Cryogenic Gas Bottle Development & Realization- Role of Non-Destructive Evaluation

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Abstract

Cryogenic Gas bottles are Liquid Hydrogen (LH_2) submerged bottles used for storing gaseous Helium in C-25 Cryogenic Engines for the upper stage of new generation launch vehicle. These gas bottles are made out of Ti-α alloy forgings realized from indigenous sources. The design requirements stipulate the allowable flaw size that is safe for the function of the gas bottle. Non-destructive testing methods were established to assure the hardware devoid of any unacceptable defect.

This paper provides the details of NDE carried out and the practical aspects of defect evaluation during the realization cycle of the gas bottles. Limited access due to close vessel configuration calls for enhanced methods for radiography and interpretation. Continuous improvements made during the development of gas bottle testing are also brought out in this paper. Various NDE techniques used from the raw material stage to the final acceptance and qualification of the hardware are also described. Effect of process improvements in AE response is also described here. ND support for acceptance & qualification of the Cryogenic gas bottles are also delineated in this paper.

Key words: Titanium alpha alloy, cryogenic, Nondestructive Evaluation (NDE), Ultrasonic Testing (UT), Acoustic Emission (AE), Radiography Testing(RT)

1.0 Introduction

Titanium and its alloys are widely used in various aerospace applications by virtue of the distinct advantages like high specific strength, good response to thermal treatments, good machinability etc. Out of these, two alloys viz. ELI grade Ti-α & β alloy and Ti-α alloy are currently favored for cryogenic applications, in which Ti-α alloy can be used down to 20K temperature. The Cryo stage of launch vehicle requires pressurization gas bottles submerged in LOX propellant tank (at 90K temperature) made of Ti-α & β alloy. However, to reduce the stage mass, bottles made of Ti-α alloy submerged in LH2 propellant tank (at 20K temperature) was proposed. By using Ti-α gas bottles would bring down the requirement of total number of gas bottles from five to two numbers, thereby saving the upper stage mass thus gaining equivalent amount of payload. Ti-α gas bottle fabrication procedure, non destructive inspection adopted at different stages of fabrication for qualification and improvement suggested based NDE observations on realized hardware for getting better quality product are describe in the paper.

2.0 Processing Route of Ti- α Alloy Cryo Gas Bottle

Titanium α-alloy Cryo Gas bottles are realized through forging, machining and welding route. It is consist of three components i.e bimetallic adaptor, upper and lower hemispherical domes. Bimetallic adaptor (BMA) is fabricated by friction welding of Ti-α alloy and AISI 321 stainless steel tubes with pure aluminum AA1050 as interlayer, serve as transition joint between stainless steel fluid lines and titanium gas bottles. Hemispherical domes are realized from billets by hot closed die forging at near to β-transus temperature [1, 2] of the alloy in gas fired or electrical furnace. Domes are pre-machined at different thickness level and subjected to vacuum and mill annealing to control hydrogen level and relieve the residual stresses. Subsequently, components are welded by electron beam welding (EBW). Post weld Non Destructive Evaluations are done to ensure the weld region is devoid of any kind of unacceptable surface or sub-surface discontinuity. Gas bottles are subjected to hydro proof pressure test (PPT) as acceptance level test [3].

