RESERCH ON ULTRASONIC THICKNESS MEASUREMENT OF COOLING CHANNEL LIGAMNENTS IN A LIQUID ROCKET COMBUSTION CHAMBER

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ABSTRACT

The regenerative cooling combustion chamber of a liquid rocket engine is exposed to a large temperature difference between the combustion gas and the liquid fuel. This temperature difference induces thermal strain, and coolant channel ligaments in a combustion chamber are deformed throughout cyclic firing tests. Evaluation of this deformation is very important since chamber life is usually related to such deformation. In the present study, ultrasonic tests (UT) based on the pulse reflection method were conducted to obtain ligament thickness. From the test results, the applicability of a flat probe and that of a focus probe for thickness measurement were shown for deformed ligaments. Results of analysis indicated that the focus probe was advantageous with regard to spatial resolution. However, the amplitude of the ultrasonic wave and the accuracy of thickness measurement in the flat probe were larger than those in the focus probe in the measurement tests.

1. Introduction

The regenerative cooling combustion chamber of a liquid rocket engine is exposed to a large temperature difference between the combustion gas and the liquid fuel. Figure 1 shows the structure of a regenerative cooling combustion chamber. Multiple coolant channels are machined in an inner cylinder made of copper alloy and then covered by the electroforming technique. The covered inner cylinder is reinforced by a jacket made of nickel alloy. In such a regenerative cooling structure, ligaments in a combustion chamber are exposed to a large temperature difference between inner combustion gas and outer cooling fuel under firing conditions. This induces thermal strain and the ligaments are deformed throughout cyclic firing tests. Evaluation of ligament deformation is very important since chamber life is usually related to such deformation [1)-5)]. To predict the chamber life, finite element method (FEM) analysis is often conducted to calculate the strain and the deformation of chamber ligaments [6)-8)]. However, there are few experimental data with which to compare the numerical data. The primary objective of the present study was to establish a method to obtain quantitative data on ligament deformation to evaluate chamber soundness.

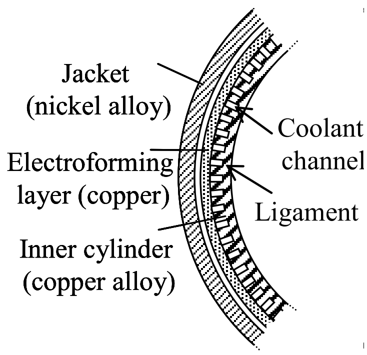


Figure 1: Structure of the regenerative cooling combustion chamber

In this study, ultrasonic tests (UT) based on the pulse reflection method were conducted to obtain ligament thickness. A UT based on the pulse reflection method is a simple technique which has been used as an on-site measurement technique for such things as power plants and aircrafts.

In the tests, a small-sized flat probe and focus probe (diameter: 3 mm) were used because the aspect ratio of the cooling channel in recent combustion chambers is high (for example, ligament width is about 1 mm). To measure such micro-structural ligaments requires a high spatial resolution. To evaluate the applicability of the technique for an actual rocket chamber, several types of ligaments (normal, concave and convex) were machined having the same geometry as ligaments in an actual chamber. In addition, numerical simulations of ultrasonic wave propagation were conducted to determine the characteristics of wave propagation using a flat probe and a focus probe in micro-structural ligaments.

2. Specimens and Test Setup

2.1 Specimens

To evaluate the applicability of the UT technique for an actual rocket chamber, plain and curved specimens were manufactured. Figure 2 shows a photograph of the two types of specimens. Each specimen was made of copper alloy and several coolant channels were machined into the specimens. Concerning the curved specimen, its curvature was similar to that of configuration to the throat region of an actual combustion chamber.

