United States Patent

[11] 3,629,774

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[73] Assignee **Scientific Advances, Inc.**

Continuation-in-part of application Ser. No. 523,205, Jan. 26, 1966, now abandoned, Continuation-in-part of application Ser. No. 609,372, Jan. 16, 1967, now abandoned. This application Oct. 21, 1968, Ser. No. 772,464

[54] **PROGRESSIVELY COLLAPSIBLE VARIABLE RESISTANCE ELEMENT**
16 Claims, 26 Drawing Figs.

[52] **U.S. Cl.** **338/114,** 117/226, 252/502, 338/99
[51] **Int. Cl.** **H01c 13/00**
[50] **Field of Search** 338/2, 36, 47, 99, 114, 4, 42; 117/226, 227; 252/511, 502, 503, 510, 512

[56] **References Cited**

UNITED STATES PATENTS

2,042,606	6/1936	Kotowski	252/511
2,472,214	6/1949	Hurvitz	338/36 X
2,679,569	5/1954	Hall	117/226
2,734,978	2/1956	Bulgin	338/2 X
3,099,578	7/1963	Hunter	117/226

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ABSTRACT: A resistance element of elastic material has at least an interconnected portion coated with a nonfriable electrically conductive material forming an electrical path that changes its resistance as a function of the state of tension or compression of the resistance element. A conductive material is prepared from particulate electrical conductive material, an elastic binder and a solvent. Pretreatment of an elastic material of elastomer foam prior to application of conductive material produces a useful resistance element.

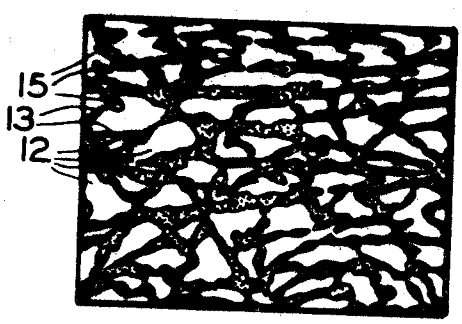


FIG. 1

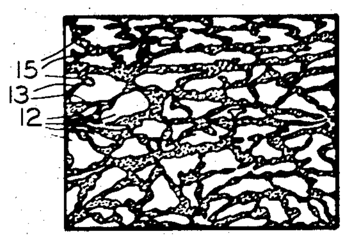


FIG. 2

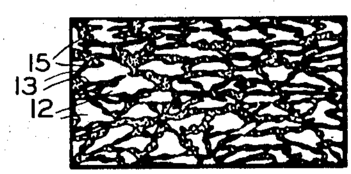


FIG. 3

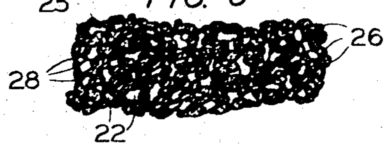


FIG. 4

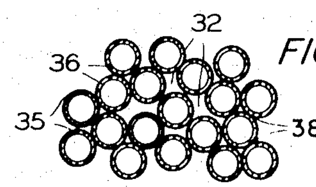
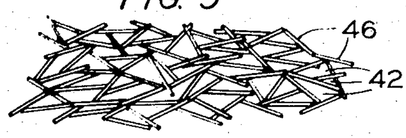


FIG. 5



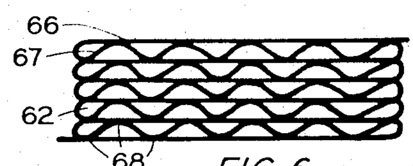
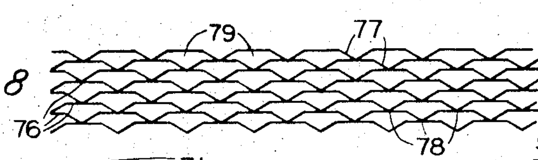


