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Development and evaluation of corrosion resistant coating for expandable rock bolt against highly corrosive ground conditions

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ABSTRACT

Expandable rock bolts are widely used in hard rock mines as an efficient ground control product. However, capacity and service life can be significantly reduced if the metallic body is subjected to corrosion. In some hard rock mines in the U.S., highly corrosive ground conditions exist, and it has been reported that inflatable rock bolts have corroded within a few months after installation. To provide mining industry a cost-effective inflatable bolt and combat the corrosion issues, Jennmar Corporation, Inc., and its subsidiary Keystone Mining Services, LLC (KMS), analyzed corroded bolt samples, identified root causes, evaluated properties of various coating materials, and developed a new inflatable rock bolt, Python M3™, that is protected with an innovative PyFlexU2™ coating. The new generation Python M3™ features improved steel chemistry for reliable performance, modified profile for better inflation, and surface preparation and coating application. The PyFlexU2™ is impervious to liquid and air, durable, and UV resistant. With a flexible, adhesive, and highly corrosion-resistant undercoating, and a very hard sacrificial surface coating, the PyFlexU2™ coating system provides the Python M3™ superior protection against chemical corrosion and physical scratch damage. The under-coating has exceptional flexibility and adhesion to prevent coating micro-cracks or fractures after bolt inflation and possesses excellent corrosion resistance to acids (pH < 3), alkalis (pH > 11), fuels, and salt solvents. The corrosion and scratch resistant PyFlexU2™ coating offers very effective bolt protection for extra longevity in highly corrosive environments. The Python M3™ coated with PyFlexU2™ has been tested in the most challenging conditions, including laboratory corrosion tests in extreme acidic and basic solvents, rock slurry, and borehole scratch insertion tests. With demonstrated corrosion and scratch resistance, the product has been greatly welcomed by hard rock mines in the West and is currently installed in large scale. This paper identifies the root causes of the bolt corrosion, discusses the analysis process, and details laboratory and underground tests carried out on the Python M3™ coated with PyFlexU2™. The Python M3™ and PyFlexU2™ are subjects covered by pending U.S. Patent Applications assigned to FCI Holdings Delaware, LLC.

1. Introduction

Expandable rock bolts have been widely used for rock reinforcements, particularly in underground hard rock mines, for over 35 years due to low cost, easy installation, effectiveness, and favorable deformability in shear mode. An expandable rock bolt, such as Python, is made of a steel tube that is folded into an Omega shape in the cross-section (Fig. 1). During installation, the bolt is inserted into a borehole and inflated with high pressure water. The inflated tube generates frictional full-length anchorage due to contact stress and mechanical interlock at the bolt-rock interface.

However, support capacity and service life of an expandable rock bolt can be significantly reduced if the metallic body is subjected to corrosion. Grounds containing sulfur or chloride content, when exposed to air and water, can produce acidic environments, which quickly initiates metal corrosion and reduces the effective strength and diameter of the bolt body. Under such conditions, a rock bolt will deteriorate rapidly. Prior studies indicate that the ultimate strength of a rock bolt dropped significantly due to pitting or stress corrosion cracking [1]. The bolt corrosion problem in certain geo-environments becomes so severe that it can cause failure of the reinforcement. In some hard rock mines in the U.S., highly corrosive ground conditions exist, and it has been reported that expandable rock bolts have corroded within a few months after installation. The unexpected bolt failures have resulted in roof falls, interrupted mining production, and have forced the mine operator

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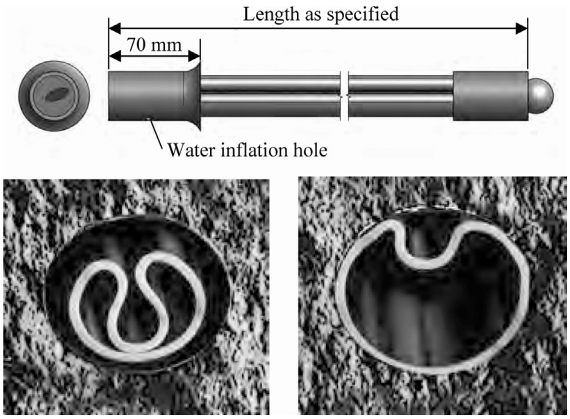

Fig. 1. Expandable rock bolt (Python by Jennmar).

to perform expensive and strenuous rehabilitation on a regular basis due to safety hazard concerns.

