# International Space Station Powered Bolt Nut Anomaly and Failure Analysis Summary

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**Abstract**

A key mechanism used in the on-orbit assembly of the International Space Station (ISS) pressurized elements is the Common Berthing Mechanism (CBM). The mechanism that effects the structural connection of the CBM halves is the Powered Bolt Assembly. There are sixteen Powered Bolt Assemblies per CBM. The CBM has a bolt which engages a self aligning Powered Bolt Nut (PBN) on the mating interface; see Figure 1. The Powered Bolt Assemblies are preloaded to approximately 19 kilo pounds (KIPs) prior to pressurization of the CBM. The PBNs mentioned below, manufactured in 2009, will be used on ISS future missions. An on orbit functional failure of this hardware would be unacceptable and in some instances catastrophic due to the failure of modules to mate and seal the atmosphere, risking loss of crew and ISS functions. The manufacturing processes which create the PBNs need to be strictly controlled. Functional (torque vs. tension) acceptance test failures will be the result of processes not being strictly followed. Without the proper knowledge of thread tolerances, fabrication techniques, and dry film lubricant application processes, PBNs will be, and have been manufactured improperly. The knowledge gained from acceptance test failures and the resolution of those failures, thread fabrication techniques and thread dry film lubrication processes can be applied to many aerospace mechanisms to enhance their performance. Test data and manufactured PBN thread geometry will be discussed for both failed and successfully accepted PBNs.

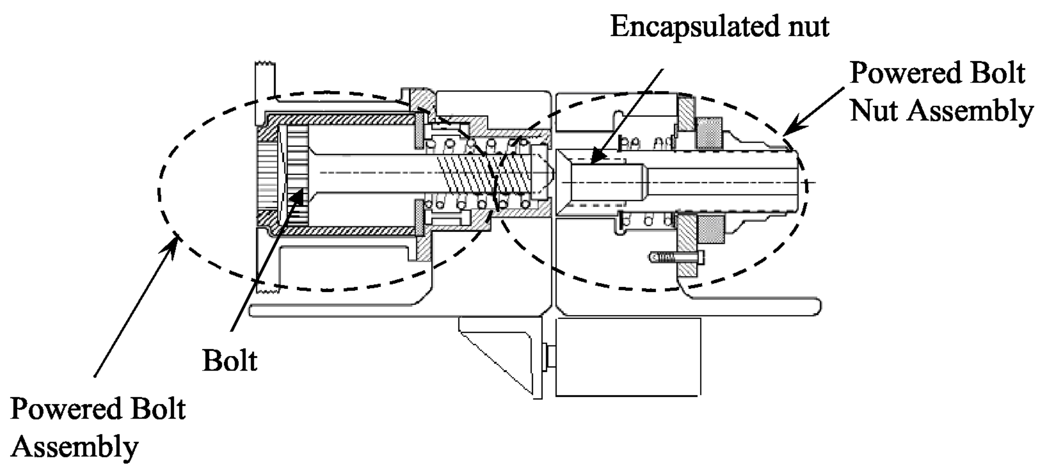


**Figure 1: ACBM Powered Bolt as mated to CBM Nut.**

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## INTRODUCTION

Boeing was contracted to deliver flight qualified PBNs for use on the ISS. Prior to the current contract, PBNs have not been manufactured since the original ISS contract with The National Aerospace and Space Association (NASA) in the mid 1990s. Recently, PBNs were fabricated in 2007 and delivered to Boeing in Huntsville Alabama for acceptance testing. Acceptance testing resulted in a PBN functional failure rate of 34%. Due to the complexity of the issue, a tiger team consisting of different engineering facets was established to determine the failure mode and to introduce corrective actions. The Assembly and Acceptance test-bed was investigated for possible causes of failure. These investigations proved the Assembly and Acceptance test-bed were not the cause of the failures. PBN build records and destructive testing of failed PBNs were also investigated for possible causes of failure. Through destructive testing and evaluation, and review of previous build records, the failure mode was identified to be a combination of out of tolerance thread dimensions, out of tolerance thread surface conditions, and improper application of dry film lubricant. Following the root cause investigation, improved process controls were implemented and a new lot of 113 PBNs were fabricated in 2009. These PBNs were acceptance tested and displayed a 0% functional acceptance test failure rate due to thread dimensions and lubrication issues; validating the implemented process controls to be appropriate. The 96 PBNs manufactured in 2007 were scrapped.