FIG. 6

FIG. 8



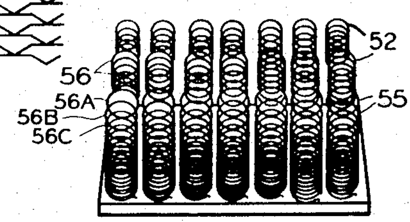


FIG. 9

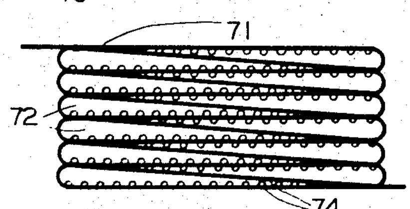


FIG. 7

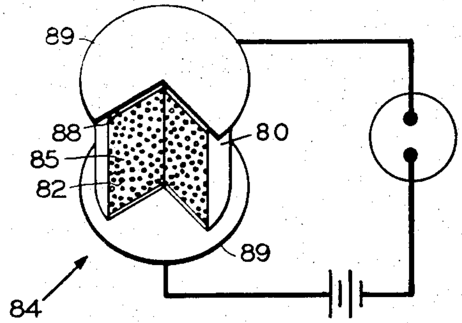


FIG. 10

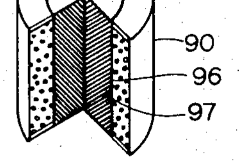


FIG. 11

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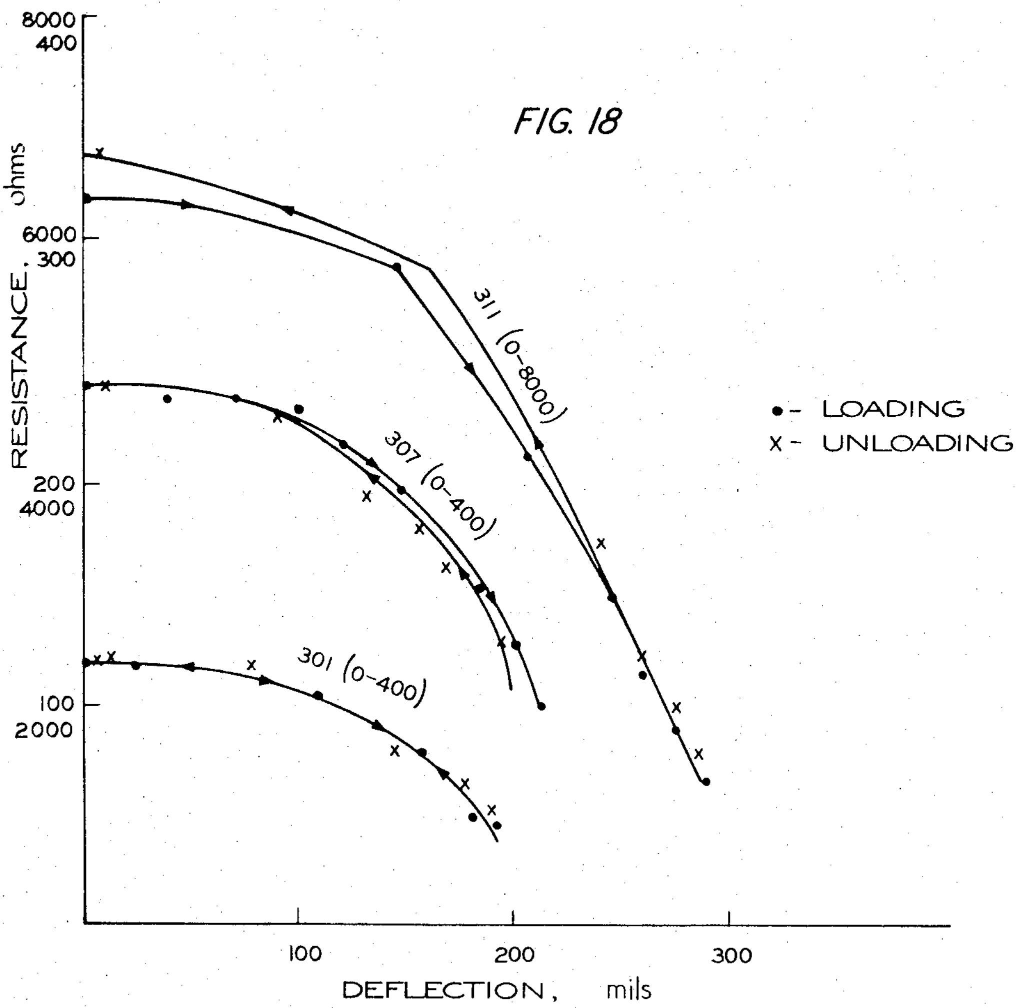

