Design of Active Composites

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Abstract

This paper is aimed at to discuss two cases of active composites, (i) ferromagnetic shape memory alloy composites, and (ii) piezoelectric ceramic-shape memory alloy composites. Here we discuss the merits of designing such active composites, for use as possible actuator materials. To optimize the nano-/micro-structures of such composites, we developed analytical models based on Eshelby type modeling. Based on the modeling study; a few cases of optimized active composites are suggested.

1. Introduction. Active materials are increasingly key materials for use in actuators. Several key active materials in their monorithic forms are identified, ferromagnetic shape memory alloys, ferroelectric ceramics, and conducting polymers, to name a few. Some of these active materials may not be robust in their monorithic form, thus, could be improved if they are designed to composites. This paper addresses some of active composites, (i) FMSA composite and (ii) SMA-piezo composites. There are three existing actuation modes associated with FSMAs using magnetic field as the driving force for actuation [1-5], namely: (i) magnetic field-induced phase transformation, (ii) martensite variant rearrangement and (iii) hybrid mechanism.

The first mechanism [1] is based on the phase change from austenite to martensite under increasing (but constant) magnetic field (H), and conversely, reverse phase transformation under removal/decreasing magnetic field. The second mechanism [2, 3] is to induce the strain in FSMA with 100% martensite phase subjected to constant H-field which acts on the magnetic moments in magnetic domains that exist in the martensite phase so as to rotate them along the easy axis, i.e., c-axis in the case of Ni-Mn-Ga and Fe-Pd. The strain induced by this mechanism is a function of c/a ratio of FSMA, i.e., the order of shear strain, given by a/c – c/a. Thus, smaller the c/a ratio, the larger shear strain can be induced by this mechanism. The c/a ratio of Ni-Mn-Ga, is reported to be 0.94, which could provide 6% or more strain. Even though the strain induced by the second mechanism is very large, the corresponding stress remains to be modest as several MPa under modest applied magnetic flux density (1T).

The third mechanism [6, 7] which we call as “hybrid mechanism”, is based on a set of chain reactions, first applied magnetic flux (or field) gradient, magnetic force,

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stress induced martensite phase transformation, resulting in the phase change from stiff austenite to soft martensite phase, leading to large displacement. The advantages of this are large stress (hundred MPa in the case of Fe-Pd), modest – intermediate strain, fast actuation time. This phase change can be applied by approaching a compact and portable magnet close to the FSMA specimen which provides a large magnetic field gradient, thus, suited for use in designing compact actuators with large force capability.

Despite the advantages of using the hybrid mechanism, there are some difficulties associated with promising FSMA materials (such as Fe-Pd and NiMnGa), namely, (i) cost of raw materials and processing and (ii) brittle behavior of some FSMA (NiMnGa). To overcome these [3], we proposed the use of FSMA composite which is composed of ferromagnetic material (soft magnet) and shape memory alloy (SMA) of superelastic grade (SE). By using the hybrid actuation mechanism, soft magnet exerts magnetic force under applied magnetic flux gradient, which is transferred to the SMA-SE material resulting in a large strain by Stress Induced Martensite (SIM). In this paper, we will discuss alternative FSMA materials using particulate FSMA composites and both experimental and theoretical studies are reported below.

Piezoelectric material is known to provide fast responsive strain, but its magnitude of strain remains modest, while the magnitude of strain induced in a SMA material of SE grade is as high as 5%, though its actuation speed is limited by heating and cooling rate if thermal actuation is used. If we can use both advantages of piezo-electrics (fast actuation speed under applied electric field) and SMA-SE (large strain), we can design a new piezo-SMA composite that could provide fast responsive actuation and large strain. With this in mind, we propose a new piezo-SMA laminate composite, the main objective being able to exploit Superelastic properties of SMA to increase actuation of Piezo-electric material under applied E-field. The method proposed here consists of two types of applied stress-E-field loading combination: - 1) An initial constant bias stress is applied so as to trigger off Stress Induced Martensite (SIM) in the SMA portion of the laminate composite, and 2) the SMA portion of the laminate composite is in Martensite start point. Then an increasing E-field is applied on the piezo-SMA specimen causing actuation in the piezo zone. This way, it would be possible to utilize the Martensite to Austenite strain (around 5-6% for SMA) in increasing the net displacement exhibited by the piezo-electric material thereby utilizing lower E-field. A preliminary model based on 1D lamination theory and another based on Eshelby's is used to predict the actuation [9-14]. Preliminary results are shown in section 4.

