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THE USE OF MARTENSITE MATERIALS IN THE DESIGN OF THERMALLY ACTIVATED SPRINGS

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INTRODUCTION

Many intermetallic compounds exhibit some rather interesting elastic properties associated with certain phase transitions known as martensite transformations (1-5). Certain alloys such as NiTi and AuCd exhibit such crystallographic changes on cooling from a body-centered cubic high temperature phase (htp) to a low temperature phase (ltp) of lower symmetry. The ltp is usually a twinned structure whose twins are very mobile under the application of stress. A specimen may deform plastically entirely by movement of twin boundaries. The elastic moduli of such materials can be significantly modified by these twinning effects. Interesting "memory" properties are also exhibited by these alloys. For example, if a severely cold-worked sample is constrained to a given shape while being given a special anneal in the htp, this shape will be retained on cooling to the ltp and then subsequently "remembered" everytime it is heated to the htp even though the sample may have been severely plastically deformed in the ltp. This "memory" is exhibited by the fact that the sample will regain its original htp shape when it is heated above its characteristic transformation temperature. These alloys exhibit large differences in their htp and ltp force constants. This fact when coupled with their "memory" properties make these alloys particularly interesting for use as thermally activated springs. The purpose of this paper is to review some of the properties of these materials and to explore some of the problems involved in their use in the design of thermally activated springs that might find use in electromechanical fuzes, switches, and timing devices.

SOME PROPERTIES OF MARTENSITE MATERIALS - A REVIEW

For some time it has been well known that certain metallic systems undergo solid state phase transitions which involve a change in crystal structure but none in chemical composition. Such phase changes which involve no long-range diffusion are known as diffusionless transformations. This kind of reaction includes a type known as the martensite transformation that exhibits certain characteristic

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crystallographic features which have been reviewed by Bilby and Christian,(1) and Christian,(2) and Christian, Read, and Wayman,(3) and Wayman (4). In general, on cooling, these reactions involve the transformation of the crystal to a phase of lower symmetry, e.g., the gold-cadmium system, where the high temperature CsCl cubic phase transforms to an orthorhombic phase on cooling at about 60°C for the 47.5 at % cadmium composition (5). The most significant feature (in fact, the one proposed (1) as a criterion for these reactions) is a characteristic shape change which takes place as a given volume of the crystal transforms (6,7).

The martensite transformations occur on cooling below some transformation temperature, M_s, but they also can be induced by the application of various stresses. The effective elastic moduli of such materials can be significantly modified by these twinning effects. Later in this report we shall have occasion to determine such effective moduli from experimental stress-strain curves.

In general, the application of a stress gives rise to a change in the M_s temperature. Intrater, Chang, and Read (8) reported the effect of a tensile stress on the M_s of annealed Au 47.5 at % Cd alloys. They found parallel upward shifts of the transformation temperatures for heating and cooling. In both cases the magnitude of the shift was proportional to the applied stress. These results were in part due to the fact that the length increase during transformation on cooling and the length decrease on heating were equal. Cross (9) has obtained similar results for NiTi. Application of the appropriate form of the Clausius-Clapeyron Equation permitted calculation of the heat of transformation, λ_m. We shall find below that this will be an important quantity to know for the calculation of the thermal energy needed to operate special springs made from martensite materials.

Some interesting changes in the mechanical properties of a material accompany the crystallographic changes that occur during a martensite transformation (10,11). Buehler, Gilfrich, and Wiley,(12) who studied the intermetallic compound NiTi with stoichiometric composition, reported some interesting memory effects associated with the martensite transformation in this alloy. They found that if an initially straight wire is deformed at room temperature by coiling it into a helix, and is then heated, the wire rapidly straightens out to its original shape at about 65°C. The demonstration apparently can be repeated an indefinite number of times. This memory phenomenon has been used in the design of several interesting electromechanical relaxation oscillators, (9,13) as well as in several models of expanding antenna arrays for our space program (9). This rapid reversion of a sample to its original shape on heating has also been observed in the gold-cadmium alloys, where it could be accounted for in terms of the crystallography of the transformation (14).