FIG. 18

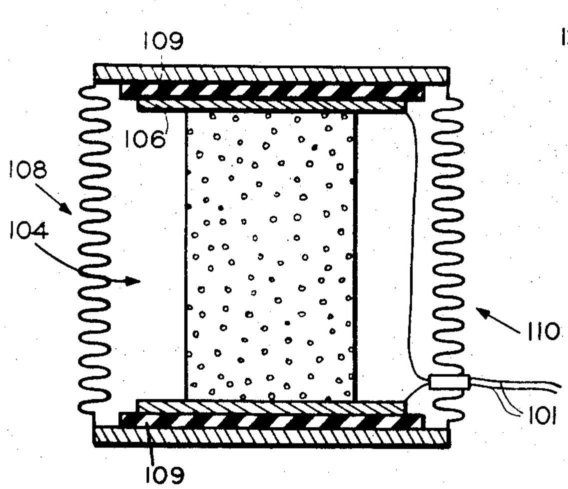

FIG. 12

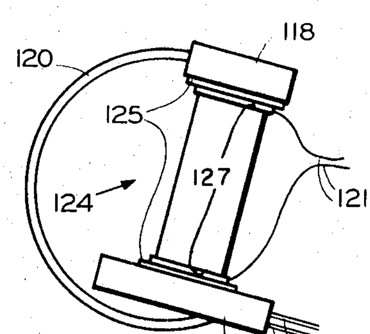

FIG. 13

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FIG. 19

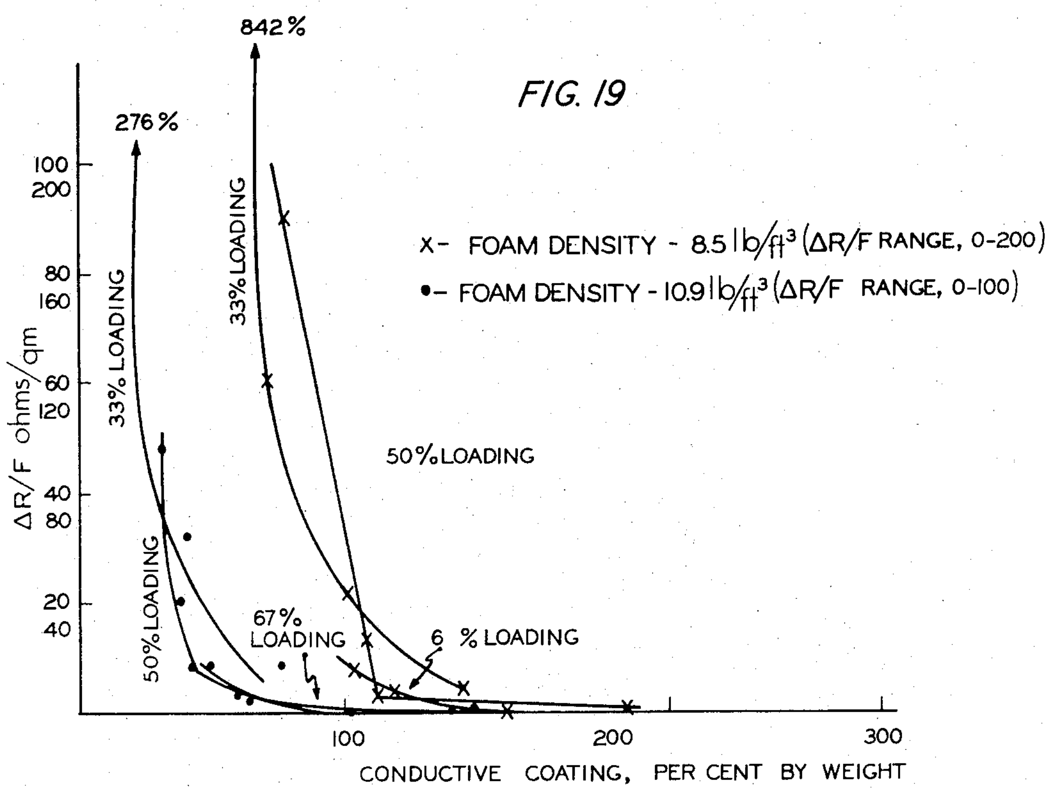


FIG. 14

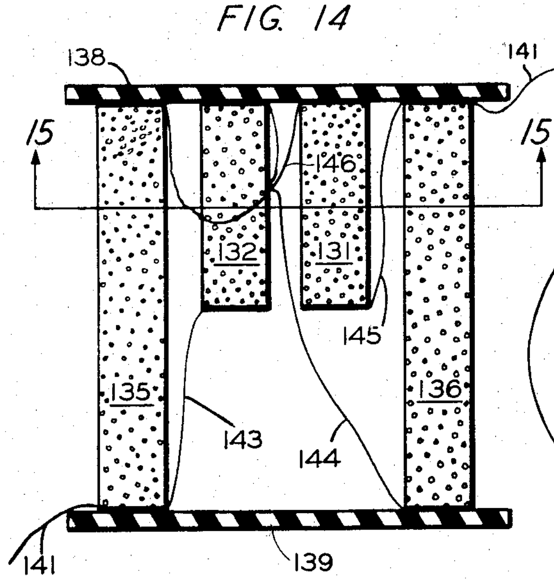
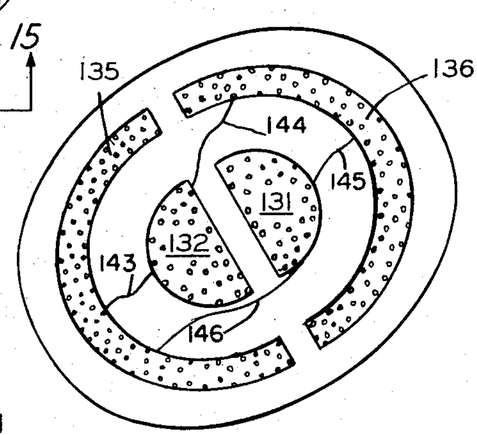


FIG. 15



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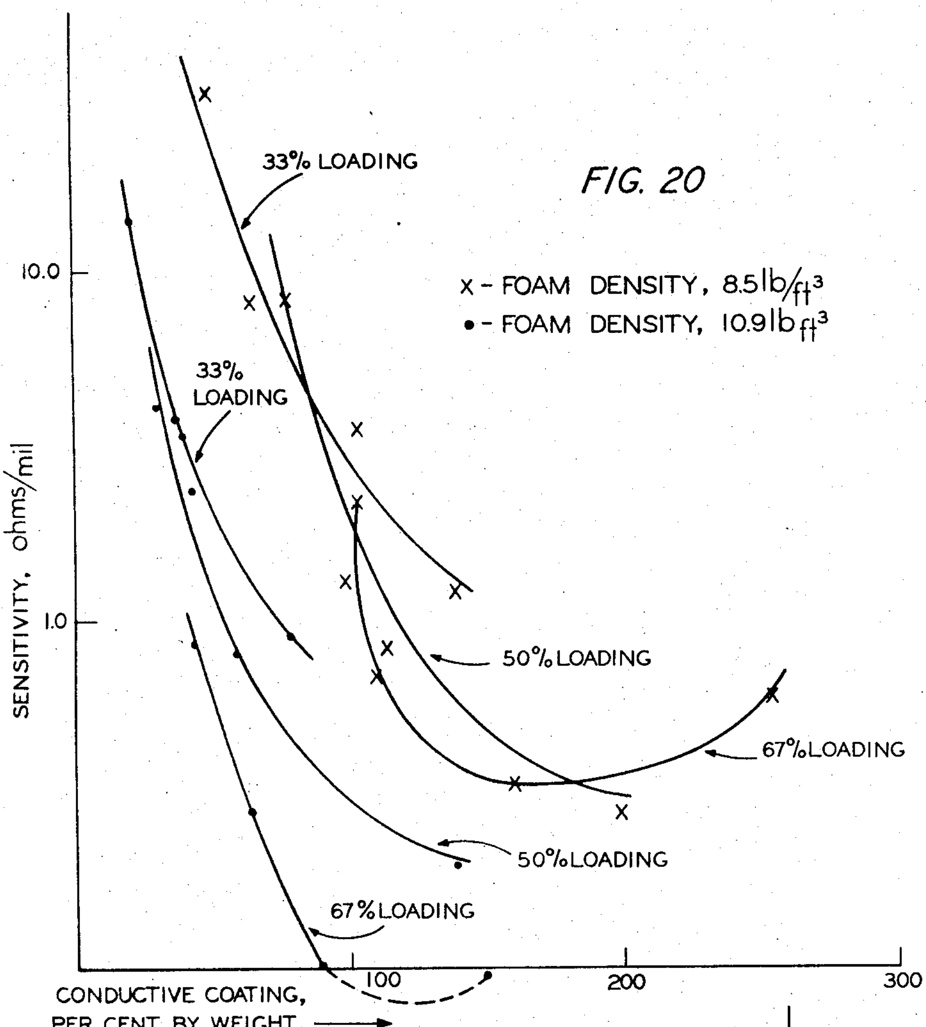

