Smart Stress-Memory Patch Sensor for Fatigue Damage of a Single Steel Bar JIS G 3502 – Galvanized Wire – JSS II 11 - 1994

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ABSTRACT. *A new fatigue sensor called smart stress-memory patch, which can estimate the cyclic number, the stress amplitude and the maximum stress from the measurement of crack length and acoustic emission (AE), is proposed to evaluate the fatigue damage of such infrastructure as bridges and ships, in particular for a single steel bar JIS G 3502 – Galvanized Wire – JSS II 11 – 1994 (*$l = 400mm$*,* $\phi = 7mm$*) used for Suspension Bridge ("Rainbow Bridge" – Tokyo – Japan). The fatigue crack growth behaviour of thin electrodeposited (ED) Cu specimen for this sensor is investigated (*$l = 40mm$*,* $w = 5mm$*,* $s = 0.1mm$*). The modified stress intensity factor is proposed to introduce the master curve of fatigue crack growth, because the fatigue growth behaviour of this patch is affected by the maximum stress and the stress ratio. AE signals are also measured to estimate the AE onset stress and examine Kaiser effect of ED Cu specimen.*

INTRODUCTION

Structural Health Monitoring (SHM) is very important to ensure the safety of infrastructure. The fracture of structure is caused by the excessive loading, corrosion, creep and fatigue. Especially, a sensing method which avoids the fracture caused by fatigue is required. The monitoring of strain and displacement is essential to estimate fatigue damage in the case of bridges and ships. Currently, the strain gauges have been used to measure strain and displacement. However, there are several problems in the real applications of these strain gauges such as complicated cables, high cost, restriction by environment and so on.

Recently fatigue sensors, which do not measure strain nor displacement but estimate fatigue damage of structure, have been proposed. The objective of these fatigue sensors is the monitoring of the fatigue damage of bridges for a long period, and the fatigue damage is estimated by the crack growth of fatigue sensor attached on the single steel bar JIS G 3502 – Galvanized Wire – JSS II 11 – 1994. Table 1 shows the chemical and mechanical properties of the steel bar. One of the advantages of these fatigue sensors is off-line, while there are some problems that the applied stress or cyclic number must be measured or estimated by another system and fatigue characteristics must be same between the sensor and the structure [1,2].

Table 1. Chemical and Mechanical Properties of the steel bar JIS G 3502

Chemical	**C**	**Si**	**Mn**	**P**	**S**	**Cu**
SWRS82B	0.80 ÷ 0.85	0.12 ÷ 0.32	0.60 ÷ 0.90	0.025	≥0.025	≥ 0.20

Item		**Unit**	**Specification**
Dimension	**Diameter**	**mm**	**7.00 ± 0.08**
	Deviation	**mm**	≤ 0.08
Mechanical Property	**Tensile**	**N/mm²**	**1570 ÷ 1770**
	0.7% elongation strength	N/mm²	≥ 1160
	Elongation	%	≥ 4.0
	Twisting	Times	≥ 12
	Coiling	3d x 8 times	No defect
Zinc	Zinc	g/m²	≥ 300
	Adhesion	5d x 2 times	No defect
Mass	Nominal Mass	Kg/m	0.301

In this study, a new sensing method called "smart stress-memory patch" to monitor the fatigue damage of structure such as bridges and ships is proposed in order to overcome the above problems of fatigue sensors. This patch can measure the cyclic number, the stress amplitude and the maximum stress. In the present paper, the patch at issue is introduced and its characteristics are evaluated by fatigue test and acoustic emission (AE) measurement.

SMART STRESS MEMORY PATCH

Feature

The aims of this smart stress-memory patch are the estimation of the cyclic of number, stress amplitude and maximum stress, as well as evaluation of the fatigue damage of infrastructure. Cyclic number and stress amplitude are estimated from crack lengths of multiple sensors, and the maximum stress is estimated from Kaiser effect of AE measurement, respectively. The schematic image of this patch is shown in Figure 1. For a certain period the patch is fixed to a structure by screw to easily remove from itself and to measure AE behaviour after removal. Furthermore, the fatigue damage is evaluated from S-N curve of the structure, which shows the relationship between the stress amplitude and the fatigue cycles up to failure. In this study the structure under examination is the steel bar JIS G 3502 – Galvanized Wire – JSS II 11 – 1994. The connection between the sensor and the steel bar was made with a suitable attachment in stainless steel.

