Use of Soft-Metal Engineered Surfaces to Minimize Galling of Carbon Steel Bolting Materials in Gasketed Joints at Elevated Temperatures.

DANIEL N. HOPKINS
CRAIG D. HARRINGTON
STEVE GREENWELL

NOVA Machine Products Inc – Curtiss-Wright Flow Control Corporation Nuclear
18001 Sheldon Road
Middleburg Heights, OH
44130

Abstract

Bolting materials with soft-metal engineered surfaces applied using the PlasmaBond™ process retain their qualifications as pressure boundary materials. These thin, highly adherent gold or silver surfaces significantly reduce the risk of galling for joints that are heavily loaded, operate at elevated temperature, and remain stagnant for long periods. Soft-metal engineered surfaces have demonstrated in joints assembled by tensioning and the more common practice of torquing, offer improved galling resistance compared to non-coated components. Field experience has shown that engineered surfaces can be used to create “metallurgical contrast” that is more effective against galling than conventional lubricants.

1. Introduction

Laboratory testing and field experience has shown soft metal engineered surfaces (such as gold and silver) provide effective galling protection even in very harsh environments. These thin, highly adherent metallic films create a substantial “contrast” in the chemical composition and physical properties between the two contacting surfaces. This significantly reduces the risk of galling under harsh conditions where conventional lubricants are often not effective. Galling results in an unnecessary waste of time, money, and materials. In a nuclear facility, workers can also accumulate radiation dose in the course of repairing galling damage.

Understanding how threaded fasteners with soft metal engineered surfaces respond in gasketed joints requires an interdisciplinary understanding of metallurgy, tribology, and the design requirements for a leak free gasketed joint. When joints are assembled by a tensioning process, tribological issues are relatively straightforward. However, when joints are assembled by torquing, tribology governs how applied torque is converted into fastener load. During assembly, failure (a leaking joint) is typically caused by insufficient fastener load or excessive variations in fastener load. During disassembly, failure is a stuck fastener.

Test equipment that simulates a gasketed joint, and test procedures that simulate repeated torqued assembly cycles has been developed to assess the galling resistance of carbon steel bolting materials with soft-metal engineered surfaces under harsh service conditions. The design of the test apparatus and the test procedures clearly distinguish between the assembly and the disassembly process. This work is focused on galling, which is primarily associated with disassembly (remember galling can and occasionally does occur during assembly), but Texas Utilities learned it was necessary to carefully control how the fasteners were assembled before galling issues could be meaningfully addressed.

2. Friction, Wear and Galling

Friction, wear, and galling are distinctly different phenomena but the circumstances under which they occur often seem similar. This discussion is based on clean, dry surfaces that would generally be considered smooth. When such surfaces touch, asperities (microscopic high spots) are the only locations where the objects actually make contact. The net surface area that is in *actual* contact is therefore only a small fraction of the *apparent* contact area [1]. Under load, the asperities flatten, either elastically or plastically, until there is sufficient contact area to carry the load with no further deformation.

When two solid surfaces are in contact and in relative motion, microscopic particles from the tips of the asperities can be dislodged from one or both surfaces. Heavier loads tend to dislodge more and larger particles, which can move about in the interface. If the wear particles are expelled from the interface and the concentration of particles remains low, the impact on friction is negligible. If wear particles remain trapped in the interface they may suffer further deformation and work harden which contributes to abrasion thereby accelerating wear. If wear particles reattach to the solid surface this is “adhesive wear” and is the precursor to galling and friction at the interface can increase dramatically. Galling is characterized by relatively large pieces of metal being torn from one surface and deposited on the other. If galling occurs during assembly, fastener preload might be reduced to a point where the leak tightness of the joint can not be assured.

When an interface is under load, shear forces in excess of the friction force are needed to cause the surfaces to slide across each other. Galling, wear, and friction only occur while an interface is moving under load. Under certain circumstances, it is possible to have relative motion at the interface with virtually no wear. Hard surfaces and surfaces with substantial metallurgical contrast often can carry somewhat higher loads without suffering from wear. Friction remains reasonably consistent over a wider range of applied load because the engineered surface provides additional margin against onset of adhesive wear.

