Technical Characteristics of

FLEXINOL®

Actuator Wires

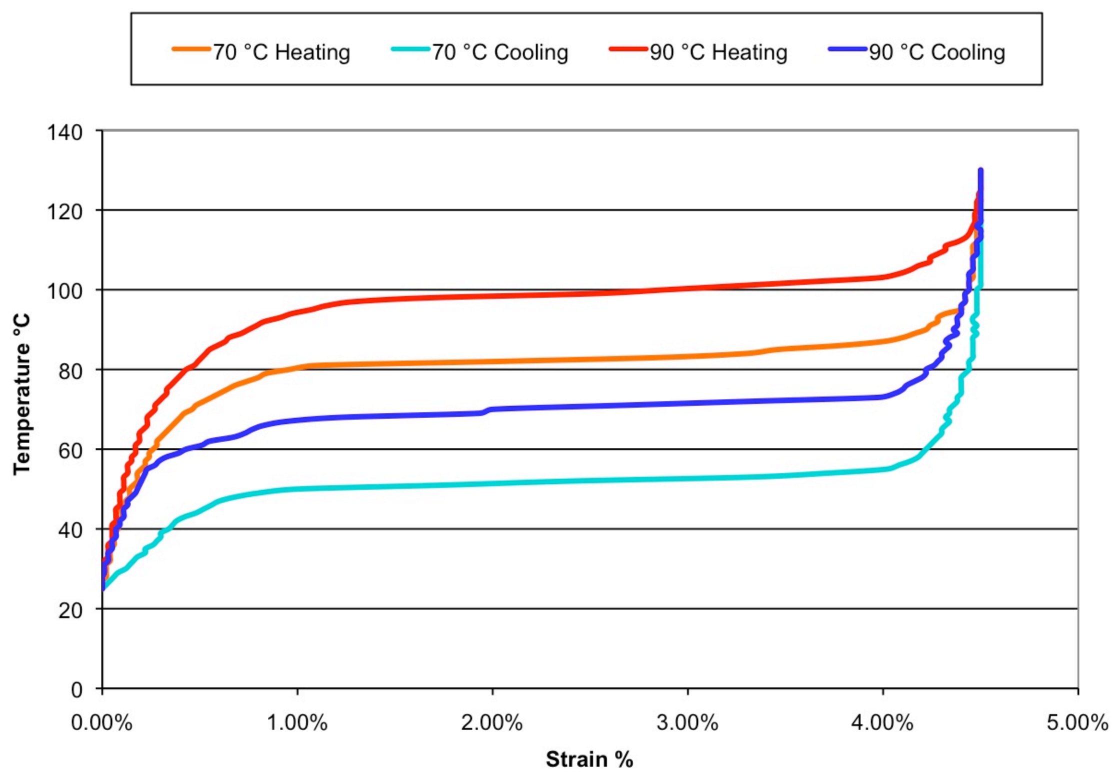
Flexinol® Actuator Wires are small diameter wires which contract like muscles when electrically driven. Smaller than motors or solenoids, cheaper and generally easier to use, these wires perform physical movement across an extremely wide variety of applications.

Table of Contents

1562 Reynolds Avenue, Irvine, California 92614 USA 714-436-1206 714-436-0511 fax http://www.dynalloy.com

NICKEL - TITANIUM ALLOY PHYSICAL PROPERTIES

1. Density	0.235 lb/in^3 (6.45 g/cm^3)
2. Specific Heat	0.20 BTU/lb * °F (0.2 cal/g * °C))
3. Melting Point	2370 °F (1300 °C)
4. Latent Heat of Transformation	10.4 BTU/lb (5.78 cal/g)
5. Thermal Conductivity	10.4 BTU/hr * ft * °F (0.18 W/cm * °C)
6. Thermal Expansion Coefficient	
Martensite	3.67x10^{-6}/°F (6.6x10^{-6}/°C)
Austenite	6.11x10^{-6}/°F (11.0x 10^{-6}/°C)
7. Poisson Ratio	0.33
8. Electrical Resistivity (approx.)	
Martensite:	32 micro-ohms * in (80 micro-ohms * cm)
Austenite:	39 micro-ohms * in (100 micro-ohms * cm)



