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Stress corrosion of rockbolts in Australian coal mines

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ABSTRACT: Stress corrosion cracking (SCC) has been reported to be a significant cause of premature failure of rockbolts in Australian coal mines [1]. At some mine sites, failure of rockbolts due to SCC has occurred well within the twelve to eighteen month design life of longwall gateroads. Failure is often associated with installations in coal and carbonaceous shales containing clay bands. The use of very high tensile grade steel is commonly used in many of these mines and it is thought that the low impact toughness of this steel may be a significant contributor to SCC failure. While laboratory corrosion studies have been undertaken to assess the metallurgical influence on SCC, the results do not correlate with field observations. A possible contributor to the enhanced incidence of premature failure in recent years may be due to the increase in extraction width from 250 m to 400m in many Australian longwall mines that can lead to an increase in the loading on the rockbolt. This paper examines the current state of knowledge concerning rockbolt failure in Australian coal mines.

1. INTRODUCTION

Australia is the world's largest exporter of coal worth nearly $A22.5 billion in export earnings in 2006-07. While longwall mining accounts for approximately only 18% of total coal production, this proportion is likely to increase as surface open cut operations reach their economically viable limits [2]. The incidence of stress corrosion cracking (SCC) of rockbolts has been reported in several of the thirty-odd longwall mines operating in Australia, with at least three mines reporting a high incidence of premature failed bolts [1].

The School of Mining Engineering at the University of New South Wales has recently commenced a research project into SCC of rockbolts in Australian coal mines.

The objectives of the project are to identify the environmental causes of SCC and ultimately provide a tool for the identification of SCC high risk environments within a coal mine. The subsequent knowledge and understanding gained about the SCC environment will be applied in building a laboratory facility for testing of various rockbolts. The laboratory facility will enable the development and testing of new coal mine rockbolts to withstand SCC.

2. ROADWAY STRESSES IN AUSTRALIAN LONGWALL MINES

The extraction of coal using the longwall coal mining system involves large areas of coal some 250m wide by 2000m long which need to be initially blocked out. These areas are delineated by development tunnels or roadways driven within the coal using Continuous Miners or similar coal cutting machinery. The roadways are cut into the near horizontal coal seam forming a rectangular profile. Weak to moderate strength sedimentary rock layers are present in the roof and floor of the roadway, typically these include shales, claystones, siltstones and sandstones.

Over the years various means have been employed to ensure the stability of these roadways and other underground excavations as the surrounding rock mass is subjected to high levels of stress. In more recent times accepted practice is to install fully encapsulated rockbolts to reinforce and enhance the natural strength of the surrounding rock mass.

Many factors contribute to the magnitude of the high stress seen in the rock mass. For example when the longwall is in operation, the shearer cuts coal from the seam while hydraulically actuated shields provide temporary support. After the longwall passes, the roof collapses filling the void. This failed zone has little ability to carry the vertical stresses resulted from the deadweight of the overlying strata, consequently the load must be redistributed to the perimeter of the longwall which include the adjacent roadways [3].

In addition to vertical stresses, the rock mass in most of the coalfields in eastern Australia is subjected to high horizontal stresses induced by tectonic forces within the earth's crust. These stresses are re-distributed around the typical 250m wide longwall extraction. The horizontal stresses act to form a circular more stable opening. These stresses though can cause the bedded sedimentary rock layers to bend and buckle under this stress re-distribution around the roadway.

Rockbolts are installed across the bedded rock layers to reinforce the rock by tying together the rock layers so as to resist bending and buckling. Installation of a rockbolt involves first drilling into the rock after which a steel rebar bolt is inserted together with high strength two part polyester resin that encases the rockbolt. The resin provides a bond or coupling of the steel rebar to the surrounding rock mass. The rockbolts vary in length between 1.5 and 3 m. Dimensions of size and weight are limited to enable manual handling but with increasing stresses and need to reduce the incidence of rock falls the industry has moved to using higher strength steels.

As the rock layers undergo deformation, the resultant load induced or transferred to a rockbolt can be high. Deformation can sometimes result in cracking of the resin leaving it free to the ingress of fluids. Ground water often carrying dissolved minerals and gases from the surrounding rock mass can migrate along these cracks and can come into contact with the exposed section of the steel bolt. Interaction between the fluids and steel can lead to corrosion of the highly stressed rockbolt that can eventually lead to failure via the mechanism termed SCC.

