Identifying and Avoiding Hydrogen Embrittlement Failures in Bolts

Tech Brief 140201 F

Integrated Systems Research, Inc.

February, 2014

steve.carmichael@isrtechnical.com

Abstract:

Two types of hydrogen embrittlement can occur in high strength alloys. The first type is referred to as *hydrogen environment assisted cracking* (HEAC) and the second is *internal hydrogen assisted cracking* (IHAC). High strength bolts under significant preload can exhibit both types of failures.

This tech brief identifies the difference between the two mechanisms and how they can be linked to the process zone of the stress concentration in the component. The relationship between the crack front K field and the stress concentration process zone, where HEAC and IHAC initiate, is discussed.

Since high strength bolts can be susceptible to these types of failures, a brief discussion on an overall design strategy of bolted joints is also undertaken.

Mechanism for Hydrogen Embrittlement

Hydrogen environment assisted cracking (HEAC) is a cathodic reaction while *internal hydrogen assisted cracking* (IHAC) is a migration of dissolved hydrogen already present in the alloy to regions of high tensile stress concentration. The difference between them is the source of the hydrogen, internal or external and whether the concentration of hydrogen is created by a chemical reaction or migration of dissolved hydrogen already present in the alloy.

Hydrogen, being small relative to atoms that constitute metallic alloys, can fit within interstitial sites and grain boundaries. This relative size difference enables the diffusion of hydrogen in metals even at room temperature.

The actual mechanism that reduces the fracture toughness and creates the embrittlement is subject to debate. The current prevailing opinion, however, is that hydrogen entrapped within the metallic alloys reduce the strength of the covalent bounds resulting in the reduction of fracture toughness and promoting subcritical crack growth.

The migration or absorption of hydrogen to sites of high stress concentration is likely due to the crystal lattice expansion in the process zone of the notch or crack front. The expansion of the lattice structure facilitates the diffusion of hydrogen into these local sites. The hydrogen concentration at these sites can be orders of magnitude greater than the bulk concentration in the metallic component.[1]

Without the high tri-axial stress state present in the process zone the amount of hydrogen absorbed into a metallic component tends to be negligible. In the presence of water vapor, hydrogen gas or electrolyte and a high tri-axial stress state, however, a cathodic reaction can occur as hydrogen is absorbed into the dilated lattice structure. This type of embrittlement is considered environmentally assisted since the reaction is driven by a source of hydrogen outside the component (HEAC).

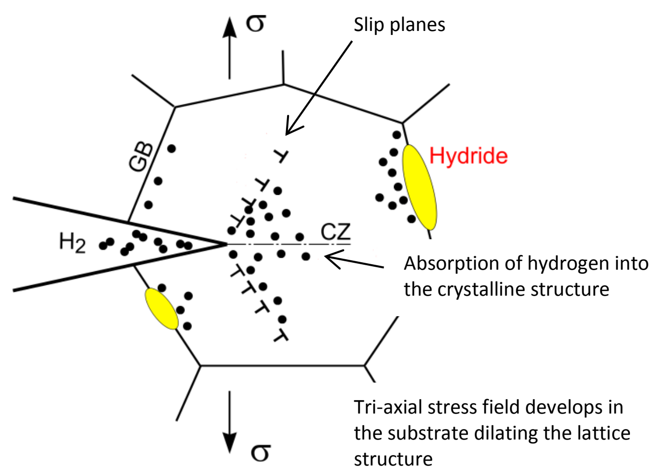

Figure 1 – HEAC Mechanism

In contrast to HEAC, stress corrosion cracking (SCC) is an anodic process. In this case the various elements and compounds present in the alloy dictate which electrochemical reaction occurs. Both SCC and hydrogen embrittlement (HE) can be transgranular or intergranular. One common example of intergranular SCC is seen in austenitic stainless steels where carbide formation depletes the chromium adjacent to the grain boundaries during welding. The chromium depleted zone is anodic to the unaffected grains. This type of corrosion tends to show itself in a network or web of cracks developed along grain boundaries.

[1] Fracture Mechanics, Fundamentals and Applications 3rd Edition, T.L. Anderson, CRC, 2005, p. 531

The Process Zone and Hydrogen Embrittlement

The crystalline lattice expansion, promoting the absorption or migration of hydrogen in a metallic alloy, is due to the hydrostatic stress present just below the surface of the crack front or notch.

The level of crystalline dilation, produced by the hydrostatic stress, is controlled primarily by the yield or flow strength of the alloy. Once the stress field has reached this value the load begins to be shed to other regions of the path. There is a large body of evidence that indicates the threshold HEAC stress intensity for martensitic low-alloy steels drops as a function of increase in yield strength. This behavior is pronounced below a yield strength of 200 ksi.[2] For low-alloy martensitic steels a yield strength of 200 ksi typically corresponds to a hardness above 36 HRC.