There is also a large change in the elastic constants that accompany the phase change. For example, in the NiTi stoichiometric material, the effective Young's modulus E has been found to change by a factor of approximately 3 to 4 on heating. Such a result can be calculated from the force vs displacement data for a NiTi rod shown in Figure 1. Similar properties were exhibited by the AuCd alloys (15). Such a large change in Young's modulus makes such materials very attractive for the construction of special thermally activated springs, whose design will be discussed below.

We shall base our spring design calculations entirely on the properties of the NiTi alloys as typical martensite materials. There are two reasons for this choice. First, an extensive literature documenting the physical properties of this system already exists. Much of this work has been accomplished by the group at the Naval Ordnance Laboratories (NOL) which has done considerable work on this system (16-21). In fact, the alloys near the stoichiometric composition have been given the trade name Nitinol (nickel titanium-Naval Ordnance Laboratory) in recognition of the extensive research done by the NOL people on this material. The second reason for our choice of Nitinol is that the equiatomic compound is reasonably ductile at room temperature and below so that the material can readily be fabricated into sheet and wire stock useful in a variety of devices. In this respect Nitinol seems to be rather exceptional in that most martensite materials having a high temperature cesium chloride phase are quite brittle. This brittleness of most interesting materials no doubt has been a deciding factor in preventing the commercial utilization of the interesting mechanical properties of such materials.

In some applications it might be desirable to have a different M_s than that available with Nitinol. It is possible to accomplish this by adding a third element to a given alloy or by choosing other related binary alloys. For example, Rothwarf and Muldawer (22) have demonstrated that the transformation temperature of AuCd alloys can be lowered significantly by the addition of silver. Similarly, Wang (23) has shown that M_s can be varied over a wide range of temperatures for a series of CsCl-type equiatomic phases in binary alloys of transition elements such as TiFe, TiCo, TiNi, ZrRu, and ZrPd. Many other binary alloys exist that exhibit martensite transformations. These include CuAl, CuSn, CuZn, AuCu, AuMn, MnAs, MnBi, AgCd and AgZn. Such materials have a variety of M_s temperatures which vary with deviations from stoichiometry. Thus, it seems that it might be possible to choose a material with an M_s suitable for any given application.

THE DESIGN OF THERMALLY ACTIVATED SPRINGS

Cantilever Springs. In discussing the elastic properties of martensite materials we mentioned the fact that the Young's modulus E for NiTi can change by a factor of 3 to 4 on heating. The tensile measurements of Cross (9) give $E_{1tp} = 3.5 \times 10^6$ psi (2.42×10^{11} dynes/cm^2) at 38° C and $E_{htp} = 11.5 \times 10^6$ psi (7.94×10^{11} dynes/cm^2) at 71° C. Using the same material (kindly furnished to us by Mr. Cross) we have carried out a series of studies to acquaint ourselves with the peculiar properties of this material. In Figure 1 we show the force vs displacement characteristics for a NiTi rod having a diameter of 0.254 cm and a length of 11.2 cm when it was used as a cantilever spring. The ltp curve taken at room temperature (T = 23° C) shows a large mechanical hysteresis on unloading. The htp curve, taken with the sample heated to 150° C by passing a current of 15 amperes through it, shows a much steeper loading behavior and far less hysteresis than does the ltp curve. From the slopes of the loading curves, Young's modulus E can be determined. This is done by invoking the relationship for a cantilever rod supported at one end (24):

$$E = \frac{64FL^3}{3\pi d^4 Y} \tag{1}$$

where F is the force in dynes applied at a distance, L centimeters, from the point at which the rod of diameter, d centimeters, is clamped. Y is the displacement in centimeters of the free end from its straight rest position. Using this equation and our measurements, we obtained an $E_{1tp} = 2.24 \times 10^{11}$ dynes/cm^2 and $E_{htp} = 7.28 \times 10^{11}$ dynes/cm^2 which gives good agreement with the tensile results of Cross. Equation 1 may be used to design thermally activated cantilever springs, whose various modes of operation will now be discussed.

