as three-dimensional analysis. Thus, an additional measurement test and analysis should be conducted to confirm the data accuracy.
4. Conclusions and Outlooks

The applicability of the neutron diffraction method for the regenerative cooled combustion chamber of a cryogenic liquid rocket engine was shown from the results of the neutron and X-ray diffraction methods. Furthermore, the residual strain shown by the measurement tests and shown by that the FEM analyses indicated the same tendency.

Future developments regarding strain measurement tests are aimed at those applied to the new combustion chamber which has no nickel cylinder and is scheduled to be performed cyclic firing tests (Fig. 16). The strain change in the chamber is investigated by comparing the strain after the cyclic firing tests with that before the tests. Regarding the experimental facility, the improved RESA will be used which have a larger size stage and high efficiency of strain measuring (Fig. 16).

Acknowledgments

The strain measurement tests by the neutron diffraction method were conducted on Relocation promotion program of Neutron application technology hosted by Ministry of Education in Japan. In this study, support and advices were given by the members at Neutron Residual Stress Analysis Group in Japan Atomic Energy Agency. The authors wish to acknowledge the support of all concerned parties.

Fig. 16. New combustion chamber and facility (RESA)

References