Transactions of the Materials Research Society of Japan 29[7] 2955-2958 (2004)

Recent development of Smart Materials

Yoshitake NISHI and Hiromasa YABE
Department of Materials Science, Tokai University, 1117, Kitakaname, Hiratsuka, Japan
Fax: 81-463-581218, e-mail: am026429@keyaki.cc.u-tokai.ac.jp

This paper describes recent development of smart materials operated by changes in temperature, hydrogen gas pressure and magnetic field. Based on nano-scale structural changes, smart materials with a smart principle function of power have been successfully developed. To get high power, new bimorph materials of magnetostrictive Fe-Pd alloy film and hydrogen storage $LaNi_5$ films were developed. High susceptibility with high resistance to noise was also found for the giant magnetostrictive Fe-Pd alloy film. The large displacement is also obtained in unimorph structure composite constructed by the polymer sheets with and without hydrogen storage $LaNi_5$ powder dispersion. In order to obtain multi-functional smart materials, unimorph materials driven by glass transition have been developed. Here, the multi-functions including shape changing are high resistance against irradiation for metallic glass, high heat resistance and high transparency for glassy ceramics, and large displacement with light weight for polymer.

Key words: power, actuator, nano-scale controlling, smart

1. INTRODUCTION

Intelligent materials are often defined as a useful substance for human beings with an ability of crisis control. Smart materials are the practical intelligent materials, such as shape memory alloys. Influences of liquid-quenching on shape memory properties of Cu-Ni-Al, Ti-Ni-Cu and Cu-Al-Ni shape memory alloys have been studied.[1-4] However it difficult to obtain the strong power and high responsive actuator with high power and high resistance to environmental noise to apply practical use. In order to get high responsive actuator, magnetostrictive Fe-Pd alloy unimorph structural film operated by magnetic field successfully has been developed.

In order to apply the practical sensor and actuator related to hydrogen energy system, high power actuators generated by hydrogen pressure change have been expected. New unimorph materials of hydrogen storage $LaNi_5$ films have been developed. Furthermore, to obtain large displacement generated by hydrogen pressure change, the unimorph materials constructed by polymer sheets with and without hydrogen storage $LaNi_5$ powder dispersion has been also developed.

Finally, to obtain multi-function including shape changing with high resistance to irradiation for metallic glass, with high transparency and high heat resistance for glassy ceramics, and with large displacement and light weight for polymer, unimorph smart materials driven by glass transition have been developed.

Therefore, the recent developments of smart materials operated by changes in temperature, hydrogen gas pressure and magnetic field are introduced.

2. EXPERIMENTAL

Following methods carried out preparation and evaluation of the actuator derived by Fe-Pd film on silicon substrate. To form the film of the fine columnar texture, a DC magnetron sputtering process was performed. The base pressure was less than 3.9×10^{-5} Pa and the leak rate was 5.0×10^{-7} $Pa \cdot m^3/s$. The sputtering conditions were 6.0×10^{-2} Pa of Ar gas pressure with 200 W of DC sputtering power and 3600 s of sputtering time. The film was deposited about 2□m in thickness on substrate.

The magnetic property was measured by a vibrating sample magnetometer (VSM; Model BHV-55, RIKEN). VSM I-H curve showed small hysteresis and strong plane anisotropy of magnetization. The in-plane magnetostriction ($\lambda_{//}$) of film was measured by a cantilever method. The Young's modulus was measured by a nano-indenter method (nano-indenter;ENT-1100a, ERIONIX).

$LaNi_5$ hydrogen storage alloys were prepared by arc melting (ACM-DS01 DIAVAC Ltd.) and subsequent annealing for homogenization. The block sample was pulverized by several hydrogen cycles of adsorption and desorption using ultra high purity H_2 gas (7N), the resulting powder was classified to obtain a mean grain size between 60 and 100 μm in diameter. To obtain hydrogen storage thin films that showed high resistance to pulverization and fatigue, thin films were prepared by the flash evaporation process using the pulverized $LaNi_5$ powders on polyimide substrate (Kapton (R) 500V, DU PONT-TORAY Co. Ltd.). The substrate temperature was varied from 319 K to 325 K. The base pressure was less than 1.0×10^{-3} Pa, and the deposition rate was 0.7 nm/s. The dimensions of the polyimide substrate were 5 mm in width, 30 mm in length, and 0.011 mm in thickness. The thickness of the $LaNi_5$ film was about 200 nm. The prepared films were activated using ultra high purity H_2 (7N) at 60 bar in a reaction tube made of SUS316. Activation was performed by the hydrogen absorption for 10 minutes and evacuation for 10 minutes. The temperature of the activation process was RT. The adsorption/desorbtion cycle was repeated 30 times. The activated bi-material was then transported to a reaction bed made of silica glass.