3. SCC IN ROCKBOLTS

The typical failure surface of a rockbolt that has been subjected to SCC is shown in Figure 1. This figure illustrates typical brittle failure of a rockbolt which was initiated from a small crack at the bottom of the bolt; as evident by the lines radiating from crack. The failure surface is essentially flat and at right angles to the applied stress.

Fig. 1**.** View showing evidence of brittle failure of a rockbolt [1].

Failed rockbolts often indicate only limited plastic deformation. Typically the rockbolts are seen to have been subjected to brittle failure due to the growth of cracks associated with corrosion as indicated in Figure 2. Figure 2(a) shows cracks as revealed by Magnetic Particle Impregnation (MPI) on a rockbolt: note that cracks usually initiate at stress raisers such as the base of ribs on a hot rolled bar. Figure 2(b) indicates the SCC which developed at the base of a rib on a hot rolled rockbolt. This would cause a drastic reduction in bolt strength and probably led to brittle failure of the bolt: note the steel bar is white and the rib extends up to the top right hand corner [1].

In Australian coal mining, strata control practise focuses on achieving a high bond strength between the rockbolt and borehole surface to create a stiff reinforced beam to support the immediate roof above the roadway. To achieve this stiff reinforcement the size of the resin bond annulus is minimised in an attempt to ensure the ribs of the rebar place the resin into compression against the sidewalls of the borehole. This approach has been adopted at all Australian underground coal mines. It is an approach though that contrasts with the hardrock mining and civil tunnelling sectors where they attempt to achieve a thicker annulus.

While contributing to a stiff member, the thinner resin annulus can result in the rockbolt being more exposed to water ingress and hence susceptible to the effects of SCC. Traditional ground anchor corrosion protection is reliant on a plastic sleeve which inhibits water ingress. However this tends to reduce bond strength and also requires a larger annulus.

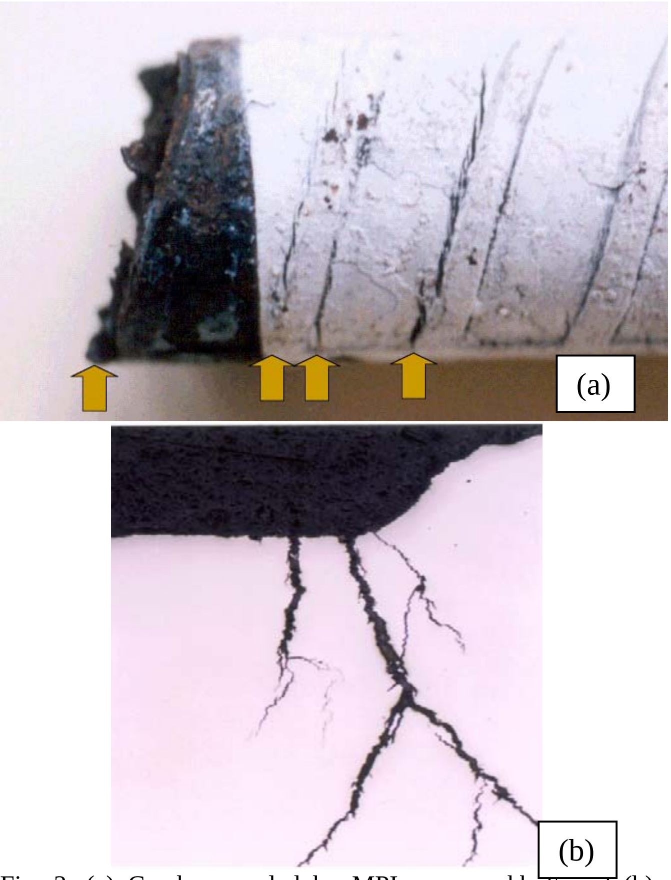

Fig. 2. (a) Cracks revealed by MPI on a rockbolt and (b) indications of SCC that developed at the base of a rib on a hot rolled rockbolt [1].

A disadvantage of full length resin bonded rockbolts is that it makes it more difficult to detect failed rockbolts. Currently, there is no reliable non-destructive test method available that is in regular use; hence there is no means presently available to quantify the magnitude of the risk of roof failure in underground coal mines.