Modes of Spring Operation. Figure 1 is also useful for illustrating the possible modes in which a thermally activated spring might be used. For certain applications, it might be useful to have a given load undergo some displacement on heating. Such a case is shown in Figure 1 as the horizontal line (1) at a force of 1.5×10^5 dynes. Obviously work can be obtained from application of such a method. However, the efficiency of the process is small. By measuring the power and the time needed to transform the rod from the ltp to the htp for the situations shown in Figure 2, it was determined that the work performed was only 0.01 to 0.05% of the energy needed to heat the sample into the htp. It is interesting to note that, within certain limits, the greater the load, the greater the work one can obtain from the process. This behavior is clearly illustrated in Figure 2 where the displacements obtained for a number of heating and cooling cycles are shown for different masses hung from the end of a NiTi rod of nearly the same composition and dimensions as that discussed in Figure 1. The sample was heated into its htp by passing a 15-ampere current through it. Liquid nitrogen was then used to quickly cool it back to room temperature. A cathetometer was used to observe the equilibrium end points in each phase. It is clear that the cycling was quite reproducible. The vertical line (3) in Figure 1 demonstrates the large increase in force that is possible if the rod were constrained to a nearly constant displacement on heating to the htp. Again, it is apparent from Figure 1 that a greater force can be obtained when the rod is constrained at a greater displacement. In general, a given device will operate between the extreme cases (1) and (3), i.e., along a line such that the spring will contract (in this case) when it is heated, as is shown by line (2). It is conceivable that these modes for operating such springs can find considerable application in a variety of temperature activated electromechanical devices.

Helical Springs. It is useful to consider the design problem encountered in using thermally activated helical springs. The pertinent design equations and an illustrative example will now be presented. A useful characteristic of a helical spring is the force constant, F_c, necessary to compress it a unit distance. F_o is also known as the scale of the spring. In general, one has from Hooke's Law:

$$F = F_o\, y, \tag{2}$$

where F is the force required to compress the spring a distance, $y = (L_o - L_{htp})$, and L_o is the uncompressed length of the spring. For a helical spring made of cylindrical wire stock of diameter d, one has (25)

$$F_o = \frac{d^4 G}{8iD^3 k} = \frac{dG}{8ic^3 k} \tag{3}$$

where G is the modulus of elasticity in shear or torsion, D is the diameter of the spring, i is the number of active coils, which is greater by one-half coil than the number of free coils (26), and k is a stress factor which is a function of the diameter ratio, c = D/d, the spring index. For closely coiled springs

$$k = \frac{4c-1}{4c-4} + \frac{0.615}{c} \tag{4}$$

Maleev (25) plots k vs c and shows that the stress factor increases very rapidly with the decrease of the spring index, c. Usually it is advisable to have c > 3. The shear modulus, G, is theoretically related to Young's modulus, E, by the relation

$$G = \frac{E}{2(1 + u)} \tag{5}$$

where u is Poisson's ratio which is 0.33 (12) for NiTi.

In designing a thermally activated spring to provide a given force (curve 3, Figure 1) in the htp, one need consider only the high temperature elastic constants for use in Equations 3 and 5. For example, it was desired to have a compressed spring to activate a mechanical chain of events on being heated. A final force, F_{htp}, of 4 oz (2.8×10^4 dynes) was required from a spring with a constrained length, L, of 0.250 inches (0.635 cm) and a maximum diameter, D, of 0.250 inches (0.635 cm). It was also desired to minimize the length of wire, L_w, to be heated.

$$L_w = \pi i D \qquad (6)$$

The problem was to determine an uncompressed spring length, L_o, and the corresponding initial pitch of the spring, P_o, where

$$P_o = i/L_o \qquad (7)$$

Several solutions are possible to this problem depending upon the choice of wire and spring diameters. Using Equations 2 and 3, one finds

$$L_o = L_{htp} + (F/F_o)_{htp} = L_{htp} + \frac{F_{htp} 8ic^3k}{dG_{htp}} \qquad (8)$$

or

$$L_o = L_{htp} + \alpha i$$

and (9)

$$\alpha = \frac{8F_{htp}c^3k}{dG_{htp}}$$

where α is the compression per turn. Using $E_{htp} = 7.9 \times 10^{11}$ dynes/cm^2, which is Cross' value at 71° C, one can obtain $G_{htp} = 3.0 \times 10^{11}$ dynes/cm^2 from Equation 5. If one chooses $d = 0.010$ inches (0.025 cm) and $D = 0.125$ inches (0.318 cm), then $c = D/d = 12.5$, and from Equation 4 one has $k = 1.12$. Substituting the appropriate values in Equation 9, one finds $\alpha = 6.4 \times 10^{-2}$ cm/turn. If one chooses $i = 5$ turns for some mechanical stability, then $L_o = L_{htp} + 5\alpha = 0.635$ cm $+ 0.320$ cm, $L_o = 0.995$ cm and $P_o \cong 5$ turns/cm. Of course, a somewhat shorter spring with fewer turns would also have satisfied the constraints.