3. Risk factors for galling

Risk involves considering the likelihood and consequences of an occurrence. Consequences are assessed on a case by case basis but likelihood (probability of occurrence) can be estimated through experience. Various investigators are likely to rank these risk factors differently but most investigators would probably agree that similar materials should be the number one risk factor.

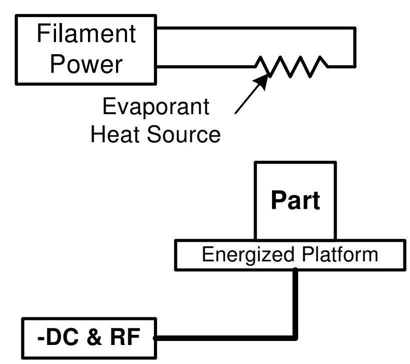
(1) Similar chemical compositions and mechanical properties;
(2) High load across the interface;
(3) Elevated temperature;
(4) Hard particles in the moving interface;
(5) Extended stagnant time;
(6) Metallurgically clean surfaces.
(7) Number of torqued assembly cycles (A risk unique to fasteners with PlasmaBond surfaces)

Some materials, like aluminum and austenitic stainless steel, are very susceptible to galling even at moderate temperatures and at moderate loads. Metallic engineered surfaces have a unique risk associated with poor adhesion. If relatively large "sheets" of the metallic layer become dislodged this creates patches of clean metal substrate that are available to directly contact the opposing surface. Poor "wetting" would be the analogous behavior for a conventional lubricant.

4. The PLASMABOND ™ process

The patent pending PlasmaBond™ process is an enhanced vacuum coating process that is used to deposit very thin (less than 1 micron), strongly adherent metallic layers on a wide range of metal or nonmetal substrates, typically found in nuclear and non nuclear facilities. The item to be treated is solvent cleaned and is often glass bead blasted. Final cleaning may include back-sputtering that is conducted in vacuum immediately prior to depositing the metallic layer and is intended to produce an ultra clean surface. This high degree of surface cleanliness is considered essential to achieve the desired adhesion of the deposited surface.

The engineered surfaces are deposited from a low-pressure energetic vapor flux (mixture of ions, recombined neutrals, and vapor) that surrounds the item to be treated. The metal is introduced into the space surrounding the item using heated filaments. Deposited materials used in this process are very pure to ensure that potentially harmful trace contaminants are not present.



PlasmaBond Schematic

Figure 1

A negative electrical charge is used to create the plasma, and to attract the metal ions. The most intense zone of potential gradient extends for 2 or 3 cm from the item. This strong potential gradient results in a "dark space" where ion concentrations are low because they are rapidly drawn to the charged object. Evaporant ions are accelerated toward the substrate and impact with kinetic energy on the order of 100eV. The recombined neutrals and the vapor are believed to impact the surface with kinetic energy in the approximate range of 0.01 to 10 eV. On average, the impact energy is high compared to vapor deposition and produces a strong bond with the substrate.

The metal vapor deposits predominately in a line-of-sight path from the evaporant source, but the metal ions that enter the dark space are able to coat the item 3-dimensionally. The ions are also able to penetrate into relatively narrow cavities in the substrate. This occurs as a result of (1) evaporant ions experiencing scattering collisions in the plasma and (2) the applied charge.

During high-energy plasma deposition, metallurgical structures could be affected by the dramatic increase in substrate temperature. This is not acceptable when the substrate is an ASME-qualified pressure-retaining bolt. The PlasmaBond process uses a low flux density, which limits the number of energetic impacts so temperature rise in the substrate material is negligible. Metallographic examination has confirmed the PlasmaBond process does not alter metallurgical structures or produce a heat-affected zone.

5. Requirements for a gall-resistant engineered surface

Galling risk can be substantially reduced by engineered surfaces with the following characteristics:

(1) Creates substantial metallurgical contrast between the opposing surfaces.
(2) Does not introduce hard particles into the moving interface.

Engineered surfaces typically consist of two or possibly three layers. Each layer may be a pure element or an alloy. The galling resistant engineered surfaces used in this work consisted of two layers (Ni-AgPd). Unlike conventional lubricants the thin metallic layer is solid. Its inherent structural integrity and the fact that it is well supported by the substrate allows it to remain in place and structurally sound under heavy loads and at high temperatures for extended periods of time.

