Preventing failure of the anchoring system in underground coal mines

H Chen¹, H.L. Ramandi¹, A Crosky², S Saydam¹

¹School of Minerals and Energy Resources Engineering, UNSW Sydney, Australia.

²School of Materials Science and Engineering, UNSW Sydney, Australia.

Abstract. Cable bolts are commonly used as anchoring element in many underground mines. Reports on the premature failure of cable bolts in underground coal mines due to stress corrosion cracking (SCC) have been increasing in the past two decades. The previous studies found that the diffusion of atomic hydrogen into steel causes the SCC in cable bolts, which is known as hydrogen-induced stress corrosion cracking (HISCC). While the research on the mechanism of the HISCC in underground mines needs to be continued, it is essential to develop prevention measures to avoid such a failure. In this study, a variety of prevention measures that claim to prevent corrosion of steel were examined. Specifically, barrier coating, i.e., polymer, epoxy coating, as well as the sacrificial coating, i.e., hot-dip galvanising, methods were tested. Testing specimens were made by inserting loading pins between locked cable bolt king wires (coated) to simulate the in-situ stress condition. Cable bolt specimens were then fully immersed into a hydrogen sulphide solution to determine their resistance against HISCC. The test results showed that all the coatings had delayed the failure in varying degrees, but very few have significantly extended the time to fracturing. The polymer and epoxy coatings have become breached during the testing, and the failure occurred shortly after. The galvanised coating was dissolved in the testing solution and again allowed access of the solution to the steel surface, and subsequently resulted in failure. This indicates that these coatings can be potentially applied to prevent SCC failure; however, their impacts on the performance of bolts, such as their bonding with grout and bolt, still need to be considered.

1. Introduction
Catastrophic failure of cable bolts and rock bolts have been increasingly reported in the past two decades [1, 2]. Stress corrosion cracking (SCC) involving hydrogen diffusion into the steel, known as hydrogen-induced stress corrosion cracking (HISCC) [3], has been identified as the cause of such failures [4]. Failure of bolts can significantly affect the productivity of mining operations and is also a major threat to daily operation safety.

Rock bolts and cable bolts are used in mining and civil industries predominantly as ground support tools. They are installed in pre-drilled holes in the roof of tunnels to stabilise the surrounding rock strata. Cable bolts are made from high carbon cold-drawn steel and have much higher strength than rock bolts. Being cables, they are also flexible, allowing them to have lengths (up to 12 m), which are substantially greater than the tunnel height. As a result, in many cases, they are used to extend through the weaker layers of strata (such as coal and clay) and anchor into the solid and stronger rock layers above. However,
Mechanics and Rock Engineering, from Theory to Practice
IOP Conf. Series: Earth and Environmental Science 833 (2021) 012164
doi:10.1088/1755-1315/833/1/012164

the high load on cable bolts can also significantly increase their susceptibility to SCC and reduce their service life [5]. Both cable bolts and rock bolts have been shown to be highly vulnerable to SCC [2, 5]. SCC is a type of corrosion failure that occurs in particular environments in specific materials under load. SCC failure does not normally occur when the stress on the material is below a critical value. However, this critical value in most cases is much lower than the yield point of the material, and it can vary with the environment [6]. This makes SCC failure challenging to predict. Moreover, its occurrence cannot usually be detected until the final fracture occurs. There are several ways that SCC can initiate on a metal surface. Two of the most common SCC initiation mechanisms are hydrogen diffusion into the metal [4] and pitting corrosion [7].

Hydrogen-induced SCC (HISCC) is produced by hydrogen diffusion into the metal. This produces a type of hydrogen embrittlement in which atomic hydrogen diffuses into the metal, degrades the mechanical properties of the material (strength and toughness) and causes cracking below the yield strength of the material [8]. The concentration of atomic hydrogen plays an important role in SCC occurrence [9]; once the concentration of the diffused hydrogen reaches a critical level, cracking is initiated under external loads. The source of hydrogen varies in different conditions. It can be from a corrosion process in an acidic environment releasing H⁺, H₂S reaction with iron, decomposition of water or microbial activities [9, 10]. Tarui et al. [11] have suggested that the SCC susceptibility of a material is strongly related to its microstructure and strength. Since cable bolts are made from cold drawn steel, which has a tensile strength of more than 1800 MPa, they would be expected to be highly susceptible to HISCC. In addition, Toribio et al. [12] has suggested that the manufacturing process (cold drawing) of cable bolts could heavily increase vacancy and dislocation density in the material. These sites would act as hydrogen traps, which increases the hydrogen concentration in the steel.

