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Stress Corrosion Cracking of Rock Bolts

P Gray[1]

ABSTRACT

This paper outlines the mechanism of Stress Corrosion Cracking (SCC) and how it can cause premature failure of rock bolts. SCC occurs due to the progressive development and growth of cracks in the surface of a metal, and it is caused by the combined effects of stress and a corrosive environment affecting susceptible metals and alloys. It can occur in most metals including stainless steel. It is not a new phenomenon, but its effect on rock bolts has only been recognised recently.

Rock bolt failures caused by SCC appear to be brittle failures which occur at less than the ultimate tensile strength of the bolt. In the mining industry, SCC failures of rock bolts can occur a few months, or after many years of exposure to stress and a corrosive environment. If SCC of rock bolts is suspected, then the rock bolts should be examined by a metallurgist, and steps should be taken to reduce the problem.

Considerable research in the past has shown that SCC is a complex phenomenon and no one mechanism can explain all cases of SCC failures. It is therefore unrealistic to expect research to find a complete solution to SCC failures of rock bolts, but simple measures can be taken immediately to reduce or minimise the SCC problem. These measures include:

- to ensure that rock bolts are fully encapsulated with resin; and,
- to use rock bolts that are less susceptible to SCC.

Background

Rock bolts were used for the first time in the underground coal industry in Australia in the late 1940's at BHP's Elrington Colliery, near Cessnock in NSW. Today, rock bolts are in widespread use throughout the underground mining industry, as well as being used in the civil engineering and tunnelling industries. Rock bolts have played a major part in the improvement of roof conditions for the Australian mining industry, and hence have improved productivity and efficiency.

Nevertheless rock bolts are used in the harsh mining environment where there are often difficult ground conditions, and rock bolts can be subjected to high stresses, and sometimes also with corrosive groundwater conditions. When the stresses on the rock bolt exceeds the strength of the bolt, then rock bolt failure does occur.

Rock bolt failure can occur either by tensile failure, or by shear failure, or by failure of the bolt anchor system (resin or mechanical anchor). Geotechnical engineers attempt to minimise rock bolt failures by increasing the number and the capacity of the bolting systems used, and by optimising the mining stress conditions (by changing pillar size, mining direction etc). However, failure of rock bolts is something which does occur in the mining industry.

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Stress Corrosion Cracking

Some mines have reported unusual rock bolt failures. These rock bolt failures appear to be brittle failure of the bolt, which occurs at less than the ultimate tensile strength of the bolt. BHP have examined these failed bolts and the failure mode has been identified as "Stress Corrosion Cracking".

Stress Corrosion Cracking (SCC) is a progressive fracture mechanism which can occur in virtually all metals. It was first identified by the British Army in India in the late 19th century when cracks appeared in brass cartridge cases from ammunition. The cartridge case developed high tensile hoop stresses when the bullet was inserted and this combined with high temperatures, high humidity and traces of ammonia in the air, caused SCC to occur. SCC has also been found in Bronze Age swords, and it is therefore not a new phenomenon, but its effect on rock bolts has only been recognised recently.

SCC occurs due to the development and growth of cracks caused by the combined effects of stress and environmental conditions affecting susceptible metals and alloys. A sustained tensile stress and a corrosive environment (not necessarily acidic) can cause the development of small cracks which propagate into the susceptible metal (in this case a rock bolt). These small cracks initiate tensile failure which can be sudden and unpredictable.

In the mining industry, SCC failure of rock bolts can occur a few months or after many years of exposure to stress and a corrosive environment.

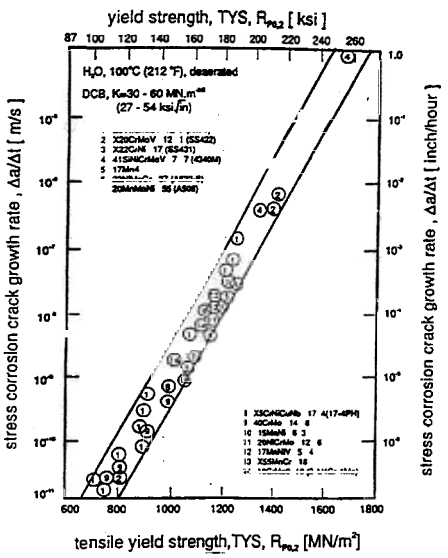

Fig. 1 - SCC growth rate vs tensile strength for high strength steels (after Atrens & Wang, Ref.1)

SCC is a complex phenomenon and no one mechanism can explain all cases of SCC failures, but it is known to occur in many metals and alloys including Aluminium, Titanium, Brass, Steel and Stainless Steel (see Figure 2).

Fig. 2 - A polished and etched metallographic cross section showing typical transgranular SCC in stainless steel

One form of SCC is often called Hydrogen Embrittlement (HE). When high strength steels are stressed and are also exposed to environments that release hydrogen, HE cracking can occur. Cross Section (Figure 2) see cracks in Stainless Steel.

