Shape Memory Materials

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Edited by
Toshio Saburi

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Proceedings of the International Symposium and Exhibition on Shape Memory Materials SMM '99, held in Kanazawa, Japan, May 19-21, 1999

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Toshio Saburi

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Preface

"International Symposium and Exhibition on Shape Memory Materials (SMM'99)" was held at Ishikawa Kosei-Nenkin Hall in Kanazawa from May 19 to 21, 1999, as a satellite meeting to "International Conference on Solid-Solid Phase Transformations (PTM'99)" in Kyoto. The symposium was also in a series of successful symposia of SMM'86 in Guilin, SMM'94 in Beijin, in addition to China-Japan Bilateral SMM'97 in Hangzhou.

The symposium was quite timely and successful from the following reasons. SMM are becoming more and more important as smart materials or intelligent materials, which already exist. Superelastic wires are being used for antenna of cellular phones, and medical stents and guide wires are going to be a big business too. Some rapid progresses are being made in fundamental studies also, such as the kinetics of martensitic transformations, premartensitic behavior, aging problem, thin film SMA etc. Furthermore, new experimental techniques are becoming available, such as imaging plate, TEM with energy filter, AFM, glazing angle x-ray reflection technique etc. So, it was a good time to discuss all of them together.

The number of participants to this symposium was 163, including 8 accompanying persons. Among them the number of foreigners was 68 from 19 counties. Thus, the size of the symposium was just appropriate to make good discussions, and to learn both fundamentals and applications, which are basically important to promote the science and technology of SMM. In fact, good discussions were made in a friendly atmosphere throughout the symposium. Since the period of the symposium was limited within 3 days, about 1/3 of the papers were presented as posters. To facilitate the poster presentation, poster preview (within 3 minutes) sessions were held, which turned out to be very useful and effective for both listeners and authors.

All the works of program making and editing the present proceedings were done by Professor T. Saburi with Osaka University (presently with Kansai University) as a chairman, and the members of the Editorial Committee. All other secretarial works were done by the members of Kanazawa Institute of Technology under the supervision of Mr. N. Iwashita, Secretary General, and under the actual leadership of Professors K. Shimizu and Z. Yajima. The exhibition of SMM was organized by Mr. J. Kobayashi through cooperation of Japan Association of SMA. Professor Youyi Chu and the Nonferrous Metals Society of China contributed to the success of the symposium by sending many delegates from China. I would like to thank all these members for their tremendous works, without which the present symposium would not be operated.

On behalf of the Organizing Committee, I would like to thank all invited speakers and participants, who actually made the present symposium meaningful and successful. Especially, I would like to thank Professor Jim Krumhansl, ex-president of the American Physical Society, who gave an excellent symposium lecture and sent a message for our work in the 21 century. Thanks are also due to co-sponsors and financial supports, as listed in the separate sheet, who made this symposium possible.

With a hope for a further development of SMM in the 21 century,

Kazuhiro Otsuka
Chairman, Organizing Committee
SMM'99

Editor's Note:

This volume contains the Proceedings of the International Symposium and Exhibition on Shape Memory Materials (SMM'99) held in Kanazawa, Japan, 19-21 May, 1999. The Proceedings consists of 18 invited and 89 contributed papers presented at SMM'99. The papers included are those which have actually been presented orally or by poster. The papers were grouped in 13 sections in nearly the same way as that of the symposium itself. The papers presented by poster were distributed in an appropriate place according to their contents. All the papers were peer reviewed. The Editorial Committee selected the referees from those who attended the symposium. On behalf of the Editorial Committee, I would like to express sincere appreciation to all the authors and the reviewers. I also would like to thank Dr. T. Fukuda for his help in this editorial work.

Toshio Saburi
Chairman, Editorial Committee
SMM'99

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Multiscale Science: Materials in the 21st Century

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Keywords: Martensite, Multiscale Science, Shape Memory, Patterns, Complex Materials

Abstract

The main difference between materials science in the next century and the one closing is that it will be necessary, in explaining and measuring materials, to consider *simultaneously* several different and distinct scales of phenomena. Shape memory materials have been one of several classes of new systems which have made us aware of the need for new guiding principles.

Introduction

This paper is mostly about concepts, except for the data for a few examples. Its purpose is mainly to stimulate discussion of the theme that many new materials can only be understood by recognizing the simultaneous presence of phenomena at multiple, distinct scales. That idea implies that, both in theory and experiment, one can no longer specialize in one of: first-principles electronic structure calculations, defect morphology, elastic properties, etc. *alone* in order to understand a widely growing class of new complex materials. All who have worked with martensite know that it is a paradigm for the multiscale concept.

About concepts- allow me to make a few remarks, standing back from the details of any particular topic, on the nature of the pursuit of science. First, I paraphrase some thoughts of Gerald Holton, the Harvard science historian. One cannot build the edifice of Science without bricks; indeed, it is the bricks on which most of us work . Fine. Second, however, an architecture (*organizing principles*) is also essential for putting the bricks together in coherent fashion. As a corollary, an architecture also helps us predict to a limited degree where a field may be going, at least in the near future. In that way we now see a large class of multiscale materials which can be designed into many applications, but only by having information about their properties at many levels and how these interact..