One can simply evaluate the other cases illustrated in Figure 1 by using the suitable htp and ltp values of G in the design equations as well as the pertinent spring dimensions for a particular design.

SOME THERMAL CHARACTERISTICS OF NITINOL

Heat Capacity and Heat of Transformation. It is, of course, important that one know the thermal energy needed to activate a spring. In general, this requires a knowledge of the specific heat as a function of temperature for the material in its low and high temperature phases. In addition, for a given martensite transformation there is a heat of transformation, λ_m, which can be a large fraction of the heat necessary to activate a spring. We shall again consider the data available for Nitinol and shall find that certain complications exist.

Berman, West, and Rozner (27) have studied the heat capacity of an equiatomic NiTi alloy in the temperature range from 25° to 220°C. For their sample, which had been vacuum arc-melted, hot-swaged, annealed 2 hours at 800° C, and cooled overnight in the furnace at a vacuum of 10^{-6} Torr, they obtained certain anomalous effects on three successive cycles. In Figure 3 we have replotted their results for their second run. Between 65° and 110° C, a large peak appears in the specific heat curve. The area labelled B (above the horizontal dashed line) represents the λ_m. For three successive runs they obtained a smaller λ_m. The three heats of transition listed in chronological order were 4150 J/mole, 3831 J/mole, and 3375 J/mole. The estimated uncertainty in each case was 10 J/mole or less, so that clearly the heat of transition exhibited anomalous behavior on cycling. The values reported by Berman et al. are considerably larger than those reported by previous workers. Wang, Buehler, and Pickart (28) reported a λ_m of 2600 J/mole for an alloy having 51 at % Ni, while Dautovich, Melkvi, Purcy, and Stager (29) found a value somewhat higher than this for a 50 at % Ni alloy. The work of Dautovich et al. was consistent with the results of Wasilewski, Butler, and Hanlon (30) who obtained a λ_m of 3100 J/mole for an equiatomic NiTi alloy. It should be pointed out that the various investigating groups used somewhat different heat treatments for this material. The variation in heat treatment might play a significant role in determining the value of λ_m because of the various stress levels that might have existed in the alloys at the time a measurement was begun. The striking decrease in λ_m observed by Berman et al. for successive runs may well be evidence for this type of effect. Of course, the effects of different impurity concentrations and differences in composition may also be determining factors in giving the observed variations in λ_m.

Some recent data presented by Buehler and Cross (31) may be evaluated to show the effect that stresses play in changing λ_m and T_m, the midpoint temperature of the martensite transformation. Cross maintained a fixed strain in a 100-mil diameter, 6-inch length of Nitinol rod (49.6 at % Ni) by increasing the tensile force as temperature was increased. The force necessary to maintain a given strain was found to increase steeply in the region of the martensite transformation and then leveled off to a constant value above the transformation region. Furthermore, as the strain was increased T_m increased. Such behavior is similar to that observed for the Au 47.5 at % Cd alloys by Intrater, Chang, and Read (8) for the effect of tensile stress. Cross' results are shown in Figure 4. Applying the appropriate form of the Clausius-Clapeyron Equation (8) to these data one can obtain λ_m as a function of strain:

$$\lambda_m = \frac{T_m \epsilon}{\rho(1-\epsilon)} \left(\frac{\partial \sigma}{\partial T}\right)_\epsilon \qquad (10)$$

where ϵ is the constant strain maintained as the stress, $\sigma = F/A$ in dynes/cm^2, is varied with the absolute temperature, T, in ° K, and ρ is the NiTi density, 6.45 grams/cm^3, while A is the cross-sectional area of the 100-mil rod. In evaluating λ_m, we have chosen the values for $(\partial F/\partial T)_\epsilon$ from the curves in Figure 4, at a temperature, T_m, which represents the point at which 50 percent of the final constant high temperature force has been applied. The results for λ_m and T_m as a function of strain, ϵ, are presented in Figure 5. It is clear that λ_m rises continuously with strain up to a value of 58 J/gram (6200 J/mole) for a strain of 10 percent. The values of λ_m reported by the workers mentioned above are comparable to those calculated using Equation 10 for strained material.