Pure silicone rubber attached was supporting materials to bend the composite material. The sample size of the composite material was $30 \times 5 \times 1.0$ mm^3; length × width × thickness. Hydrogen storage alloy powder (0.65 g) was mixed and dispersed within pure silicone rubber (KE45, Shin-etsu Silicon Ltd., 0.065 g). The chemical composition of hydrogen storage alloy powder was analyzed by energy dispersive X-ray spectroscopy (EDS: JSM-6301F, JEOL Ltd.).

After evacuation for hydrogen desorption, a video recorder monitored the material shape change under different loads.

The samples composition was analyzed by energy disperse X-ray spectroscopy (EDS; JSM-6301F, JEOL). The film crystal structure was analyzed by thin film X-ray diffraction (XRD; X'Part-MRD, PHILIPS). The film texture was observed by means of field emission scanning electron microscopy (FE-SEM; JEM-6000 series WDS/EDS system, JEOL).

3. RESULTS and DISCUSSION

3.1 Giant magnetostrictive Fe-Pd film with high power, high susceptibility and high noise resistance

Fe-30at%Pd alloy shows shape memory effect. The strain induced by low magnetic field was firstly observed.[5] Shape memory effects were apparently observed in the rapidly solidified Fe-30at%Pd alloy.[6]

A new high responsiveness wireless actuator, driven by the magnetic field of Fe-45at%Pd alloy film on a silicone substrate, has been prepared by using a DC magnetron sputtering process.[7-10] The in-plane magnetostriction of the film has been obtained from measurements of the bending of a rectangular cantilever consisting of the film and substrate. All film devices have been saturated in the applied magnetic field of 0.5 kOe. The Fe-Pd alloy films show high magnetostrictive susceptibility in low magnetic field.

One serious obstacle to applying a practical wireless actuator is its stress dependent magnetostriction yielded by the magnetic field. To evaluate the stress dependence, the tensile stress dependence of magnetostriction in Fe-45at%Pd bi-metal has been measured.[11-14] The applied magnetic field drastically enhances the magnetostriction of all loaded samples for below 0.4 kOe. A large magnetostriction has been induced by the magnetic field even under a large tensile loading stress. Thus, the magneto-driving Fe-Pd alloy film actuator can be operated by applied magnetic field from earth magnetic field to 0.5 kOe under large loading stresses.

Another potential obstacle is actuator response time. To evaluate the load dependent response speed of the new actuator, the magnetostrictive susceptibility has been obtained at different tensile loading stresses. The susceptibility has been calculated by the differential values of the magnetostriction quantity in the applied magnetic fields. Figure 1 shows the relationship between the applied magnetic field and the susceptibility of the Fe-45at%Pd alloy film at different loading stresses. The magnetic field below 0.16 kOe increases the susceptibility for unloaded sample. The maximum value of susceptibility is found at 0.16 kOe. The loading stress dependent relationships between susceptibility and magnetic field are also observed. The tensile loading stress decreases the maximum value of magnetostrictive susceptibility. Furthermore, the tensile loading stress also increases the magnetic field at the maximum peak value of magnetostrictive susceptibility-magnetic field curves. An initial stage of magnetostriction is usually caused by easy mobile factors acted by weak magnetic field. If the tensile loading stress prevents to move the factors, decreasing the maximum magnetostrictive susceptibility value and increasing the magnetic field at the maximum magnetostrictive susceptibility value against loading can be explained.

Fe-Pd alloy film shows large magnetostriction and high magnetostrictive susceptibility under 0.5 kOe. To evaluate the moving potential as magneto-driving actuator, the magnetostrictive properties have been measured under different tensile loading stresses. Although the small tensile loading stress decreases the maximum value of magnetostriction, strong magneto-driving actuator of the Fe-Pd alloy film can be constantly operated by the magnetic field under larger loading stress for high magnetostrictive susceptibility.

The maximum value of magnetostrictive susceptibility is found at 0.16 kOe. Although the small tensile loading stress decreases the magnetostrictive susceptibility below 0.25 kOe (Fig.1), a high responsiveness magneto-driving actuator of the Fe-45at%Pd alloy film can be operated by the larger magnetic field above 0.25 kOe under smaller loading stress of 16.6 kPa. As shown in Fig.1, high resistance to noise is found in giant magnetostrictive Fe-Pd alloy film.[10] The film will be applied for the delay circuit and speaker.