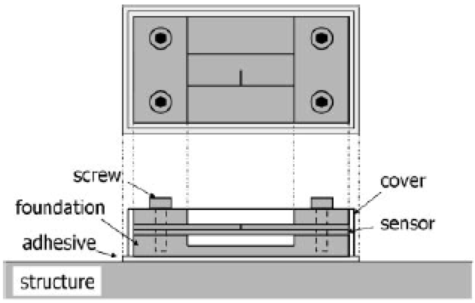

Figure 1. Image of the Smart Stress-Memory Patch sensor

Estimation of Cyclic Number and Stress Amplitude

The relationship between the crack growth rate and the range of the stress intensity factor under fatigue cyclic loading is well-known. The crack growth process is divided into three stages and the stable crack growth is observed in the second stage, where is represented as the Paris law. Using Paris equation, the cyclic number, N, is expressed as a function of the normalized final crack length, α_f, and the stress amplitude, $\Delta\sigma$, as follows:

$$\frac{da}{dN} = C\left(\Delta K\right)^m$$
$$N = C^{-1}W\left(\Delta\sigma\sqrt{\pi W}\right)^{-m}\int_{\alpha_0}^{\alpha_f}\left\{\sqrt{\alpha}\, f\left(\alpha\right)\right\}^{-m} d\alpha \qquad (1)$$

where W is the width of specimen, α_0 is the normalized initial crack length, α is the normalized crack length, C and m are empirical constants of the Paris law and $f(\alpha)$ is the shape factor of the stress intensity factor.

Furthermore, if two sensors of different properties are employed, two equations on the cyclic number N can be obtained and the cyclic number and the stress amplitude can be estimated as shown in Figures 2(a), 2(b).

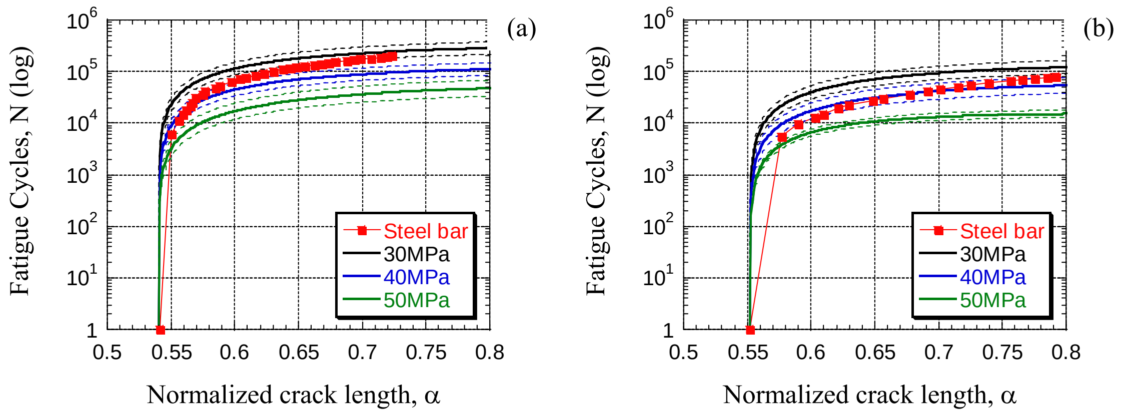

Figure 2. (a) Cyclic number obtained from the crack lengths in 3 sensors As-received and steel bar ($\sigma_{STEEL} = 104MPa$); (b) Cyclic number obtained from the crack lengths in 3 sensors heat-treated and steel bar ($\sigma_{STEEL} = 104MPa$)

Estimation of the Maximum Stress

AE event is generated due to microcraking, slip deformation and so on when materials is loaded. It is well known that microcracking and slip deformation are generally irreversible phenomena.. After smart stress-memory patch is removed from the structure, AE measurement is conduced during tensile loading. Then, the maximum stress can be estimated as the onset stress when AE activity increases due to Kaiser effect, as shown in Figure 3.

