The effectiveness of epoxy coating for preventing microbially induced corrosion of rock bolts

The effectiveness of epoxy coating for preventing microbially induced corrosion of rock bolts

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Abstract. In the past two decades, the corrosion failures of rock reinforcement bolts in underground coal mines have been increasingly reported. Preliminary studies have shown that these failures were predominantly related to pitting and stress corrosion cracking. The analyses in affected mines indicated microbially induced corrosion (MIC) as one of the primary corrosion causes. As such, there is an urgent demand from industries to develop methods to mitigate MIC-associated failures of rock bolts in underground coal mines. This study examined epoxy coating to determine its effectiveness in preventing biofilm formation on steel surfaces and, in turn, averting MIC. The corrosion-causing bacteria were isolated and enriched from groundwater samples collected from the affected mine sites. Coated and uncoated rock bolt samples were prepared from the bolts and incubated in media in the absence and presence of the corrosion-causing bacteria. Fluorescence microscopy imaging found no evidence of bacterial biomass growth on the surface of the epoxy-coated steel surfaces after 30 days, while the non-coated surfaces were colonised by biomass. The observations suggest the potential of epoxy coating for bolt MIC prevention. Future studies to assess the applicability of epoxy coating in the underground mine environment are recommended.

1. Introduction

In the underground mining and civil tunnelling industries, rockbolts and cable bolts are most commonly used to stabilise the rock mass in the roof strata. The performance of the rock reinforcement bolts is critical for the safety of mineworkers and to avoid economic loss caused by the bolt replacement downtime. In the past decades, failures of bolts have been reported from underground mines and tunnels across the world [1-12]. Many companies involved in the underground mining and tunnelling industry are concerned about the integrity of their rock reinforcement bolts in underground mines. In response to the question raised by the industries, a number of analyses were conducted on the failed bolts, which identified the failures were primarily due to stress corrosion cracking and localised corrosion [13-17]. The preliminary study had found that one of the main causes of the failure is Microbially Induced Corrosion (MIC) [18].

About one-fifth of metal corrosion is reported to be related to MIC [19]. Bacteria can form a biofilm layer on the metal surface and act as an electron acceptor. The electron transportation from metal to bacteria creates an electrochemical cell that causes corrosion on the anode (metal surface) [20]. Since the corrosion products and other contaminations frequently cover the affected material, it is almost unlikely to detect MIC by visual observation [21]. Once the biofilm is formed on the metal surface, the

electrochemical reaction produces hydrogen ions and enhances the growth of MIC-causing bacteria [22-24].

In order to prevent MIC activity, the biofilm formation on the metal surface needs to be prevented. The barrier coating can provide a physical barrier between the metal and the corrosive environment and stop the corrosion from bacteria and other corrosive chemicals in the environment. Therefore, the barrier coating can theoretically stop MIC. However, several challenges still need to be addressed before the application of any coating to the rock reinforcement bolts. For example, coatings require to be durable when exposed to complex loading and chemical conditions in underground environments.

This study used epoxy as the coating material due to its excellent physical properties (toughness and flexibility) and chemical stability. The coated and uncoated specimens were immersed in a solution containing bacteria isolated from the groundwater samples from an underground mine in Australia. All specimens were evaluated by confocal fluorescence microscopy to study the biofilm formation on the surface.

2. Materials and methods

The test coupons were manufactured from a rock bolt (HSAC 840) commonly used in the Australian coal mining industry, as shown in Figure 1. The chemical compositions and mechanical properties of the rock bolt, as provided by the supplier, are reported in Chen [18]. The coupons were 200 mm in length with a 15 mm wide slot cut along the centreline for a length of 100 mm in the centre of the specimen. A 30 mm diameter loading pin, made from a piece of the rockbolt, was then inserted in the centre of the slot. This produced a load of approximately 600 MPa (equivalent to the yield strength) on the specimen [13, 15].

