Bursting of a scuba cylinder made of an aluminum alloy

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(Summary)

Scuba or aqualung is an automatic self-breathing system for underwater diving, and it has been widely used for leisure diving. A scuba cylinder made of an aluminum alloy suddenly burst right after it was filled with air. According to the investigation after the incident, it was identified that there were a number of the cracks along the axis of the screw part of cylinder. The causes of the cracks were inter-granular corrosion and stress corrosion cracking (SCC). Countermeasures, such as the revision of the regulations for the safety of scuba cylinders, were carried out.

1. Component

A scuba cylinder made of an aluminum alloy (Capacity : 10. 3liter, External diameter : 185 mm, Thickness : 13.5mm, Length : 628mm, Material : A6351-T6, Maximum filling pressure : 21.6MPa (220kgf/cm^2), Manufacturer : Luxfer Gax Cylinders. (See Fig. 1)

2. Event

Air was filled into the scuba cylinder at the air filling station. After the pressure reached 20.1 MPa (205kgf/cm^2) and the filling was finished, the cylinder suddenly burst when the scuba cylinder was being changed. The filling tube whipped around, and the operator was bruised on the right leg. Figure 2 shows the fracture surface of the burst cylinder. Although the cylinder burst into two portions and flew across the room, the damage resulting from the accident was not serious because the filling station was in a half basement.

The following related accidents were revealed after the accident.

○ Overseas

There were seven burst accidents of the A6351-T6 cylinder in the U. S. A., Australia and New Zealand.

○ Domestic

About 53,000 A6351-T6 cylinders were imported from 1985 to 1990, and a total of 10,462 cylinders were re-inspected over the last five years.

During the air filling of an A6351-T6 cylinder at the filling station of Hachijoujima, Tokyo on August 8th, 2000, leakage from the shoulder of the cylinder occurred.

The aluminum alloy material used for scuba cylinders was changed from A6351-T6 to A6061-T6. However, similar cracks were found in the A6061-T6 cylinders.

According to the results of inspection of cylinders at the inspection station of Okinawa Prefecture from January to April 2001, the cracks along the axis inside the screw were found in nineteen (eleven of Luxfer Gas Cylinders and eight of Aluminum Precision Product) out of 487 A6061-T6 cylinders. Four of the nineteen cylinders which had a long crack were closely investigated, and it was found that the cracks had lengths from eight to eleven mm and depths from one to eighteen mm.

The following results were obtained from the fault tree analysis.

○ Figure 6 : The fault tree diagram focused on the fracture mode, fracture mechanism and fracture process.

The scuba cylinder burst into two pieces without showing LBB (Leak Before Burst). The fracture surface consists of a symmetrical old surface and a newly created surface in the screw part of the cylinder. The origin of the failure is the old fracture surface, and the final rapture was occurred in a ductile fracture mode. The old fracture surface was the axial crack from the screw of cylinder , and the fracture was caused by inter-granular corrosion. The crack did not propagate from the screw surface to the outer surface of the cylinder, but from the screw surface to inside the cylinder through its shoulder. The fracture had the "thumb-nail shape" (Figure 4). The "thumb-nail shape" is a distinctive feature of stress corrosion cracking. The thumb-nail cracking did not penetrate into the cylinder: however, the cracking propagated remaining very thin layer of the ligament, and the scuba cylinder burst at last.

Figure 7: The fault tree diagram focused on the inadequacy and inferiority of the design and manufacturing of the scuba cylinder (1).

The aluminum alloy material used for scuba cylinders was initially A6351-T6. However, it was proven that A6351-T6 showed characteristics of Sustained Load Cracking (SLC). Therefore, the material was changed to A6061-T6. However, a great many cylinders made of A6351-T6 are still being used.

Figure 8: The fault tree diagram focused on the inadequacy and inferiority of the design and manufacturing of the scuba cylinder (2).

Stress corrosion cracking, which induces thumb-nail cracking, resulted from inter-granular corrosion at the surface of the screw part of the cylinder. Although there was some general and localized corrosion at the inside of the shoulder, body and bottom part, deep inter-granular corrosion was not found. Through the metallographic observation of the vertical section of the cylinder, it was found that the crystal grain became course and crystal grain showed anisotropic growth. They were caused by the warm working during manufacturing the head and the recrystallization during solution treatment. The susceptibility to inter-granular corrosion and stress corrosion cracking was increased by the coarseness and the aeolotropic shape of the crystal grain.