Figure 3 shows the configuration of normal ligaments in a specimen. Ligament with a thickness of 1 mm were machined in a configuration similar to that of ligaments in an actual combustion chamber. To confirm the accuracy of ultrasonic thickness measurement, different thicknesses of ligaments (0.5 and 2.0 mm) were also machined into a specimen. In addition, to imitate deformed ligaments in cyclic firing tests, convex and concave ligaments were created in a specimen by wire-electrical discharge machining. Figure 4 shows the configuration of the concave and convex ligaments in a specimen. The curvature and thickness of ligaments (R 1.85 and 0.6 mm) were selected by referring to an actual deformed ligament in a combustion chamber.

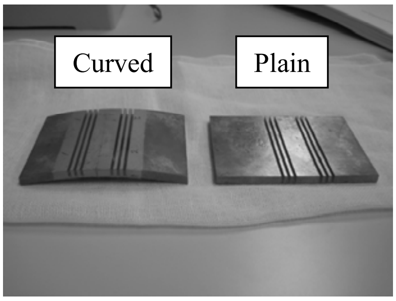


Figure 2: Photograph of specimens

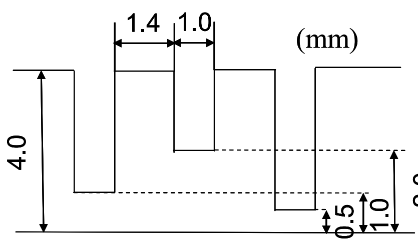


Figure 3: Configuration of normal ligaments in a specimen

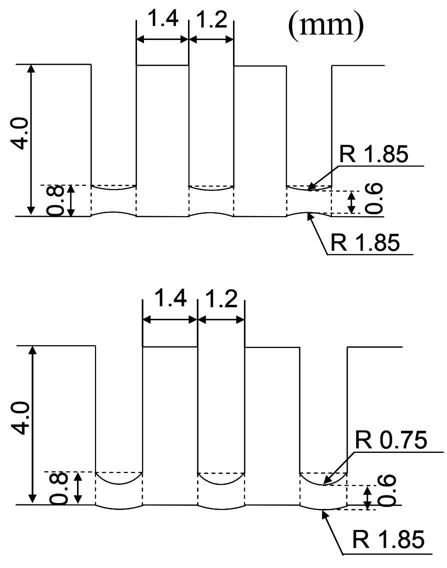


Figure 4: Configuration of concave [upper] and convex [lower] ligaments in a specimen

2.2 Test setup

In firing tests of an combustion chamber, it is time-consuming to detach a combustion chamber from a test stand. To obtain many data on ligament deformation after each firing test, a simple, on-site measurement technique is essential to unnecessitate detachment and reattachment of the combustion chamber.

For these reasons, the ultrasonic thickness measurement technique based on the pulse reflection method was chosen for these tests. Figure 5 shows a photograph and a schematic of the test setup. An ultrasonic probe is in direct contact with a specimen coated with contact medium (liquid). An Ultrasonic wave is generated by the probe and propagates into a ligament of a specimen. The ultrasonic wave is then reflected from the lower surface of the ligament back to the probe. Received echo signals from the probe are transmitted to a ultrasonic thickness gauge (GE Inspection Technologies CL400) and ligament thickness is calculated from A-scan data of the thickness gauge.

Figure 6 shows a schematic of the two types of ultrasonic probes. In the flat probe, the piezo element is not curved and the ultrasonic wave propagates linearly from the element. On the other hand, the curvature of the piezo element in the focus probe has the wave focus point of 0.5 mm below the tip of the delay. The frequency of both probes is 15 MHz and the diameter of the piezo element is 3 mm. Delays are made of polystyrene.

Concerning the focus probe, three types of delays were manufactured for these tests. By using the probe which has a small tip diameter, the spatial resolution is expected to improve for thickness measurements. Figure 7 shows a photograph of a focus probe and delays. The diameters of the delays are 1, 2 and 3 mm, respectively.

