ARTECH CORP.
14554 Lee Road • Chantilly, Virginia 22021-1632
(703) 378-7263 • Washington, D.C. Metro 968-TEST • Fax (703) 378-7274

FRACTOGRAPHIC AND MICROSTRUCTURAL EXAMINATION OF A RUPTURED DOT-3AL SPECIFICATION COMPRESSED GAS CYLINDER

BY

Vishwanath Sahay
Paul J. Lare

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INTRODUCTION

This report details microstructural and fractographic analysis of the segments of a DOT E-6498-2216 ruptured cylinder. Reportedly, the cylinder had failed in 18 pieces while being refilled. The subject cylinder was made from Al6351 aluminum alloy under Exemption 6498 and marked in accordance with 49 CFR Part 178.46. The cylinder was manufactured by Luxfer USA for Scott Aviation; date of manufacture: 9-1980. One fractured piece of an exemplar cylinder was also provided for comparison analysis. As reported, this cylinder was made similar to the subject cylinder; it had been in service for 10-12 years. The cylinder had been over-pressurized to failure; over-pressurization exceeded the design burst pressure. No other details of this cylinder are available at this time.

Analysis was performed under the direction of the DOT COTR.

SAMPLE DESCRIPTION

The major pieces of the exploded pressure cylinder are shown in Figure 1, in a best fit arrangement, that was based on the center nine (9) pieces (Figure 2) having been one continuous piece that had been analyzed previously. The remaining major pieces were then arranged on the basis of exterior and interior surface features and fracture profiles, as indicated in Figure 3.

Exterior and interior surfaces of the nine (9) sectional pieces comprising Figure 2 are shown in the as-received condition in Figures 4 through 8, and the remaining seven (7) major fracture pieces are shown in Figures 9 through 13, also in the as-received condition. Ten fracture fragments, shown in Figure 14 in the as-received condition, could not be located in the arrangement of pieces (Figure 1) due to their small size and fracture surface damage. Figure 15 details the as-received condition of the valve as having corroded, deformed, and several sheared threads, the "O" ring seal, and the over-pressurizing rupture disc protection mechanism. Identification markings from the heavy wall area of the top of the cylinder are shown in Figure 16. The significance of the letter "A" following "Lot Code X59" and the unidentifiable symbol to the left of "X59A" is not known at this time (Figure 17). Enlarged views of the as-received condition of the threaded areas of the fracture pieces (2), (4), and (1I) are shown in Figure 18, revealing additional cracks in the interior formed surface of the neck and in the more corroded areas of the threads.

For comparison with the exploded cylinder material, a small section of an exemplar cylinder(Figure 19) was provided, wherein the exemplar cylinder had been burst tested in excess of the design burst pressure. The extent of over-pressurization is not known at this time.

FRACTURE EXAMINATION OF THE SUBJECT CYLINDER

Subsequent to visual examination of the fractured pieces, selected fracture surfaces were examined under optical and scanning electron microscope (SEM).

FRACTURE SURFACE #1 - The fracture section was retrieved from the neck region of the cylinder, shown earlier in the report. A macro view of the fracture surface is presented in Figure 20. The failure appeared to have initiated on the inside surface in the thick region near the neck. The fracture section was solvent-cleaned using standard laboratory practices. Optical microscopic examination at higher magnifications revealed the presence of a considerably large population of dark streaks all over the fracture surface (Figure 21). These streaks were thin slender voids having textured surfaces as depicted in the SEM micrograph in Figure 22. Examination of several of these voids suggests that chunks of dross* had been entrapped in the material at various locations during manufacturing and voids had formed at those locations when the mass of dross dislodged or pulled out during the fracture process. It should be noted that the presence of dross in the material is detrimental to its physical properties.

SEM micrographs exhibiting typical fracture features at locations noted in Figure 20 are presented in Figures 23-32. Note that locations 1-5 are in the region having large grain structure (refer to the microstructural examination section of this report).

Figure 23. The shape and orientation of dimples shown in the fractograph taken at location 1 indicate that the failure initiated in the threads in tearing mode

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* Dross is a metal oxide inclusion.

due to overload and progressed inward.

