Design of FePd spring actuators

Taishi Wada*, Cheng-Chun Lee** and Minoru Taya***
Center for Intelligent Materials and Systems, Univ. of Washington,
BOX 352600, Seattle, WA98195-2600, USA

Abstract

A design concept of the spring actuators based on the ferromagnetic shape memory alloy (FSMA) is presented. The coil spring made by a FSMA is activated by the attractive magnetic force produced by electromagnets, which is usually not uniform. When the magnetic field is applied, each turn of the spring comes into contact with the neighboring turns one by one, stacking from the turn closer to the yoke of the electromagnet. As a result, entire shrinkage of the spring accompanied by large liner stroke is achieved. This actuator is energy-efficient, since almost all magnet flux originated from electromagnet discharges into the ferromagnetic spring. The performance of the spring actuator, i.e. the output force and stroke, depends on many factors, such as the diameter and the pitch of the spring or the dimension of the cross section of the spring wire, and so on. We processed successfully a spring actuator driven by a hybrid magnet based on the above principle by using polycrystalline FePd alloy. Since the stiffness of the FePd coil spring become softer due to the martensite phase transformation, the movement of the actuator is accelerated during actuation.

Keywords: actuator, coil spring, FePd, wire, ferromagnetic shape memory alloy, superelasticity, hybrid magnet, electromagnet, permanent magnet

1. INTRODUCTION

Recently, strong attentions are paid to ferromagnetic shape memory alloys (FSMAs) as important smart materials, which are adaptive for lightweight, yet high power engineering actuators [1-3]. The conventional thermoelastic shape memory alloys (SMAs), which can be activated by either temperature or external loading, such as TiNi alloys, exhibit large strain and also bear large stress. However their actuation speed is usually slow, since the actuation speed is limited by the heating/cooling rates of the SMAs. On the other hand, FSMAs are driven by applied magnetic field and/or magnetic field gradient, which cause the deformation due to the martensitic phase transformation, and hence can provide very fast actuation speed with reasonably large strain and stress capability. Among various FSMAs, the polycrystalline FePd alloy [4] is practically promising to be applied as an actuator material, owing to the good mechanical properties, such as shape memory effects, superelasticity and high ductility, and so on.

Since the uniform (constant) magnetic field alone is found to be disadvantageous as a driving force [5], we proposed so-called hybrid mechanism for actuator applications [6] and is adopted in the present paper. The key step in the mechanism is the stress-induced martensite phase transformation produced by applied magnetic field gradient, thus enhancing the displacement, as the stiffness of Fe-Pd is reduced from stiff to soft during the austenite to martensite transformation [7].

The present paper shows a new concept of the spring actuator based on FSMA alloys driven by hybrid magnet system composed of permanent magnets and electromagnets. The performance of the FePd coil spring actuator controlled by DC amplifier is investigated. The development of ductile polycrystalline FePd wires and processing it into coil springs are also described.

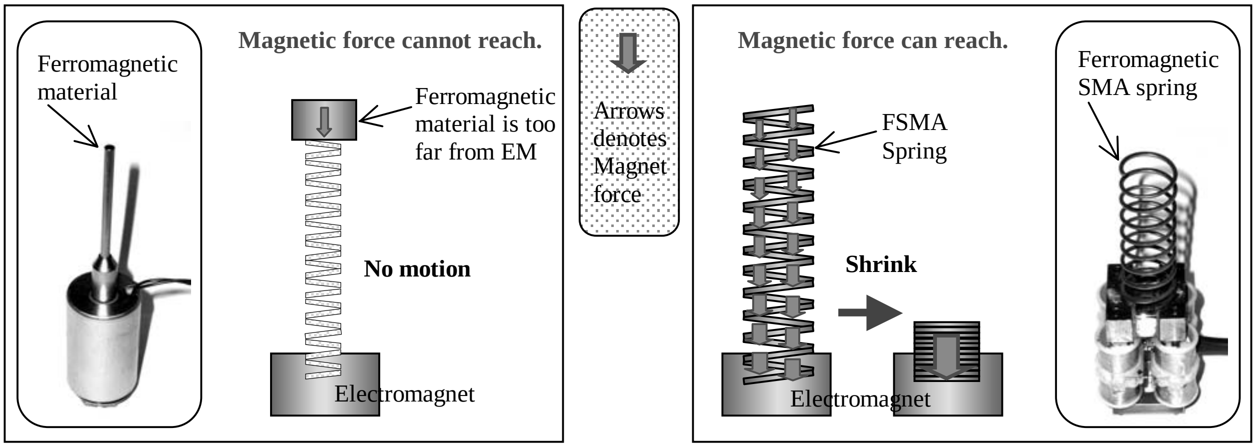
2. BACKGROUND OF DESIGN CONCEPT

2.1 New design of a linear actuator different from conventional linear motors

It is beneficial for accomplishment of both large stroke and force of the spring actuator made from FSMA. It is because that the stiffness of the spring made from FSMA become smaller than those of the spring made from the other ferromagnetic materials due to the high mechanical properties, such as stress-induced martensite phase transformation or superelasticity.

Various kinds of actuators, which convert electromagnet energy to mechanical energy to achieve a liner movement or stroke, have been elaborated. Although a linear motor actuator is frequently used to get a large liner stroke, use of permanent or electromagnet is crucial for smart designing of high performance actuators. It should be pointed out that the action of the coil spring can reach far from the power source (electromagnets), since the output force and stroke can transmit through the long coil spring. This is an essential difference from the linear motor.

*wada@u.washington.edu, **rynlee@u.washington.edu, ***tayam@u.washington.edu; Center for Intelligent Materials and Systems, Department of Mechanical Engineering, University of Washington, BOX352600, Seattle, WA98195-2600, USA



A commercial solenoid

The present spring actuator

Fig.1. Essential difference of axial linear movement between the solenoid and the present spring actuator.

