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Fundamental Research on Stress-Wave-Emission Method for Pressure Vessels

By

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Summary: Fundamental research for the application of the Stress-Wave-Emission method to nondestructive inspection and safety monitoring of structures is carried out experimentally.

Firstly, Stress-Wave Emission of a model pressure vessel is observed during hydrostatic testing. Time differences in Stress-Wave Emission signals are measured between four sensors attached to the surface of the vessel wall, and their source points are located by triangulation technique using an electronic computer. Stress-Wave Emission that is radiated at pressures lower than the proof pressure is due to the structual imperfection which is liable to cause a fracture.

Secondly, low-cycle fatigue testing of a model pressure vessel is monitored by the Stress-Wave Emission method using a single-channel system simplified for practical use. During the 1st pressure cycle, a large amount of Stress-Wave Emission is recorded at high pressures. From the 2nd to about the 5300th cycle, scarcely any Stress-Wave Emission is detected, which is the result of non-reversibility of the Emission called Kaiser effect. Subsequenty, a small amount of the Stress-Wave Emission caused by fatigue crack growth is observed at every pressure cycle until the crack penetrates the vessel wall at the 5375th cycle. The usefulness of this method to predict the fatigue failure of the vessels in service is shown.

Thirdly, it is observed that a full-size titanium-alloy rocket chamber under hydrostatic testing emits very large Stress-Wave Emission on account of twinning of the material.

The Stress-Wave Emission method is demonstrated to have a potential value for nondestructive testing and safety monitoring of pressure vessels.

1. INTRODUCTION

During the plastic deformation or fracture of a solid material, very weak elastic stress waves are radiated from the material due to the release of its potential energy. This phenomenon is called Stres-Wave Emission (here after called SWE) or Acoustic Emission. "Cry of tin" is a striking instance of the SWE which is so large that it is audible to the naked ear. The source mechanism of the SWE has not been made clear yet. Authors are carrying investigations into the fundamental properties of the SWE for several kinds of aluminum alloys and steels under plastic deformation [*2*][*3*][*12*]. Relations between the SWE and slip-band formation are under consideration now.

The present paper describes the basic research for the application of the SWE method to nondestructive testing and safety monitoring of pressure vessels. The paper is three fold. First, with a model pressure vessel under hydrostatic testing, SWE is observed and the SWE source points on the vessel are located by triangulation technique [4]. Second, SWE from a model pressure vessel during low-cycle fatigue testing is investigated in connection with fatigue crack growth in structures [5]. Third, full-size spherical rocket chamber during hydrostatic testing is monitored by the SWE method. Experimental results demonstrate the usefulness and the problems that are to be solved to implement the SWE method for practical use.

2. Experimental Procedure

2-1 *Instrumentation set-up*

Fig. 1 shows the block diagram of the instrumentation set-up for recording and source locating of the SWE for a pressure vessel during hydrostatic testing. The SWE signals are detected by four accelerometers attached to the surface of the vessel. These accelerometers have a resonance peak of about 45 kHz. Output signals of the detectors are amplified by low-noise wide-band amplifiers. The

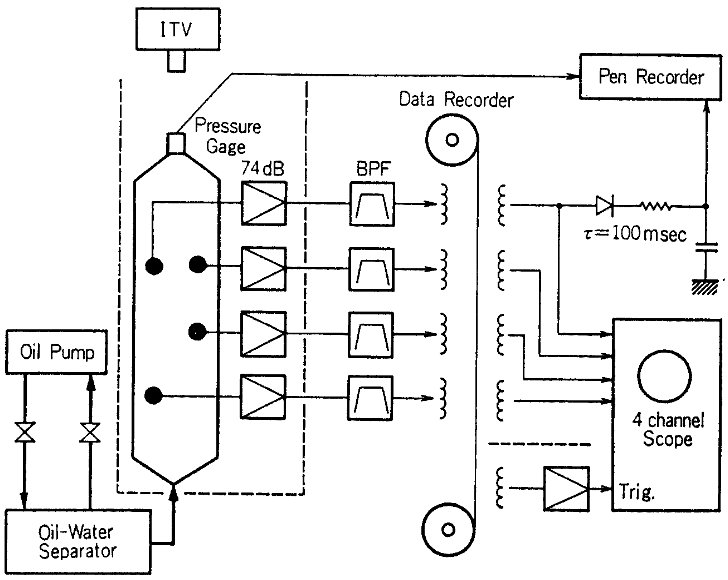

Fig. 1. SWE recording and locating system.

