Dec. 10, 1968 R. E. BARKER, JR 3,415,712

BIMATERIAL THERMOSENSITIVE ELEMENT

Filed Oct. 31, 1963 2 Sheets-Sheet 1

Fig. 1a.

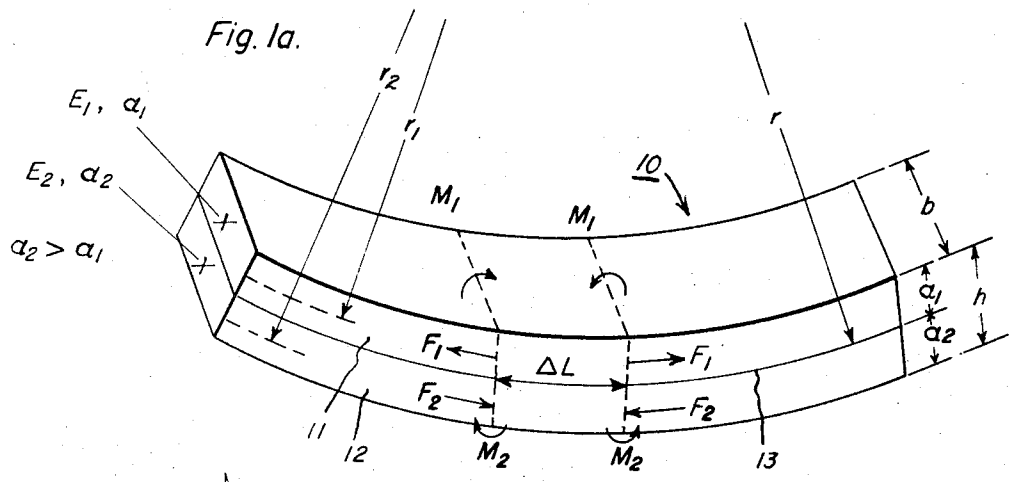


Fig. 1c.

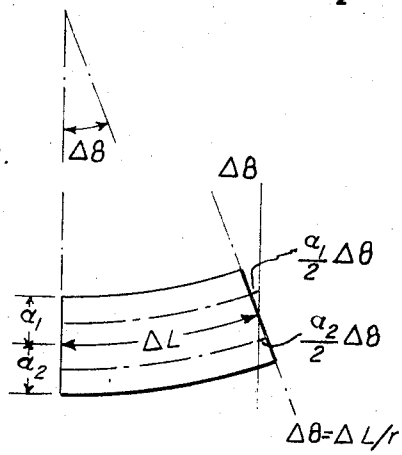


Fig. 1b.

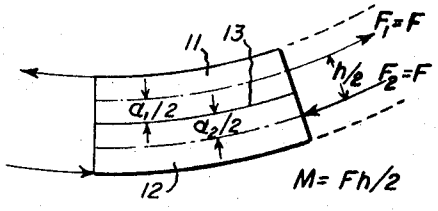


Fig. 4.

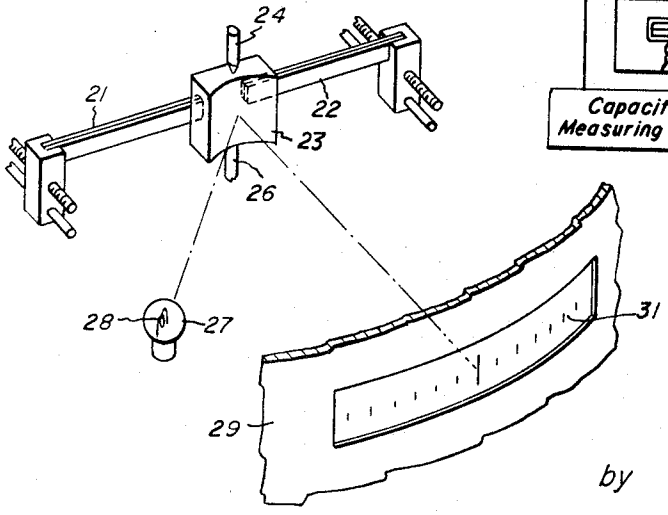
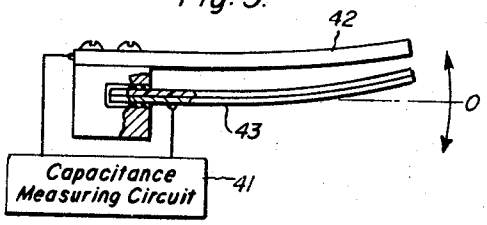


Fig. 5.