Typical Temperature vs. Strain Characteristics for Dynalloy's standard 158°F (70°C) "LT" and 194°F (90°C) "HT" Austenite start temperature alloys, at 172 MPa

1562 Reynolds Avenue, Irvine, California 92614 USA 714-436-1206 714-436-0511 fax http://www.dynalloy.com

Introduction

Flexinol® is a trade name for shape memory alloy actuator wires. Made of nickel-titanium these small diameter wires contract like muscles when electrically driven. This ability to flex or shorten is characteristic of certain alloys that dynamically change their internal structure at certain temperatures. The idea of reaching higher temperatures electrically came with the light bulb, but instead of producing light these alloys contract by several percent of their length when heated and can then be easily stretched out again as they cool back to room temperature. Like a light bulb both heating and cooling can occur quite quickly. The contraction of Flexinol® actuator wires when heated is opposite to ordinary thermal expansion, is larger by a hundredfold, and exerts tremendous force for its small size. The underlying technology that causes the effect is discussed in Section 5. The main point is that movement occurs through an internal "solid state" restructuring in the material that is silent, smooth, and powerful.

This effect can be used in many ways. The list of viable applications is too long for any single listing. A safe assumption is that any task requiring physical movement in a small space with low to moderate cycling speeds is something that most likely will be better done with actuator wires. Many of the tasks currently being done with small motors or solenoids can be done better and cheaper with Flexinol® actuator wires. Since the actuator wires are much smaller for the work they do a number of new products and improved designs on existing products are readily accomplished.

For new users of Flexinol® actuator wires, Dynalloy, Inc. strongly recommends that an overview of what can be done first be established. This can be done by obtaining one of the Dynalloy, Inc. kits, which is made for such familiarization. Secondly, new users should consider obtaining from Dynalloy, Inc. or other consultants a "Proof of Concept" working model. This is not only useful as an internal marketing and sales tool. It also helps the new user to see how those with more experience approach the specific task in hand. Knowing this provides immeasurable insight into how to proceed and helps reduce the redundancy of reinventing existing techniques. One can always improve on existing methods and sufficient legal and other safeguards can be readily employed to ensure protection of proprietary ideas.

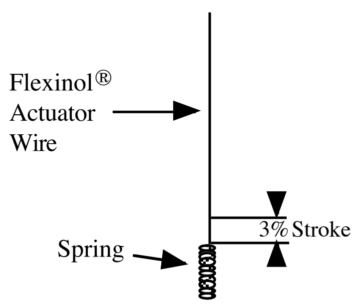
1562 Reynolds Avenue, Irvine, California 92614 USA 714-436-1206 714-436-0511 fax http://www.dynalloy.com

Section 1. Movement

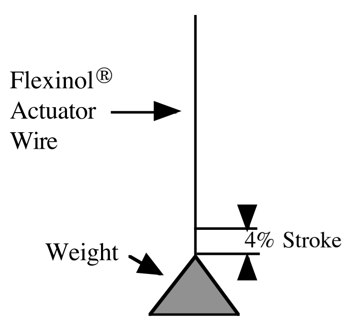
The movement or stroke of Flexinol® actuator wire is measured as a percentage of the length of the wire being used and is determined, in part, by the level of stress one uses to reset the wire, or to stretch it in its low temperature phase. This opposing force, used to stretch the wire, is called the bias force. In most applications, the bias force is exerted on the wire constantly, and on each cycle as the wire cools, this force elongates it. If no force is exerted as the wire cools, very little deformation or stretch occurs in the cool, room temperature state and correspondingly very little contraction occurs upon heating. Up to a point the higher the load the higher the stroke. The strength of the wire, its pulling force and the bias force needed to stretch the wire back out are a function of the wire size or cross sectional area and can be measured in pounds per square inch or “psi”. If a load of 5,000 psi (34.5 MPa) is maintained during cooling, then about 3% memory strain will be obtained. At 10,000 psi (69 MPa), about 4% results, and with 15,000 psi (103 MPa) and above, nearly 5% is obtained. However, there is a limit to how much stress can be applied.