Here it should be pointed out that the design concept of the present spring actuator is similar to the conventional solenoid, which is commercially and generally available. However the present axial actuator has the large advantage over the solenoid. Figure 1 shows the essential difference between the present actuator and the solenoid. If the ferromagnetic material portion of the solenoid, which is a movable shaft, were far from the electromagnet, the shaft would show little movement, since the magnetic force originated from the electromagnet can not hardly reach. On the other hand, the present spring actuator could eliminate this week point. Moreover the stroke of the spring actuator can be much larger than that of the solenoid, since the entire FSMA spring itaself can feel the magnetic flux which transmits the spring wire and reaches the end-top of the spring. One of the enormous merits of the present spring actuator is that the large stroke can be achieved and furthermore the larger stroke can be generated by using “the stacking effect of the spring wire, as described later.

2.2 Force originated from electromagnets

For simplicity we assume that the force generated by magnetic field, which acts on ferromagnetic materials, classify into two cases; one is the short-range force, the other is the long-range force. The short-range force, F_1, is a kind of Coulomb force between two ferromagnetic plates separated by the distance of d, and is written as, $F_1 = B^2 S^2 / 2\pi\mu_0 d^2$, where B is magnetic induction, S is the surface area of the each plate and μ_0 is permeability of free space. The long-range force along x-axis, F_2, arises under the inhomogeneous magnetic field strength, and acts on a magnetic dipole, m, and given by $F_2 = mV\, dB/dx$, where V is the volume of the magnetic dipole. F_1 is possibly larger than the force F_2, since the force F_1 is in inverse proportion to d^2 and hence becomes huge when d is very small. The design of the spring actuator is based on the above-mentioned concept in that the driving force of the actuator comes mainly from the force F_1 with small or zero distance d. It is noted that the proposed concept of the spring-based actuator, which is activated by not only the force F_2 but also the strong force F_1, becomes more efficient by using the stacking effect of the spring wire, which would be clarified later on. Note that it is very important to use the force F_1 efficiently when we optimize the designing of the present spring actuator.

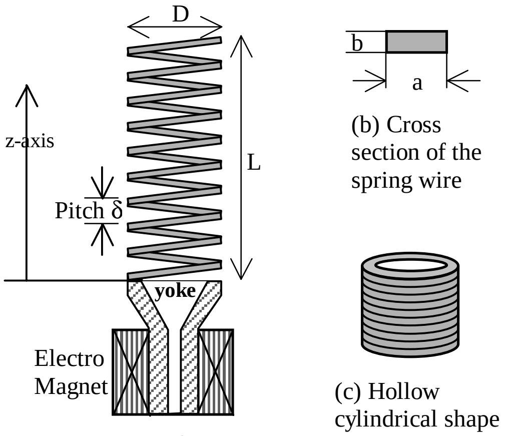
2.3 Energy efficiency

For increasing the energy efficiency of the spring actuator, it is better to decrease the stiffness of the spring. The input electromagnetic energy E_{in} is expressed as the sum of the output energy (the work of the actuator) E_{out}, the elastic energy $E = \int (\sigma\varepsilon)/2d\varepsilon$, which is stored in the coil spring, and the energy loss W, that is, $E_{in} = E_{out} + E + W$. The energy loss can not be avoidable when the energy conversion from electromagnet to mechanical energy occurs. From this point of view, this actuator must have more advantage since almost all magnetic flux originated from electromagnet is discharged into the ferromagnetic spring, as discussed in the next section. We assume that the energy loss can be ignored. Then, the above formula is written as $E_{in} = E_{out} + E$. Since the energy efficiency is described by $E_{out}/E_{in} = 1 - E/E_{in}$, the smaller elastic energy stored in the spring, E, results in higher energy efficiency. This means that use of the spring with smaller stiffness is better for designing the energy efficient actuator.

The stiffness of the spring made from FSMAs becomes small when the materials strained, because these materials show the stress-induced martensite phase transformation. If we use FSMA materials, the energy stored in the coil spring, E, become small when the spring shrinks or elongates, and hence high energy-efficiency can be obtained. The so-called hybrid mechanism, which is described in the previous section, is in accord with the above energetic consideration.

3. MECHANISM

The coil spring made from a ferromagnetic material is mounted on a yoke which is inserted in the electromagnet, see Fig.2(a). The z-axis is parallel to the center axis of the yoke from which the magnetic flux is generated and goes into the bottom of the coil spring. Figure 2(b) shows the cross section of the spring wire, which is the rectangular shape with the long side, a, and the short side, b. When the coil spring subjected to a external force along the center axis of the spring, it shrinks from the length of $L=n\times\delta$ into $n\times b$ and each turn of the spring completely contacts with the neighboring turns, where δ and n are the pitch and the turns of the spring, respectively. That is, the coil spring becomes the shape of a hollow cylinder after entire shrinking, see Fig.2(c). In the event that the first turn of the coil spring is directly fixed to the yoke, the pitch δ should be the function of the value of z, i.e. $\delta=\delta\,(z)$, where z is the distance from the yoke along the center axis of the spring. The function $\delta(z)$ should increase slightly when the value of z is very small, and the derivative $d\delta/dz$ $(z=0)$ must be zero in order to connect the coil spring to the yoke directly.



(a) Side view of the spring actuator driven by a electromagnet

(b) Cross section of the spring wire

(c) Hollow cylindrical shape of the coil spring after shrinkage

Fig.2. Schematic illustration of the ferromagnetic spring actuator. L is the length of the coil spring with n turns.

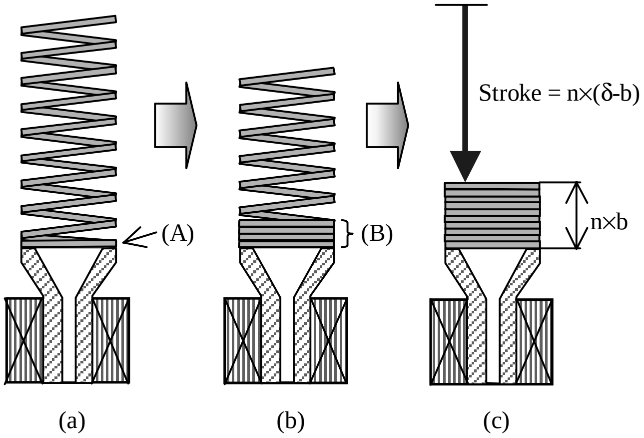
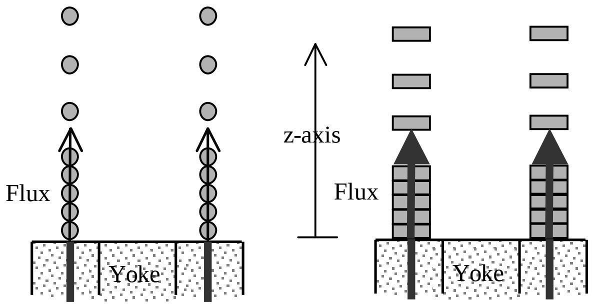


Fig.3. Mechanism of the spring actuator movement. The first turn of the coil spring denoted as (A). The portion (B), which is stacking of the coils spring, acts as a kind of yoke. Finally the all turns of the spring comes into contact with each other and stack completely on the yoke like (c).