Testing and field experience suggest that about 1000 atom layers (200 nm) is sufficient to provide an effective soft metal barrier to galling. A base layer, such as nickel, is intended to strongly bond to the substrate and aid in the adhesion of the working surface. The overall thickness of the PlasmaBond engineered surface typically ranges between 300 and 1000 nm. The working surface, in one embodiment, may represent at least half of the total deposited thickness, and the balance of the deposit thickness is in the base and transition layers. Typically bond strength for PlasmaBond-deposited engineered surfaces is 50 MPa (7 ksi) or higher.

Experience has shown the chromium transition layer should be avoided when galling resistance is desired. It is believed that chrome particles contribute “hard debris” in the interface. Preliminary work also suggests that nickel performs better that titanium as a base layer. Sometimes “active” metals are somewhat gall prone, and the soft-metal working surface does not appear to effectively screen the gall prone nature of titanium.

When engineered surfaces are used in an industrial setting, it is necessary to ensure the substrate’s qualifications as a pressure boundary material are maintained. The PlasmaBond deposition process does not increase substrate temperature by more than a few degrees so material bulk properties are unaffected and the material retains its qualification as a pressure boundary material. The deposited layers are chosen to be chemically compatible with the working environment and metallurgically compatible with the substrate. Materials that are to be deposited on the surface have strict limitations on trace contaminates that might harm the substrate material.

Bond strength for the PlasmaBond-applied surfaces typically exceed 50 MPa (7 ksi) between the various deposited layers and between the surface and the substrate. This bond strength is sufficient for a soft metal engineered surface because the soft metal surface is very malleable and is well supported by iron-base or nickel-base substrates with yield strength ranging between about 200 MPa (30 ksi) and 1000 MPa (150 ksi). A minimum yield strength of 720 MPa (105 ksi) is specified for the carbon steel bolting materials used in these tests. Visual assessments (of engineered surfaces with gold working layers) suggest this bond strength is sufficient to ensure the malleable engineered surface remains well adhered to the substrate in spite of local plastic deformation of the substrate material.

On a microscopic scale, where galling initiates, there is a substantial contrast in chemical composition and physical properties. Applied loads induce stress fields that certainly will penetrate the very thin (typically 300 to 1000 nm) engineered surface layer, so the mechanical response of the engineered surface is strongly influenced by the mechanical properties of the substrate.

Common non-destructive examination techniques (ultrasonic, magnetic particle, and dye penetrant) are unaffected by the deposited film. Glass bead blasting is often used to prepare the surface prior to depositing an engineered surface. Small surface-connected cracks may be “peened” shut by the action of the glass beads. However, this concern can be adequately addressed with an appropriate baseline inspection prior to surface preparation.

6. Comparison of the galling protection provided by engineered surfaces and conventional lubricants

It is important to realize that the galling protection provided by engineered surfaces relies on “metallurgical contrast” while the galling protection provided by conventional lubricants relies on “avoiding contact” of the solid surfaces. These are very different mechanisms.

Engineered surfaces achieve maximum galling resistance by designing then with a substantial “metallurgical contrast” (large differences in chemical composition and mechanical properties) between the surfaces that are in contact. Metallurgical contrast can be achieved by applying either harder or softer deposited coating surfaces. Testing has shown that hard surfaces provide less effective galling protection [2]. It is believed that local deformation of the substrate causes the hard surfaces disbond and spall, which injects hard particles into the moving interface. PlasmaBond-applied soft metal surfaces appear to be malleable, ductile, and remain attached to the substrate even when the substrate is plastically deformed.

When a low shear strength metal is deposited on one of the sliding surfaces in contact, the friction force during sliding will be reduced. Soft silver or gold films shear easily and prevent surface asperities from coming into frequent contact. This relatively easy shear at the contact points produces fewer asperity/asperity interactions, which results in lower friction and reduced wear. Soft-metal engineered surfaces provide effective wear reduction when adhesive wear predominates [3]. Particles preferentially dislodge from the soft material so these soft materials, that do not tend to work harden, are the dominant debris in the interface. Furthermore, when small hard particles are introduced into the interface, these hard particles can get "buried" in the soft metal surface, which immobilizes them so they will do no harm.