The total heat per unit mass, Q/m, needed to raise the temperature of a spring from 25° C to 110° C can be written as

$$Q/m = \int_{25^\circ C}^{110^\circ C} C^*(T)\,dT + \lambda_m \qquad (11)$$

The upper limit of 110° C was chosen since Figure 3 indicates that the transition is essentially completed by 110° C. C*(T) represents the nearly horizontal curve of Figure 3 which does not include the peak region, B. On evaluating the first term of this expression, one obtains a value of 4250 J/mole, which is comparable to the λ_m values reported by Berman et al. Thus, it is clear that any variations in λ_m on cycling would yield significant variations in the heat needed to operate a spring. It would also be of great importance to have a standardized heat treatment procedure that would yield a rather well controlled value of λ_m. This would be especially true for those applications where a limited quantity of heat would be available to drive the transformation.

Thermal Diffusivity and Thermal Conductivity. Springs such as we have been discussing can be activated in several ways: by infrared or solar radiation; electrical heating; or thermal conduction of heat down the length of the spring. In the first two cases the heat is supplied somewhat uniformly along the length of the spring and more than enough energy is usually available to raise the sample temperature above its transformation temperature. In the last case, however, one is usually concerned with transferring heat down a spring from a heated end and one deals with a situation where only a limited amount of energy may be available. This end may be connected directly to some source of energy or may be connected to some conduction rod which brings the heat from some remote source. One may be required to deal with heat sources whose power output varies with time, i.e., the temperature vs time waveform at the heated end of the rod might be a delta function, a single square wave of a certain duration, a sinusoid, or a step function. In each case one would like to know the temperature distribution along the spring as well as the resultant mechanical response that one might expect as a function of time. It is conceivable that under certain conditions a spring might not be fully transformed along its entire length and thus its effective force constant would lie somewhere between those characteristic of the ltp and htp. In any case the standard differential equation for heat flow would have to be satisfied (32)

$$\frac{\partial T}{\partial t} = D\frac{\partial^2 T}{\partial X^2} - \frac{2H}{\rho c R}T \tag{12}$$

where we have assumed that a given spring can be represented as a finite thin rod and where the thermal diffusivity, D, is given by

$$D = \frac{k}{\rho c} \text{ in cm}^2\text{, sec} \tag{13}$$

k is the thermal conductivity in watts/cm-° K, ρ is the density in g/cm^3, c is the specific heat in J/g-° K, H is the surface conductance losses due to radiation and convection in watts/cm^2-° K, and R is the radius of the rod.

Goff (33) gives a value for the thermal conductivity at 300° K as being 0.20 watts/cm-° K, while a value of 51.1 J/° K-mole (0.49 J/g-° K) can be calculated from the data of Berman et al. (27) for the value of the specific heat at the same temperature. The density of NiTi is listed as 6.45 g/cm^3 by Buehler (16). Thus, the diffusivity, D, for NiTi is 0.063 cm^2/sec. This is a factor of over 19 smaller than the diffusivity of copper (D_{Cu} = 1.22 cm^2/sec). This low diffusivity for Nitinol thus leads to difficulties in employing it for applications that require a fast thermal response. The low thermal conductivity also requires that in a steady state situation Nitinol sustain large temperature gradients. Thus, in applications that require heat conduction to activate a spring it is possible that the total length of material in a given spring may not transform unless a very high temperature pulse is applied to the heated end. It is clear that where such an application is of importance, a martensite material with better thermal characteristics than Nitinol is desirable. Nevertheless, the thought occurred to us that the characteristics of Nitinol might be improved by plating with copper to give a composite with more desirable thermal properties.

