Effects of Mg concentration on the corrosion fatigue crack behavior of Al-Mg coating layer

Sarita MORAKUL\textsuperscript{1}, Yuichi OTSUKA\textsuperscript{2}, Yukio MIYASHITA\textsuperscript{1} and Yoshiharu MUTOH\textsuperscript{1}

\textsuperscript{1} Nagaoka Univ. of Technology Dept. of Mechanical Engineering
1603-1 Kamitomiokamachi, Nagaoka shi, Niigata, Tokyo, 940-2188 Japan
\textsuperscript{2} Nagaoka Univ. of Technology Dept. of System Safety
1603-1 Kamitomiokamachi, Nagaoka shi, Niigata, Tokyo, 940-2188 Japan

In order to improve the corrosion resistance properties of structural steel (SS400) for bridge construction in corrosive environments, coatings of Al-Mg mixtures were deposited to protect SS400 substrates. This study observes the in-situ observation of cracks and focuses on the interfacial crack initiation and the corrosion fatigue crack behavior of the Al-Mg coating layers deposited on SS400 with different Mg concentrations. The investigation was carried out by using the four point bending (4PB) test in order to detect the interfacial strength between coatings and substrates of Al-Mg mixtures. Acoustic emission (AE) signals during the entire 4PB test were also measured in order to monitor the crack initiation and crack propagations and were analyzed by fast Fourier transform (FFT). The interfacial strength of Al-Mg coated SS400 decreases after immersion in NaCl \textit{aq}. There was little change in the interfacial strength of the Al-Mg coatings by different Mg concentrations in the ranges of present study.

\textbf{Key Words}: Al-Mg coating, corrosion resistance enhancement, 4 points bending (4PB) test, coating delamination

1. Introduction

A typical bridge material, \textit{structural steel} (SS400), is known for having very low corrosion resistance. By coating on the SS400 with the mixture of aluminum and magnesium, its surface can be protected from corrosion. Li \textit{et al.} showed that bonded Al-Mg mixture as coating layers result in high corrosion resistance (Li \textit{et al.}, 2009). However, the effect of the Mg concentration on the mechanism of corrosion resistance improvement is still unclear, thus it becomes necessary to optimize the ratios of the Al-Mg mixture in the coatings in order to obtain the highest environmental protection for the substrates. Moreover, there is evidence showing that pre-oxidation treatment of coatings increases cracks in the boundary between substrate and coating (interfacial delamination) but has little influence on the vertical cracking of the top coating (X.Q MA \textit{et al.}, 2001). In such cases, the strength of the coating is defined by the first interface delamination. This study observes the effect of different percent weight (\%wt) of Mg in Al-Mg coatings and the thickness of coating layers on the corrosion fatigue behavior of SS400 for bridges and similar structures. In order to detect the first delamination on the coating layer, an acoustic emission (AE) sensor was used and by using fast Fourier transform FFT analysis significant formation of signal that define the initial delamination in the coating layer is obtained (X.Q MA \textit{et al.}, 2001 and Laonapakul and Otsuka, 2012). This study is conducted by preparing rectangular samples of SS400 coated with a mixture of Al and Mg coating layers that have 100 or 200 \textmu m thicknesses. These coated samples are then put to the four points bending (4PB) test where the specimen is bent in four fixed points of the sample (Laonapakul and Otsuka, 2012). Observation of the specimens is done \textit{in situ} by using optical microscopy and AE methods to detect the initial breaking of the coating. On real scenarios bridges are subjected to cyclic loads and are also exposed to severe corrosive environments such as raining or wet winds containing seawater. In order to make a more realistic assessment of the life span and strength of coated materials it is necessary to carry out the cyclic test in

2. Experimental Procedure

2.1 Specimen Preparation
Specimens were provided as rectangular plates and its dimension is 50 mm X 10 mm X 3 mm thick coated by Al-Mg in 2 and 5 %wt of Mg. The average thickness of coating layer was about 200 μm. To observe the initial coating delamination, a slit on the coating layer is milled in order to limit the initial point of observation. The slit was 3 mm wide and 0.3 mm of depth. The slit edge of the coating layer is shown in Fig. 1. The test will be conducted in air condition and immersed in artificial sea water for 7 days and 30 days respectively in order to observe the decrease in interface strength of coating by the immersion.