Figure 9: The fault tree diagram focused on the load history, environment and material of the cylinder.

A corrosion environment is required to induce inter-granular corrosion. A corrosion environment and tensile stress are both required to induce stress corrosion cracking. The possibilities of the existence of interstitial water and salt were investigated. The filling of the cylinder with air is usually conducted through a mother cylinder. Because of inevitable inadequacies in the compressor, the drain separator and the activated carbon absorption equipment, if interstitial water and salt exists in the mother cylinder, interstitial water and salt would naturally occur in the scuba cylinder as well. Even if there were no interstitial water and salt in the mother cylinder, if some water and salt remained in the valve of the scuba cylinder, there would be interstitial water and salt in the scuba cylinder. It is also possible that interstitial water and salt could occur in the cylinder because of insufficient pressure in the scuba cylinder before the filling of the air. Although the exact cause cannot be specified, it is possible that the cause is one or more of those processes mentioned above. In reality, it was found that there were traces of interstitial water and salt together with corrosion in the inner surface of most of the scuba cylinders that were investigated.

Figure 10: The fault tree focused on the inspection of the cylinder.

It is regulated by law that scuba cylinders must be inspected once every five years. The burst cylinder had passed the inspection three times in the past. However, it is unknown whether or not a detailed visual inspection of the screw part was performed in any of the past inspections. If a detailed visual inspection had been conducted and if it had been determined that there was no cracking, then we must conclude that the detection of the cracking was not possible and that the cracking existed without being observed. It is difficult to find inter-granular corrosion along the axis at the shallow surface of the scuba cylinder by visual inspection. Even if the cracking becomes the thumb-nail type, the mouth of the cracking at the screw part is very small, so considerable technique and experience is required for successful visual inspection.

Figure 11: The event tree of the bursting of the scuba cylinder caused by stress corrosion cracking.

The scuba cylinder was made of the problematic A6351-T6 aluminum alloy. Furthermore, the grain around the part of the screw become coarse and the grain shape aeolotropic due to the warm working and the solution treatment during the manufacturing of the head part of the cylinder. On the other hand, it appears that water and salt got into the cylinder during the filling of the air. Therefore, the inter-granular corrosion apparently had been accumulating for a long time, and the stress corrosion cracking by the hoop tensile stress caused by the inner pressure of the cylinder changed the inter-granular corrosion into the thumb-nail cracking form. The thumb-nail cracking was not observed by visual inspection of the cylinder. The cracking grew under the continuous use of the scuba cylinder. Finally, the scuba cylinder burst, starting at the cracking, during the filling of the air.

3. Course

On August 23rd and September 8th, 2000 and April 24th, 2001 an advisory bulletin was issued to each prefecture for distribution to the owners of scuba cylinders, air filling stations and cylinder inspecting stations by the Safety Division of the Nuclear and Industrial Safety Agency (NISA) of the Agency for Natural Resources and Energy (ANRE) in the Ministry of Energy, Trade and Industry (METI).

After the cracking was found in the cylinders made of A6061-T6, the NISA informed each prefecture on July 4th, 2001 that a committee had been established by the NISA in the High Pressure Gas Safety Institute of Japan (HPGSI) to investigate the possibility of bursting of cylinders made of A6061-T6.

The committee for the investigation of the scuba cylinders made of aluminum alloys, chaired by Professor Hideo Kobayashi of the Tokyo Institute of Technology, completed its investigation and opened its report to the public on the HPGSI website on October 19th, 2001.

4. Cause

This case had a typical complex set of causes. Six causes are shown below. If one of these causes had not occurred, the burst accident would not have happened.

(1) Material (A6351-T6)

In proper selection of a material which is susceptible to continuous load cracking, inter-granular corrosion, and stress corrosion cracking

(2) Manufacturing (coarse crystal grain)

Inadequate procedure for manufacturing and heat treatment of the head part of the cylinder

(3) The occurrence of interstitial water and salt in the cylinder

(4) The extreme difficulty of observing the cracking during visual inspection

(5) No occurrence of LBB (Leak Before Burst)

It is required that there should be LBB at the maximum filling pressure during the manufacturing. That is, even if the cracking on the surface caused and extended by the stress corrosion cracking, a detectable leakage should precede the burst by the penetration of cracking, so the safety can be maintained. However, LBB is only required for the parts of the container that are thinnest. The screw, shoulder and bottom of the container, which are thicker than body, are not subjects of the requirement. It was found that the LBB was not enforced for the thumb-nail cracking at the screw part.