A detailed experimental study was undertaken by Rothwarf, Auerbach and Ford (34) to determine the thermal and mechanical characteristics of copper-plated Nitinol rods. In that work certain effective thermal parameters were defined for Nitinol-copper composite rods for use in the analysis of the heat flow problem. It was assumed that the composite rod could be represented by an equivalent rod with certain effective properties: a density, ρ^*; a specific heat, c^*; a thermal conductivity, k^*, and a diffusivity, D^*, that could be derived from the separate thermal properties of the Nitinol and the copper. It was further assumed that the temperature was constant through a given cross section, i.e., that the temperature varied only along the length of the rod so that the one-dimensional heat flow equation, Equation 12 was applicable. An experimental study of the steady-state temperature distribution along a composite rod gave support to the assumptions. Therefore, this formulation was used by Friedman (35) to obtain the pertinent parameters needed in evaluating the time-dependent solutions to the heat flow equation for copper-plated Nitinol rods when certain time-varying sources of heat were applied to one end.

Elastic Properties. Even though copper plating increased the effective diffusivity and thus decreased the thermal response time of a given Nitinol rod, the effect of such a procedure on the elastic properties was not readily apparent. Extensive measurements of the force versus displacement curves were taken for a rod after each new layer of copper had been deposited (34). It was found that copper plating tends to eliminate the large differences in the elastic constants that exist between the high and low temperature phases of Nitinol. A theory was developed (34) which closely describes the elastic behavior of composite copper-Nitinol rods in terms of the Young's moduli of the copper and the Nitinol. The above studies showed that while diffusivity is increased by copper plating, the deflection or force changes,which accompany the transformation of the copper-Nitinol composite decrease. Nevertheless, for certain stringent design constraints one might wish to sacrifice some of the memory properties for the more rapid thermal response which can be had with copper plating.

NITINOL SPRINGS AS COMPONENTS IN SMALL CALIBER FUZES

This study was initiated to evaluate the possibility of using "memory" metals as thermally activated springs in small caliber fuzes. It soon became quite clear that either there was insufficient data available in the literature to evaluate most of the "memory" materials for this application or that they did not possess sufficient ductility to permit their fabrication into spring stock. The only material found that satisfied both of these criteria was Nitinol. However, its low thermal diffusivity makes its usefulness for this application uncertain.

To thermally activate a Nitinol spring fully, approximately 6800 J/mole (64 J/gm) are needed. If one considers the helical spring described above as being typical of the size needed in a fuzing application (it is 5 centimeters in length, which corresponds to a mass of 0.016 grams), one would require an energy of approximately 1.0 J to activate the spring. In the case of a small caliber fuze, two methods of obtaining this energy were considered. The first was from the aerodynamic heating of the projectile itself while it was in flight. The other was the use of a resonance effect which might pump enough energy into the projectile interior during the portion of the flight when ultrasonic velocities were attained. In each case, the heat for activation of the spring was to be supplied via conduction down the length of the spring. In a companion report (35) Friedman has solved the heat flow equation, Equation 12, by assuming certain pertinent boundary conditions derived from a knowledge of typical projectile aerodynamic characteristics. He concludes that the usefulness of Nitinol is just marginal for this application. Under certain geometric conditions and with a certain copper plating it might just be possible to attain the desired force to initiate a certain train of mechanical events within some specified time.

CONCLUSIONS

The use of martensite memory materials in the design of thermally activated springs is an intriguing concept. This is a concept that can definitely be implemented for a number of practical applications by using the Nitinol alloy. However, this particular alloy has poor thermal properties that preclude its use in devices that must respond rapidly to thermal inputs. For its use in a disarming device Friedman recommends that an attempt be made to construct such a device, but indicates that its usefulness is just marginal. It is clear that much more basic research is needed on the metallurgical, mechanical, and thermal properties of other martensite systems. This can be a long, tedious process with no assurance of ultimate success in achieving better thermal properties since most alloys have poor thermal properties. Thus, a value judgement must be made by management as to whether the intriguing applications of these materials justify the extensive research program necessary to develop suitable materials.

