On the Contradiction of Applying Rolled Threads to Bolting Exposed to Hydrogen-Bearing Environments

B. D. Craig, Stress Engineering Services

Summary
Numerous industries continue to experience bolting failures as a result of hydrogen stress cracking (HSC) when exposed to hydrogen-bearing environments such as seawater with cathodic protection (CP) or as a result of insufficient baking after plating operations. This paper describes the mistaken, but long-held, belief that because rolled threads are beneficial for fatigue resistance, they are at best not injurious to the performance of bolting from other causes of failure such as environmental cracking.

Introduction
The process for manufacturing external threads on bars of steel and other alloys is accomplished typically by grinding, machine cutting, or rolling of the threads. Historically, the benefit of thread rolling on fatigue resistance of threaded fasteners has been demonstrated in practice and from laboratory testing. This benefit has become so second nature that most standards and practices recommend or simply expect that rolled threads will be applied to fasteners for fatigue resistance in service with no apparent downside. However, recent failures of bolting in many applications have highlighted the lack of understanding of and the disadvantages of rolled threads when environmental cracking is a factor and the risk of failure increases significantly compared with that of machined threads.

This paper presents an examination of the effect of rolled threads on the cracking susceptibility of bolting from hydrogen cracking as a result of plating operations and external sources of hydrogen such as CP. Only external threaded fasteners are considered in this paper.

The Benefit of Rolled Threads on Fatigue Resistance
The well-documented benefit of rolled threads on fatigue resistance is shown, for example, in **Fig. 1** (ASM 1990). As stated in the *ASM Handbook, Volume 1: Properties and Selection: Irons, Steels, and High-Performance Alloys* (ASM 1990), there is a marked improvement in fatigue strength of bolts when the threads are rolled after heat treatment compared with cut or ground threads. This was further confirmed by Ifergane et al. (2001), as well as others. These authors also reported the increase in hardness in the thread area of American Iron and Steel Institute (AISI) 4340 bolts compared with the core for threads rolled after heat treatment to be 468 Knoop hardness number (KHN) [45 hardness Rockwell C (HRC)] vs. 368 KHN (37 HRC), respectively. The machined threads only showed a 2-HRC increase in the thread area.

Because of this recognized benefit of rolled threads on fatigue resistance of bolts, many industry standards either explicitly or implicitly encourage the application of rolled threads after final heat treatment, thereby creating a significant hardness gradient from the threaded area into the core, where the specified hardness of bolts is measured. The standardized ignoring of the large hardness, and by correlation stress gradient, in the thread area is contradictory and detrimental to hydrogen-cracking resistance. By only considering the hardness of the core as sufficient to define the mechanical properties of bolting, the risk of environmental cracking is completely ignored.

Standards Used for Subsea and Other Bolting
There are many standards for bolting, studs, screws, and other bolting, all of which cannot be addressed in this paper. Instead, several selected standards dealing with subsea and structural fasteners are presented as examples of the widely accepted use of rolled threads for such fasteners, but without proper consideration for the risk of cracking in hydrogen-bearing environments.

***ASTM A193/A193M-15* (2015) and *ASTM A320/A320M-15* (2015).** These widely applied standards address heat treatment after thread rolling only for Grades B7M and L7M bolting, with the implication that all other grades of bolting can be thread rolled after heat treatment. There are no requirements for hardness measurement or control for rolled threads after heat treatment.

Subsea Bolting. Subsea bolting for petroleum and natural-gas operations are specified by *API RP 17A* (2002)/*ISO 13628-1* (1999) in accordance with various grades of *ASTM A193/A193M-15* (2015) or *ASTM A320/A320M-15* (2015) for carbon- and low-alloy steels and austenitic stainless steels. This standard also limits hardness for closure bolting to 35 HRC maximum for carbon- and low-alloy steels because of concerns for hydrogen embrittlement from the CP system. However, there is no mention of rolled threads, inferring that overall hardness measured in the bolt core is sufficient to comply with these standards.

Guidelines for subsea-bolting materials were recently suggested by DNV GL (2009), which limit the maximum hardness of many different alloys used for subsea bolting such as low-alloy steels, duplex stainless steels, precipitation-hardening nickel-based alloys, and titanium alloys. However, these guidelines do not recognize explicitly the risk of rolled threads and hydrogen cracking. In fact, there are several statements regarding the benefit of rolled threads that imply from a fatigue standpoint that rolled threads are desirable.

