Danger of Fragmentation Failures of Composite Gas Fuel Cylinders with Micro- and Macrodamages of Inner Metal Shell

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Abstract. Gas fuel cylinders (GFCs) for motor vehicles are a source of man-made danger with such damaging factors as thermal radiation, open flame, as well as shock air waves and fragments in a case of an explosive nature of depressurization. To increase reliability of GFC, it is urgent to study causes of their fracture under various conditions of operation, in particular in a cryolithozone. A purpose of this paper is analysis the fragmentation of GFC to identify factors affecting safety of operation of gas cylinder vehicles in the sharply continental climate conditions. A character and causes of premature destruction of two metal-composite cylinders for compressed natural gas, occurred in winter and summer time, were investigated. It is found that the destruction was induced by defects of an inner steel shell of the cylinders (mechanical damage, presence of a decarburized layer, and hydrogen degradation), which caused initial cracks formation according to a fatigue mechanism. The main natural and climatic factor that stimulated reaching a state of overload in GFC with the defects of the inner shell was environment temperature fluctuations. Results of the paper can be used to improve operational capability of GFC, to ensure the safety of their operation and development of compensatory measures.

1. Introduction
Conversion of the vehicles to natural gas as motor fuel is largely due to the environmental safety of a gas engine. At the same time, the gas fuel cylinders (GFC) are the source of man-made danger with such damaging factors as the thermal radiation, open flame, as well as the shock air waves and fragments in the case of the explosive nature of depressurization. In connection with the reported cases of GFC emergency ruptures including those established on passenger transport, it is urgent to identify the causes of these fractures. In addition to expert significance, data obtained are important for an increase of reliability and performance of GFC in various operating conditions (including a rather wide range of ambient temperatures). The purpose of this work is to analyze the GFC fragmentation failures to identify factors affecting the safety of operation of gas cylinder vehicles in the sharply continental climate conditions.

2. Objects and methods of research
Cylinders for compressed natural gas, destroyed during operation in the sharply continental climate of Central Yakutia, were investigated. The cylinders have the following dimensions: a length of 1470
mm, a diameter of 322 mm, and a capacity of 97.2 l; a mass of 79.6 kg, and a working pressure of 20.0 MPa. They consist of the inner metal shell (a liner) and an outer glass-epoxy layer. The closely fitting glass-epoxy pressure layer, as a rule, excludes the fragmentation of the liners. In connection with this, a throwing of fragments during the rupture of the cylinders under study indicates a loss of strength of the pressure layer and its local cohesion with the metallic shell by the time of the final fracture.

When examining the fractures of technical objects, one of the main methods is fracture diagnostics, which allow one to identify centers, nature, and sequence of destruction processes, its features and causes in relation to structure, material properties and taking into account the operating conditions [1, 2]. To study the surface of fracture, the methods of optical and scanning electron microscopy were used. The composition chemical analysis was carried out, the microstructure was studied, and the mechanical properties of the metal of the liners at room temperature were determined.

3. Main results and discussion

3.1. Analysis of GFC fracture, which occurred in winter

The emergency GFC fragmentation occurred in a warm garage after 9 h following a refill with the gas, which conducted at the outside temperature -33 °C. The vehicle was placed in a warm room approximately 30 min after the refill. With 15 years of an average service life of metal-composite fuel cylinders, the operating time of the ruptured cylinder was 30 months; 2 months before the incident, its planned examination was carried out.

With the rupture, there were formed 4 fragments of the upper part of the liner (Figure 1 (a)) and the almost undeformed fragment of the lower one, retaining the plastic layer (Figure 1 (b)). Deformation of fragments of the cylinder indicates that the pressures are reached in it, which are higher than the designed ones. Surfaces of fractures are typical for ductile fracture – they are matte, fibrous, and with lateral bevels.

![Figure 1. General view of the fragments of the exploded cylinder: (a) – fragments of the liner upper part; (b) – bottom.](image)

It is believed that a rise of the cylinder diameter by more than 2.5% characterizes the technical condition of the glass-reinforced plastic layer before the fracture. Measurements showed that the maximum rise of the diameter is more than twice the critical increase. This confirms that at a moment of the cylinder rupture the pressure layer no longer performed its functions and was practically absent in an area of the fracture, i.e. all the load fell on the metal.
On the fragment IV near the fracture surface, the extended mechanical damage (EMD) with dimensions up to 130x7 mm of a non-obvious origin was revealed (Figure 2). It could not have arisen during the operation or fracture of the liner, since it consists of two partially overlapping damages ≈ 68 and 62 mm long with different widths and with different inclinations to the surface of the liner. EMD is a stress concentrator that increases a risk of fracture.

GFCs experience multiple cyclic loads with the high pressure when filling with the gas; in addition, the variable loads arise when a vehicle moves. Therefore, the common cause of the fracture of the cylinders is the metal fatigue. As is known, the macro- and microstructure of fatigue fractures has a characteristic appearance due to cyclic advancement of cracks with the formation of fatigue lines and fatigue striations [1, 2]. Precisely these features are revealed in relief of the fracture bordering EMD (Figure 3).

Figure 2. Area of fragment IV with extended mechanical damage (between arrows).

Figure 3. Surface area of fatigue crack (a) and its microstructure (b).

3.2. Analysis of fracture of GFC, which occurred in summer
This case of emergency GFC fragmentation rupture occurred in summer in hot weather (up to +32 °C) also shortly after the refill with the gas. The operating time of the cylinder was 4 years; the examination was carried out 10 months before the accident.