Figure 2 shows the effective stress field at the transition region between the head and shank of a 12 point bolt. The dual lobe stress field associated with a crack propagating in Mode I can be seen at the re-entrant corner.

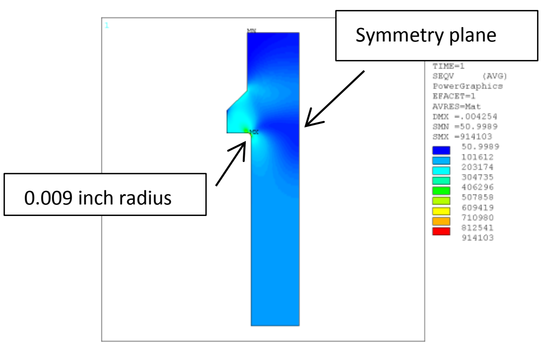

Figure 2 – 0.25 Inch 12 Pt Bolt

For plane strain conditions the plastic zone at the front of the notch transition can be estimated by the equation below:

$$r_{o\varepsilon} = \frac{1}{6\pi}\left(\frac{K}{\sigma_y}\right)^2 \qquad \textbf{Equation 1}$$

Where ***K*** is the level of the stress intensity field in front of the notch. The stress intensity is estimated from equation 2.

[2] Reference Figure 3

$$K = \left(\frac{k_t - 1}{2}\right)\sigma\sqrt{\pi r} \qquad \textbf{Equation 2}$$

Where k_t is the elastic stress concentration of the reentrant corner and r is the notch radius.

The elastic stress concentration for this reentrant corner is 9.4. Table 1 provides the estimated K field as a function of bolt strength. The bolt is assumed to be preloaded to 80 percent of proof stress based on the tensile net section of the threads. The plane strain plastic zone, associated with the reentrant corner notch, is estimated to be 0.0095 inches.

Table 1 – Effective Bolt Head to Shank K Field

Effective K Field at Reentrant Corner - 0.25 Inch 12 Pt Bolt			
ASTM Grade	**Proof Strength**	**Nominal Shank Stress**	**K**
	ksi	**ksi**	**ksi-in$^{0.50}$**
A325	85	50	36
A354	120	71	50
A574	140	83	59

Figure 3 provides a plot of the cross over between the threshold HEAC of low alloy steels in a 3.5% NaCl solution and the K field associated with the stress concentration at the head/shank bolt transition as a function of yield strength.

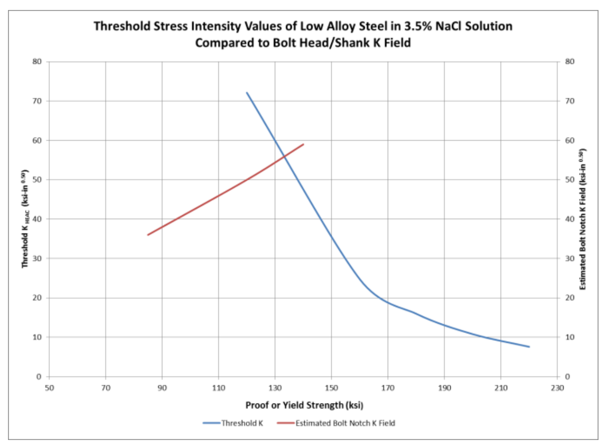

Figure 3[3]

The chart above shows that increasing the strength of the bolt is not a productive approach in addressing hydrogen embrittlement. A much more

[3] Threshold data curve fit from Corrosion Prevention and Control, 33rd Sagamore Army Materials Research Conference, 1986, Gangloff

useful strategy is to improve the joint efficiency so that a lower strength bolt can be employed. This is typically accomplished by improving the line of action of the applied joint load relative to the clamping action of the bolts or increasing the size and/or number of the bolts.

The stress state in the notch process zone is governed by a tri-axial stress field just below the surface. The stress tensor is the combination of a mean and deviator tensor. The deviator tensor is a measure of the distortion that the stress state creates from a spherically symmetric state. This behavior is primarily responsible for producing material flow and accumulating damage on shear planes. The mean tensor on the other hand does not distort the atomic lattice structure but dilates it.

