NanoMuscle: Bridging Nanotechnology to Practical Application

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ABSTRACT

Martensitic transformations occurring in shape memory alloys (SMA) are known to be involved in the formation of nano and micro-scale twinning. The resulting valuable materials properties have been at the center of many application development efforts for decades. In spite of certain success stories, lingering problems associated with the physics of shape memory effects have hindered more widespread applications of these fascinating materials. This paper describes a recent development in the field of SMA actuators involving a beneficial folded construction of the active elements. This improvement has resulted in a considerable widening of the range of possible applications.

I. NANO SCALE STRUCTURES IN SMA

Much excitement has been generated in recent years by nano-science breakthroughs. A common characteristic of such developments has been the discovery of novel properties of materials of common composition but with dimensions in the nanometer range. The development of nano-structured materials has also inspired a renewed interest in shape-memory alloys (SMAs), a class of materials known for the better part of a century[1],[2]. It is now well known that the favorable properties of SMA's are related to their propensity for pervasive twinning, a lattice modulation linked with displacive phase transformations.

Another feature of much present-day nano-science is found in the self-assembly, ordering and orientation of nano-structures, especially in the presence of a template or other symmetry-breaking boundary conditions. Such effects are extensions of ordering phenomena well known in phase transitions, such as the growth of an ordered lattice from an amorphous melt in the presence of a crystalline seed, or the formation of ordered ferroelectric domains in the presence of applied electric fields. In the case of SMA's, favorable orientation of the martensitic domains is achieved primarily by thermo-mechanical treatments such as drawing, annealing and cold-working, although other means are available as well.

II. TECHNOLOGICAL APPLICATIONS

Transformations between the twinned phase (martensite) and the untwined phase (austenite) are accompanied by large mechanical effects known as shape-memory effects (SME). Applications of SME are proliferating in such diverse areas such as automotive, security/locking, medicine, aerospace military and consumer products.

For many of these applications, the main competition is presented by small electric motors or solenoids. At the heart of everything from instrument clusters to cell phones, these motors and solenoids produce revenue in excess of $17B annually. Most are based on principles of electromagnetism discovered by Faraday over 170 years ago.

With such an entrenched technology as a competitor, the adoption of new technologies may be slow, but endowed with huge economic potential.

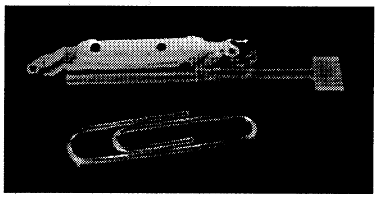


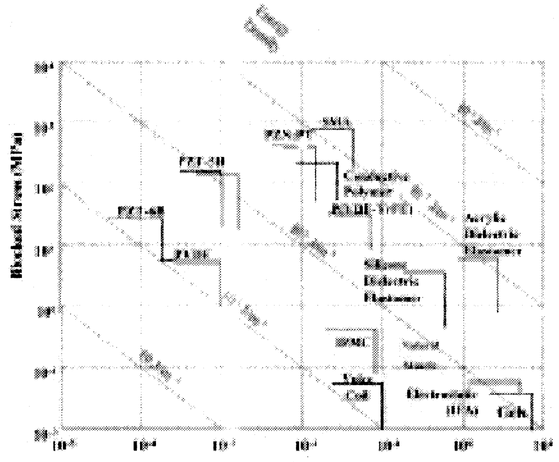
Fig. # 1.Folded SMA geometry offers miniature size and low cost

NanoMuscle, Inc. manufactures a new motor based on materials with nano-scale features. With significant development and orders for millions of NanoMuscles™ so far, they are on their way to becoming the first commercially viable alternative to the small electric motor.

III. WHY USE SMA?

Although most of today's high volume actuators are built using small electromagnetic motors or solenoids, there is an increasing demand for smaller more efficient systems from a wide range of market segments including Consumer Electronics, Medical, Automotive and Computer Peripherals.

However, as the scale of an electromagnetic motor shrinks below about 2 cm^3 it becomes increasingly inefficient to operate and expensive to manufacture. Below 1 cm^3 (the volume of a NanoMuscle actuator) electromagnetic motors and solenoids generally become too expensive for use in high volume devices, and too power hungry for battery-operated devices.



