Prevention of catastrophic corrosion failure of rockbolt and cable bolt in underground coal mines

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ABSTRACT: The catastrophic corrosion failures of rockbolts and cable bolts in underground coal mines have been reported from several mines in the past few decades. Many of the failed bolts have been in service for a short period. The preliminary studies have found that the failures occur by hydrogen-induced stress corrosion cracking (HISCC) and microbial-induced corrosion (MIC). In these types of failures, the local environment where the bolt was installed is the key to initiating and accelerating the corrosion process. This study investigates the capabilities of polymer coating and galvanising technologies for preventing bolt corrosion failures. We use our previously developed HISCC and MIC reproduction method to reproduce the corrosive environment in the lab. The laboratory study shows the benefit of polymer barrier coating compared to galvanising in an extreme environment, and it also has good resistance to MIC.

Keywords: Ground support safety, corrosion, rockbolt, cable bolt, stress corrosion cracking, microbiological induced corrosion.

1 INTRODUCTION

Cable bolts and rockbolts are used as primary and secondary anchoring systems in many underground mines, particularly in the Australian underground coal mines. In the past two decades, there has been a rise in reports concerning the early failure of cable bolts and rockbolts in underground coal mines due to stress corrosion cracking (SCC). Previous studies have established that the SCC in both rockbolts and cable bolts occur due to hydrogen diffusion into the material, known as hydrogen-induced stress corrosion cracking, HISCC (Craig et al., 2016; Wu et al., 2018).

SCC is a type of corrosion failure that only occurs when a material is under stress (tensile and/or shear) in a corrosive environment. SCC failure normally does not occur when the stress on the material is below its critical value. However, in most cases, this critical value is much lower than the material's yield point. It can vary by the changes in the environment (Toribio & Ovejero, 2005), which makes SCC failure difficult to predict, i.e. it can not be identified until the final fracture occurs. There are several ways that SCC can initiate on the metal surface; two most common initiation methods for SCC are 1) hydrogen diffusion (HISCC) (Wu, et al., 2018) and 2) formation of pitting corrosion (McCafferty, 2010).

HISCC is a type of hydrogen embrittlement that occurs through hydrogen penetration (diffusion) into the material, which consequently degrades the mechanical properties of steel (strength and roughness) and causes cracking below the yield strength of the material (Gamboa & Atrens, 2003). The cause of HISCC is dependent on the concentration of atomic hydrogen, which diffuses into the material (Ćwiek, 2010). Once the hydrogen reaches its critical concentration, the cracking process may occur. The source of hydrogen to cause such failure could come from many sources, such as the corrosion process in an acidic environment which releases H+, H_2S reaction with iron, decomposition of water, and microbial activities (Javaherdashti, 2011; Ramandi et al., 2018).

In many underground mining environments, the cause of HISCC can be due to the localised bacterial species. The corrosion-causing bacteria found in the groundwater of the mines can initiate localised corrosion and/or produce H_2S, which leads to catastrophic failure of the bolts. While the research to understand the process of SCC occurrence in underground mines is still required, finding a prevention solution to protect the bolts from HISCC and microbially induced corrosion (MIC) (Chen et al., 2021) is crucial.

In this study, we analyse and compare the HISCC resistance of hot-dip galvanising on the bolts and UNSW-modified polymer coatings. The UNSW-modified coating is tested in extremely acidic and bacterial environments to examine its corrosion resistance. We test the coating on coupons manufactured from rockbolts and cable bolts used in the coal mining industry.

Figure 1. Fractured cable bolt (above) and rockbolt (below) due to HISCC from the mines.

