Pressure measurement at the center of imploding detonation waves was carried out using a piezofilm stress gauge (PVF2). From the present measurement, the maximum pressures averaged within 2 and 3 mm in radius from the geometric implosion center are almost proportional to the initial pressure; 

\[ P_{\text{max}(r=2\text{mm})} = P_0 \times 1.2 \times 10^{-4} \quad \text{and} \quad P_{\text{max}(r=3\text{mm})} = P_0 \times 9.0 \times 10^{-3}. \]

The measured pressure is compared with estimated one based on the selfsimilar solution of imploding shock waves.

1. Introduction
It is well known that one can obtain very high pressure and temperature by focusing shock waves in a gas phase [1,2]. Terao made experimental studies on cylindrically or spherically imploding detonation waves and reported that the ratio of pressure at the implosion center to the initial one reaches ten thousand [3-5]. To measure pressure at the center of such imploding detonation waves, a pressure sensor needs to have high frequency response and to bear both high pressure and high temperature. Usual pressure sensors are easily damaged or destroyed owing to the severe conditions.

In the present work, pressure measurement at the center of the imploding detonation was carried out using a piezofilm stress gauge (PVF2) fixed at one end of the stainless steel rod whose other end faces the implosion center.

2. Experimental apparatus
2.1 Detonation chamber
Structure of the imploding detonation chamber is shown in Fig. 1. It mainly consists of three parts; a detonation tube, a cylindrical divergent space, and a conical convergent space. A conventional spark plug is set at one end of the detonation tube to ignite a mixture in the chamber. The detonation tube is long enough for transition from deflagration to detonation under present experimental conditions. At the entrance of the divergent space, the detonation wave changes its direction and travels radially outward. However, it is once decoupled into a shock and a reaction front because of rapid area change. Then the detonation wave, which propagates cylindrically, is initiated again at several hundred mm from the center. When the wave reaches the outer wall of the divergent space, it moves into the convergent space through 96 holes of 18 mm in diameter. Since the cross section of the convergent space is rhombic, the detonation still diverges at first until it reaches the position of 350 mm from the center. Finally, from this position, the spherically imploding detonation wave is realized. Using the present configuration of the convergent space, the spherical implosion can be expected without any transverse waves between the upper and lower wall of the convergent space [5].

As a test gas, a 19 % (vol.) propane-oxygen mixture was charged into the chamber. A initial pressure, \( P_0 \), varied from 13 to 67 kPa.

2.2 Measurement system
In the present work, a piezofilm stress gauge (PVF2) was used for pressure measurement at the implosion center because of its wide application pressure range and its short response time (less than 0.4 \( \mu \text{s} \)). Schematic of the pressure measurement system is shown in Fig. 2. To protect a thin insulator film of the gauge surface from high temperature, a stainless steel rod was mounted at the chamber center and one end surface of the rod receives pressure due to the implosion. On the other end surface, the PVF2 was fixed so that the transmitted pressure through the rod can be measured. The diameters of the rod facing the convergent space, \( \phi \), were 4 and 6mm.
To measure pressure during the implosion process except at the center, a conventional pressure transducer (Kistler 6201B) was placed in the radial direction. Arrival of the detonation wave was detected using ion probes [3].

3. Results

3.1 Convergency

When a dummy metal rod was mounted at the implosion center, some scratches were observed on its surface after experiments. From these scratches, which are due to high pressure and high temperature during the implosion process, one can check convergency of the implosion. Figure 3 shows the surface of a stainless steel rod after 10 shots were made. Most of scratches are located within a circle of several mm in diameter. Although the implosion center does not agree with the geometric one in each shot, it is found that the imploding detonation converges at least within 2 mm in diameter. This is also confirmed from the pressure measurement mentioned below.