FIG. 20

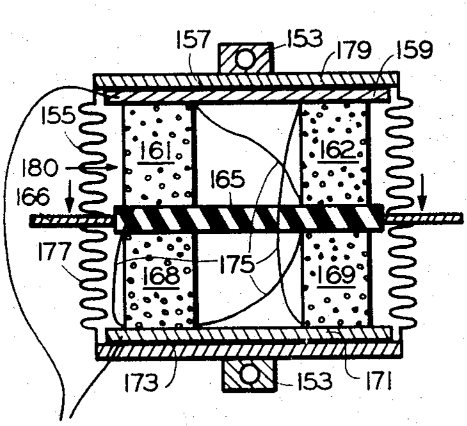

FIG. 16

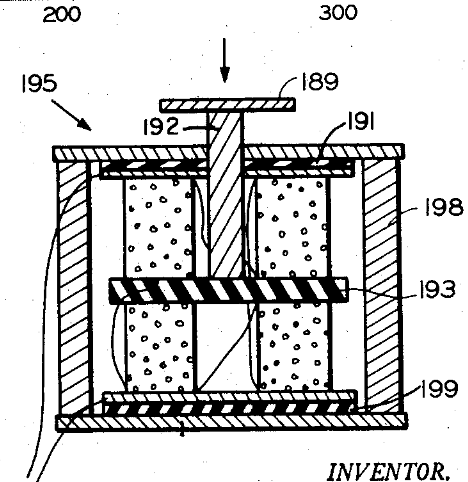

FIG. 17

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FIG. 21

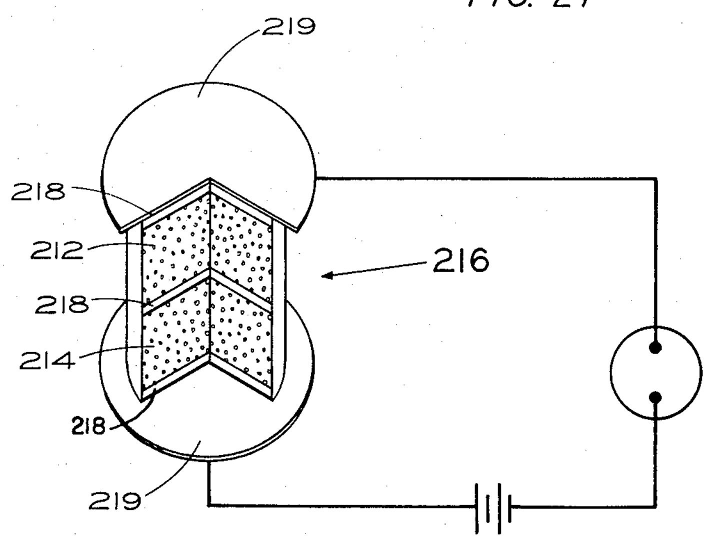
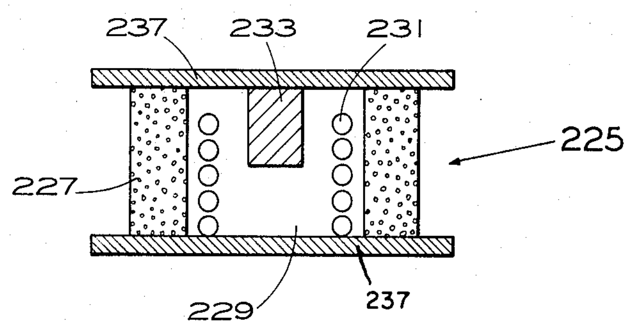


FIG. 22



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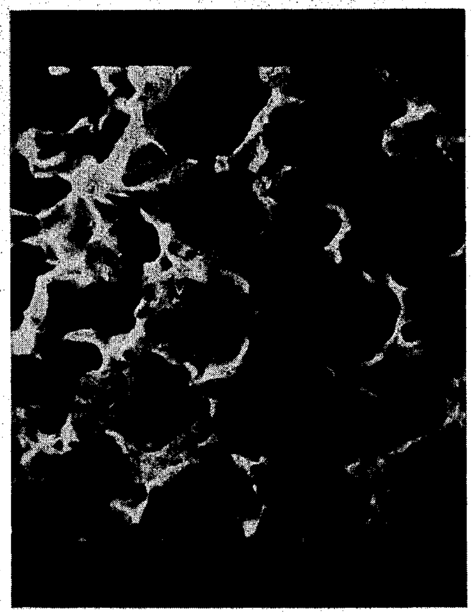

