Case Study on the Failure Analysis of Fasteners used for Aerospace Applications

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Abstract

Aerospace structures have the primary role to provide and maintain necessary external aerodynamic shapes while withstanding the flight loads and environments. Many of the structures are configured to have joints with fasteners. Typical load bearing fasteners have single point failure probability and hence quality control of these is of prime importance for mission success. Fasteners that have load-bearing requirements, used in launch vehicle structures, are fabricated from high strength low alloy steel. Application requirements demand these elements to remain in pre-loaded condition for months and in different environments at production and launch sites, to withstand temperature profiles and vacuum pressures. Such demands highlight the requirement to have control in the production of fasteners right from the design and analysis through material selection, product realization and testing.

The objective of this paper is to discuss, the significance of various NDE methods being used during fastener realisation stages and in aiding failure investigation, analysis and the corrective actions taken, through case study. Fastener failures in structures were attributed mainly to hydrogen embrittlement and stress corrosion cracking.

As a batch of fastener in production may have hundred to fifteen thousand numbers, NDT was introduced to screen them right from the ingot stage. Wedge tests were introduced to decide acceptance of high strength fasteners. It was interesting to note that many a times the failure was reported visually while disassembly and the cracks in the fasteners were seen with naked eye. Further investigation strengthened the need for a quality control plan for visual inspection and the same was introduced. The importance of the calibration of torque wrenches and its proper use were the other requirement that was systematized. In the design area improvements were effected through proper material selection of fasteners for different type of environment and the estimation of friction co-efficient for the different type of joints and using the same for the estimation of preloads. The case studies provide details of not only the process improvements but also on the interpretation efforts on different standards and their requirements especially in the area of high strength (above 1380 MPa) fasteners.

1. Introduction

Launch vehicle structures are designed to carry out multiple functions of withstanding static and dynamic loads, housing critical packages and as protection to payloads. Primary structures are load-bearing structures and they provide the necessary strength and stiffness and are responsible for the performance of the vehicle structure. Stage motors, tankages, interstage structures and payload fairings belong to this category. In addition to primary structures, there are other structural elements such as fuel tanks of control systems, pressurisation gas tanks of liquid stages, appendages and module mountings and brackets which are not usually subjected to aerodynamic/primary loadings, are called secondary structures. Failure of the structural systems can be catastrophic to the mission.

Fasteners play an important role in ensuring the function, fit and form of the structural assemblies. Since the structures are designed with a factor of safety in the range of 1.25 to 1.05, there are structural elements wherein a fastener failure becomes a single point cause for mission failure. Hence failure of fasteners, during assembly and testing, is an occurrence that needs to be investigated thoroughly by a failure analysis. This paper describes a case study on the failure analysis of aerospace fasteners and the corrective action taken. It highlights the Non-Destructive testing carried out during failure investigations and the tests that were introduced during process and product realization of fasteners.

Fastener failures were reported during assembly and integration of test set up and launch vehicles and this needed a thorough analysis. A case study on failure that started various quality improvement efforts is described in this paper.

2. Failure of M12x1.25x25 L Hex. Socket Screws (Property Class: 1250 Mpa)

2.1 Fastener Description

Size: M12x1.25, 25 long-4h Hexagonal socket head cap screw, fully threaded Material: Made of 35NCD16 High strength steel as per standard AIR 9160C Surface Coating: Cadmium electroplated as per standard AMS QQ P 416. It is used in the nozzle divergent hardware in the compliance ring assembly of the 4m-diameter motor. A failure alert note was raised by quality assurance for the failure of this fastener. Based on this failure analysis was carried out by the failure analysis board.
2.2 Failure Description

During the re-assembly of Integrated test setup of the nozzle one M12x1.25x25mm long bolt failed during pre-torquing at the compliance ring to divergent nozzle interface. While carrying out this operation one of the fastener head got sheared out of 104 fasteners and two more started yielding. Yielded fasteners were removed and visually inspected and cracks were found. All the fasteners were left, after application of torque, in the assembled condition for 5 months for the vectoring test. Fig. 1 gives the joint detail.

3. Failure Analysis

Fastener failure was a single point failure that can lead to non-fulfillment of test objectives. Hence the analysis was focused on finding the root cause. Initially metallurgical analysis of the broken pieces was carried out.

3.1 Metallurgical Analysis

The failed bolt was subjected to detailed metallurgical observations and salient features are as hereunder.

1. The fracture surface under scanning electron microscope revealed intergranular (IG) mode of fracture
2. Intergranular feature was seen throughout the fracture surface.
3. There was absence of any corrosion product on the fracture surface.
4. Microstructure consisted of tempered martensite, typical structure for the hardened and tempered steel.
5. The crack propagation was along the grain boundaries (Fig. 2)
6. Crack branching at the tip was absent.

It was inferred that the bolt failed due to hydrogen embrittlement.