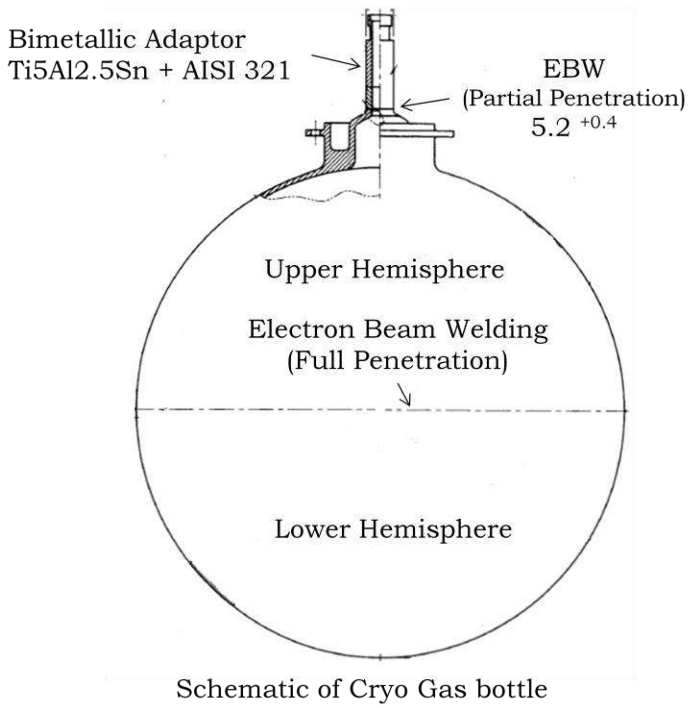

Figure. 1 : Schematic Diagram of Cryo Gas Bottle

3.0 Non Destructive Evaluation

Following Non Destructive techniques are used from raw material stage to Proof Pressure Testing (PPT) for ensuring the hardware is devoid of any unacceptable flaw.

a) Ultrasonic testing for qualifying the raw materials (i.e Dome forgings)
b) Radiography and Videoscopy inspection for weld joint qualification
c) Acoustic Emission monitoring during Proof Pressure Testing

3.1 Ultrasonic Evaluation at Raw Material Stage

The gas bottles are to be used in liquid hydrogen environment (at 20K). For raw material qualification, maximum allowable size of the flaw shall be limited to critical crack size of the material at 20K. Ultrasonic evaluation is used at raw material stage for forging qualification. Based on the design requirements & acceptable flaw size, material should pass the NDT requirement of AMS 2630 Class A1 for both normal beam and angle beam. Ultrasonic pulse echo method with 4MHz normal and angle beam probe are selected for this purpose.

Forgings of ten gas bottles are scanned using both normal and angle beam probe. Normal beam scanning is meeting the requirement of AMS 2630 Class A1 at 25mm thickness level. But, it is difficult to inspect by angle beam due to poor single to noise (S/N) ratio at 25mm thickness level. Subsequently, angle beam scanning attempted at pre-machine stage of 12mm thickness level. At this stage, S/N ratio improved slightly; top and middle portion of the forging had met AMS 2630 Class-A (∅2.0 mm FBH) requirements, while bottom portion had met only AMS 2630 Class-B (∅3.2 mm FBH) level. Further, angle beam scanning was tried after mill annealing at final machining stage of 5.4mm thickness level. At this stage, significant improvement observed in the S/N ratio i.e+6 dB with respect to 'F" notch and the component had met the requirement of AMS 2630 Class-A1. It was also noted that lower frequency (2 MHz) probe gave better S/N ratio compared to 4 MHz probe. Owing to the higher noise level come across at 25mm thickness stage, additional UT scanning has been introduced at 12mm and 5.4mm thickness level to ensure that all the forging have met UT flaw level requirement of Class A1 for both normal & angle beam.

Figure 2: Sectors identified for ultrasonic testing on hemisperical dome

3.2 Nondestructive Evaluation of Weld Joints

The gas bottle components are joined by electron beam welding (EBW) at two stages; viz. upper hemispherical dome to BMA partial penetration butt joint and upper hemispherical dome to lower hemispherical dome full penetration butt joint.

To simulate the EBW parameters prior to actual job welding, a test ring of similar joint configuration is welded and qualified by radiography test (RT). The actual job welding of the cir-seam joint is undertaken only upon the NDE clearance of the above stage [3]. Similar simulation is done for the BMA to Upper hemisphere welding too. For this case also, RT is used for evaluation in addition to depth of penetration checking by cut opening the weld joint of the trial specimen [3].

On completion EBW of both joints, the weld joints are subjected to visual inspection (VT), Radiographic (RT) and Videoscopic Inspection (VI). Videscopic inspection of the bottle interior is essential to understand the presence and distribution of weld spatters inside the bottle in and around the weld joints.

Post weld radiography acceptance of porosities is done as per AMS 2680 and limited to 10% of final thickness. Based on RT data of ten realized gas bottles, it was observed that weld repairs were mainly due to unacceptable porosities. In cryo gas bottles maximum number of welds repair is restricted to 2 times. Therefore, unacceptable porosities after 2^{nd} time repair leads to rejection of the hardware.