(a) Circular cross section

(b) Rectangular cross section

Fig.4. Cross section view of the coil spring and stacking effect of the coil spring. The magnetic flux can easily go into the stack of the rectangular cross section of the spring wire.

Figure 3 shows the sequential mechanism of the spring actuator movement. When the electromagnet is switched on, the first turn of the spring (A) is attracted to the yoke and comes into contact with the top face of the yoke, see Fig.3(a) and compare with Fig.2(a). This turn (A) works as a new yoke after contact with the original yoke. Therefore the second turn of the spring is attracted to the first turn (A) and comes into contact with it. Since the same motion is repeated, the turns which contact with the neighboring turns works as if they were yoke (potion (B)), as indicated in Fig.3(b). Accordingly all turns of spring comes into contact with the neighboring turns, accomplishing that the coil spring shrinks entirely, see Fig.3(c). Hence the maximum stroke of the spring actuator is n×(δ-b).

In order to make full use of the above-mentioned mechanism, i.e. "the stacking effect of the coil spring", each turn of the spring should contact with the neighboring turns perfectly. Thus, the rectangular shape of the cross section of the spring wire is better than the circular one, even though the circular cross section is more popular and conventional, see Fig.4. The magnetic flux can easily penetrates into the stack of the spring wire with rectangular cross section rather than that with the circular cross section.

Since the magnetic attractive force is usually very small at the top portion of the coil spring before shrinking, the stacking mechanism might be the only possible way to move the coil spring. Note that the mechanism is not complete if the first turn of the coil spring closest to the yoke does not make contact with it. Thus, the pitch δ should be determined so as to induce the elastic or superelastic deformation of the first turn of the coil spring due to the magnetic force around the top portion of the yoke.

4. RESULTS

4.1 FePd wires

When a coil spring deforms, the shear-stress concentration occurs near the surface of the spring wire. The above concept is workable as far as the coil spring is made from a ferromagnetic material and shows elastic and reversible deformation if the pitch δ is small. However it would bring even larger actuation of the spring actuator if it were made of FSMA material, since it shows superelasticity above the martensite transformation start temperature, so that the stress concentration at the surface of the spring wire is accommodated by the phase transformation. Especially when the pitch δ of the spring is designed to be large to get huge stroke of the actuator, large shear stress arises at the surface of the spring wire. In this case, use of FSMA is quite effective for accommodation of the stress concentration and increase of the spring displacement.

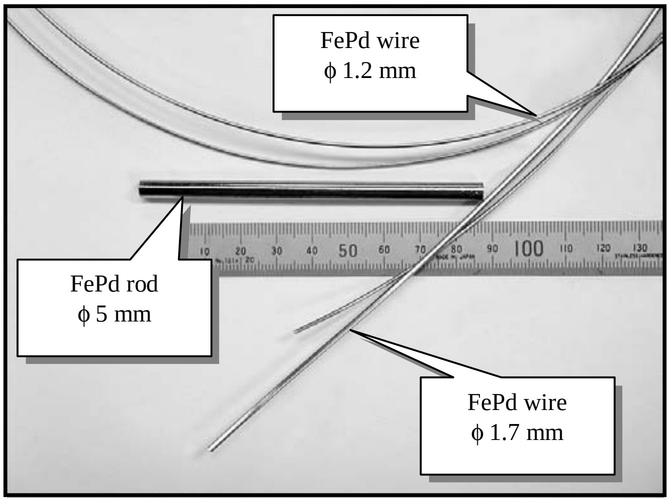
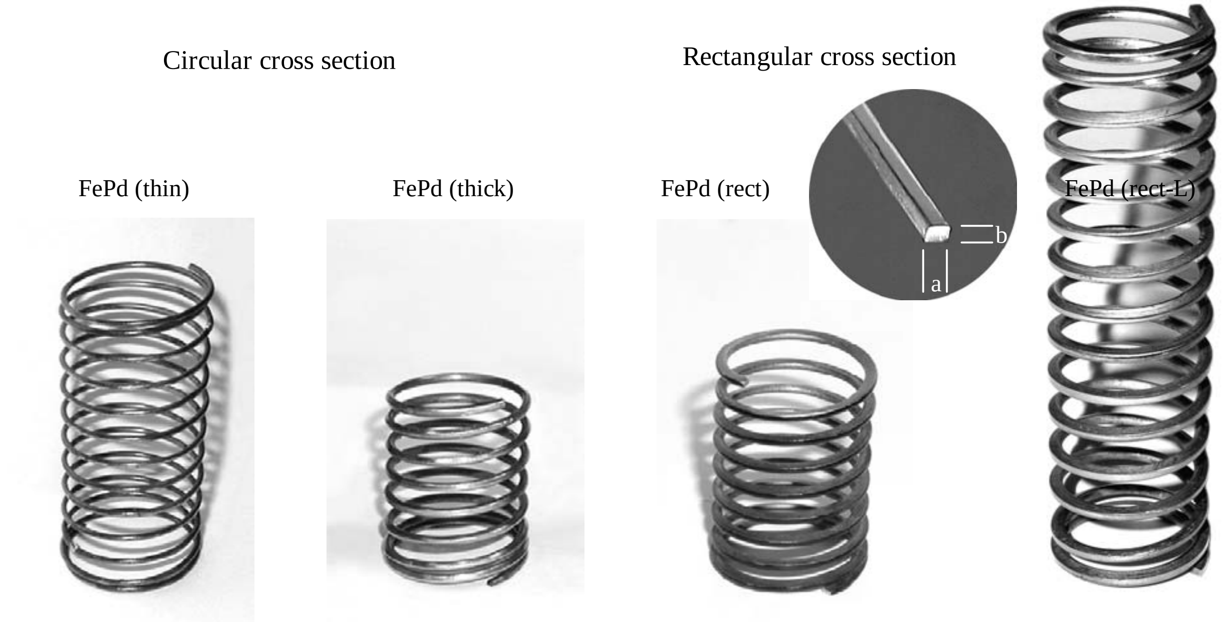


Fig.5. FePd wires with circular cross section cold-drawn from FePd rod.

