The stronger the better is not necessarily the case for fasteners

By Bill Eccles, Bolt Science

Have you ever come across a situation in which a high strength, plated fastener has failed in a brittle manner? Hydrogen induced cracking of plated high strength fasteners is relatively common.

It is also common for the blame to be attached to some fault in the manufacturing process rather than the service environment in which the fastener is placed. Rather than a manufacturing flaw it could be due to the choice of the type of fastener, coupled with the service environment in which the fastener is placed, that is the root cause of the failure. This is not widely recognised.

Many fastener users, crudely put, think that 'stronger is better'. The thinking is that structural failure can be catastrophic not only in terms of material/replacement costs but also the indirect costs related to the loss of company reputation. By using a higher strength fastener, the assumption is that the risk of such a failure occurring will be reduced. But in regard to fasteners, given the adverse effect that hydrogen can have on high strength fasteners, stronger is often certainly not better.

With fasteners, brittle type failures can be especially troublesome since they can occur unexpectedly giving no warning. The most common type of brittle fracture in fasteners is due to the poisonous effects that hydrogen can have on the strength of some steels. The deleterious effect that hydrogen can have on steel was first reported in a paper to the Royal Society in 1875 by W. H. Johnson. Since that time the topic has been studied extensively but is still the subject of research and controversy.

Hydrogen induced cracking, commonly referred to as hydrogen embrittlement, can occur to high strength steels and certain other metals such as titanium and certain stainless steels. Atomic hydrogen can enter the material during the production process or during its service life (as a result of corrosion or hydrogen in the atmosphere) causing a catastrophic brittle fracture. This occurs at a stress level well below the yield strength of the fastener. Figure 1 shows a M10 electroplated 12.9 socket head cap screw cracked under the head due to embrittlement. One of the characteristics of hydrogen embrittlement is that it may only affect a small proportion of a batch of fasteners.

This reduction of load carrying ability does not happen immediately the hydrogen enters the steel. Once atomic hydrogen is introduced at the surface of the part, there is a migration of the hydrogen over time to the grain boundaries, flaws and inclusions in the material. The effect of the hydrogen is to cause a reduction in the defect formation energy and a decrease in the inter-atomic bonding energy. Atomic hydrogen can also bind together to form hydrogen gas (H_2) whose pressure build-up at a crack tip can also have a deleterious effect. By these mechanisms a normally ductile material can behave in a brittle manner.

Figure 1: M10 electroplated 12.9 screw cracked under the head

With the fastener under stress (which usually means once it is tightened), cracks are initiated once the local concentration of hydrogen, at a particular defect, exceeds some critical value.

Brittle fracture of fasteners that have been exposed to hydrogen during the manufacturing process can occur, typically, between 1 and 24 hours following tightening. If a fastener fails in a brittle manner in some period following the first day subsequent to tightening, there is an increasing likelihood that the hydrogen was introduced into the steel from the environment rather than during the manufacturing process.

Essentially for a fastener to be affected by a brittle fracture due to hydrogen, there must be three factors present:

1) The fastener must have been introduced to hydrogen.
2) The material must be susceptible - generally the higher the tensile strength/hardness of the fastener, the greater is the risk from this type of brittle fracture.
3) The fastener must be subjected to a high tensile stress. The stresses imposed into the fastener by the tightening process are usually sufficiently high given the other two factors being true.

The Venn diagram shown in Figure 2 illustrates the interaction of these three factors.