In the past, the mining industry commonly relied on either a cathodic sacrificial coating (zinc galvanization, zinc epoxy, etc.) or barrier-type coating (epoxy, polyurethane, plastic, etc.) to protect the expandable rock bolt. However, in highly corrosive conditions, both coating systems are either ineffective or vulnerable due to micro-cracking or splitting of the coating during bolt inflation, or scratch damage of the coating during bolt insertion. Zinc in the cathodic sacrificial coating, such as galvanized finish or zinc epoxy, is an excellent corrosion-resistant protection in alkaline conditions but performs poorly in an acidic environment. The barrier-type coating will not provide bolt body a good protection against corrosion unless the coating material is inherently stable in extreme acidic condition and stays intact during bolt insertion and expansion. For example, there is evidence that the polymeric coating "Obdura AP" is ineffective due to coating micro-cracking during inflation and its inherent vulnerability combating extreme acidic conditions [2]. It is technically difficult to develop a barrier-type coating for an expandable bolt that requires a significant amount of flexibility and a great deal of surface hardness to resist scratches.

To provide the mining industry a cost-effective, expandable rock bolt and combat the corrosion issues, Jennmar Corporation, Inc., and its subsidiary Keystone Mining Services, LLC (KMS), analyzed corroded bolt samples and ground condition, identified root causes, evaluated properties of various coating materials, and developed a new rock bolt Python M3™ that is protected with an innovative PyFlexU2™ coating.

The new PythonM3™ features improved steel chemistry for reliable performance, modified profile for better inflation, and surface preparation and coating application. The PyFlexU2™ is impervious to liquid and air, durable, and ultraviolet (UV) resistant. With a flexible, adhesive, and highly corrosion-resistant undercoat and a very hard sacrificial topcoat, the PyFlexU2™ coating system provides the Python M3™ a superior protection against chemical corrosion and physical scratch damage. The Python M3™ coated with PyFlexU2™ has been tested in the most challenging conditions, including laboratory corrosion tests in extreme acidic and basic solvents and borehole scratch insertion tests in the field. With demonstrated corrosion and scratch resistance, the product has been greatly embraced by hard rock mines in the U.S., and is currently in large-scale usage in the mining industry.

2. Corrosion root cause analyses

To identify root causes of corrosion failure of the expandable rock bolt, field samples, including corroded bolt samples and relevant rock samples, were collected from collaborating hard rock mines and tested in Jennmar Research Center in Pittsburgh, PA.

2.1. Inflation test of expandable rock bolts

If the coating is not flexible enough, the coating in vicinity of the folded area of the expandable bolt can be prematurely damaged during inflation. To verify the hypothesis, bolt samples were collected and inflated in an unrestricted manner.

Prior to the test, the samples were visually checked, and the coating on all of the samples was fairly uniform and free of any pre-existing damages. Visual inspection after inflation indicated that some samples showed micro-cracks and large cracks at the shoulder area, as shown in Fig. 2. The coating was cracked, debonded from the base metal, and could be peeled off. In addition, a series of micro-cracks occurred on two shoulder areas almost along the entire bolt length. Preliminary laboratory inflation tests indicate that, if there is a lack of sufficient flexibility, coating failure could occur during bolt inflation.

2.2. Analysis of field bolt sample

It is reported that the expandable bolt rusted quickly (within months), could be pulled out manually, and the coating flaked off. Fig. 3 shows the corroded Omega-AP bolts recovered from underground. By visual inspection, it appears that the corrosion is worse at the tongue and shoulder of the previously folded area than at the back of the bolt.

To identify primary corrosion chemical species and corrosion mechanisms, the field bolt sample was analyzed via scanning electron microscopy/energy dispersive spectroscopy (SEM/EDS) of the rust on the field sample. The corrosion analysis indicates that the following:

(1) The sample experienced a semi-uniform and pitting corrosion. The contact pH measured approximately 5.5 on the bolt surface.
(2) Analysis of the corrosion products collected from the corroded bolt surface via back scattered electron (BSE) images and EDS spectra (Fig. 4) indicated that the corrosion products contain significant amounts of sulfur and chlorine.
(3) Data collected indicate that, with the chlorine detected primarily at the corrosion front, chloride corrosion is likely the primary driving mechanism.
(4) It was concluded that the failure appeared to be environmentally governed and caused by corrosive attack by acidic ground conditions.

2.3. Evaluation of corrosive ground condition

To evaluate the corrosiveness of the strata that the expandable rock bolt was subjected to, rock samples were collected from nine different sites that are considered representative of corrosive ground conditions in the collaborating mine. The rock samples were evaluated for pH units per EPA Method 9045D, sulfate analysis per EPA Method 3050B, acidic digestion, and chemical composition using Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) following EPA Method 6010C. Table 1 are the test results of pH units and sulfate concentration.

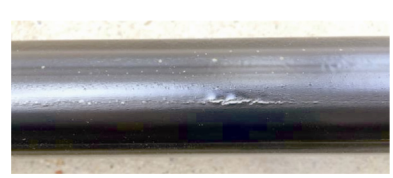

Fig. 2. Coating cracks due to bolt inflation (Omega-AP).