Discussion

There has been extensive research on martensites, as well as polymers and biopolymers, over the past several decades, and an extensive set of methods, theoretical and experimental, has been developed, atomic, mesoscopic, and macroscopic, often to deal only with one particular set of phenomena.

Consider the scales involved in many recent materials.

Atomic	10^{-1}nm	electronic structure phonons chemical bonds
Nanophenomena	1-20nm	defect configurations twin boundaries tweed domain walls Kuhn length; polymers dislocations biomolecules; helices, sheets
Mesoscale	10^{2} - 10^{4}nm	martensite patterns (ditto: ferromagnets, ferroelectrics), polymer science (biopolymers), cracks
Microscopic	10^{6} - 10^{8}nm	continuum mechanics shape memory smart materials ferromagnets, ferroelectrics elastic, thermal from microstructure

Obviously, there are many, many examples from many different areas of science and engineering. The list above is materials and biomaterials oriented. For interested readers here are some selected general references. [2] [3] [4] [5]

It can be said that the roles of twin boundaries, invariant plane strain and habit planes, mesoscopic Landau-Ginsburg descriptions , and electron theory of bulk phase energies have been quite successful in analyzing many properties of martensite. The recent review of shape memory alloys by Otsuka and Wayman [6] is a comprehensive, up to date discusssion of all of these ingredients and their contributions to functional behavior.

Precursors; The Next Frontier

Can it be said that the understanding of martensites is complete? Not quite. For the past 35 years in diffuse x-ray scattering, peculiar anomalies characteristic of small amounts of the martensitic "phase to be" seem to appear up to 10-100 degrees above the first order transformation temperature, in the cubic (austenite) phase; these cannot be critical fluctuations. Sometimes they have been referred to as a ghost lattice. While the Bragg spots remain those of the cubic (austenite) lattice the diffuse spots are largely incommensurate and have special anomalies associated with them. They were first systematically studied by Tanner, and later Nakanishi [7] and when imaged had a spatial modulation pattern reminiscent of "tweed". This name continues to be applied. Because it occurs at a fine scale (nanometers) and does not involve much strain energy, it does not appear to first order in the bulk thermodynamics, but it can make significant differences in transformation kinetics.
There are many variations of these **precursors**, but in general they are ubiquitous in first order displacive transformations in alloys. More on this later.

A bibliography, as well as a recent theory of tweed, can be found in the recent paper by Kartha et al. [8]. Figures 1 and 2 show images of model-simulated [8] and experimental [9] tweed in the austenite (cubic) phase of $Ni_{62.5}Al_{37.5}$ alloy, tens of degrees above the Martensitic start temperature Ms.

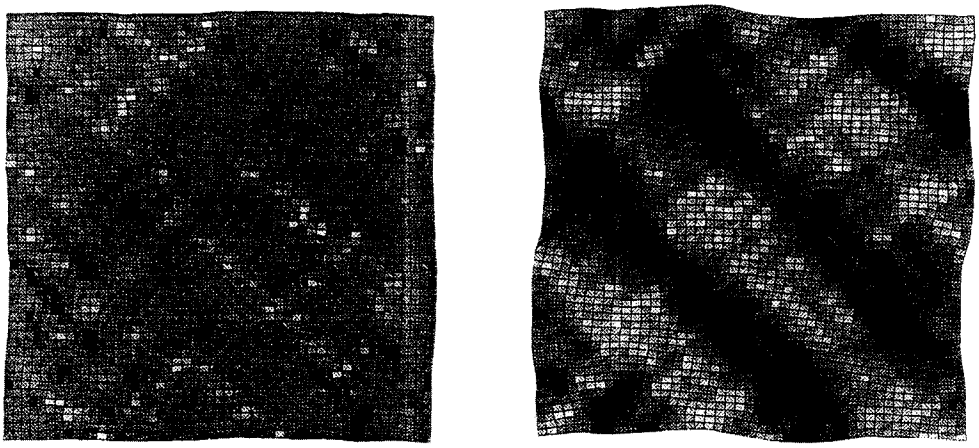

Figure 1. Simulated tweed on a square lattice [8]. On the left, well above Ms is fine tweed; the long range order is *cubic*. There are three regions; white and black are orthogonal rectangular regions, and gray is the parent square phase. The tetragonal distortions are smaller than the fully developed martensitic transformation strains. Their size is limited by an elastic coherence length. The tweed coarsens as temperature is lowered (right), converting to twinned martensite finally.