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BIMATERIAL THERMOSENSITIVE ELEMENT

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Fig. 2.

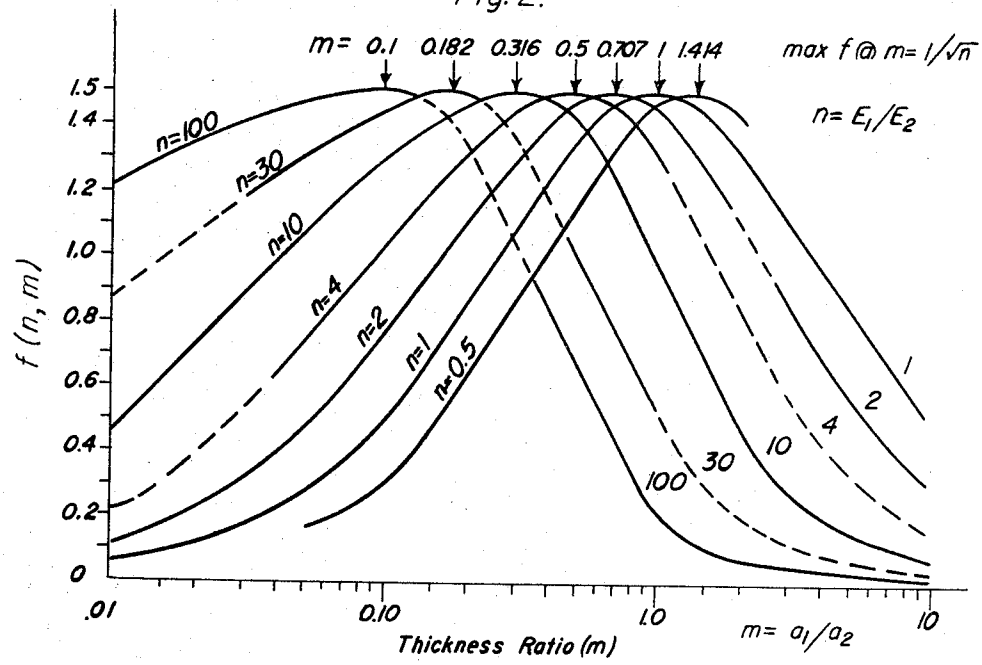
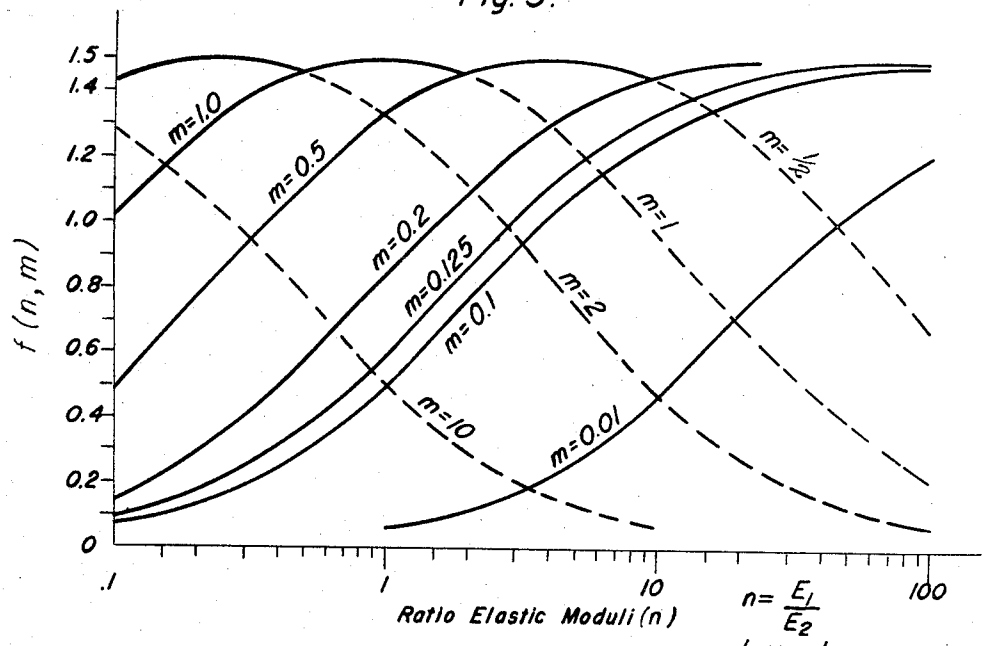


