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Destruction of Cryogenic Pressure Vessel and Piping by Shock Wave

In recent years, the usage of cryogenic fluids as coolant are gaining more attention due to their capability to fulfill the requirements of today's advancing low temperature industrial applications. As a result, the use of a cryogenic pressure vessel and piping in LNG-tank, LN_2, O_2 *tank for food processing applications and medical applications are becoming more important. In a cryogenic pressure vessel and piping, the reduction of thermal insulation by a small initial damage leads to an internal pressure rise and occurrence of flashing, which leads to a secondary crush of the vessel. In this study, a shock wave was applied to a pressure vessel and piping filled with cryogenic fluid and various observations were made. The internal pressure time history was measured and the safety of the cryogenic pressure vessel and piping was considered.*
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1 Introduction

The safety countermeasure of cryogenic pressure vessels for liquid nitrogen, oxygen, and LNG depends on the pressure release by a blow valve. The operating temperatures of these liquids are very low in comparison with the atmospheric temperature. Therefore, cryogenic fluids always have boiling energy. A leakage accident is likely to be associated with the subsequent disaster of an inner cryogenic fluid's explosive boiling "flashing" [1–4]. It is important to examine the effect of cryogenic pressure vessel and pipe when exposed to an extremely low temperature or when they undergo shock due to the collision, earthquake, traffic accident, etc. The shock tolerance of pressure vessel materials at the cryogenic temperature range is necessary to consider their safety. Recently, the studies on shielded pressure vessels subjected to space debris impact [5], the fracture response of the tube under internal static and detonation loading [6] and welded aerospace tank [7] are reported. However, the reported results are based on room temperature. The properties of shocked material in the temperature range of 100 K and below are not widely known. Therefore, we carried out experiments on test pipes exposed to shock loading at cryogenic temperatures and investigated the fracture of the test pipe and its fragments. Hardening was observed in the surface of the shocked test piece. Also, we conducted the experiments on pressure vessel and piping filled with cryogenic fluid by applying a shock wave.

In this paper we report the safety of cryogenic pressure vessel with vacuum thermal insulation when subjected to shock wave loading.

2 Test Pipe and Specimen Under Cryogenic Temperature

2.1 Experimental Apparatus and Method. Figure 1 shows the outline of the experimental device used in the present study. A container made of paper and surrounded by insulating material was used to keep the liquid nitrogen. The pipe was placed on the bottom of the container and cooled by liquid nitrogen. The dimensions of the pipe were 22 mm outer diameter, 18 mm inner diameter, and 2 mm in thickness. Two different materials, namely, mild steel and SUS 304, were used. A high explosive SEP (Asahi Chemical Industry Co. Ltd., Japan, PETN: 65%, paraffin: 35%, density: $1310\ \mathrm{kg/m^3}$, detonating velocity: $6970\ \mathrm{m/s}$) of weight 10 g placed above the test pipe was used to strengthen the shock wave. The gap between the explosive and the pipe was filled with insulating material to prevent uninitiating. A No. 6 electric detonator (Asahi Chemical Industry Co. Ltd., Japan) was used to detonate the explosive.

2.2 Results and Discussions. Figures 2(*a*) and 2(*b*) show the photographs of a mild steel pipe before and after the application of a shock wave, respectively, at cryogenic temperature. The test pipe fractured into pieces inside the cryogenic container. This could be the remarkable example of cold brittleness. The result of shock loaded SUS 304 is shown in Figs. 3(*a*) and 3(*b*). In this case the amount of deformation was less. This can be attributed to the hindrance of the crystal movement at cryogenic temperatures that avoids slip deformation to take place, and thus only twin deformation can take place.

In order to develop a further understanding of the contributing factors affecting the hardness of these materials, a plate test piece was used and shock loaded at the same cryogenic temperature. The test piece used was SUS 304, which is generally used for low temperature structures.