2 MATERIAL AND METHODS

2.1 HISCC acidic test

We create an extremely acidic environment to accelerate the HISCC process on the bolts, similar to those observed from in-service failed bolts. The cable bolt coupons are designed according to our previous three-point bending method (Wu et al., 2018) and loaded near the material's yield stress during the test (Figure 2). We deform cable bolts' king wires and rock bolts by inserting a loading pin into a section of slotted bolts. Two 150 mm king wires with a pair of locking rings installed 75 mm apart towards each end make the cable bolt coupons. A 6 mm loading pin made from the same material (king-wire) is inserted between the two locking rings at the centre. The loading pin produces a load of approximately 1600 MPa, equivalent to 94% of the yield strength at the centre of both wires (Wu et al., 2018b). The rock bolt coupons are 300 mm in length with a 15 mm wide slot cut along the centreline for a length of 100 mm in the centre of the coupon. A 30 mm diameter loading pin, made from the same material as HSAC 840 rock bolt, is then inserted at the specimen's centre. The pin produces a load of approximately 600 MPa (equivalent to the yield strength) on the centre of the coupon (Craig et al., 2016).

The cable bolt coupons are tested in three groups: uncoated, hot-dip galvanised and polymer coated. After the coupons are prepared, the test solution that is proven to create the HISCC is prepared using NaCl, Na_2S, and acetic acid (Wu et al., 2018a) for the immersion test (pH 2.4). All coated coupons and uncoated control coupons are fully immersed in the test solution for 120 hours. The solution is refreshed every 24 hours to maintain the H_2S concentration. Each coupon is immersed individually in a 1 L solution to ensure the chemistry of the solution is not affected by the chemical reaction between acetic acid and bolts. This HISCC acidic immersion test aims to confirm that the bolts could resist the most extreme corrosion environment. Since the cablebolt has the lowest SCC resistance compared to the rock bolt, it is used to test the limits of the coating method could be applied to the bolts.

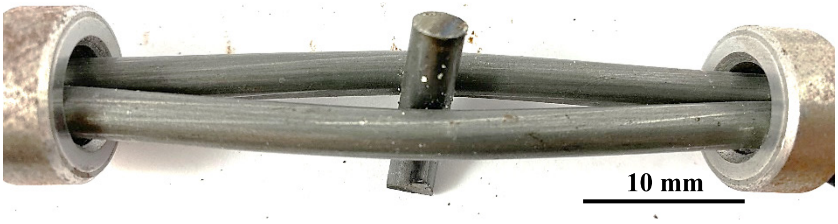

Figure 2. Design of cable bolt coupons.

2.2 Anaerobic MIC test

The typical SCC-causing bacteria: Sulphate Reducing Bacteria (SRB), which are found and enriched from mine water samples of New South Wales (Australia) underground coal mines, are used in this study to examine the role of bacteria in the corrosion failure of rockbolt. The SRB are grown in an anaerobic bicarbonate-buffered medium prepared in serum bottles sealed with PTFE septa and aluminium crimp caps. Per litre of media contains 20 mL 50X salts medium, 1 mL SL-9 medium, 1 mL 1000X vitamin solution, 1 mL 1000X trace element B, 1.12 g sodium lactate, 0.71 g sodium sulphate, 2.5 g sodium bicarbonate, 1 mg resazurin, 0.05 g sodium sulphide nonahydrate and 0.024 g cysteine. The medium is purged with N_2 gas (99.99%). Deoxygenated mine water (5% v/v) is added after autoclaving the medium. All cultures are incubated at 30 °C in static conditions.

Sulphate concentrations are quantified by precipitation with barium under acidic conditions as a measure of SRB activity. A buffer solution is prepared, which contains 30 g magnesium chloride hexahydrate, 5 g sodium acetate trihydrate, 1g potassium nitrate and 20 mL glacial acetic acid (>99%) per 1000 mL of solution. Stock sulphate solution is prepared with 100 mg sodium sulphate in 1 L filtered sterilised distilled water. The stock solution is then diluted in sterile distilled water to make 50 ml standards with concentrations of 5mg/L, 10mg/L, 15mg/L, 20mg/L, 25mg/L, 30mg/L, 35mg/L and 40mg/L. Similarly, 5 mL aliquots of the solutions are diluted with 45 mL sterile distilled water. 10 mL of buffer solution is added to the diluted samples and standards, and a spoonful (~20 mg) of BaCl2 crystals, is added while stirring for 1 minute. The absorbance of the precipitates is measured immediately at 420 nm using an Agilent Cary 60 UV-Vis spectrophotometer.