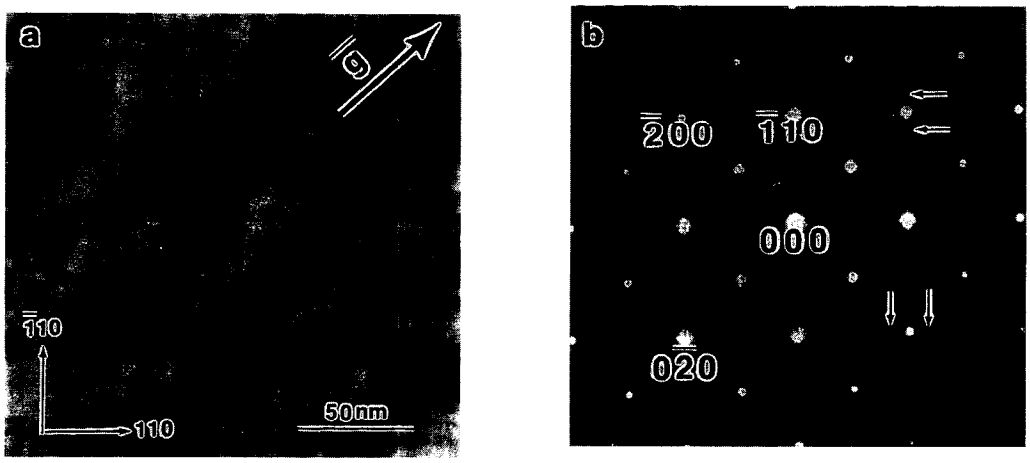

Figure 2. Experimental tweed for same alloy , Tanner et al. [9]: a) Conventional high resolution transmission electron microscope; b) Diffraction pattern; imaging diffuse satellites also produces tweed images.

The only Bragg spots seen are for the cubic austenite phase. Living in that phase are the weak modulations having strains of the same symmetry as the martensite transformation strain (though much smaller) i.e. they are precursors imbedded in the austenite host, but do not destroy long range (cubic) order. Details can be found in [8] and [9]. Often they are difficult to see with ordinary observational methods; but they are ubiquitous in nonstoichimetric, or additively stabilized, transforming alloys. Their scale is 5 -20 nm. They are in essence *strain* spin-glasses.

Does such small scale strain have much practical consequence? One might think not. This is not the case. There are significant affects in the macroscopic thermal expansion of A - 15 martensite. Finlayson and Smith [10] Figure 3 have found for many materials that well above M_s (23K), *in the cubic phase* of V_3S_i, the thermal expansion can be *anisotropic*!! Furthermore, the anomalous thermal expansion begins at just about the tweed starting temperature (**approximately 50K in** V_3Si) observed by direct electron microscopy [11]. Circumstantially, there seems little doubt that the tweed is the source of this thermal expansion anomaly. Indeed, that can be explained in nearly quantitative fashion [Krumhansl and Finlayson, to be published] so the conclusion is that in addition to the familiar twin boundaries, domains, etc. this nanometerscale modulation, the tweed precursor, adds new phenomena which are *even reflected in macroscopic properties*! Another tweed-caused property seen, in Figure 3, is that the presence of this highly stress-polarizable modulation significantly "rounds" what should be a sharp first order transformation. That behavior also needs further analysis. What may be the case is that tweed is an additional factor in macroscopic elasticity.

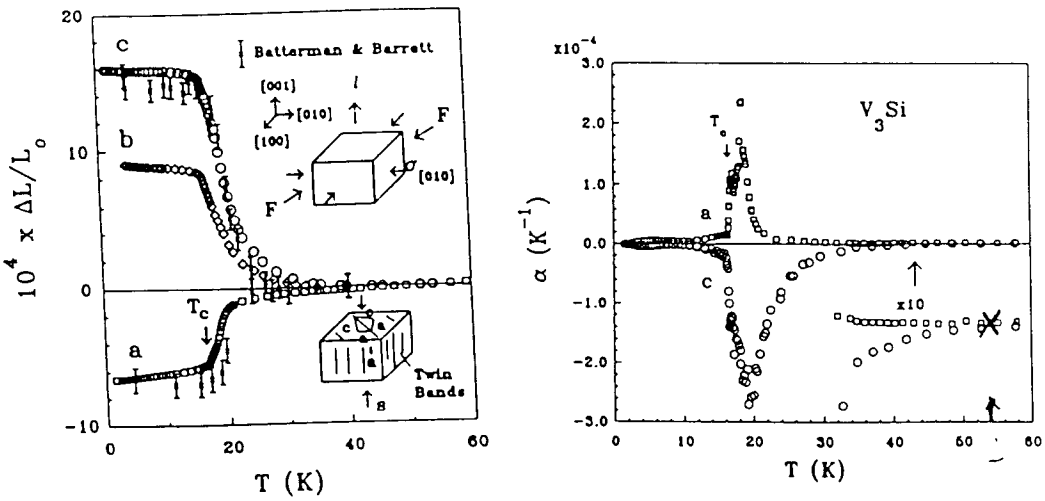

Figure 3. From Liu, Finlayson and Smith [10]. Anisotropic thermal expansion of V_3Si in the cubic austenite phase. Reproducible results require very small applied stresses, either uniaxial or biaxial (see [10]). Comparison with older x-ray data of Batterman and Barrett shown on the left, actual extension. The deduced unexpected anisotropic thermal expansion shown on the right, with inset showing onset approximately 40K above Martensite transformation temperature.

Those are the experimental facts. Can the theory of tweed (Kartha et al. [8]) allow us to put the data on a quantitative basis? To test whether the precursors can be represented by the spin-glass model proposed there, we postulate the following scenario: 1) As one comes down in temperature in the cubic phase toward the transformation temperature, theory proposes that there is a "tweed start" temperature at which the ghost martensite-like regions begin to form (Fig. 1); 2) The local transformation free energy that drives the spin glass tweed supports them and places localized stress on the host lattice, which in turn macroscopically distorts elastically; 3) This then observed macroscopic thermal expansion increases as temperature is lowered due to the increase of the tweed density; 4) the role of the very small applied stress is to give preferred orientation to the otherwise random tweed orientations. The resulting anomalous macroscopic expansion is much larger than anharmonic Gruneisen models would predict.