Fig. 23

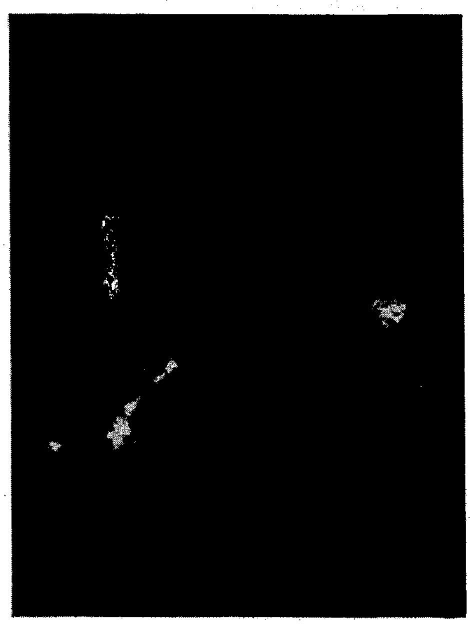

Fig. 24

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Fig. 25

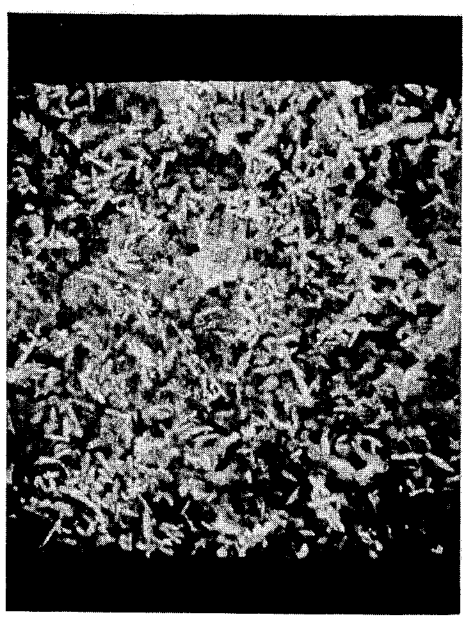

Fig. 26

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PROGRESSIVELY COLLAPSIBLE VARIABLE RESISTANCE ELEMENT

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of copending application Ser. No. 609,372 filed Jan. 16, 1967, now abandoned which was a continuation-in-part of application Ser. No. 523,205 filed Jan. 26, 1966, now abandoned.

BACKGROUND OF THE INVENTION

This invention relates to a resistance element and method of making a conductive material and, more particularly, this invention relates to an elastically collapsible resistance element having an electrical resistance varying with the state of tension or compression of the resistance element. This invention further relates to low-cost transducers constructed from the aforesaid resistance element.

There is a need for low-cost devices which when included in an electrical circuit change their electrical properties when disturbed mechanically or produce an e.m.f. as a result of a disturbance by or movement relative to a surrounding medium. These devices find especially widespread use for transducers. Known devices are available that are selected on the basis of the specific quantity to be measured and the environment surrounding the device. Unfortunately, most of the known devices capable of meeting the requirements of a given environment are expensive. For example, strain gages electrically responsive to a change of length are used in a variety of transducer configurations. In addition, certain rare earth compounds are known to be electrically responsive upon application of pressure and have found use in transducer constructions. Although accurate, the cost of each of the above devices is prohibitive where it is desired to use a low-cost device to measure primarily quantitative differences in many units such as the measurement of oil pressure in the engine block of an automobile. A low-cost device that has been used in the latter applications includes an arm which is actuated mechanically to traverse a coil connected in an electrical circuit. The movement of the arm and the resistance of the circuit change with the amount of force applied to the arm. These devices are complicated by the number of parts required and often fail as a result of material breakdown.

Two recent approaches to the problem of providing a low-cost transducer are based on the use of resistance elements of nonmetallic materials that are rendered electrically conductive. Deutschle (U.S. Pat. No. 3,011,063) shows a transducer comprising a sheet member of mechanically deformable material having an electrical resistance that varies with the state of deformation of the material. Conductive rubber is found to be a satisfactory material. Although this approach has merit, it has been found that an elastomer and an electrically conductive material cannot be combined so as to leave the elastic and electrical properties of each material unaffected by the presence of the other. Bulgin (U.S. Pat. No. 2,734,978) describes coating the surfaces of the cell walls of a nonconducting elastic cellular material with an adherent coating of a pulverulent electrically conductive material such as powdered carbon. Some difficulty arises in connection with use of the resistance elements of Bulgin as a result of flaking or spalling of the pulverulent material from the surfaces of the cells upon deformation thereof. Further, the elements have only one specific range of resistance and a definite sensitivity and thus are limited to applications wherein this sensitivity and range of resistance is satisfactory. The low-cost transducers made from the aforementioned resistance elements suffer from the additional disadvantages of low output and lack of temperature compensation.

Accordingly, it is an object of this invention to provide a simple low-cost resistance element. It is a further object of this invention to provide a method of making a conductive material.

It is a still further object of this invention to provide a resistance element including elastic and electrically conductive material in a manner so as to leave the properties of the former unaffected by the presence of the latter.

It is another object of this invention to provide a resistance element including elastic and electrically conductive portions in an integral structure that will not loose its mechanical or electrical properties after repeated deformations.

SUMMARY

The present invention provides a resistance element which typically comprises an elastic material having a progressively collapsible skeletal structure and a nonfriable elastic electrically conductive continuous coating adherent to at least an interconnected portion thereof, the coating having an average thickness of about 0.05 to 0.25 of the thickness of the skeletal structure, and the element filling less than about 25 percent of the volume within its outer boundary. The coating comprises an elastic binder and electrically conductive particles dispersed therein to form a substantially smooth outer surface at which the conductive particles are substantially, but not completely, embedded. The conductive material typically comprises about 10 to 25 percent of the volume of the coating.