The overview photograph of the SUS 304 test piece shocked at room temperature and cryogenic temperature are shown in Figs. 4 and 5, respectively. Fracturing was not observed in the test piece, even though the pieces were bent by the shock wave for both room and cryogenic temperature. The amount of bending was more at a room temperature shocked piece compared to that of cryogenic temperature. The test samples were cut in the transverse direction and the Vickers hardness was measured. The measured position is shown in Fig. 4(*b*). The positions 1, 2, and 3 correspond to the center of bending, the surrounding part of bending, and an undeformed part, respectively. At each position, the hardness was measured at intervals of 1 mm from the shocked surface. The measured hardness values are shown in Fig. 6. The short dashed lines represent the hardness value of the material before shock and the long dashed lines represent the hardness value at cryogenic temperature. SUS 304 does not experience more change

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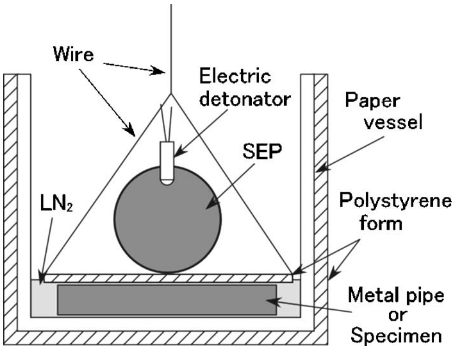

Fig. 1 Outline of the experimental device

in hardness at the cryogenic temperature. At each position, the hardness value in the case of shock loading at a cryogenic temperature is higher than the corresponding hardness value of shock loaded SUS 304 room temperature. This can be attributed to the following reason. SUS is stronger at a low temperature and can be deformed without fracture at a cryogenic temperature. It is also due to the fact that the deformation at low temperature increases mean dislocation density compared to he deformation at room temperature [8]. From these results, it can be concluded that even though the pressure vessel and piping does not break at the first shock, considering the secondary crush that took place, it is ex-

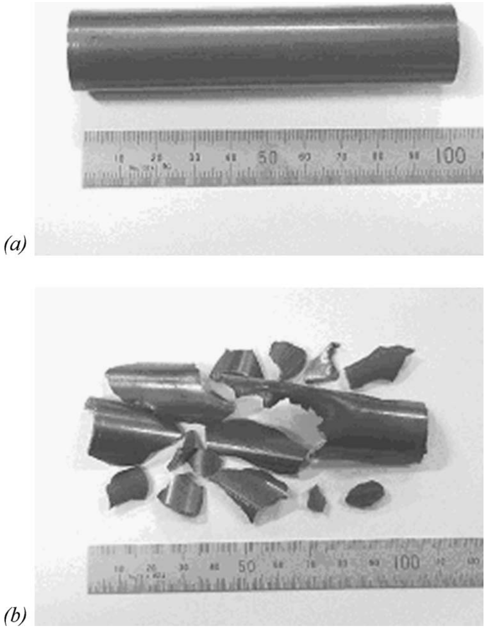

Fig. 2 Photographs of mild steel pipe before and after the application of shock wave at cryogenic temperature (87 K). (*a*) Before; (*b*) after.

Fig. 3 Photographs of SUS 304 pipe before and after the application of shock wave at cryogenic temperature (87 K). (*a*) Before; (*b*) after.

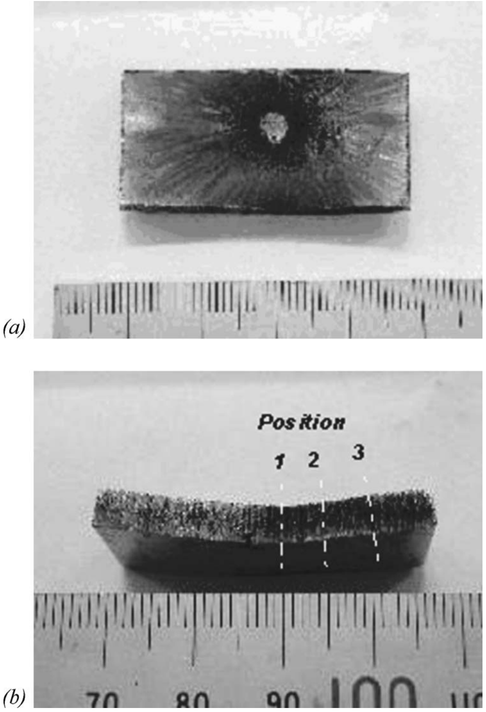

Fig. 4 Photograph of shocked SUS 304 at room temperature. (*a*) Top view; (*b*) side view.

