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Examination of rockbolt stress corrosion cracking utilising full size rockbolts in a controlled mine environment

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ABSTRACT

Previous studies had identified that a testing protocol was required to examine stress corrosion cracking (SCC) of full sized rockbolts under simulated *in situ* conditions. As a result, a load frame capable of inducing both tensile and bending loads on a rockbolt specimen, erected within a controlled mine environment (CME) laboratory was constructed. The newly designed and purpose built Bend and Tension Loading Apparatus (BaTLA) was used to conduct both static and slow strain rate (SSR) tests on rockbolt specimens in an acidified sodium chloride solution containing hydrogen sulphide in the CME. It was found that SSR testing provided an appropriate analogue for examining rockbolt susceptibility to SCC and was thus used to examine the effect of grit blasting, galvanising and varying steel grades on the SCC resilience of rockbolts. Of these, 300 grade steel and galvanising provided the most promising resistance to SSC, while grit blasting provided a 40% improvement in resistance compared to untreated HSAC 840 grade rockbolts.

1. Introduction

Stress corrosion cracking (SCC) is a material failure mechanism characterised by the growth of fine dendritic cracks through the cross section of a material. SCC occurs when a susceptible material is exposed to a corrosive environment while subject to a high tensile stress. The resulting crack growth is orthogonal to the direction of applied stress, and continues until it is of a sufficient length to result in the catastrophic failure of the material by mechanical overload that is characterised by brittle fracture. SCC is not necessarily accompanied by significant surficial corrosion and is thus, easily overlooked in general inspection of engineering structures. Its insidious nature means that its impact on the mining, energy and construction industries, as well as the economy at large, is likely to be underestimated [1]. The typical fracture surface of a rockbolt that failed due to SCC can be seen in Fig. 1.

SCC of rockbolts was first noted to occur in the 1990s after a series of falls of ground in UK coal mines [2,3]. SCC was subsequently identified in an Australian underground coal mine during the mid-to-late 1990s [4]. This resulted in a field based study conducted through UNSW Australia (formerly known as The University of New South Wales) that identified approximately nine mines as being potentially affected by rockbolt SCC [5,6].

This study showed that SCC was more prevalent in mines having thick coal roofs, particularly if clay bands or strata shearing in the bolting horizon were present. Furthermore, rockbolts were more susceptible to SCC if made of high tensile, low toughness steel. Finally, it was observed that the presence of some water in the roof strata was necessary to cause SCC.

A more recent study conducted in China identified SCC as being one of many issues affecting rockbolts in the underground Chinese coal mining industry [7]. Furthermore, anecdotal evidence, which is beginning to prompt serious research in the United States [8], has indicated that rockbolt SCC is a globally pervasive phenomenon, affecting rockbolts in a wide range of mining conditions.

Notable laboratory based testing of SCC in rockbolts has been carried out by Atrens et al. [9–15]. They focused on the use of a Linearly Increasing Stress Test (LIST) at a rate of 0.019 MPa s^{-1} using highly acidic testing solutions ($pH = 2.1$) and small scale samples made from rockbolt steel. The synthetic testing solutions were described as being "*characteristic of chemistries that might be found in underground water samples at mine sites*" [13]. However there was no basis or citation given to justify its use. They used this testing arrangement to investigate a wide range of steel chemistries used in the manufacture of rockbolts.

Another study carried out aimed to assess the suitability of the German standard DIN 50929 to predict corrosion of rockbolts in underground mines [16]. Part of this study focused on SCC of

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Fig. 1. A rockbolt affected by SCC. The area of initial crack growth can be seen as the dark brown section on the left hand edge of the failure surface. On this rockbolt, several cracks have initiated simultaneously and have overlapped during their growth. The remaining failure surface can be seen as speckled silver and grey, indicating brittle fracture.

rockbolts and utilised 6 mm diameter re-bar, as well as several strands of cable bolt wires as test specimens. They employed a two-point bending arrangement as described in ASTM G39 and exposed the specimens to a wide range of corrosive environments. This study did not report any specimens failing by SCC, however they did note that transverse cracking was observed on several of the specimens [16].