Figure 24.	The fractograph appeared to be featureless. Some overload dimples were also observed.
Figures 25. & 26.	The fractographs show similar characteristics as in Figure 24.
Figure 27.	It exhibits featureless facets as in Figures 24-26. The failure is still due to overload. The fracture initiated along the metal fold on the inside surface, formed during manufacturing process.
Figures 28. & 29.	These fractographs are taken from the regions having finer grain structure. The failure mode is typical of overload. Unlike featureless facets in Figures 24-27, a relatively larger number of dimples was observed.
Figures 30. & 31.	The fractographs are from locations 8 and 9 respectively. They show a mixed mode of fracture consisting of dimples and intergranular failure. Both features are indicative of failure due to overload.
Figure 32.	Fractograph from the shiny edge of the fracture exhibits features of shear overload failure.

FRACTURE SURFACE #2 - A section from the neck region containing threads was removed from the piece shown in Figure 8. An undisturbed view of the inside surface of the section is presented in Figure 33. Notice crack-like features in the threads as well as on the adjacent internal surface. A through-thickness saw cut was made along the dotted line shown in Figure 33a. A fresh fracture was created by flexing the remaining ligament; the newly created fracture contained the crack-like feature shown in Figure 33b. An enlarged view of the lab-created fracture surface is presented in Figure 34. The crack-like feature was about 0.017 inch deep. Its color was similar to the rest of the inside surface of the cylinder which suggests that the crack was formed during the manufacturing process. The presence of such cracks is detrimental to integrity of the cylinder because they offer a ready site for cracks to propagate under favorable stress conditions.

SEM micrographs exhibiting fracture features at locations indicated in Figure 34 are shown in Figures 35-37; these fractographs were taken from the region having large grain structure.

Figure 35. Fractograph shows featureless facets as exhibited in Figures 24-27; smoothness of these facets suggests that there was no interfacial cohesion in those areas. Fractograph also shows some areas having dimpled rupture.

Figure 36. It shows similar features as in Figure 35.

Figure 37. Fractograph exhibits featureless facets and some

dimpled ruptures. A semi-quantitative chemical analysis, using energy dispersive spectroscopy (EDS), of the particle-like object in the micrograph was performed and result was compared with that of the matrix. No difference in chemical composition was detected. Similarity between the two chemistries suggests that the particle is part of dross which was entrapped in the material during manufacturing.

FRACTURE EXAMINATION OF THE EXEMPLAR CYLINDER

An as-received view of the fracture surface is presented in Figure 38. Because it was badly contaminated, it had to undergo extensive cleaning prior to examination. Unlike the subject cylinder, the material of the exemplar cylinder was almost free from dross and voids. See Figure 39; compare this Figure to Figure 21. SEM examination revealed that the mode of failure was similar to that of the subject cylinder; it exhibited typical features of overload fracture (Figure 40). The featureless facets seen in Figures 24-27 and 35-37 were not observed on the exemplar fracture surface.

MICROSTRUCTURAL EXAMINATION

Prior to initiation of the microstructural examination X-ray radiographs were taken of the thick-wall fracture pieces to locate any detectable injurious subsurface defects that could affect the structural integrity of the cylinder. Shown in Figure 41 is a positive print of an X-ray radiograph of fracture piece (4) in which several indications could not be related to surface damage. A transverse section was taken through the indication closest to a longitudinal fracture for metallographic comparison with a transverse section from the exemplar fracture sample. The sections were metallographically prepared in accordance with the standard practices of ASTM E3. As can be observed in Figure 42, the as-polished surface contains a relatively higher and more elongated inclusion content than observed for the exemplar surface. This observation was made on the basis of utilizing several metallograph preparation procedures and polishing materials to evaluate possible polishing artifact complicity.

To evaluate the cause of fragmenting of the subject cylinder into eighteen (18) pieces, metallographic sections were taken in and around the threaded, heavy-wall area as well as from the thinner wall areas having longitudinal and transverse fractures. Shown in Figures 43-46 are examples of dross entrapment that were found in all sections except for the singular exemplar fracture sample. As a result, all fracture surfaces were examined at magnifications of 7X to 40X with a stereoscopic microscope, and all fracture surfaces were found to contain delaminated segments of dross that varied in thickness and length.