3.2 Pressure measurement

In the pressure history obtained using the PVF₂, there can be seen some peaks. The time interval between arrival of the detonation wave at \( r = 20 \text{ mm} \) and the first peak measured by the PVF₂ is about 19 \( \mu \text{s} \). This value almost coincides with sum of time for propagation of the detonation wave from \( r = 20 \text{ mm} \) to the center and time for travel of a pressure wave in stainless steel rod. The other peaks are due to reflection of pressure waves at both ends of the rod and are neglected in pressure evaluation. Figure 4 shows the maximum pressure at the implosion center, \( P_{\text{max}} \), plotted against \( P_0 \) for the different rod diameter, where \( P_{\text{max}} \) is defined as the value of the first peak. It is shown in Fig. 4 that \( P_{\text{max}} \) is almost proportional to

\[
P_{\text{max}} = P_0 \times 12 \times 10^4.
\]

From comparison of the proportional constant, Eqs. (1)-(2) also confirm that the imploding detonation converges within 2 mm from the center.

Figure 5 shows pressure profiles measured with the conventional pressure transducer. The time is negative during
the implosion process and is zero when the wave reaches the chamber center. The pressure of the wave front increases rapidly near the implosion center, which is due to the effect of spherical convergence. Since the manner of area convergence changes from spherical to cylindrical at \( r = 5.5 \) mm, the incident wave reflects at this position (the first reflection). The transmitted wave then reflects at the implosion center (the second reflection). The maximum pressure shown in Fig. 5 corresponds to that of the second reflected wave.

4. Discussion

According to the self-similar solution of implosion shock waves by Guderley [3], which is valid near the implosion center, the following relation is obtained.

\[
P / P_0 \propto (r / r_0)^a,
\]

where constant \( a \) is dependent on the manner of area convergence and the ratio of specific heat of the gas. Eq. (3) is also valid for imploding detonation waves, since an effect of heat release is negligible as compared to the driving mechanism of area convergence [2]. This means that one can treat the imploding detonation wave as a very strong shock wave. As shown in Fig. 6, the peak pressure of the incident wave, \( P_1 \), and the second reflected wave, \( P_{r2} \), can be estimated as follows:

\[
P_1 / P_0 \propto (r / r_0)^{-1.1\pm0.2},
\]

\[
P_{r2} / P_0 \propto (r / r_0)^{-1.4\pm0.1}.
\]

Since maximum pressure near the center is obtained after the second reflection, \( P_{max} \), measured with PVF2 should be compared with \( P_{r2} \). Eq. (5) is valid for the spherical convergence and thus \( P_{r2} \) at \( r = 2 \) mm and at \( r = 3 \) mm for \( P_0 = 53 \) kPa are estimated by the following manner. From Eq. (5) and \( P_{r2} / P_0 \) of 1500 at \( r = 20 \) mm, the value of \( P_{r2} \) at \( r = 5.5 \) mm is calculated. Then using \( a = -0.8 \pm 0.1 \) for the case of the cylindrical implosion [3], \( P_{r2} \) at \( r = 2 \) mm and at \( r = 3 \) mm are estimated to be 1.1 GPa and 0.77 GPa respectively. These values are about 50% higher than those obtained from Eqs. (1)-(2). However, the reflected wave is followed by expansion waves [6]. This means that the pressures averaged over the rod surface must be lower than the above values. Thus the discrepancy is acceptable in magnitude. The result of this comparison supports validity of the present method for high pressure measurement of imploding detonation waves.

5. Conclusion

Pressure at the center of imploding detonation waves was obtained by measuring the pressure transmitted through stainless steel rods using the PVF2 pressure gauge. The maximum pressures averaged within 2 and 3 mm in radius from the implosion center are almost proportional to the initial pressure in the range from 13 to 67 kPa and are estimated by the following relations:

\[
P_{max}(r=2\text{mm}) = P_0 \times 1.2 \times 10^{-4},
\]

\[
P_{max}(r=3\text{mm}) = P_0 \times 9.0 \times 10^{-3}.
\]

References