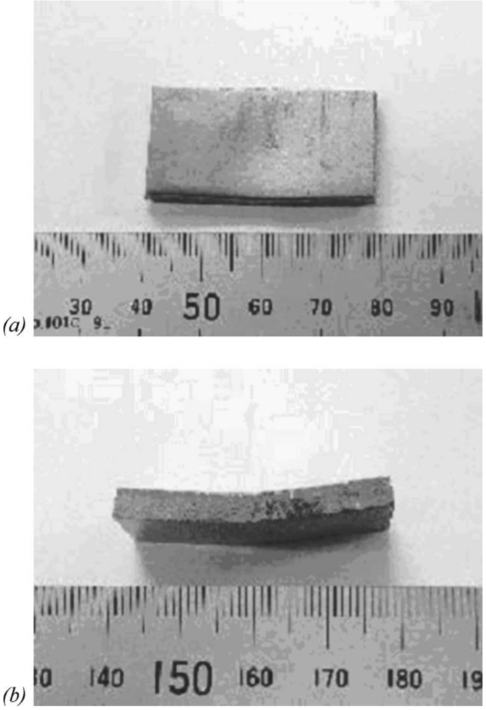

Fig. 5 Photograph of shocked SUS 304 at cryogenic temperature (87 K). (*a*) Top view; (*b*) side view.

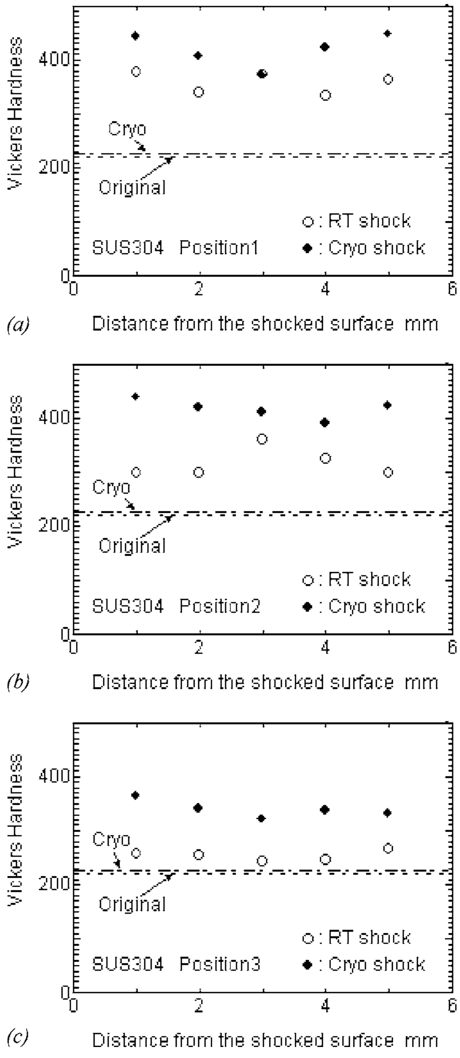

Fig. 6 Relationship between Vickers hardness and distance from the shocked surface in the case of SUS 304. (*a*) Position 1; (*b*) position 2; (*c*) position 3.

pected that the surface of pressure vessel might have hardened by the first shock with the exposure of the cryogenic temperature.

3 Experiment on Liquid Nitrogen Tank

In order to investigate in detail about the behavior of the LN_2 tank when shock was applied, a commercial LN_2 tank filled with LN_2 was placed in a tank, and the shock wave was applied by the detonation of an explosive.