Fig. 3.



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BIMATERIAL THERMOSENSITIVE ELEMENT

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6 Claims. (Cl. 161—183)

This invention relates to improvements in the construction of bimaterial temperature-sensitive strips useful in thermomicroswitches, temperature-sensitive capacitors and temperature indicating devices in general and in the construction of the microminiaturized versions of such devices in particular.

Both bimetallic and bimaterial temperature-sensitive constructions are known in the prior art, but the sensitivity of these earlier constructions is, in each instance, substantially less than the response that theoretically can be made available from the coupled materials of differing linear thermal expansivities.

Investigation has shown that many variables are involved in the functional relation between the components of a bimaterial or bimetallic strip in effecting thermal deflection and whereas the parameter that is most often emphasized is the difference in the linear thermal expansivities of the two materials chosen ($\Delta\alpha=\alpha_2-\alpha_1$), a thorough analysis has shown that the ratio of elastic moduli ($n=E_1/E_2$), the ratio of material thicknesses ($m=a_1/a_2$) and the total strip thickness ($h=a_1+a_2$) must be considered limiting factors of substantial importance. It has further been established that $\Delta\alpha$ and n cannot be freely chosen independently of each other and to provide an optimum bimaterial construction both of these parameters should be considered in selecting the proper pair of materials. To some extent, the effect of difference in the elastic moduli of the materials may even be compensated for by proper adjustment of the value of m.

In the past the design of bimetallic and bimaterial strips have been limited for the most part to consideration of the coefficients of expansion of the two materials whose interaction is being relied upon to effect deflection in response to changing temperatures. Apparently in the development of bimaterial strips not only has there been a lack of appreciation of the sizeable effect of the aforementioned parameters, n, m and h, on the system, but also, in each instance an additional component is introduced to the erstwhile two-component system in the form of a bonding agent or an external bonding mechanism. When the two-component system is complicated by the introduction of some external bonding mechanism, as for example, rivets, cement, glue, etc., several objectionable aspects are introduced; namely, the fabrication of the temperature-sensitive strip is more complicated, the deflection per degree temperature change for the completed strip is reduced, changes which occur in the properties of the adhesive layer with time may necessitate periodic recalibration and the presence of either rivets or an extra lamina in the form of a layer of adhesive greatly complicates the design considerations, extending far beyond the complexity of a two-component structure.

Thus, an object of the present invention is the provision of a true bimaterial strip construction for use as a temperature sensing element wherein the construction consists solely of a two-layer system.

Another object of the present invention is to provide a method for constructing a bimaterial strip properly integrating the two-components to enable the composite strip to function as an accurate sensor of temperature without the introduction of an additional component or layer to the system to effect the integration.

A further object of this invention is the provision of an economical temperature-sensing construction more sensitive than those heretofore available in the art.