Pitting corrosion is another major cause of SCC. It is generally associated with non-metallic inclusions and can occur simply due to the presence of a corrosive environment [13] or due to differential oxygen concentration [14]. The latter occurs when the oxygen concentration is lower in some regions of the corrosive environment than in others. The metal in contact with the low oxygen regions becomes anodic relative to the remainder and undergoes corrosion. This leads to pitting if the anodic regions are small. Beavers et al. [14] have reported that sites containing wet clay often produce a low oxygen anode initiating pitting corrosion. Pitting produces a stress concentration which can then initiate SCC [15].

Coatings can be used to protect against corrosion and thus SCC. There are two basic types of coating, barrier coatings and sacrificial coatings. Barrier coatings provide a physical barrier between the metal and the corrosive environment. However, if the coating is breached, the corrosive environment can access the underlying metal and corrosion can then take place. Paints and bitumen are examples of barrier coatings. Sacrificial coatings also provide a barrier. However, these coatings are anodic to the underlying metal and can therefore provide protection at breaches in the coating. This is known as sacrificial protection. An example of the sacrificial coating is galvanising on steel.

It is noted that, in a prior study, Satola [16] examined the effectiveness of both barrier and sacrificial coatings in resisting corrosion of cable bolts, but their effectiveness in resisting SCC was not evaluated. It is further noted that, in addition to the effect of corrosion on the cable bolt strands themselves, corrosion has also been shown to reduce the effectiveness of the barrel and wedge fittings that anchor the cable bolts [17].

In this study, several barrier coatings, and also galvanising, were evaluated for their ability to protect against HISCC. Accelerated HISCC testing was conducted under severe conditions (low pH, dissolved H₂S) using a solution specifically formulated to promote hydrogen entry into the steel.

2. Materials and methods

2.1 Fabrication of coupons

The test coupons were fabricated from the straight central king-wire of unused plain super strand cable bolts. The wires were cold drawn eutectoid steel wires with a diameter of approximately 6 mm. The
chemical composition and mechanical properties of the wires, as provided by the cable bolt supplier, are given in Table 1.

The design of the cable bolt coupons is shown in Figure 1. The coupons consisted of two parallel wires 150 mm in length with a pair of locking rings installed 75 mm apart towards each end. The locking rings were made from a 0.8% carbon steel to minimise any galvanic effect between the locking rings and wires. The specimens were loaded by inserting a pin made from the 6 mm king-wire midway between the two locking rings. This produced a load of approximately 1600 MPa, which is equivalent to 94% of the yield strength [18]. An installation frame was used to ensure that the loading pin and locking rings were placed in the desired locations [19].

| Chemical composition wt% | Mechanical properties |
|--------------------------|-----------------------|
| C  | Si  | Mn  | P  | S  | Cr  | Yield (MPa) | UTS (MPa) | Elongation % | Hardness (HV<sub>10</sub>) |
| 0.85 | 0.31 | 0.66 | 0.01 | 0.01 | 0.11 | 1700 | 1820 | 18 | 502 |

Table 1. Chemical and mechanical properties of cable bolt.

![Figure 1. Design of cable bolt coupon.](image)

2.2 Coating materials
Four different coating materials were used on the cable bolt coupons. These are listed in Table 2 and are referred to as Coatings 1-4. For proprietary reasons, only limited information (if any) was available. Coating 1 was a high molecular weight polymer coating containing dipropylene glycol dimethyl ether and 2-butoxy ethyl acetate. Coating 2 was an epoxy enamel containing titanium oxide filler. Coating 3 was an aluminium- filled bitumen. Coating 4 was hot-dipped galvanising.

| Coating # | Name     | Type                                                      |
|-----------|----------|-----------------------------------------------------------|
| Coating 1 | Everbrite | High molecular weight polymer coating containing dipropylene glycol dimethyl ether and 2-butoxy ethyl acetate |
| Coating 2 | Epoxy enamel | Epoxy enamel containing titanium dioxide. |
| Coating 3 | Silvershield | Aluminium doped bitumen |
| Coating 4 | Hot dipped galvanising | Zinc coating |

Table 2. Selected coating materials.