After the rupture, 3 fragments of the liner were found (Figure 4). According to the results of the studies, the main physicochemical reason of the premature fracture of the liner is intensive decarbonization of the metal of the inner surface due to long-term contact with a hydrogen-containing medium [3]. The condition of progress of hydrogen degradation of the structure at normal temperatures is the presence of significant tensile stresses [4]; precisely these stresses are created in a

Figure 4. General view of the fragments of the exploded cylinder inner shell: (a) – fragment of the upper part; (b, c) – fragments of the bottom.
wall of the liner under the action of high pressure. The hydrogen getting into steel reacts with cementite, decomposing it into iron and methane: \( \text{Fe}_3\text{C} + 2\text{H}_2 \rightarrow 3\text{Fe} + \text{CH}_4 \). The decarbonization is confirmed by the features of the structure near the surface and in central zones of the wall, by differences in these zones in terms of carbon content (0.27% vs. 0.36%) and microhardness (1750 MPa vs. 2800 MPa). A depth of the decarburized layer is \( \approx 6.7\% \) of the wall thickness with the permissible 5%.

The hydrogen degradation of the structure [5] with the appearance of multiple pores and crackings (Figures 5 (a), (b)) caused a concentration of stresses and initiation of the fatigue cracks. Porosity is also traced on the surface of the fatigue fractures (Figure 5 (c)).

![Figure 5. Hydrogen degradation of liner metal: pore (a), cracking of inner surface of wall (b), pores on fatigue fracture (c).](image)

### 3.3. Brief description of process of cylinders rupture

As is shown above, the rupture of both cylinders is due to macro- and microdamages of the liners, served as the stress concentrators, from which the fatigue cracks started. The liners are made of 30XMA steel (Russian analogue of 34CrMo4 steel) with the finely dispersed troostitic-sorbic structure combining the sufficiently high strength with a good level of ductility and toughness. Mechanical tests have shown that the metal of the liners generally meets requirements of norms. Therefore, in spite of the local damages by the fatigue cracks and hydrogen corrosion, the liners ensured integrity of the cylinders before reaching the critical level of stresses. At some time, the pressure increase due to the expansion of the gas in the cylinders (in the warm garage in one case and in the hot weather in the other) was critical and led to a beginning of significant deformations (swelling) of the liner at places of stress concentration, primarily in the zones of the fatigue cracks.

The stresses arising during the deformation of the liner were transferred to the glass-reinforced plastic layer. During use in such materials there occurs accumulation of damages, density of which increases with time, leading to a decrease of the strength of the reinforcing layer, its detachment from the metal and mechanical instability of the entire structure [6-8].

On the basis of general postulates of degradation mechanisms of composite materials and taking into account the specific nature of the fracture of metal structures, the beginning of avalanche fracture of the cylinders depended on two main factors. Firstly, it depended on a capability of the liner metal to the plastic deformation without losing its stable character. Secondly, it depended on a destruction rate of the outer layer restraining the expansion of the liner, which causing the accumulation of elastic energy in the "liner-pressure layer" system.

At the time when the liner and pressure layer ceased to be the single structure jointly receiving the action of the loads, the final stage of fracture began, at which the glass-reinforced plastic in the places of swelling was already practically absent, and the metal of the liner took over the entire load. In these conditions, in addition to the existing cracks, the new ones appeared in it [9]; avalanche spread and fusion of the cracks transferred the process to the stage of momentary fragmentation fracture of the cylinders with release of a large reserve of accumulated elastic energy (an explosion).
3.4. Danger of fragmentation fractures of GFC in a sharply continental climate

Considering the conditions of operation of the gas cylinder motor vehicles in Yakutia, first of all, one should take into account the factor such as the outside air temperature. High amplitudes of the temperature fluctuations characteristic of a sharply continental climate can have a particularly unfavorable effect on the GFC reliability. Indeed, as is shown above, the temperature differences led to the dangerous increase in the excess pressure and played a role of the aggravating factor for a breakdown of the integrity of studied GFCs. In addition, the main causes that increased the technosphere danger and caused the GFC fracture (the presence of mechanical and structural defects) are associated with the stage of their production.

It should also be noted that there reasonably appear questions about the risks associated with deterioration of the reliability of metal-plastic GFCs after their technical examination. During the hydraulic tests, fibers of the glass composite pressure layer, which were weakened in the process of operation, can be destroyed, or aggravation of damage of the metal of the liner is possible. In 2013, at meetings of the United Nations Economic Commission for Europe, when considering the questions of safety of transportation of liquefied gas, it was noted that the hydrotests can stimulate the spread of the cracks in gas transportation tanks [10, 11]. In addition, advisability of expansion of use of non-destructive testing methods was recognized. These methods provide detection of defects that are not detected during the hydrotests and can lead to the accidents in a rather short time after the conducted examination [10, 11].

4. Conclusion and Recommendations

The studied cases of GFC fragmentation fractures during the operation under the conditions of the sharply continental climate of Yakutia were induced by preoperational mechanical and structural damages of the metal liner. Hence it is obvious the conclusion about importance of improvement of defectoscopic control procedures by the manufacturer. It should also be supposed that at the extreme outside air temperatures it is advisable to correct limiting values of filling up with the gas and regulate the operating conditions of the gas cylinder motor vehicles immediately after the refill. In addition, it is necessary to study in depth the questions of a negative impact of the routine hydraulic tests of the reliability and safety of GFC with the certain level of operational damages to the material of the liner and composite layer.

5. References

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