## THREAD FABRICATION

Internal thread geometry of an encapsulated nut is difficult to inspect following machining, leaving the thread geometry acceptability to rely primarily on the fabrication processes used during manufacturing. The PBNs are kept to a tolerance of nine ten-thousandths (.0009) of an inch on the internal thread pitch diameter dimensions to ensure proper bolt to nut clearances after the application of lubricant. It is difficult to maintain these thread dimensions because the nut must be machined and then lapped to ensure surface finish requirements. The PBNs are made of cold worked Nitronic 60, a difficult austenitic alloy to machine because of its susceptibility to internal stresses caused by cold working. If the machinist does not take the proper precautions during machining, these internal stresses will cause the metal to distort during the machining process. These distortions, which may cause mating issues later during acceptance, will be grounds for rejection of the hardware.

The machinist must ensure adequate and uniform lapping over all the internal threads with a hand tool specially made for the PBN thread dimensions to ensure burrs are removed and the required 16 micro-inch finish is obtained. The lapping process for the 2009 PBNs consists of machining a bolt to proper dimensions and covering it with lapping compound. When choosing a hand tool to lap the nuts and remove burrs left from machining, the hand tool material must be softer than the nut base material. This is to ensure the burrs will be removed and the base metal will not be damaged by galling with the hand tool. The best way to ensure an adequate finish is to fully engage the softer material tool with lapping compound multiple times to wear down any burrs left from machining. This process was implemented for the 2009 PBNs to smooth out burrs and meet required finishing while opening the nut pitch diameter before the application of lubricant. Figure 2, shown in the Appendix, is a surface finish error (burr) that occurred due to inadequate machining and lapping of the 2007 PBNs. This error may seem minuscule, but when requiring the Powered Bolt to autonomously attach two pressurized elements of the ISS together, a small burr will quickly break through the thin dry film lubricant and cause galling of the Powered Bolt Assembly.

The PBNs fabricated in 2007 were polished with a lathe and polishing sponge. The lathe and sponge method is unable to polish in the grooves of the PBN threads; therefore this method will not meet the thread call out and finish of the specified PBN drawing. This process not only leaves room for potential burrs but also does not evenly open the thread pitch. Using a lathe and sponge technique could also damage the threads of the nut if the machinist calculates dimensions wrong or a sizable previously made burr gets caught on the lathe. The PBNs fabricated in 2009 were correctly dimensioned and lapped to open the pitch diameter in order to meet the PBN drawing specifications.

During this anomaly investigation, it was found that the past design of the PBNs was incorrect. The depth of threads called out on the design drawing exceeded the thread area of the encapsulated nut. Only 15 to 16 threads were able to be machined into the PBN barrel given the amount of depth allotted for the threads. However, the thread dimension call-out of the drawing stated 18 threads should be machined into the nut barrel. This was discovered when running a go/no-go gauge in the PBNs before lubrication to check for correct thread dimensions. The gage would only go 15 to 16 turns depending on the PBN. Repercussions of this mistake not being found would have been seen during the lubrication process while running a thread cutting tap into the nut in order to clear lube out of each thread groove. The cutting tap would have passed the last thread of the PBN barrel and cut into the base metal at the bottom. This design flaw was never caught during mating of the PBN with the Powered Bolt because the Powered Bolt only enters the PBN with 14 turns.

## LUBRICATION

Dry film lubricants are used in space applications and specifically with the Powered Bolt Nuts for their thermal stability, low abrasivity and low shear strength. Dry Film Lubrication of the PBNs is another important aspect of manufacturing which ensures a smooth running system with no galling issues and consistent torque-tension characteristics of the mechanism. Each PBN should have values above 800 inch-pounds throughout cycles 2 through 24 of acceptance testing. Unacceptable test data from the PBNs manufactured in 2007 can be seen in Figure 3 of the Appendix. If the PBNs are not fabricated or lubricated correctly, testing torque limits above 800 inch pounds will be seen during cycles 2 through 24 of acceptance testing resulting in a failed acceptance test. The Acceptance test for the PBNs is a very rigorous test. A Powered Bolt (PB) is cycled into a PBN 28 times under a normal operating load. Cycles 0 and 1 are at ambient pressure and temperature. Cycles 2 through 21 are under vacuum at ambient temperature. Cycle 22 is under vacuum and at cryogenic temperatures. Cycle 23 is under vacuum and at hot temperatures. Cycle 24 is at vacuum at ambient temperatures. To finish the test, Cycles 25 through 28 are at ambient temperature and pressure. Figure 4 of the Appendix shows complete acceptance test data of all of the 2009 PBNs. The 2009 Acceptance test data shows more consistent torque-tension behavior of the correctly fabricated PBNs compared to the failed 2007 PBNs.