These and other objects may be obtained in the present invention wherein a properly chosen pair of different materials, at least one of which is a thermoplastic, upon being subjected to the proper surface treatment and then being heated in contact with each other, will join during cooling thereof to form an integral bimaterial temperature-sensing element for use in temperature indicating devices and in temperature-sensitive electrical components.

The exact nature of this invention will be readily apparent from consideration of the following specification related to the annexed drawings in which:

FIGS. 1*a*, 1*b* and 1*c* are schematic illustrations of a bimaterial strip constructed according to this invention having notations thereon for reference in the analysis of the effect of the various parameters determinative of the curvature of such a strip under the effect of temperature changes;

FIG. 2 is an array of a series of graphs plotted of the values of $f(n, m)$ as a function of m for various positive real values of n;

FIG. 3 is an array of a series of graphs plotted of the values of $f(n, m)$ as a function of n for various positive real values of m;

FIG. 4 is a schematic representation of such a bimaterial strip mounted to provide, after proper calibration, an accurate temperature indicating device; and

FIG. 5 shows the application of a bimaterial strip constructed according to this invention as a thermosensitive electrical device.

In order to illustrate the effect of the ratio of the elastic moduli and the ratio of component material thickness on the thermal deformation of bimaterial strips, reference is made to FIG. 1 and the notations thereon.

These notations represent the following properties and dimensions of the bimaterial strip **10** composed of laminae **11** and **12**, which are different materials:

(1) all symbols having the subscript 1 refer to the upper layer of material, lamina **11**;
(2) all symbols having the subscript 2 refer to the lower layer of material, lamina **12**;
(3) the symbols employed have the following connotation: r (radius), ΔL (segment of length, F (force), M (bending moment), α (linear thermal expansivity), a (thickness), b (width), h (height), T (temperature, and I (moment of inertia).

At some reference temperature T_0 the strip **10** would be straight (r=infinity). If α_2 is greater than α_1, the curvature displayed in FIG. 1 corresponds to a positive temperature change $\Delta T=T$ (ambient temperature) $-T_0$. Considering element ΔL of bimaterial strip **10** and the stress acting thereon it may be seen that the uniform bending moments, M_1 and M_2, acting thereon are equal and opposite as are the forces F_1 and F_2, which act on the lengths ΔL of the respective laminae **11**, **12** of the element **10**. Along the interface **13** it is assumed that both components **11** and **12** always maintain a common length and are not displaced relative to each other. Upon exposure to an increase in temperature ΔT, the length of the upper component **11** expands by the quantity

$$\alpha_1\Delta T\cdot\Delta L$$

In addition, the upper component **11** is also stretched an extra amount $(F_1/E_1a_1b)\Delta L$ along its central axis due to the expansion of the lower component **12**, which is attempting to expand by the amount

$$\alpha_2\Delta T\cdot\Delta L$$

Actually the upper component **11** restrains the lower component **12** whereby component **12** experiences a compression $(F_2/E_2a_2b)\Delta L$. This is represented in FIG. 1(*c*) as a shortening by the distance $\alpha_2\Delta L/2r$ or expressed an-

other way, $\alpha_2\Delta\theta/2$, where r is the radius of curvature of the neutral axis and $\Delta\theta=\Delta L/r$.

The purpose of this derivation is to establish the contributions to the above-noted changes in interfacial lengths due to the effects of thermal expansion, tension or compression, overall strip thickness and curvature. Thus:

$$\frac{\Delta L_{\text{interface}}}{\Delta L_{\text{original}}}=\alpha_1\Delta T+\frac{F_1}{E_1a_1b}+\frac{a_1}{2r_1}=\alpha_2\Delta T-\frac{F_2}{E_2a_2b}-\frac{a_2}{2r_2} \quad (1)$$