Source: DARPA and SRI International

Fig. # 2 SMA actuators deliver superior energy density

This limitation led NanoMuscle to the choice of SMAs to produce controlled movement. In addition, SMAs were selected because actuators based on them have an energy density higher than that of any other actuator technology. As can be seen from the diagonal contours in Fig. # 2, SMAs have 1,000 times the energy density of natural human muscle and 10,000 times the energy density of a voice coil motor, making them attractive as the basis of a new class of very small, powerful actuator.

IV. LIMITATIONS OF TRADITIONAL SMA

Despite the implied promise of small powerful actuators, a number of problems have hindered the wide spread deployment of conventional SMA devices in commercial applications. These problems have included (a) limited bandwidth, (b) low efficiency, (c) ambient temperature restrictions, (d) non-deterministic operation, and (e) short cycle life.

To understand some of these limitations, it is useful to review the operating principles of SMA actuators. As illustrated in Fig. # 3, the length of an SMA element can be changed by varying the temperature of the alloy between its M_f and A_f transition temperatures. Heating above A_s results in contraction, while cooling below M_f results in the alloy returning to its starting geometry. Thus, the heat flow rate controls the achievable strain rate.

Heat inflow is usually resistive. Such heating is mainly limited by the external circuitry and the available electrical power and it can easily exceed the needed contraction rate. In fact, SMAs can exhibit some of the fastest contraction times of any known mechanical system.

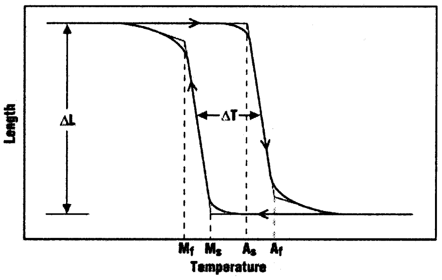
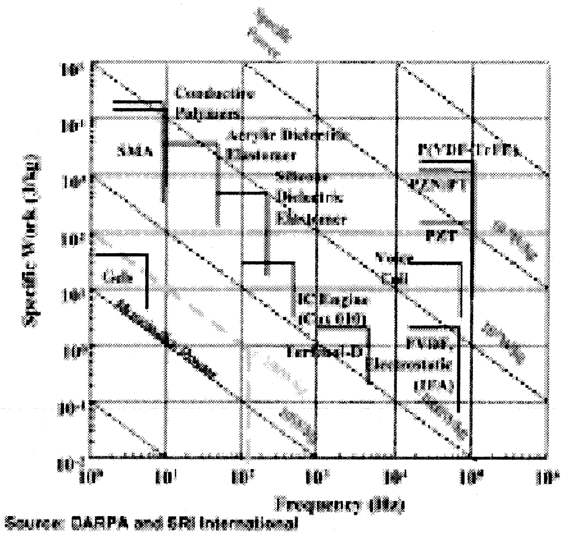


Fig. # 3. Temperature dependence of SMA material

Heat outflow depends mostly on the temperature difference between SMA and environment. Since the temperatures are usually close, the heat flux is small and decreasing as the actuator cools. The problem is worsened by the hysteresis in the length-temperature relationship of Fig. #3 and the need to recover the starting position at the end of a cycle. To do that requires cooling the SMA even more. Slow cooling is thus the main obstacle in the path of higher bandwidth. As can be seen from Fig. # 4 this puts conventional SMA at a disadvantage when compared to other actuator technologies.



Source: DARPA and SRI International

Fig. # 4 Conventional SMA actuation bandwidth limitation

The shortcomings historically associated with SMA devices have been successfully tackled by the NanoMuscle™, a novel folded-geometry actuator (Fig. # 1) developed by NanoMuscle, Inc. Its achievements will be examined below.

V. THE FOLDED-GEOMETRY SOLUTION

The following table summarizes the main advantages. As can be seen, the folded-geometry device (Nano) is fifteen times faster and yet is twice as energy efficient.

