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An experimental framework for simulating stress corrosion cracking in cable bolts

Saisai Wu[a], Honghao Chen[b], Peter Craig[a,c], Hamed Lamei Ramandi[a,*], Wendy Timms[a], Paul C. Hagan[a], Alan Crosky[b], Bruce Hebblewhite[a], Serkan Saydam[a,*]

[a] *School of Mining Engineering, UNSW Sydney, NSW 2052, Australia*
[b] *School of Materials Science and Engineering, UNSW Sydney, NSW 2052, Australia*
[c] *Jennmar Australia Pty Ltd, Sydney, Australia*

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ABSTRACT

Stress corrosion cracking (SCC) of cable bolts in underground mines is a universal issue with limited cost effective solutions at present. Understanding the SCC mechanism of cable bolt failure is crucial in maintaining effective ground support and hence increasing the safety and productivity of underground mines. However, to date, no practical laboratory system has been developed to replicate the SCC mechanism which occurs in underground mines. In this study, based on the chemical properties of mine water, an acidified solution containing sulphide is synthesized. The solution is exposed to the wire strands from cable bolt in the laboratory to model service failure. It is shown that the applied stress intensity and time to failure have an inverse power law relationship in wires of cable bolts. Similar features are observed in both laboratory-failed specimens and the service-failed cable bolts under macroscopic and microscopic examinations, demonstrating the ability of the proposed framework to simulate failure of cable bolt subjected to SCC in the laboratory. Furthermore, the impact of stress intensity and hydrogen concentration on SCC are examined and a cohesive failure mechanism on the cable bolt SCC crack initiation, growth and catastrophic failure are presented. The proposed framework can be applied to the reinforcement materials for improved understanding of the SCC mechanism in underground mines and tunnels.

1. Introduction

The challenges of maintaining safe and productive excavation in rock continue to increase, particularly as more challenging geological conditions are encountered in deeper mines. Cable bolts are one of the dominant forms of high capacity support used in Australian underground coal mines (Chen et al., 2014, 2015; Galvin, 2016). Cable bolts and rockbolts are bonded to the rock strata and provide a clamping action across discontinuities within the rock, thus maintaining the load bearing capacity of rock strata and preventing the strata from collapsing (Hadjigeorgiou and Potvin, 2011; Kılıc et al., 2002; Li et al., 2016, 2017; Oliveira and Diederichs, 2017). Cable bolts having length of up to 10 m are widely used as permanent rock reinforcement due to their substantial flexibility and favourable mechanical properties in underground mines. They have been developed from swaged cables (Schmuck, 1979) to modified bulbed and nut-caged cables, which greatly increase their anchorage and load transfer capacity. Typically, rockbolts and cable bolts are installed in predrilled holes at regular spacing in the mine roof as part of the primary roof support system in development roadways (Dolinar and Martin, 2000). Cable bolts are also used for additional secondary support, installed at later stages of a mine operation.

Despite remarkable developments in cable bolting technology, failures are still observed in the cable bolts themselves, as well as within the grout, surrounding rock mass, cable-grout interface and grout-rock interface (Chen et al., 2016; Goris, 1990; Potvin et al., 1989; Windsor and Thompson, 1994). These failures not only compromise the safety of the working environments, but also reduce operational efficiency at the mines. Among these failure modes, the grout-rock interface failure is the most common while bolt failure is less likely to occur (Chen et al., 2016; Potvin et al., 1989). However, recent research has shown an increase in the frequency of bolt failure due to SCC (Crosky et al., 2002; Craig et al., 2015; Galvin, 2016; Chen et al., 2018; Wu et al., 2018). This is becoming a significant issue in many underground mines in

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* Corresponding authors.
E-mail addresses: saisai.wu@unsw.edu.au (S. Wu), honghao.chen@unsw.edu.au (H. Chen), PCraig@jennmar.com.au (P. Craig), h.lameiramandi@unsw.edu.au (H.L. Ramandi), w.timms@unsw.edu.au (W. Timms), p.hagan@unsw.edu.au (P.C. Hagan), a.crosky@unsw.edu.au (A. Crosky), b.hebblewhite@unsw.edu.au (B. Hebblewhite), s.saydam@unsw.edu.au (S. Saydam).