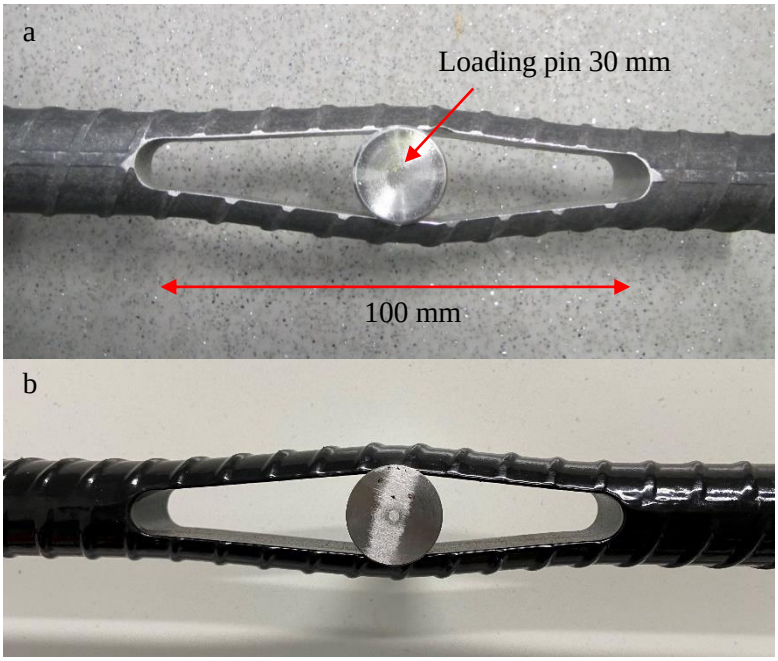

Figure 1. Design of the testing coupons. a: uncoated and b: epoxy coated.

The testing environment for this experiment was designed according to an underground mine environment in the state of New South Wales of Australia, where the bolt failure had occurred. The groundwater sample used in the Sulphate Reduction Bacteria (SRB) immersion tests was collected from the dripping roof water in the tunnels where the failed bolts were found. The groundwater analysis has shown that the concentration of corrosive ions is low, and the pH is near neutral [18].

DNA extraction and sequencing were conducted on 25 mL of the groundwater sample previously described by Bürgmann and Lee [25]. The analyses found several bacteria known to cause MIC, including *Thiobacillus*, *Desulfovibrio*, *Desulfotomaculum* and *Sulfurospirillum* [18]. *Desulfovibrio* and

Desulfotomaculum are well-known Sulphate-Reducing Bacteria (SRBs) known to produce MIC in steel [26, 27]. Therefore, SRB cultures were enriched from the groundwater sample and used for the experiment.

Both coated and uncoated coupons were immersed in a solution containing SRB culture in a 1 L Schott bottle and sealed with rubber septa. Each sample was prepared in triplicate. Each bottle was then purged with N_2 gas for 30 mins to remove all oxygen in the solution to create an anaerobic environment. The test bottles were kept in the dark at room temperature for 30 days.

After the test, the coupon surface was imaged for biomass detection using a DeltaVision Elite inverted fluorescence microscope. The fractographic and detached biomass analyses were conducted using a NanoSEM 230 field-emission scanning electron microscope (FE-SEM).

3. Results and discussion

The metal surface and coatings conditions were examined by a low magnification stereomicroscope (Figure 2). Figure 2a shows no clear evidence of severe corrosion occurring on uncoated coupons. It is shown that the corrosion failure caused by SRB is mainly by hydrogen-induced stress corrosion cracking, HISCC [18]. HISCC generally does not show a significant mass loss on the metal surface. The SRB-rich solution actually creates an environment promoting the *Desulfovibrio* activities: oxidising the organic material (lactate) and reducing sulphate (SO_4^{2-}) to sulphide (S^{2-}) [23, 28-31]. Therefore, the overall metabolism of the SRB generates H_2S by producing (S^{2-}) and then reacting with (H^+) in the environment. Therefore, the hydrogen diffuses into the steel and leads to a brittle fracture. This fracture occurs typically below the material's yield strength is driven by HISCC.

Figure 2b shows after 30 days of immersion, the condition of the coating material is still the same as at the start. The SRB-rich environment did not degrade or damage the coating, suggesting that the epoxy coating could potentially protect the rock bolt from MIC.

To further investigate the MIC effects on the rock bolt, a section from each coupon, coated and uncoated (20 mm in length from the centre), was cut and immersed in a staining solution made by 4% formaldehyde and stored at 4 °C until staining. The specimen was then examined by a DeltaVision Elite inverted fluorescence microscope to investigate biofilm formation on both coupons' surfaces. Figure 3a presents a fluorescence image obtained from the uncoated rock bolt coupon. The blue area in the image represents the biomass. This result gives strong evidence that the SRB has grown on the rock bolt surface and formed biofilms. The formation and growth of the biofilm likely caused the reaction explained earlier, which would potentially lead to a HISCC. In order to confirm the biofilm observed in Figure 3a was formed by *Desulfovibrio,* the biomass was detached from the surface and examined by FE-SEM (Figure *4*). Many small worm-like micro-organisms were observed, which comply with the finding from Chen [18]. Figure 3b shows the fluorescence image of the epoxy-coated rock bolt coupon, which indicates that there has been no biomass on the epoxy-coated coupon. This confirms the significant potential of epoxy coating for MIC prevention.