The rockbolt samples are prepared as the disc (Figure 3) and placed in centrifuge tubes filled with the bacteria solution mentioned above.

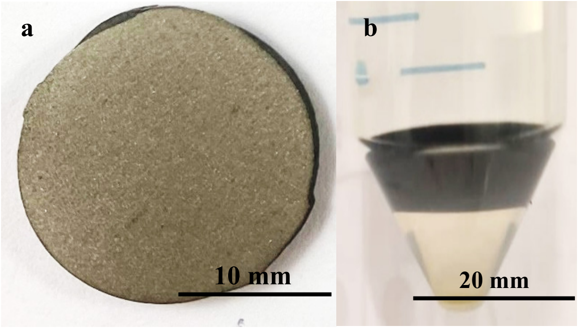

Figure 3. MIC immersion test (a: rockbolt disc sample; b: sample immersed in SRB solution).

3 RESULTS AND DISCUSSIONS

3.1 HISCC acidic test on cable bolt coupons

The test results of uncoated and galvanised coupons are shown in Figure 4. The results demonstrate that both uncoated and hot-dip galvanised cable bolt coupons crack during the test. Table 1 shows the time to fracture of each type of coupon. It shows the galvanised coupons last longer in the testing solution than uncoated ones; however, they still fail after 20 hours of testing. In an acidic environment, Zn coating reacts with H^+ very fast and cannot protect the underneath material well. Moreover, Zn coating can not stop hydrogen diffusion, which means it only has little resistance to HISCC. The time to failure in this experiment shows the service time of the bolts in the most extreme HISCC environment, which shows a relative SCC resistance of different coatings. According to the report from the mines, the SCC failure normally occurs from a few weeks from the installation to few years. If the testing specimen can pass the 100 hours test in the laboratory, it will also reach the designed service life in coal mines.

For the UNSW-modified polymer-coated coupons, the coating remains in good condition after the immersion test. The coupons are examined by Leica M205 A stereo microscope, and no crack is observed on the surface. It is observed that the polymer barrier coating can successfully prevent the HISCC failure of cable bolt coupons in an extremely acidic environment. The galvanisation dissolves in the test solution, allowing the corrosive environment access to the steel surface and resulting in failure.

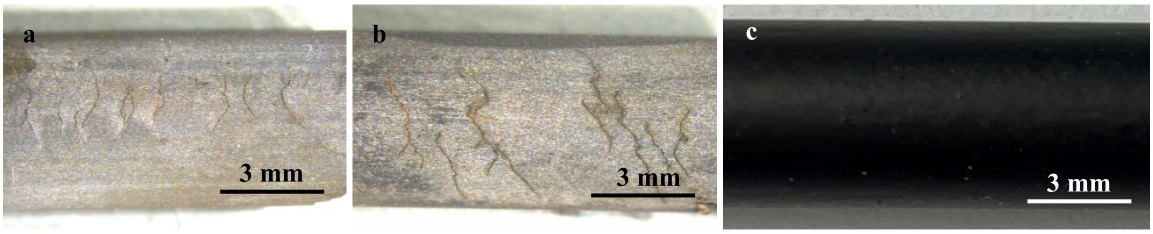

Figure 4. HISCC acidic test results for cable bolt coupons (a: uncoated; b: galvanised; c: polymer coated).

Table 1. HISCC acidic test results for cable bolt coupons.