2.3 Test solution
It is difficult to fully simulate in the laboratory the environment in underground mines where SCC failure has occurred. However, a solution of acidified sodium sulphate has been shown to produce SCC failure of cable bolts similar to that observed in service failed bolts under laboratory conditions [4]. The reaction between sodium sulphide (Na2S) and acetic acid (CH3COOH) produces hydrogen sulphide (H2S),
which is known to promote HISCC [4]. Sodium chloride (NaCl) was added to the solution to simulate the typical salt concentration in groundwater. The composition of the test solution is given in Table 3. The solution is very aggressive and greatly accelerates HISCC failure.

A reference solution was also made with the same chemical composition but without sodium sulphide. The reference solution was used to confirm that failure of the test coupons was due to the presence of hydrogen sulphide rather than simply due to the acidic environment.

| Solute   | Mass (g/l) | Molarity (mol/l) |
|----------|------------|------------------|
| NaCl     | 0.5        | 0.008            |
| Na₂S     | 3          | 0.04             |
| CH₃COOH  | 25         | 0.42             |

2.4 Testing
Testing was conducted by placing the test coupons in plastic containers containing the test solution and then placing the containers inside a test chamber, as shown in Figure 2. The test chamber was then covered with a sheet of 5 mm thick tempered glass. Filtration fans filled with GC Sulfursorb Plus were placed next to the chamber to absorb any hydrogen sulphide released from the solution.

During the testing, a camera was set up to track the status of the individual coupons continuously at all time. Photos of the immersed coupons were taken at 10-minute intervals to identify the total time to failure of each coupon. Testing was conducted for 120 hours or until failure, whichever came first. Each coating was tested in triplicate, and the results from the three test coupons then averaged.

Three uncoated cable bolt coupons were tested in the test solution and another three tested in the reference solution. The test procedure for the uncoated specimens was the same as that for the coated specimens.

2.5 Sample preparation for fractographic analysis
After testing, the coupons were removed from the test solution and the time to failure recorded. All specimens were then cleaned with ethanol and photographed to record their appearance. The surface condition of the coating was then examined using a Leica M205 A stereo macroscope.

The fractographic analysis was carried out on representative samples for all coatings for which the coupons underwent failure. The fractured wires were cut ~20 mm below the fracture surface and the fracture surface, then ultrasonically cleaned in Ajax inhibited hydrochloric acid for 20 seconds to remove surface corrosion product. The specimen was removed from the cleaning solution and immediately rinsed with water and ethanol to remove any acid remaining from the cleaning process. The cleaned fractures surfaces were then examined using a Hitachi S3400 scanning electron microscope.
(SEM) operated at 15 kV. The scanning electron microscopy was carried out in the Electron Microscopy Unit at the Mark Wainwright Analytical Centre at UNSW Sydney.

3. Results and discussion

3.1 Results of immersion test

The average time to failure for each of the three cable bolt coupons for each of the coatings is shown in Figure 3. The uncoated coupons failed in 5 hours. The coupons with Coating 3 failed in 18 hours, the coupons with Coating 1 failed in 20 hours, while the coupons with Coating 2 failed in 80 hours. The galvanised coupons failed in 50 hours. The coupons tested in the reference solution (no sodium sulphide) also remained un-failed, confirming that hydrogen sulphide was required to cause failure.

The short time to failure for the uncoated cable coupons is indicative of the highly aggressive SCC nature of the solution. The polymer coating (Coating 1) and the asphalt coating (Coating 3) both extended the life of the cable bolt coupons slightly but were unable to provide adequate long-term protection.

The galvanised coupons also failed in a relatively short time. This is considered to be due to the dissolution of the zinc coating in the acidic test solution (pH 2.5-2.8). A galvanised cable bolt test coupon of a similar configuration was found to fail in an underground mine after the localised dissolution of the coating, indicating that similar behaviour can occur in service.

The epoxy coating (Coating 2) performed better but again was unable to protect for the full duration of the test. An earlier study of SCC of buried steel pipelines reported that epoxy coating could improve the SCC resistance [20].

![Figure 3](image-url)  
**Figure 3.** Average time to failure (hours) for the tested coupons.