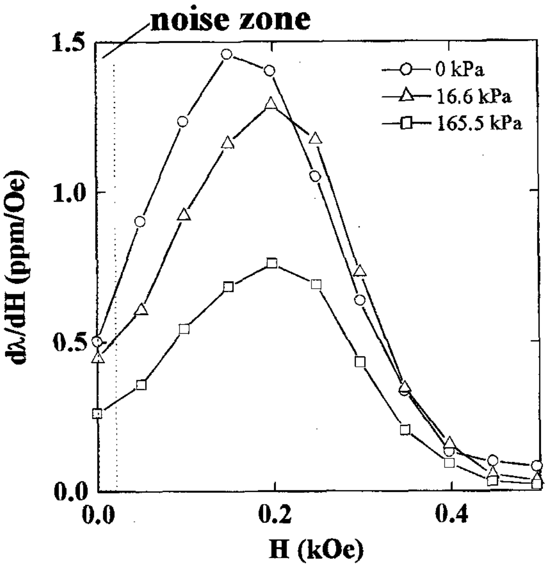

Figure 1. Relationship between applied magnetic field (H) and magnetostrictive susceptibility (dλ/dH) of Fe-45at%Pd alloy film at different loading stresses

3.2 High power actuator driven by hydrogen storage alloy film with polyamide supporting film

The large volume expansion of about 25% was observed for hydrogen storage $LaNi_5$ alloy. To obtain high power, bimorph actuators operated by hydrogen gas pressure have been developed. A new high power unimorph structural actuator, driven by the large volume expansion of hydrogen storage $LaNi_5$ alloy film on a polyamide substrate, has been prepared using a flash evaporation method.[11] A large strain change in the material, which was operated by the hydrogen pressure change.

One serious obstacle to applying such a material to a practical actuator is its load dependence strain yielded by the shape change. To evaluate the load dependence, the strain has been measured. Figure 2 shows the relationship between the applied hydrogen operation time (*s*) and the strain yielded by shape change $\Delta \varepsilon$ (ppm) of hydrogen storage alloy film at different loads. Large strain is induced at long time of hydrogen operation. The large strain over 150 ppm is observed at above 600 s of operation time of unloaded sample.

The results indicate that the high hydrogen pressure induces the large strain, because of large expansion on hydrogen absorption. When the load is large, the pressure-strain curve is small. Hence, the load dependence has been observed at hydrogen storage LaNi$_5$ alloy film. The strain can be also operated under a large loading condition. These measurements suggest that a new hydrogen storage alloy-based actuator can be developed that is expected for new type strong actuator materials for hydrogen energy system.

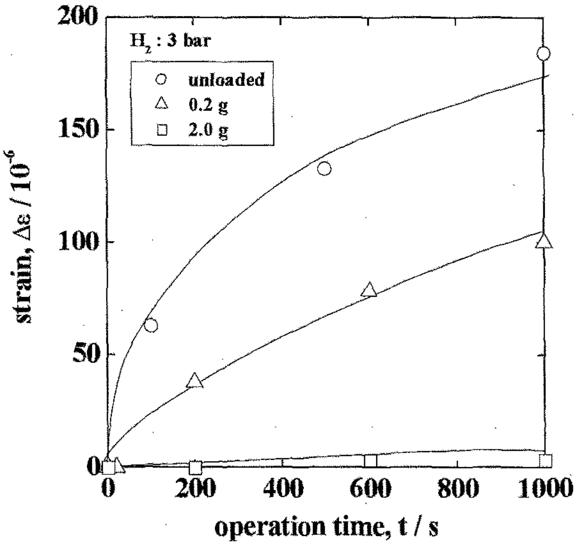

Figure 2 Relationship between applied hydrogen operation time and strain yielded by shape change of hydrogen storage alloy film at different loads.

3.3 **Load dependence**

Figure 3 shows load dependent strain of actuator materials developed, together with Ni-Ti shape memory alloy.[12] Although the strain of Ni-Ti ally is higher than that of the other materials below 30 MPa of loading stress, the large resistances to load are found in the load dependent strain lines for actuators deriven by Fe-Pd thin film and hydrogen storage alloy film. The results show that the large powers can be developed.

3.4 **Long displacement soft actuator driven by silicon rubber sheets with and without hydrogen storage alloy powder operated by H_2 gas pressure**

The large displacement, operated by the hydrogen pressure change, is obtained in unimorph structural composite constructed by the polymer sheets with and without hydrogen storage LaNi$_5$ powder dispersion.[13] Figure 4 shows photographs of the shape of the soft actuator at different operation times. The large shape changes have been observed at long operation time. This soft actuator shows reversible shape change by hydrogen absorption and desorption

Large strain is found at long hydrogen operation time. On the other hand, the long hydrogen operation time shortens the radius of curvature. The large strain over 2000 ppm has been observed at above 10000 s of operation time. The soft actuator shows large shape change as large as that of Ni-Ti shape memory alloy.