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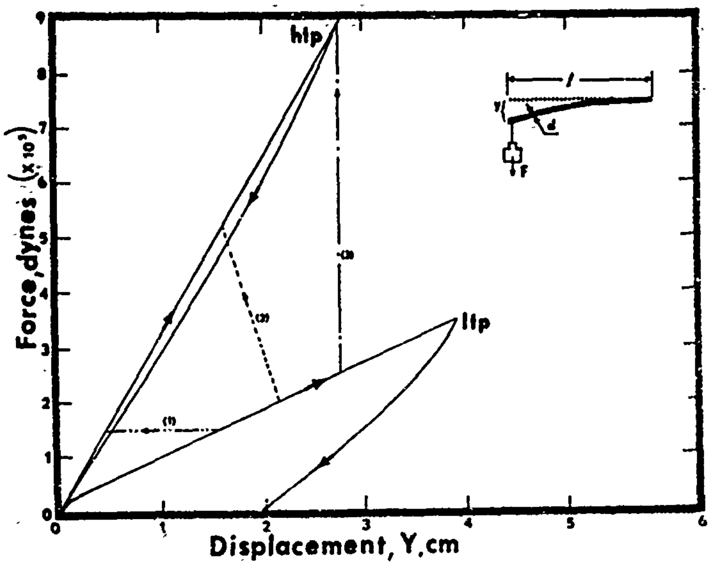
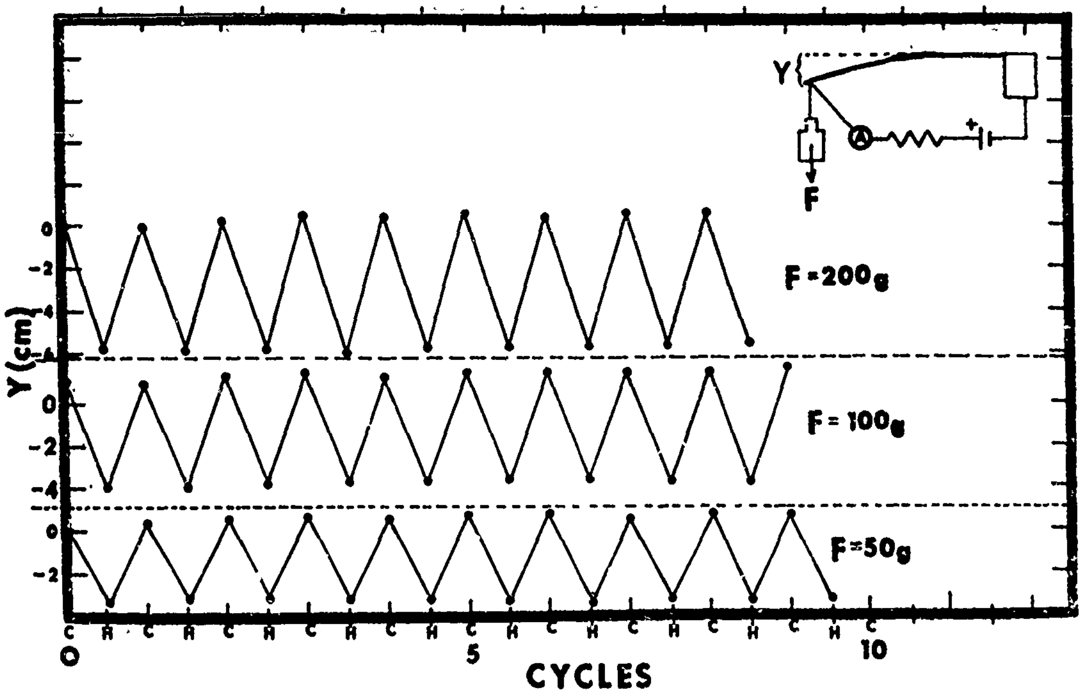


Three different modes of spring operation are indicated - (1), (2), and (3).