Far more important to stroke is how the wire is physically attached and made to operate. Dynamics in applied stress and leverage also vary how much the actuator wires move. While normal bias springs that increase their force as the Flexinol® actuators contract have only 3-4% stroke, reverse bias forces which decrease as the actuator wires contract can readily allow the wire to flex up to 7%. Mechanics of the device in which it is used can convert this small stroke into movements over 100% of the wires' length and at the same time provide a reverse bias force. The stress or force exerted by Flexinol® actuator wires is sufficient to be leveraged into significant movement and still be quite strong. Some basic structures, their percent of movement, and the approximate available force they offer in different wire sizes are as follows:

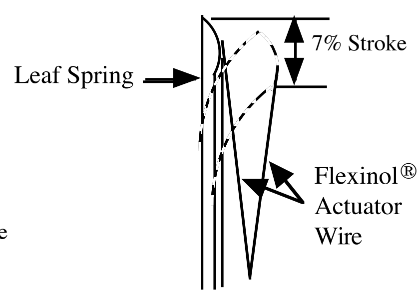
Normal Bias Spring



Dead Weight Bias



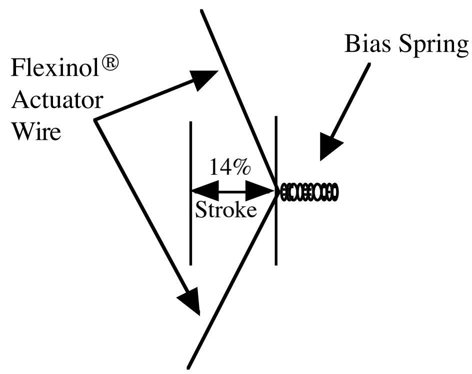
Leaf Spring Bias



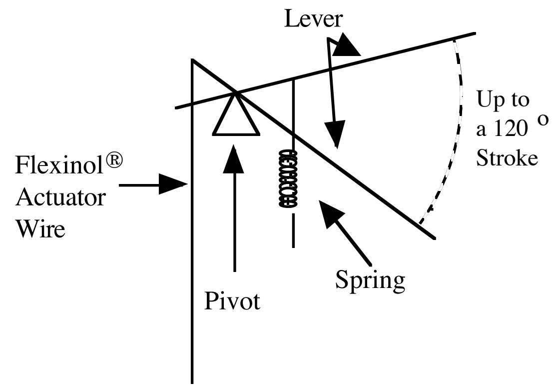
1562 Reynolds Avenue, Irvine, California 92614 USA 714-436-1206 714-436-0511 fax http://www.dynalloy.com