CONVENTIONAL LUBRICANTS

Lubricants are very sophisticated materials. Their viscosity, thermal stability, chemical affinity (ability to wet) for metallic surfaces, can be altered (within limits) to satisfy a given set of interface friction, load, and temperature requirements. Even the most viscous conventional lubricants with strong tendency to wet metal surfaces have negligible shear strength compared to a solid making them vulnerable to being "squeezed out" of the interface. Gaps form in the lubricant and eventually the asperities are in direct metal to metal contact. These gaps in the lubricant layer develop within a few hours or possibly within a few months depending on the applied load, temperature, time, and the lubricant properties. At the time of disassembly, galling risk is high in these areas of direct metal to metal contact. Lubricants are also known to collect hard particles that can contribute to galling risk during disassembly.

On a longer time scale, (months to years) heat and time can alter a lubricant's chemical structure and physical properties. Elevated temperature can selectively remove a lubricant's more volatile components causing it to become stiff and hard and may actually impede movement at the interface. If the lubricant hardens and retains its chemical affinity for the interface surfaces, it can effectively "glue" the interface together. Technically, this is not galling, but the joint still can't be dismantled.

It is interesting to notice that risk factors for galling and lubricant failure are surprisingly similar. Risk factors for lubricant failure include:

(1) High load across the interface
(2) Elevated temperature
(3) Hard particles in the moving interface
(4) Extended stagnant time

In an industrial situation, the subtle differences that might be used to distinguish between galling and lubricant failure are usually not recognized.

7. Measuring fastener performance and galling resistance using a simulated gasketed joint.

A means of consistently reproducing representative mechanical, and environmental conditions was needed to assess the galling resistance provided by PlasmaBond soft metal engineered surfaces. The mechanical conditions included a means of consistently applying and maintaining a substantial fastener load and also simulate the "soft" nature of a gasketed joint during the torqued assembly process. The fasteners were exposed to temperatures near the maximum expected operating temperature in the nuclear plant and the effects of long stagnant periods also had to be assessed.

Assurance that fastener load could be maintained in a narrow range (within about 10%) was considered critical to the galling test. Measurements of fastener preload for a given applied torque show that fastener performance (conversion of applied torque to fastener load) can be maintained for several assembly cycles – the torquing and de-torquing of the fasteners [2]. It was later determined that when the load bearing surfaces were wiped between successive assembly cycles, fastener performance noticeably declines (increased friction) when assembled without lubricant [4]. Subsequent tests showed fastener performance (torque to load) declined very rapidly on successive assembly cycles when the fasteners were heated for as little as 3 days, then assembled without lubricant. This experience clearly showed a suitable assembly lubricant was needed to maintain fastener loads in the desired range.

Heated Test Block

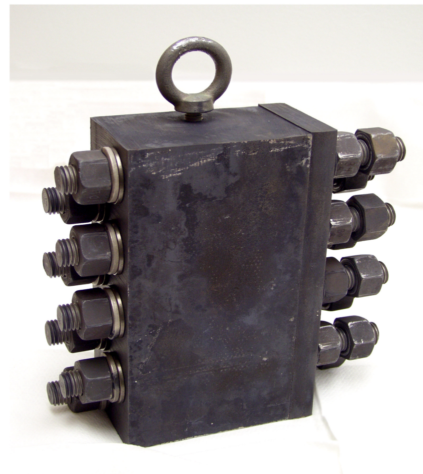


Figure 2

Test blocks that mimicked gasketed joints were designed and built, while test procedures that reflect field techniques for assembling gasketed joints by torquing were developed. Belleville washers were used to simulate the 0.5 to 0.8 mm (20 and 30 mils) "crush" in the sealing element in a gasketed joint. Compliance (deformation in response to an applied load) for the load cell used to measure fastener assembly performance was measured and also determined to be reasonably similar to a sealing element.

For practical reasons, there was a desire to shorten the time for the test, but there was no reason to expect the commonly used Arrhenius approach (raising the temperature to simulate longer exposure times) would affect the behavior of the contrasting metal surfaces. It did however; seem likely that an increased load would have a detrimental effect on the galling resistance of the soft-metal engineered surfaces. Based on engineering judgment it was decided to shorten the tests by using increased fastener load rather than by raising the temperature.

