Review

Smart materials and processing for mover engineering

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This paper describes research developments of smart materials and processing for mover engineering. Smart materials and processing related to high power and high responsiveness successfully developed in 2004 were developed for giant magnetostrictive Tb-Fe and Sm-Fe and movable film device with hydrogen storage alloy. To obtain reliability related to elasticity, fracture resistance and fatigue resistance, we developed processing of joining of metal and carbon fiber and electron beam irradiation treatment to obtain high fracture toughness of carbon fiber (CF), CFRP, C/C composite materials and PZT for movable technology.

Keywords: Smart materials, Processing, Giant magnetostriction, Hydrogen storage alloy, Reliability

I. INTRODUCTION

One French philosopher defied that “Intelligent” means an ability of crisis control. Materials mean useful substances. Intelligent materials should be like American dreams. If smart materials are defined as real intelligent materials, realization of smart materials by processing is the most important point to activate new markets in current world. Based on nano-technologies related to magnetic field, dangling bonds, point defects, atomic distance, proton and phase transformation, smart materials and their processing for movable technology were expected. To obtain moving force and reliability for mover technology, processing related to magnetron sputtering, percussion welding and electron beam irradiation was applied for smart materials and processing for movable technology.

II. UNIMORPH TYPE OPTICAL SCANNER CONSTRUCTED WITH GM FILM

Fig. 1 shows schematic illustration of a unimorph type giant magnetostrictive device. Unimorph devise was consists of a movable thin films layer and a substrate layer supported. The operating principle was approximately as same as the bimetallic strip in a thermostat. When an expansion occurred by stimulation, large displacement of a bending movement was obtained.

Fig. 2 shows schematic illustration of the unimorph type optical scanner device prepared by using a giant magnetostrictive thin film. The device had unimorph structures and could be divided 3 parts of a giant magnetostrictive thin film as a driving component, a non-magnetostrictive polyimide substrate as an elastic film and a silicon wafer as a reflecting mirror. The part of the magnetostrictive film prepared by DC magnetron sputtering process showed the strain by applying magnetic field, whereas the elastic film exhibited no magnetostriction. Therefore, the bending motion of unimorph device can be observed, as shown in Fig.1. The driving component was consisted of a Tb-Fe
film, which was deposited on the polyimide substrate to drive the reflecting mirror and connected to the mirror part, as shown in Fig. 3.

Fig. 1. Principle of unimorph device constructed with movable and supporting thin films.

Fig. 2. Schematic illustration of giant magnetostrictive thin film multimorph device with sizes.

III. GIANT MAGNETOSTRICTIVE ALLOY THIN FILM

An optical scanner consisting of a unimorph giant-magnetostrictive Tb-Fe alloy film was prepared by DC magnetron sputtering, as shown in Fig. 3. The Tb-Fe alloy film was deposited onto a polyimide substrate and an Al thin film on the untreated surface of the polyimide substrate served as a reflecting mirror. Optical scanning characteristics of the device were examined by a bending cantilever method using a He-Ne LASER under a magnetic field. The device showed reflection angle displacement of 1.3 degrees of along the x axis and 1.6 degree along the y axis at 1100 kA/m. An applied magnetic field in range from 20 to 500 kA/m reproducibility produces a reversible linear displacement. Based on the results, the Tb-Fe alloy film device could be applied as an optical sensor.

Fig. 4 shows magnetostriction $\Delta \lambda_{\parallel}$ of a TbFe$_{17}$ film used for the optical scanning device. It was found that the magnetostricticton of the film was linearly increased around the applied magnetic field of 5 kOe the maximum value was about 1200 ppm at 15 kOe.

Fig. 5 shows relationship between the applied magnetic field versus the reflection angle and the displacement of the beam spot displayed by the optical scanner on the screen.

Fig. 3. Schematic illustration of measurement system of displacement of beam spot.

Fig. 4. Field dependent magnetostriction for TbFe$_{17}$ thin film.

Fig. 5. Relationship between applied magnetic field vs. reflective angle $\theta$ and scanning displacement $D$ on screen.
The reflection angle and the displacement of the beam spot linearly increased from 0 kOe to 5 kOe in any cases of the magnetic field directions for X or Y axes as well as Fig.4. The device showed not only high linearity, but also reproducibility. The tiny hysteresis curves were also observed. It is, furthermore, possible that the device could be applied for practical use.