1562 Reynolds Avenue, Irvine, California 92614 USA 714-436-1206 714-436-0511 fax http://www.dynalloy.com

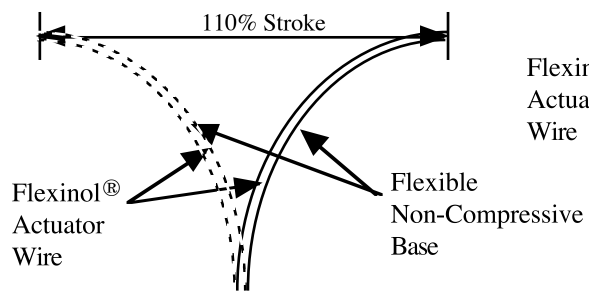
Right Angle Pull



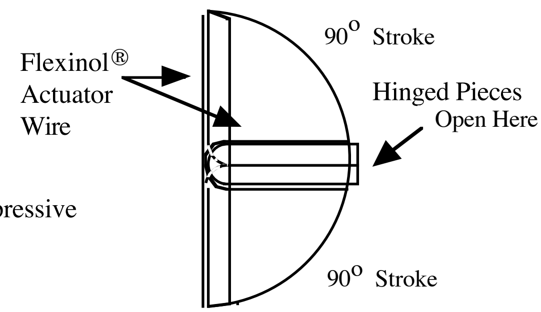
Simple Lever



Adjusting Curvature



Clam Shell



Stroke and Available Force Table

	Approx. Stroke	0.003” Wire (0.076 mm)	0.006” Wire (0.15 mm)	0.010” Wire (0.25 mm)
Normal Bias Spring	3%	0.18 lb (80 g)	0.73 lb (330 g)	2.05 lb (930 g)
Dead Weight Bias	4%	0.18 lb (80 g)	0.73 lb (330 g)	2.05 lb (930 g)
Leaf Spring Bias	7%	0.18 lb (80 g)	0.73 lb (330 g)	2.05 lb (930 g)
Right Angle Pull	14%	0.04 lb (20 g)	0.18 lb (83 g)	0.51 lb (232 g)
Simple Lever (6:1 ex)	30%	0.024lb (11 g)	0.10 lb (47 g)	0.29 lb (133 g)
Adjusting Curvature	110%	0.006 lb (3 g)	0.026 lb (12 g)	0.075 lb (34 g)
Clam Shell	100%	0.007 lb (3.2 g)	0.028 lb (13 g)	0.082 lb (37 g)

Section 2. Electrical Guidelines

If Flexinol® actuator wire is used in the appropriate conditions, then obtaining repeatable motion from the wire for tens of millions of cycles is reasonable. If higher stresses or strains are imposed, then the memory strain is likely to slowly decrease and good motion may be obtained for only hundreds or a few thousands of cycles. The permanent deformation that occurs in the wire during cycling is heavily a function of the stress imposed and the temperature under which the actuator wire is operating. Flexinol® wire has been specially processed to minimize this straining, but if the stress is too great or the temperature too high, some permanent strain will occur. Since temperature is directly related to current density passing through the wire, care should be taken to heat, but not overheat, the actuator wire. The following charts give rough guidelines as to how much current and force to expect with various wire sizes.

Diameter Size inches (mm)	Resistance ohms/inch (ohms/meter)	Pull Force* pounds (grams)	Cooling Deformation Force* pounds (grams)	Approximate** Current for 1 Second Contraction (mA)	Cooling Time 158°F, 70°C "LT" Wire *** (seconds)	Cooling Time 194°F, 90°C "HT" Wire *** (seconds)
0.001 (0.025)	36.2 (1425)	0.02 (8.9)	0.008 (3.6)	45	0.18	0.15
0.0015 (0.038)	22.6 (890)	0.04 (20)	0.016 (8)	55	0.24	0.20
0.002 (0.050)	12.7 (500)	0.08 (36)	0.032 (14)	85	0.4	0.3
0.003 (0.076)	5.9 (232)	0.18 (80)	0.07 (32)	150	0.8	0.7
0.004 (0.10)	3.2 (126)	0.31 (143)	0.12 (57)	200	1.1	0.9
0.005, (0.13)	1.9 (75)	0.49 (223)	0.20 (89)	320	1.6	1.4
0.006 (0.15)	1.4 (55)	0.71 (321)	0.28 (128)	410	2.0	1.7
0.008 (0.20)	0.74 (29)	1.26 (570)	0.50 (228)	660	3.2	2.7
0.010 (0.25)	0.47 (18.5)	1.96 (891)	0.78 (356)	1050	5.4	4.5
0.012 (0.31)	0.31 (12.2)	2.83 (1280)	1.13 (512)	1500	8.1	6.8
0.015 (0.38)	0.21 (8.3)	4.42 (2004)	1.77 (802)	2250	10.5	8.8
0.020 (0.51)	0.11 (4.3)	7.85 (3560)	3.14 (1424)	4000	16.8	14.0

* The Heating pull force is based on 25,000 psi (172 MPa), which for many applications is the maximum safe stress for the wire. However, many applications use higher and lower stress levels. This depends on the specific conditions of a given design. The cooling deformation force is based on 10,000 psi (70 MPa), which is a good starting point in a design. Nonetheless, this value can also vary depending on how the material is used.

