The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

Variation of electric resistance of Cu-Al-Mn superelastic alloys under cyclic tension

*Y. Araki[1)], K.C. Shrestha[2)], M. Yamakawa[3)], N. Yoshida[4)], T. Omori[5)], Y. Sutou[6)] and R. Kainuma[7)]

[1), 2), 4)] *Department of Architecture and Architectural Engineering, Graduate School of Engineering, Kyoto University, Kyoto 615-8540, Japan*
[3)] *Department of Architecture, Tokyo Denki University, Tokyo 120-8551, Japan*
[5), 6), 7)] *Department of Materials Science and Engineering, Tohoku University, Sendai 980-8579, Japan*
[1)] *araki@archi.kyoto-u.ac.jp*

ABSTRACT

This paper examines the feasibility of Cu-Al-Mn superelastic alloy (SEA) bars as possible self-sensor components, taking electrical resistance measurement as a feedback. This work studies the relationship between strain and electrical resistance measurements of SEAs. Such relationship can be used in determining the state of a SMA-based structure effectively, without separate sensors, by appropriately measuring the changes in electrical resistance during and after structure's loading history. Quasi-static cyclic tensile tests are conducted to investigate the relationship between electrical resistance and strain for a 4mm diameter Cu-Al-Mn SEA bar. It was demonstrated that linear relationship between the electrical resistance and the strain can be achieved for Cu-Al-Mn SEA bar with minimal hysteresis. The test observations support the feasibility of newly developed Cu-Al-Mn SEA bars, characterize by low material cost and high machinability, as a multi-functional material both for structural and sensing elements.

1. INTRODUCTION

The interest has been increasing on the use of innovative materials as multi-functional components, that would act both as structural components as well as self-sensing components (Housner *et al.* 1997). Structural control and seismic applications of shape memory alloys (SMAs) to civil engineering structures have been studied by a

---

[1,3,6)] Associate Professor
[2)] Postdoctoral Fellow
[4)] Researcher
[5)] Assistant Professor
[7)] Professor

number of researchers (Dolce *et al.* 2000; Ozbulut *et al.* 2011). Shape recovery characteristics of SMAs upon unloading without any temperature variances are called as superelasticity. Also SMAs having superelasticity at room temperature are called as superelastic alloys (SEAs). Application of SEAs to civil structures has a potential to contribute both to effective structural control, with shape recovery and structural damping, and to monitoring of structural members with electric resistance feedback.

Several works have been published on the variance of electric resistance with strain at variable temperature and loading conditions in Ni-Ti and Cu-Al-Be SEAs (Airoldi *et al.* 1998; Li *et al.* 2005; Novak *et al.* 2008; Gedouin *et al.* 2010; Cui *et al.* 2010). It has been reported in the works that linear relationship can be observed between the electric resistance and the strain in SEAs. The variance of electric resistance is caused by transformation from austenite to martensite phases. However, to the authors' knowledge, Cu-Al-Be SEAs have inferior superelasticity to Ni-Ti SEAs. Ni-Ti SEAs, on the other hand, come with high material cost and low machinability that largely limit their extensive use in practical applications.

The present study examines the feasibility of Cu-Al-Mn SEA bars as sensing devices through electrical resistance feedback. Recently, it was demonstrated that Cu-Al-Mn SEAs have mechanical properties comparable with Ni-Ti SEAs, while Cu-Al-Mn SEAs have low material cost and high machinability (Araki *et al*. 2011). This paper reports on quasi-static tensile tests performed to study the variation of electric resistance of Cu-Al-Mn SEA bars at room temperature.

2. TEST PROGRAM

Cu-Al-Mn SEA bar of 8mm diameter and 150mm length was prepared with nominal composition of Cu-17 at.% Al-11.4 at.% Mn by Furukawa Techno Material Co., Ltd. The SEA bars were obtained by hot forging and cold drawing. The solution treatment was conducted at 900 ºC, followed by quenching in water, and they were subsequently aged at 200ºC to stabilize superelastic property. The martensite start temperature, M_s, the martensite finish temperature M_f, the austenite start temperature A_s, and the austenite finish temperature A_f of above bars are, $M_s = -74°C$, $M_f = -91°C$, $A_s = -54°C$, and $A_f = -39°C$. The original 8mm diameter bar was threaded 20mm length at the ends to grip the rod specimen as shown in Fig. 1 and the remaining central part of the rod of length, L 106mm was reduced with sectional diameter D of 4mm in order to avoid fracture at the threaded portion. Here, the relative grain size d/D, defined as the ratio between average grain size d and the bar diameter D, is about 4.