In the absence of external forces, one can see from the symmetry of the problem that

$$F_1=F_2=F \quad (2)$$

and

$$M_1+M_2=\text{total couple}=F(a_1+a_2)/2 \quad (3)$$

From the elementary beam theory, the bending moment M is related to the "flexural modulus" EI and the curvature l/r by the relation

$$M=EI/r \quad (4)$$

where E is the tensile modulus and, for a beam of rectangular cross-section *ab*, the second moment of area is given by

$$I=a^3b/12 \quad (5)$$

Combining Equations 3 and 4:

$$\frac{E_1I_1}{r_1}+\frac{E_2I_2}{r_2}=\frac{F}{2}(a_1+a_2)=\frac{F}{2}h \quad (6)$$

In Eq. 1 and in Eq. 6, $r_1\approx r_2\approx r$ (provided $r\gg h$) so that

$$\frac{2}{r}\left[\frac{E_1I_1+E_2I_2}{bh}\right]\left[\frac{2}{E_1a_1}+\frac{1}{E_2a_2}\right]+\frac{h}{2r}\approx(\alpha_1-\alpha_2)\Delta T \quad (7)$$

$$\frac{1}{r}\approx\frac{(\alpha_2-\alpha_1)\Delta T}{\frac{h}{2}+\frac{2}{bh}[E_1I_1+E_2I_2]\left[\frac{1}{E_1a_1}+\frac{1}{E_2a_2}\right]} \quad (8)$$

For rectangular cross-sections:

$$\frac{1}{r}\approx\frac{(\alpha_2-\alpha_1)\Delta T}{\frac{h}{2}+\frac{1}{6h}[E_1a_1^3+E_2a_2^3]\left[\frac{1}{E_1a_1}+\frac{1}{E_2a_2}\right]} \quad (9)$$

Following the introduction of dimensionless variables $n=E_1/E_2$, $m=a_1/a_2$ and the use of the relations $a_1=mh/(m+1)$ and $a_2=h/(m+1)$, Eq. 9 may be expressed:

$$\frac{1}{r}=\frac{(\alpha_2-\alpha_1)\Delta T}{h}\left\{\frac{6(m+1)^2}{3(m+1)^2+(m^2+1/mn)(mn+1)}\right\} \quad (10)$$

The term in brackets will be denoted by $f(n, m)$. Equation 10, and therefore $f(n, m)$ applies to virtually all situations involving one dimensional bending of bimaterial structures by thermal forces. As an approximation, it applies to some two dimensional problems. The direct dependence of curvature (k) on $\alpha_2-\alpha_1$ and on ΔT are results which are normally expected. Likewise, an inverse dependence on h is fairly plausible. Due to the more complicated form of $f(n, m)$ it is necessary to consider its functional properties in some detail in order to see how l/r depends on elasticity and thickness ratios.

From this rather complex analysis one sees that many variables are involved in the functional relation determinative of thermal deflection in a bimaterial strip and that although the quantity that has been predominantly considered in the past in such design is $\Delta\alpha=\alpha_2-\alpha_1$ (i.e., the difference in linear thermal expansivities of the two materials), it may be appreciated from the above analysis that the ratio of elastic moduli $n=E_1/E_2$, the ratio of the thickness of the bimaterial laminae **11** and **12** and the overall thickness of strip **10** are also limiting factors of considerable importance.

Further analysis has established that the maximum value of $f(n, m)$ is 1.5 and a series of curves may be plotted of the values of $f(n, m)$ as a function of m for various positive real values of n (FIG. 2) and, as well, a series of curves may be plotted of the values of $f(n, m)$ as a function of n for various positive real values of m (FIG. 3). These curves provide useful tools for designing bimaterial strips having maximum unrestrained curvature.

For example, if h and m are predetermined factors so that the thickness of the laminae, but not the specific materials are fixed, then a tentative choice of materials available in the requisite thicknesses to satisfy the demands for h and m may be made such as to provide a large value for $\Delta\alpha$. This will then determine n and if the location of the intersection of the value for m with the curve for the chosen value of n is close to a value of 1.5 (the maximum) for $f(n, m)$ which is the case when $n=m^{1/2}$, then a good selection of materials has been made. If not, another selection of materials must be made. Ordinarily the choice of materials yielding a large value for $\Delta\alpha$ will also provide a large value for n.