** The contraction time is directly related to current input. The figures used here are only approximate since room temperatures, air currents, and heat sinking of specific devices vary. On small diameter wires (<= 0.006" diameter) currents that heat the wire in 1 second can typically be left on without over-heating it.

*** Approximate cooling time, at room temperature in static air, using a vertical wire. The last 0.5% of deformation is not used in these approximations.

1562 Reynolds Avenue, Irvine, California 92614 USA 714-436-1206 714-436-0511 fax http://www.dynalloy.com

Section 3. Cycle Time

The contraction of the Flexinol® actuator wire is due solely to heating and the relaxation solely to cooling. Both contraction and relaxation are virtually instantaneous with the temperature of the wire. As a result mechanical cycle speed is dependent on and directly related to temperature changes. Applying high currents for short periods of time can quickly heat the wire. It can be heated so fast in fact that the limiting factor is not the rate at which heating can occur but rather the stress created by such rapid movement. If the wire is made to contract too fast with a load, the inertia of the load can cause over stress to the wire. To perform high speed contractions inertia must be held low and the current applied in short high bursts. Naturally, current which will heat the wire from room temperature to over 212 °F (100 °C) in 1 millisecond, will also heat it much hotter if left on for any length of time.

While each device has quite different heat sinking and heating requirements, a simple rule of thumb test can be used to prevent overheating. Measuring the actual internal temperature of the wire across such short time periods is somewhat problematic, however, one can tell if the actuator wire is overheated simply by observing if the wire immediately begins to cool and relax when the current is shut off or not. If it does not begin to relax and elongate under a small load promptly, when the power is cut, then the wire has been needlessly overheated and could easily be damaged. Simple visual observation is all that is needed to design measured heating circuitry.

Flexinol® actuator wire has a high resistance compared to copper and other conductive materials but is still conductive enough to carry current easily. In fact one can immerse the wire in regular tap water and enough current will readily flow through it to heat it. All of the conventional rules for electrical heating apply to the wire, except that its resistance goes down as it is heated through its transformation temperature and contracts. This is contrary to the general rule of increased resistance with increased temperature. Part of this drop in resistance is due to the shortened wire, and part is due to the fact that the wire gets thicker as it shortens, roughly maintaining its same three-dimensional volume. It makes no difference to the wire whether alternating current, direct current, or pulse width modulated current is used.

Again relaxation time is the same as cooling time. Cooling is greatly affected by heat sinking and design features. The simplest way to improve the speed of cooling is to use smaller diameter wire. The smaller the diameter the more surface to mass the wire has and the faster it can cool. Additional wire, even multiple strands in parallel, can be used in order to exert whatever force is needed. The next factor in improving the relaxation or cooling time is to use higher temperature wire. This wire contracts and relaxes at higher temperatures. Accordingly the temperature differential between ambient or room temperature and the wire temperature is greater and correspondingly the wire will drop below the transition temperature faster in response to the faster rate of heat loss.

Other methods of improved cooling are to use: forced air, heat sinks, increased stress (this raises the transition temperature and effectively makes the alloy into a higher transition temperature wire), and liquid coolants. Combinations of these methods are also effective. Relaxation time can range from several minutes (i.e. delay switches) to fractions of milliseconds (i.e. miniature high speed pumps) by effective and proper heat sinking. The following page gives some idea of the effect these various methods have.