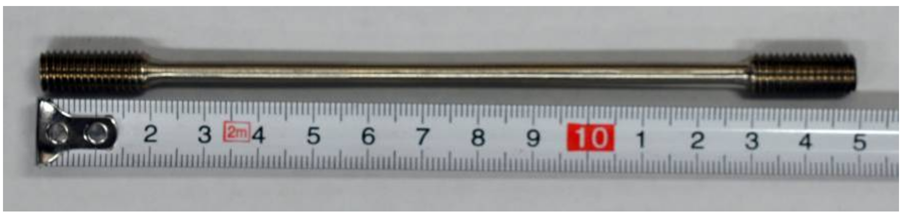


Fig. 1 Photograph of an SEA bar test specimen

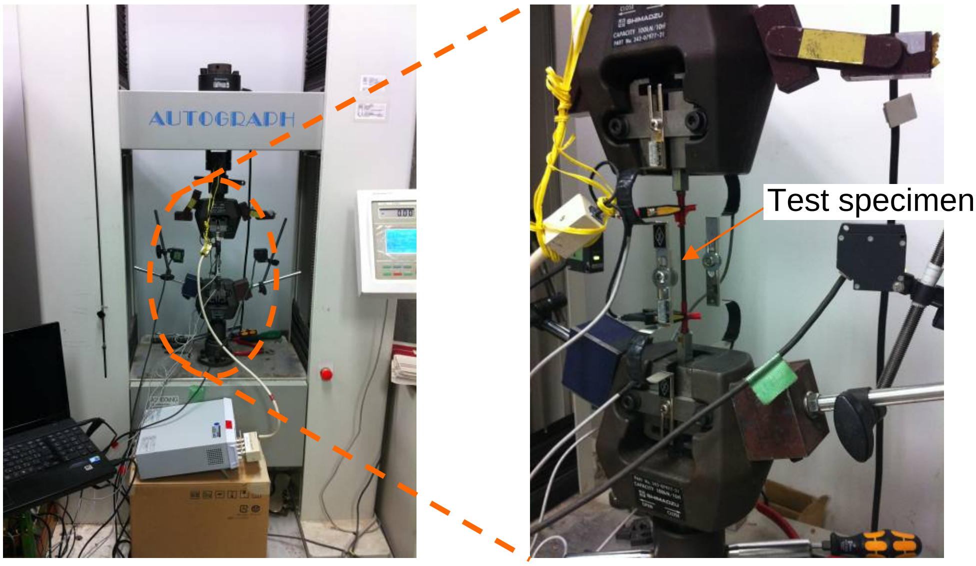


Fig. 2 Photograph of test set-up

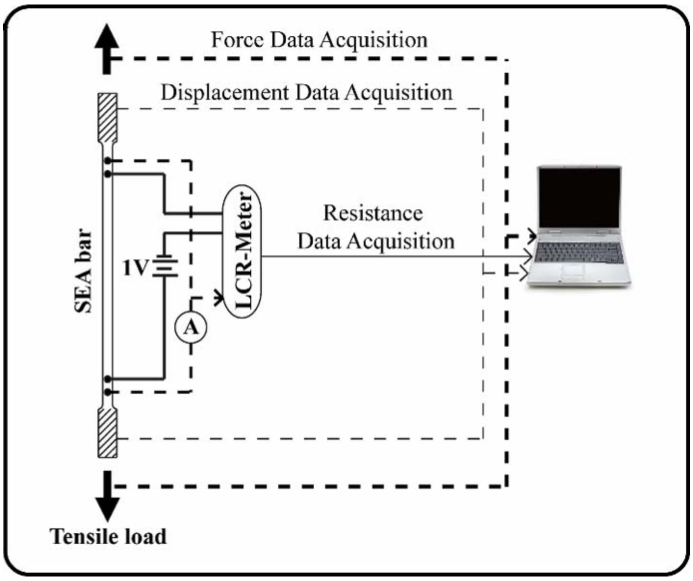


Fig. 3 Schematic representation of test set-up and layout

Figs. 2-3 show the test set-up for quasi-static tensile test with specific layout followed to measure the change in resistance during the loading/unloading cycle of the SEA bar specimen. Electric resistance measurements were done using LCR-Meter at 1V input voltage. Electric resistance measurements were made at the range of 100 mΩ for data acquisition. Displacement measurements were made using the laser displacement transducers in between the cross-heads, and also with clip-type displacement transducers (PI-gauges) as shown in Fig. 2. Strain was computed from the displacement measurement recorded at PI-gauges. Data sampling was done at 100Hz frequency.