Since it was found that FePd alloy has high mechanical properties and has high ductility, a sharp contrast from the other FSMAs, we adopted FePd alloy for the FSMA coil spring driven by the hybrid mechanism. Figure 5 shows the FePd rod and FePd wires which we processed successfully. The FePd rod was melted and solidified in a induction furnace. The FePd wires with circular cross section were made from the FePd rod with 5mm diameter by using the method of cold drawing in room temperature. We also processed successfully the FePd wire with rectangular cross section by means of the process similar to that of the wire with circular cross section. These wires were annealed in a furnace and winded into coil springs mechanically and annealed again to keep the shapes of the springs. Figure 6 shows the photographs of the FePd coil springs made from the FePd wires, where the specifications of the coil springs are summarized in the table. Three kinds of the FePd coil springs were made; FePd(thin), FePd(thick) and FePd(rect), the first two have circular and the last has rectangular cross section. The FePd coil springs have almost the same diameter of spring D, however have different spring constant because of the different shapes and dimensions of the wire cross sections. Note that "a" is lager than "b" in the FePd(rect) coil spring, where "a" and "b" are two sides of rectangular cross section of the wire shown in Fig.6(c). We can easily understand why the length of "a" should be larger than "b" by seeing the illustration of Fig.4(b). The magnetic flux, which originated from the yoke, can go into the stacking of the FePd wire, however can reach only limited height of the stacked wire, since the intensity of the magnetic flux decrease during propagating into the stacked wire. From Figs.2-4, it is concluded that the shape of the cross section of the FePd coil spring should be rectangular and the side "a" should be larger than the side "b", as to obtain high performance of the coil spring actuator.



FePd coil springs	Length of spring, L [mm]	Diameter of spring, D [mm]	Shape of the cross section of the spring wire	Dimensions of the spring wire, diameter, d [mm]	Spring constant for 1 pitch, k [N/mm]
FePd (thin)	53	25	circular	d=1.2	0.29
FePd (thick)	34	26	circular	d=1.7	2.3
FePd (rect)	70	26	rectangular	a=2.0, b=1.2	1.5
FePd (rect-L)	95	26	rectangular	a=2.5, b=1.9	5.3

Fig.6. FePd coil springs made from the FePd wires and their specifications.

4.2 FePd spring actuator

Sequential movement of FePd(thin) coil spring is exhibited in Fig.7. together with the movement of Fe coil spring which has the same shape and dimensions as the FePd(thin) coil spring. These two coil springs are driven by the hybrid magnet with the electric resistance of 20Ω, which is composed of not only electromagnets but also permanent magnets. When the electromagnets are turned off, both FePd(thin) and Fe coil springs keep their natural length. The FePd(thin) coil spring shrinks with the huge stroke of 20mm when the direct current of 1A is applied, see Fig.7(b). This stroke is 20 times larger than that of Fe coil spring. It may show the high effect of use of FSMA as a coil spring. However, the surprising difference looks too enormous, since the spring constant of FePd(thin) is only about 2.5 times softer than that of Fe. It seems that the huge difference between them is caused not only by the effect of the hybrid mechanism of FSMA but also by the stacking effect of the coil spring since the FePd(thin) spring shows stacking and Fe does not, as we can see in Fig.7(b). Both effects are attributed to the 20 times improvement. When the direct current of 3A is applied, the FePd(thin) coil spring exhibits complete shrinkage with 40mm displacement while Fe coil spring shrinks only 6mm, which is 7 times smaller than FePd(thin). The difference of the displacement under electric current of 3A between the FePd(thin) and Fe springs is smaller than that for the case of 1A. It is because that the movement of spring is not linear to the applied direct current as described later in the next section. The actuation speed of the FePd(thin) spring actuator for entire shrinkage is about 0.03s if the direct current of 3A is applied suddenly, i.e. the current-time curve is a kind of step function. Note that the displacement of the spring shrinkage depends on the strength of the applied direct current and therefore can be controlled and determined for a desired position by the applied direct current amplifier. This controllability and large stroke of the present spring actuator would satisfy the high performance required for the use in several kinds of tough conditions.