1562 Reynolds Avenue, Irvine, California 92614 USA 714-436-1206 714-436-0511 fax http://www.dynalloy.com

1562 Reynolds Avenue, Irvine, California 92614 USA 714-436-1206 714-436-0511 fax http://www.dynalloy.com

Relative Effects of Cooling Methods

	Improvement in Speed
Increasing Stress	1.2:1
Using Higher Temperature Wire	2:1
Using Solid Heat Sink materials	2:1
Forced Air	4:1
Heat Conductive Grease	10:1
Oil Immersion	25:1
Water with Glycol	100:1

*These improvements are not accumulative on the same basis when used together.

Better cooling methods are likely to require more current or heat to move and/or hold the wire in an "on" position. In some cases one may wish to quickly turn the wire on (that is electrically heat it until it contracts) then hold it on for some time. This will likely require a two-step driving current with a larger current to heat the wire and a reduced current to keep it hot without overheating it. There are a number of simple circuits, which will do this.

Section 4. Miscellaneous

Cutting - Flexinol® actuator wire is a very hard and anti-corrosive material. It is so hard that cutting it with cutters designed to cut copper and soft electrical conductors will damage the cutters. If you plan to do much work with Flexinol® actuator wires a good high quality pair of cutters like those used to cut stainless steel wires will be a good investment.

Attaching - Attaching Flexinol® actuator wires to make both a physical and an electrical connection can be done in several ways. It can be attached with screws, wedged onto a PC board, glued into a channel with conductive epoxies, and even tied with a knot. The simplest and best way is usually by crimping or splicing. With crimping machines both electrical wires and hooks or other physical attachments can be joined at once. Flexinol® wires tends to maintain the same volume, so when they contract along their length, they simultaneously grow in diameter. This means the wires expand inside the crimps and hold more firmly as the stress increases through pulling. While this works to the advantage in crimps it can be a disadvantage if glues or solder is used, as the material tends to work itself loose in those cases. Flexinol® wire is a very strong material and is not damaged by the crimping process. Dynalloy, Inc. can provide wire that is already crimped at specified intervals. One can then solder or spot-weld to the crimps if such manufacturing methods are preferred.

Accompanying Materials - Flexinol® actuator wires work by internal resistance or other heating methods. Their temperature is often over 212 °F (100 °C) and they often apply pressure with a high force over a small area of the device they are attached to, so it is a good idea to use temperature resistant materials in connection with them. Such materials if used in direct contact with the wire will also need to be non conductive so as to not provide an electrical path around the Flexinol® actuator wire. Silicone rubber, Kapton (used to make flexible circuit boards), ceramics, and glass are good examples.

Strain Reliefs - Over stress can damage Flexinol® wires by permanently stretching (or elongating) them or by reducing the stroke over which they contract. To prevent this one should design products with strain reliefs in them. Care should also be taken to prevent manual interference with their contraction or movement as this can over stress the wire. In other words if the device gets stuck and cannot move or is forced backwards while operating a problem can be created breaking or adversely affecting the actuator wires' performance. Protective measures against this should be used.

Reverse Biases - Although Flexinol® actuator wire moves about 4.5% when lifting a weight or when contracting against a constant force, one can improve this stroke by designing mechanisms which have a reverse bias force. The bias force is the force that elongates the wire in its rubber-like martensitic phase. A reverse bias force is one that gets weaker as the stroke gets longer. This can be done with leaf springs or with designs that give the Flexinol® actuator wires a better mechanical advantage over the bias spring or force as the stroke progresses.

Performance Margins - Although very stable compared to other similar alloys Flexinol® actuator wires will permanently stretch out or strain with large cycles strokes and high stresses. At stresses below 15,000 psi (103 MPa), permanent strain will remain less than 0.5% strain even after hundreds of thousands of cycles. At 20,000 psi (138 MPa), perhaps 1% permanent strain will occur after 100,000 cycles, and with higher stresses proportionally more will occur.

1562 Reynolds Avenue, Irvine, California 92614 USA 714-436-1206 714-436-0511 fax http://www.dynalloy.com

Section 4. Miscellaneous cont'd.

Good engineering design dictates that one should take into account the amount of memory strain, possible small decreases in the amount of that strain during operation, and some permanent deformation of the wire during cycling if the design is to meet expectations. Pushing all performance aspects of the wire to the limit from the outset of its cycling is likely to lead to disappointment at an early stage in the product life.