The lubrication process for an encapsulated nut is very difficult due to its confined area. Most machinery is unable to enter the nut barrel and spray lubricant evenly over all threaded areas. The common process for applying dry film lubricant to small diameter internal threads is to use a spray gun with a long nozzle. The lubrication thickness and uniformity are dependent on several variables; fan speed, speed of the nozzle through the threads, nozzle pressure, agitation rate of lubrication slurry, and nut temperature. If any of the variables are miscalculated or misused, the nut will be processed with agglomerations of the lubricant or areas without lubricant. PBNs may contain both agglomerations of lubricant and areas of no lubricant simultaneously. Each of these defects are hard to detect without proper equipment and knowledge. A borescope is commonly used to look at the internal threads of nuts, but without the knowledge of what to look for, these defects can go undetected.

Dry film lubricant, which is applied to internal threads using common practices, has an unpredictable thickness. Thickness is almost impossible and usually too expensive to measure in an indestructible manner. If the lubricant is too thick, this will cause high torque limits during acceptance testing leading to failure of the nuts. Thickness of the PBN lubricant was also a reason for failure for some of the previously built PBNs. A way to defer from dry film lubricant being too thick is to use a thread cutting tap. On previously built PBNs a roll forming tap or a specially manufactured forming tap was used. Both the roll forming tap and specially manufactured forming tap were not sufficient enough to cut through the cured ceramic base coat of the lubricant; this problem will be similar for most ceramic base dry film lubricants. During this process, the roll forming tap became stuck in the nut barrel on various PBNs and had to be cycled multiple times into the nut. Much force had to be applied to the tap to smooth and cut out lubricant. This process increases the risk of damaging the lubricant or the threads of the PBN. A thread cutting tap should only be used on the fully cured ceramic base coat of the lubricant. Dry film lubricants may be applied in multiple coats and a thread cutting tap should not be used on the top coat. The thread cutting tap will strip the top coat off the base coat and the lubrication properties of the top coat and the lubrication system will be lost.

When deciding on a thread cutting tap, the end thickness of the lube must be taken into consideration. Adding the end thickness of the lubricant and subtracting the top coat not yet applied to the nut pitch diameter will ensure the thread cutting tap only clears out the unneeded base coat of the lubricant and leaves an even and smooth base coat on the threads. Figure 5, shown in the Appendix, is an agglomeration of ceramic particles after curing of the lubricant and before using the thread cutting tap. Another benefit of using a thread cutting tap is cutting out debris which may come loose later during acceptance testing. This loose debris gets caught between the threads and causes torque spike anomalies in acceptance test data. This debris can also lead to false failures. Spraying the top coat of lubricant over a loose base coat will cause a loss of both top coat and base coat as debris during testing. Loosing the top coat and base coat in areas will cause the lubrication system to function improperly, leading to higher torque readings and possibly galling. For each PBN, the thread cutting tap was used only one time to mitigate cutting into too much lubricant or causing damage to the lubricant. Using a thread cutting tap on dry film lubricant is not an easy process and difficult to do by hand. The PBNs were placed in a vice while a hand tool was used to gain cutting torque in order to cut through the cured ceramic base coat. After the correct thickness of the base coat was obtained through proper tapping of the nut the top coat of the lubricant system was applied. The variables stated earlier in this section are now controlled to ensure a consistent uniform lubrication throughout production.