There is remarkable additional corroboration. First, as noted above [11] high resolution electron microscope studies show conclusively that there is a well defined tweed start temperature, in the manner of a true phase transition, at about 55-60K Second, although the model of [8] was two dimensional, assuming that it can be generalized, the Sherrington-Kirkpatrick model of the spin-glass onset leads to a second order transition. In that case there should be critical behavior, and the plot of log[tweed density] inferred from thermal expansion data as in Fig. 3 vs. log[$|T-T_{w.\,start}|$] should give a straight line and critical exponent. Such a preliminary plot from data, and a curve fitting program taking tweed start at 60.38K, is shown in Fig. 4. The results look promising, but there is much further quantitative work to do in order to put this analysis on a firm foundation.

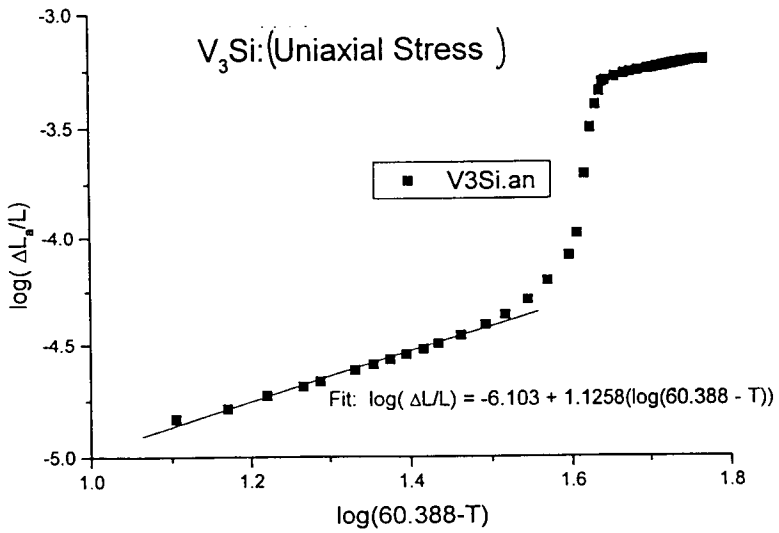

Figure 4. Log anisotropic precursor thermal expansion vs. log [$T- T_{tweed}$]; see text. (Finlayson and Krumhansl, in preparation).

Some Summarizing Thoughts

We can learn many things from the examples above.

1) In materials such as twinning martensites, and shape memory materials specifically, we have become familiar with the fact that multiscale phenomena are inherent. And measurement techniques must be different and suitable for each scale. To experimentalists this is apparent. Analagous features are found in polymers and biopolymers.

2) For theorists the pathway is not so clear. New methods at each different scale are needed. For example, the best local density electronic structure calculations can hardly yield twin boundaries, geometric theory of martensite, habit plane descriptions,etc.; by contrast strain-Landau-Ginsburg methods handle these aspects of the physics quite well, analogous to their usage in ferroelectrics.

3) In essence those methods are "effective field theories" chosen to suit the scale of the phenomena at hand. A trenchant discussion of this aspect of the appropriate physics for multiscale systems can be found in the introductory sections of the recent review by M. E. Fisher [12] of the background and development of renormalization group (RG) theory. Fisher regards that truly deep insight is to be gained from Landau theory, as supplemented by Ginzburg, (LG). What RG was needed for was to correct those exceptional situations when critical fluctuations occurred; these are infrequent in most materials. None the less one can then speak of a Landau-Ginzburg-Wilson (LGW) effective field theory; this is the method of choice and great power when dealing with multiscale problems. Specifically, as Fisher points out the introduction of order parameters at different scales "exposed a novel and unexpected *foliation* or level in our understanding of the physical world". There are serious corollaries from this insight.

4) There may be a large class of physics problems where the deeply imbedded methodology of "reduction from first-principles" approach, is not only inefficient, but also impossible for computational or formal reasons; **the *foliation* just referred to is a major wall blocking the idea that materials can be designed from first-principles.** Quoting Fisher again:

" Frequently, indeed, in modern condensed matter theory one *starts* from this intermediate level with a physically appropriate LGW Hamiltonian *in place* of a true (or, at least, more faithful or realistic) microscopic Hamiltonian; and *then* one brings statistical mechanics [..... or other methodology..., my insert] to bear to understand the macroscopic level. The derivation and validity of the many types of initial LGW Hamiltonians may then be the object of separate studies to relate them to the atomic level".

5) To summarize, for emphasis, the materials scientist of the next century must be able to recognize the presence of interacting significant multiscale phenomena.. This means also to be able, at one time, to use methods and theories suitable to several scales. The example above embodying nanoscale tweed with macroscopic thermal expansion is a case in point.

Challenging, yes; but the many new material properties which may be obtained will be the reward.

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I thank the organizers and sponsors of this meeting, and especially Professor Kazahiro Otsuka. I would also like to thank my close colleagues Gerhard Barsch and Jim Sethna as well as others, Alan Bishop, Wenwu Cao, Phil Clapp, Bob Gooding, Bob Kohn, Ekhard Salje, Trevor Finlayson and several of my former graduate students with whom discussions over the years have helped to shape the viewpoints reported here.