3.2. Macroscopic analysis

All specimens were examined after testing using a low magnification stereo microscope to establish the condition of the surface coatings. Representative examples of the surface of the test coupons are shown for each of the coatings in Figure 4. The surface of the uncoated specimen contained numerous subcritical cracks, which had not grown to sufficient size to cause fracture (Figure 4a). Coating 1 had become darkened during exposure to the test solution and contained numerous small orange coloured blisters (Figure 4b). Regions where the coating had been lost completely resulted in the exposure of the underlying metal. A large region of the underlying metal had become exposed adjacent to the fracture surface. Coating 2 also contained blisters while a large region of the underlying metal had again become exposed adjacent to the fracture surface (Figure 4c). Subcritical cracks were also observed in the bare metal. Breaches in the coating were also evident in Coating 3 (Figure 4c), with a strip of bare metal again being present adjacent to the fracture surface. In view of these observations, it is considered that for Coatings 1-3 the coating had become lost in localised areas during exposure to the test solution. This provided direct contact of the test solution with the metal surface, causing cracking to occur similar to that which occurred in the uncoated specimens. The longer time to failure for the coated specimens...
simply reflects the time required for the coating to become breached, which means the acidic solution and the bending destroys the coated material.

The galvanised coating was also removed during exposure to the test solution (Figure 4e), allowing cracking to occur. This confirms the view expressed earlier that the failure of the galvanised coupons is due to the dissolution of the galvanised coating. While galvanising sacrificially protects small breaches in the coating, it can no longer provide sacrificial protection once sufficient coating has been removed. It is noted that numerous subcritical cracks were present on the bare surface of the galvanised sample (Figure 4e).

3.3. Fractographic analysis

The fracture surface of representative examples of all test specimens which underwent failure was examined using SEM. The fractures in the cable bolt specimens had a stepped profile, as shown in [18]. This consisted of a short initial transverse plateau extending from the outer surface of the test specimens, followed by a lengthier longitudinal section, and, finally, a second transverse plateau. The same crack profile has been observed in service-failed bolts in which the initial plateau and the longitudinal section have been shown to be due to SCC, with the final plateau being due to final overload failure.
SEM images of the fracture surfaces in the initial plateau region are shown in Figure 5 for representative examples of the failed cable bolt coupons with the different coatings. All fracture surfaces show tearing topography surface (TTS), consisting of tear ridges connecting very fine facets, which was also observed for service-failed cable bolts [8]. TTS is considered to be indicative of hydrogen-induced SCC (HISCC) [21]. HISCC occurs from the diffusion of hydrogen into the steel, which weakens the interatomic bonding and promotes cracking [8]. HISCC is to be expected in the test coupons since the solution was formulated specifically to promote hydrogen ingress into the steel.

The similarity of the fracture surfaces in the test coupons and the service failed bolts indicates that the mechanism of failure is the same in both cases. Accordingly, it is considered that the findings from the coating tests should be applicable to underground mines. It is noted that the test solution used was specifically formulated to allow accelerated testing. The extent of acceleration is evident when the failure time for the uncoated test specimens is compared with service failure times. The uncoated test specimens survived only 3-5 hours, while service failures take months and usually years.

![Figure 5. Fracture surface of coupons. a) Uncoated; b) Coating 1; c) Coating 2; d) Coating 3; e) Galvanised.](image)

4. Conclusions
All coatings examined delayed the SCC failure to different extents but unable to provide protection for the full 120 hours testing period.

The polymer coating, the bitumen coating and the epoxy coating all became breached during the testing allowing the test solution to access the underlying metal. This resulted in failure similar to those observed in uncoated specimens.

The galvanised coating underwent dissolution in the test solution, again allowing access to the steel surface and subsequent failure. Such a failure has been observed in underground mines.

The fracture surfaces of the failed test coupons were similar to those observed in service failed cable bolts. They exhibited a tearing topography surface (TTS) that indicates that the failure has occurred by hydrogen-induced SCC.