***ASTM F606/F606M-14a* (2014).** This standard addresses mechanical and hardness testing of all types of fasteners and for all alloy types such as steels, stainless steels, and nonferrous alloys. While this standard requires hardness testing, it does not consider the higher hardness expected in the threads of rolled-thread fasteners. It also expressly requires hardness testing on the unthreaded shank of bolts, thereby completely ignoring the significant difference in hardness between the threads and the bolt body.

The requirements of the preceding standards are summarized in **Table 1.** It is apparent from these few representative standards that thread rolling is not specifically addressed, nor is any requirement for hardness testing of the thread area after rolling. The use

Original SPE manuscript received for review 12 May 2015. Revised manuscript received for review 4 August 2015. Paper (SPE 178431) peer approved 19 August 2015.

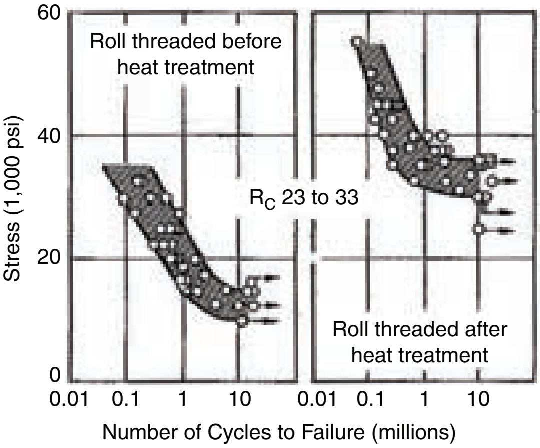

Fig. 1—The benefit of thread rolling after heat treatment compared with rolling before heat treatment for fatigue performance of steel fasteners.

of Rockwell C or Brinell hardness testing is inadequate to determine the hardness of rolled threads accurately, which can only be completely determined by use of low-load microhardness testing. Moreover, in most cases, these standards leave the question of thread rolling before or after heat treatment to the manufacturer. It is common practice to roll threads after heat treatment on steels, but more complicated for precipitation-hardening alloys, such as stainless steels and nickel-based alloys that are strengthened by this mechanism.

Standard Requirements for Stress Relief After Rolling and Baking After Plating. In addition to the preceding standards, other standards address threads for application in severe-service applications, such as H_2S environments, as *NACE MR0175/ISO 15156-2:2009* (2009) does for sour service. This standard states "Threads produced by cold forming (rolling) are acceptable in steels that otherwise comply with the heat treatment and hardness requirements of A.2.1.2," or in other words, not harder than 22 HRC, which implies the core of the stud with no hardness limit for the rolled threads. No requirement for stress relieving after rolling is specified.

Another important consideration is the pre- or post-plating baking of fasteners required by many industry standards. It is mistakenly assumed that this "bake out" completely removes the hydrogen absorbed during pickling and plating operations. Many of these standards require a minimum post-bake of 3 hours at 375°F (190°C) if the overall hardness of the fastener is equal to or greater than 40 HRC. *ASTM F1941*-10 (2007) only requires post-plate baking if the specified hardness (meaning the core hardness) of the bolting is 40 HRC or greater. The baking time and temperature can range from 2 to 24 hours and 350 to 450°F (177 to 232°C), respectively, on agreement between the purchaser and the manufacturer. As discussed in the following, this can be completely inadequate to eliminate the risk of cracking from hydrogen, and more significant yet, it does not consider the role of a hard layer produced by thread rolling.

ASTM B850-98 (2015) provides a range of post-coating thermal treatments on the basis of tensile strength and certain considerations for surface-hardened parts (but not specifically rolled threads). For example, the treatments range from 374 to 428°F (190 to 220°C) for a minimum of 12 to 22 hours for a range of tensile strengths of 1201 to 1800 MPa (174 to 261 ksi).

In a simplistic view of hydrogen absorbed into alloys (especially steels) during plating, the hydrogen diffuses to various traps, some of which are reversible and some of which are irreversible. The distribution of hydrogen in traps is nonuniform through the alloy, and it is the reversible hydrogen, which is mobile, that promotes crack initiation and propagation. This form of hydrogen cracking is often referred to as internal hydrogen embrittlement (IHE). Baking, or post-coating thermal treatment, changes this distribution and, depending on the thickness and type of plating applied, can allow hydrogen to egress easily or not. However, the benefit of this thermal treatment, even if the hydrogen is not significantly reduced in the alloy, is to more evenly distribute the hydrogen, thereby reducing the amount of mobile hydrogen available to initiate cracking.