If dry film lubricants are applied in a liquid form, the substrate must be heated to ensure proper evaporation of the carrier liquids (commonly known as flashing). If proper flash is not reached, the carrier liquid will migrate with the lubricating particles and pool at its potential energy equilibrium. This pooling will cause uneven lubrication. A result of uneven lubrication can be seen in the case of the Powered Bolt Nuts acceptance test failures. The coefficient of friction was not met during these tests and high torque limits were reached, leading to failure. The dry film lubricant used in this process, Vitro-lube NPI-1220C, is a resin bonded ceramic coating, therefore if the lubricant is not properly flashed, an amber coloration can be seen in resin rich areas; see Figure 6 of the Appendix. This specific dry film lubricant was chosen because of its thermal vacuum stability and because of its ability to perform reliably under the high load rates of the Powered Bolt assembly; 1.03 Mega Pascal (MPa) of contact stress. Vitro-lube NPI-1220C was also selected due to its superior wear life as compared to other dry film lubricants. This specific dry film lubricant is made up of two parts; a ceramic base coat and a resin top coat. Some dry film lubricants are not resin bonded and the resin rich areas in Figure 6 will not be seen. Areas of high ceramic content can also be seen if Vitro-lube NPI-1220C is not flashed properly; these areas form where the majority of the ceramic base coat pool during lubricant application. Ceramic pooling of a failed PBN can be seen in Figure 7 of the Appendix. This result of improper flashing of dry film lubricant can be used as a guide for non-resin bonded lubricants. When using a non-resin bonded lubricant the surface characteristics will be different between base metal and dry film lubricant.

Oxidation protection given to the substrate ceramic by the phenolic resin was a main factor in choosing resin bonded dry film lubricant for the powered bolt nuts. In the case of PBNs, Molybdenum disulfide ($MoS_2$) will not oxidize to Molybdenum trioxide ($MoO_3$), a poor lubricating material, in air due to the use of the top coat resin. A downfall to using $MoS_2$ over other dry film lubricants is it will fail due to high coefficients of friction when testing in high humid atmospheres under high loads. $MoS_2$ will oxidize to $MoO_3$ in high humid atmospheres under high loads. Most non resin-bonded dry film lubricants will slowly oxidize in air environments, such as storage warehouses, leading to early failures of the lubricant.

A way of analyzing lubricant for composition is using an Energy Dispersive Spectrometer (EDS). This equipment will show if lubricant is missing from the threads. The EDS indicated that the ceramic base coat was applied to the threads before the resin top coat. Figure 8, located in the Appendix, shows EDS images of a PBN which failed acceptance testing. Spectrum 1 is of a non-amber colored area and Spectrum 2 is of an amber colored area. The chemistry shows the absence of the Molybdenum disulfide ($MoS_2$) and Antimony (Sb) which make up the ceramic base coat of Vitro-lube NPI-1220C. This absence of ceramic base coat is a direct cause of not preheating the PBNs before lubrication.

Depending on a substrate's thickness and material type, the temperature of the substrate itself may differ in order to properly flash the carrier liquid. The flash temperature will also differ for lubricants depending on the carrier liquid used. The 2009 batch of PBNs were preheated in an oven/furnace for a specified amount of time at a temperature predetermined based on the PBNs material thickness and the carrier liquid (in this case isopropyl alcohol). A thermocouple was attached to the internal threads of the PBN while in the oven to evaluate the surface temperature where the flashing of the lubricant would take place. During production, the PBNs were taken out of the oven and prepared for lubrication; wheeled to station, set-up properly, etc... Depending on the technician, some of the PBNs would not be lubricated for 10 minutes, loosing their flash temperature. It was realized that the PBNs needed to retain flash temperatures during production. To retain this temperature, mitigating risk of improper lubrication, a 3 minute time limit was placed on the PBNs to be out of the oven before being lubricated. Some dry film lubricants, for example Vitro-lube NPI-1220C, are applied in multiple coatings. To ensure proper flashing throughout all coatings, mechanisms must have an out of oven time limit placed upon them to retain their flash temperature during lubrication. This added preheat process to the lubrication method of the PBNs ensured proper flashing of the dry film lubricant leading to even lubrication of the nut threads and less production variation. At completion of the lubrication process the PBNs exhibited dark spots throughout the nut. Further analysis of these dark spots showed it to be excess top coat. This excess top coat was deemed acceptable because it was not thick enough to cause mating problems and the excess top coat will not cause a lack of lubrication of the system. During acceptance testing this excess top coat will be burnished into the ceramic base coat as is the rest of the top coat.

## CONCLUSIONS

For future manufacturing of PBNs and other Aerospace mechanisms which have dry film lubrication similar to the Powered Bolt Mechanism, proper processes must be established to ensure a reliable part is produced. These process enhancements will minimize part to part variation and acceptance test failures while avoiding added costs and delays in delivering a final product to the customer.