Figure 1 indicates that SCC can occur in a wide range of steel types (after Atrens, Ref.1). However, Figure 1 also shows that higher strength steels are generally more susceptible to SCC than lower strength steels. It can be seen that the crack growth rate is approximately 10^{-6} m/sec for steels with an ultimate tensile strength (UTS) of 1400 MPa, compared to a crack growth rate of only 10^{-11} m/sec for steels with a UTS of 600 MPa (Ref 1).

Nevertheless, SCC only occurs within a narrow band of conditions involving the stress, the environment (the corrosive conditions), and the susceptible alloy.

Stress corrosion cracking failures of rock bolts

An SCC failure of a rock bolt typically appears to be a brittle failure. An SCC failure surface is normally a fracture plane at right angles to the axis of the bolt (the direction of the axial force), and there is no necking of bolt adjacent to the fracture surface. The fracture surface is frequently located at the end of the exposed free length of the bolt immediately below the resin encapsulation.

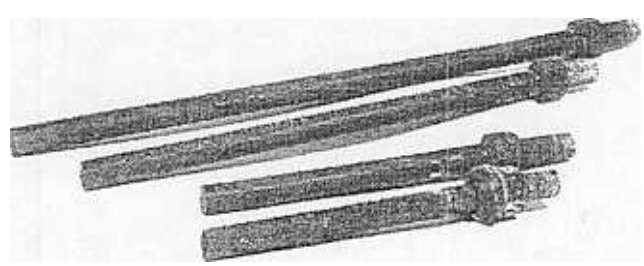

Fig. 3 - Typical SCC rock bolt failures

The surface condition of the bolt often does not show significant surface corrosion, and the end bearing plate commonly indicates that the maximum axial force on the bolt was less than the yield strength of the bolt.

A typical SCC failure of a rock bolt is shown in Figure 3.

Detailed investigation of SCC failures using Magnetic Particle Impregnation (MPI) techniques reveals that many small SCC cracks develop in the bolt adjacent to the ultimate fracture surface. These small cracks frequently develop at the base of the rib profile where there is a sharp change in angle on the longitudinal section of the bolt, and this creates a "stress raiser" in the bolt (see Figure 4).

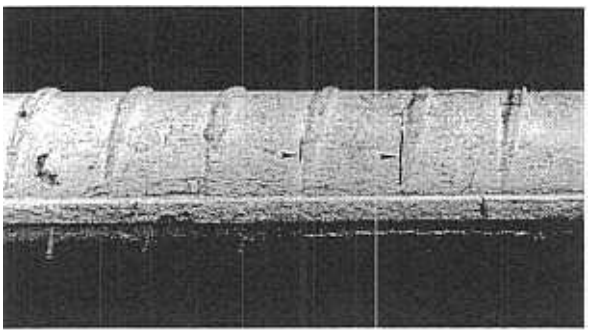

Fig. 4 - SCC at the base of the ribs on a rock bolt

SCC cracks are usually less than 1mm deep, and are dendritic in section (see Figure 5). The crack which initiates SCC failure can be located by the fracture lines which radiate out from it as shown in Figure 6, and this crack is less than 1mm deep.

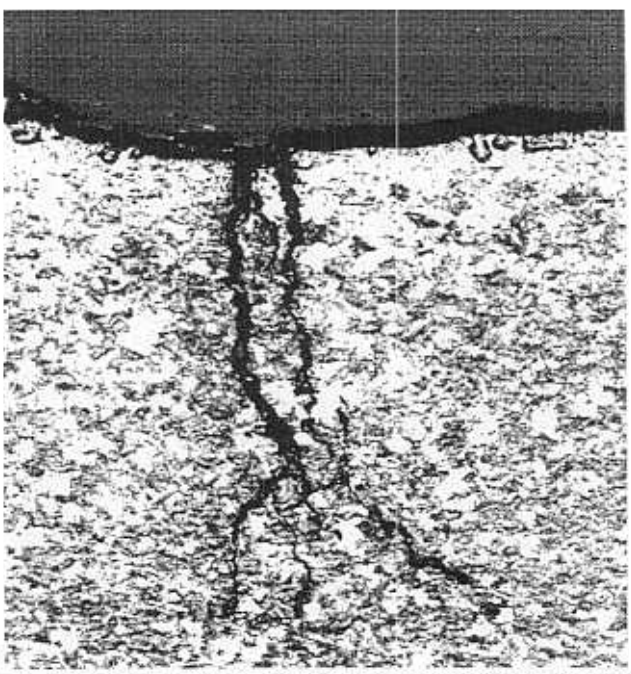

Fig. 5 - Dendritic nature of SCC at the base of the rib profile

SCC bolt failures have occurred in mines with "wet" roof conditions, ie where water has been dripping from the roof, and in mines where the roof conditions appear relatively dry.

Observed SCC bolt failures have occurred in mines between approximately 12 months and 24 months from the time of installation.