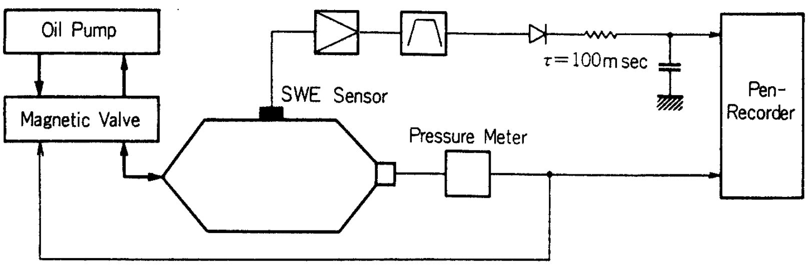

Fig. 2. Simplified SWE recording system.

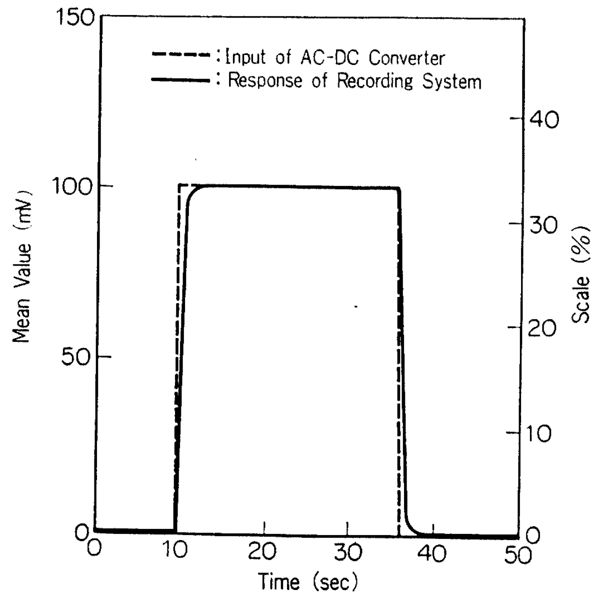

FIG. 3. Transient response of the recording system.

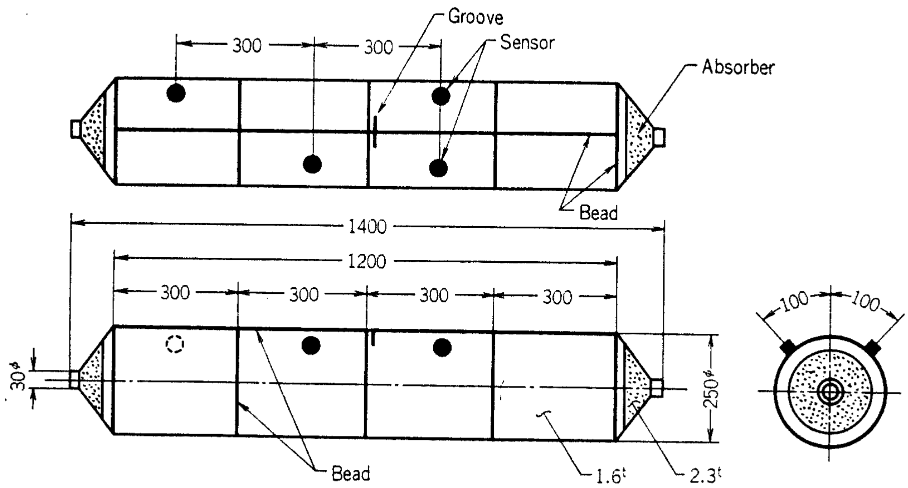

FIG. 4. Model pressure vessel for hydrostatic testing.

band-pas filters set between 30 and 150 kHz reduce the influence of the low-frequency mechanical noise from the pressuring pump and the high-frequency Gaussian noise in the amplifiers. A four-channel data recorder records the filtered signals on a magnetic tape at a speed of 60 inches per second. The recorded signals are reproduced at a tape speed of 3 inches per second, displayed on a four-channel triggered oscilloscope, and are photographed automatically. From the photographs, time differences in the rising of the so-called "burst-type" SWE signals between the four detectors are measured one after the other. Their source points on the vessel are calculated by triangulation technique using an electronic computer. The mean values of the SWE signals are recorded on a pen recorder introducing an AC-DC converter. Time constant of the convertor is set to 100 msec., which plays an important part to get reliable data.