Longevity Testing - Flexinol® actuator wire can be over stressed and damaged even though it seems to be working. Much like actual muscles can be strained when called upon to do work above their actual capacity. The device may work in such a way that it is difficult to calculate the actual stresses involved. A good suggestion is to perform life cycle tests before assuming that a device which has worked a few times will continue to work millions more times. Fatigue which is damaging to Flexinol® actuator wire will usually show up in the form of wire elongation or reduced stroke within the first few hundred strokes. As one works with the material a "feel" for what is "working" will develop. The best rule of thumb is to use enough Flexinol® actuator wire to be sure one is well within the parameters in which it can work.

Precise Positioning - Given close temperature control under a constant stress one can get quite precise position control. Control in microns or less is to be expected. The problem is precise temperature control. The temperature is determined by an equilibrium between the rate of heating and the rate of cooling. Heating by electricity makes control of that easy, but the cooling is dynamically affected by changes in room temperature, airflow and so on. In practical terms this means that precise control is usually not feasible unless one can control the heat loss or has dynamic feedback through a closed loop system and can use this to control the heating rate.

Contact Dynalloy, Inc. Freely - There is no practical way for the authors to include everything that has been learned or will be learned in this short document. We have thousands of customers who call and contribute to our general understanding of typical application solutions. In most cases, we have already encountered problems which seem new to the first time user, so whenever possible we are happy to pass on these suggestions and be of help. We want your project to succeed, so please do not hesitate to call for assistance.

1562 Reynolds Avenue, Irvine, California 92614 USA 714-436-1206 714-436-0511 fax http://www.dynalloy.com

Section 5. Underlying Technology

Flexinol® is a trade name for very high performance, shape memory alloy, actuator wires. Made of nickel-titanium these small diameter wires have been specially processed to have large, stable amounts of memory strain for many cycles. In other words, they contract like muscles when electrically driven. This ability to flex or shorten is characteristic of certain alloys that dynamically change their internal structure at certain temperatures. Flexinol® wires contract by several percent of their length when heated and then easily elongate again by a relatively small load when the current is turned off and they are allowed to cool.

The function of the Flexinol® wire is based on the shape memory phenomenon which occurs in certain alloys in the nickel-titanium family. When both nickel and titanium atoms are present in the alloy in almost exactly a 50%/50% ratio, the material forms a crystal structure which is capable of undergoing a change from one crystal form to another (a martensitic transformation) at a temperature determined by the exact composition of the alloy. In the crystal form that exists above the transformation temperature (the austenite) the material is high strength and not easily deformed. It behaves mechanically much like stainless steel. Below the transformation temperature, though, when the other crystal form (the martensite) exists, the alloy can be deformed several percent by a very uncommon deformation mechanism that can be reversed when the material is heated and transforms. The low temperature crystal form of the alloy will undergo the reversible deformation fairly easily, so the "memory" strain can be put into the material at rather low stress levels.

The resultant effect of the shape memory transformation of the Flexinol® wire is that the wire can be stretched about 4-5% of its length below its transformation temperature by a force of only 10,000 psi (69 MPa) or less. When heated through the transformation temperature, the wire will shorten by the same 4-5% that it was stretched, and can exert stresses of at least 25,000 psi (172 MPa) when it does so. The transformation temperature of the NiTi alloys can be adjusted from over 212 °F (100°C) down to cryogenic temperatures, but the temperature for the Flexinol® actuator wire has been chosen to be 140 – 230 °F (60 - 110 °C). This allows easy heating with modest electrical currents applied directly through the wire, and quick cooling to below the transformation temperature as soon as the current is stopped. Heating with electrical current is not required, but it is perhaps the most convenient and frequently used form of heat.

