The structural analysis of the material resulting from the destruction by explosion of a compressed air cylinder

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Abstract: In this paper is presented the structural analysis carried out on samples from a compressed air cylinder subjected to explosion. The air cylinder was mounted on public transport bus. The risk that the incident would repeat with other similar cylinders carrying compressed air required a detailed study regarding the causes that led to the catastrophic degradation. The research by micro and macro structural analysis has highlighted several factors that have increased the damage. The optical micrographs are obtained using an Olympus metallographic microscope equipped with a digital camera, with the possibility to automatically assign the microstructure magnification and with automatic software for linear measurements. The research regarding the appearance of the inner surface of the compressed air cylinder container has highlighted an accentuated corrosion process, developed in the thickness of the cylinder wall with a non-uniform thickness. The break occurred near the welding, known as thermal influence zone (the analyzed cylinder being welded longitudinally). The research has shown that intercrystalline corrosion associated with pitting (punctiform) corrosion developed between the dendrite branches leads to an intense metal degradation in the wall depth and, in limited cases, causes perforation of the metal wall, increasing the explosive fracture development. A factor that influenced the corrosion process in the ZIT area was the mounting of the compressed air cylinder with the welded area at the bottom of the component.

1. Introduction

A compressed air cylinder mounted on a public transport bus and subjected to an explosive rupture due to corrosion degradation was investigated in the Structural Materials Characterization Laboratory. The corrosion, as a result of the chemical and electrochemical reactions due to the material interaction with the environment, has as effect the partially or totally materials degradability, as in the present research.

The corrosion process may be defined as a heterogeneous oxidation-reduction reaction at the metal/medium interface, where the metal is oxidized and one or more components of the medium are reduced by the manufacturer's location the condensate drain hole near the longitudinal welding cord [1-3]. The component quality is given by the material nature, purity, and it depends on the elaboration and casting processes, respectively [4-7]. The mentioned component in this study, a compressed air cylinder was in the first phase visually analyzed, as a general condition, both on the outside and on the inside.

2. Materials and methods

2.1. Chemical analysis of steel sheet
Table 1 presents the results of the chemical composition on steel sheet. In accordance with the classification system EN 10020, the steel grade is classified as non-alloy steel.

**Table 1. Chemical composition of the cylinder sheet determined by spectrophotometer.**

| No | Chemical element | Analysis for sample I | Analysis for sample II |
|----|------------------|-----------------------|------------------------|
| 1  | Si               | 0,82 ± 0,08           | Si 0,88 ± 0,08         | Si 1,02 ± 0,09         | Si 1,11 ± 0,09 |
| 2  | W                | trace ± trace         | W trace ± trace       | Mo trace ± trace       | Mo trace ± trace |
| 3  | Fe               | 98,99 ± 0,39          | Fe 98,94 ± 0,37       | Fe 98,74 ± 0,43       | Fe 98,63 ± 0,39 |
| 4  | Mn               | 0,19 ± 0,03           | Mn 0,17 ± 0,03        | Mn 0,17 ± 0,03        | Mn 0,21 ± 0,03 |
| 5  | Cr               | trace ± trace         | Cr trace ± trace      | Cr 0,06 ± 0,02        | Cr 0,05 ± 0,02 |

2.2. Macrostructural analysis of the damaged compressed air cylinder

After the damage by explosion, the degraded compressed air cylinder component was brought to the laboratory and analyzed both as a modification of the shape and dimensions but also as regards the corrosion process (figure 1). The breaking of compressed air cylinder was occurred near the welding area (the analyzed compressed air cylinder being longitudinally welded). The compressed air cylinder was mounted with the welded area at the bottom. The drain valve was placed at the bottom near the weld area. Checking the appearance of the inner surface of the compressed air cylinder container has highlighted a severe and massive corrosion process.

In the macrostructures shown in figure 2 at 100x magnification, a thick film of relatively continuous, heterogeneous corrosion products, consisting of mixed oxides, is observed on the inner surface of samples taken from the compressed air cylinder body. The visible effect of corrosion on the steel wall of compressed air cylinder is the appearance of rust (hydrated iron oxides) as in figures 2a and 2b and the change in the thickness of the cylinder walls.

![Figure 1. The surface aspect of compressed air cylinder subjected to explosive rupture.](image-url)
zone-FZ, the heat-affected zone - HAZ, the base material – BM, in the immediate proximity of welding) the amount of oxides is very high. According to the standards, the samples are impure, with rating over 5. The largest amount of oxides (black points) being in FZ, then in HAZ and then in BM.

![Figure 2](image2.jpg)

Figure 2. The macrostructural analysis of the inside surface of the compressed air cylinder material: (a) the area without explosive rupture, (b) the area with explosive rupture.

2.3. Microstructural analysis

The qualitative and quantitative analysis of non-metallic inclusions of polished and unetched metallographic samples, under standardized conditions, using the chart comparison method with standard charts, at 100X magnification of optical microscope was performed. The expression of the steel purity was done by inclusions rating. Non-metallic inclusions are particles of impurities trapped mechanically in the solidified steel. They are not part of the steel structure but might come from the reactions that occur in liquid steel, especially from deoxidation and solidification.