Fig. 2 shows a block diagram of the simplified SWE system for practical use. This instrumentation is enough to observe the fundamental properties of the SWE from structures, though it cannot be used to locate the SWE source points. With this system, low-cycle fatigue testing of a model pressure vessel and hydrostatic testing of a full-size rocket chamber are carried out. A PZT thickness-mode vibrator is introduced as a SWE detector for the latter case, while the accelerometer is used for the fatigue testing, in the former case. The transducer has a thickness-mode resonance of about 130 kHz. The same electronic instruments as mentioned above, i.e. the amplifier, the filter etc. are used. Fig. 3 shows the transient response of the recording system.

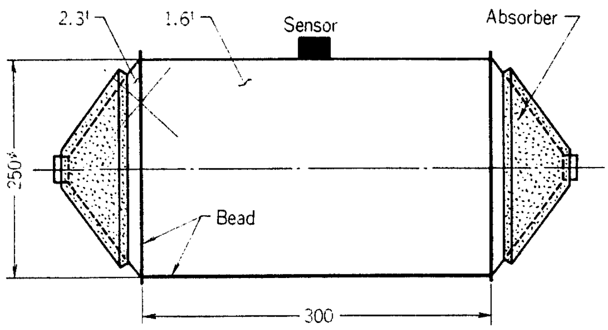

FIG. 5. Model pressure vessel for low-cycle fatigue testing.

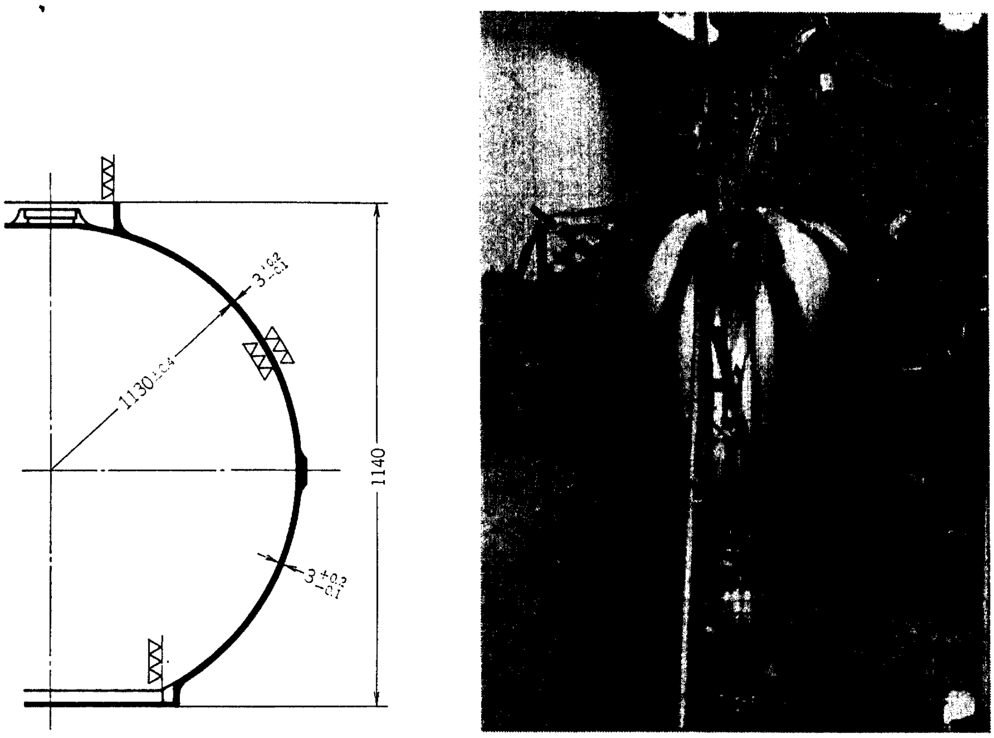

FIG. 6. Titanium-alloy M-3A rocket chamber.