Scully et al. (2004) studied the detrapping and egress of hydrogen in cadmium-plated steel as a function of temperature and time. They found that hydrogen trapped at reversible traps, such as carbides, could actually intensify with short baking times, but, after sufficiently long times at 374°F (190°C), would egress if no plating were present or if the plating was thin and porous. However, thicker plating inhibited the egress of hydrogen from the steel. Thus, the reality of post-plate baking is far more complicated than suggested by industry standards and not always effective in removing hydrogen to low enough levels to prevent IHE in service. Moreover, the work of Scully et al. (2004) was not performed on steels with rolled threads. The large amount of surface cold work imparted during rolling will generate significant dislocation densities because of the plastic deformation. Dislocations are known to be reversible traps that may or may not interfere with hydrogen egress during baking.

Stress State and Hardness Profile of Rolled vs. Machined Threads

As mentioned previously, Ifergane et al. (2001) presented the large increase in hardness in the thread area compared with the core of a bolt after thread rolling. These are typical outcomes of rolling; however, less well-documented is the corresponding residual stress distribution in the thread area and just below it in the core of the

Standard	Allowable Threading Processes	Threading Before or After Heat Treatment	Hardness Tests
ASTM A193 (2015), Grade B7	All	Not specifically stated, but implied after heat treatment	Rockwell C or Brinell per *ASTM F606* (2014) on the end of the bolt
ASTM A193 (2015), Grade B7M	All	Before heat treatment	Rockwell C or Brinell per *ASTM F606* (2014) on the end of the bolt
ASTM A320 (2015), Grade L7	All	Not specifically stated, but implied after heat treatment	Rockwell C or Brinell per *ASTM F606* (2014) on the end of the bolt
ASTM A320 (2015), Grade L7M	All	Before heat treatment	Rockwell C or Brinell per *ASTM F606* (2014) on the end of the bolt
ASTM A354 (2011)	Not specified	Option of the manufacturer	Rockwell C or Brinell per *ASTM F606* (2014) on the end of the bolt
ASTM F606 (2014)	All	Not specified	Rockwell C or Brinell on the shank or the end of the bolt

Table 1—Summary of American Society for Testing and Materials (ASTM) standards requirements.

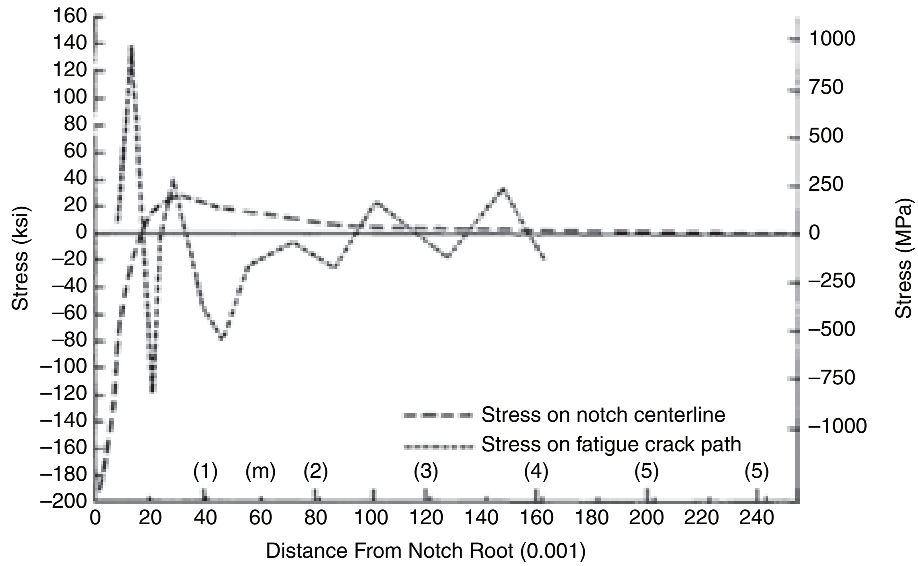

Fig. 2—Stresses below a rolled notch as a function of distance from the root.

bolt. The benefit of thread rolling on fatigue life is attributed to the compressive stresses imposed by the plastic deformation used to form the threads, which produce a notch (stress concentration).

For any system under stress at equilibrium, the stresses must be balanced. In other words, if there exists a large compressive stress, there must be a corresponding and equal tensile stress. Early work that used the slip-line theory and finite-element analysis (FEA) (Vassilaros 1980) demonstrated this stress pattern quantitatively for a rolled notch in INCONEL® alloy 718. **Fig. 2** shows the stress distribution from the notch, which is under considerable compressive stress at the root of the notch, and the rapid increase in stress to a tensile stress of 30 ksi at a distance of 0.030 in. below the notch root. Contrary to the results of Vassilaros (1980), Toribio et al. (1991) found by X-ray measurements that the residual stresses in the root of rolled bolt threads were all tension stresses in the axial direction and compressive in the circumferential direction.