(6) The lack of other accident information

There were similar accidents in foreign countries, but the information regarding those accidents was not properly conveyed.

5. Immediate Action

The material used for scuba cylinders has been changed from A6351-T6 to A6061-T6. However, cylinders that are made of A6351-T6 are still being widely used. Furthermore, cracking along the axis in the screw part of cylinders that are made of A6061-T6 was also found. Therefore the following practical countermeasures are suggested.

(1) Apart from the inspection conducted once every five years, the owner of the scuba cylinder should be required to conduct a visual inspection for finding cracking along the axis in the screw part. This inspection should be required by law. It should be noted that special technique and experience are required for proper visual inspection.

(2) Air filling operators should be warned of the importance of the competence and maintenance of the air filling station.

(3) Owners of scuba cylinders should be warned of the importance of protecting cylinders from interstitial water and salt.

(4) Manufacturers and importers should be required to improve the criteria for the manufacturing and heat treatment of the head part of the cylinder. The rental system for scuba cylinders is widely used. Therefore, the user of the scuba cylinder is not always the owner. The relationship, processing chain and responsibilities of the user, the owner, the operator of the air filling, the inspection station, the manufacture, and the importer must be clarified.

(5) Research on stress corrosion cracking of the 6000 series aluminum alloy should be increased.

6. Countermeasure

Based on the results of the study by the committee for the investigation of scuba cylinders made of aluminum alloys, on October 19th and November 23rd, 2001, a meeting of the high pressure gas division of the high pressure and gunpowder safety branch of the Research Committee for the Natural Resources and Energy was held. In the meeting, an article on "the concrete method of the countermeasures for the maintaining safety of scuba cylinders made of aluminum alloys" was recommended for inclusion in the report.

Special proposal was made for the revision of the safety regulations for cylinders to require a visual inspection of the screw part once a year in addition to the full inspection conducted once every five years.

Thus, according to this proposal, the additional clause (the ministerial ordinance No. 84 issued on June 10th, 2002) of the safety regulations for cylinders (the ministerial ordinance No. 50) was put into effect. This clause specifically establishes that the period of inspection of scuba seamless cylinders made of aluminum alloys be once a year in article 24 of the safety regulations for cylinders. It was also establishes that the inspector must certify that there is neither harmful damage such as the cracking along the axis of cylinder nor malfunction around the screw part in article 3 No. 5 of notice No. 150 (visual inspection), which establishes the various details such as markings as well as the inspection methods based on the safety regulations.

The High Pressure Gas Safety Agency had voluntary standards, "the regulations for an inspection of the cylinder for the scuba (KHKS 004-1983) ", that were actually applied. However, the standards were old and intended for cylinders made of steel. Therefore, taking into account the proposals from the investigation of the accident, a revision of the standards was commenced with the intention of treating both aluminum and steel cylinders.

The committee for the revision of the regulations for the inspection of cylinders for SCUBA, which was chaired by Professor Hideo Kobayashi, Tokyo Institute of Technology and established in the cylinder division of the technical members of the High Pressure Gas Safety Agency , held its first meeting on January 24th, 2002. The self-established regulations, "regulations for the inspection of seamless cylinders for scuba", were published in July 2002.

7. Knowledge

Complex causes:

The most accidents are caused by the results of conflicts among a number of individual causes. In accidents having complex causes, the projecting cause will usually be regarded as the major cause. There are two causes of complex causes. In the first case, there is one major cause, and the other causes just accelerate the major cause. In the second case, there are a number of major causes, and if any one of the major causes fails to occur, the accident will not happen.

Particularly in the investigation and analysis of accidents involving the destruction of machinery, the material is generally named as the major cause, and investigations and experiments are focused on the material. That is, the material is treated as being suspect from the beginning. This is natural, because the destruction of the machinery is the destruction of material. The problem is with the conclusion of the investigation and analysis of the accident. In Japan, the number of major causes given for an accident is usually very large, and therefore the material related factors will certainly be named among the major causes. The designation of a large number of causes is based on an aspect of Japanese culture that stipulates that the social responsibility of an accident should be vague and the responsibility should be divided between 1) the user and manufacturer of the machinery, and 2) the manufacturer of the material.

It is necessary to study sufficiently the results from a complex cause and to carefully consider the results.