2-2 *Pressure vessels*

Fig. 4 shows the model pressure vessel for hydrostatic testing. The material is hot-rolled mild steel, and gas welding is introduced. The cylindrical vessel is of 250 mm in diameter and 1400 mm in length. Fig. 5 shows another model pressure vessel used in low-cycle fatigue testing. These vessels are the same, except that they vary in their length. The M-3A spherical rocket chamber is shown in Fig. 6, which is made of titanium alloy (Ti-6 Al-4V) and is of about 1100 mm in diameter.

3. Results and Discussion

3-1 *SWE and its source location*

Fig. 7 shows SWE from the model pressure vessel during hydrostatic testing. About 60 seconds after the beginning of the test, the hydrostatic pressure exceeds 32 kg/cm^2 and the SWE increases with a run. This abrupt increase is due to the start of yielding simultaneously through out the vessel wall.

For SWE source-point locations, it is necessary to reveal the propagation velocity of the SWE. Previous studies have shown that the SWE in a thin plate bears dispersive characteristics similar to the Lamb wave [8]. Fig. 8 shows the propagation velocities of the SWE in a tensile specimen gained by actual measurement. Since the velocity varies as a function of the frequency times the thickness of the plate, it is very hard to estimate the value in advance. In the present experimentation, four sensors are placed asymmetrically on the vessel wall as shown in Fig. 4, so the source points are to be calculated without a preliminary knowledge on the SWE velocity. Fig. 9 shows the location of the SWE sources on the vessel wall. Their serial numbers are in the order of detection as shown in Fig. 7. Fig. 10 shows a photograph of the rising of the SWE signals corresponding to the source No. 3. Figs. 7 and 9 demonstrate that most of the SWE observed at pressures lower than

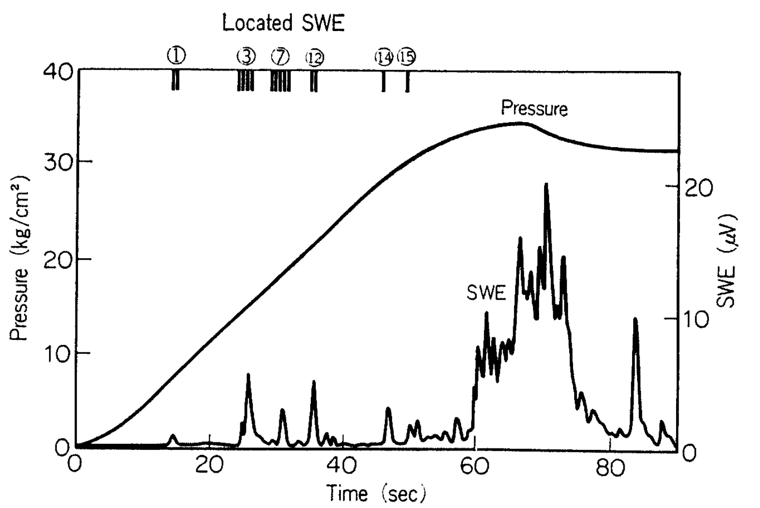

FIG. 7. SWE for hydrostatic testing.

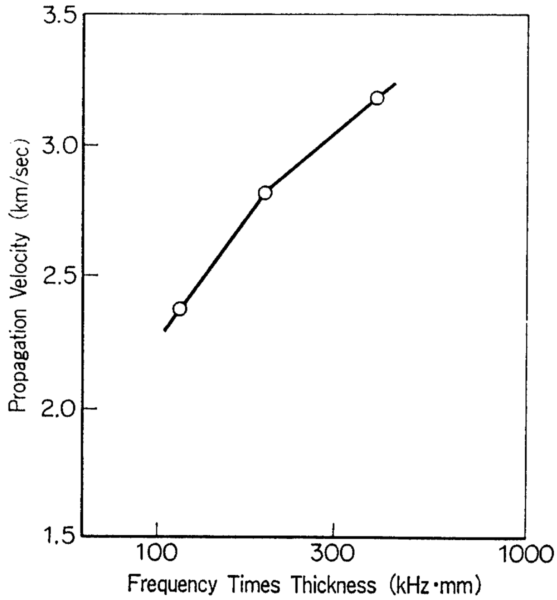

FIG. 8. SWE velocities in a thin plate.