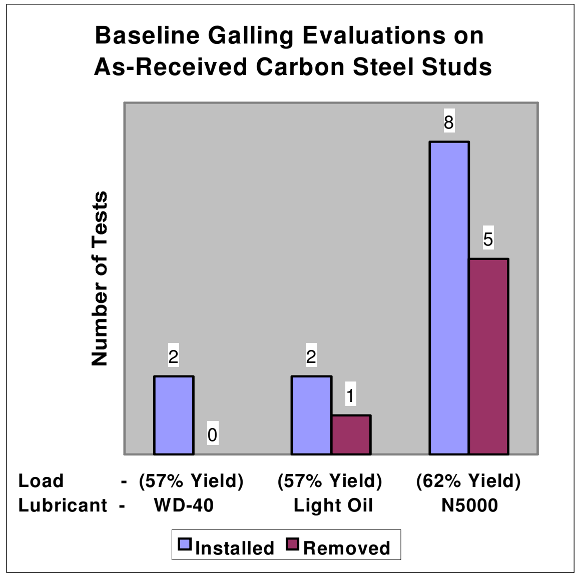
EQUIPMENT:

No.	Part	Material	Treatment
56	Studs:	A-193-B7; ¾" (19mm)-10	(12) Clean and Degreased (Figure 1) (44) Ni-AgPd 500 nm thick (Figures 2,3)
56	Nuts:	A-194-2H ¾" (19mm) -10 Heavy Hex	Clean and Degreased
56	Hardened Washers:	Carbon Steel - 1/8" (3.2mm) thick, Flat	Clean and Degreased
56	Belleville Washers:	Inconel - 1/8" (3.2mm) Thick	20mils compression at 7000 pounds load (0.5mm compression at 30kN load)
4	Test Block:	Carbon Steel - 4-1/2" x 3" x 9"	Eight ¾" x 4-1/2" through-holes.
4	Lower Plate:	Carbon Steel - ½" x 3" x 9"	Drill and Tap eight ¾" through holes

Preliminary tests were conducted to identify critical details in the main test, ensure suitability of the test procedures, and to assess the overall severity of the test. These tests exposed the fasteners to 325EC (616EF) for periods of about 70 hours.

The main test was again conducted at 325EC (616EF) but the duration of the operating cycles ranged between 70 and 2040 hours. This large variation in exposure time was intended to assess how longer exposure times (50,000 hrs.) might affect galling risk. The target value for fastener load was set at about 111 kN (25,000 pounds) which corresponds to about 75% of specified yield strength for this material. Up to 12 assembly cycles were planned, but we intended to continue the test until we experienced a 5% galling rate in any given cycle.

Figure 3



8. Test results

Baseline tests were conducted to evaluate various candidate assembly lubricants and to assess the overall severity of the test equipment, procedures and conditions. Figure 3 presents results from twelve (12) untreated carbon steel fasteners that were cleaned, degreased then assembled using various assembly lubricants. Loads were moderate (57 to 62% of the yield), temperature was 325EC (616EF) and exposure was 3-days.

Eight of these untreated studs were assembled using LotTite N5000. Loaded to 62% yield, and exposed to 325EC (616EF) for 3 days. LocTite N5000 is commonly used in the nuclear industry and is widely considered an effective lubricant. Three of the eight studs galled during disassembly even though the loads and temperatures seem quite typical. The 38% failure rate suggests that N5000 provides less than adequate galling protection during disassembly. These results confirmed that the equipment, assembly procedures, and operating conditions produce significant galling risk.