Nițu et al. (2009) measured the Vickers microhardness of threads rolled onto carbon steel with a starting hardness of 2060 MPa [210 Vickers hardness (HV)], and when combined with FEA of the threads, determined the new yield strength corresponding to the higher hardness. Then, the von Mises equivalent residual stress in the thread area was determined when the threads were unloaded. **Fig. 3** shows the results of these investigations and the significant hardness, yield strength, and residual stress increase, especially on the thread flank from rolling. The highest stress and hardness were found in the thread flank because of the square-thread form used in this investigation. Other thread forms will develop regions of high hardness and strength that are slightly different, depending on the thread form, but the significant increases over the core hardness and strength will still appear.

It is apparent from the few papers cited here that thread rolling will increase hardness in the thread area with a corresponding increase in tensile stress beyond the expected compressive stresses that are touted as beneficial for fatigue resistance.

The Risk of HSC of Rolled Threads in Hydrogen Environments

The term HSC is used here to describe the several different mechanisms of cracking caused by hydrogen, but is further qualified in the following subsections on the basis of whether the hydrogen is internal, as a result of pickling and plating, or external from CP. Historically, industry at large has referred to cracking in hydrogen environments as hydrogen embrittlement, and while this is technically not correct, the term persists. HSC of alloys is a very complex subject that affects every industry and yet remains largely unpredictable except for some simple rules such as hardness and yield strength control to limit the risk of HSC. This section presents several examples of failures of bolting that resulted from hydrogen that was generated during plating operations before service or from CP in service, and the role that rolled threads played in these failures.

Structural Steel-Anchor Bolts/Rods. Recently, a number of anchor rods made from *ASTM 354*-11 (2011) Grade BD steel suffered catastrophic failure on the New Bay Bridge in San Francisco,

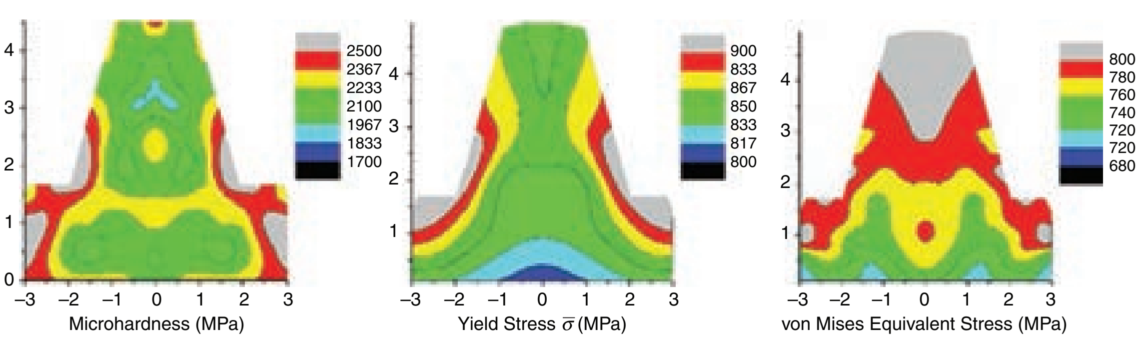

Fig. 3—Microhardness measurements (left), calculated new yield stresses (center), and residual stresses (right) resulting from thread rolling of a plain carbon steel. For comparison, 2500 MPa equals 256 HV.

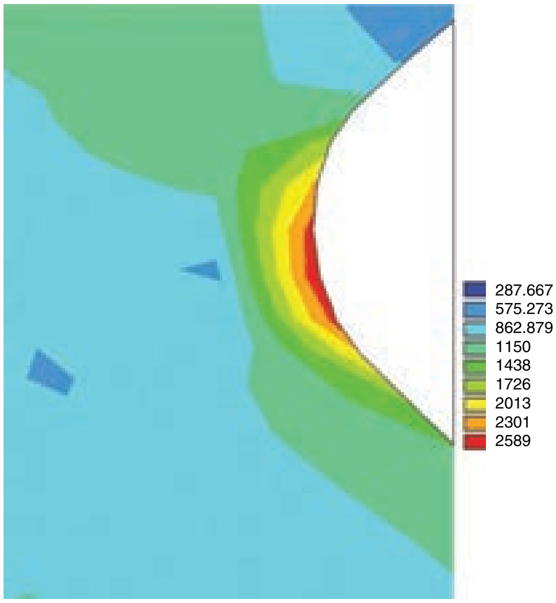

Fig. 4—Stress distribution in the root of a last engaged thread as determined by FEA. The stress values shown at right are in N/mm^2.