If, on the other hand, neither h nor n is fixed, but the pair of available materials are set, then FIG. 3 would be used with the known value of n (from the values for the elastic moduli for these materials) to choose a value of m such as to yield a value of $f(n, m)$ as close to the maximum value of 1.5 as possible. This maximum occurs when $m=n^{-1/2}$. Having thereby chosen the ratio of thicknesses of the laminae (a_1/a_2), inspection of Equation 10 dictates that h, which is the sum of a_1 and a_2 be as small as feasible in view of the application.

When there are no limiting criteria, that is, no predetermined values for n, m or h, the design may easily be effected by trial and error by tentatively choosing a pair of materials providing a large $\Delta\alpha$. Next the graphs of FIG. 3 would be employed to seek the best available value for m. If the best value of m available from this initial choice of materials does not suit, it may be necessary to repeat the process with a new choice of materials.

However reliable the derivation of mathematical relationships of design factors may be in the provision of means for selecting optimum pairs of materials for producing desired constructions of the bimaterial strips, the reliability of such design selections can only be retained by unifying the two selected materials without the introduction into the system of a bonding layer such as a glue, cement or other adhesive, or the introduction of mechanical fastening means, such as rivets, because by the inclusion of additional components beyond the two-component system considered in the design the sensitivity (curvature per degree of temperature change) of the thermosensitive element is reduced substantially below the sensitivity available by the use of these same materials bonded in the manner described herein.

Thus, in order to avoid this pronounced disadvantage of the prior art constructions it was decided to completely eliminate the use of a separate bonding agent by using a suitable thermoplastic material as at least one of the laminae and bonding this thermoplastic lamina directly and permanently to the second component of the system by heating the thermoplastic to the extent necessary to melt the surface thereof at the interface and then allowing the components to cool together.

One mode for the preparation of a plastic-metal thermo-sensitive element is as follows: a sheet of bisphenol A polycarbonate resin (described in U.S. Patent No. 2,946,766 in the names of Schnell et al. issued July 26, 1963) is placed upon a sheet of clean aluminum foil, the two laminae are urged into close contact with each other, by a biasing force, the biasing force is removed, the pair of laminae are heated to a temperature above the softening transition temperature (about 170° for the polycarbonate film) to melt the plastic and then the com-

bination of materials is allowed to cool. Once cooled, a satisfactory plastic-to-metal bond results.

In one particular construction an aluminum sheet 1 mil in thickness was employed in combination with bis-phenol A polycarbonate film 8 mils in thickness. After heating and then cooling as described above, the integrated laminate was easily cut to produce strips of the desired size.

In the case of various other plastic-metal combinations that may be effected, the surface of the metal lamina may first be roughened before cleaning the metallic surface thoroughly to insure adequate bonding with the melted plastic.

Strips embodying one or more plastic laminae will not withstand exposure to temperature above the glass transition of the particular plastic or plastic laminae employed (about 140° C. for bis-phenol A polycarbonate) and will not exert as much force as a bi-metallic strip of equal size, but such bimaterial strips are adequate for the uses disclosed herein, can be made at a fraction of the cost of bimetallic strips and can be provided in a wider range of sizes.

Among the metals suitably employed in combination with a plastic lamina in the construction of a thermosensitive laminate are the following, for example:

TABLE I

[Values are given for 27° C.]

Metal	A	B	C	D	E	F	G
E_1[BN/m.^{2}]*	410	340	210	135	100	69	200
α_1[p.p.m./° C.]	5.0	4.5	1.6	5.6	8.0	23	16

*Units: 1[Billion Newtons/m.^{2}]=10^{10} [dyne/cm.^{2}]=1.6×10^5 p.s.i.

Key:
A—Tungsten.
B—Molybdenum.
C—Invar (63.8% iron, 36% nickel, 0.2% carbon).
D—Fernico (53.0% iron, 29% nickel, 17% cobalt).
E—Titanium.
F—Aluminum (Al is included as a reference and also because of its convenient form as aluminum foil).
G—Steel.