Figure 4

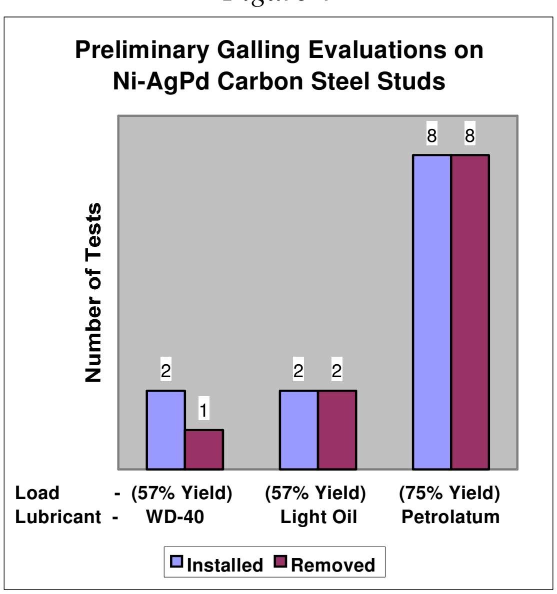


Figure 4 shows results of the preliminary tests on twelve (12) studs with Ni-AgPd PlasmaBond surfaces. Overall thickness of Ni-AgPd layer was about 500nm on the inclined thread surface. The tests showed that "light" assembly lubricants (WD-40 and mineral oil) were unsatisfactory because fastener preloads could not be maintained in the desired range. These "light" assembly lubricants were not included in the main test. Petrolatum's performance as assembly lubricant was shown to be at least equal to that of N-5000 on fasteners with Ni-AgPd engineered surfaces. These studs were loaded to 75% of yield and this is considered to be a very high stress under TXU design philosophy. Petrolatum's chemical structure breaks down under heated, so it is unlikely to act as "glue" in an interface.

The objective of the main test (Figure 3 and 4) was to determine practical operational limits for PlasmaBond-treated fasteners installed using torque. This test involved 32 fasteners and as before, they had Ni-AgPd PlasmaBond surfaces that were about 500nm thick on the inclined thread surface. The fasteners were exposed to 325°C (616°F) for times that ranged between 70 and 2040 hours. The test was stopped after the eighth cycle because 2 of the 30 (more than 5%) fasteners installed at the beginning of the cycle galled during disassembly.

Galling risk was assumed to increase as a result of mechanical damage accumulated during each assembly cycle and with increased exposure time. The test plan included many assembly cycles and a wide range of operating times.

Figure 5

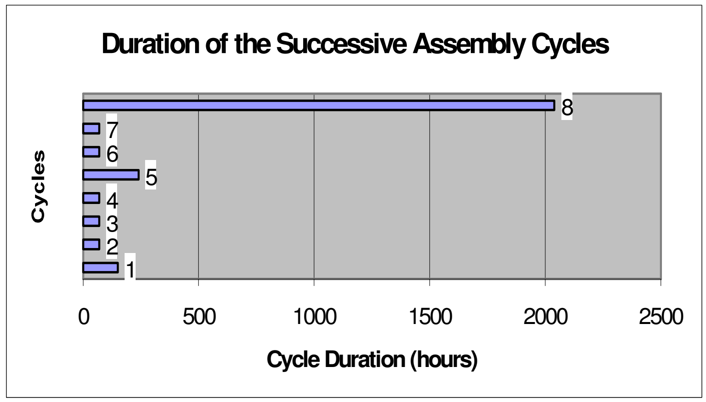
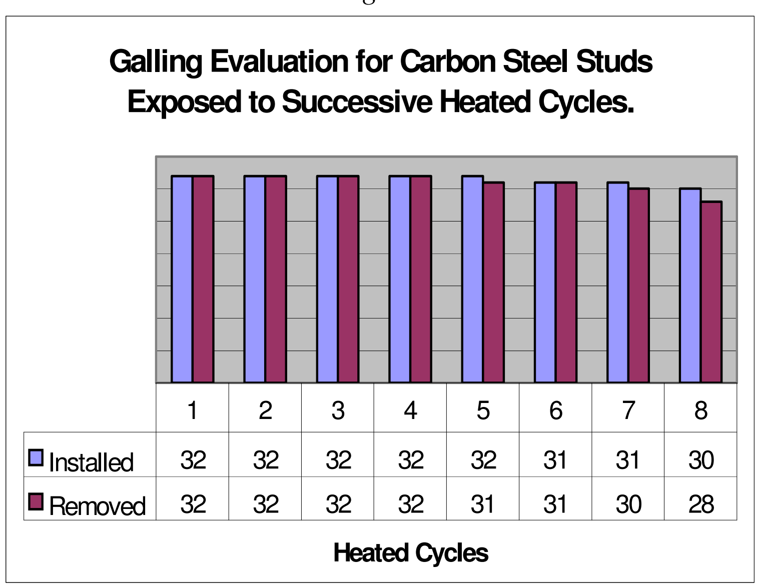


Figure 5 shows the duration of each of the eight assembly cycles. As before, the fasteners were exposed to 325°C (616°F) but loads were raised to about 75% of the material's specified yield strength. Exposure duration for the first seven cycles was relatively short ranging between 70 and 240 hours. To assess the galling risk of long-term exposure the duration for cycle eight was increased to 2040 hours. The total "accumulated" exposure time was nearly 2800 hours.