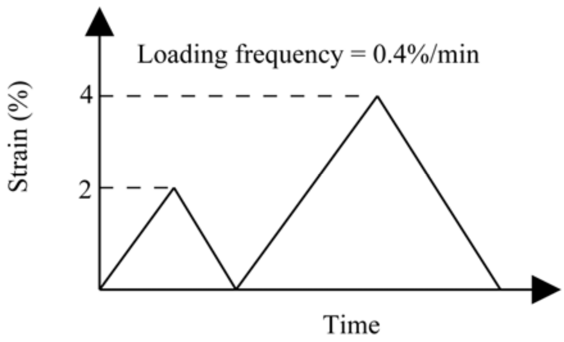
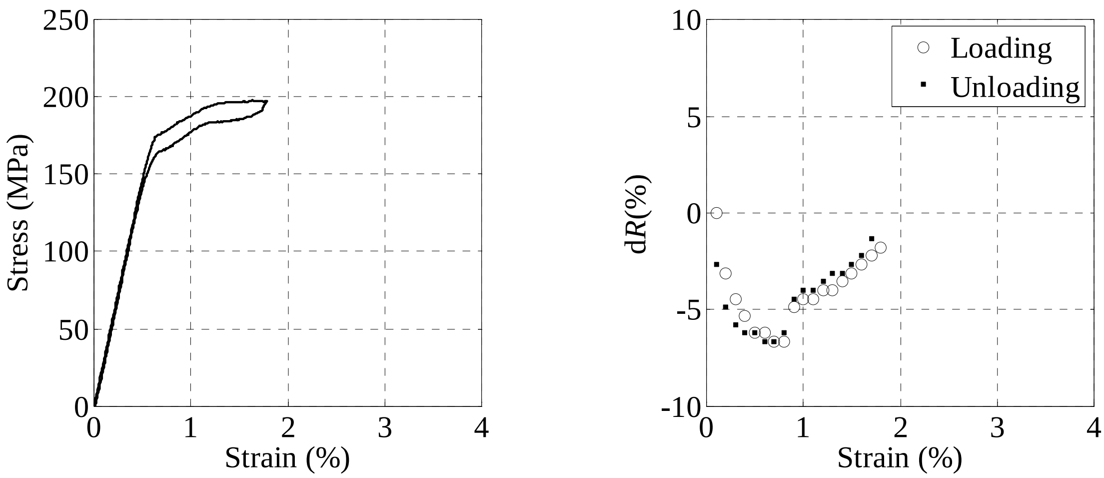


Fig. 4 Loading history



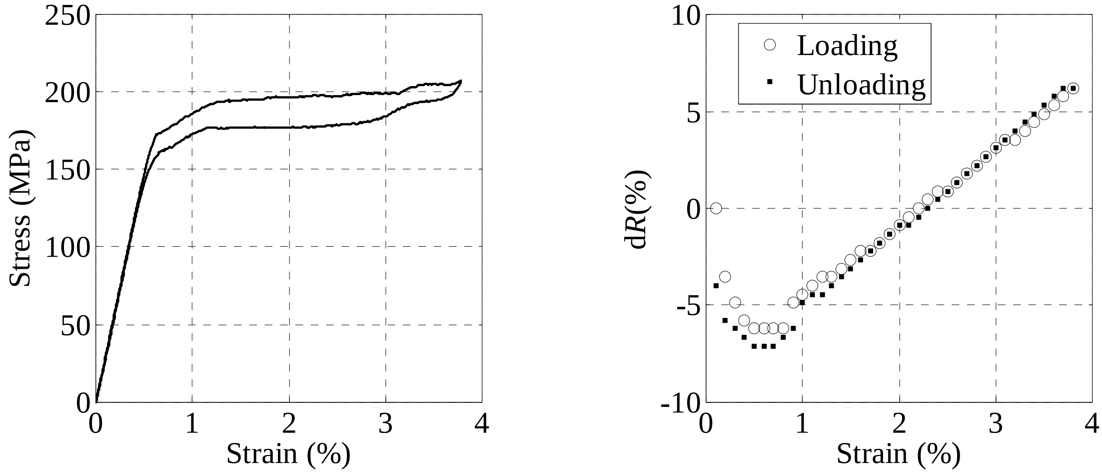
(a) (b)

Fig. 5 Experimental results for 2% target strain: (a) Stress, σ versus strain, ε, and (b) Change in resistance, dR versus strain, ε

The adopted loading history is shown in Fig. 4. The applied strain rate was 0.4%/min at room temperature. Two different target strain amplitudes were chosen, first at 2% and second at 4%. Strain was obtained from the displacement measurements of grips. Respective resistance measurements were made during the loading/unloading history using LCR-Meter.