8. On the Side

The English name for a pressure vessel is 'cylinder". However, in Japanese, a pressure vessel is called "bomb". A bomb in English is an explosive, and a Japanese 'bomb' carries this meaning as something that could explode, becoming a deadly weapon that flies around after the explosion.

○ Applications of the vessel

The applications of the vessel range from industrial use, to medical use, home use and leisure. The gas contents vary with application, such as air, oxygen or nitrogen.

○ Shape of the vessel

The shape of the vessel is similar to that of a sake bottle in that it has a thin neck, a broad bottom and a raised bottom. The function of the thin neck is to serve the contents a little at a time. The function of the broad bottom is for stability when standing upright. The function of the raised bottom is for increasing the stability in the upright position.

○ The material of the vessel

The gas is light but the vessel is heavy. In the past, the vessels were constructed to be stout and heavy like a safe because the gas was considered to be precious and dangerous. However, mass consumption of the gases has changed this perspective, and in accordance to the request for lower weight, the material has been changed from steel to aluminum and further to composite materials.

○ Corrosion starts from the bottom of a vessel

When the vessel made of steel is exposed to rain, it starts to corrode from the outer surface and bottom. Cases where a hole penetrates the body and the vessel explodes occur more often when corrosion starts from the outer surface than when corrosion starts from the inner surface.

○ How much corrosion can the vessel incur and still be safe ?

A vessel will be safe even if half of the body thickness is corrode. Vessels are built to be that strong.

○ The vessel itself is a projectile

When a vessel explodes, in addition to splinters of the vessel material, the vessel itself can become a projectile. If the valve is opened abruptly, the vessel would fly like a rocket because of the pressure release. A light vessel will fly more easily.

○ The gas must leak before the explosion

It is dangerous if a vessel explodes suddenly. Even if stress corrosion cracking occurs, if the gas leaks before the explosion when the cracking penetrates the body, the potential for explosion would be detected, and it might be possible to avoid the explosion by lessening the pressure. This is called Leak Before Break/Burst, or LBB. According to the manufacturing standards for vessels, design for LBB is required. With LBB design, we can be confident that the gas will leak before the explosion.

9. Primary Scenario

01. Ignorance
02. Insufficient Knowledge
03. Prejudice
04. Production
05. Hardware Production
06. Manufacturing of machinery and equipment
07. Cylinder
08. Aluminum alloy
09. Inappropriateness of material decision
10. Inappropriateness of manufacturing and thermal treatment condition
11. Usage
12. Operation/Use
13. Use of equipment and material
14. Interstitial water and salt
15. Failure
16. Fracture/Damage
17. Stress Corrosion Cracking (SCC)
18. Usage
19. Maintenance/Repair
20. Inspection
21. Difficulty of crack detection
22. Failure of Leak Before Break (LBB)
23. Failure
24. Large-Scale Damage
25. Burst

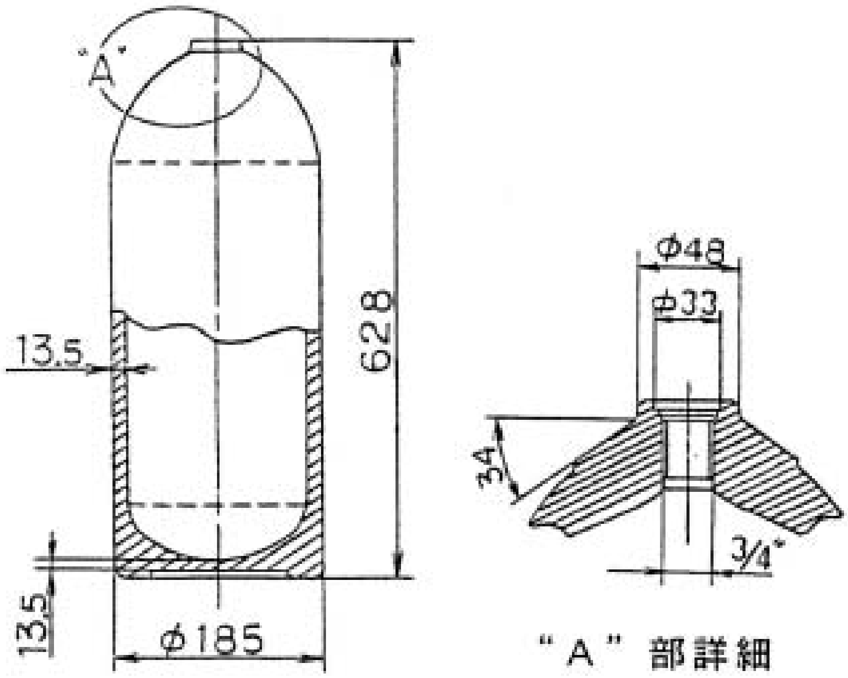

Fig. 1 Major dimension of cylinder.