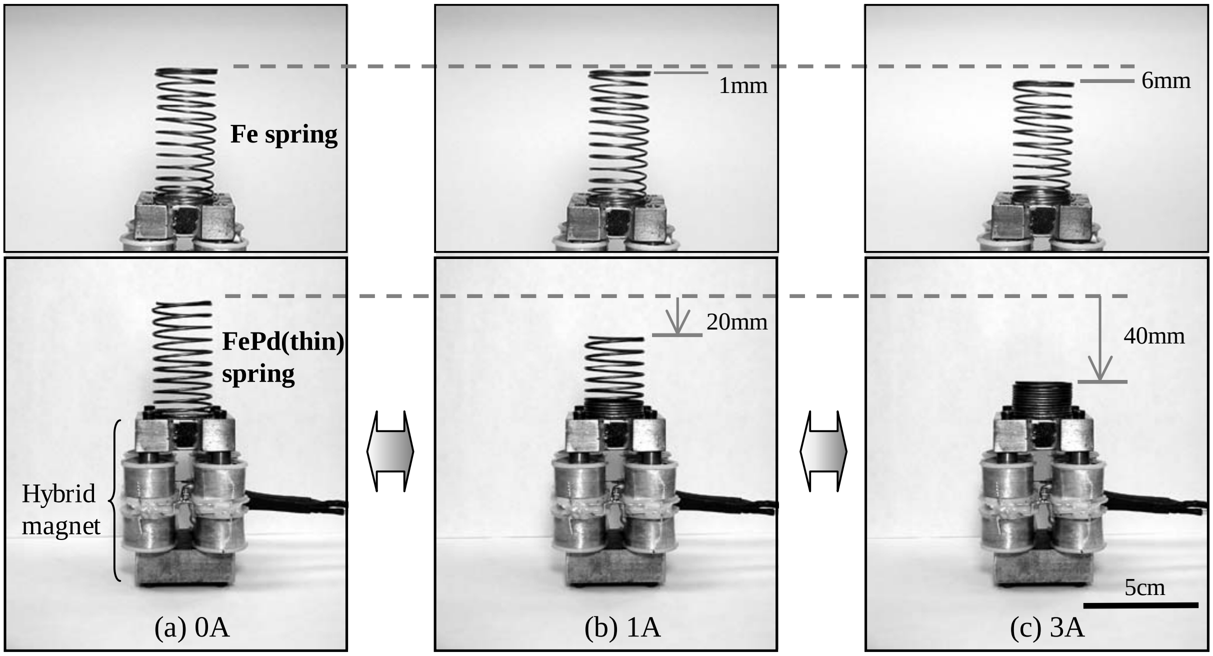


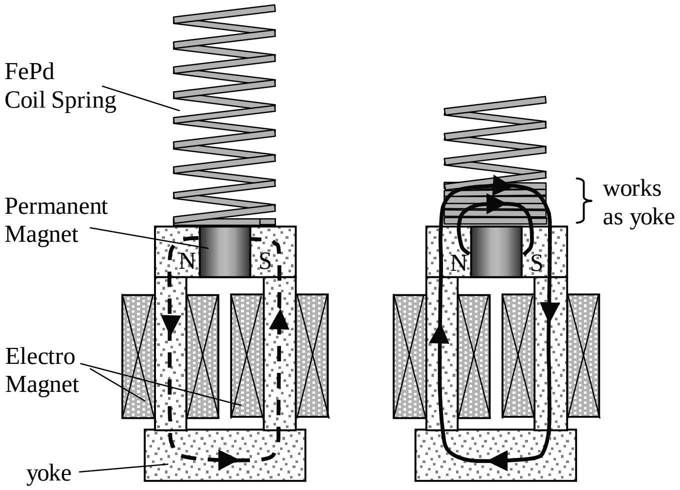
Fig.7. FePd (thin) coil spring actuator driven by hybrid magnet. The motion of the FePd spring is compared with the Fe spring with the same shape and dimensions. The spring constant of FePd (thin) and Fe spring are 0.29N/mm and 0.84N/m, respectively. The weight and electric resistance of the hybrid magnet are 0.3kg and 20Ω. The actuation speed of the FePd (thin) actuator is about 0.03s. The applied direct current is the step function of time, i.e. ON-OFF mode.

5. DISCUSSION

5.1 Design concept of hybrid magnet driving unit

It should be pointed out in Fig.7 that use of hybrid magnet is also important in addition to use of FePd FSMA coil spring in order to achieve the high performance of the spring actuator. Design concept of the hybrid magnet to drive the coil spring is discussed here. The schematic illustration of the hybrid magnet used in Fig.7 is shown in Fig.8, which consists of electromagnets, a permanent magnet and the yoke. During the time that the electromagnets are turned off, the magnetic flux generated from the permanent magnet flows in the yoke and makes a close loop, as shown in Fig.8(a). After the electromagnets are turned on, which produce the magnetic flux in the inverse direction to that of the permanent magnet, the magnetic flux that comes both from the permanent magnet and from the electromagnets is pushed upward and penetrate into the spring wire. As a result, each turn of the coil spring is attracted to the permanent magnet and accumulates on it, working as a temporary yoke. Since both magnetic powers of the permanent magnet and electromagnets are utilized, the hybrid magnet is much stronger than the electromagnets itself, yet can accomplish the on-off switching unlike the actuator with only permanent magnet. A similar concept was used to design a powerful reactance electromagnetic motor [8].

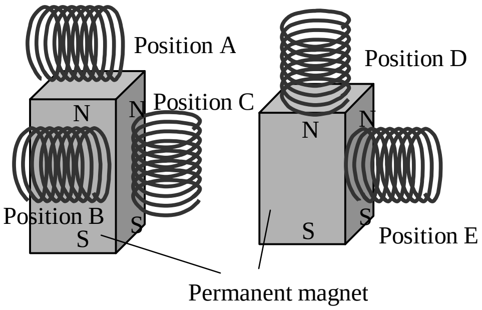
To procure the closed loop of magnetic flux by using the yoke, the relative position and direction between a coil spring and a permanent magnet should be investigated in Fig.9, where the five kinds of positions, A, B, C, D and E are considered. The position A and D are useless since the closed loop can not be realized. Thus, we focus only on position B, C and E. In Fig.9(a), which illustrate the shrinking motion along a permanent magnet, the position B is considered to be preferable than the position C since the movement of the coil spring in the position B is usually better than the position C. Consequently both the position B for sliding along and the position E shrinking toward a permanent magnet are selected to be most useful. Figure 10 shows the photos of the two types of the hybrid magnet, which are designed and manufactured here. The hybrid magnet TYPE A is utilizing the position E, where the coil spring is placed on the top of the permanent magnet, as shown in Fig.10(a), and the coil spring shrinks toward the hybrid magnet if the electromagnet is turned on. While the hybrid magnet TYPE B is utilizing the position E, where the coil spring is surrounded by some numbers of the permanent magnets, as shown in Fig10(b), and the coil spring shrinks along the permanent magnets. In this paper, only the TYPE A is used. It should be pointed out that the TYPE A and TYPE B have almost the same high performances.