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The Industrial Applications of Shape Memory Alloys in North America

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Keywords: Electrical Connectors, Seals, Connectors, Automotive Controls, Safety Valves, Antennas, Aircraft Actuators, Industrial Clamping Devices, MEMS, Aerospace Release Devices

Abstract

Literature in the recent past on shape memory effect alloys dwelt principally on the physical metallurgy, crystallography and kinetics of the shape memory phenomenon. By contrast, we now have books and conference proceedings devoted to the engineering aspects of SMAs, their technology and application. The dominant role SMAs now play in the field of medical and orthodontic devices is well documented and will be reviewed by others in this conference. In this paper we will discuss the commercial applications for shape memory alloy devices in the North American market; applications which are in many cases also produced in European countries and Japan.

The early success of shape memory alloy couplings for joining tubing and pipe in the late 1960's was not followed by other large volume applications until the advent of shape memory eyeglass frames, brassiere underwires and cellular phone antennas. Many other applications have now evolved into mature markets and these will be reviewed.

In addition to the many commercial applications cited, there are a number of other fields in which shape memory alloys are destined to play a major role; these include smart materials and adaptive structures, MEMS devices, infrastructure systems and electrical power generation and distribution. These applications are being developed with private and government funding and will also be briefly discussed.

Introduction

A few days before Christmas in 1970 the first successful demonstration of a shape memory alloy *Cryofit* coupling took place on the Grummon F-14 fighter airplane. This demonstration of the reliability in a high pressure hydraulic system lead to the production of over a million couplings in the ensuing years. In the thirty years from that date there have been thousands of patents issued on every conceivable application for shape memory alloys, yet, remarkably, the list of truly commercial successes is quite small; where by commercial we imply many thousands per year. Indeed, as everyone knows, the major niche which these alloys now occupy is in the field of medical and dental devices and instruments. Nevertheless, there is great activity in a number of fields which portend an ever expanding role for these remarkable alloys.

Current Commercial Applications:

The application of *Cryofit* couplings has been confined principally to military aircraft hydraulic systems with a smaller volume utilized in the petroleum, petrochemical and power industries. The advent of the wide hysteresis NiTiNb alloy has made the application of SMA couplings and joining devices more attractive. With the successful application of the ferrous shape memory alloys for large piping installations in China, it seems likely that in time this will also become truly commercial in scale in North America. Another form of coupling is a wire ring made by welding and first used to create a reliable bond of wire braid to an electrical conductor This backshell connection is shown in Fig.1 and in Fig.2 is illustrated a ring seal for joining a thin wall cup to its base. This joining device has been broadly used for sealing and joining electrical, electronic and mechanical devices and provides reliable operation over a temperature range of from -65^0C to 300^0C.

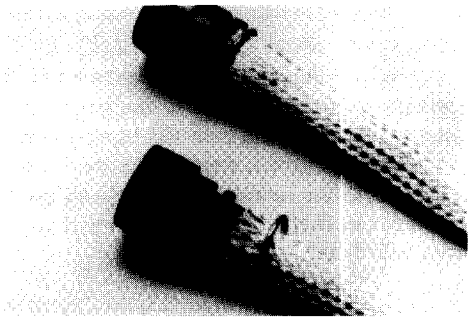


Fig.1 Backshell Connector

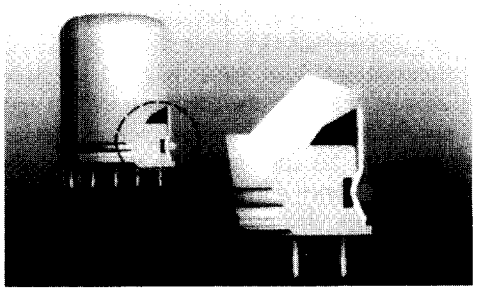
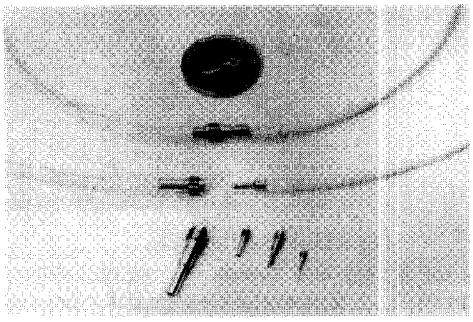


Fig.2 Electronic Container Seal

Variations of these sealing systems have been exploited to provide electrical connections which operate in severe environments. The earliest of these small, highly reliable, connectors, the *Cryocon* is shown in Fig.3. A shape memory ring closes the fingers on the female copper alloy electrical connector, but when cooled to below the M_F temperature the beryllium copper fingers can exert sufficient force to open the connector, as shown in Fig. 4. The requirements for connecting large circuit boards in computers to interconnect cables required a connector which when closed exerts a large force to

minimize contact resistance but when the connection is being made have virtually zero force to prevent contact damage. An example of a Betaflex™ ZIF, zero insertion force, connector is shown in Fig.5.