California (Chung 2014). The failures were attributed to HSC or, more specifically, hydrogen-environment embrittlement (HEE), a term used to differentiate cracking caused by exposure to the service environment in contrast to hydrogen that is present from manufacturing operations such as plating, which is termed IHE. The source of hydrogen in these failures was not identified clearly, although there was some CP in parts of the system and the bolts were hot-dipped galvanized, which could also introduce hydrogen into the steel (IHE). Whereas Chung (2014) speculated that there would be significant hardness increases in the threads as a result of thread rolling, no data were presented to support this view, although it is consistent with other data presented in this paper. On the contrary, another group of investigators strongly disputes that such an increase in hardness occurs in the area of the rolled threads and further indicates that rolled threads enhance the HSC resistance of bolts because of the residual compressive stresses created by thread rolling (Townsend 2015). Yet, as shown in **Fig. 4** and in Fig. 3, higher hardnesses are consistently measured in rolled threads, and as already discussed, the residual stresses in bolt threads are far from well-understood, but are most likely not simply residual compressive stresses. These latter authors did not report the microhardness data, which was considered too scattered, and relied instead on HRC, which is insufficient to discern and describe short-range changes in hardness. The short-range changes in hardness within the rolled area can be accurately measured with low-load microhardness measurements only (see, for example, Ifergane et al. 2001). These speculations and misconceptions around hardness and residual stress in rolled threads further emphasize the lack of understanding of this subject.

Subsea Bolting: CP and Plating Issues. Failures of subsea bolting are common in the offshore industry, but, because of the need for ever greater strength, the frequency of failures appears to be on the rise. Some examples of such failures that underscore the misunderstanding of global bolt-mechanical and -hardness properties and the risk of HSC from HEE and IHE are presented.

Wolfe and Joosten (1988) reported on HEE failures of Monel® alloy K-500 bolts in seawater as a result of exposure to CP. The failures occurred in bolts that had threads rolled after final heat treatment, resulting in a hardness of 39 HRC in the thread area vs. 35 HRC in the core. Subsequently, bolts were heat treated after thread rolling, but failures from HEE created by the CP system continued to occur. Thus, in a very severe-charging environment, HEE can still occur regardless of the material and processing.

Recent failures of Inconel® alloy 718 subsea bolting were attributed to excessive hardness in the thread area, as high as 500 HV (49 HRC), compared with the recommended hardness maximum for these bolts of 35 HRC (*Barracuda & Caratinga Leasing Company B.V v. Kellogg Brown & Root LLC*, Case 1:11-cv-07827-PGG 2011). Failure was attributed to HEE caused by hydrogen generated by the CP system. There was also some possible contribution from delta phase; however, this was inconclusive.

High-strength-steel bolts are also subject to failure in subsea applications as a result of IHE and HEE. For example, the Bureau of Safety and Environmental Enforcement (BSEE) issued a report concerning the failures of H4 connector bolts in the Gulf of Mexico that were manufactured from AISI 4340 low-alloy steel and zinc plated according to an outdated version of *ASTM B633, Standard Specification for Electrodeposited Coatings of Zinc on Iron and Steel*, which did not require post-plate baking (BSEE 2014). These bolts were manufactured to a minimum hardness of 34 HRC and a maximum of 38 HRC. The failed bolts did not receive a post-plate bake; however, the most current editions of *ASTM B633-13* (2013) require that bolts with hardness values greater than 31 HRC or a tensile strength greater than 1000 MPa (145 ksi) be both pre- and post-baked. The failures were attributed to IHE from hydrogen remaining in the bolts after plating, but contribution to failures from the CP system (HEE) could not be ruled out.

Stresses in Roll-Threaded Bolts Under Axial Tension

To this point, the discussion and consideration of roll threaded fasteners has dealt only with the increased hardness, strength, and residual stresses developed during thread rolling. Once these roll-threaded bolts are placed in service, they are stressed in tension under applied torque loads, and when not properly performed, may include bending stresses, as well. Therefore, the resulting stress distribution in bolts under stress is quite complex and beyond the scope of this paper. However, for discussion purposes, several important factors are considered to elucidate the addition of detrimental stresses added to those already in place in the thread area that will adversely impact cracking resistance in hydrogen-bearing environments.

Bolt tightening by use of torque control can be limited to general elastic deformation of the bolt or, in some applications with high-torque, intentionally stressed into the plastic region. Even in the case of elastic tightening, the thread roots are often stressed beyond the yield strength.