Figure 6 shows one (1) fastener galled during cycle 5, another during cycle 7 and two (2) fasteners during the eighth cycle. The two galling events in cycle 8 are believed to have occurred due to the combined effect of damage that had accumulated over eight assembly-operating-disassembly cycles and the relatively long (2040 hour) duration of cycle eight. After this series of tests the free span of the studs had stretched about 2 percent indicative of the high stress imposed on the fasteners.

Figure 6



As was expected, the galling risk appears to increase with successive assembly cycles. The time-dependent component of galling risk appears to accumulate more quickly at early in the cycle. This data (very approximately) suggests that about half of the time-dependent galling risk in a 100,000-hour operating cycle, might accumulate during the first 1000 hours.

9. Field experience

Sixteen (16) PlasmaBond-treated Steam Generator primary manway studs (Comanche Peak) were installed (using tensioning) with no conventional lubricant. After they were exposed to 330ºC for 17 months they were easily removed by hand. Visual examination revealed no flaking or disbondment.

Fifty-two (52) reactor vessel head closure studs (Comanche Peak) with engineered surfaces were installed (using Tensioning) with LocTite N-5000 lubricant then exposed to 315ºC for 17 months. The studs were easily removed and visual examination revealed the engineered surfaces showed no signs of flaking or disbondment even after they were subjected to "IceSolv" blast cleaning with CO_2 pellets propelled by air at 0.8 MPa (120 psi) to remove the old lubricant.

Stainless steel trunnion bolts used to seal the lids on radioactive filter canisters (Comanche Peak) routinely galled making it necessary for maintenance workers to enter the radiation field near the filter canister and remove the damaged trunnion bolts. TXU has experimented with an earlier version (Ni-AgPd) engineered surface on these trunnion bolts and to date, no further galling has been reported.

10. Conclusions

1. PlasmaBond engineered surfaces provide effective gall resistance without altering an item's bulk properties. Only one of the surfaces needs to be treated created the desired metallurgical contrast.

2. The galling protection provided by soft-metal engineered surfaces deposited using the PlasmaBond process is superior to the galling protection provided by conventional lubricants. As conditions become more harsh (high loads, elevated temperature, long stagnant times) this disparity in galling protection becomes bigger.

3. When the fastener loads are limited to about 60% of yield, galling resistance of the PlasmaBond surface remains effective for a finite number of torqued assembly cycles.

4. The risk of a galling failure for fasteners with soft metal PlasmaBond engineered surfaces and no conventional lubricant accumulates for a period of time after installation. After some time (a few weeks) the galling risk appears to accumulate at a very low rate and in fact may remain essentially constant.

5. Appropriate use of engineered surfaces can result in operation and maintenance cost savings through greater operational reliability, less frequent maintenance, easier disassembly, fewer repairs of galling-related damage, and extension of component life.

11. References

1. I. M. Hutchings, "TRIBOLOGY: Friction & Wear of Engineering Materials" Edward Arnold, London, 1992

2. Hopkins, D. N., Harrington, C. D., and Bill R. Black, "Reduce Maintenance Costs by Using engineered Surfaces to Control Friction and Galling", WEAR - An International Journal on the Science and Technology of Friction, Lubrication, and Wear, Atlanta, Georgia, April 25-29, 1999.

3. D. H. Buckley, "Surface Effects in Adhesion, Friction, Wear, and Lubrication," Elsevier, Amsterdam, 1984

4. Hopkins, D. N. and Harrington, C. D., "Use of Engineered Surfaces to Reduce Galling, Control Friction, and Save Money", 1998 ASME Pressure Vessel and Piping Conference, San Diego, California, July 26-30, 1998.