A preferred form of progressively collapsible variable resistance element according to the invention comprises a three-dimensional network of interconnecting strands of elastic material integrally interconnected by nexuses at spaced points to form the skeletal outline of a multitude of polyhedrons each face of which is polygonal and common to a pair of adjacent polyhedrons, substantially all of the faces being open and free from membranous elastic material; and a nonfriable elastic coating, substantially covering the interconnecting strands and nexuses without substantially filling the open polygonal faces, which comprises an elastic binder and electrically conductive particles dispersed therein to form a substantially smooth outer surface at which the conductive particles are substantially, but not completely, embedded in the binder. The average thickness of the coating is generally less than about 0.5 of the radius of the interconnecting strands and the network typically has about 10 to 100 polygonal faces per lineal inch. There may also be at least one intermediate layer of elastic material, preferably silicone rubber, between the skeletal network and the coating. The skeletal network is preferably formed of a polyurethane resin and the conductive particles are preferably carbon.

Another useful form of the progressively collapsible variable resistance element may comprise an interwoven structure of fibrous strands, a layer of elastic material substantially covering those strands and bonding them at spaced points of intersection to form a three-dimensional interconnected network substantially free of membranous material in the areas between strands, the elastic layer imparting elasticity to the structure as a whole, and a nonfriable elastic coating substantially covering the network without substantially filling the areas between strands, which comprises an elastic binder and electrically conductive particles dispersed therein to form a substantially smooth outer surface at which the conductive particles are substantially, but not completely, embedded in the binder.

The invention also includes a method of making a nonfriable elastic coating having conductive particles dispersed therein to form, when applied, a substantially smooth outer surface at which the conductive particles are substantially, but not completely, embedded which comprises the steps of heating the conductive particles under vacuum to remove impurities, cooling the conductive particles to a predetermined temperature insufficient to cause vaporization of a selected liquid, adding to the conductive particles, to form a paste, a liquid that does not vaporize at that temperature, adding a flowable elastic material to the paste to form a conductive composition, mixing the conductive composition to disperse the conductive particles uniformly therein, and adding a catalyst to the mixed composition to promote cross-linking of the elastic material.

Additional liquid may be added to the conductive composition after mixing to reduce its viscosity to a level that enables the composition to penetrate freely into substantially all of the open cellular regions of an elastic porous mass. The liquid may be a solvent or an emulsifying agent.

Also included is a method of making a progressively collapsible variable resistance element from a substantially completely open-celled, three-dimensional network of interconnecting strands of elastic material which comprises applying to at least a portion of the outer surface of the network a flowable nonfriable conductive coating comprising an elastic binder and electrically conductive particles dispersed therein to form a substantially smooth outer surface at which the conductive particles are substantially, but not completely, embedded, spreading the coating on the network until it is evenly distributed over the outer surface thereof, centrifuging the network to remove excess coating, and drying and curing the coated network to set the elastic binder. The network may be saturated with a liquid before applying the coating.

In the drawings:

FIG. 1 is a sectional view of a relaxed resistance element according to the invention;

FIG. 2 is a sectional view of the resistance element of FIG. 1 in a compressed state;

FIG. 3 is a sectional view of another resistance element according to the invention;

FIG. 4 is a sectional view of still another resistance element according to the invention;

FIG. 5 is a sectional view of yet another resistance element according to the invention;

FIG. 6 is a sectional view of still another resistance element according to the invention;

FIG. 7 is a sectional view of another resistance element according to the invention;

FIG. 8 is a sectional view of still another resistance element according to the invention;

FIG. 9 is a perspective view of yet another resistance element according to the invention;

FIG. 10 is a perspective view partially in cross section of a transducer according to the invention;

FIG. 11 is a perspective view partially in cross section of another resistance element for the transducer of FIG. 10;

FIG. 12 is a sectional view of a load cell made from the transducer of FIG. 10.

FIG. 13 is a perspective view of a Bourdon tube made with read-out means including a transducer according to the invention;

FIG. 14 is a sectional view of a temperature compensated transducer according to the invention;

FIG. 15 is a sectional view along the line 15—15 of FIG. 14;

FIG. 16 is a cross-sectional view of a high output temperature compensated transducer according to the invention;

FIG. 17 is a cross sectional view of another high output temperature compensated transducer according to the invention;

FIG. 18 is a graph of the hysteresis behavior of a transducer made from the resistance element according to the invention;

FIG. 19 is a graph of the sensitivity or change of resistance per unit of force applied to a variety of resistance elements made according to the invention;

FIG. 20 is a graph of the sensitivity or change of resistance per change of unit length for a variety of resistance elements made according to the invention.

FIG. 21 is a perspective view of a transducer having controlled resistance characteristics according to the invention.

FIG. 22 is a cross-sectional view of another transducer having controlled resistance characteristics according to the invention.

FIG. 23 is a photomicrograph (20X) of a section of a coated, reticulated polyurethane foam resistance element according to this invention.

FIG. 24 is a photomicrograph (100X) of a cross section of one of the interconnecting strands of the resistance element shown in FIG. 23.

FIG. 25 is a photomicrograph (200X) of a portion of the cross section of a strand such as shown in FIG. 24, showing the conductive coating.

FIG. 26 is a photomicrograph (5,000X) taken to the surface of the conductive coating on an interconnecting strand such as shown in FIG. 25.

The invention includes within its scope a resistance element and method of making a conductive material wherein the resistance element includes an elastic material having a progressively collapsible structure having at least an interconnected portion thereof coated with a nonfriable electrically conductive material. In one embodiment, the conductive material forms an electrical path through the aforesaid resistance element. It has been found that the use of the aforesaid resistance elements in a low-cost transducer obviates many of the difficulties attendant upon low-cost transducers heretofore in use and provides many advantages.