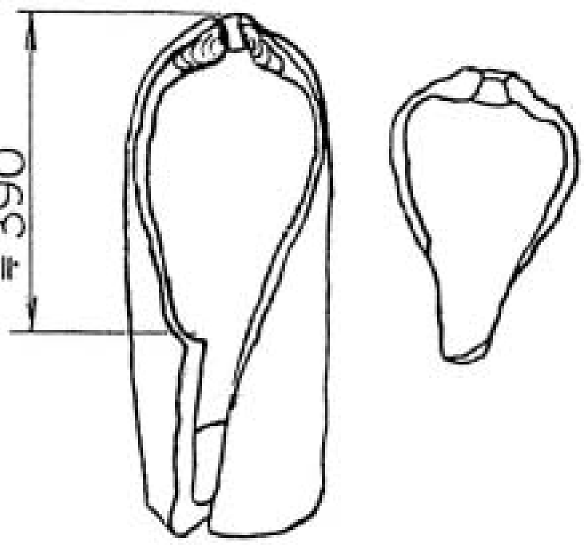

Fig. 2 Fracture surface of broken cylinder.

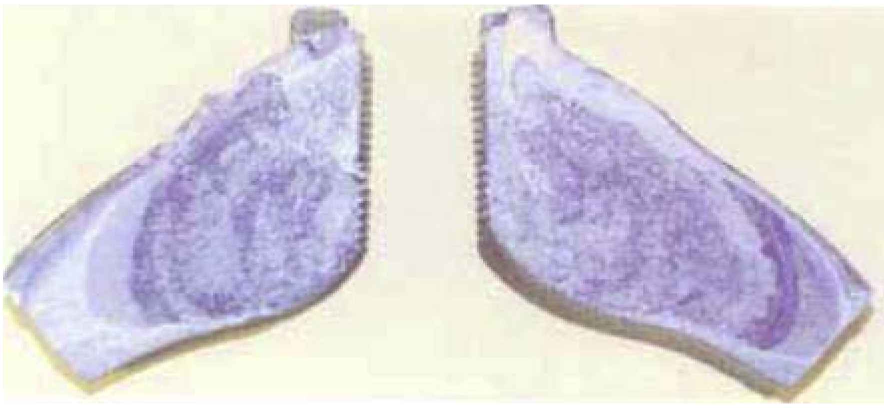

Fig. 3 Old fracture surface.

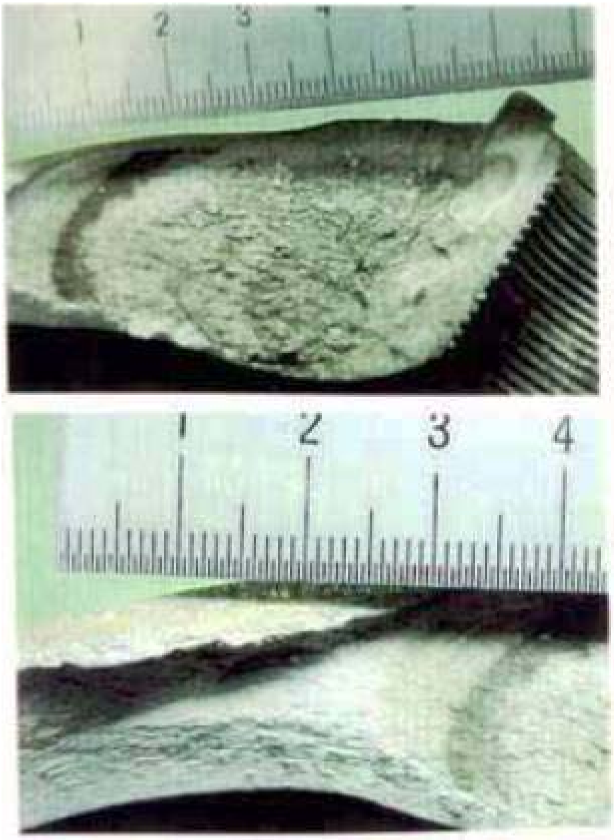

Fig. 4 Thumbnail-shape fracture surface.

Fig. 5　Metallographic observation results.