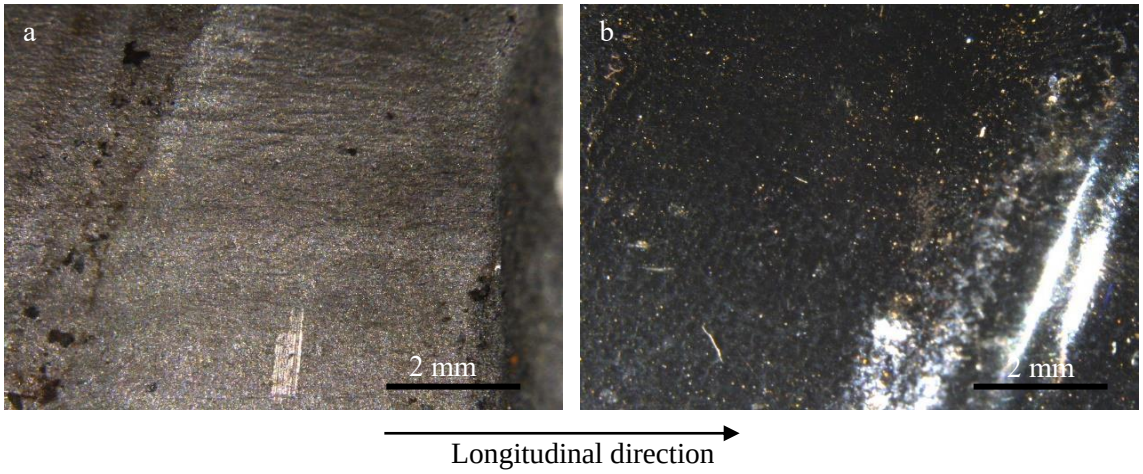

Figure 2. Macroscopic images of the rock bolt coupons surfaces after testing. a: uncoated coupon and b: epoxy coated coupon.

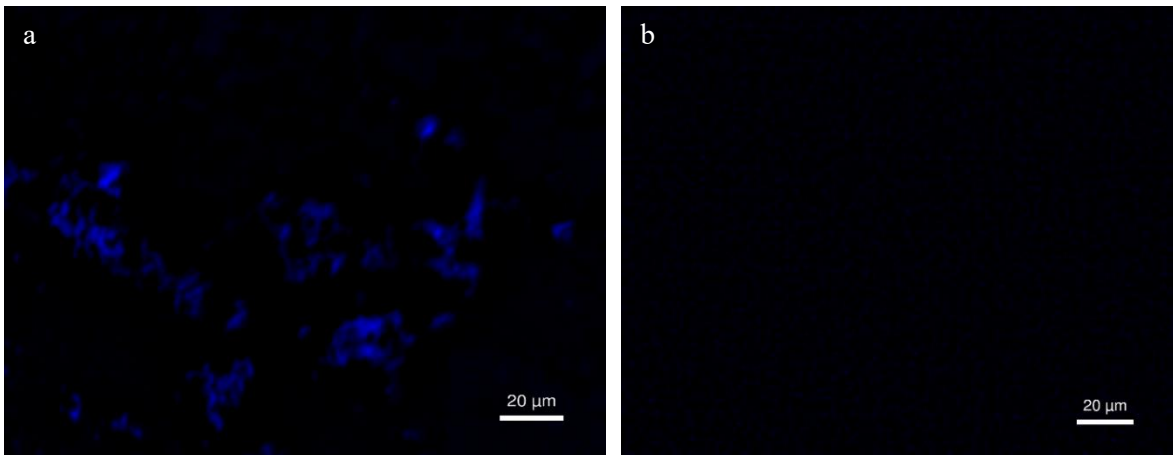

Figure 3. a: fluorescence image obtained from the uncoated rock bolt coupon and b: no biomass attachment was observed on epoxy coated rock bolt coupon.

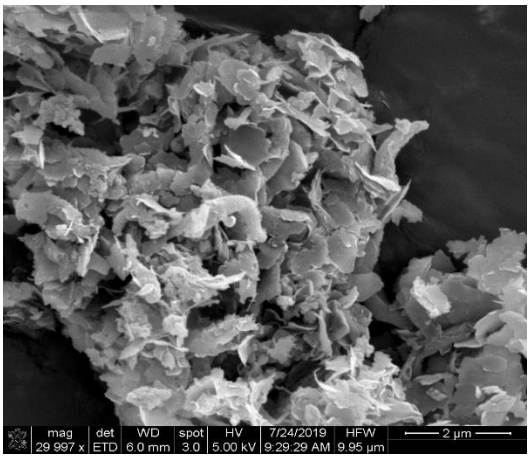

Figure 4. FE-SEM image obtained from the detached biomass from uncoated rock bolt coupon.

4. Conclusions

- The SRB collected from the underground mine water can form biomass on the rock bolt surface and cause MIC.
- The epoxy coating does not rupture or breach in SRB-rich environments.
- The epoxy surface may provide unfavourable conditions such as adverse physicochemical properties (e.g. hydrophobic surface, surface energy) or surface morphometry (roughness and porosity) for adhesion of SRB to initiate biofilm formation. Future investigations to understand SRB prevention mechanisms of fusion bonded epoxy surfaces are still required.

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