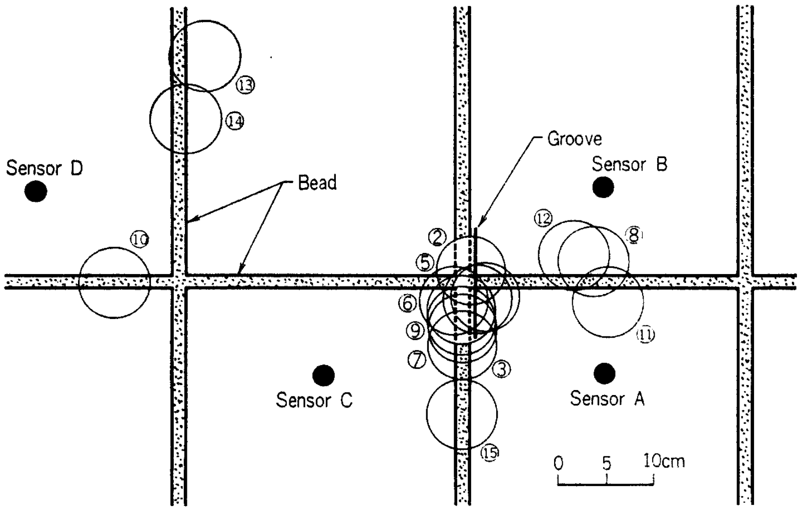

FIG. 9. SWE source locations on the vessel wall.

20 kg/cm² originates in the imperfect region, grooved as a defect on the vessel wall. At higher pressures, the source points spread to the circumferences.

3-2 *SWE during fatigue testing*

Fig. 11 shows the cyclic pressures for low-cycle fatigue testing of the model pressure vessel in Fig. 5. From the 1st to 10th cycle, the pressures are controled by hand. After the 11th cycle, a servo-valve controls the pressures automatically. The maximum pressure of the pump is so high that the pressures make serrated changes. Figs. 12(A) to (C) show the SWE for the fatigue testing. During the

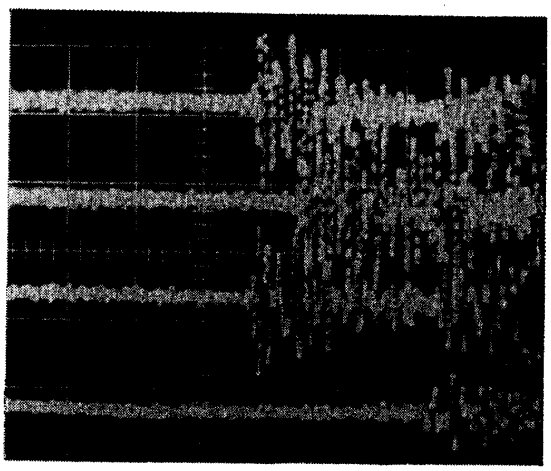

FIG. 10. Rising of burst-type SWE signals.

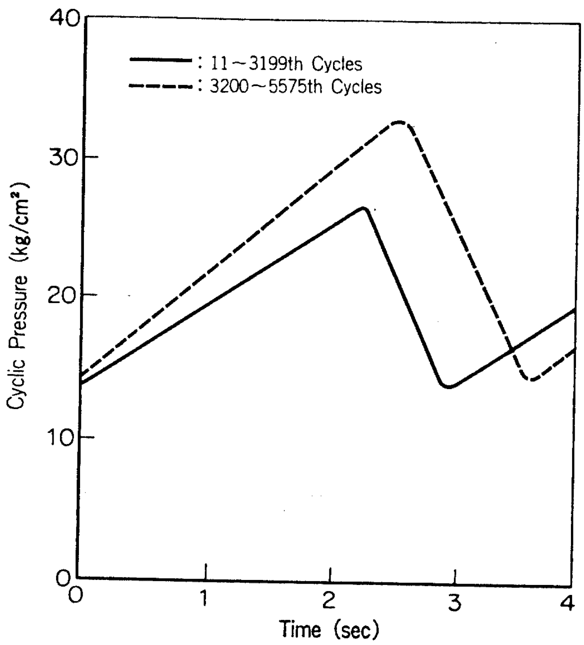

FIG. 11. Cyclic pressures of fatigue testing.