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Australia. SCC of anchorage systems was first noted in the 1990s after a series of roof collapses in the UK coal mines (Parrot, 1997; Arthur, 2006). However, this type of failure has been identified as a growing international problem over the past two decades in underground mines around the world (Craig et al., 2014; Arthur, 2006; Spearing et al., 2010; Kang et al., 2013; Hadjigeorgiou et al., 2008; Crosky et al., 2002; Kang et al., 2016). SCC is not only restricted to bolts that have been installed for a long time. Investigations have shown that SCC leads to failure of bolts which are less than 2 years old (Craig et al., 2015; Crosky et al., 2004, 2012). SCC occurs when a susceptible material is subject to consistent tensile stress, often induced on the bolt surface through a shearing action of the rock mass, while exposed to a corrosive environment (Elias et al., 2013a; Gray, 1998; Lynch, 1988; McCafferty, 2010; Vandermaat et al., 2012). Once a crack reaches the critical length at which the remaining area cannot bear the load, sudden and catastrophic overload failure occurs. In underground mines and tunnels the combination of geotechnical mining-induced stress and presence of groundwater are the factors responsible for the failure of the bolts (Crosky et al., 2002). SCC initiates and grows slowly orthogonal to the direction of applied stress on the bolts which may last months or years without any signs of damage (Gamboa and Atrens, 2003a; Vandermaat et al., 2016; Villalba and Atrens, 2007).

Numerous mechanisms have been proposed for development of SCC (Hertzberg, 1996; Jones, 1998, 1992) among which hydrogen embrittlement (HE) is known to be one of the predominant mechanisms that is involved in cracking of high strength steels (Gamboa and Atrens, 2003b; Perrin et al., 2010; Villalba and Atrens, 2009). For HE development, coexistence of hydrogen and metal in the environment is a key factor. In such an environment, hydrogen can degrade the mechanical properties of structural alloys. It reduces steel's ductility and degrades the fracturing behavior of steel by delayed cracking at a stress level below the yield strength. In the HE process, atomic hydrogen diffuses into the iron lattice and expands the metal lattice. Once hydrogen reaches a critical concentration, hydrogen-induced cracking may occur (Ćwiek, 2010). The sources of hydrogen in steel are many including charge neutralisation of the hydroxyl ions in acidic environments, liberation of atomic hydrogen by the iron-H_2S reaction, decomposition of water molecules, and corrosion processes (Ćwiek, 2010). Atomic hydrogen in the environment can react to generate gaseous molecular hydrogen or diffuse into the bulk of material as absorbed hydrogen (Coudreuse et al., 1997; Sharp et al., 2001). The hydrogen absorption rate is mainly influenced by surface adsorbates which are generally called recombination poisons. The recombination poisons promote hydrogen absorption by preventing atomic hydrogen from combining to form a hydrogen molecule. The ability of atomic hydrogen to diffuse into the steel is promoted (Biezma, 2001) when atomic hydrogen recombination is retarded. The amount of absorbed hydrogen is dependent on the condition of the metal surface. Furthermore, the grade, strength and microstructure of steel has a huge influence on the susceptibility of steel to hydrogen degradation (Tarui et al., 2002). It is shown that steels having a tensile strength greater than 1600 MPa are extremely susceptible to HE (Ćwiek, 2010). Cable bolts used in mines are manufactured using a cold drawing technique that provides cables with tensile strength in excess of 1800 MPa, which are therefore highly susceptible to HE. The cold work process increases the extraordinary sites in steel such as the vacancy concentrations and dislocation density (Toribio and Valiente, 2006). These extraordinary sites are susceptible for hydrogen accumulation, thus hydrogen concentrations at these sites are much higher than normal interstitial sites.