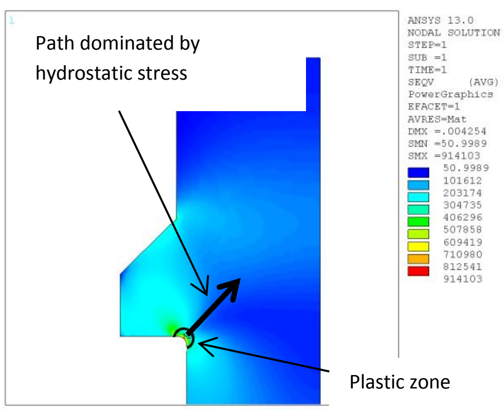

Figure 4 – Process Zone at Notch

Figure 5 provides the principal stresses along the path normal to the reentrant corner as shown in the figure above.

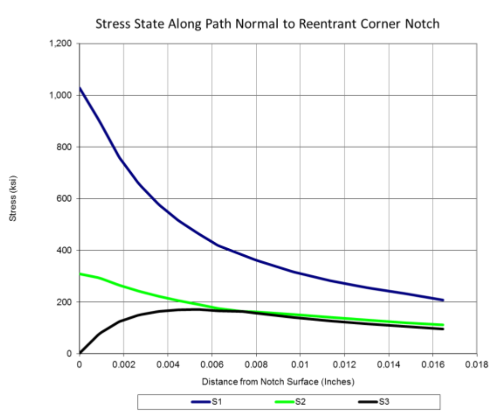

Figure 5

At the notch surface a bi-axial stress state occurs due to the free surface. Approximately 0.007 inches into the corner S_2 and S_3 become equal in magnitude and sign creating a tri-axial state with significant hydrostatic or mean stress. The hydrostatic stress in this case is greater than the octahedral stress which is responsible for creating material flow in the region.

The effective or octahedral stress along with the hydrostatic stress is shown in Figure 6.

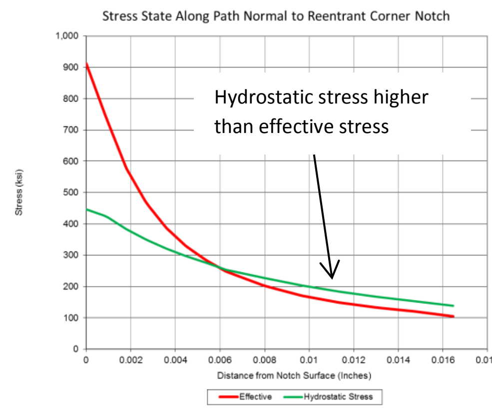

Figure 6[4]

The concentration of hydrogen in these regions can be orders of magnitude higher than the overall alloy as a whole.

Typically, a bolt experiencing HE will fail within 24 hours of installation. The failure is due to the reduction of fracture toughness as a function of time as the hydrogen migrates within the alloy or is absorbed into the stress concentration sites. For bolts the fracture will occur at either the first thread above the nut engagement or at the transition between the head and shank. Figure 7 is an example of such a failure between the shank and bolt head. The fracture surface has a relatively smooth surface associated with a brittle failure rather than one with peaks and valleys which is a surface texture associated with a ductile rupture. The cupping seen in the picture is due to the plane stress condition that occurs at the free surface.

[4] Stress field is based on the preload being 80% of the yield in the thread tensile net section. The yield strength in this case is 200 ksi.

Figure 7

Considerations for Bolted Joint Design:

Good joint design practice minimizes the bolt strength required to meet the functional objectives. Other than bolt strength, there are several other design parameters engineers have at their disposal in optimizing a bolted connection. They are: minimizing the line of action between the bolts and where the external load is introduced into the joint, the number and size of bolts, and the joint geometry. Reference [Optimizing Bolted Joint Geometry for Fatigue Resistance]

Often high strength bolts are plated to avoid stress corrosion cracking. Ironically, this practice can facilitate the possibility of hydrogen embrittlement. It is not the electro-plating itself but the acids used to clean the fastener prior to plating that creates the condition of entrapped hydrogen. If electro-plating is considered necessary, the hardness of a high-strength low alloy steel bolt should not exceed 36 HRC. If socket head cap screws are employed (metric grade 12.9) and plating is considered necessary the parts must be baked at 375 to 400 F within an hour after plating for at least four hours.

Conclusions:

The fracture toughness of high strength alloys can quickly be reduced by the cathodic reaction of hydrogen absorption or migration to areas of concentrated tensile stress.

Addressing this potential failure mechanism requires minimizing the stress concentration in load transitions, minimizing the strength requirements to meet design objectives and ensuring that manufacturing processing does not provide a source of hydrogen enrichment. The higher the alloy strength the greater the propensity for the absorption or migration of hydrogen to sites of stress concentrations. Care should be exercised in specifying high strength martensitic low-alloy bolts in hydrogen rich environments. It is good practice for fasteners in these applications to have a hardness less than 36 HRC. Optimizing structural load paths can go a long way in addressing this potential failure issue by allowing lower strength alloys to be employed while at the same time meeting design life requirements.