2. Ferromagnetic Shape Memory Alloys (SMA) Composites. Several samples of Fe-NiTi composite with varying weight concentrations of constituent powders under various experimental conditions are processed by Spark Plasma Sintering machine newly installed at CIMS, University of Washington, Seattle (Dr. Sinter SPS-515S, Sumitomo Coal Mining Co., Japan). The SPS machine was installed by DURIP funding under AFOSR Grant (FA9550-04-1-0343). The ordinary metallurgical route for processing particulate composites using powder metallurgy i.e., standard sintering produces unwanted reaction products destroying the original properties of SMA and ferromagnet due to elongated processing time at high temperature. In the present work, sintering conducted using the SPS machine consists of applying high temperatures for as short a time as 5 minutes in vacuum accompanied by an applied pressure of around 50 MPa followed by rapid cooling using Argon gas producing remarkably good results [12]. The sintering process is conducted in a vacuum of around 5-6 Pa. These composites after processing are subjected to various characterization tests namely Density Measurement using Archimedes principles, SEM, XRD, DSC, VSM and finally Compression tests. Based on optimizing the SE properties, various SPS temperature conditions, heating rates, volume fractions are tested [13].

Figure 1 shows the cross sections of NiTi-Fe composite processed by SPS method where island-shaped phase is NiTi powders of SE grade and continuous phase (matrix) is pure Fe-powders. The magnetization (M) – magnetic field (H) relation of the NiTi-Fe composites with several volume fractions of NiTi are measured and the results are shown in Figure 2. The magnetization at saturation (M_s) of the composites are measured from Figure 2 and summarized in Fig. 3 and Table 1 where the predicted values of M_s by our new analytical model are also shown, resulting in a good agreement. The analytical model for predicting magnetic properties has been already successfully implemented [14]. Figure 3 shows the compression stress-strain curve of NiTi-Fe composite, showing reasonably good superelstic behavior.

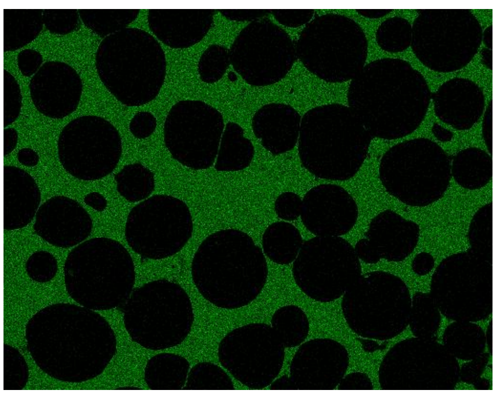

Figure 1: Composition map of NiTi-Fe composite. Fe is the matrix phase.

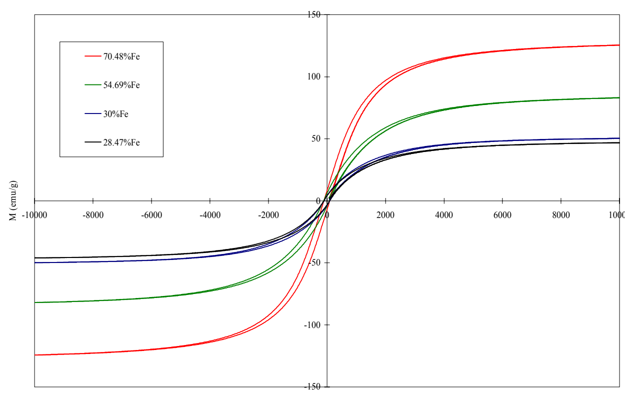

Figure 2: M-H curve for various NiTi-Fe composites measured using Vibrating Specimen Magnetometer.

