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CASE REPORT

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An Explosion of a CNG Fuel Vessel in an Urban Bus

ABSTRACT: An investigation is presented of the explosion of a CNG (compressed natural gas) fuel vessel, called a liner, in an urban bus. The explosion happened at a gas station 10 min after filling was completed. There were no traces of soot and flames at the failed liner, which would be indicative of explosion by ignition of the gas. The filling process of the station was automatically monitored and recorded in a computer. There was no unusual record of the filling system that indicated excess pressure at the time of the accident. There were cracks on the liner that were initiated at the outer surface of the cylindrical shell located at a point 4 cm above the lower dome where cracks did not originate easily as a result of overload. Chemical analysis was performed on a specimen that was cut from the liner, and there was no peculiarity in the mix. Mechanical analysis was performed on the specimens and showed that the hardness was not in the specified range because of inadequate heat treatment of the metal. The hardness of the liner was strictly controlled in the manufacturing process. All the liners that were manufactured at the same period with the failed liner were recalled for examination.

KEYWORDS: forensic science, CNG vessel, liner, hardness, heat treatment

To reduce air pollution, the fuel of urban buses is being replaced from diesel to compressed natural gas (CNG) in Korea. About two million urban buses that use natural gas fuels have been in service since December 2007. According to the manufacturer's specification, the fuel vessel of a CNG bus, called a liner, is manufactured by a deep drawing and ironing (DDI) process with 34CrMo4 material followed by several steps of heat treatment (1). The 34CrMo4 is chrome molybdenum steel that is expressed by the DIN standard; the equivalent steel as per the AISI standard is 4135 or 4137. It is commonly used for mechanical structures through hot working with heat treatment. The cylindrical shell of the liner, called a composite cylinder, is wound by fiber glass with epoxy for reinforcing the circumferential strength. The normal filling pressure of a CNG liner is set to 207 bar or higher. This demands special care for the filling system of a station and the components of a bus fuel system to prevent the potential danger of an explosion that results in heavy casualties. This case report presents an unusual accident of an urban bus that was caused by the explosion of a liner.

Case Report

The liner of an urban bus exploded at the station 10 min after filling. Fortunately, the bus was not in service and was parked, awaiting a change of driver. No casualties were recorded. The bus had a total of eight liners, which were tied with parallel pipe lines. The liner that was the sixth from the front side of the bus

FIG. 1—*(a) The gas station where the accident took place. Arrows indicate the flight path of a cylindrical shell and a lower dome. (b) The damage to the bus that was parked beside the bus that featured the explosion. The quadrangle indicates the trace where the cylindrical shell went through this adjacent bus.*

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FIG. 2—*The location of liners. The bus had a total of eight liners that were tied with parallel pipe lines. The liner that was the sixth from the front side of the bus had exploded.*

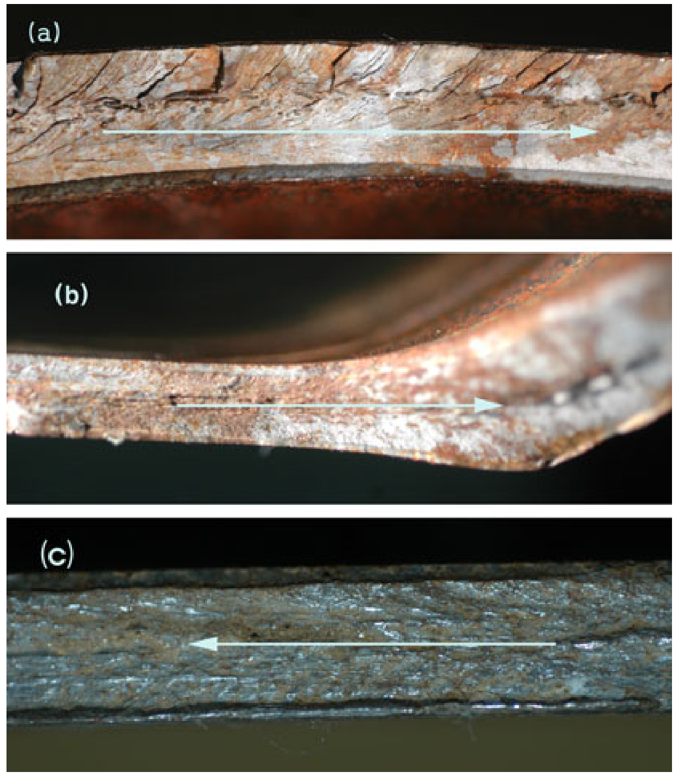

FIG. 4—*(a) The fractured surfaces of the lower dome (refer to point A in Fig. 3*a*). Chevron patterns are clearly visible. The arrow indicates the direction of crack propagation. (b) The fractured surfaces of the lower dome (refer to point B in Fig. 3*a*). Chevron patterns are clearly visible. The arrow indicates the direction of crack propagation. (c) The fractured surfaces of the cylindrical shell (refer to point C in Fig. 3*c*). Chevron patterns are clearly visible. The arrow indicates the direction of crack propagation.*