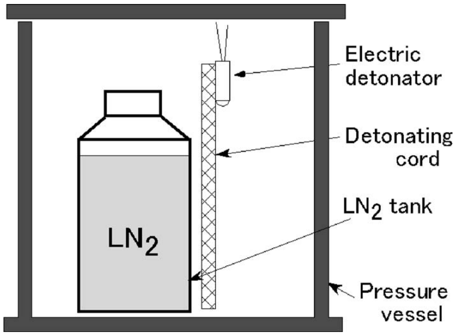

Fig. 7 Schematic arrangement of experimental set up for the case of LN_2 tank

Fig. 8 Photograph of LN_2 tank before shocked

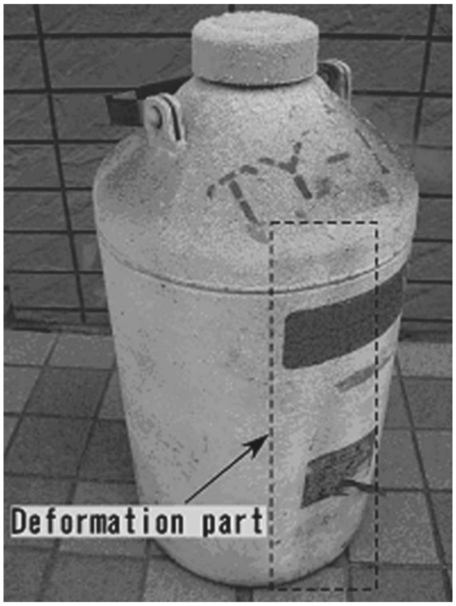

Fig. 9 Photograph of LN_2 tank after shocked

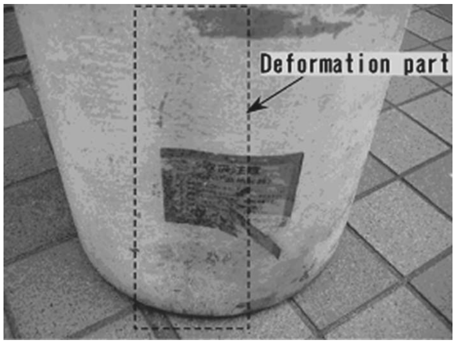

Fig. 10 Photograph of LN_2 tank after shocked (enlarged)

Fig. 11 Photograph of LN_2 tank after shocked (side view)

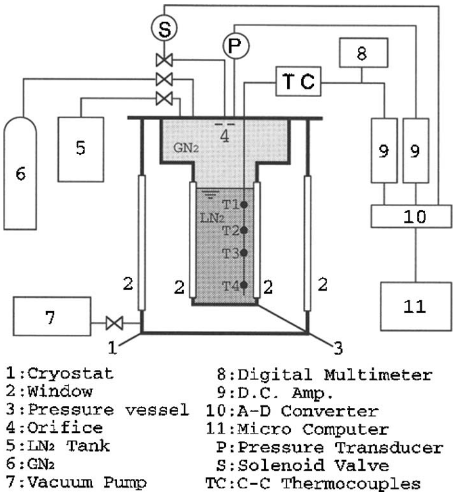

Fig. 12 Experimental apparatus for the case of LN_2 flashing

3.1 Experimental Apparatus and Method. Figure 7 shows the schematic arrangement of the experimental set up used for this study. The pressure vessel container was made by steel. The LN_2 tank filled with LN_2 was placed inside the container. The size of the tank was 510 mm height, 270 mm outer diameter with 10 L capacity. The inner wall and outer wall of the tank were made by SUS 304 and aluminium alloy, respectively. The explosive used was a detonation fuse of 6308 m/s detonating velocity provided by Japan carlit Co., Ltd. The length and the diameter of the detonating fuse were 500 and 5.3 mm. The No. 6 electric detonator was used for the initiation of explosives (Asahi Chemical Industry Co. Ltd., Japan). The distance between the tank and explosive was 10 mm. The pressure value estimated by numerical calculation is about 112 MPa in this distance.