Another type of degradation that may cause corrosion and consequently SCC in steels is microbiologically influenced corrosion (MIC) in which anaerobic sulphate-reducing bacteria (SRB) play a crucial role (Biezma, 2001; Hamilton, 1985; Javaherdashti et al., 2006; Rao et al., 2000; Walch et al., 1989). Water samples collected near bolts that have failed by SCC have shown the presence of SRB in the mine environment (Vandermaat, 2014). SRB are able to oxidise sulphur or reduce sulphate to form free sulphuric acids. These bacteria can create a highly localised corrosive environment through the development of biofilms, which can be significantly different in terms of pH, dissolved oxygen (DO), and organic and inorganic chemical species to that of the bulk chemical media. The areas attacked by such organisms can have a local pH as low as 2–4 (Al-Nabulsi et al., 2015; Hamilton, 1985; Little et al., 2007). In underground spaces, regions such as clay bands or rock masses saturated with groundwater can provide anaerobic environments that are ideal for the bacteria to thrive in. One of the most significant products of SRB is hydrogen sulphide, which can react with rust to produce ferric sulphide. Evidence of the existence of ferric sulphide in the crust formed on the surface of bolts was found by Vandermaat (2014). Furthermore, hydrogen sulphide is a common hydrogen recombinant poison which would increase hydrogen absorption and accelerate the failure process (Oriani, 1985). This may account for the fast failure of some bolts, i.e. within two years of installation.

Several laboratory experiments have been carried out to examine SCC in anchorage systems. Satola and Aromaa (2003) conducted SCC tests using rebars and steel strands using a 2-point loading arrangement with a constant deflection. Specimens were loaded to 85% of yield strength while exposed to a wide range of corrosive conditions. However, they did not report any specimens failing by SCC. Aziz et al. (2014) performed laboratory experiments to recreate service failures using water collected from the Shoalhaven River in New South Wales (NSW), Australia. The bolts were loaded while the water was dripping and flowing freely over the bolt surfaces; nevertheless, no SCC failure was observed after 3.5 years. More recently, Vandermaat et al. (2016) developed a testing protocol to examine the SCC of full-scale rockbolts. The rockbolts under load were immersed in the groundwater collected from a mine site where SCC failures had been found. This testing program represented the most realistic system designed to investigate SCC in the literature to date although no sign of failure was observed after one year. It is unclear why SCC failure has not occurred in these simulated environments. However, it can be concluded that more complex factors are involved in SCC other than just the presence of groundwater. Hence, further investigation into cable bolt environments to identify suitable synthetic solutions, together with development of a testing system for simulating the SCC failure in the laboratory are required. These will assist in gaining insights into the cable bolt SCC failure mechanism through conducting relevant testing programs within a controlled laboratory environment.

The remainder of the paper discusses an innovative framework where SCC failure of cable bolts has been created in a laboratory using an acidified solution synthesized based on mine groundwater chemistry. Experimental conditions have been designed to accelerate SCC occurrence during sensible laboratory test durations. Intensity of applied stress on each specimen is measured and plotted against time to failure. After failure, the fracture surfaces and adjacent sub-critical cracks of the laboratory-failed and service-failed cable bolts are examined using a scanning electron microscopy (SEM). Hydrogen concentration measurement in unused and failed bolts is employed to further assist in understanding the failure mechanisms leading to SCC of cable bolts.

2. Materials and methods

2.1. Synthesized solution

To prepare a synthesized solution for laboratory testing of SCC, water samples are collected from roof bolt drippers installed at twelve underground coal mines in Australia where SCC failures has been previously reported. The major ion concentrations in the water are analysed by the UNSW Mark Wainwright Analytical Centre using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). The water chemistry of the mines, presented in Table 1, demonstrates that the groundwater samples are characterized by low concentrations