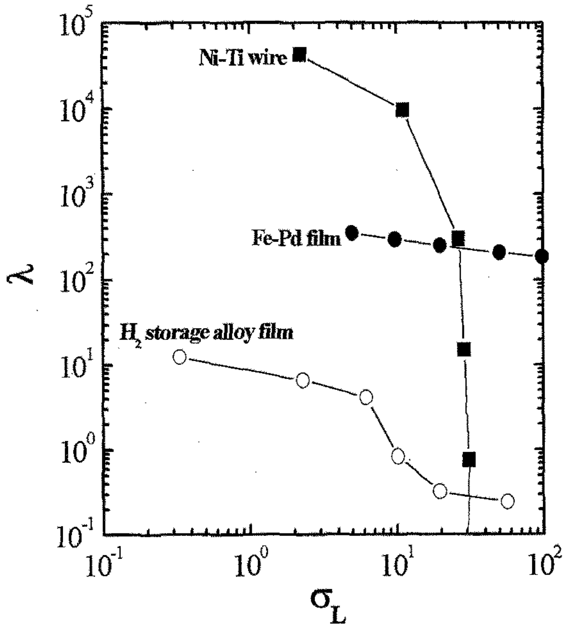

Figure 3 Load (MPa) dependent strain (ppm) of actuator materials developed, together with Ni-Ti shape memory alloy.

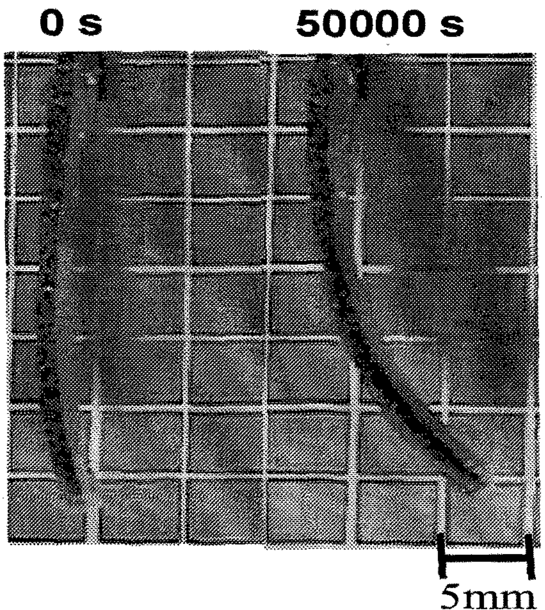

Figure 4 Photographs of shape of soft actuator at different operation times.

3.5 **Multi-functional unimorph structural actuators driven by glass transition**

The large volume change can be expected at glass transition temperature, if the driving materials are glassy structure of metal,[14,15] ceramics,[16,17] and polymer[18]. The multi-fimctions including shape changing has been expected for high resistance to irradiation for metallic glass[14,15], high heat resistance with high transparency for glassy ceramics of sodium glass and silica glass[16,17], and large displacement with light weight for polymer[18], respectively. To apply coating materials for car body, scratch repairing partially related to shape memory[19] and high corrosion resistance against acid rain[20] are found in silicon polymer coating materials. In order to obtain multi-functional actuators, unimorph materials deriven by volume change at glass transition temperatures have been developed.

Figure 5 shows temperature dependent strains of glass-crystal bimetal, bi-ceramics glass and polymer-metallic crystal. The driving temperature of polymer is apparently lower than that of bimetal and bi-ceramics. Furthermore, the large displacement has been observed for polymer and ceramics above glass transition temperature, whereas the small displacement is found for glassy alloys and ceramics below glass transition temperature.

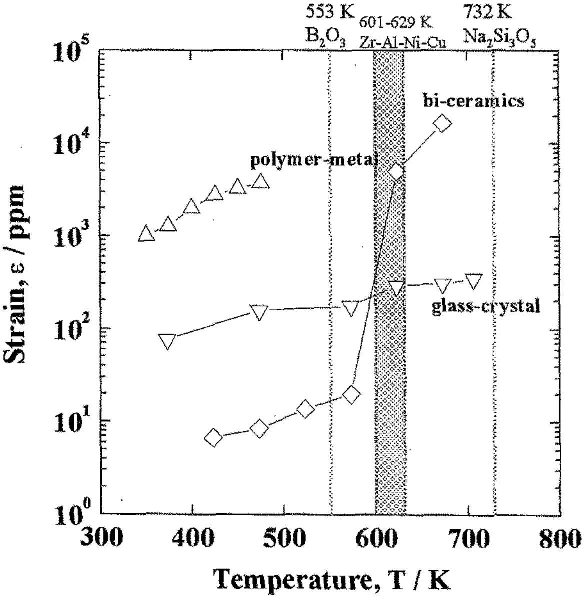

Figure 5 Temperature dependent strains of glass-crystal bimetal, bi-ceramics glass and polymer-metallic crystal.