3.2 Results and Discussions. The photograph of the LN_2 tank before and after the application of a shock wave is shown in Figs. 8 and 9, respectively. The outer wall of the liquid nitrogen tank was initially maintained at room temperature by a layer of thermal insulation. When the shock wave was applied, the outer wall deformed by shock and thermal insulation dropped, resulting in frost on the walls tank (see in Figs. 9–11). In this case a pressureless tank was used, and thus there was no rise in pressure inside the tank. The internal pressure may increase in the case of a pressurized tank leading to the destruction of the tank.

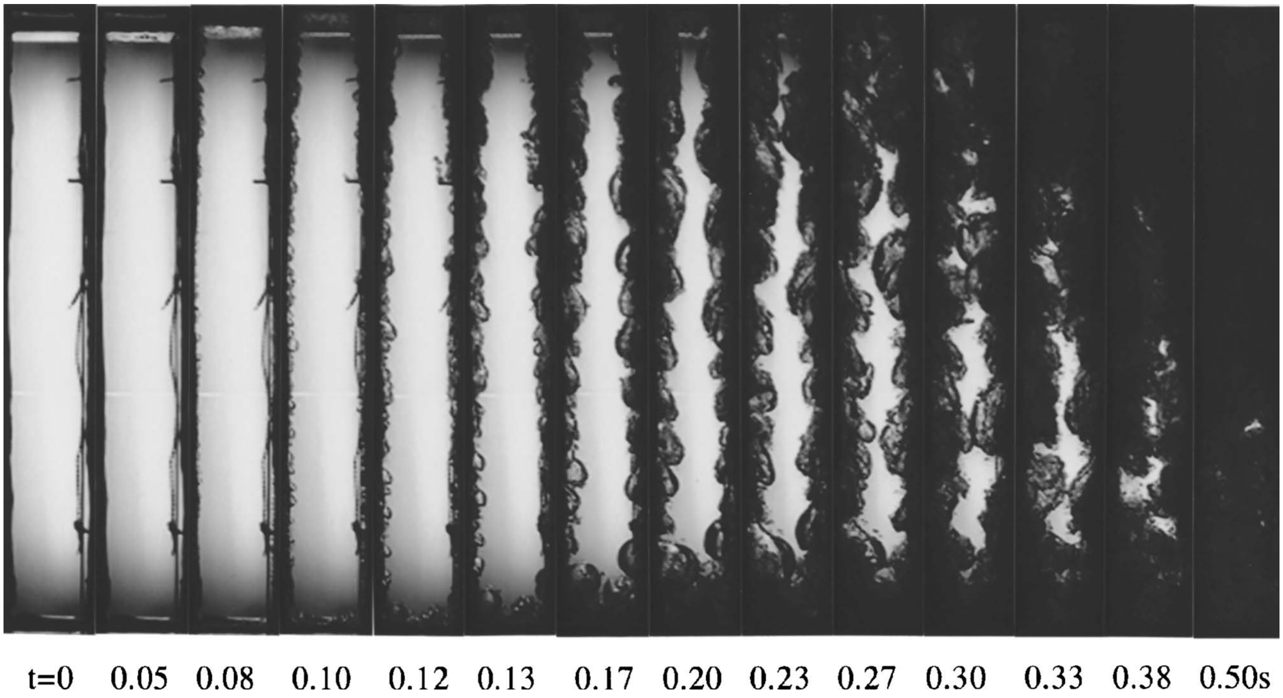

Fig. 13 Flashing aspect under pressure release. p_i=546.6 kPa, T_1=93.3 K, T_2=91.3 K, T_3=90.5 K, T_4=89.9 K, With backlight; Bright area: liquid (unboiling) part; dark area: boiling part.