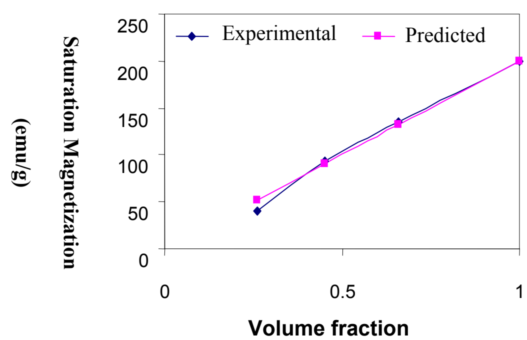

Figure 3: Saturation Magnetization vs. Volume Fraction of Fe

Volume fraction of Fe (f)	M_s (Experimental)	M_s (Predicted)
0.26133	40	52.266
0.4522	93	90.44
0.6582	135	131.64
1.0	200	200

Table 1: Comparison of Experimental and Predicted Saturation Magnetization values [14]

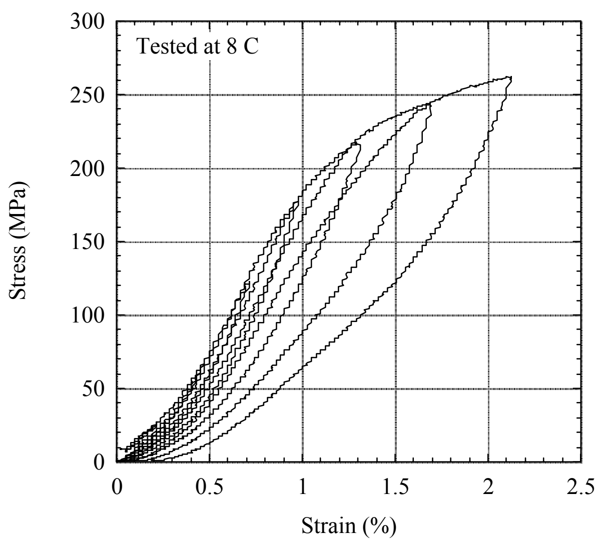

Figure 4: Compression Stress-Strain curve of NiTi-Fe composite exhibiting SE.

Following sections enumerate an analytical model based on Eshelby's model with Mori-Tanaka's mean field theory for prediction of stiffness properties of the FSMA composite [11, 15 – 17].

3. Analytical Models.

The particulate Fe-NiTi composite has an approximated microstructure as shown in Figure 5. Fe particles being much smaller than NiTi powders tend to form the matrix phase of the composite after sintering. NiTi thus occupy the inhomogeneity and constitute the fiber phase of the composite. For the sake of simplicity in modeling, the loading part of the SS curve can be divided into three 'linear' stages namely (see Fig. 6): 1) NiTi is in 100% Austenite phase; 2) NiTi undergoes a transformation from Austenite to Martensite phase; and 3) NiTi is in 100% Martensite phase. Since the yield stress of Fe-Mn-Si alloy (soft iron) is higher than that of martensite start stress NiTi and comparable with martensite finish stress of NiTi, the Fe matrix is expected to remain in pure elastic loading throughout the three loading stages as assumed in the present model.