Susceptibility to intergranular corrosion was also examined after finding evidence of this mechanism at a localized spot on the interior surface in the area of angular transition of the bottom to the side wall, as can be seen in Figure 47. Further evidence of this attack was found along the length of the thread though not as a continuous process, as indicated in Figures 48 and 49. Evidence of cold work on the upper portion of the thread (Figure 49) suggests that a thread mismatch, such as a tapered metric thread might produce, may have occurred at some point in the cylinder's service lifetime.

Microstructural variation was found in the thickest wall section adjacent to the threaded hole. At the wrinkled internal surface, cracks were found to emanate from radial surface texture notches (Figure 50) that were produced during thermal-mechanical forming of the top of the cylinder. A relatively high inclusion content appeared to be dispersed in a large recrystallized grain structure. At the level of the bottom thread a slight increase in microconstituent alignment was observed (Figure 51). A highly aligned microstructure with very large, elongated grains was found at the level of the top thread (Figure 52). Also observed within the thick wall area of the threaded hole were several places in which a stacking or pile-up of microconstituents and unidentified inclusions occurred, as shown in Figure 53.

DISCUSSION

Fractographic examination of the failure suggests that the failure was catastrophic and occurred due to overload conditions. The overload conditions may have been created either by over-pressurization or inherent weakness due structural anomalies in the material. Evidence of structural anomalies found were -

a.) A large population of voids on the fracture surfaces

b.) The presence of smooth/featureless facets on the fracture face near the inside surface in the neck region. These facets are areas where there was a complete lack of interfacial cohesion. These are a kind of discontinuity which was carried over from casting of the raw material blank to manufacture of the cylinder. Most likely, the discontinuity would be in the form of shrinkage which can exist as a region of interdendritic void(s) sometimes associated with suspended dross, during the various stages of solidification. When extruded, to form the cylindrical precursor to the final product, the shrinkage/dross volume compresses and realigns in accordance with flow constraints of the metal, due sealing or healing of the void cannot occur because of the oxide skin of the void and/or the presence of dross. Obviously, the higher the content of the dross in the cast billet blanks, the poorer will be the mechanical properties of the final product, with transverse properties being more affected than longitudinal properties due to the realignment and distribution of the dross. Furthermore, the observed microstructural variation in the thick wall region adjacent to the threads suggests a mechanical response that may additionally reduce the transverse properties to the levels less than the design properties.

The presence of radially oriented surface notches on the interior surface at the bottom of the threaded hole presents potential sites for corrosion activity. The deterioration of the threads by corrosion, however it occurred, raises the question of whether or not the valve can be explosively ejected.

CONCLUSIONS

The following conclusions are drawn on the basis of the findings and observations relating to the sample material contained herein:

1. The quality of the manufactured cylinder that fragmented is poor due to the presence of excessive detrimental dross content which was not found in the exemplar fracture sample.
2. The high detrimental dross content severely reduces the transverse properties that result in significantly reduced toughness and increased likelihood of fragmentation on pressurizing.
3. Corrosion of the threads and evidence of thread mismatch may have influenced the service life of the cylinder.

RECOMMENDATIONS

1. Analyze unidentified microconstituents/inclusions, conduct trace element analyses, and analyze corrosion product(s) to assess potential involvement in loss of structural integrity in manufactured pressure cylinders.

2. Determine transverse mechanical properties of the heavy wall material adjacent to the threaded hole for the fragmented and the exemplar cylinder.
3. Calculate the burst pressure from the bulge of the unruptured disc.
4. A statistically significant number of failed cylinders should be examined to draw a correlation among causes of failures.
5. Consideration should be given toward establishing an evaluation program to determine the remaining life and/or safe (risk-free) operation of existing cylinders manufactured under exemption and DOT 3AL 3000, incorporating the following elements:
    A. DOT collection of a statistically significant number of cylinders with manufacturing and inspection records and certifications.
    B. X-ray radiography and visual inspection of threaded hole and internal surface of heavy wall area.
    C. Pressure cycling and burst testing at several levels of cycling.
    D. Examine and characterize failures.
    E. Characterize chemical and transverse mechanical properties.
    F. Analyze data for predictability of failures.
6. Stress analysis of original design parameters.

7. Recommendations listed above may be useful for a policy decision aimed at regulating such cylinders still in service.