3. EXPERIMENTAL RESULTS

Figs. 5-6 illustrate the results for the variation in electric resistance during the quasi-static loading on the given SEA specimen. Observation for the target strain amplitude of 2% is shown in Fig. 5, and for the strain amplitude of 4% is shown in Fig. 6. Stress and resistance measured at each strain increments are presented. Electric resistance variation has been presented as the change in resistance defined by $\mathrm{d}R = (R - R_{\mathrm{initial}}) / R_{\mathrm{initial}}$, where R_{initial} is the resistance measured at initial/unloaded state. It should be noted that during the tests the value of R_{initial} recorded was 2.12 $\mathrm{m\Omega}$.



(a) (b)

Fig. 6 Experimental results for 4% target strain: (a) Stress, σ versus strain, ε, and (b) Change in resistance, d*R* versus strain, ε

For both strain amplitudes, the characteristic stress-strain behavior observed was similar, shown by typical flag shaped hysteresis, with transformation stress of 170MPa and elastic modulus of 30GPa. Note here that the relatively low elastic modulus is due to the displacement measurements between grips. The stress plateau is clearly observed with negligible hysteresis, which is typical for large grain to diameter ratio value (*d*/*D*=4).

Figures in the right column of Figs. 5-6 illustrate the resistance versus strain characteristics for the given strain amplitudes. As shown in the figures, there is slight decrement in resistance measurement before reaching the transformation stress, where phase transformation initiates. Then afterwards, there is a linear increment of resistance with corresponding increment in strain. Hence, a distinct region is defined for the resistance variation at the start of phase transformation. Furthermore, during the unloading process, the variation in electrical resistance followed almost the same path as during the loading process, with negligible hysteresis observed.

4. CONCLUSIONS

The variation of electric resistance of Cu-Al-Mn SEA bars has been examined under cyclic tension with two different target strain amplitudes of 2% and 4%. Slight decrement in resistance was observed before the stress reached the transformation stress. After reaching the transformation stress, linear variation of electric resistance with increasing strain was clearly observed. The linear relationship between the electric resistance and the strain was also observed during the unloading cycle. Such linear relationship demonstrates the capability of Cu-Al-Mn SEA bars as a multi-functional component as a structural element as well as a sensing element, which can be used for both structural control and monitoring purposes.

ACKNOWLEDGEMENTS

The present research was supported by the A-STEP program (#AS2315014C) provided by Japan Science and Technology Agency (JST). The authors would also like to acknowledge Prof. Tetsuji Matsuo of Department of Electrical and Electronic Engineering, Kyoto University for providing important comments and recommendations during research meetings.

REFERENCES

Airoldi, G., Lodi, D.A. and Pozzi, M. (1998), “The electric resistance of shape memory alloys in the pseudoelastic regime”, *J Phys. IV : JP*, **7**(5), C5-507-C5-512.

Araki, Y., Endo, T., Omori, T., Sutou, Y., Koetaka, Y., Kainuma, R. and Ishida, K. (2011), “Potential of superelastic Cu–Al–Mn alloy bars for seismic applications”, *Earthq. Eng. Struct. Dyn.,* **40**(1), 107–115.

Cui, D., Song, G., Li, H. (2010), “Modeling of the electrical resistance of shape memory wires”, *Smart Mat. Struct.,* **19**, 055019.

Dolce, M., Cardone, D. and Marnetto, R. (2000), “Implementation and testing of passive control devices based on shape memory alloys”, *Earthq. Eng. Struct. Dyn.*, **29**(7), 945-968.

Gedouin, P.A., Chirani, S.A., Calloch, S. (2010), “Phase proportioning in CuAlBe shape memory alloys during thermomechanical loadings using electric resistance variation”, *Int. J. Plasticity,* **26**, 258-272.

Housner, G.W., Bergman, L.A., Caughey, T.K., Chassiakos, A.G., Claus, R.O., Masri, S.F., Skelton, R.E., Soong, T.T., Spencer, B.F. and Yao, J.T.P. (1997), “Structural control: past, present, and future”, *J Eng. Mech.*, *ASCE*, **123**(9), 897–971.

Li, H., Mao, C.X. and Ou, J.P. (2005), “Strain self-sensing property and strain rate dependent constitutive model of austenitic shape memory alloy: experiment and theory”, *J. Mat. Civil Eng.*, **17**(6), 676-685.

Novak, V., Sittner, P., Dayananda, G.N., Braz-Fernandes, F.M., Mahesh, K.K. (2008), “Electric resistance variation of NiTi shape memory alloy wires in thermomechanical tests: Experiments and simulation”, *Mat. Science Eng. A,* **481-482**, 127-133.

Ozbulut, O.E., Hurlebaus, S. and Desroches, R. (2011), “Seismic response control using shape memory alloys: a review”, *J. Intelligent Mat. Systems Struct.*, **22**(14), 1531–1549.