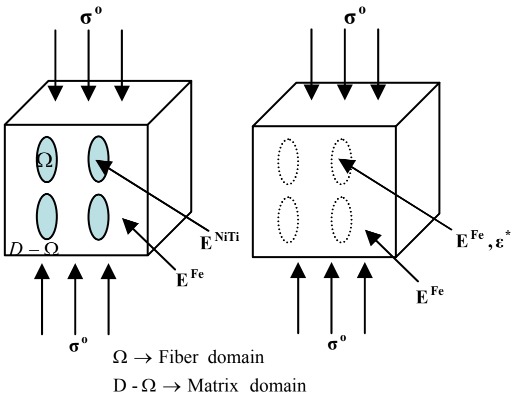

Figure 5: Approximated micro-structure of NiTi-Fe composite. Eshelby's model with Mori-Tanaka's mean field theory is used to predict the SS curve for stage 1 and 3 loading.

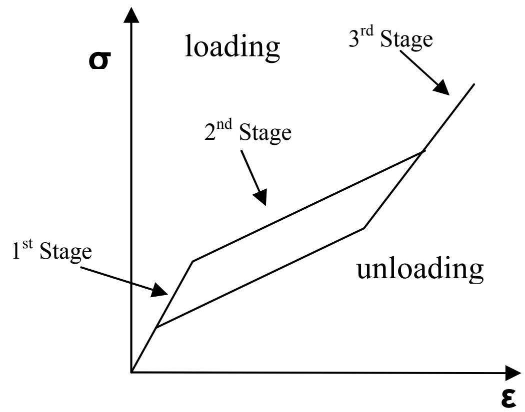

Figure 6: Linearized version of SS Curve of SMA exhibiting SE

4. Design of Piezo-SMA composites. Piezo-SMA composite is a new concept in taking advantage of both piezoelectric material (fast response under applied E-field) and SMA-SE (large strain under SIM phase transformation i.e., SE deformation). We have made a preliminary design of laminated piezo-SMA composite; Figure 7 where the top and bottom layers are SMA and middle is piezoelectric material. It is to be noted in Figure 6 that the SMA layers also play the role of electrodes.

To induce larger strain in SMA-SE phase, a constant compressive stress is applied first so as to induce "bias compressive stress" in both piezo and SMA phases in X_1- direction. Then E-field is applied along the X_3-direction. We shall explain first the simple 1D model, then 3D model by a new Eshelby's model below.

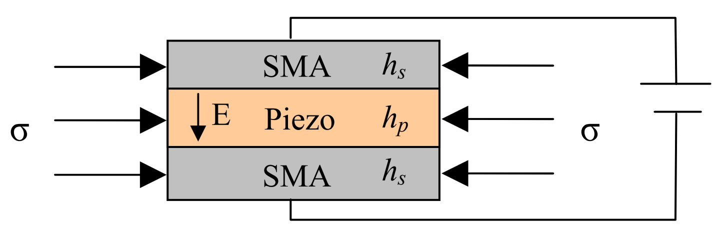

Fig. 7: Composite subjected to applied stress σ, and applied electric filed E, where h_s: thickness of SMA, h_p: thickness of piezo.

Eshelby's Model for Piezo-SMA Composites

The composite is piezoelectric matrix, reinforced with discontinuous shape memory alloy fibers, as shown in Fig. 8.

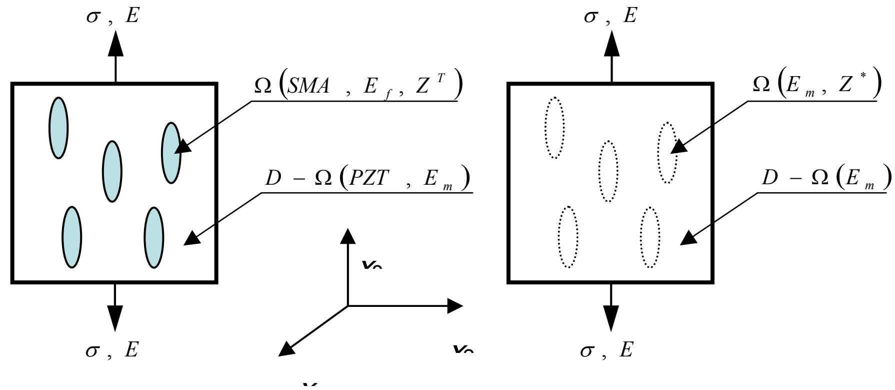

Figure 8: Piezo-SMA composite

Sample calculations

In this study, the composite is short CuMnAl fiber reinforced PZT matrix composite, whose properties are as follows. The magnitude of applied stress to initiate martensite start of the fiber is calculated to be 154 Mpa, and the relations between the strain and electric field of the composite and PZT only are predicted and are shown in Fig. 9.