(a) EM: turn OFF
PM: Closed loop

(b) EM: turn ON
PM: Flux is pushed up

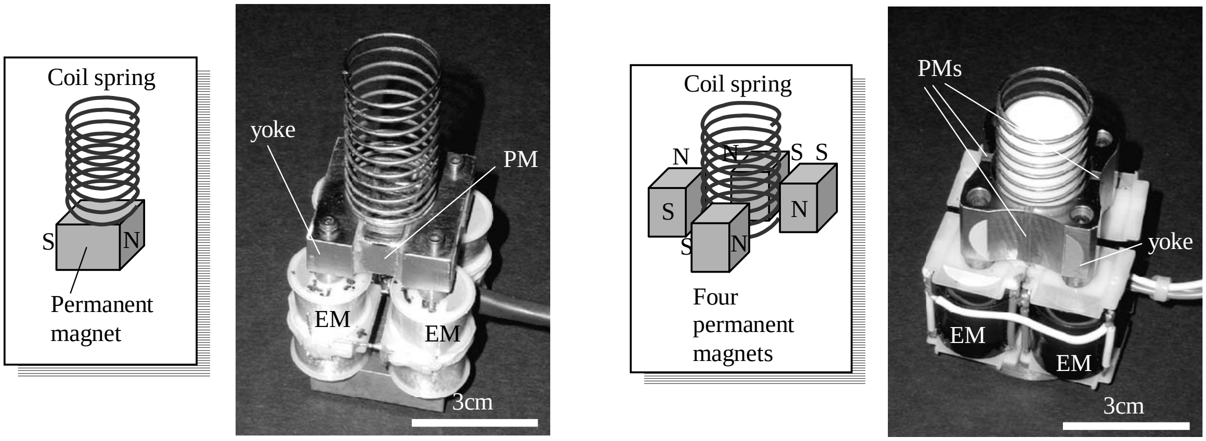
Fig.8. Concept of the hybrid magnet composed of electromagnets, a permanent magnet and the yoke to achieve the closed loop.



(a) Shrink (Sliding)
along PM

(b)Shrink
toward PM

Fig.9. Relative position and direction of the coil spring against the permanent magnet. Five types of positions, A, B, C, D and E exist. The position A and D are not utilized since the closed loop can not be realized.



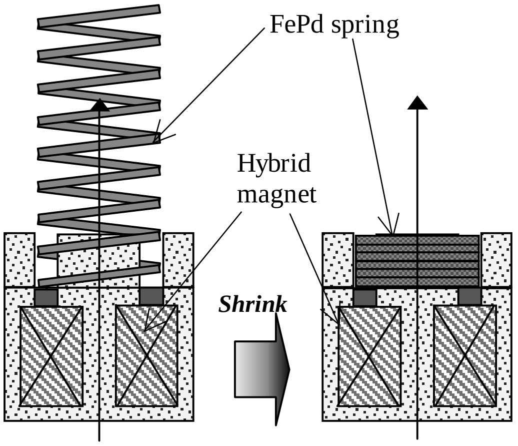
(a) Hybrid magnet TYPE A which uses the position E in Fig.9. The coil spring is placed on a permanent magnet.

(b) Hybrid magnet TYPE B which uses the position B in Fig.9. The coil spring is surrounded by a few permanent magnets.

Fig.10. Two types of hybrid magnet which are designed and manufactured by the present authors.

5.2 FEM calculation

In order to optimize the designing of the hybrid magnet for driving the FePd spring, it is quite useful for us to calculate the magnetic force by FEM. Figure 11 shows the other design of a hybrid magnet utilizing the Position E and one of the results of the FEM calculations of magnetic vectors and fluxes performed by using ANSYS, assuming that the Neodymium permanent magnet has the relative permeability μ_r=1.17 and the coercive force H_c=835,000(A/m). In the calculation, the actual B-H curves of FePd and Fe yoke are inputted. Note that the magnetic flux should not leak out into the air from the yoke. Magnetic flux should be confined both when the electromagnet is turned on and off. If the magnetic flux, which is originated from both electromagnet and permanent magnet, makes a closed loop in the FePd spring wire and the yoke, we can get strong magnetic forces acting on the FePd spring wire.



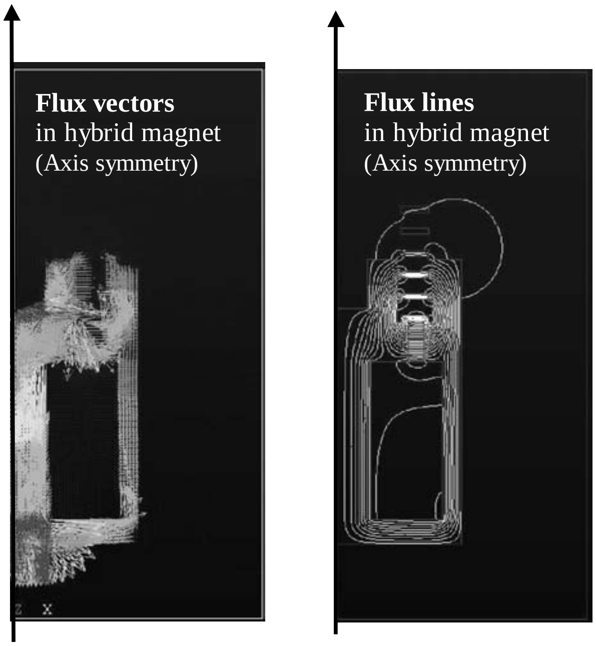


Fig.11. FEM calculation of magnetic flux in a hybrid magnet with Position E, which differs from Type A and B.

5.3 Performance of FePd coil spring actuators

Both motion of lifting-up and pushing-up of the weight are achievable in the present spring actuator. Figure 12 shows the lifting-up motion of the FePd spring actuator, where combination of the FePd(thick) coil spring and the hybrid magnet TYPE A are used. The hybrid magnet amounted upside down and the weight (dead load) are connected to the tip of the FePd(thin) coil spring. After the electromagnets are turned on, the weight is lifted up immediately. The performances of this actuator are the force (weight) of 400gf and the stroke of 15mm, better than the first design, i.e. the FePd(thin) spring actuator, where the maximum force of 100gf and stroke of 40mm were recorded.