Some polymers appropriate for use in bimaterial strips are, for example:

TABLE II

[Values are given for 27° C.]

Polymer	PA [1]	PXO [2]	VC [3]	PE [4]	PTFC [5]	PC [6]	PS [7]
E_2[BN/m.^{2}]	1.9	2.4	0.36	1.0	1.5	2.3	3.2
α_2[p.p.m./° C.]	150	~60	200	240	70	65	73

[1] Polyamide (nylon).
[2] Polyxylylene oxide.
[3] Polyvinylidene chloride.
[4] High density polyethylene.
[5] Polytrifluorochloroethylene (Kel-F).
[6] Bis-phenol A polycarbonate (Lexan resin manufactured by General Electric Company).
[7] Polystyrene.

The notation of fourteen exemplary metals and plastics, leading to a total of 49 metal/plastic combinations (and 42 plastic/plastic combinations) is not intended to be an exhaustive list. Additional plastic materials for which values for E and α have not been included herein are; for example, polyethylene terephthalate (Mylar), polyphenylene oxide polymers in general (of which polyzylylene oxide has been noted above) as described in U.S. patent application Ser. No. 212,128, Patent 3,306,875 filed in the name of Allan S. Hay on July 24, 1962 and assigned to the assignee of this invention, polymethylmethacrylate, copolymers of vinyl chloride and vinyl acetate (Vinylite resins) and ethyl cellulose. If desired, the metal lamina may be replaced by a thermosetting plastic possessing sufficient strength and flexibility in thin layers.

The parametric values for a series of suitable plastic-metal bimaterial combinations are catalogued below with the subscript 1 referring to the metal lamina and the subscript 2 referring to the plastic lamina:

TABLE III

	$\Delta\alpha=\alpha_2-\alpha_1$ [p.p.m./° C.]	$n=E_1/E_2$	$q=\alpha_1/\alpha_2$	$m=a_1/a_2$*	$kh/\Delta T$† [° C^{-1}]
Al/Bisphenol A polycarbonate resin	42	30	0.354	0.18	63×10^{-6}
Mo/Polyethylene (high density)	236	340	0.019	0.054	354×10^{-6}
Steel/Polyvinylidene chloride	184	555	0.080	0.042	276×10^{-6}
Invar/Polyethylene (high density)	238	210	0.0067	0.069	357×10^{-6}

*The value given for the thickness ratio m is the one corresponding to the maximum value of $f(n,m)$ as discussed above, wherein $m=n^{-1/2}$. In the four cases shown, the metal strips are, in order, about 1/5, 1/18, 1/24, and 1/14 as thick as the plastic strips.
†From Eq. (10) above, the maximum curvature (k) is $1.5\Delta\alpha\cdot\Delta T/h$, thus $kh/\Delta\alpha=1.5\Delta\alpha$, h is the total thickness a_1+a_2.

If all of the strips have the same value of m then the results for $kh/\Delta T$ will be very different from those shown in the preceding table. This is because $f(n,m)<1.5$ unless $m=n^{-1/2}$.

In FIG. 4 an application is shown of the use of the bimaterial strip of this invention in a temperature-indicating device. As shown a pair of adjustable-mounted bimaterial strips **21** and **22** are mounted as shown to either side of and at the rear of pivotally-mounted mirror **23** with the distal end of each strip **21** and **22** in contact with the rear of mirror **23**. The strips **21** and **22** are identical in composition, physical proportions and calibration and are mounted so that any change in temperature from the "zero" temperature at which the strips **21** and **22** are straight will cause these strips **21**, **22** to deflect in the same rotational sense. Mirror **23** is pivotally-mounted on bearings **24**, **26** to be rotated about a vertical axis in response to deflection by one or the other of strips **21** or **22** upon a change in temperature. Bulb **27** with heated filament **28** directs rays of light to mirror **23**. Because of its concave configuration mirror **23** focuses an image of the filament **28** as a line of light upon translucent screen **29** at a location depending upon its position about its axis is of rotation, which position depends in turn upon the ambient temperature. A proper temperature index scale **31** is imprinted upon the surface of screen **29** such that the image of filament **28** is superimposed on scale **31**. Screen **29** or scale **31** is properly located relative to the "zero" position of mirror **23** and strips **21** and **22** and, after calibration, this device provides an accurate indication of ambient temperature. Since only one of strips **21** and **22** are actually causing rotation of mirror **23** at any instant, a single bimaterial strip properly linked to mirror **23** will suffice, if desired.