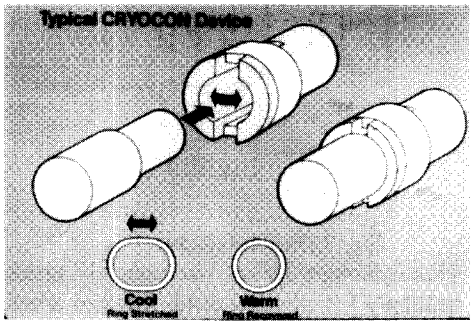
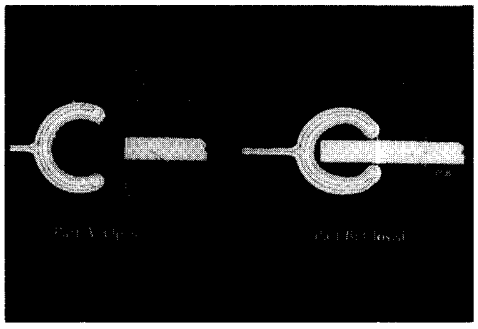


Fig.3 Cryocon™ Connectors Fig.4. Connector Operation

Actuators, usually in the form of tension or compression springs, are being used in a variety of large volume applications. A recent example of is a SMA spring to control the opening of a General Electric Co. self cleaning oven door. Fig. 6 shows the NiTi SMA spring with its bias spring assembly used for this purpose.



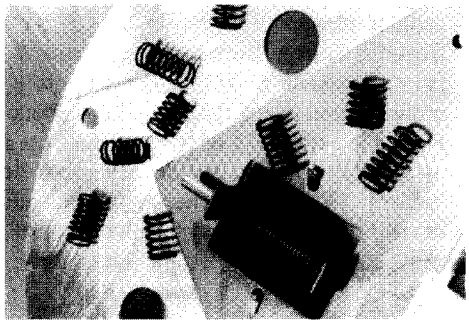


Fig.5 Betaflex™ Connector Fig.6 G.E. Co Oven Door Springs

An early automotive application was for a spring which opened and closed shutters to protect fog lights from flying debris. Another automotive application is a SMA spring actuator employed in the automatic transmission of Daimler Benz cars to control transmission fluid flow on engine warm up. A more recent engine application is the sealing of a hole in a diesel engine injector. During manufacturing it is necessary to drill a small hole through the injector outer wall and through an inner wall connecting two cylinders, as shown in Fig. 7. After this operation it is necessary to seal the outer wall hole; brazing in a sealing plug did not have sufficient reliability. The shape recovery of a pre-stretched and precision ground pin inserted in the hole has proven very successful; the 3mm diameter 10mm long NiTiNb sealing pins are shown in Fig. 8.

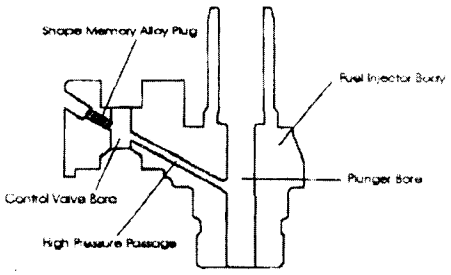


Fig. 7 Diesel Injector

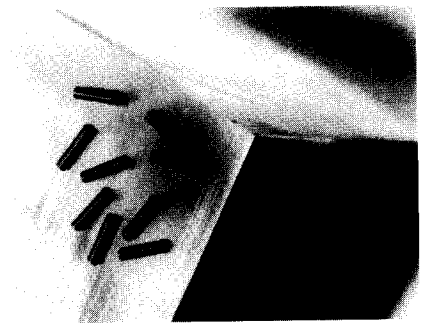


Fig.8 Hole Sealing Pins

This technique makes the assembly process quite easy and avoids the requirement of heating a complicated semi- finished article to the high temperature required for brazing with the potential for distortion. By contrast the shape recovery of the NiTiNb pin is effected at below 200^0C.

Shape memory alloys have achieved a permanent place in high end eye glass frames where the nose and ear pieces fabricated of NiTi provide comfort and exceptional resistance to damage. The flexibility of manufacturing these items has lead to their broad use in the ever changing world of eyeglass fashion.

Another high volume application is the use of superelastic NiTi wire for the antenna on cellular phones. The earlier use of stainless steel antennas presented the problem of frequent damage from bending, typically being caught in car doors and windows. . The great resistance to permanent set offered by NiTi wire has made this the universally preferred antenna; a typical cellular phone with antenna is shown in Fig. 9.

From the early days of both copper based shape memory alloys and the now dominant nickel-titanium family devices have been proposed for safety in the home and in industry. One of the earlier systems developed for European markets was the Proteus link device for releasing doors in the event of fire, and the Proteus gas line safety valve, both using copper based CZA alloy actuators.

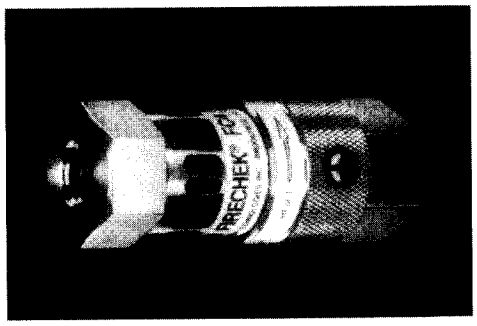


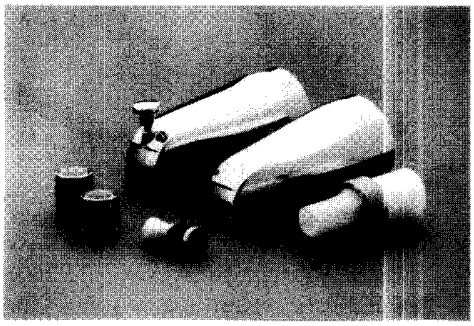
Fig.9 Cellular Phone Antenna

Fig.10 Firecheck™ Valve.

