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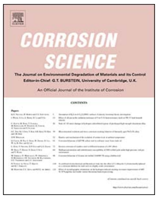

Effects of environmental factors on stress corrosion cracking of cold-drawn high-carbon steel wires

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ABSTRACT

Premature failure of cable bolts due to stress corrosion cracking (SCC) is a phenomenon that has reported to occur in underground environments. This paper presents an experimental study to determine the impacts of environmental factors on SCC in high-carbon steel cable bolts used in ground support system. The service life of the wire strands was measured under a range of accelerated SCC conditions using three- and four-point loading jigs. Fractographic analyses of the fracture surfaces of the failed wires displayed typical features indicating that hydrogen embrittlement was involved in SCC in these tests. It was shown that the presence of hydrogen sulphide is more critical than its concentration in SCC. The pH and level of applied stress were determined to have a direct impact on the occurrence of SCC. The deflection angle of the crack path was observed to be an inverse polynomial function of the applied stress level in the wire. This demonstrated the significance of the stress level on the fracture mechanism of cable bolts. Furthermore, the use of a protective galvanised coating on cable bolts was found to be a promising countermeasure against SCC. The results of this study provide detailed insight into the environmental factors involved in SCC of high-carbon steel wires and can be further used for setting guidelines for assessment of environments which cause susceptibility to SCC.

1. Introduction

Stress Corrosion Cracking (SCC), which is a type of environmentally assisted cracking, is a degradation process where the resistance of metals and alloys to crack initiation and growth is significantly lowered, and can consequently lead to catastrophic failure of structural components [1,2]. SCC is more threatening than traditional cracking failure because it leads to abrupt, brittle failure of structures prior to expected ultimate elongation. There are three contributing factors that cause SCC including a susceptible material, stress and a corrosive environment. This makes the SCC mechanism quite complex as it depends on the type and level of stress, material and medium properties [3,4]. SCC in prestressed concrete structures has been widely studied and has greatly increased the knowledge of the understanding causes and mechanisms of SCC failure. Several SCC mechanisms have been proposed to account for the brittle failure of metals or alloys under the synergistic effects of stress and corrosive medium including anodic dissolution [5,6], film breakdown [7], surface mobility [8], surface diffusion in a stressed solid [9], and hydrogen embrittlement (hydrogen assisted stress corrosion cracking) [10–12]. However, the exact mechanism of SCC in some critical environment-material combinations is still unknown [2,13,14].

Cable bolts are increasingly being relied on as high capacity supports in underground mines and tunnelling projects because of their substantial flexibility and favourable mechanical properties [15–17]. Cable bolts 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 them from collapse [18–22]. One of the earliest references noting SCC as an issue affecting underground support system was by Gray [23] who noted that rockbolt failures occurred at stress levels less than the material's ultimate tensile strength and determined the cause of failures to be SCC. Later, Crosky, et al. [24], Craig, et al. [25] and Craig, et al. [26] reported an increase in the frequency of ground support system failure due to SCC in underground coal mines in Australia. Corrosion-induced failure has also been reported in many countries around the world [27–30]. Following this, extensive research into SCC of support system has continued; however, the literature about SCC of cable bolts in underground mine

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environments is still limited. SCC is not restricted to old bolt installations, which have been in service for long periods, but can also effect the newly installed bolts with a service life of less than two years [26,31,32]. SCC not only compromises the safety of working environments in mines but also reduces their operational efficiency.

One of the determining factors for SCC occurrence is the chemical species within the environment [33]; hence, it is essential to understand the influence of individual chemical species that exist in the mine environment on SCC process. Previous studies have shown the existence of sulphate reducing bacteria (SRB) in the crust formed on the surface of rockbolts in underground coal mines [26,34]. These types of bacteria can create a highly localised corrosive environment through the development of biofilms; the areas attacked by such microorganisms can have a local pH significantly different from that of the bulk medium [35–37]. One of the most significant products of SRB is ferric sulphide (Fe_2S_3) which is also contained in the crust formed on the surface of the bolts. It was found that an acidified solution containing sulphide as an agent can be used to accelerate the process simulating *in-situ* SCC in the laboratory [38]. Although, in the last two decades, SCC of cable bolts in underground coal mines has been recognised as a serious issue, the significance of load bearing capacity of cable bolts and the influence of individual chemical species found in the mine environment on SCC is not well studied. From the viewpoint of SCC prevention, it is reported that a galvanised coating can effectively protect the steel from general corrosion [38–40]; however, its role against SCC of cable bolt wires is not known.