To minimize the porosities in EB welding, stringent pre-weld cleaning procedure with isopropyl alcohol (IPA) and acid pickling with adequate acid ratio are introduced, vacuum level controlled at $< 2 \times 10^{-4}$ mbar during EBW and increased the time of post weld vacuum cooling from 10 minutes to 30 minutes by delaying the chamber venting.

The joint integrity of BMA to Dome weld joint is assessed by RT that reveals in addition to normal type of weld defects, fitment gap of the inner surface if any in the joint. So, in one of the gas bottles, a gap of 1 mm width was observed at inside stepped region [figure 8]. This was due to improper suiting of mating components. Subsequently, to control the gap, a sharp corner is introduced at the stepped locations of the mating parts and maintained positive clearance of 50µm at outside diameter during weld set-up.

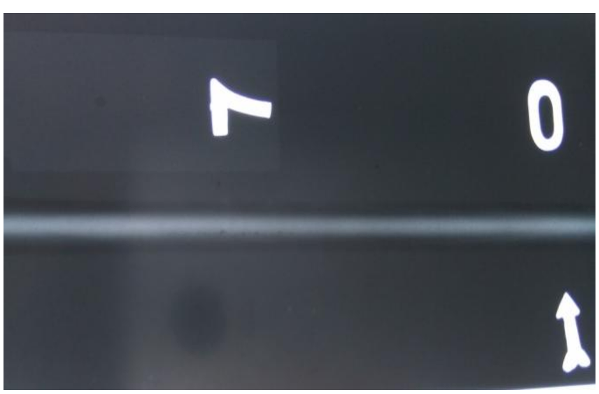

Figure 3: Porosity observed on Dome to Dome Cir-seam Joint

Figure 4: Internal weld spatter observed in videoscopy(Courtesy: QIT QCG-MM VSSC)

Figure 5: Weld Spatter observed on Test Ring

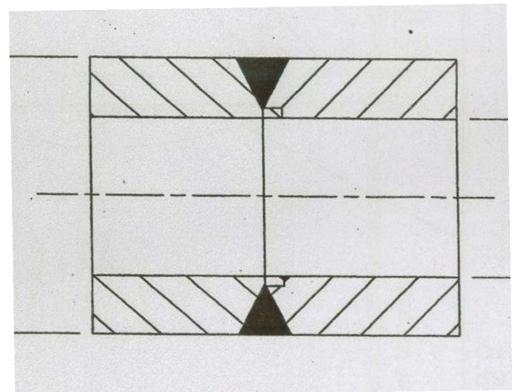

Figure 6: BMA to Dome cir-seam joint configuration

Figure 6: Trial fitting of BMA to suiting component

Figure 7: BMA to Dome Cir-seam Weld

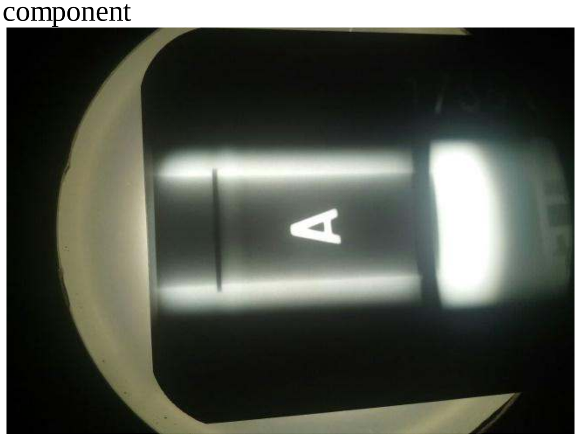

Figure 8: BMA to Dome Cir-seam Weld with inside gap

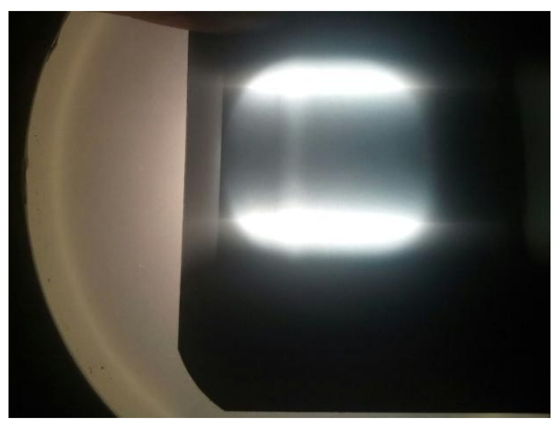

Figure 9: BMA to Dome Cir-seam Weld without inside gap

3.3 Acoustic Emission Monitoring during Hydro Proof Pressure Test

Acoustic emission sensors are used to monitor any active flaw during room temperature hydro proof pressure testing of cryo gas bottle. Eleven numbers of AE sensors are deployed for each test, covering critical cir-seam weld region, top adaptor area and bottom location.