A more recent application in the field of safety is the Firechek™ gas valve, This device vents the air supply to a pneumatically operated gas cylinder flow valve in the event of a local rise in temperature. By removing air pressure from the valve it automatically closes and prevents the release of hazardous gases into the environment. The advantage of this particular design, shown in Fig.10, is the ability to check its operation and then reset it to its safety condition; the Firechek is finding use in semiconductor manufacturing where pyrophoric and poisonous gases are employed in the diffusion processes, and in chemical and petroleum plants.

In the field of domestic applications, shape memory valves have been developed for the prevention of accidental burns from hot water in sinks, tubs and showers; these are also being used in hotels and hospitality locations. In the event that the water temperature coming from the faucet reaches a temperature where there is the possibility of scalding, approximately 48^0C, the SMA actuated valve shuts off, and will not reopen until the water temperature is safe. When shut the valve allows a small flow of water to clear the line of hot water and permit the valve to reset. Valves for tubs, sinks and showers are shown in Fig.11.

In modern manufacturing processes it is often required to move parts from one machine to another for various stamping or machining operations. Usually a number of parts are mounted on a plate and rigidly secured using manual mechanical or hydraulic clamping devices. The problem with mechanical clamping is assuring consistency of the clamping force, a requirement for precision machining operations. Hydraulic clamping is more cumbersome and requires air pressure lines throughout the machining area. A recent development promises much greater flexibility and ease of parts change by replacing the manual or hydraulic clamps with ones actuated with shape memory alloy cylinders. Fig. 12 shows the design of the Electralok ™ clamp which features part locking with the power to the SMA actuator off, a result of the spring characteristics of the "H" clamp. When heated, the shape memory cylinders expand causing the "H" clamp to deflect and release the part. Part loading with this device is very fast, taking only 3 minutes to load 64 work pieces, and clamping force is in excess of 2500N. Other, similar, clamping devices have been designed using SMA spring actuators.



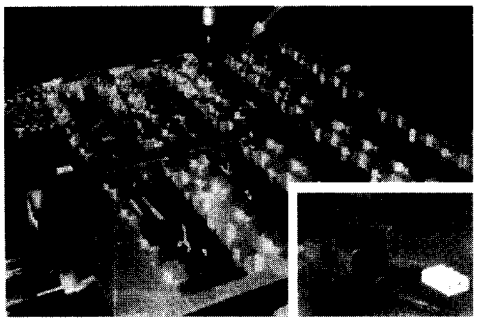


Fig. 11 Antiscald Valves Fig.12 ElectraLock™ Clamp

Smart Materials and Adaptive Structures are now common terms and a large amount of research is being devoted to ways in which SMAs can be utilized in aeronautical and

space structures. A major effort is underway in Europe and the United States on smart rotors for helicopters. Helicopters are limited in their use by their high vibration and noise. These characteristics impact both maintenance costs as well as their acceptance as shuttle craft between inner cities and airports. A principal source of noise and vibration is blade vortex interaction which is a result of the impact each blade encounters when it hits the vortex shed by the blade in front. A second source of vibration is due to small differences in blade contour resulting from the manufacturing process; this requires a means for balancing the blade flight path so that all blades fly in exactly the same plane., and as a result have minimum vibration A tracking control has been developed using a small twin tube SMA actuator which controls the position of a small tab on the trailing edge of the blade. Positioning accuracy is $\pm 0.25^{O}$ over a range of $\pm 7.5^{O}$. Critical in this design is weight and size; the actuator shown in Fig.11 is 2.5cm x 2.5 cm x 16.5cm, and with all electronic controls attached it weighs less than 400gm.. Another example of adaptive structures is the use of a SMA ring to control the clearance between compressor blade tips and the casing in the compressor section of a gas turbine. When the turbine is started the blades elongate almost immediately due to centrifugal force requiring that on start up there is adequate clearance to avoid blade contact with the casing. As the casing warms to the operating temperature it expands increasing the tip clearance. Since the efficiency of the turbine is adversely affected by a large clearance, a method to reduce its magnitude is attractive. The approach is to use a CuAlNi SMA ring which surrounds the blades at each stage of the compressor. The ring is initially stretched to a dimension where its inner diameter provides the required starting clearance. As each stage of the compressor warms to the operating temperature for that stage the ring undergoes shape memory recovery which reduces the ring inner diameter and thus the clearance. The rings are assembled with an inner ring of the same alloy heat treated to have no shape memory, but having the same coefficient of thermal expansion To obtain a running clearance of 0.1mm the ring tolerances are very critical as is their thermal stability. This is an example of the need for a high temperature SMA; the CAN alloys can be formulated to give quite high A_S temperatures, but their long time stability at elevated temperatures is poor.