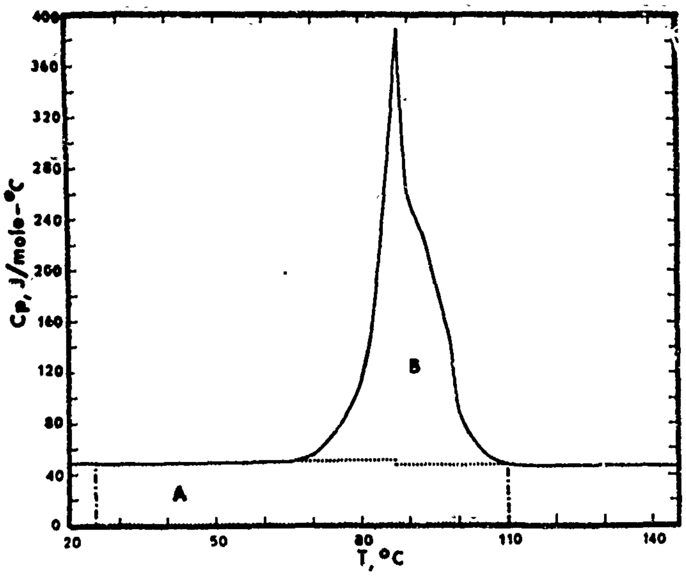
(1) A given load can undergo a cyclic displacement on heating and cooling;
(3) A large increase in force is possible if the rod is constrained to a nearly constant displacement on heating to the htp;
(2) An intermediate case between (1) and (3).

Figure 1. Force vs Displacement Curves for a Nitinol Rod (0.254 cm diameter, 11.2 cm long from point of support to point at which the weight is suspended) in its High Temperature Phase (htp) at 150° C, and Partially Transformed to its Low Temperature Phase (ltp) at 23° C



Different sets of measurements for various masses suspended from the end of the rod indicate that the greater the load, the greater the work one can obtain from the process.

Figure 2. Displacements for a Number of Heating and Cooling Cycles for a NiTi Rod



The area labelled B represents the heat of transformation, λ_m.

Figure 3. Specific Heat of NiTi vs Temperature

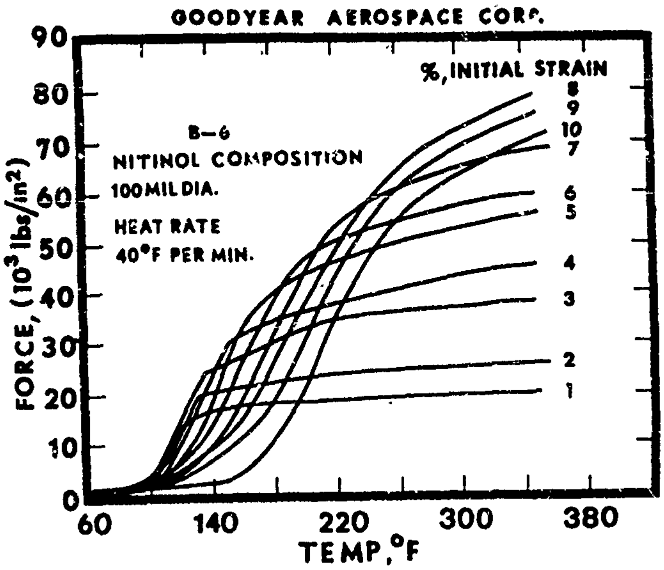


Figure 4. Force required to Maintain a Fixed Strain, ε, in a 100-mil diameter Nitinol Rod vs Temperature

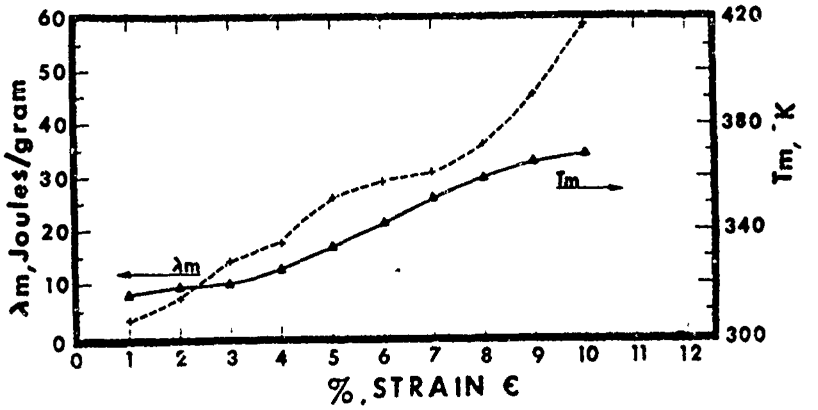


Figure 5. The Heat of Transformation, λ_m, predicted from the Clausius-Clapeyron Equation, vs Strain, ϵ; the Midpoint Temperature, T_m, of the Martensite Transformation, on Heating at Constant Strain, vs Strain