Consequently, one hazard stemming from SCC is a breakdown in the reinforcement member that can eventually lead to a fall of ground with the possible resultant outcomes of damage to infrastructure, lost production and death and injury of operators.

The risk of a roof fall is exacerbated in an active longwall roadway subject to high stresses associated with longwall extraction. Typically the longwall face is accessed by two roadways, one for the conveyor belt and the other for operators and materials. A roof fall in either can result in a number of undesirable consequences especially for operators who travel along these roadways. If the fall of ground occurs on the main conveyor belt it can stop production. A fall can also block emergency exits or even general access to the underground workings of the mine as well as create many secondary risks of lost ventilation and power to the face.

The downtime with a fall of ground can equate to lost production from downtime of the longwall of up to A$1M per day, requiring anywhere from three days to three months depending on the severity of the fall to recover access through the roadway not to speak of equipment damage.

4. PREVIOUS RESEARCH INTO SCC OF ROCKBOLTS

4.1. The Australian Coal Association Research Program 1999-2002 project

The earliest research in this area was conducted in the late 1990's and early part of this decade. Between 1999 and 2002 a study titled *Premature Rockbolt Failure* was undertaken in Australia funded by the Australian Coal Association Research Program (ACARP), Project No. C8008 [1]. The project measured the incidence of prematurely failed rockbolts in Australian coal mines. It identified that the problem was not isolated to specific cases but more widespread and occurred to varying degrees in different geology, ground water and in different rockbolt steels. The study concluded that the factors that were likely to contribute to SCC were:

- roof lithology containing clay bands and thick coal sections;
- presence of groundwater;
- use of high tensile steels - approaching 1000 MPa tensile strength; and
- possibility of bacterial corrosion.

The project found that it was often difficult to identify prematurely failed rockbolts and therefore to quantify the scale of the problem. Trialling of non-destructive testing devices, many of which were still in development, was undertaken and highlighted the potential for ultrasonic testing of in-situ steel bolts to identify failed rockbolts.

One particular focus of the study was steel composition and resulting mechanical properties. There was a high incidence of failed rockbolts that were of high carbon steels having low impact toughness.

Although useful in highlighting SCC as a potential issue in coal mines, the scope of the project was limited to considering only failure analysis of broken rockbolts that had been recovered from mine sites. The study did not address the possible environmental factors impacting on SCC.

The final ACARP report suggested that seven critical issues needed to be addressed, these included the following.

1. A comprehensive field evaluation of non-destructive test devices for rockbolts.

2. Development of metallurgy and corrosion surface test procedures and database expansion.
3. An investigation and documentation of the properties of new steel products.
4. An investigation into the extent of potential bacterial corrosion of rockbolt steel and possible remedial actions.
5. Development of industry guidelines to minimise SCC problems, including bolt and steel traceability.
6. Documentation of the extent of brittle failures of rockbolts in threaded sections with regard to hanging structures from roof bolts.
7. Introduction of an Australian standard for rockbolts specifying a minimum toughness level.

4.2. UK Coal Project

Similar results to the ACARP study were found with comparable steels in a study undertaken in the late 1990's in the UK coal mining environment [4].

In this case the focus of the study was primarily on the metallurgical aspects of SCC. The failure mechanism associated with crack growth leading to sudden brittle failure was investigated. This led to the development of a British Standard that requires all high tensile rockbolts to have a minimum impact toughness of 23 Joules as determined by the Charpy "V notch" test. The chemistry of such steel requires special attention to achieve high impact toughness with an attendant higher cost of manufacture.

4.3. Australian Research Council

In response to recommendations in the ACARP report [1] to benchmark rockbolt steel performance for toughness, the Australian rockbolt and steel manufacturers partnered with the University of Queensland in an Australian Research Council (ARC) Linkage Project titled *Metallurgical influences on stress corrosion cracking of rockbolts* – Project No. LP0453646. This project was completed in 2007.

The study focussed primarily on metallurgical influences and assumed hydrogen imbrittement was the main mechanism of crack growth that led to premature failure by SCC.

The study encompassed laboratory tests using machined blocks of different steels rather than actual cold-drawn rockbolts. The steel samples were subjected to a Linearly Increasing Stress Test (LIST) [5]. A corrosive environment was created involving a low pH solution and an electrochemical potential applied to promote hydrogen embrittlement.