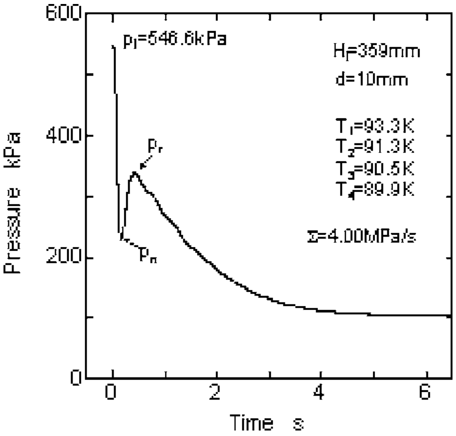

Fig. 14 Pressure-time history under depressurization in the pressure vessel

4 Experiment on Liquid Nitrogen Flashing

We carried out the experiments on LN_2 flashing in order to investigate in detail the effect of liquid nitrogen by the pressure release in a LN_2 tank dropped thermal insulation level.

4.1 Experimental Apparatus and Method. The experimental apparatus is schematically illustrated in Fig. 12. The apparatus consists of a cryostat (pressure vessel and vacuum jacket), vacuum pump, liquid nitrogen tank, and measuring systems. The vacuum jacket is 680 mm in length, 215 mm in outer diameter, and has a pair of BK7 glass windows (54 mm × 374 mm). The pressure vessel of dimensions 592 mm × 50 mm × 50 mm uses a pair of acrylic windows (50 mm × 360 mm) for the observation of flashing events. An orifice is mounted on the top of the vessel to control the rate of depressurization. A pressure transducer and four copper-constantan thermocouples were set on the pressure vessel.

To maintain a higher level of thermal insulation, the vacuum pump was used to evacuate to the order of 10^{-4} Pa and the liquid nitrogen was allowed to flow from the LN_2 tank to the pressure vessel. After the vessel was filled with the desired amount of liquid nitrogen, the initial pressure in the vessel was set to a prescribed level by self-pressurization (150–550 kPa). The experiment of flashing was conducted by the sudden opening of the electromagnetic valve, which, in turn, results in the sudden release of liquid nitrogen from the vessel. The pressure was measured by the transducer, which was connected to the A/D converter. The digital data was processed by a microcomputer. The boiling behavior caused by depressurization was observed using a video camera.

4.2 Results and Discussions. Figure 13 shows the photograph flashing behavior in the case of a 10 mm orifice diameter. The initial pressure and liquid level was 546.6 kPa and 359.0 mm, respectively. At 0.05 s, after the depressurization started, boiling started from the vapor-liquid interface, where the liquid temperature is the highest [9], and proceeded to the bottom along the wall of the vessel. During this period, there was no significant boiling in the center of the liquid. At this stage, superheating of the core liquid increased with time without resolving its nonequilibrium state by boiling. When the boiling front reached the bottom of the vessel (0.10 s), violent boiling occurred in the whole area and the vapor-liquid mixture spread throughout the vessel (0.50 s). The pressure time history for this condition is shown in Fig. 14. The pressure in the vessel falls sharply from the initial pressure p_i, reaches a minimum pressure p_n, and then recovers up to the value of p_r by explosive boiling. Finally, the pressure in the vessel approaches the atmospheric pressure. Thus, the damage of thermal insulation of a cryogenic tank has a possibility of inducing a subsequent explosive boiling. The rapid internal pressure rise caused by explosive boiling may induce secondary shock and lead to failure of the vessel, if the internal pressure exceeds the pressure released by the leak valve.

5 Conclusion

The effect of shock wave loading at the cryogenic condition on the pressure vessel and piping was studied using test pieces, specimen, and LN_2 tank. The behavior of liquid nitrogen with pressure release was studied by liquid nitrogen flashing. The results, in the case of shock loading at cryogenic temperature, shows a higher hardness value in the test pieces than that of shock loading at room temperature. Although LN_2 tank was not destroyed by the shock of the detonation fuse, the fall of vacuum thermal insulation by deformation may induce subsequent secondary explosion.

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