This paper details the specific environmental parameters that affect SCC of cable bolts, and also explores the role of galvanising in preventing or prolonging the service life of cable bolt. Three- and four-point loading jigs were prepared and a wire extracted from a cable bolt was placed into each jig. Each jig was adjusted to apply a different level of stress to simulate the wide range of stress levels encountered in underground mines. These jigs were then immersed into acidified solutions with different pH and sulphide concentrations. The time to failure with change of each parameter was measured to quantify the influence of individual parameters on SCC. Furthermore, fracture surfaces and adjacent sub-critical cracks of the failed galvanised specimens and non-galvanised specimens were examined using the scanning electron microscopy (SEM) technique to confirm whether the specimens had failed by SCC.

2. Material and methodology

2.1. Materials

ASTM G39 recommends the use of flat, polished specimens for investigating fundamental aspects of the SCC mechanism in steels. However, this alters the outer surface profile of the specimen while it is known that corrosion can be affected by mill-scale, decarburisation, geometry and the presence of manufacturing faults [41,42]; hence, it is critical to preserve the integrity of the specimen surface profile. In this study, the straight central wire strand of a cable bolt was used in the laboratory tests. The steel grade of the specimen is SWPR19N according to Japanese standard JIS G 3536. The chemical composition and mechanical properties of the specimen are provided in Tables 1 and 2, respectively. The stress-strain curve of the specimen, obtained from tensile test, is shown in Fig. 1. The transverse view of the specimen microstructure shows curing of the pearlite lamellae in a random manner as presented in Fig. 2a. The longitudinally oriented pearlite microstructure is shown in Fig. 2b. Wires of the same steel type were hot dip galvanised with a 100 µm zinc layer to evaluate the impact of galvansing on SCC of cable bolts.

Table 2
Mechanical properties of the specimen.

Maximum load	Elongation	Surface striction	Ultimate Tensile Strength	Average Hardness
44.37 kN	4.8%	28%	1820 MPa	502 HV10

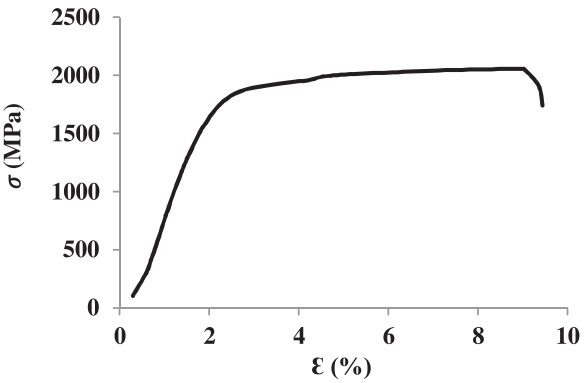

Fig. 1. Stress–strain curve of the wire strand specimen.

2.2. Testing frames

Three- and four-point loading jigs were used for SCC experimentation of the cable bolt. This method was used because of its ability to simulate underground geotechnical stress conditions experienced by cable bolts. The three- and four-point loading jigs are presented in Figs. 3 and 4. In both scenarios the specimens are supported at two points while a bending stress is applied to the centre of the sample with the use of a loading screw. The three- and four-point loading tests create a bending moment and associated tensile stress in the outer radius of the specimens. The tension generated in the outer radius of the specimen provides a realistic loading analogue that mimics the bending and tensile stress experienced by cable bolts *in-situ*.

In the three-point loading arrangement, the tensile stress on the outer fibres of the specimen ranges from zero at the outer support posts to a maximum stress at the centre loading point. In the four-point loading test, the stress develops from zero at the outer supports to a maximum between the inner supports where the peak stress is constant. The four-point bend frame, by virtue of its geometry, allows for a greater resolution and a high level of accuracy in the amount of stress applied. Furthermore, the four-point specimen is less prone to the effects of crevice corrosion and bi-axial stress state caused by the contact at the loading point. However, as cable bolts are manufactured from helically spun wires, stress may concentrate at the maximum deflection point when a tensile force is applied to the bent wire. This stress concentration is similar to the stress generated at the centre loading point in the three-point loading tests. Therefore, to carry out a compressive assessment of the SCC in cable bolts, both the three- and four-point

Table 1
Chemical composition of the specimen (wt.%).

C	Si	Mn	P	S	Mo	Ni	Al	Cr	Cu	Ti	V	Fe
					<					<	<	
0.85	0.31	0.66	0.013	0.009	0.01	0.02	0.02	0.11	0.01	0.01	0.01	Balance