Key process enhancements discovered during this manufacturing anomaly resolution include:

Thread Fabrication

- When lapping a surface, a method which is capable of obtaining the desired surface finish in every thread, groove, etc… must be determined and controlled. In this case, manual thread lapping with a "softer" tool and lapping compound, lapped multiple times worked well to wear down any burrs left from machining.
- Polishing with a lathe and sponge method was eliminated.
- Us of a go/no-go gauge before lubrication to check for correct thread dimensions was implemented.

Lubrication

- To maintain consistent lubrication thickness a thread cutting technique was implemented over a thread rolling tap. Consideration of final lubricant dimensions is a key aspect of choosing a cutting tap.
- A preheating process was implemented to obtain proper flash temperature. Due to the migrating capabilities of dry film lubricants that are applied on to substrates as liquids, it is beneficial to preheat all mechanisms to defer and risk of lubricant pooling or lack of lubricant in less energy potential areas.
- Imposing an out of oven time limit during the lubrication process to keep the mechanisms at flash temperature.

All of these process enhancements placed upon dry film lubricated aerospace mechanisms will ensure proper system operation of equipment, minimize the risk of failure, and minimize product variation during production.

## AKNOWLEDGEMENTS

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## APPENDIX

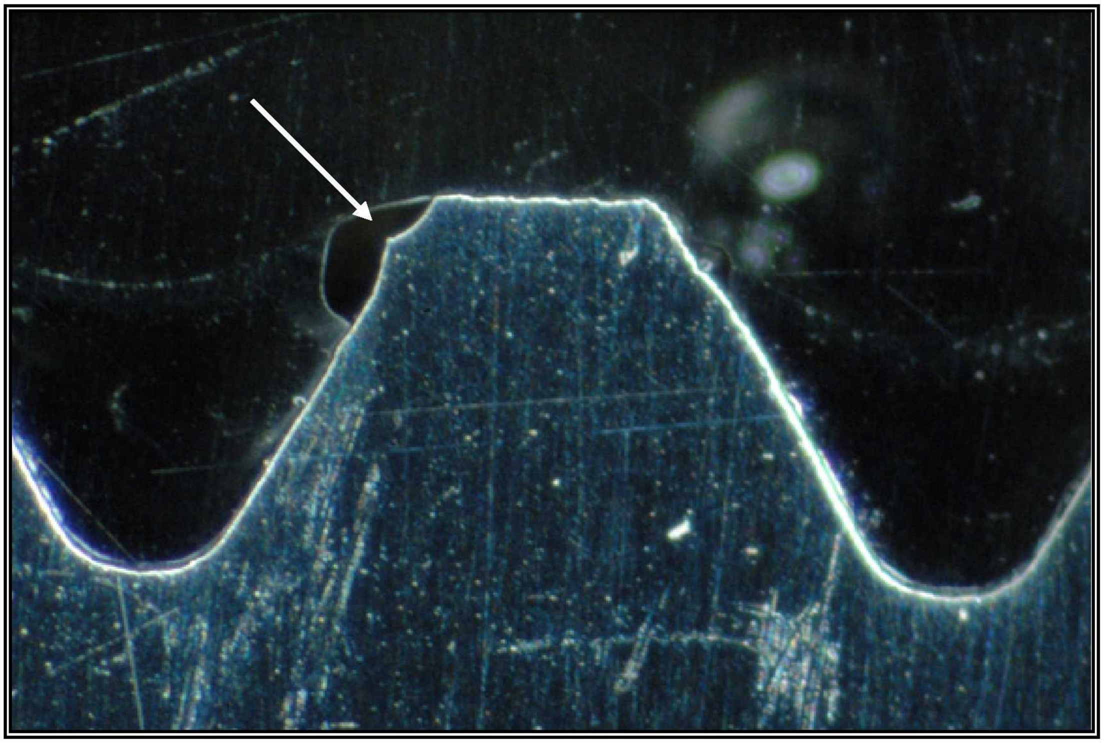

**Figure 2: Surface Finish error, burr; 500x magnification**

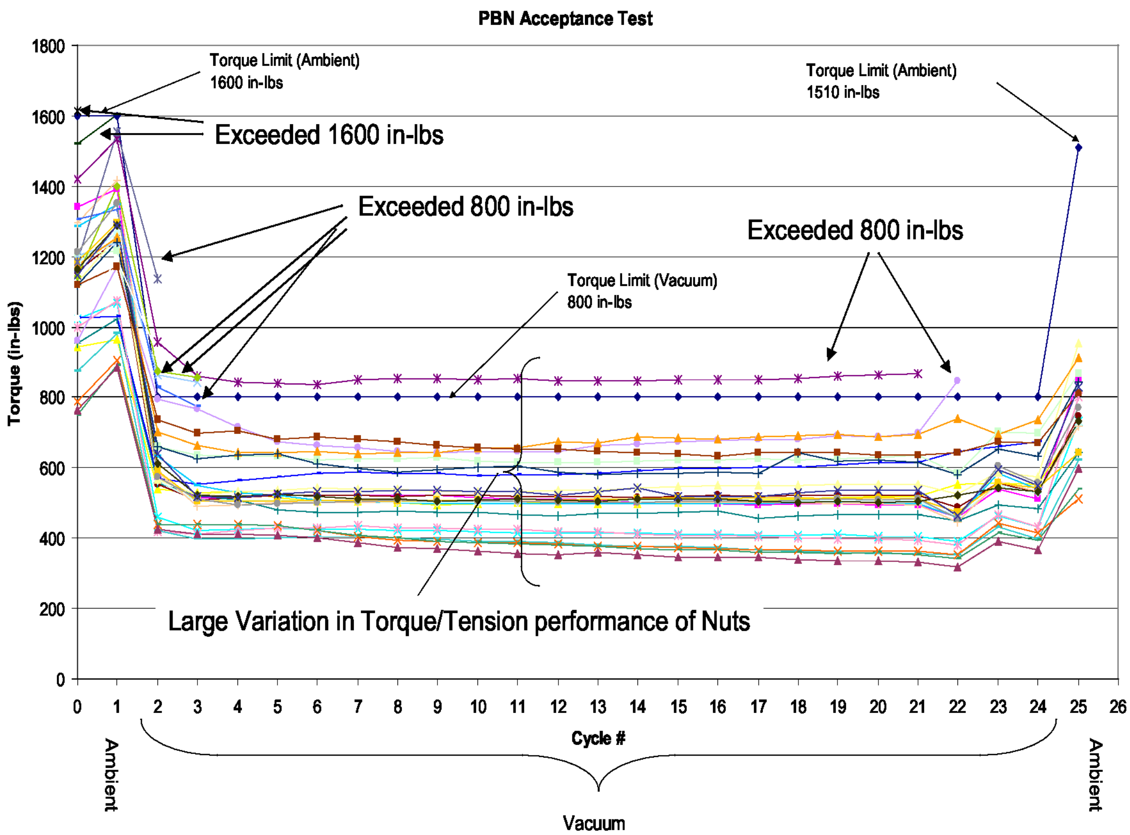


**Figure 3: Acceptance test data from failed PBN lot of 2007**

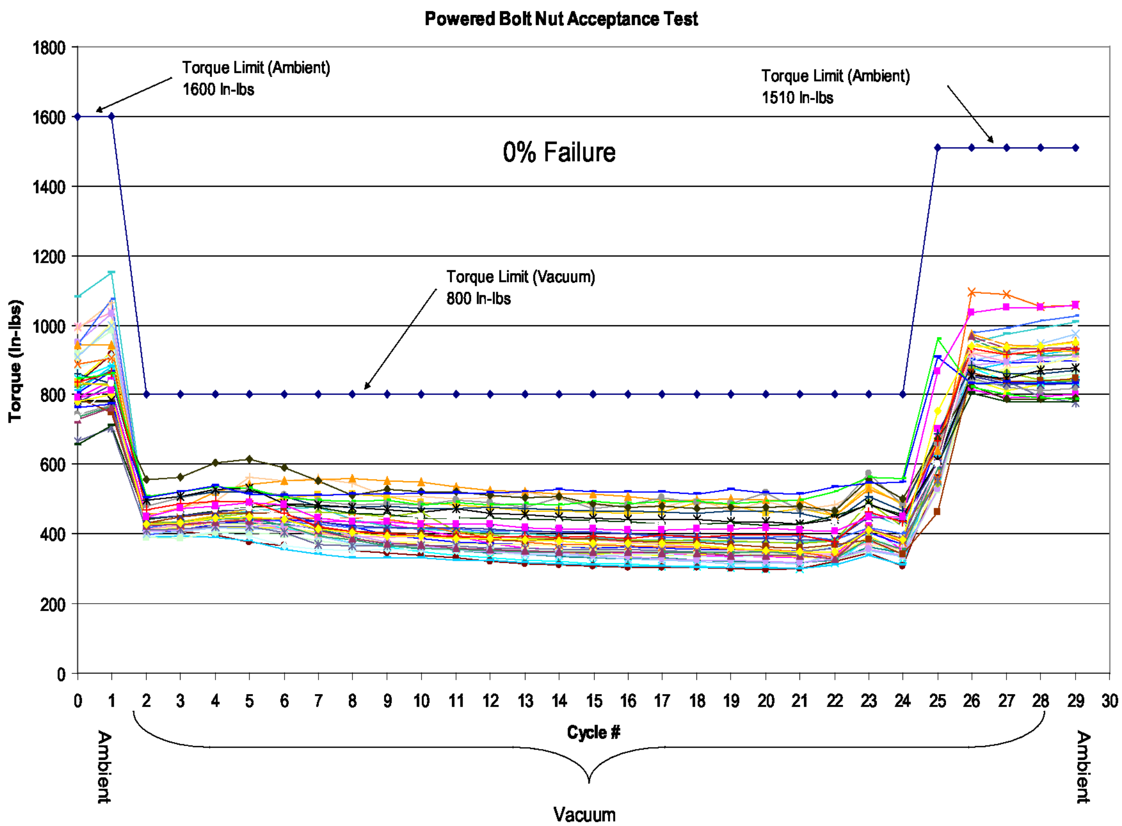