The device in FIG. 5 is a device wherein a change in capacitance occurs in response to a change in temperature. This change in capacitance is sensed by capacitance measuring circuit **41**, which in turn can be used to control a servomotor (not shown) or other such equipment. With the arrangement shown the capacitance between electrode **42** and bimaterial strip **43** will increase with an increase in temperature. If desired, two bimaterial strips similar to strip **43** could be employed with the plastic layers

facing each other and the second bimaterial strip taking the place of electrode **42**. By providing contacts to each of the metal electrode layers of these strips with a wire conductor leading from each metal electrode to capacitance measuring circuit **41** about twice as large a change in capacitance per degree change in temperature is produced as in the device illustrated in FIG. 5.

It has therefore been shown that by the practice of the invention disclosed herein the full benefits of sophisticated theoretical considerations in the design of bimaterial thermo-sensitive laminates may be secured in the final commercial embodiment, a development not recognized heretofore in the art. As a result a bimaterial strip of low cost both in material content and process of manufacture may be produced which functions to render large deflection with constant reproducibility.

Various modifications are contemplated and may obviously be resorted to by those skilled in the art without departing from the spirit and scope of this invention, as hereinafter defined by the appended claims, as only preferred embodiments thereof have been disclosed.

What I claim as new and desired to secure by Letters Patent of the United States is:

1. A bimateral thermosensitive element consisting solely of two unified strips, the first strip being a thermoplastic material selected from the class consisting of bis-phenol A polycarbonate and polyphenylene oxide and the second strip being a metal having a thickness ⅕ or less than the thickness of said thermoplastic material, said strips being integrally bonded without the use of a bonding agent to provide a common interface to obviate relative displacement during deflection of said element with changes in ambient temperature.

2. A bimaterial thermosensitive element as in claim **1**, in which the difference in linear thermal expansivities of the two strips has a magnitude of at least 5 p.p.m./C°.

3. A bimaterial thermosensitive element as in claim **1**, in which the value of the ratio of the thickness of the second strip to the thickness of the first strip is approximately equal to the reciprocal of the square root of the ratio of the elastic modules of the second strip to the elastic modulus of the first strip.

4. A thermosensitive element consisting of a layer of a thermoplastic material selected from the class consisting of bis-phenol A polycarbonate and polyphenylene oxide integrally bonded to a layer of a metal having a thickness ⅕ or less than the thickness of said thermoplastic material and the difference in linear thermal expansivities of the two layers has a magnitude of at least 5 p.p.m./C°.

5. A thermosensitive construction comprising in combination in a plurality of bimaterial elements consisting essentially of an integrated pair of strips, one of said strips being a thermoplastic material selected from the class consisting of bis-phenol A polycarbonate and polyphenylene oxide and the other being a metal having a thickness ⅕ or less than the thickness of said thermoplastic material, one strip having a major surface area thereof in integrally bonded relationship with a major surface area of said other strip, to obviate relative displacement during the deflection of said element with changes in ambient temperature.

6. A thermosensitive element consisting solely of a layer of aluminum metal united firmly with a layer of bis-phenol A polycarbonate to obviate relative displacement along the interface therebetween during deflection of said element with changes in the ambient temperature, said metal having a thickness of ⅕ or less the thickness of said polycarbonate.

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HAROLD ANSHER, *Primary Examiner.*

U.S. Cl. X.R.

156—306, 311; 161—213; 73—363.5