Threads by their very geometry create a stress concentration that also must be taken into account when considering the stress distribution of bolts. The stress-concentration factor is highest in the first engaged thread and decreases for successive threads, moving in the direction of the bolt end. For threaded-pipe connections, the last engaged thread is often the location of highest stress.

Hussain et al. (2008) analyzed the stress-concentration effect on stressed bolts by use of FEA. Fig. 4 shows their results for one thread form, with the expected highest stress in the thread root. In this example, the highest stress at the last engaged thread was 2589 N/mm^2 (376 ksi). When these stresses are superimposed on the high residual stresses from thread rolling, the risk of HSC is extremely high.

While there have been efforts to develop stress-intensity factors for threaded bolts with cracks at the thread root (Toribio 1992), these likely do not apply to roll-threaded bolts subjected to hydrogen environments. It is well-recognized that HSC initiates on a microstructural scale ahead of the crack tip, and then propagates both back toward the free surface and into the crack plane (Troiano 1960; Novak et al. 2010). This distance between the crack tip, or thread root here, and the initiating crack is referred to as the critical distance, which is still not theoretically understood. This behavior is certainly even truer for rolled threads because the location of tensile stresses may lie below the compressive layer, as suggested in Fig. 2.

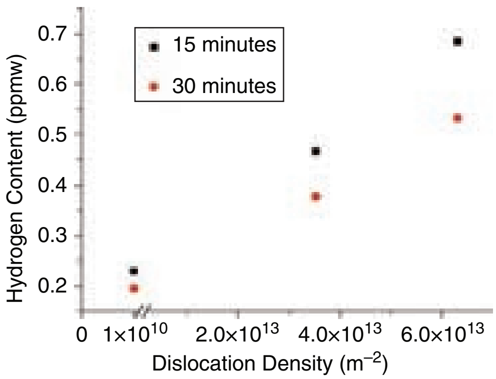

Fig. 5—Hydrogen solubility as a function of dislocation density in a ferritic steel. The values at 15 and 30 minutes represent the time delay before analysis of the hydrogen content.

Discussion

The long-held belief and resulting standardization of thread rolling after all thermal treatments of fasteners, while beneficial for fatigue resistance, is counterproductive to developing optimum resistance to hydrogen cracking in many service environments. Moreover, the common use of the shank and core hardness of fasteners to define their properties is misleading and risky, especially in environments where hydrogen is present or hydrogen is accumulated internally from plating. The severe cold work in the threads imparted by rolling will result in a significant increase in dislocation density in this region, producing a high trapping density for hydrogen atoms in and adjacent to the known location for crack initiation ahead of the thread root (notch). Enos and Scully (2002) demonstrated that for heavily cold-worked cold-drawn steel wires that also contain high dislocation densities, hydrogen trapped at dislocations required temperatures of 300 to 400°C to detrap the hydrogen. This, of course, means that current temperature requirements for baking out hydrogen from high-strength bolts, as described previously in the subsection Standard Requirements for Stress Relief After Rolling and Baking After Plating, would be insufficient to deplete the internal hydrogen.

As would be expected, the hydrogen solubility increases with increasing dislocation density, as shown by **Fig. 5** (Song 2015). The dislocation densities are even higher for quenched and tempered steels that have been highly cold worked, which would be more indicative of steel bolting. Takaki et al. (1992) measured the density to be as a high as 10^{16} m^{-2}. Thus, the layer of cold work from thread rolling can be characterized as one that is high in hardness; high in residual stress; and, because of the significant increase in dislocation density, high in mobile-hydrogen content that is available for crack initiation. Furthermore, for those bolts that are exposed to CP, the hydrogen diffusion and trapping will be highest in the region most prone to HEE at stresses most likely to initiate cracking, even though the core of the bolt may be resistant to HSC.

It can be concluded that rolled threads on bolts that are baked out according to current industry standards are done so at temperatures insufficient to remove hydrogen trapped in the cold-worked area of the threads, and more so for bolts that are not baked. Furthermore, the high hardness and yield strength in this area combined with high residual stresses from rolling superimposed on the applied axial stresses will easily promote HEE when exposed to subsea CP systems.

Conclusions

There is a serious lack of understanding regarding the state of stress in and adjacent to the hardened layer produced by thread rolling, which is further compounded and unknown when bolt-tightening stresses are applied. Additionally, the amount of hydrogen trapped in this region of the threads has not been measured, nor has the egress of hydrogen during thermal treatments after plating. Furthermore, the hydrogen-absorption characteristics of a compressed region overlaid with complex applied loads resulting from tensile loads and bending are completely unknown and have not been studied. Therefore, the widespread use of bolting and fasteners without regard for the service environment will continue to cause major failures until a more-informed and -deliberate approach to specifying bolt-manufacturing methods for specific service environments is adopted.