EXPERIMENTAL PROCEDURE

Materials and Geometry

The patch was made of electrodeposited (ED) copper because of its good corrosion resistance, stable crack growth and easily observation of the crack length. As-received and heat-treated (400°C, 30 min) ED Cu coupons with 0.1 mm thickness were prepared for the fatigue test and AE measurement. Heat-treated (400°C, 30 min) rolled Cu coupon with 0.2 mm thickness was also used for AE measurement. The mean grain size was about 2 μm for the As-received ED Cu coupon, about 4 μm for the heat-treated ED

Cu and about 40 µm for the heat-treated rolled Cu, respectively. All coupons were cut into 40 mm length and 5 mm width. Furthermore, a single edge notch with curvature of about 150 µm was introduced at the center from one side and then a fatigue pre-crack was extended under the maximum stress of 24 MPa until total crack length reached to about 2.7 mm prior to the fatigue test. The fatigue damage was detected in a single steel bar JIS G 3502 – Galvanized Wire – JSS II 11 – 1994 used for Suspension Bridge with lengths of $l = 400mm$ and diameter of $\phi = 7mm$.

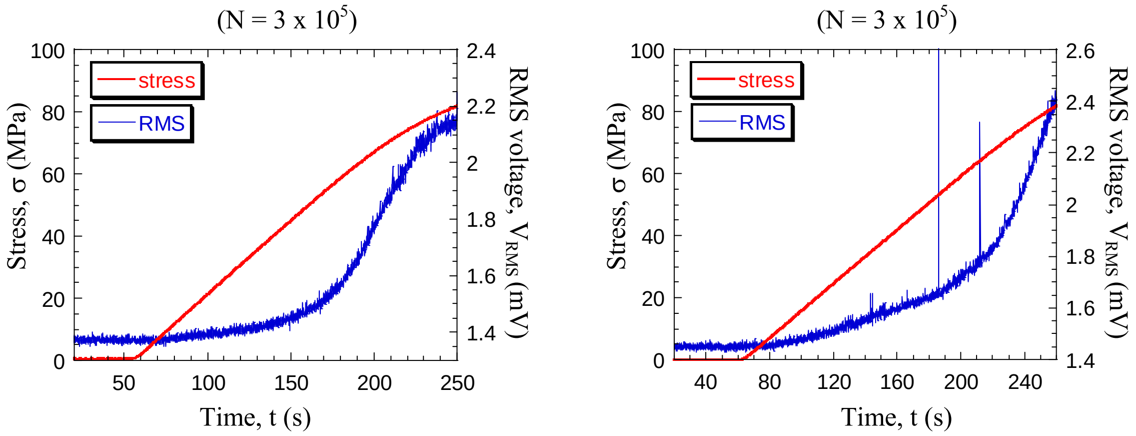

Figure 3. Maximum stress obtained from the onset stress of AE activity after fatigue loading for 33kN ($\sigma_{STEEL} = 78MPa$) on the steel bar

Fatigue Test

Fatigue cracks generally start at the surface of the material or at large inclusions promoted by high stresses, surface roughness, fretting, corrosion, etc. The following crack growth (on a macroscopic level) usually occurs perpendicular to the main principal stress and depends on the material, the material thinkness and the orientation of the crack relative to principal material directions. Furthermore, the crack growth also depends on the cyclic stress amplitude, the mean stress and the environment.

The fatigue test was carried out in tensile loading under the constant maximum stress of 30, 40 and 50 MPa on the sensor, with the stress ratio of 0.1 and the frequency of 20 Hz. The fatigue test on the system (steel bar and sensor) was carried out in tensile loading under the constant maximum stress of 80, 86 and 89 MPa on the steel bar, with the stress ratio of 0.1 and the frequency of 20 Hz. The effects of the maximum stress and the stress ratio on the fatigue crack growth behaviour were investigated. The growth of the crack length was recorded automatically per minute by Video Microscope – Digital Microscope – VHX 800X – KEYENCE. A crack growth rate was calculated by the incremental polynomial technique and the stress intensity factor was obtained from the equation of a SECT (single edge cracked tension) specimen in stress intensity factors handbook [3], as follow:

$$\Delta K = \Delta\sigma\sqrt{\pi W\alpha} \times \left\{0.265(1-\alpha)^4 + (0.857+0.265\alpha)\big/(1-\alpha)^{3/2}\right\} \quad (2)$$

AE Measurement

AE behaviour was measured to obtain the maximum stress using Kaiser effect during tensile loading. Three types of specimens were prepared. These were a smooth specimen, a notched specimen with 0.5 normalized notch length and a cracked specimen after fatigue crack growth. AE behaviour under monotonic loading was measured to estimate the onset stress of AE, and AE behaviour after fatigue loading was also investigated to examine Kaiser effect. AE sensor (M304, Fuji Ceramic Corp.) was attached to the surface of each specimen and AE waveform was recorded by CWM (continuous wave memory) system. The cross-head speed for the tensile loading was 0.1 mm/min and 200 KHz high pass filter was employed in AE measurement.