The study showed that low carbon microalloyed steels which have high impact toughness were susceptible to SCC. However high carbon steels and cold worked steels were less likely to succumb to SCC. It was stated that the conflicting findings between the laboratory results and the field evidence suggest that the testing technique may not be the best approach [5].

5. WHERE TO NEXT?

The Australian underground coal mining industry has a significant stake in better understanding SCC. Once the mechanisms are identified and the factors that control it understood then it effects can be better managed to limit or better still eliminated thereby ensuring the design life of rock support systems can be achieved and hence improving the integrity of underground excavations.

A number of industry players including three coal mining companies and a rockbolt manufacture have expressed support for a proposed joint research project.

The proposed three year project will have laboratory and field test components.

Initially data will be collected from the field which can be used to characterise the geological and geochemical environment including determining the quality of ground water and quantity of water inflow in selected active mining areas. At least three mine sites in different coalfields will be targeted in an effort to consider a range of geological conditions.

The characteristics of the rockbolts installed at the mine sites will be recorded including for example steel grade, amount of pretension and type of resin.

The proposed field work will involve:

- collecting ground water samples and obtaining rock core samples;
- monitoring of the roof displacement; and
- use of various non-destructive rockbolt testing equipment to monitor the rockbolts.

It is also proposed that ground water samples will be collected from the field test sites every quarter during the first year, as often ground water ingress about a roadway can reduce and change in physical appearance over time. The collected water samples would be analysed to identify the corrosive elements and any changes in concentration with time. The geological characteristics of the surrounding rockmass will be analysed and logged at each site.

This will be repeated at three monthly intervals over 24 months. At the end of this time, a number of rockbolts will be overcored and recovered for metallurgical analysis.

The main roof response measurement used by many mine site geotechnical engineers is roof displacement but without possible correlation to stresses induced in the rockbolts. Currently there is no proven non-destructive means of determining the integrity of fully bonded rockbolts though these types of testing technologies have steadily developed over the past decade. The use of some of these devices will be assessed during the field tests. The use of such tools may become vital in future assessments of the effectiveness of newly developed corrosion resistant roof control products.

The current project proposal will also include testing of same steels which was used in the Gamboa and Atrens study [6, 7]. These steels will also be used in the field trials and to calibrate the developed laboratory test method.

Metallurgical failure analysis will be conducted on both recovered rockbolts from the field and laboratory.

6. CONCLUSIONS

The recent resources boom has seen many new coalfields under development or consideration, and many existing mines expanding into more difficult mining areas. The conditions experienced at some operations are likely to require remediation from SCC with some means of providing corrosion protection. Consideration is sometimes given to using such products as galvanised bolts but there is little evidence of its efficacy.

Some mining operations have experienced such severe ground conditions that many millions of dollars are spent on rehabilitation of existing main access roadways to ensure continuity of operations. Further expenditures are incurred to increase the density of ground support along highly stressed longwall development roadways to prevent ground failures.

The methods of corrosion protection for coal mines must be designed around a small resin or grout annulus that is integral to the coal mine rockbolt system.

Corrosion protection in the hardrock and tunnelling industries is often based on creating a barrier to fluid ingress such as using polymer coatings and/or sleeves around the rockbolts. These approaches are not suited to coal mining as they reduce the stiffness of the reinforcement system and do not allow for load transfer. The material properties of polymers have a possible de-bonding effect likewise with the plastic sleeve [8].

In order to progress knowledge on the failure mechanisms associated with SCC, a project is proposed that not only aims at determining the chemistry or biology behind corrosion in coal mines but aims at developing an accelerated corrosion testing method to simulate the underground coal mine environment. It is anticipated that once the factors have been determined then the project will target the testing of various corrosion protection techniques that could be used in Australian coal mining roof control practices. The potential benefits of this study is to develop better support systems to reduce the incidence of roof falls, savings on cost on rehabilitation of long term roadways, improved productivity in underground coal mines.

Knowledge of the chemical processes leading to Stress Corrosion Cracking is required before development of suitable products can proceed. The development of a laboratory test method specific to the coal mining environment is critical in developing products that are compatible with the high stress environments often found in coal mines and the life span requirements of its roadways.

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