Recommendations

Serious and comprehensive studies need to be performed to define the stresses on rolled threads for heat-treatable alloys such as steels and age-hardenable nickel-based alloys and cold-worked alloys, such as austenitic stainless steels, even in the absence of applied loads. Additionally, these results should be further extended to include the effect of axial and bending loads on the stresses at rolled-thread roots. Finally, detailed hydrogen permeation and hydrogen concentrations should be determined for the complex stresses developed from thread rolling and the applied stresses during loading of bolts and fasteners. Simply assuming that compressive stresses generated by thread rolling are sufficient to deter HSC is overly simplistic and most certainly wrong.

References

API RP 17A, Recommended Practice for Design and Operation of Subsea Production Systems, third edition. 2002. Washington D.C.: American Petroleum Institute.

ASM. 1990. *ASM Handbook, Volume 1: Properties and Selection: Irons, Steels, and High-Performance Alloys*, p. 298. Materials Park, Ohio: ASM International.

ASTM A193/A193M-15, Standard Specification for Alloy-Steel and Stainless Steel Bolting for High Temperature or High Pressure Service and Other Special Purpose Applications. 2015. West Conshohocken, Pennsylvania: ASTM International. http://dx.doi.org/10.1520/A0193_A0193M-15.

ASTM A320/A320M-15, Standard Specification for Alloy-Steel and Stainless Steel Bolting for Low-Temperature Service. 2015. West Conshohocken, Pennsylvania: ASTM International. http://dx.doi.org/10.1520/A0320_A0320M-15.

ASTM 354-11, Standard Specification for Quenched and Tempered Alloy Steel Bolts, Studs, and Other Externally Threaded Fasteners. 2011. West Conshohocken, Pennsylvania: ASTM International. http://dx.doi.org/10.1520/A0354-11.

ASTM B633-13, Standard Specification for Electrodeposited Coatings of Zinc on Iron and Steel. 2013. West Conshohocken, Pennsylvania: ASTM International. http://dx.doi.org/10.1520/B0633.

ASTM B850-98(2015), Standard Guide for Post-Coating Treatments of Steel for Reducing the Risk of Hydrogen Embrittlement. 2015. West Conshohocken, Pennsylvania: ASTM International. http://dx.doi.org/10.1520/B0850-98R15.

ASTM F606/F606M-14a, Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, Direct Tension Indicators, and Rivets. 2014. West Conshohocken, Pennsylvania: ASTM International. http://dx.doi.org/10.1520/F0606_F0606M-14A.

ASTM F1941-10, Standard Specification for Electrodeposited Coatings on Threaded Fasteners [Unified Inch Screw Threads (UN/UNR)]. 2007. West Conshohocken, Pennsylvania: ASTM International. http://dx.doi.org/10.1520/F1941-10.

Barracuda & Caratinga Leasing Company B.V v. Kellogg Brown & Root LLC. 2011. Case 1:11-cv-07827-PGG, Doc. 3-3 (Filed 11/02/11) http://blog.internationalpractice.org/wp-content/uploads/2011/11/Petrobrasarbaward.pdf.

Bureau of Safety and Environmental Enforcement (BSEE). 2014. QC-FIT Evaluation of Connector and Bolt Failures Summary of Findings. QC-FIT Report #2014-01, BSEE, Washington D.C. (August 2014).

Chung, Y. 2014. Corrosion on the New Eastern Span of the San Francisco-Oakland Bay Bridge. *Materials Performance* **53** (11): 58–63.

DNV GL. 2009. JIP-Guideline for the Specification, Design and Installation of Fasteners for the Offshore Oil and Gas Industry. Energy Report No. 2008-1656/1201FBR-21, DNV GL, Oslo, Norway.

Enos, D. G. and Scully, J. R. 2002. A Critical-Strain Criterion for Hydrogen Embrittlement of Cold-Drawn, Ultrafine Pearlitic Steel. *Metallurgical and Materials Transactions A* **33** (4): 1151–1166. http://dx.doi.org/10.1007/s11661-002-0217-z.

Hussain, M. T. K., Samad, Z., Suhaib, S. et al. 2008. Analysis of Stress Concentration Factor in Bolted Joint Using Finite Element Method. *International Journal of Mechanical and Materials Engineering* **3** (1): 38–45.