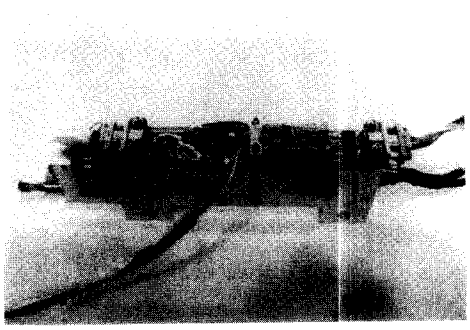


Fig.13 Helicopter Blade Control

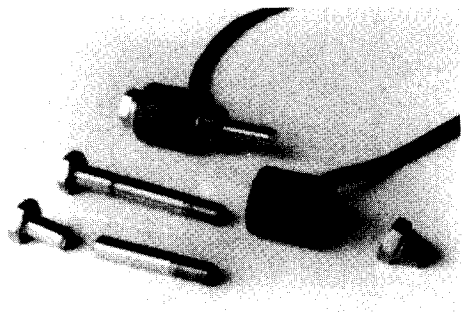


Fig.14 Frangibolt™

For the control of aerodynamic performance in different regions of the flight envelope it is the objective a many studies to find ways of using SMA materials embedded or attached to an aircraft wing structure to change its contour in flight. A barrier to this

application lies in the very opposite requirements imposed by the fact that a wing is required to be very stiff, yet to change its contour it must have flexibility. A variety of flexible ribs and spars have been studied to make possible these divergent requirements. One technique for in flight control of the wing is to provide wing twist using a large torsion tube actuator. The required twist angle to change the flight characteristics is quite small and one quarter scale wing models have been successfully wind tunnel tested. A parallel effort is underway to use shape memory actuators to control the shape of hydrofoils such as the control surfaces on submarines.

Space applications for shape memory devices have been brought to a practical level in the Russia space program for deploying large antennas and for joining and assembling antenna masts on the MIR space station. In the United States' space program shape memory actuated bolts for release of payloads after launch has proven successful. The Frangibolt™ uses a pre-compressed SMA cylinder which causes the fracture of a notched bolt when it undergoes shape recovery. This device, shown in Fig.14, is much safer than the conventional explosive release devices. Another interesting recent use of a shape memory device was in the Gamma Ray Spectrometer. This instrument must, when deployed, have no contact with the surrounding frame in order to maintain the detector at cryogenic temperature, however when launched it must survive high G forces. Shown in Fig.15 are the four CZA shape memory rods which support the spectrometer during launch and then retract when in orbit to allow the spectrometer to float free. In addition, this satellite uses another shape memory release device to open the container on the sensitive germanium detector which must be protected from contamination during assembly and launch.

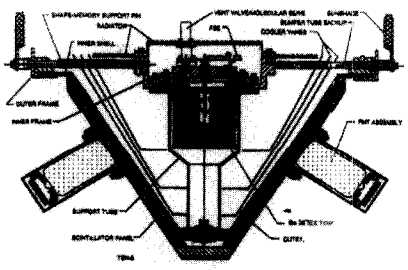


Fig.15 Gamma Ray Spectrometer

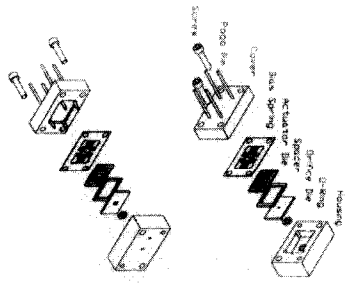


Fig. 16 MEMS Valve

No discussion of the future applications for shape memory alloys would be complete without mention of micro-electromechanical systems, MEMS. Using semiconductor etching techniques, devices have been fabricated which at this time have dimensions in the millimeter to micron range. Minivalves have been developed which have performance and pressure capabilities of electrically actuated vales orders of magnitude greater in size and weight. NiTi films sputter deposited on silicon substrates are photoetched to form the actuator elements in these devices. The films are then freed by back-etching the silicon substrate. The minivalves are assembled with an "0" ring and a biasing element and two etched silicon top and bottom plates to create the completed valve. The valves are used

for the control of liquid and gas flow and as pneumatic control valves for instruments and have dimensions of 15x9x7.5mm. A typical valve is illustrated in Fig.16.
Several years ago the Electric Power Research Institute convened a conference on the potential applications for shape memory alloy devices in the electric power industry. There were presentations on circuit breakers, remote temperature indicating devices, safety systems for nuclear power systems, devices to minimize the sag in transmission power lines, and actuators to remove ice from overhead conductors. Studies are underway to demonstrate various actuator concepts for the ice removal problem. A devastating ice storm in Northeastern United States in 1998 increased the focus on a SMA actuator solution.
A final SMA application which should be mentioned is the use of these alloys for the control of damage to buildings and infrastructure during earthquakes. The results of a major study of this application was presented in Rome, Italy this year, summarizing the findings of a program funded by the European Union. Very encouraging results were obtained for isolation and energy absorption devices using large cross section NiTi bars in torsion Previous studies have shown the efficacy of using large CZA cylinders for base isolation of buildings. Earthquakes are an ever present danger in most areas of the world and the successful exploitation of SMAs for seismic damage control would be lead to a significant new market for these alloys.

Acknowledgements: Frangibolt™ and the MEMS valves are products of TiNi Alloy Co.; Electralok™ is a product of ITN Energy Systems, Inc., AMCI, Inc. have the rights to Cryocon and Cryofit connectors, Betaflex™ is a product of CVI/Beta Ventures, Inc.