pressure cycle	pressure	hoop stress
1~10	0~27.6 kg/cm²	0~21.5 kg/mm²
11~3199	13.8~26.9	10.8~21.0
3200~5375	14.1~32.4	11.0~25.2
5375	penetration of fatigue crack	

1st pressure cycle, considerable SWE is recorded at pressures higher than 15 kg/cm^2 in the same manner as Fig. 7. Scarcely any SWE is detected from the 2nd to about the 5300th cycle, which is the result of non-reversibility of the SWE, i.e. the so-called Kaiser effect. Subsequently, a small amount of the SWE is observed at every pressure cycle until the crack penetrates the vessel wall at the 5375th cycle. These emissions are attributable to the fatigue crack growth in the vessel wall.

3-3 *SWE from a titanium-alloy rocket chamber*

Fig. 13 shows the SWE from the titanium-alloy rocket-chamber during hydrostatic testing. Unlike the previous experiments, a great amount of the SWE is observed at low pressures, which is caused by twinning of stress-intensified regions of the vessel wall. In usual materials, peak values of SWE for crack initiation or growth are larger than those for the plastic deformation by a factor of 10^3 or higher.

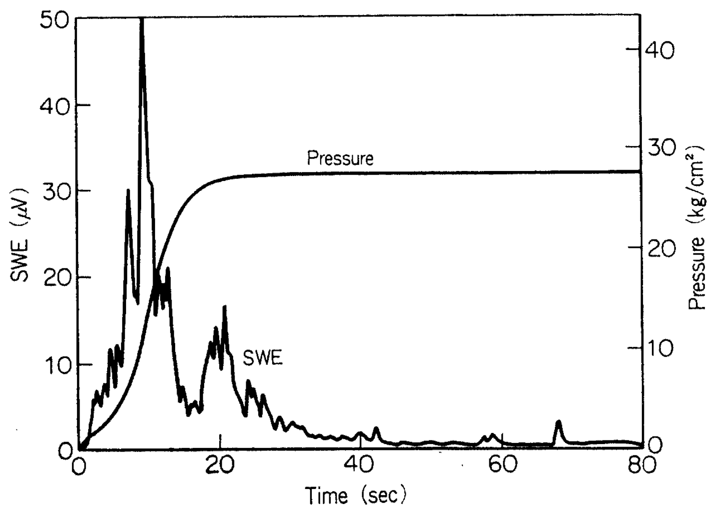

FIG. 12 (A)

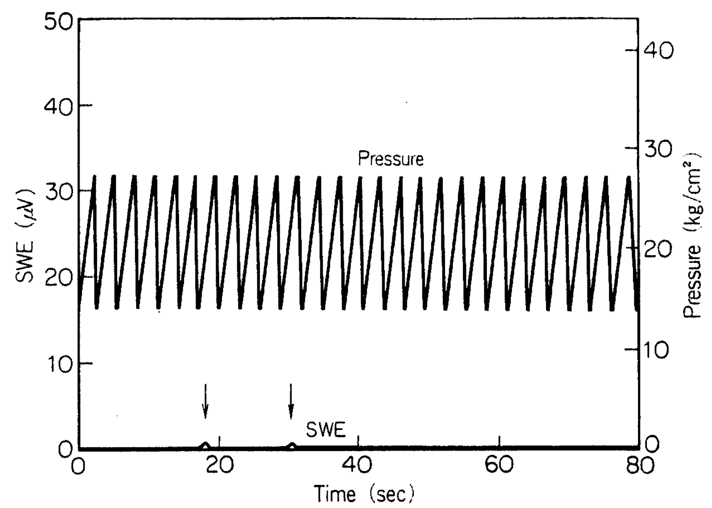

FIG. 12 (B)