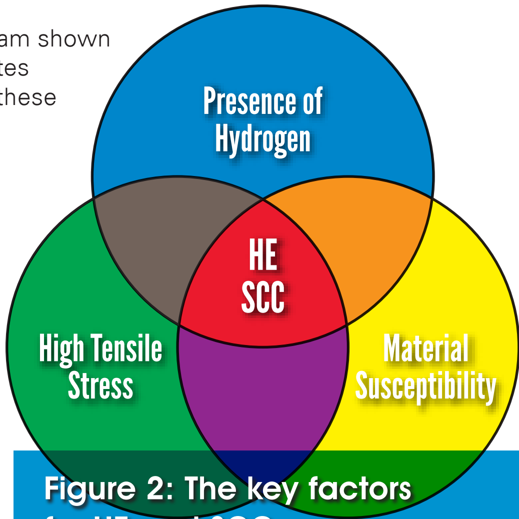

Figure 2: The key factors for HE and SCC

There are many ways that hydrogen can be introduced into the steel during the manufacturing process. The most common means is during the electroplating process. It can also be introduced from pickling, gas carburising, heat treatment and also during thread rolling, machining, and drilling due to the break-down of lubricants.

In many instances with fasteners the source of hydrogen contamination comes from the electroplating process. It is somewhat rare for non-electroplated fasteners to fail as a result of hydrogen embrittlement. On high strength electroplated fasteners, in order to reduce the risk of hydrogen embrittlement, a heat treatment operation immediately following plating can be performed. (This type of heat treatment is frequently referred to as baking.) The relevant standard giving guidance on the topic is ISO 4042 (Fasteners electroplated coatings). When high tensile fasteners are electroplated (property classes 10.9 and 12.9), a heat treatment operation is required within four hours of plating. Essentially the sooner the baking is completed following plating the better is the efficacy of the treatment. ▶

Typically the heat treatment involves holding the fasteners at a temperature of between 200°C to 230°C for between 2 hours - 24 hours. Again, in broad terms, longer is better. If the baking operation is delayed greater than four hours after plating, irreparable damage (micro-cracking) to the fastener may have already occurred. (Localised residual stresses may be present in the fastener causing hydrogen to migrate to high stress areas).

The purpose of the baking process is to remove as much hydrogen as possible and distribute any remaining hydrogen away from the surface. The surface of a fastener is usually highly stressed due to stress concentration effects. Research indicates that it is the local concentration of hydrogen that can be critical rather than the total content. The baking process facilitates the movement of the hydrogen within the steel so that it can become bonded within the steel structure at 'traps' such as inclusions. In such traps, hydrogen is not free to migrate to the high stress areas. Baking, if done properly, significantly reduces the risk of hydrogen embrittlement but will not fully eliminate the risk. To quote from the ISO 4042 standard: "Complete elimination of hydrogen embrittlement cannot be assured."

To assess the efficacy of the baking, the ISO 4042 standard specifies that when the core or surface hardness is above 320HV (applicable to 10.9 and 12.9 fasteners), an investigation is to be conducted using a test to detect hydrogen embrittlement. One such test is ISO 15330 (Fasteners - preloading test for the detection of hydrogen embrittlement) which involves tightening the fasteners close to or at yield for 48 hours. To pass the test there should be no breakage or visible cracks. The standard also states that for fasteners of hardness in excess of 365HV (property class 12.9 and 10.9 fasteners which are at the higher end of their permitted hardness range), a written agreement should exist between the customer and the manufacturer to define how to manage the risk of hydrogen embrittlement. If no such agreement exists then recommended practices should be followed to reduce the risk.

Once the product/fastener is in service, hydrogen can be introduced into the steel as a result of cathodic protection or corrosion reactions. The brittle failure of steel, as a result of the introduction of hydrogen from the environment subsequent to assembly, is commonly referred to as stress corrosion cracking (SCC).

There is often no difference in the features between HE due to the hydrogen being introduced during the manufacturing process and that due to hydrogen being introduced in a service environment. With HE, the fastener made from a susceptible material is first exposed to hydrogen followed by stressing (due to tightening) which leads to a delayed brittle fracture. With SCC the fastener that is made from a susceptible material is tightened and then exposed to hydrogen, which subsequently leads to a brittle fracture. Differentiating between HE and SCC is problematic and is not a trivial matter. Usually the time from tightening to brittle fracture occurring is a crucial indicator. If failure occurs shortly after tightening HE is the likely cause. If it occurs a significant period following tightening, SCC must be suspected. There is a transitional zone in which it could be either. This is not just of academic interest. If it is HE then the fastener supplier is often held to be responsible for supplying a defective part. If it's SCC, it can be argued that the customer has selected an inappropriate fastener type/finish for the application. When a fastener fails, the cost of the actual fastener is usually insignificant relative to the overall cost of the failure.