Characteristic	Nano	Coil	Delta
Cycle Time (msec)	300	4,500	15×
Contract Time (msec)	120	580	5 ×
Extend Time[1] (msec)	180	3,920	22×
Energy (Watt Secs)	0.159	0.335	22 3%
Rated Cycle Life	1M	0.2M	20%
Foot Print[2] (mm^2)	207	169	82%

Table 1. Folded SMA actuators versus SMA coils

In the table, a Toki coil actuator (Toki BMX15015) and a device similar to the one shown in Fig. # 1 (NM30HS) are compared, both lifting a 30gram load over a distance of 4mm at an ambient temperature of 25 C. Other coil-based actuators (e.g. Omron) provide similar results.

The reason for these advantages will now be reviewed.

VI. LONGER STROKE

A straight SMA wire has a maximum percentage contraction in the 2% to 4% range. Since typical applications require stroke lengths in the 4 mm to 8 mm range this implies a device that is between 10 and 20 cm long, an inconvenient form factor in many cases.

A common approach to solving this problem is to trade force for displacement. This can be done by a lever (Furukawa, Dynalloy et al.) or a coil (Toki, Omron, et al). In both cases the stroke is increased and the available force decreased.

For a coil type SMA actuator (e.g. Toki, Omron) the reduction in available force is dramatic. For a given force output, the coil will require an SMA wire diameter that is 3_ thicker than a straight of wire. In turn, this will require 8_ more current to heat and will operate 15_ more slowly.

The ideal SMA actuator would be one that packaged a long length of straight SMA wire into a smaller package without reducing available force. This would enable smaller diameter wires to be used, which in turn would greatly improve speed and efficiency. This is one of the main results of the patent-pending sliding plane geometry.

Consider the simplified diagram of Fig. # 5:

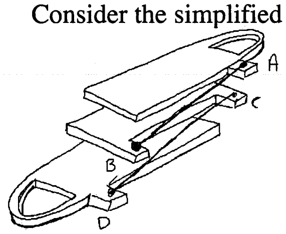


Fig. # 5. Folded geometry by patented sliding planes

The three metal plates are electrically conductive, forming a “daisy chain”-like series connection through SMA wires. When a potential difference is introduced between the top and bottom plates, each wire is resistively heated and contracts by 4% of its length.

However, since the rigid plates are also mechanically connected in series, the overall relative displacement between points A and D is the sum of the individual strokes available from segments AB and CD, or 8%. It is important to note that this stroke multiplying effect does not reduce the available force and so relatively narrow diameter SMA wires can be used. This increases the efficiency of the system and greatly improves speed.

VII. HIGHER BANDWIDTH

When an SMA wire is heated, the cooling time is a nonlinear function of the radius, as depicted in Fig. # 6. For example, halving the wire diameter approximately quarters the cooling time.

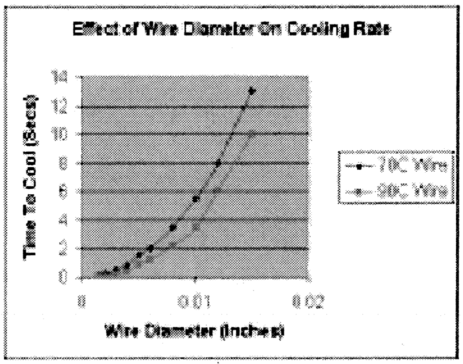


Fig. # 6. Wire diameter has a dramatic effect on cooling time

Since the sliding plates allow thinner wires, speed improvement also results. However this is not the only packaging innovation that enables NanoMuscle actuators to provide higher speed.

In the folded geometry, SMA wires are pre-tensioned against mechanical end-stops. This means that the alloy does not need to return all the way to the M_f before the next cycle can begin. Moreover, this effectively “cuts-off” 80% of the cooling time. By mechanically restricting the range of motion of the SMA wires inside the actuator, the life of the device is also extended.

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[1] Toki actuator only returned to 7% position in this time

[2] Excludes Connecting Wires

Another innovative speed improvement comes from the convenient heat sink formed by the stacked metal plates. Thus, by increasing the thermal mass and the surface area over which the device can exchange heat, the steady and transient cooling response are improved. At the same time, sensitivity to ambient variations is also reduced.