**Figure 4: Acceptance test data from passed PBN lot of 2009**

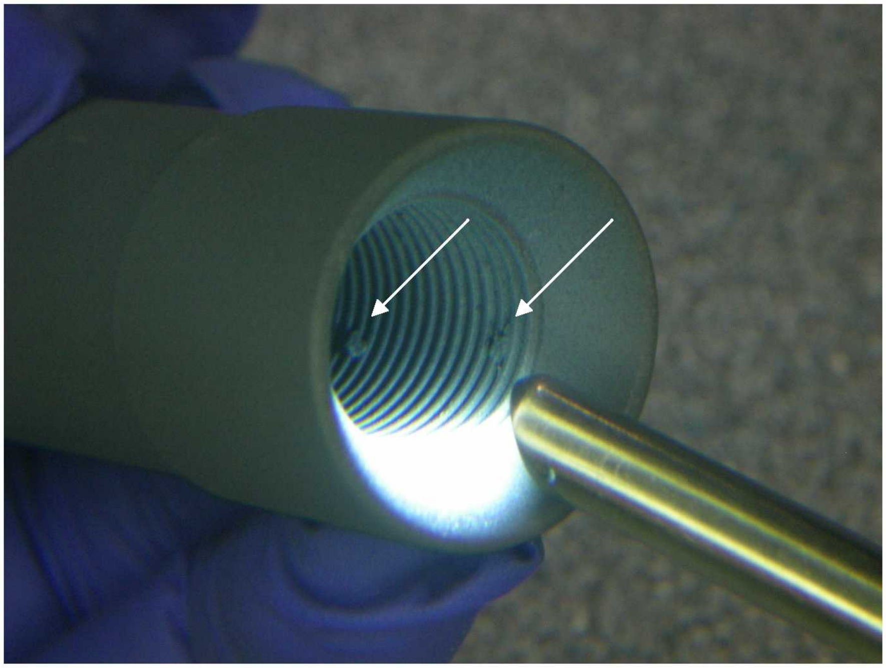

**Figure 5: Agglomerations of base coat ceramic of Dry Film Lubricant**

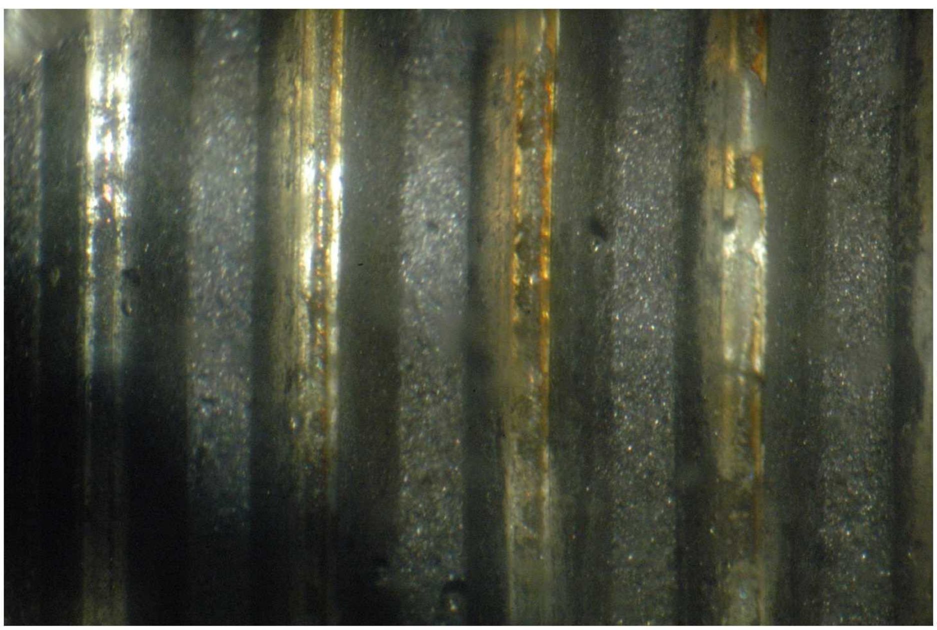

**Figure 6: Amber coloration of resin binder; 50x magnification**

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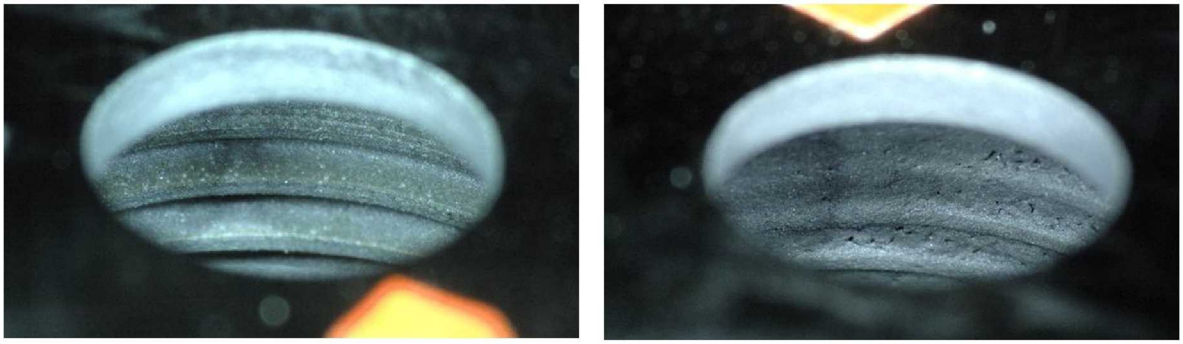

**Figure 7: 2 180° views of a failed PBN; 50x magnification**

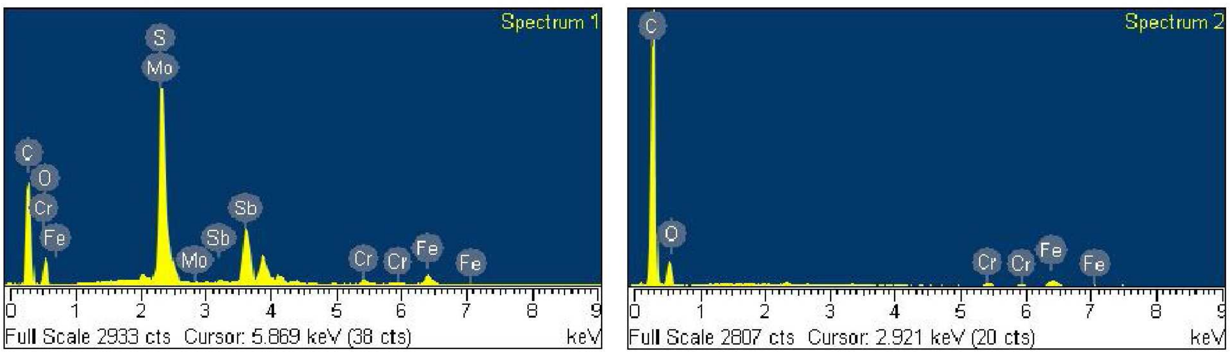


**Figure 8: Differences in coating chemistry of PBN**