According to the invention, the elastic material can be made from a variety of materials and may assume many different configurations. The electrically conductive coating material must be nonfriable but most importantly should be firmly adherent to the elastic material. An important feature of this invention is that the composition of the conductive coating material can be tailored to the environment in which it is to be used. The conductivity of the conductive coating and the degree of its influence on the elasticity of the elastic material are selected with reference to the sensitivity of the system of which it is to comprise a component member. For example, where high sensitivity is required, the conductivity is relatively low and the coating exerts little or no influence on the elastic behavior of the elastic material.

The requirement that the conductive coating material be adherent to at least a portion of the interconnected portion of a structure having the ability to collapse or extend progressively upon compression or tension can be better understood by reference to FIGS. 1 and 2. In FIG. 1, a cross section of an embodiment of a resistance element selected for purposes of illustration is in a relaxed position. The element comprises a cellular foam having the cell walls 13 of the interconnected cells 12 bonded with a conductive coating 15. The structure of FIG. 1 is elastically compressed in FIG. 2 causing cell walls 13 of the relaxed structure to collapse so that the space in each cell 12 decreases as well as the ratio of void to solid space in the cellular element. It will be obvious that this decrease of void space will occur progressively with compression of the cellular element. When conductive coating 15 is adherent to cell walls 13 according to the invention, the closer proximity of areas of conductive coating 15 upon compression decreases the length of the current path and thus the electrical resistivity. The conductive coating 15 yields with the movement of cell walls 13 as a result of being nonfriable and adherent. It is not necessary that coating 15 be as elastic as the material of the cell walls 13 because a firm bond of coating 15 to elastic cell walls 13 insures elastic movement of the entire structure. Upon relaxation of the foam of FIG. 2, interconnected cells 12 will open progressively and the electrical resistance will increase until it reaches the relaxed position of FIG. 1. Extension or stretching of the relaxed structure of FIG. 1 will cause a further increase of resistance. Thus, the resistance element is suitable for measurement of either tensile or compressive forces.

THE ELASTIC MATERIAL

While a cellular structure such as is present in an elastic foam has been shown in FIGS. 1 and 2 for purposes of explanation, numerous other materials and configurations of materials are suitable for the practice of this invention. The only requirement is that the interconnected portion of the elastic material adherent to the conductive coating collapses or extends progressively in relation to deformation or extension of the elastic material. Satisfactory elastic materials include those having the inherent characteristics of high resilience (low elastic modulus) or those having a high elastic modulus but formed into a highly resilient shape.

Referring to FIG. 3, an elastic material comprises a porous body of small irregularly shaped particles 26 held together at points or small contact surfaces 28. In a typical embodiment, each particle 26 may have an interconnected cellular network as exemplified in the photomicrograph of FIG. 23. A conductive element is prepared in one method by first bonding the contact points by preliminary coating of the particles with a bonding material and subsequent compaction to the desired level of porosity. The degree of porosity depends on the size required for the voids 22. The bonded porous mass is then impregnated with a conductive coating material 25 which bonds to the free surfaces defining void spaces 22. Alternatively, the bonding material used for preliminary coating of the particles can also serve as the conductive coating where satisfactory bonding can be achieved at the contact points with the conductive coating. Upon compression of the porous mass, conductive coating 25 is brought into tighter contact over larger areas by progressive closing of void spaces 22 to cause a change of electrical resistance.

In FIG. 4, another porous body comprises a plurality of hollow spheres 36 bonded at their contact points 38 and defining the void spaces 32, the spheres having thereon a conductive coating 35. Instead of hollow resilient spheres, the resistance element of FIG. 4 can comprise solid spheres of resilient material unitized in a porous mass such as the body of irregular particles of FIG. 3. Further, the body can comprise a plurality of spheres or irregular shapes of sponge rubber bonded at their contact points. In addition to spheres, cylindrical shapes or ellipsoids, prolate spheroids, etc., randomly disposed in a porous mass and bonded at their contact points provide a suitable material.

In FIG. 5, intermingled fibers, flakes or shells 46 form a strong elastic fibrous unit containing therein void spaces 42. To form a three-dimensional network capable of the elastic movement required for the elastic material according to the invention, the fibers or flakes 46 are interlocked along their length either by chemical combination, by means of secondary forces, or by mechanical entanglements. A mass of randomly oriented steel fibers can be interlocked by mechanical entanglement. By first coating the fibers with a solution of latex or other bonding material, such as silicone rubber, chemical combination is used to interlock the fibers. In addition to steel wire, numerous other fiber materials are satisfactory. For example, hog's hair coated with a latex solution can provide an elastic material having excellent resilience. A typical bonded junction of fibrous strands as in FIG. 5 may appear in cross section as in the photomicrograph of FIG. 24.

For a material having a high elastic modulus, a variety of configurations can provide the high resilience needed for the practice of the invention. Referring to FIG. 6, a metal comprises a plurality of overlapping portions of alternate flat layers 66 and corrugated layers 67 wherein the walls of the corrugated layers form cells 62 having a cross-sectional area increasing with distance from the point of contact 68 of corrugated layers 67 and flat layers 66. The angle defined at the intersection of flat layers 66 with corrugated layers 67 should be relatively low to insure a progressive closing or opening of cells 62 upon compression of extension.

Referring to FIG. 7, a modification of FIG. 6 is a metal foil having a plurality of overlapping portions 74 forming stacked cells 72 having a depth increasing with distance from the point of contact 71 with its adjacent cell. A portion of the metal inside of cells 72 is embossed so that ease of contact is assured upon progressive closing or opening of cells 72 upon compression or extension of the elastic body.