![Figure 3](image3.jpg)

Figure 3. Analysis of non-metallic inclusions on the polished samples (100X): (a) in the cross-section of the base material (BM), the steel sheet near the welding cord; (b) in the heat-affected zone (HAZ) of the longitudinal weld; (c) in the fusion zone (FZ) of the longitudinal weld.

To find out if the large amount of oxides presented in figure 3 is the result of the intercrystalline corrosion developed in the compressed air cylinder wall from the corrosive interior environment, a lot of metallographic samples for purity, from the outer surface of the compressed air cylinder, an area almost unaffected by corrosion were prepared (figure 4). The results are clear. The steel unexposed to corrosion shows a specific grade of pure materials (Pmax = 1.5). The oxides
represented in figures 1, 2, 3 are oxides due to the corrosion processes developed in the wall thickness from the interior of the cylinders formed during working process.

![Figure 4. Analysis of non-metallic inclusions of steel on the sample from the outer surface of the compressed air cylinder (100X).](image)

2.4. Microstructural analysis of metallographic etched samples

In order to highlight the nature of the structural constituents, their size and distribution, metallographic samples grinded, polished to mirror gloss and etched with Nital metallographic reagent (3% nitric acid in ethyl alcohol) were performed. The microstructural analysis on the transverse surfaces through the compressed air cylinder wall was carried out. Samples from the body of the damaged compressed air cylinder and the welding area were also taken (coded P1).

3. Results and discussions

Figure 5 shows the microstructures in the compressed air cylinder wall on the sample P1 taken perpendicular to the welded joint. The microstructures present the structural aspects in the steel sheet material (base material-BM), the heat affected zone (HAZ) and the fusion zone (FZ).

The microstructures of figures 5a, 5b, 5c and 5d, made in the HAZ/BM area, highlight the non-uniform corrosion of the compressed air cylinder wall. Thus, near the welded joint, the steel wall measures 1239-1324 µm. Approaching the welded area, the HAZ area caused an acceleration of corrosion, and the wall thinned considerably to just 1023 µm. The microstructures are made with an Olympus metallographic microscope equipped with a digital imaging camera, with the possibility of automatically assign the microstructure magnification and with automatic software for linear measurements.

The corrosion process, so complex and non-uniform, is explained, on the one hand by the fact that a rusty surface always exhibits a larger area of corrosion compared with the same glossy surface and, on the other hand, corrosion occurs both on the irregularities picks and in their depth, where a multitude of microcracks that can develop rapidly and can contribute to the degradation of the steel are formed. Fine grains embedding a very large grain boundary area increasing accelerated intercrystalline corrosion (grain or subgrade grain boundaries are in fact dislocation walls, areas with a huge amount of linear imperfections that conserve high free energy, high instability, a high corrosion susceptibility, so a low corrosion resistance).

The presence of fine tertiary cementitious precipitates -Fe3CII - many in number on the grain boundary can lowers the corrosion resistance of steel by the occurrence of galvanic couplings between the carbides and the neighboring areas between the grains. The heat - affected zone (HAZ) is of particular importance for the welded joint quality of the as it connects the seam to the welded piece. It's an area with fine grains, as fine as approaching to the seam area.
Figures 5e, 5f, highlight a Widmastätten ferrite-pearlite/pearlite coarse structure with acicular separation in dendritic grains due to fast cooling. This structure has low ductility and tenacity. By removing from the seam area, the heating temperature decreases, the grains diminish and the Widmanstätten character decreases gradually. The columnar, lacy and dendritic grains, specific of FZ can increase accelerated corrosion in the stitch thickness, as evidenced by the polished and unetched section of figures 6a and 6b. In this heterogeneous, tense structure, the direction of propagation of catastrophic rupture through HAZ is highlighted. In the welding cord, in the FZ area, the microstructures of figure 6 shows the Widmanstätten coarse ferrite-pearlite structure with columnar, lace-shaped separations within the grains. The presence of non-metallic inclusions (welding slag), porosity, shape and distribution of heterogeneous structural constituents can increase an accelerated local corrosion.
The pitting (punctiform) corrosion as indicated in figures 6c, 6d, is manifested more pronounced. The rupture was propagated, as shown, in the most dense area in local [1, 8-11] corrosion microvolts. Intercrystalline corrosion associated with pitting corrosion developed between the dendrite branches leads to intense metal degradation in wall depth and, in extreme cases, causes the perforation of the metal wall, obviously, increasing the development of explosive rupture [12-16].

4. Conclusions

The steel sheet from which the compressed air cylinder was made corresponds chemically and structurally for this purpose.

The damage by explosion of compressed air cylinder was caused by excessive corrosion inside the cylinder. The corrosion was occurred generalized throughout the cylinder, but catastrophic (intergranular, pitting) only in the welding cord and heat-affected zone (HAZ).

The area from which explosive rupture was initiated was the heat-affected zone (HAZ) in the inner area of the weld, because it had a significantly lower thickness than the thickness of the welding cord. Excessive corrosion of the welding cord (FZ area) and the heat-affected zone (HAZ) was increased by the tensions and structural conditions different from those specific to the steel sheet of the base material, as well as by the manufacturer's location of the condensate drain hole near the longitudinal welding cord (the welding cord has been in most of the time in contact with the condensate water coming from the city traffic air which is the more polluted).
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