IV. MOVABLE FILM DEVICE WITH HYDROGEN STORAGE ALLOY

The LaNi$_5$ hydrogen storage alloy is a potentially attractive material for high power bimetal actuators because of its ability to expand up to 25% in volume by hydrogen absorption. This high-volume expansion of the LaNi$_5$ hydrogen storage alloy generates a tremendous force, resulting in the plastic deformation of a thick-walled 18-8 stainless steel reaction cell which thickness was 0.5 x 10$^{-3}$ m. If a new actuator using a hydrogen storage alloy could be developed, this power could be triggered by a change in the absolute hydrogen pressure around the sample. Thus, a unimorph structural actuator was constructed, driven by the volume expansion of hydrogen storage LaNi$_5$ alloy film. A hydrogen storage La-Ni alloy film, prepared by flash evaporation, showed a reversible shape change. In previous works, the LaNi$_5$ alloy becomes pulverized after a number of hydrogenation cycles. An actuator made up of a non-pulverized hydrogen storage alloy film might be used as a pressure controller of hydrogen storage systems. A thin film of the alloy shows a high resistance to pulverization; thus, the thinning enhances the material’s fatigue resistance. The pressure-composition isotherm usually exhibits a plateau region as mixture of hydride and metal phases. On the other hand, almost linear isotherm can be obtained for the LaNi$_5$ alloy films deposited with more disordered crystal structure. In such case we expect a long lifetime for a new actuator driven by a LaNi$_5$ alloy thin film. In order to apply this material to a practical actuator in the field of hydrogen energy systems, the composition dependence and load dependence of the strain produced by a shape change have been studied for the LaNi$_5$ alloy film. However, the actuator with low responsiveness is a serious problem for applications directed to a broad market. To enhance this responsiveness, a platinum catalyst has accelerated the dissociation rate of hydrogen gas. Furthermore, palladium often also acts as a catalyst. Thus, we have coated the surface of a polyimide-supported LaNi$_5$ film with palladium using magnetron sputtering vapor deposition in order to investigate its effects on the shape change responsiveness of this new unimorph structural device. Since controlling the hydrogen concentration in film by reversible pressure change drives this device, this film device can be expected as a sensor and/or a controller of hydrogen gas flux in various hydrogen-related devices. As shown in Fig.6, it was shown that the initiating time (incubation period) for the actuation to be measured after hydrogen gas exposure was reduced from 100 s to 1 s by the palladium surface treatment. It was found that the high responsiveness induced by the palladium treatment was mainly caused by the high permeability of hydrogen in palladium film at room temperature. This significantly improved mechanical response was attributed to the switching of the reactions in the rate determining steps. The rate determining reaction after the palladium treatment was no longer the dissociation of hydrogen gas molecules on the sample surface, but the hydrogen diffusion in the LaNi$_5$ film, rather than the hydrogen permeability through the palladium thin film.

![Graph showing relationship between reaction time and stress](image)

Fig. 6. Relationship between reaction time after exposure to hydrogen under 1.2 x 10$^5$ Pa, and strain generated by shape change, $\varepsilon$, of the devices with a Pd-treated, Pt-treated and untreated LaNi$_5$ hydrogen storage alloy films.
V. RELIABILITY OF MATERIALS AND PROCESSING FOR MOVER ENGINEERING

As reliability functions, fatigue limit prediction method for PZT ceramics\(^6\) high fracture toughness of C/C composite materials\(^5\) and CFRP\(^6\) and homogenization with high strength controlling for transparent glassy materials\(^7,8\) were developed. As shown in Fig. 7, EB-irradiation enhanced the tensile strength. The creation of these 'reliable' properties largely depended upon such causative factor as dangling bond formation. Percussion welding has been applied to the joining of carbon fiber to metals.\(^9\) The CF-Metal percussion welding is useful tool to prepare cell electrodes and CF temperature sensor with high heat resistance. The joining potential employed ranged from 160 to 210 V at a condenser capacity of 100 \(\mu\) F. Using a tensile test for fine fibers, fracture stress was obtained for optimum joining potential. Fracture occurred at the welding heat-affected zone of the carbon fiber near joining part. As shown in Fig. 8, the heat resistance of CF-Ni junction was higher than that of CF-soldering alloy junction. Furthermore, based on the concept of CF-Metal welding, iron-aluminum joining, which was expected by light parts of automobiles, was just developed by using carbon fiber junction.

![Graph showing tensile strength vs EB irradiation dose](image)

**Fig. 7.** Tensile strength (\(P_f=0.5\)) of carbon fiber against EB-irradiation dose.

VI. CONCLUSION

Smart materials related to high power and high responsiveness were successfully developed in 2004 for giant magnetostrictive Tb-Fe and Sm-Fe and movable film device with hydrogen storage alloy. In order to obtain reliability related to elasticity of C/C composite materials, fracture resistance of CFRP and fatigue resistance of PZT, we developed processing of joining of metal and carbon fiber and electron beam irradiation treatment for movable technology.

![Graph showing temperature vs stress](image)

**Fig. 8.** Tensile strength (\(P_f=0.5\)) of carbon fiber - (soldering alloy and nickel) junctions at elevated temperatures.

REFERENCES