Pushing-up motion of the FePd spring actuator is shown in Fig.13, where the FePd(rect) coil spring and the hybrid magnet TYPE A are utilized. The FePd(thick) coil spring is amounted on the hybrid magnet and the weight (dead

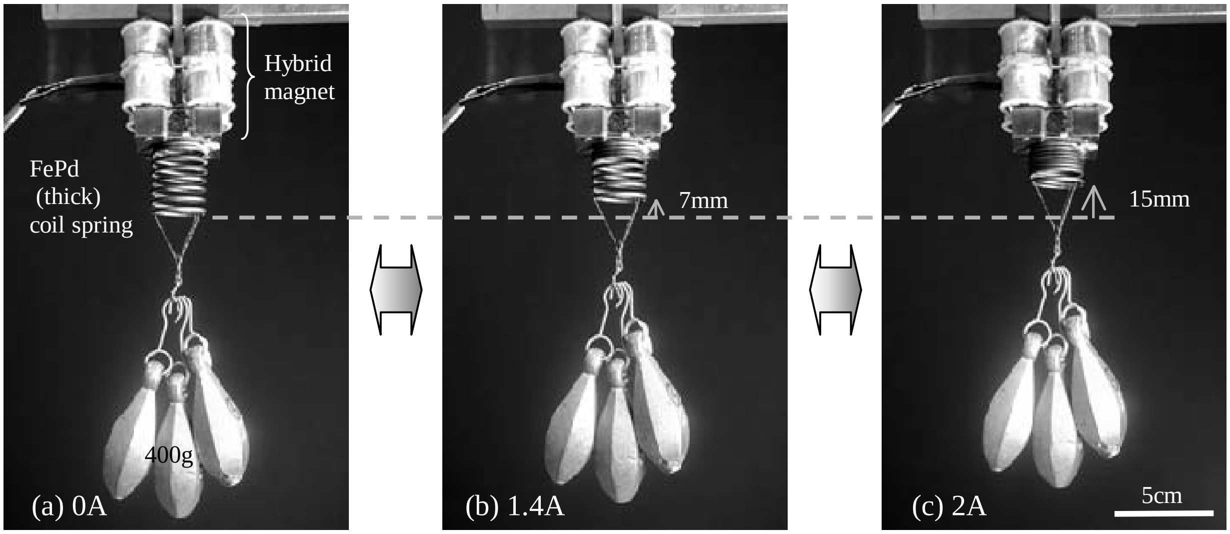


Fig.12. Lift-up motion achieved by using FePd (thick) spring actuator that can deliver the output-force of 400gf and stroke of 15mm, which are the larger force and smaller stroke than FePd (thin) spring actuator. The hybrid magnet of TYPE A, which is same as Fig.7, i.e. FePd (thin), is used.

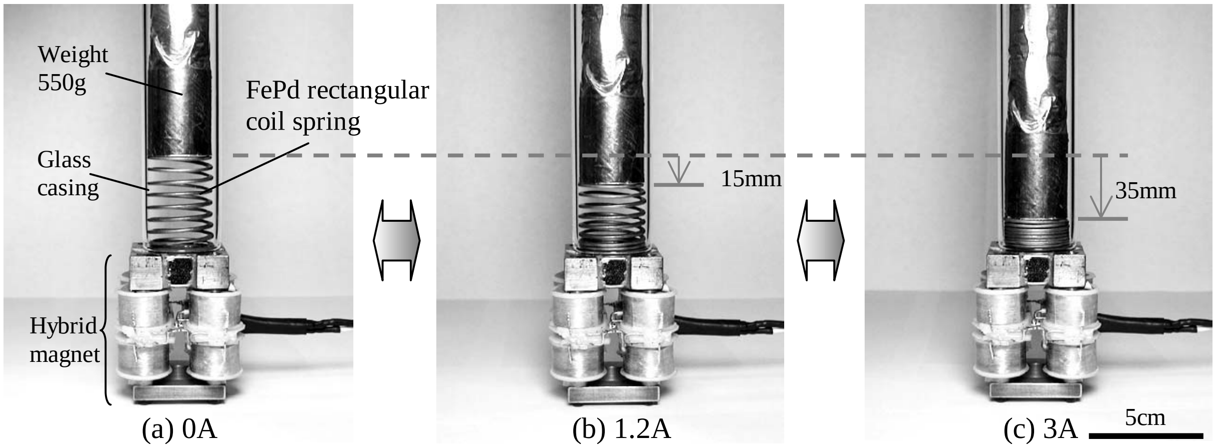
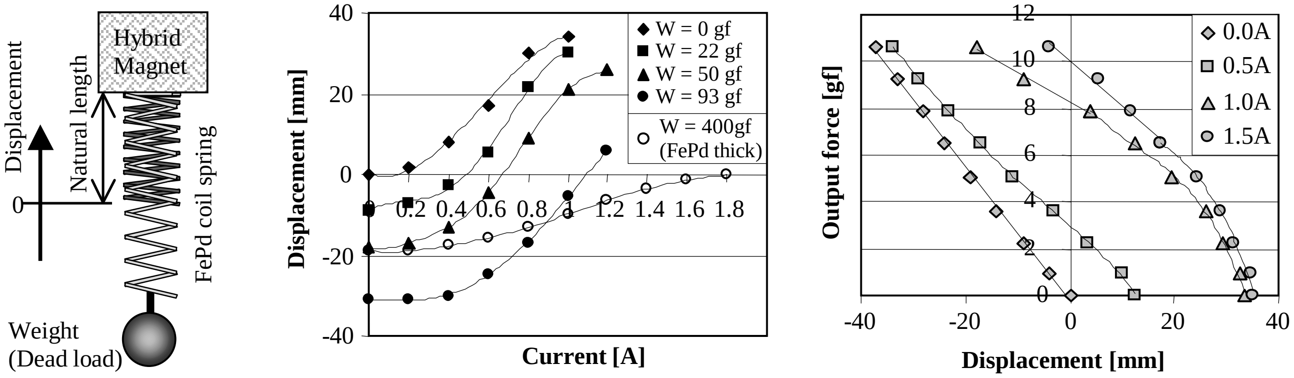


Fig.13. Pushing-up motion achieved by using FePd (rect) spring actuator which can deliver the output force of 550gf and stroke of 35mm, which are the larger force than FePd (thick) and almost same stroke as FePd (thin) spring actuator, indicating the effect of the rectangular shape of the cross section. The hybrid magnet TYPE A, which is same as Fig.7, is used.

load) is placed on the spring. The spring and weight are inserted into a glass casing and are stabilized vertically. The performances of this actuator are the force (weight) of 550gf and the stroke of 35mm, which are the larger force than FePd (thick) and almost the same stroke as FePd (thin) spring actuator, indicating that the rectangular shape of the cross section really gives rise to increase the performance of the spring actuator.