More recently, Aziz et al. attempted to recreate *in situ* service failures and investigated possible environmental and metallurgical factors responsible for rockbolt SCC in the laboratory [17]. Here, the rockbolts were loaded both axially, and with an applied torsion stress. They were exposed to water collected from the Shoalhaven River in New South Wales, Australia, that was allowed to drip on to and flow freely over the surface. This test represents the most realistic arrangement in investigating rockbolt SCC in the literature to date, however after a duration of 3.5 years, no SCC failures were reported in this testing program. It is unclear why failure was not obtained in this testing protocol, however it may be linked to the water samples used (river water as opposed to mineralised ground water), the testing duration or the level of applied stress.

With the exception of Aziz et al. [17], all of the aforementioned investigations have focused on the use of either reduced size or smooth surface specimens made from rockbolt stock material. The advantage of this is that small samples are easier to load and manage, however several issues are raised by this approach. In particular, the use of reduced size specimens for experimentation usually results in a focus on the bare steel core within, meaning that: the effects of mill scale and decarburisation associated with the manufacturing process are not examined; the effects of large surface geometries such as ribs, and smaller surface defects such as laps and burrs, are neglected; and machining practises used in sample preparation may result in unwanted residual stress or heat treatment in and on the surface of the test specimen.

It is known that surface features such as mill scale can have an effect of the corrosion performance of a material [18], and is likely to impact on SCC initiation and propagation mechanisms. The use of full-sized test specimens examines the full range of factors otherwise excluded through the use of reduced-size specimens. As a result, a novel laboratory based investigation into SCC of rockbolts through the use of full-sized specimens was developed and is presented in this paper. The investigation required the design and construction of new laboratory testing equipment in order to recreate the service conditions experienced by rockbolts *in situ*.

This paper will be presented in three sections. Firstly, a description of the laboratory and testing equipment design. Secondly, details and results of the bend testing protocol. Finally, details and results of the tension testing protocol.

2. Laboratory and equipment design

In order to investigate the phenomenon of SCC in rockbolts in underground coal mines, a testing laboratory capable of recreating the service conditions experienced by rockbolts was required. As a result, a Controlled Mine Environment (CME) laboratory was constructed at UNSW Australia to maintain temperature and humidity conditions throughout testing. Temperature was maintained between 20 and 23 °C, and humidity between 80 and 85% RH.

In order to carry out SCC experimentation, an apparatus capable of simulating the loading conditions experienced by rockbolts *in situ* was required to induce a stress to the rockbolt test specimens. This required the apparatus to be versatile and allow for multiple loading arrangements. It was identified that the load placed on rockbolts would result in a combination of tensile- and shear-stresses when installed underground. As a result, a loading frame capable of reproducing these two loading scenarios was considered. However, due to the technical difficulties associated with designing and manufacturing an apparatus capable of generating 'true shear' loading conditions, it was decided to examine axial and bend loading instead.

The bend test was chosen in an attempt to simulate the tight radius of deformation generated in a bolt during shear loading. Although the radius produced by the bend test is not as sharp as what is experienced during a true shear-loading event, the principle of generating an interior and exterior radii is achieved. Thus, the final loading assembly was named the Bending and Tension Loading Apparatus (BaTLA). A total of six BaTLA frames were constructed and used in this study.

The BaTLA is composed of two parallel, upright C-Section steel supports, and held together at the top and bottom by 4 cm thick steel end-plates. These end-plates were drilled to facilitate insertion and removal of rockbolts from the apparatus. Within the apparatus is housed the bend loading assembly, comprised a lateral loading screw, lateral loading arm and two rolling contacts. The apparatus also contains two rotating support pins at the top and bottom that provide the reaction force for both the tension and bend test arrangements. Schematics of the BaTLA can be seen in Figs. 2 and 3. Details of the BaTLA's design components are described by Vandermaat et al. [19,20].

Preliminary and long duration testing were conducted on rockbolts exposed to mine water. Later, an acidified sodium chloride solution containing hydrogen sulphide was used. This was an acidic solution and its composition is described in Table 1. This solution is known to cause SCC in carbon steel and has been used in the past to examine SCC in rockbolts [2] and was thus used in order to validate the testing design. It had earlier been identified in a study that solution quality tends to degrade over time, and chemical species within the solution will migrate towards steady state conditions [8]. To ensure uniform solution quality over the long testing duration used in the test program, a batching system