Ifergane, S. Eliaz, N., Stern, N. et al. 2001. The Effect of Manufacturing Processes on the Fatigue Lifetime of aeronautical bolts. *Engineering Failure Analysis* **8** (3): 227–235. http://dx.doi.org/10.1016/S1350-6307(00)00013-3.

ISO 13628-1:1999, Petroleum and natural gas industries—Design and operation of subsea production systems—Part 1: General requirements and recommendations. 1999. Geneva, Switzerland: International Organization for Standardization.

NACE MR0175/ISO 15156-2:2009, Petroleum and natural gas industries—Materials for use in H_2S-containing environments in oil and gas production—Part 2: Cracking-resistant carbon and low alloy steels, and the use of cast irons. Technical Circular 2. 2009. Houston, Texas, USA: NACE International/ISO.

Nițu, E., Iordache, M., Martiny, M. et al. 2009. Evaluation of Microhardness, Effective Stress and Residual Stress in Cold Rolling of Complex Profiles—Comparison Between Experiments and Calculations. The Annals of Dunărea De Jos University of Galați, Romania. http://www.cmrs.ugal.ro/TMB/2009/l20.pdf.

Novak, P., Yuan, R., Somerday, B. P. et al. 2010. A Statistical, Physical-Based, Micro-Mechanical Model of Hydrogen-Induced Intergranular Fracture in Steel. *Journal of Mechanics and Physics of Solids* **58** (2): 206–226. http://dx.doi.org/10.1016/j.jmps.2009.10.005.

Scully, J. R., Dogan, H., Li, D. et al. 2004. Controlling Hydrogen Embrittlement in Ultra-High Strength Steels. Presented at Corrosion 2004, New Orleans, Louisiana, 28 March–1 April. NACE-04563. NACE International.

Song, E. J. 2015. *Hydrogen Desorption in Steels*. PhD dissertation, Graduate Institute of Ferrous Technology, Pohang University of Science and Technology.

Takaki, S., Iizuka, S., Tomimura, K. et al. 1992. Influence of Cold Working on Recovery and Recrystallization of Lath Martensite in 0.2%C Steel. *Materials Transactions, JIM* **33** (6): 577–584. http://doi.org/10.2320/matertrans1989.33.577.

Toribio, J. 1992. Effect of Crack Shape and Loading Conditions on the Stress Intensity Factor for a Cracked Bolt. *OMAE* **III-B:** 363.

Toribio, J., Campos, J. M., and Sanchez-Galvez, V. 1991. X-Ray Measurement of Residual Stresses in a Rolled Bolt: Application to the Calculation of Stress Intensity Factors after Cracking. *Journal of Strain Analysis for Engineering Design* **26** (2): 103–109. http://dx.doi.org/10.1243/03093247V262103.

Townsend, H. 2015. More on the San Francisco-Oakland Bay Bridge. *The MP Blog* **54** (2): 8.

Troiano, A. R. 1960. The Role of Hydrogen and Other Interstitials in the Mechanical Behavior of Metals. *Transactions of the ASM* **52:** 54–80.

Vassilaros, M. G. 1980. Analysis of Residual Stresses Resulting From Cold Rolling of Notches and Their Effect on Fatigue Behavior. Report No. AD A089110, David W. Taylor Naval Ship Research and Development Center, Bethesda, Maryland, USA (11 September 1980).

Wolfe, L. H. and Joosten, M. W. 1988. Failures of Nickel/Copper Bolts in Subsea Applications. *SPE Prod Eng* **3** (3): 382–386. SPE-16632-PA. http://dx.doi.org/10.2118/16632-PA.

Bruce Craig is a subject-matter expert at Stress Engineering Services, and is also the senior research fellow at the Institute for Corrosion and Multiphase Technology at Ohio University. He has been involved with the evaluation of corrosive wells and the selection of alloys for these wells in addition to all the facilities metallurgy for projects ranging from Mobile Bay to the deepwater Gulf of Mexico and from the Rocky Mountains to Asia and the Middle East for more than 35 years. Craig has consulted on the completion of numerous high-pressure/high-temperature (HP/HT) and ultra-HP/HT wells and has been actively involved in research on the sulfide stress cracking and stress-corrosion cracking of alloys for sour-gas wells. He is the author of more than seven books and 95 papers. Craig holds BS, MS, and PhD degrees in metallurgical engineering from the Colorado School of Mines. He is a member of SPE and ASM International (American Society for Metals), and is a fellow of NACE International (National Association of Corrosion Engineers). Craig is also a registered professional engineer in Colorado.