3.2 Traceability Analysis

Identification of fasteners and its traceability to the processing batch and the raw material lot were analyzed. The Raw material was imported from Aubert & Duval, a reputed supplier for such materials. It was having a Heat number and acceptable Mill certificate. Subsequently gas analysis was done at an approved laboratory in Bangalore and found acceptable.

Fasteners were processed indigenously. The details of processing with respect to heat treatment and surface treatment were looked into. The specification given to the manufacturer was also examined.

3.3 Major Quality Control Observations & Improvements

3.3.1 Raw Material Stage

For the failed batch of fasteners the raw material stage of process and quality control data were analyzed. After
thorough review and deliberations the following inspection stages were introduced.

3.3.2 Ultrasonic examination (UT)

It was suggested that all the rods to be 100% ultrasonically examined (either by contact or immersion) at an intermediate stage or at the final stage of the raw material. The acceptance criteria shall be as per AMS 2630B, Class-A. This was a major step introduced for ensuring quality of the final product.

3.3.3 Process Sequence Changed

Thread rolling for the failed batch of fasteners was done before the heat treatment operation. After hardening and tempering, the hardness of the fasteners is of the order of HRC 39 to 42. So, normally the manufacturers go for rolling before heat treatment as it entails fewer die wear and longer die life. The capacity of thread rolling process for providing improved life performance, particularly improved fatigue resistance is well recognized. However, studies have proved this property improvement occurs more consistently when the threads are rolled after material strengthening heat treatment operations. Rolling threads after heat treatment induced residual compressive stresses at the thread root, which significantly increased the fatigue resistance. So it was decided to change the manufacturing process sequence to Thread Rolling after Heat treatment.

3.3.4 Heat Treatment Process

Heat treatment was done in a Vacuum Furnace. Temperature Uniformity Survey was conducted according to VSSC approved procedure and the furnace was accepted. Loading fixtures were re-designed to ensure uniform heat flow.

3.3.5 Thread Rolling

The metric threads of the fasteners are formed by a rolling process in a single run. The dies used for thread rolling process are periodically qualified. Additionally, the first-off qualification is done for each rolling batch. The qualification is carried out by checking all form and fit features of the die and the first off product.

3.3.6 Surface Treatment

The fasteners used were Cadmium plated. The cadmium plating process was done according to the standard AMS QQ P 416. Cadmium plating process comprises of a series of steps from initial degreasing, plating to final baking of the product. In the case of high strength fasteners (strength above 1200Mpa) the baking requirement is a must as per the standard. This is to reduce the chances of hydrogen embrittlement which can cause a delayed failure of fasteners. As per the above standard, the baking time specified for threaded fasteners is 23 hours minimum and it has to be performed within 4 hours after Cd plating operation.

The final quality of the plating is ensured only by meticulously following these process steps. The available process document was modified to include the requirements of baking time and transfer time.

In order to further rule out the probability of hydrogen embrittlement, time gap between plating and baking was further shortened to one hour maximum by modifying the layout of facilities in the shop.

4. NDE for discontinuities-Fastener stage

Liquid Penetrant (Dye Penetrant) inspection was done for the failed batch of fasteners after rolling, as it has been the practice. An improvement suggested in this area was to introduction of fluorescent penetrant or Magnetic Particle Testing MPT (according to ISO 3452/3453 or ASTM E1417-95a and MIL-I-6868 respectively), prior to any surface treatment. The acceptance criteria specified was according to the standard ISO 6157/3. Procedures for carrying out the tests were introduced in the work centers.

5. Confirmatory test

Fasteners used for applications wherein single point failure possibility is envisaged, tensile load test upto 75% if Ultimate Tensile Strength was introduced for such fasteners to ensure that they withstand the expected loads. Wedge tension test as per ASTM F606 was conducted on sampling basis to evaluate the capability of the fastener to sustain when stressed with a wedge under head. The fiction factors for the fasteners were also evaluated as an input for arriving at the preloading torque. It was also decided to study the vacuum deposition coating of aluminum and introduce the same instead of cadmium plating to eliminate the change occurrence of the root cause of the failure, hydrogen embrittlement.

6. Conclusion

The case study provides a systematic approach to a failure analysis of critical components. It takes into
consideration correction efforts, corrective actions and confirmatory tests to increase the confidence on the mission. Non-Destructive Testing methods like UT, PT and MPT were introduced to obtain product of consistent quality. Specific requirements of the international standards were studied and procedures were introduced to improve the process of cadmium plating. Studies were initiated to have vacuum deposited aluminized coatings on high strength fasteners instead of cadmium plating.

7. Acknowledgement

We wish to acknowledge the guidance and encouragement given by Deputy Director, Material and Mechanical Entity, Deputy General Manager, Quality Control and Inspection, Sri. A.K. Jha, Manager, Material Characterization Division and members of failure analysis board for their valuable input.

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