RESULTS AND DISCUSSION

Fatigue Crack Growth Behaviour

The crack growth of each sample was obtained from the fatigue test. Results in the case of 0.1 stress ratio are shown in Figures 4(a), 4(b). The crack growths was affected by the maximum stress and the slope of Paris Law, m , is about 2.61 and 3.00 in As-received ED and heat-treated Cu specimen respectively. The crack growth also depended on the stress ratio. It is found that the crack growth of this patch is substantially affected by the maximum stress and the stress ratio.

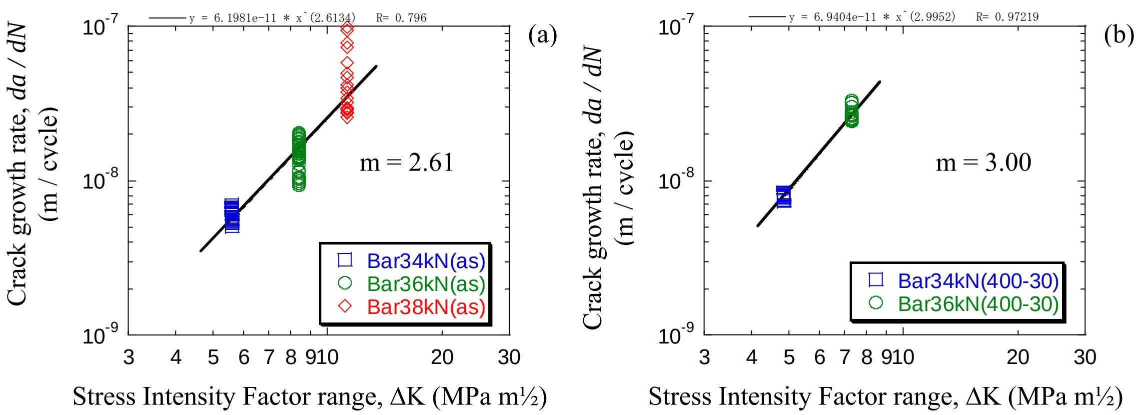

Figure 4. (a) Stress Intensity Factor under uniform displacement for steel bar (As-received) under the maximum stress of 80, 86 and 89 MPa; (b) Stress Intensity Factor under uniform displacement for steel bar (heat-treated) under the maximum stress of 80 and 86 MPa

In these results, the crack growth rates are smaller than those of bulk specimens of pure Cu in the same stress intensity factor range. Because the thicknesses of specimens were thin enough to satisfy the plane-stress state, the crack growth rates become lower as the plastic constraint factor became smaller. There exist few reports about fatigue crack growth behaviour of a thin metallic patch, while Guo reported that crack growth rate decreased with the decrease in the thickness of a bulk specimen of Al alloy. The value of *m* in the present study was also small compared with that of the bulk speciment of pure Cu (m = 3.2) [4,5]. It is considered that the small scale yielding state may not be satisfied because the plastic zone at crack tip is enough large compared with ligament of the specimen. Similar results were reported by Peralta & all. for bulk specimens of Ni and Inconel [6].