exploded. Each liner had a safety valve that operated not through pressure but through temperature, which was set to 110°C. The volume of the cylinder was 108 L with a length of 1620 mm and a diameter of 306 mm. The exploded liner was divided into two parts, the cylindrical shell and the lower dome. The cylindrical shell went through the bus that was parked beside it and flew about 500 m. The lower dome went through the wall and was found at an unoccupied area about 70 m away. Figure 1 shows the gas station where the accident took place. Figure 2 shows the liners of the bus. The filling process of the station including the operating data of the flow rate, pressure, and temperature, was automatically monitored and recorded in a computer, which was installed in the office. There was no unusual record of the filling system that might have indicated excess pressure at the time of the accident. Figure 3 shows the exploded liner. The lower dome was completely blown off from the cylindrical shell along the circumference. When the composite cylinder was removed from the cylindrical shell, a longitudinal crack was seen that developed in the inlet nozzle. Severe corrosion also developed along the longitudinal direction and the circumference near the lower dome.

Results and Discussion

There were no traces of soot and flames at the failed liner and the bus; this indicated that the liner was not exploded by ignition

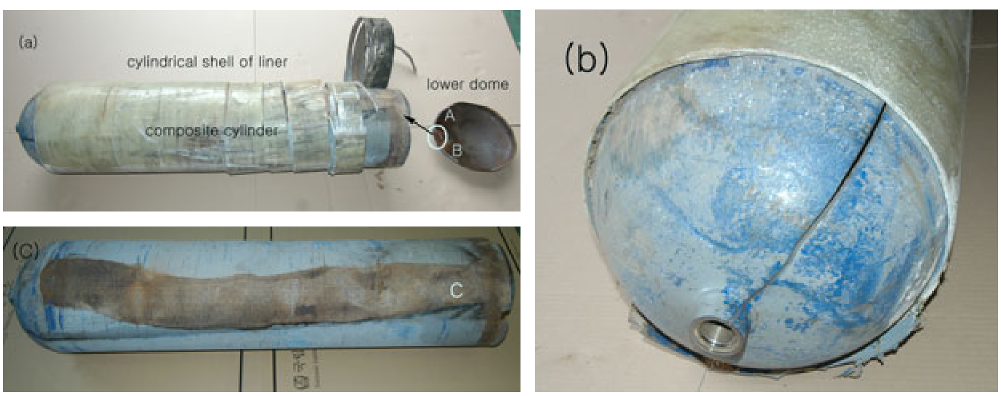

FIG. 3—*(a) The exploded liner. The lower dome was completely blown off from the cylindrical shell along the circumference. The circle indicates the location where chevron patterns converge (refer to Fig. 5*a*). The fractured surfaces of A and B are shown in Fig. 4*a,b*. (b) The inlet nozzle of the exploded liner. A longitudinal crack was developed. (c) The cylindrical shell of the liner. Severe corrosion developed along the longitudinal direction and the circumference. The fractured surface of point C is shown in Fig. 4*a*.*