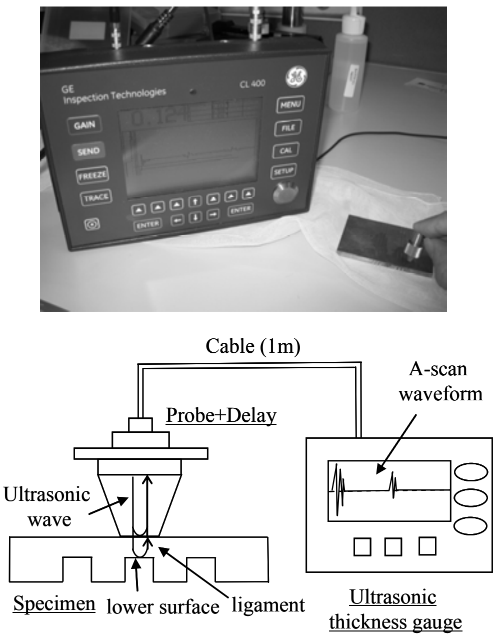


Figure 5: Photograph and schematic of test setup

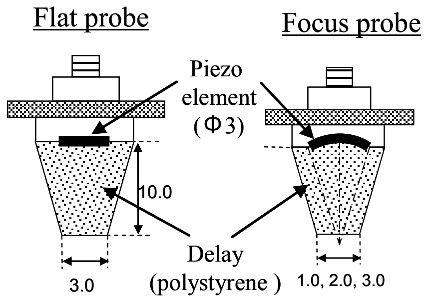


Fig. 6: Schematic of ultrasonic probes

Fig. 7: Photograph of a focus probe and delays

3. Test Results and Discussions

3.1 Thickness measurements of normal ligaments

To confirm the accuracy of a thickness measurement, normal ligaments in a plain specimen were measured by the flat probe and the focus probe. Figure 8 shows results of measurements for normal ligament thicknesses. A delay tip diameter of 3 mm was chosen for these tests. From the results, both the flat probe and the focus probe show a high accuracy of thickness measurement. Figure 9 shows A-scan graphs by the flat and the focus probe in measurement tests. Here, the longitudinal axis shows the amplitude of the detected echo and the horizontal axis shows the time. In the flat probe graph, there are strong signals of the bottom echo from the lower surface of a ligament. Ligament thickness was calculated from the time difference between bottom echoes and the acoustic velocity of copper. In the two graphs, the amplitude of the flat probe is seen to be higher than that of the focus probe. This difference indicates that the intensity of the ultrasonic wave by a curved piezo element is weaker than that by a flat piezo element.

After confirmation of the basic performance for thickness measurement detailed above, thickness measurements in a curved specimen were attempted by using the flat probe. Figure 10 shows measurement results for normal ligaments in the plain and the curved specimen. In Figure 10, there is no difference in measurement values between the plain and the curved specimen. These results indicate that the clearance between the tip of the delay and the curved specimen had no effect on measurement accuracy.

Finally, thickness measurements using a small tip diameter of delays were attempted in these tests. Regarding the focus probe, the delay tip diameter could be narrowed because the focused ultrasonic wave did not interfere with the side surface of the delay. Figure 11 shows A-scan graphs by the 1-mm and a 2-mm delay tips in measurement tests. Although a strong echo was obtained by the 2-mm delay tips, the echo could not be measured by the 1-mm delay tip. There are two reasons for the inability of the 1-mm delay tip measurement. One is that the contact area between the delay and the specimen is too small to propagate the ultrasonic wave. Another is that the probe with a small tip delay is too unstable to press against a specimen surface.