During the first hydro Proof Pressure Test at room temperature, all ten numbers of Alpha alloy Gas Bottles have registered high amplitude AE signals during the pressurization phase and pressure hold periods including MEOP & PPT holds [4]. This may be due to stress relief, micro level yielding, geometrical corrections, partial de-bond of weld spatters etc.

Based on the above, subsequently stress relieving at 540°C for 2 hours was introduced in Gas Bottle BT-11 after Dome to Dome welding stage and before Dome to BMA welding. During the first hydro PPT of this gas bottle, AE signals were found to be very less as compared to all other Gas Bottles [4]. This data has confirmed that the high amplitude AE signal during 1st PPT of CGB BT-01 to 10 was mainly due to residual stress.

In view of the improved AE response during first PPT of BT-11, it has been suggested to introduce an additional stress relieving cycle immediately after cir-seam welding. Thus, to eliminate undesirable AE observations during PPT and thereby avoiding the requirement of a second time PPT. Comparative AE data [4] of 1st PPT of CGB BT-10 and 11 are given in figure 10 &11

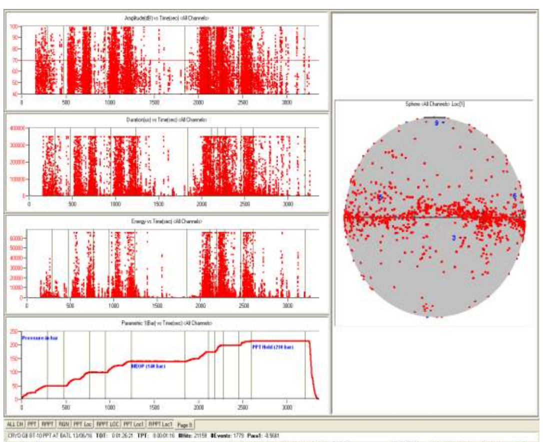

Figure 10: AE date of 1st PPT at RT of CGB BT-10 (Courtesy: EXMDSTR VSSC)

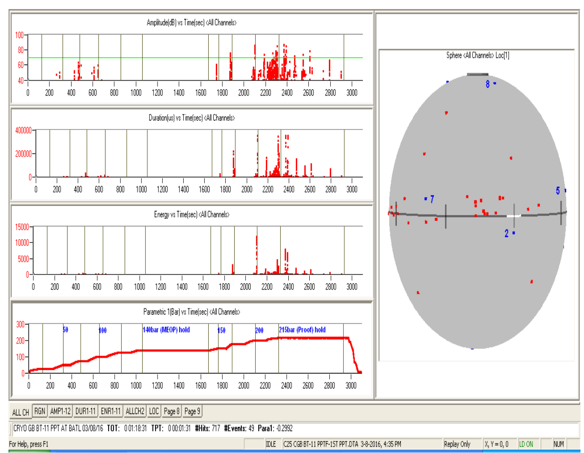

Figure 11: AE date of 1st PPT at RT of CGB BT-11(Courtesy: EXMDSTR VSSC)

4.0 Conclusion

The Titanium Alpha Gas Bottle realization is essentially a developmental activity right from forging making to the final product stage. In order to fulfill the rigorous specifications, end use requirements and acceptance criteria, various NDE techniques as described above have been put into use during the entire cycle of production and testing. Thus, NDE techniques has played a vital and integral role in materializing this crucial part for the Cryogenic Engines used in the new generation launch vehicles of ISRO.

5.0 Acknowledgement

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4. EXMD, STR, Note on AE Observation of C-25 Cryo Gas Bottle (CGB BT-10 & 11) during Room Temperature Hydro Proof Pressure Test