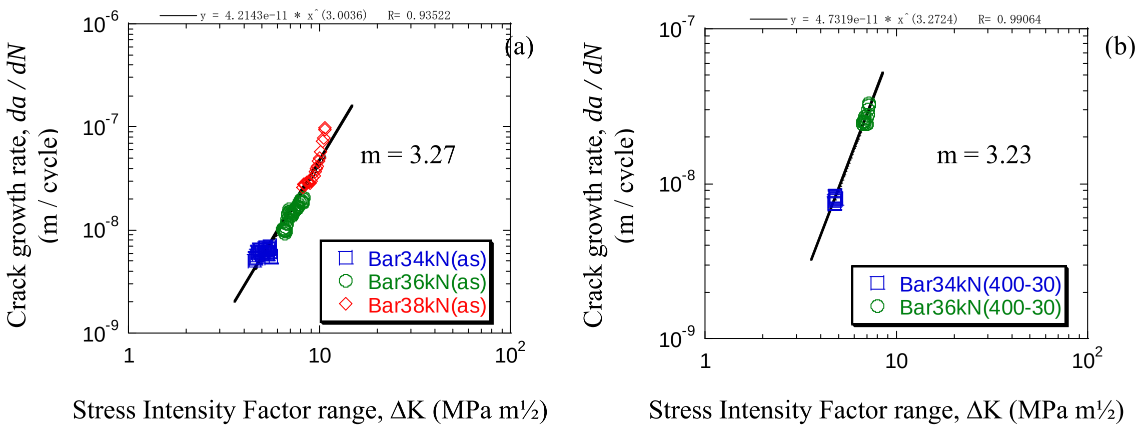

Figure 5. Corrected fatigue crack growth behaviour

Master Curve and AE Behaviour

Although the crack growth behaviour of this patch was affected by the maximum stress and the stress ratio, it is desirable that the sensor characteristic is decided from the master curve of crack growth behaviour which is not affected by the maximum stress and the stress ratio [7,9]. The master curve of crack growth behaviour, which has one-on-one relation between crack growth rate and stress intensity factor range, is taken into account. The modified stress intensity factor, ΔK, was proposed for this patch to obtain the corrosion crack growth characteristics:

$$\begin{aligned} \Delta K &= f\left(\alpha,\alpha_n\right)\left(E_{Cu}/E_{base}\right)\Delta\sigma_{base}\sqrt{L} \\ f\left(\alpha,\alpha_n\right) &= 1 + A_1\left(\alpha-\alpha_n\right) + A_2\left(\alpha-\alpha_n\right)^2 + \ldots \end{aligned} \qquad (3)$$

where $f\left(\alpha,\alpha_n\right)$ is the correction function of shape factors for As-received and heat-treated sensors respectively.

The crack growth behaviour obtained by the modified stress intensity factor was shown in Figure 5. The correction function of As-received ED Cu is

$f(\alpha,\alpha_n) = 1 - 0.98(\alpha - \alpha_n)$ and that of heat-treated ED Cu is, $f(\alpha,\alpha_n) = 1 - 0.29(\alpha - \alpha_n)$, respectively.

In these equations, α_n is the initial normalized notch length of 0.5 and the third order terms or higher are ignored because they have little influence on the results. As shown in Figure 5, the effect of the maximum stress is corrected and all data are fitted well.

AE behaviours of heat-treated rolled and ED Cu specimens with normalized notch length of 0.5 under reloading were also measured. RMS voltage for heat-treated rolled Cu started at nearly zero stress level during the first loading and AE onset stress during reloading was lower than the previous applied stress [10,12].

CONCLUSIONS

In the present paper a new fatigue sensor called the smart stress-memory patch is proposed. The fatigue crack growth behaviour and AE behaviour of ED Cu were investigated and the following conclusions are obtained.

1. The empirical master curve of crack growth, which included the effect of the maximum stress and the stress ratio, was obtained by the modified stress intensity factor.
2. The applied fatigue maximum stress can be successfully estimated by AE measurement of heat-treated ED Cu specimen.

REFERENCES

1. T. Kobayashi, O. Muragishi and K. Nihei: Key Eng. Mater. 261-263 (2004) 1313-1318.
2. Y. Fujimoto, G. Pirker, H. Ito, E. Shintaku and S. Shono: Ship. Tech. Res. 49 (2002) 33-44.
3. Y. Murakami: Stress Intensity Factors Handbook, (Committee on Fracture Mechanics, The Society of Materials Science, Japan, 1987) p.9.
4. K.Ito and M.Enoki: Mater. Trans. 48 (2007) 1221-1226.
5. W. Guo, C. H. Wang and L. R. F. Rose: Fat. Fract. Engng. Mater. Struct. 22 (19999 437-444.
6. P.Peralta, R. Dickerson, N. Dellan, K. Komamndur and M. A. Jameel: J. Eng. Mater. Tech. Trans. Am. Soc. Mech. Eng. 127 (2005) 23-32.
7. W. Elber: Eng. Fract. Mech. 2 (1970) 37-4 .
8. J. C. Newman, Jr.: Int. J. Fract. 24 (1984) R131-135.
9. P. C. Paris, H. Tada and J. K. Donald: Int. J. Fatigue 21 (1999) S35-46.
10. Y. Takahashi: Trans. JSME 67-657A (2001) 864-870.
11. A. Vinogradov: Scripta Mater. 39 (1998) 797-805.
12. V. R. Skalskyi, O. E. Andreikiv and O. M. Serhienko: Master. Sci. 39 (2003) 86-107.