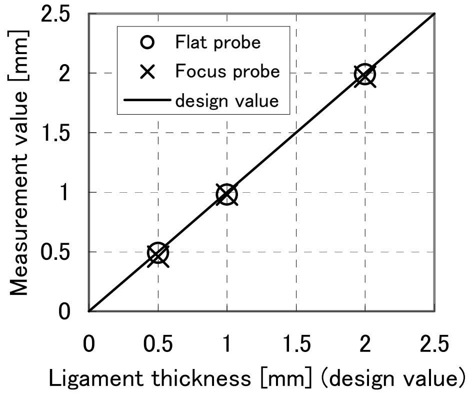
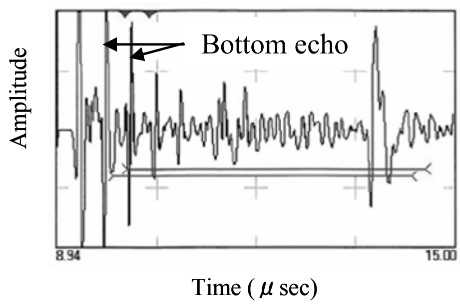
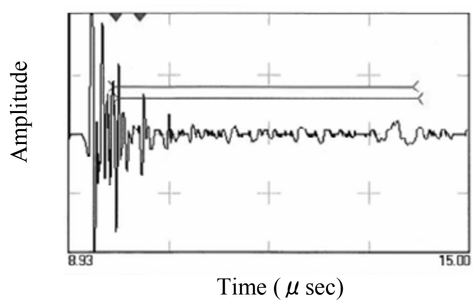


Figure 8: Results of measurements for normal ligaments thicknesses



(a) Flat probe



(b) Focus probe

Figure 9: A-scan graphs by a flat and a focus probe in measurement tests

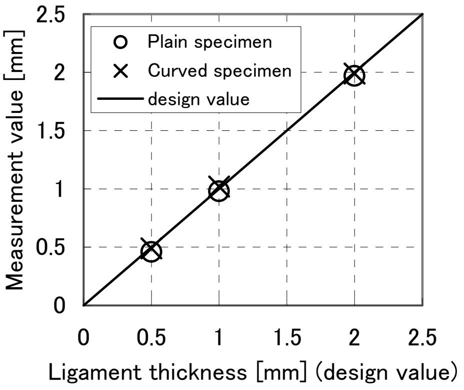
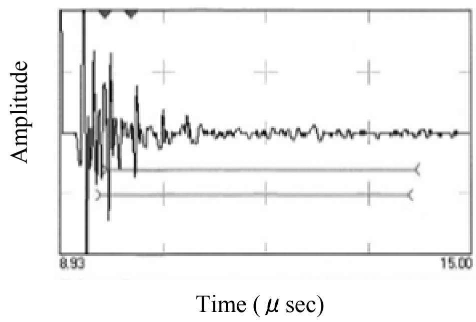
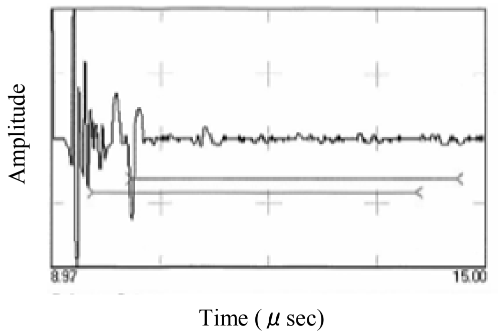


Figure 10: Results of measurements for normal ligaments in plain and curved specimens



(a) Diameter at the tip: Φ2



(b) Diameter at the tip: Φ1

Figfure 11: A-scan graphs by 1-mm and 2-mm delay tips in measurement tests

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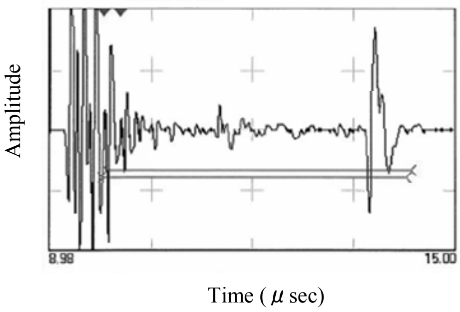
3.2 Thickness measurements of concave and convex ligaments