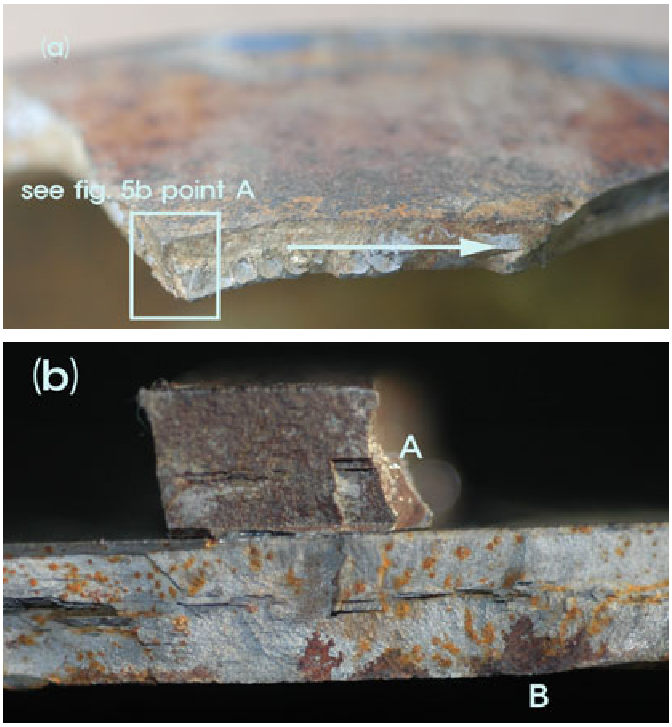

FIG. 5—*(a) Magnification of the location where the chevron patterns converge (refer to the circle in Fig. 3*a*). The arrow indicates the direction of crack propagation and the counterparts of the fractured surfaces are shown in Fig. 5*b*. (b) The counterparts of the fractured surface shown in Fig. 5*a*. Point A indicates the location, which is shown as a quadrangle in Fig. 5*a*. Point B indicates the crack origin. The crack is initiated not at the inner surface but at the outer surface, which is severely corroded.*

FIG. 6—*SEM fractograph at 100 ×. The crack-initiation point (arrow) is severely damaged by erosion, etc.*

of the gas. The fractured surfaces of the lower dome and cylindrical shell are shown in Fig. 4. Chevron patterns, which indicate the direction of the crack propagation, were clearly visible in the fractured surface (2,3). There was no beach mark that would have indicated fatigue fracture (2,3). From the chevron patterns, it can be concluded that the crack in the cylindrical shell initiated at a

TABLE 1—*The material composition of 34CrMo4 and the chemical composition of the exploded liner (wt. %). The acceptable ranges of the constituent components of 34CrMo4 are given in the first row and the corresponding concentrations for the tested liner specimen in the second row. It can be seen that all components fell within the normal values.*

	C	Mn	Si	P	S	Cr	Mo
34CrMo4	0.25∼0.38	0.4∼1.0	0.1∼0.4	<0.015	<0.01	0.8∼1.2	0.15∼0.4
Specimen	0.37	0.72	0.26	0.007	0.003	1.12	0.31

TABLE 2—*Mechanical properties of the liner. The measured yield strength and hardness of each of the four specimens taken from the failed liner. For comparison, the acceptable strength and hardness, respectively, for 34CrMo4 are given in parentheses.*

	Specimen 1	Specimen 2	Specimen 3	Specimen 4
Yield strength (Mpa) (>840 Mpa)	1068	1004	1057	978
Hardness (HV) (270∼321 HB)	485.2	443.5	495.0	456.6

point 4 cm above the lower dome. From a microscopic examination, we concluded that the crack was initiated not at the inner surface but at the outer surface that was severely corroded. Figure 5 shows the location of the crack initiation (point B). Figure 6 shows the scanning electron microscope (SEM) fractograph of the crack-initiation point (arrow). Unfortunately, the crack-initiation point was severely damaged by erosion, etc. Hence, a detailed examination was not possible. In general, when the liner is overfilled, that is, over-pressured, it commonly fails at the boundary between the cylindrical shell and the lower dome. The investigated crack-initiation point was not the place where a crack originates easily as a result of overload. The manufacturing specification of the liner showed that the liner was made of 34CrMo4 with a DDI process that was followed by several steps of heat treatment. Chemical analysis was performed through an emission spectrometer on a specimen that was cut from the liner. Table 1 shows the specified chemical composition of 34CrMo4 with the results of the chemical analysis. There was no peculiarity in the mix. Analysis of the mechanical properties, including hardness measurements, was carried out on the four specimens that were cut by a water jet from the cylindrical shell. Table 2 shows the specified yield strength and the hardness with the results of the analysis of the mechanical properties. The measured hardness showed that the hardness of the liner was not in the specified range, which indicated that the liner was poorly heat-treated. The hardness of the liner was strictly controlled in the manufacturing process to prevent the possibility of brittle fracture, etc. All the liners that were manufactured at the same period as the failed liner were recalled for examination.

From these results, we reached the conclusion that poor heat treatment during the manufacturing process was a major cause of the failed liner. Considering that the crack started at the severely corroded outer surface, which was not permitted in the specification, severe surface corrosion also acted as an additional cause of the failed liner.

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