Figure 14 shows the performance of the FePd(thin) spring actuator fixed to the hybrid magnet TYPE A, which is investigated by applying a direct current using DC amplifier. The set-up of the spring and hybrid magnet and also the definition of the measured displacement are shown in Fig.14(a). Displacement of the weight (W) lifted up by the FePd(shin) coil spring are plotted as a function of the applied direct current in Fig.14(b). Several weight, such as W=0, 22, 50 and 93g, and additionally the weight of 400g for the FePd(thick) spring actuator are examined. The displacement for each weight keeps almost constant while the current is small, since the first turn of the coil spring closest to the hybrid magnet has not yet contacted with the yoke. Accordingly the curve of the displacement does not show the linear shape. However, it seems that the displacement starts to increase almost linearly after the first turn of the coil spring comes into contact with the yoke. We can say that the non-linear displacement curve in Fig.14(b) comes from the stacking effect of the



(a) Definition of displacement

(b) Displacement of the weight lifted up by the FePd (thin) spring actuator which a direct current applied.

(c) Output force vs. displacement curves of the FePd (thin) spring actuator for the applied current.

Fig.14. The performance of the FePd (thin) coil spring actuator examined by using DC amplifier. Output force is defined by the applied dead load (weight). The hybrid magnet of TYPE A, which is same as Fig.7, is used. The electric resistance is 20Ω.

coil spring. This effect also causes the non-liner curve of the output force vs. displacement shown in Fig.14(c). The curves except for the 0A current are non-linear, exhibiting that the slopes of the curves increase in accordance with increasing of the value of the displacement. This means that the spring constant of the coil spring increases during shrinkage of the coil spring due to the stacking effect of the coil spring. On the other hand, the curve for the 0A current is linear, and the slope of the curve is identical to the spring constant of the FePd(thin) coil spring.

By reason of the above non-linear output, the present spring actuator needs to be controlled by a feedback control system for a real application purpose. Figure 15 shows an example of the control circuit system for the FePd spring actuator driven by the hybrid magnet.

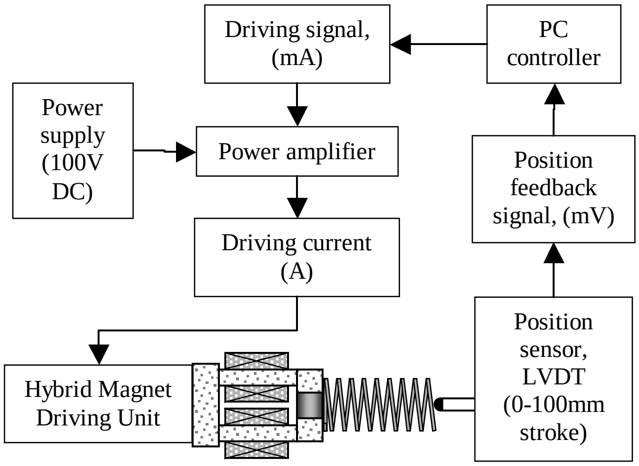


Fig.15. Control circuit system of the FePd coil spring actuator driven by hybrid magnet.

5.3 Broadening

The advantage of this spring actuator in which the driving force comes from the hybrid magnet provides flexibility of designing. Improvements and modifications to this basic embodiment of the design include the followings. (1) Further improvement of both force and stroke of the actuator is possible by development of the designing of the hybrid magnet. (2) Changing the diameter and the pitch of the spring or the dimension of the cross section of the spring wire, the output force and stroke of the actuator can be determined for given requirements of applications. (3) The movement of the actuator is sufficiently controllable by using an amplifier with a computer.

6. CONCLUSION

A linear actuator based on a coil spring made by a ferromagnetic material is presented together with the new concept of the stacking effect of the turns of the coil springs, which is driven either by electromagnets or by the hybrid magnet which consist of electromagnet and permanent magnets. The each turn of the coil spring attracted to the yoke and comes into contact with it one by one. Accordingly the entire shrinkage of the coil spring is successfully achieved accompanied by the large stroke of the spring actuator. The performance of the spring actuator, i.e. the output force and stroke, is variable by changing a lot of factors, such as the diameter and the pitch of the spring or the dimension of the cross section of the spring wire, and so on. The FePd coil springs were made from the polycrystalline FePd wires of which cross-section are circular or rectangular. The FePd spring actuator driven by the hybrid magnet based on the above principle are designed and manufactured. The performance of these actuators is found to be high enough for a practical use.

ACKNOWLEDGMENTS

This study was supported by DARPA-ONR contract (N-00014-00-1-0520). Dr.E.Garcia of DARPA and Dr.R.Barsoum of ONR are the program monitors. Further support was given by a NEDO grant on Smart Materials where Dr.A.Sakamoto was the program monitor.

REFERENCES

1. M. Sugiyama, R.Oshima and F.E.Fijita, Trans. Japan Ist.Metals, **27**, pp.719, 1986.
2. R.D.James and M.Wuttig, Phil. Mag. A, **77**, pp.1273, 1998.
3. H.Kato, Y.Liang, T.Wada, T.Tagawa, M.Taya and T.Mori, to appear in Meter. Sci. Eng. A.
4. H.Kato, T.Wada, T.Tagawa, Y.Liang and M.Taya, Proc. of 50th Anniversary of Japan Society of Materials Sciences, Osaka, May 21-26, pp.296, 2001.
5. T.Wada, Y.Liang, T.Tagawa, M.Taya and T.Mori, submitted to Acta Met.
6. Y.Liang, T.Wada, T.Tagawa, M.Taya and T.Mori, to appear in Proc. of SPIE, 2002.
7. Y.Liang, H.Kato, M.Taya and T.Mori, to appear in Scripta Meter.

8. K.Oguri, Y.Ochiai, Y.Nishi, S.Ogino and Y.Uchida, Extended Abstracts of 9th Intelligent Materials Forum, Mitoh Science and Tech, Tokyo, March 16, pp.24-25, 2000.