Although none of the coatings has provided full protection to the wires, the epoxy coating still has relatively extended the life of the wires during the test. The result suggests that if the epoxy coating's properties are improved to meet the mining requirements, such a coating may have the potential to provide full protection to the bolts in the underground environment.
References
[1] Chen H, Lamei Ramandi H, Walker J, Crosky A, and Saydam S. Failure of the threaded region of rockbolts in underground coal mines 2018. Mining Technology: p. 1-9.
[2] Craig P, Serkan S, Hagan P, Hebblewhite B, Vandermaat D, Crosky A, and Elias E. Investigations into the corrosive environments contributing to premature failure of australian coal mine rock bolts 2016. International journal of mining science and technology; 26(1): p. 59-64.
[3] Toribio J and Ovejero E. Microstructure-based modeling of hydrogen assisted cracking in pearlitic steels 2001. Materials Science and Engineering: A; 319: p. 540-543.
[4] Wu S, Chen H, Ramandi HL, Hagan PC, Crosky A, and Saydam S. Effects of environmental factors on stress corrosion cracking of cold-drawn high-carbon steel wires 2018. Corrosion Science.
[5] Wu S, Chen H, Craig P, Ramandi HL, Timms W, Hagan PC, Crosky A, Hebblewhite B, and Saydam S. An experimental framework for simulating stress corrosion cracking in cable bolts 2018. Tunnelling and Underground Space Technology; 76: p. 121-132.
[6] Toribio J and Ovejero E. Failure analysis of cold drawn prestressing steel wires subjected to stress corrosion cracking 2005. Engineering Failure Analysis; 12(5): p. 654-661.
[7] McCafferty E. Introduction to corrosion science. 2010 Springer Science & Business Media.
[8] Gamboa E and Atrens A. Stress corrosion cracking fracture mechanisms in rock bolts 2003. Journal of Materials Science; 38(18): p. 3813-3829.
[9] Ćwiek J. Prevention methods against hydrogen degradation of steel 2010. Journal of Achievements in Materials and Manufacturing Engineering; 43(1): p. 214-221.
[10] Javaherdashti R, Raman RS, Panter C, and Pereloma E. Microbiologically assisted stress corrosion cracking of carbon steel in mixed and pure cultures of sulfate reducing bacteria 2006. International biodeterioration & biodegradation; 58(1): p. 27-35.
[11] Tarui T, Maruyama N, Eguchi T, and Konno S. High strength galvanized steel wire for bridge cables 2002. Structural engineering international; 12(3): p. 209-213.
[12] Toribio J and Valiente A. Failure analysis of cold drawn eutectoid steel wires for prestressed concrete 2006. Engineering Failure Analysis; 13(3): p. 301-311.
[13] Elboujdaini M and Revie R. Metallurgical factors in stress corrosion cracking (sc) and hydrogen-induced cracking (hic) 2009. Journal of Solid State Electrochemistry; 13(7): p. 1091-1099.
[14] Beavers JA and Thompson NG. External corrosion of oil and natural gas pipelines 2006. ASM handbook; 13: p. 1015-1025.
[15] Lu B, Chen Z, Luo J, Patchett B, and Xu Z. Pitting and stress corrosion cracking behavior in welded austenitic stainless steel 2005. Electrochimica Acta; 50(6): p. 1391-1403.
[16] Satola I. Testing of corrosion protected cable bolts by double pipe axial tests. 2001 In: DC Rocks 2001, The 38th US Symposium on Rock Mechanics (USRMS). American Rock Mechanics Association.
[17] Hassell R, Villaescusa E, and Thompson A. Testing and evaluation of corrosion on cable bolt anchors. 2006 In: Golden Rocks 2006, The 41st US Symposium on Rock Mechanics (USRMS). American Rock Mechanics Association.
[18] Wu S, Chen H, Lamei Ramandi H, Hagan PC, Hebblewhite B, Crosky A, and Saydam S. Investigation of cable bolts for stress corrosion cracking failure 2018. Construction and Building Materials; 187: p. 1224-1231.
[19] Chen H, Kimyon O, Ramandi HL, Manefield M, Kaksonen AH, Morris C, Crosky A, and Saydam S. Microbiologically influenced corrosion of cable bolts in underground coal mines: The effect of acidithiobacillus ferrooxidans 2021. International Journal of Mining Science and Technology.
[20] Beavers J. Assessment of the effects of surface preparation and coatings on the susceptibility of line pipe to stress-corrosion cracking. 1992. American Gas Association.
[21] Toribio J, Lancha A, and Elices M. Hydrogen embrittlement of pearlitic steels: Phenomenological study on notched and precracked specimens 1991. Corrosion; 47(10): p. 781-791.