4.CONCLUSION

In order to obtain high power, new unimorph materials of magnetostrictive Fe-Pd alloy film and hydrogen storage $LaNi_5$ films have been developed. High susceptibility with high resistance to noise is also found for the Fe-Pd alloy film. The large displacement is obtained in composite polymer sheets with and without hydrogen storage $LaNi_5$ powder dispersion. In order to obtain multi-functions including shape changing, high resistance against irradiation for metallic glass, high heat resistance and high transparency for glassy ceramics, and large displacement with light weight for polymer, bimorph materials derived by glass transition have been developed.

5.REFERENCES

[1] Y. Nishi, Y. Miyagawa, N. Suketomo, T. Morishita, E.Yajima, Scri.Metall., 19, 1273-1276(1985).

[2] M.Sano, N. Iwataka, J.Kawanno, K.Oguri and Y.NISHI, J.Advance Science, 9, 85-86(1997).

[3] S.Furuya, Y.Tanaka, K.Mori, K.Oguri and Y.NISHI, J.Advance Science, 9, 87-88 (1997).

[4] Y.Tanaka, K.Oguri and Y.NISHI, J. Advanced Science, 10, 118-119 (1998).

[5] H.YABE, R.KONDO, K.OGURI, M.Iwase, T. KANEKO,T.KUJI,H.H.Uchida,Y.Nishi,Proc. 44th Inter. SAMPE sympo.44(1999)pp.2416-2419.

[6] H. Yabe, R. Kondo, T. Toriyama, R. Fujii, K. Oguri, S. Uchida, H.H.Uchida, T. Toriyama Y.Nishi, Proc. 2nd JAPAN International SAMPE symposium, Vol.2, (1999)pp.1045-1048.

[7] H. YABE, K. OGURI, H-H. UCHDA & Y. NISHI, Inter. J. Applied Electromagnetics and Mechanics 12, 67-70 (2000)

[8]H. Yabe, Y. Nishi, TETSU-TO-HAGANE, 88, 93-98(2003).

[9] H. Yabe & Y.Nishi, Materiaux & Techniques, 1,67-68(2002).

[10] H.Yabe & Y. Nishi, JJAP, 42, 96-99 (2003).

[11]] T. Honjyoh, H. Yabe, S.Tsubuteishi, H.H. Uchida,Y.Nishi,Jpn.Inst.Met.,67,145-148(2003).

[12] Y. Nishi and H. Yabe, J.Jpn.Inst.AEM, 10, 394-399 (2002).

[13] B. KIM, H. YABE, H.H.Uchida, Y. Nishi, Proceedings of 7th Japan international SAMPE Sympo. & Exhibition (2001)pp.943-946

[14] K. TAKASHINA, H. YABE, K. OGURI, Y. MIYAZAWA & Y.NISHI, Inter. J. Applied Electromagnetics and Mechanics 12, 101-105 (2000)

[15] T.YOSHIKAWA, K.TAKASHINA, H.YABE, Y.NISHI, J. Advanced Science, 13, 21-22 (2001).

[16] T. MATSUMURA, T. NAKAMURA, K. TAJIMA, Y. MIYAZAWA and Y. NISHI, J. Advanced Science,11, 36-37(1999).

[17] T. NAKAMURA, T. MATSUMURA, K. TAJIMA, Y. MIYAZAWA and Y. NISHI, J. Advanced Science, 11, 34-35(1999).

[18] K.Akiyama,H. Yabe, Y.Nishi,, Journal of Advanced Science, 14, 37-38 (2002).

[19] T Okada, K Mori, K Oguri and Y. Nishi, Proceedings of THE 4th European Conference on Smart Structures and Materials in conjunction, (Institute of Physics Publishing Bristol and Philadelphia, 1998) pp.567-570.

[20] K. Mori, T.Okada, K. Oguri, K. Sakamoto, and Y. Nishi", "J. Mater. Res. 13, 81-85 (1998).

(Received October 10, 2003; Accepted March 20, 2004)