2.2 Four points bending (4PB) test
Fig.2 shows the 4PB test settings used in this study, which possesses an inner span 20 mm and an outer span 40 mm. Force was applied by a servo hydraulic testing machine. All specimens were tested in air. The displacement control rate was 0.004 mm/sec. The strain gage with gage length 1 mm was attached on the compressive side in order to observe the strain during bending.

2.3 Acoustic Emission (AE)
The AE monitoring system was used during the 4PB test. A small amount of grease was used to attach an AE sensor on the tensile side of bending specimen. The AE monitoring system is composed of an AE sensor (AE 900M, NF Corporation), preamplifier (AE 912, NF Corporation), discriminator (AE 9922, NF Corporation), signal conditioning module (As-712, NF Corporation), and portable digital I/O device (NI USB 6501, National Instruments). A gain value of 30 dB on the discriminator was set in advance with a threshold value of $V_H = 0.4$ V and $V_L = 0.2$ V. The value of $V_L$ was adjusted according to the level of external noise. The relationship of peak amplitude of the detected AE signal and applied load was obtained to investigate the damages of coatings.

2.4 Damage Observation
To observe damage during 4PB test the specimens were cut in the longitudinal direction, and polished to a mirror surface. In situ observation of the side surface was carried out by using an optical digital microscope (VHX-1000, Keyence) along with AE monitoring. Based on the relationship between the accumulative AE peak amplitude and delamination behavior, the bending stress of the coating layer was calculated.
3. Results and discussion

3.1 Relation between stress-strain result and AE signal in air condition

Mechanical properties of 5% Mg with 200 μm thick, the yield strength is 590 MPa, calculated from 0.2% strain and interfacial between coating and substrate strength is 84 MPa detected from first AE signal. According to the recording microscope (Fig. 4), damage of coating layer initiated from edge slit of specimen and propagated along the interfacial surface between coating and substrate. The propagation along the interface has been continued until it meets the vertical cracks in the coating layers.

3.2 The AE signal and FFT analysis

By using AE sensor and FFT analysis, it is able to distinguish each damage mode such as crack delamination or slipping that occur during testing. The FFT analysis will give the significant waveform when AE sensor detected the energy release from crack and show in the frequency waveform which illustrated in fig. 5, fig. 6 and fig. 7. According to microscope observation can be confirmed that the initial delamination appeared meanwhile the first AE signal detected and FFT analysis show waveform illustrated in fig. 5 during the frequency range at 450-600 kHz and 700-100 kHz in air condition testing. On the other hand when the slipping occur and the specimen figure drop during applying load, the FFT analysis waveform was illustrated in fig. 6 The frequency range is non-uniform started from beginning 50 kHz. In fig. 7 show the first AE signal detected during 4PB test with 5%Mg thick 200 μm immersed to NaCl aq. for 7 days. The FFT waveform shows the uniform frequency range from 500-600 kHz and 650-1000 kHz similar to air condition test.
3.3 Interfacial strength of 5%wt Mg coating thick 200 μm

4PB test has been carried out to define the interfacial strength of Al-Mg coating with thick 200 μm. The conditions for testing are the specimen tested in air condition without immersed to NaCl aq. (artificial seawater), before the test specimen has been immersed to NaCl aq. for 7 days and 30 days respectively.

4. Conclusion

The effects of Mg concentrations of interface strength of Al-Mg coating layer were observed. As a summary:

1. The interfacial strength of Al-Mg coated SS400 decreases after exposed to NaCl aq. and there is little change in the interface strength of Al-Mg coating by different concentrations of Mg within the ranges explored.
2. FFT analysis gives significant information of the sources of each AE event. The AE signals in delamination can be successfully distinguished by differences in FFT waveforms.

The results of cyclic testing are now under consideration and are to be presented at the conference.

5. References