Although the alloy content and microstructure has some effect on the susceptibility of steel to hydrogen embrittlement, it has been found that the strength level (hardness) is the key factor. In general, the higher the strength of the steel, the greater is the susceptibility to hydrogen embrittlement. The chart shown in Figure 3 summarises the experience of the susceptibility of common fastener strength grades to HE. As a footnote, in some special circumstances, (for example in subsea applications in which cathodic protection is used) fasteners of hardness greater than 34 HRC are susceptible to hydrogen induced brittle fracture.

Property class 10.9 fasteners can experience hydrogen induced cracking. Frequently these issues result from an uneven hardness across the fastener cross section with the surface carburised.

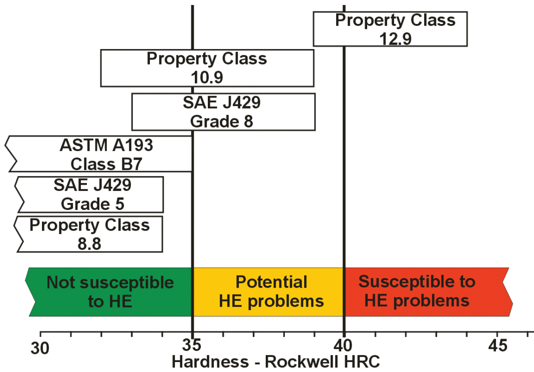

Figure 3: Common bolting materials and their susceptibility to hydrogen embrittlement

In conclusion:

- Hydrogen embrittlement, is to some degree, unpredictable and it is sensible to, whenever possible, specify fasteners that are, to a large degree, inherently less prone to this type of failure. Experience indicates that if property class 12.9 fasteners are electroplated, measures can be taken to reduce, but not fully eliminate, the risk from hydrogen embrittlement. In some applications, the consequences of joint failure as a result of brittle fracture are such that a campaign change to replace all potentially defective fasteners from a product is deemed essential even when the failure rate is very low. Usually the extent of the problem is unknown when a decision needs to be taken whether to replace the fasteners. It may be possible to identify a batch of fasteners affected and reduce the extent of the campaign but this can often be problematic. Typically, the cost of the fasteners is minimal compared to the other costs involved in such a campaign. Considering that there are other valid options available, high strength fasteners (10.9 and 12.9) should not be electroplated. Where a fastener user specifies such a product it is crucial they recognise that it is not, and cannot be, risk free.
- For most applications, property class 10.9 fasteners gives the best compromise between strength and brittle fracture risk. If you are a fastener manufacturer, consider limiting the core hardness of property class 10.9 fasteners to HRC 36 (the permitted range in the standard is HRC 33 to HRC 39) to further reduce the risk of brittle fracture.
- On 10.9 fasteners use zinc flake type coatings (Geomet, Delta Protekt, etc) or mechanical zinc plating instead of electroplating.

In my experience 12.9 socket head cap screws are frequently used in the UK particularly, not because such strength is needed in the application, but because 8.8 or 10.9 socket head cap screws are not readily available. The 12.9 fasteners are then tightened to a torque value applicable for an 8.8 fastener. There is no technical advantage in using a property class 12.9 fastener when it is tightened to a level that a lower strength fastener could sustain. (For example the fatigue endurance strength of a typical 12.9 fastener is the same as that for a 10.9 or an 8.8 fastener.) Hence, using a 12.9 fastener and tightening it to a torque value suitable for an 8.8 fastener does not reduce the risk of failure when compared to using an 8.8 fastener. A property class 12.9 is susceptible to HE and SCC problems given the right conditions. This risk is not widely appreciated by users of fasteners.

Stronger fasteners are certainly not necessarily better in some circumstances. ■

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