Fig. 6 - Fracture face of an SCC failure. Arrow shows the crack which initiated failure

SCC bolt failures are not restricted to one particular steel grade or one steel supplier, but have only been observed in high strength bolts with a minimum yield strength of 600 MPa.

Currently, based on the samples provided for testing, rock bolt failures caused by SCC have occurred in the Western and Southern Coalfields of New South. However it is possible that the problem could be more widespread than this.

In summary, SCC failed rock bolts are often characterised by:

- a sharp, brittle type fracture surface with no necking of the bolt adjacent to the fracture surface;
- failure at less than the yield strength of the bolt with no significant load on the bearing plate;
- a fracture surface located immediately below the resin encapsulation;
- SCC cracks located at the base of the rib profile.

Some indicative signs of SCC of rock bolts in a mine are:

- loose bearing plates despite obvious roof sag;
- loose rock bolts;
- broken bolts fallen out of the roof;
- unusual or heavy roof conditions.

Solutions to the SCC failure of rock bolts

Although SCC is a fundamental characteristic of metals and alloys, it only occurs within a narrow band of conditions, and is therefore a fugacious and difficult problem to solve completely. However any solution to the SCC problem needs to take account of three factors vis: stress, corrosive conditions, and metallurgy.

Stress

The tensile stress level in a bolt cannot be reduced cost effectively, since SCC failure occurs at much less than the yield strength of the steel. Very large diameter bolts would reduce the tensile stress in the bolt but would incur a significant weight penalty. Lower strength steel grades are less susceptible to SCC, but would also incur a similar weight penalty since they would by necessity have to be larger diameter bolts.

It should be noted that SCC cannot occur in an area of compressive stress and a surface compressive stress can be developed by either shot peening or by quenching (Tempcore process).

Corrosive conditions

There are a wide range of possible corrosive conditions that could cause SCC. These range from brass exposed to ammonia, mild steel exposed to caustic conditions, stainless steels exposed to chloride conditions, and high strength steels exposed to environments that can release hydrogen.

If SCC is suspected, a chemical analysis of the mine water can indicate if there is the potential for SCC to occur.

One way to reduce SCC is to prevent the corrosive conditions from affecting the steel rock bolt. This could be done with some form of coating of the bolt. An anti-corrosive coating may help, but work needs to be done to determine its effectiveness against SCC, since even stainless steel can be affected by SCC. In addition, a zinc coating (galvanising) may in some instances actually exacerbate the problem of SCC. Finally, heavy corrosion protection systems such as plastic sleeves over the bolt may significantly reduce the load transfer capability of the rock bolt.

A relatively simple measure to reduce SCC is to ensure that all bolts are fully encapsulated with resin. This will not prevent SCC completely since the resin can crack under high load and the bolt could then still be exposed to corrosive conditions.

Metallurgy

There are some steps that can be taken with the metallurgy and the bolt design to reduce SCC. Firstly, lower strength steels are less susceptible to SCC than higher strength steels. Therefore a rock bolt with an ultimate tensile strength of 900 MPa would be less susceptible to SCC than a cable bolt with an ultimate tensile strength of 1750 MPa.

Secondly, steel bars with a high surface compressive stress are also less susceptible to SCC than bars without a compressive stress. This surface compressive stress can be achieved by, for example, shot peening (as in the case of drill rods), or by quenching and tempering (as in the case of Tempcore bars).
Finally, the design of the ribs on the rock bolt has some influence on its susceptibility to SCC. On a conventional rock bolt, the rib projects from the core size of the rock bolt at a sharp angle (approximately between 60 and 90 degrees). This sharp angle creates a "stress raiser" in the bar when the bar is subjected to a tensile force, and consequently SCC cracks frequently occur at this point (see Figure 4). Rock bolts which therefore minimise this sharp angle and reduce the "stress raiser effect", are therefore preferable to ordinary rock bolts. In addition, all stress raisers in a rock bolt or cable bolt are to be avoided (eg cuts, grooves etc).

In summary, the stress conditions, the corrosive environment, the steel properties, the steel micro-structure and the bar design, are all factors which influence the potential for SCC to occur.

Recommendations

If SCC failure of rock bolts is suspected as indicated by the characteristics as outlined above, then the following is recommended:

- Inspect roadways and tunnels and collect samples of broken bolts, water samples if possible, and collect installation data (eg bolt type, steel grade, installation date etc) on SCC failure of rock bolts. Have these bolts and water samples analysed to confirm SCC or not;

- Where SCC failures are suspected, examine roof conditions with a geotechnical engineer to determine if additional support is required;

- Ensure all bolts installed in the future are fully encapsulated with resin right to the collar of the hole. Point anchored bolts with even a short free length are not recommended.

- Use rock bolts which reduce the potential for SCC to occur (ie. Bolts which have been shot-peened or Tempcored and which have a radius in the base of the rib profile).

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