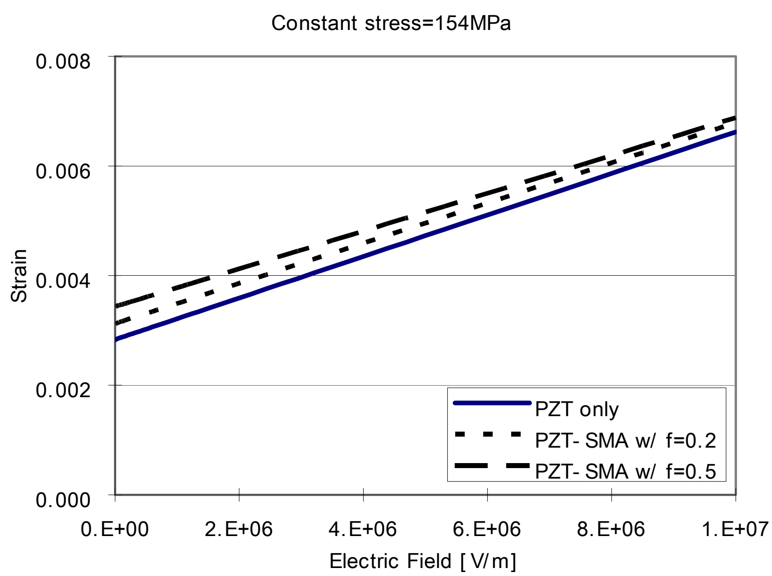

Figure 9: Strains of the PZT-SMA composite and PZT only as a function of electric filed

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References

1. S. J. Murray, M. Frinelli, C. Kantner, J. K. Huang, S. M. Allen and R. C. O'Handley, Journal of Applied Physics, **83** (1998) 7297.
2. R. D. James, R. Tickle and M. Wuttig, Materials Science and Engineering A, **273** (1999) 320.
3. K. Ullakko, J. K. Huang, V. V. Kokorin and R. C. O'Handley, Scripta Materialia, **36** (1997) 1133.
4. Y. Liang, H. Kato and M. Taya, Proc. Plasticity '00: 8th Int. Symp. on Plasticity and Current Applications, 193 (2000).
5. Y. Liang, H. Kato, M. Taya and T. Mori, Scripta Mat., **45** (2001) 569.
6. Kusaka and Taya (2004) paper
7. W.G.Deeg. PhD Dissertation, Stanford University, 1980.
8. M.L.Dunn. International Journal of Engineering Science. 32(1) (1994) 119-131.
9. Y.Mikata. International Journal of Engineering Science. 38 (2000) 605-631.
10. Y.Mikata. International Journal of Solids and Structures. 38 (2000) 7045-7063.
11. M.Taya. Electronic Composites. Cambridge University Press. (2005).
12. V.Mamedov. Powder Metallurgy. (2002) Vol. 45, No. 4: 322-328.
13. S.Gururaja, M.Taya, H.Nakayama. Processing of Fe-NiTi particulate Composite. (In writing)
14. S. Gururaja, M. Taya, H. Nakayama, Y. S. Kang, A. Kawasaki, Y. Sutou. Proceedings of SPIE. (2005) Vol. 5761, 548-556.
15. J.D.Eshelby. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences. (1957) 241, 376-396.
16. J.D.Eshelby. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences. (1959) Vol. 252, 561-569.
17. T.Mori and K.Tanaka. Acta Metallurgica. (1973) Vol. 21:571-574.