Flexinol® actuator wires' prime function is to contract in length and create force or motion when it is heated. There are limits, of course, to how much force or contraction can be obtained. The shape memory transformation has a natural limit in the NiTi system of about 8%. That is the amount of strain that can occur in the low temperature phase by the reversible martensitic twinning which yields the memory effect. Deformation beyond this level causes dislocation movement throughout the structure and then that deformation is not only non-reversible but degrades the memory recovery as well. For materials expected to repeat the memory strain for many cycles, it is best to utilize a cyclic memory strain of no more than 4-5%, and that is what is recommended with Flexinol® actuator wire.

The force that the Flexinol® actuator wire can exert when heated is limited by the strength of the high temperature austenitic phase. The phase transformation, or crystal change, that causes the memory effect has more driving force than the strength of the parent material, so one must use care not to exceed that yield strength. The yield strength of Flexinol®'s high temperature phase is over 50,000 psi (345 MPa), and on a single pull the wire can exert this force. To have repeat cycling, however, one should use no more than 2/3 of this level, and forces of 20,000 psi (138 MPa) or below give the best repeat cycling with minimal permanent deformation of the wire.

1562 Reynolds Avenue, Irvine, California 92614 USA 714-436-1206 714-436-0511 fax http://www.dynalloy.com

ACTUATOR WIRE

A SOLID STATE ACTUATOR THAT MOVES BY "MOLECULAR RESTRUCTURING"!

FOR BETTER MECHANICAL PERFORMANCE...

- In really tight places - Flexinol® actuator wires are smaller by far than alternatives. At least 1,000 times smaller than solenoids for the same work done.
- To simplify designs - Flexinol® actuator wires can often be used "as is", eliminating gear boxes, housings, bearings, and so on. Their flexible forgiving performance is easier to work with.
- In corrosive environments - Flexinol® actuator wires' high corrosion resistance really pays off.
- To reduce noise levels - Flexinol® actuator wires' movement by molecular restructuring is both electrically and acoustically quiet.
- To lower costs - Flexinol® actuator wires are inexpensive to buy and cost less to use in many applications. A nice combination for that bottom line.

SAMPLE APPLICATIONS

ELECTRONICS
Micro Circuit Breakers
PC Mount Relays
Chassis Temp. Controls
Electronic Locks
PC Mount Pilot Valves
Mechanical Latches
Subminiature Door Openers
Micro Manipulators
Retrofit Switch to Relay
Micro Clutches
Spring Loaded Releases
Board Temperature Sensors
"Clean" Actuators
Remote Switch Controllers
Read/Write Head Lifters

MEDICAL
Intravenous Med. Controllers
Steerable Catheters
Prosthetic Limbs
Surgical Instruments
Braille Displays
Vacuum Test Manipulators
Micro Pumps
Blood Pressure Test Valve
Exoskeletal Assistance

AUTOMOTIVE
Door Locks
Environmental Controls
Gear Changing Triggers
Clutch Engagement Triggers
Mirror Controls
Heater Cutoff/Sensors
Pneumatic Valve
Remote Latches
Remote Releases
Alarm Devices

APPLIANCES
Moving Louvers
Spring Releases

Door Openers
Electronic Locks
Mechanical Volt. Regulator
Mechanical Curr. Regulator
Motor Protectors
Box Temperature Control
Overheating Controllers
Hair Dryer Cutoff/Sensors
Safety Cutoffs

MISCELLANEOUS
Ultralight Remote Control
Mechanical Scanners
Camera Manipulators
Magnetic Free Positioners
Manipulator Safety
PC Cutoffs
Fiber Gate
Camera Shutters
Cuckoo Clocks
Alarm Devices Light
Light Fiber Switches
Smart Materials
Mechanical IC's
Robotic Limbs

Flexinol® Actuator Wires are small diameter wires which contract like muscles when electrically driven. Smaller than motors or solenoids, cheaper and generally easier to use, these wires perform physical movement for an extremely wide variety of applications.

1562 Reynolds Avenue, Irvine, California 92614 USA 714-436-1206 714-436-0511 fax http://www.dynalloy.com