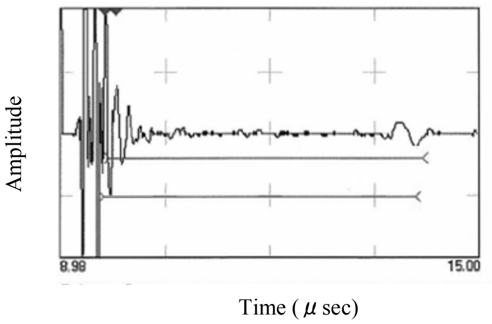
To investigate the applicability of thickness measurements for deformed ligaments in an actual chamber, thickness measurements of imitation deformed ligaments (concave and convex ligaments) were conducted using the flat probe and the focus probe. Figure 12 shows A-scan graphs of a concave ligament measurement by the two probes. By both probes, the echo could be obtained. The thickness values of the flat probe and the focus probe were 0.62 and 0.43 mm (design value: 0.6 mm), respectively. This indicates that the measurement accuracy of the flat probe was larger than that of the focus probe.

Figure 13 shows A-scan graphs of a convex ligament measurement by the flat probe and the focus probe. In these tests, the echo could also be obtained by both of the probes. The thickness values of the flat probe and the focus probe were 0.55 and 0.52 mm (design value: 0.6 mm), respectively. However, the echoes were unstable in the measurement tests. This is because the probe was unstable to be in stable contact with a convex ligament.

These results indicated that thickness measurement of a convex ligament is more difficult than that of a concave ligament. To measure the thickness of a convex ligament stably, a device to fix and stabilize the probe is necessary.

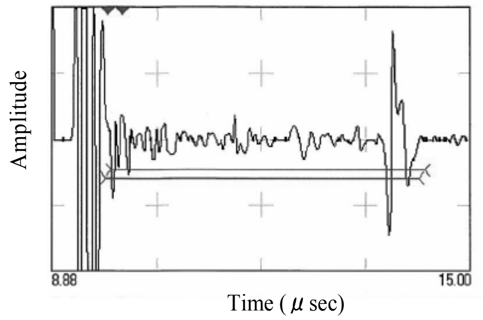


(a) Flat probe

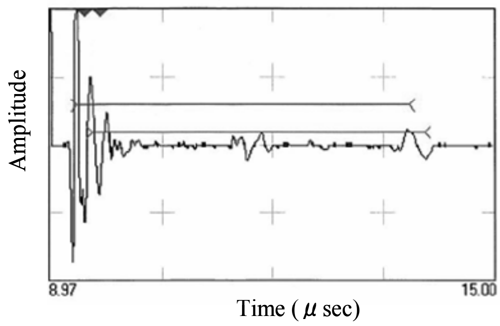


(b) Focus probe

Figure 12: A-scan graphs of a concave ligament measurement by a flat probe and a focus probe



(a) Flat probe



(b) Focus probe

Fig. 13: A-scan graphs of convex ligament measurement by a flat probe and focus probe

4. Ultrasonic propagation analysis

4.1 Calculation method for ultrasonic propagation

The numerical calculation technique used here for visualization of ultrasonic propagation is based on a finite-difference method (FDM). However, the method of calculating ultrasonic displacements of calculation nodes was newly developed based on the principal of the elastic wave equations [9)]. The analyses in this study were conducted by the Non-destructive Evaluation Group in the National Institute for Materials Science (NIMS).

Figure 14 shows the analysis model, which is geometrically the same as the probe and the specimen with convex ligaments used in the measurement tests. Two types of probes (flat and focus) were demonstrated as a 15-MHz (67 nsec/cycle) sine wave pulses. Acoustic velocities of the longitudinal wave (Vl) and the shear wave (Vs) were given the values shown in Figure 14.