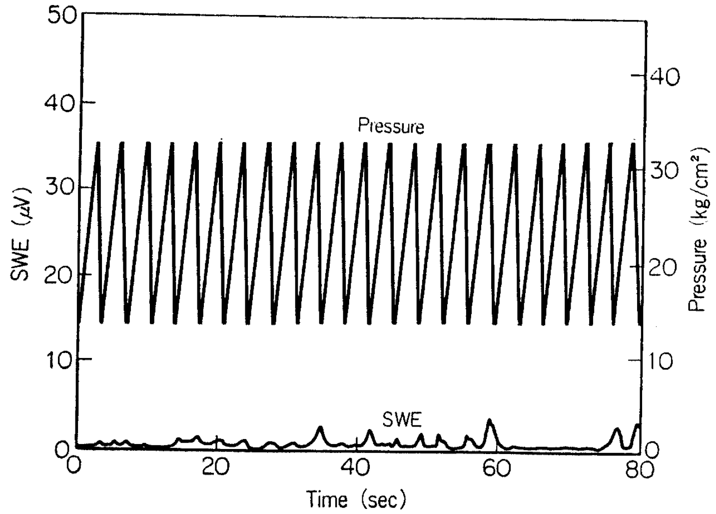

FIG. 12 (C)

FIG. 12. SWE during low-cycle fatigue testing.
(A) 1st pressure cycle
(B) between 2981st and 3007th cycle
(C) between 5353th and 5375th cycle

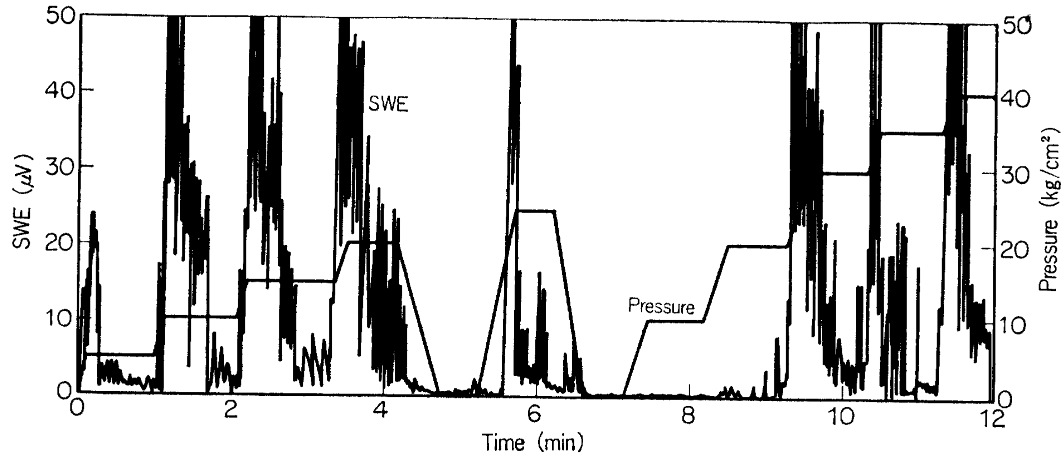

FIG. 13. SWE for the titanium-alloy rocket chamber.

As far as the titanium alloy is concerned, since the twinning radiates a huge amount of SWE, it is not clear whether a fatal crack is distinguishable from the yielding of small regions by the use of the SWE method. The figure also shows the typical Kaiser effect of the SWE.

4. CONCLUSIONS

SWE for three types of pressure vessels is investigated during hydrostatic and low-cycle fatigue testing.

In case of hydrostatic testing of the model vessel, source points of the SWE are located by triangulation technique. The SWE recorded at pressures lower than its proof pressure is traceable to the stress intensified region which is liable to cause a fracture. In order to detect structual imperfections, further investigations should be pursued intensively for SWE radiated at pressures lower than its proof pressure.

As a result of the fatigue testing of the vessel, it is made clear that the SWE method is useful for predicting a fatigue failure of structures in service.

The full-size titanium-alloy rocket chamber under hydrostatic testing emits a large amount of SWE due to twinning. Burst test of the chamber, using the SWE method, is expected to give more information on the discrimination between plastic deformation and fatal crack growth.

The SWE method is shown to have a potential value for nondestructive inspection and in-service safety-monitoring of structures such as pressure vessels.

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