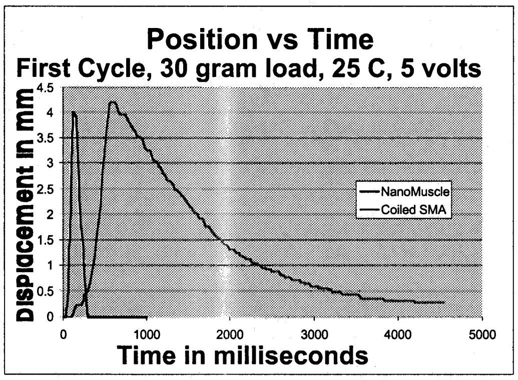

Fig. # 7. NanoMuscle actuator cycle is completed before regular SMA concludes its contraction

The effect of combining these innovations into a single device is dramatic as seen in Fig. # 7 which compares a coil actuator (Toki BMX15015) and a NanoMuscle (NM30HS) both lifting a 30gram load 4mm at a temperature of 25 C. Other coil-based actuators (e.g. Omron) provide similar results. The sliding plane device is 15_ faster. In fact it has traveled 4mm and returned when the coil has moved 0.5 mm.

VIII. HIGHER EFFICIENCY

NanoMuscle actuators are over twice as efficient as coils. As illustrated in Table 2, an NM30 actuator was compared with a Toki coil sized for 30g at 4mm. The devices deliver the same work per cycle. From the bottom row it is apparent that the coil consumes 2.1_ as much energy per cycle.

Characteristic	Nano	Toki	Delta
Contract Time (msec)	120	580	5×
Voltage (V)	5.0	1.8	0.36×
Current(mA)	265	578	2.18×
Heating Power Watts	1.325	0.578	0.44×
Energy/cycle (Joules)	0.159	0.335	2.1×

Table 2. A Nanomuscle is 2.1× as efficient as a Toki coil

IX. EXTENDED AMBIENT RANGE

The heat-sinking action of the sliding plates enables the NanoMuscle to respond fast even at higher temperatures. Fig. # 8 illustrates the advantage of a NanoMuscle over coils in the area of cooling time vs. ambient temperature.

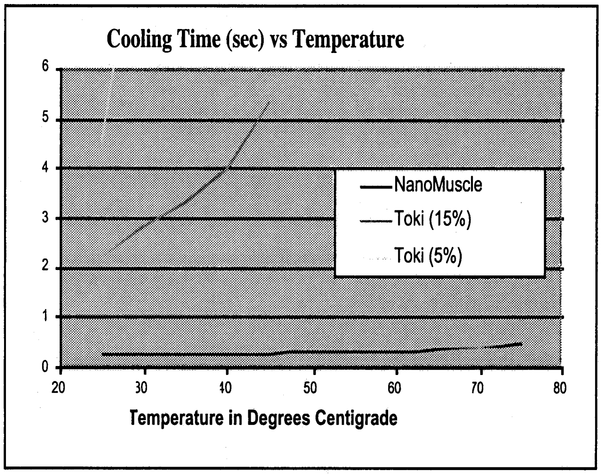

Fig. # 8. Coil based SMAs slow down dramatically at higher ambient temperatures; NanoMuscles do not.

The tests shown used a 30g load. This was inadequate to return the coil to within 5% of its start when the ambient was above 30 C and so the graph shows the time taken for cooling to within 15% of the start. This is because at these stress levels the ambient is above the coil's M_f.

X. CONCLUSION

Nano-structured SMAs arranged in NanoMuscles' folded configuration successfully mitigate known shortcomings of SMA actuators. The resulting improvements open the way for many applications, previously addressable only by other technologies.

REFERENCES

[1] K. Otsuka and T. Kakeshita, "Science and technology of shape-memory alloys: new developments," *MRS Bulletin,*, vol. 27, no. 2, pp. 91-98, February 2002.

[2] D. Mantovani, "Shape memory alloys: properties and biomedical applications" Journal of Metals, vol. 52, no. 10, pp. 36, October 2000.