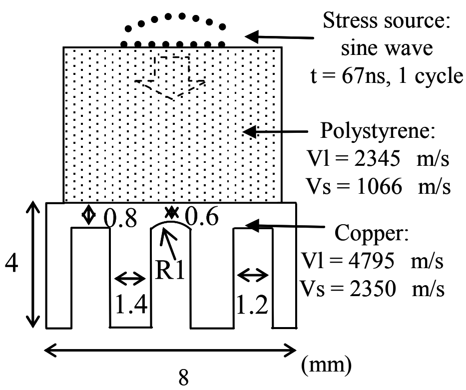


Figure 14: Analysis model

4.2 Calculation results

Figures 15 and 16 respectively show the ultrasonic wave propagation before and after reflecting the wave reached the upper surface of the specimen. In Figures 15 and 16, the area of the ultrasonic wave in the focus probe is smaller than that in the flat probe. This indicates that the spatial resolution of the focus probe is greater than that of the flat probe. Figures 17 and 18 respectively show the ultrasonic wave propagation before and after reflecting of the lower surface of the specimen. In Figure 17, the area of the ultrasonic wave in the focus probe, which was generated from the upper surface, is smaller than that in the flat probe. However, the area of the wave in the focus probe was not narrow enough to measure the tip of the curved lower surface. In fact, Figure 18 indicates that there was no difference in the form of the reflected waves between the flat probe and the focus probe. To improve the measurement accuracy, the wave area should be narrowed by using a delay with a small tip.

From the results of analysis, it was shown that a focus probe has advantages with regard to a spatial resolution. However, the experimental data showed that the amplitude of a ultrasonic wave in the flat probe is greater than that in the focus probe. In addition, it was possible to obtain the reflecting echo from the tip of the lower surface without focusing the ultrasonic wave. Thus, it is considered that the flat probe is also effective for measuring the ligament thickness in a combustion chamber.

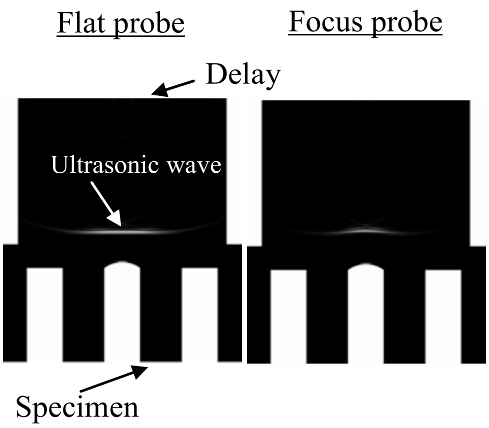


Figure 15: Ultrasonic wave propagation before the wave reaching the upper surface of the specimen

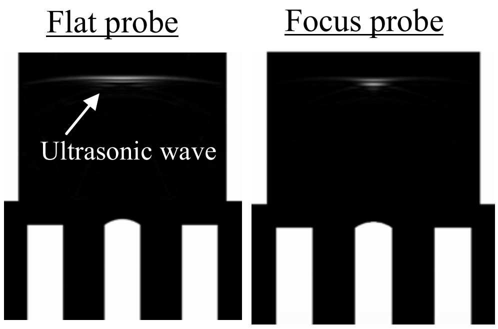


Figure 16: Ultrasonic wave propagation after reflection of the wave from the upper surface of the specimen

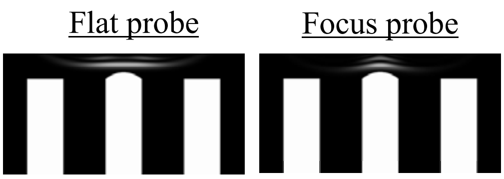


Figure 17: Ultrasonic wave propagation before the wave reaches the lower surface of the specimen

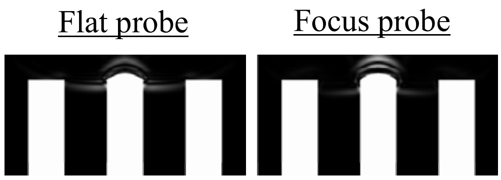


Figure 18: Ultrasonic wave propagation after reflection of the wave from the lower surface of the specimen

Conclusions

The applicability of a flat and a focus probe for thickness measurement of deformed ligaments was shown by test results. From the results of analysis, it was shown that the focus probe is advantageous with regard to spatial resolution. However, the amplitude of the ultrasonic wave and the accuracy of the thickness measurement in the flat probe were greater than those in the focus probe in the tests.

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