	Cracking (Y/N)	Time to failure (hours)
Uncoated	Y	5
Galvanised	Y	20
Polymer coated	N	N/A

3.2 *Anaerobic MIC test on rockbolt disc samples*

The triplicated uncoated and polymer-coated rockbolt bolt disc samples are immersed in bacteria solution anaerobically for 8 weeks to examine the corrosion activity on the sample surface. Figure 6 displays the visual observation image of the same samples before and after the test, which shows severe black corrosion products on the sample surface. The analysis shows the corrosion product found in the system is FeS, which forms due to the reaction of Fe and H_2S. The results demonstrate that even in an anaerobic environment, the bacteria in the environment still corrode the steel. The localised corrosion concentrates the stress and initiates the cracking. The H_2S generated by the bacteria also weakens the steel material by increasing atomic hydrogen concentration in the environment and causing stress corrosion cracking to the bolts.

The sample surface is also examined by Leica fluorescent microscopy to obtain images of biomass attached to the different samples. Figure 5 shows the number of bacteria present on the surface of two types of samples after 8 weeks. The green dots in the images represent the bacteria cells. The results show that almost no bacteria are attached to the polymer-coated surface compared to the uncoated surface, proving that the UNSW-modified polymer coating successfully prevents the MIC on the bolts.

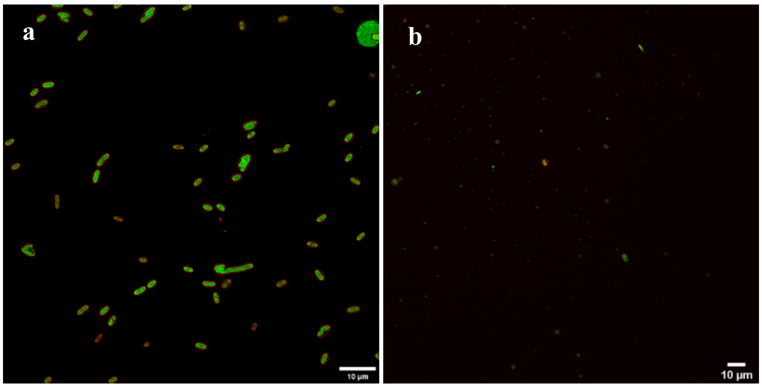

Figure 5. Fluorescent microscopy images of rockbolt sample surface (a: uncoated; b: polymer coated).

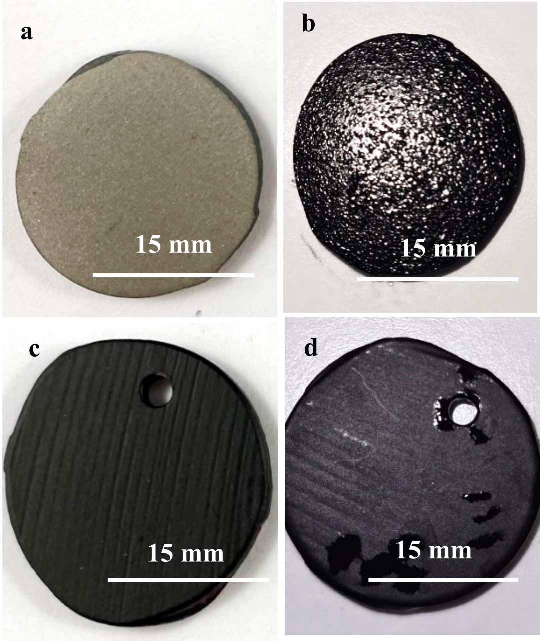

Figure 6. Anaerobic MIC test result for rockbolt disc samples. (a: uncoated before test; b: uncoated after test; c: polymer coated before test; d: polymer coated after test).

4 CONCLUSIONS

We create two aggressive environments to accelerate HISCC and MIC on cable bolts and rockbolts. In an acidic environment, the sacrificial coating (galvanising) no longer protects the bolts from HISCC, which shows the coating can protect the bolts in an extremely corrosive environment. In the MIC environment, the bacteria still heavily corrode the rockbolt material in a mild/low corrosive environment without oxygen in the system, initiating corrosion failure. We show that the UNSW-modified polymer coating can act as barrier coating and successfully protect the bolts from HISCC and MIC environments. The polymer coating has great potential to prevent the corrosion failure of rockbolts and cable bolts used in underground mines.

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