In one embodiment, the elastic body can merely comprise a series of stacked embossed plates bonded at the point of contact with their adjacent plates. Referring to FIG. 8, superimposed plates 76 having embossed portions 77 are arranged so that the embossed portion 77 contacts a flat portion on a lower adjacent plate at contact point 78. The space between the embossed portion and the flat portion of an upper adjacent plate forms cells 79. Because the stacked plates are not continuous in FIG. 8, only the underside of the plates is coated with conductive material. The current path changes when the points of contact progressively enlarge upon compression of the body. Another resistance element similar to that of FIG. 8 can be made by using alternate corrugated and flat plates rather than the continuous metal foil as described in FIG. 6. On the other hand, the structure of FIG. 8 can be made continuous by interconnecting the plates as shown in FIGS. 6 and 7. In the latter case, a first insulating coating which may be formed merely by oxidation of the metal is covered with a firmly adherent conductive coating.

In the elastic materials of FIGS. 1 through 8, an interconnected collapsible structure has a plurality of cellular units that collapse or extend progressively in relation to the applied force. The use of a plurality of cells, each opening or closing progressively with compression or extension, provides excellent reliability in comparison to a configuration where, say, a single larger collapsible cell is used. The effect provided in the multicellular structures can be provided in a structure of the latter type wherein each portion having the ability to open or close progressively in relation to applied force runs the full length of the resistance element.

Referring to FIG. 9, a plurality of springs 52 of varying pitch are placed in spaced relation to one another. Each coil 56 of a spring 52 is spaced from its neighboring coil by a distance that decreases from one end of the spring to the other end. For example, the space defined between coil 56A and 56B is greater than the space defined between coil 56B and 56C. By providing a varying pitch, progressive engagement of adjacent coils is insured upon compression of spring 52. The closest coils engage one another upon initial compression and the progressive engagement continues as a function of the coil spacing after the first coils become fully engaged. On release of the compression, progressive opening of the spring occurs. In spring 52 of FIG. 9, after the coils below 56C are in full engagement, the circumference of coil 56C progressively engages the circumference of coil 56B. When coils 56C and 56B are in full contact, coil 56B begins to progressively engage the circumference of coil 56A. When a conductive coating 55 is bonded to the coils of springs 52 according to the invention, the electrical path is progressively shortened upon compression of springs 52 and the electrical resistance decreases. In actual use, springs 52 are electrically interconnected by means not shown. The springs can be made from an electrical conductor such as steel or from an electrical nonconductor such as fiberglass.

Where the configurations of FIGS. 5, 6, 7, 8, and 9 are metals, an adherent conductive coating having a high resistance relative to that of the metal is used. In this way, changes of dimension of the elastic material that affect the resistance of the resistance element are readily apparent. Where the conductive coating can form a current path through the structure, a first insulating coating is applied to the metal. The conductive coating is then applied over the first insulating coating. Where the configurations of FIGS. 1 through 5 are nonconductors, electrically conductive material can be incorporated in the nonconductor. In most cases, the amount of electrically conductive material will be small so as to not adversely affect the elastic properties of the nonconductor. In either event, an adherent conductive coating must be applied to the nonconductor.

When using a body of elastomer foam for the elastic material of FIGS. 1 and 2, commercially available elastomer foams of silicone rubber known as Silastic RTV Silicone Rubber (trade name of Dow Corning Corporation) and RTV 7 Silicone Rubber (trade name of General Electric Company) are satisfactory. The foremost requirement for the nonconducting foams is that the cells should be interconnected so that an electrical path is available upon application of the conductive coating. A foam of controlled cell size is easily prepared by mixing appropriate quantities of elastomer and sugar or salt crystals or other soluble crystals of predetermined uniform size. When the rubber sets, the crystalline material is leached away to leave a foam body. Similarly, a heat decomposable material can also be used to locate the ultimate cell sites in the foam body. Manual working of the foam ruptures sufficient cell walls to provide the interconnection needed for an electrical path.

A useful body of elastomer foam comprises a skeleton foam of a first resilient material uniformly coated and impregnated with a second resilient material. The composite foam thus formed is used where a foam material is needed for its properties such as resilience or resistance to chemical attack but cannot be obtained commercially in a uniform cell size. For example, the properties of silicone rubber render it desirable for a foam material. Often, it cannot be obtained as a foam with a uniform cell size. Accordingly, it has been found that a suitable composite foam is available from a commercial polyurethane foam of uniform cell size having the pores thereof coated with three to four times its weight of silicone rubber. The composite has better resiliency and resistance to chemical attack than a polyurethane foam alone and a more uniform cell size than a silicone foam alone. To make the foregoing composite foam, polyurethane foam is impregnated with a solution of silicone-acetic anhydride-xylene mixture. The xylene is released along with the acetic anhydride and the silicone rubber vulcanizes in place around the polyurethane skeleton.

THE CONDUCTIVE COATING

As previously discussed, the conductive coating of this invention must be: (1) capable of being adherent to the elastic material or forming a firm bond therewith; (2) nonfriable; and (3) electrically conductive. In the preparation of the conductive element, the elastic material is ordinarily dipped in a solution of the conductive coating. Where demanded by the shape of the elastic material, impregnation is done by capillary action and can be aided by application of a vacuum. A satisfactory conductive coating includes an elastomer combined with a particulate electrical conductor. A variety of elastomers and electrical conductors can be used. For example, elastomers would include RTV (room temperature vulcanizable) silicone rubber, natural rubber latex, polyurethane rubber, etc. A satisfactory RTV silicone rubber is Clear Seal (trade name of General Electric Company). Electrically conductive materials include carbon, graphitized or partially graphitized carbon, silver, gold, copper, tungsten, aluminum, and various metals and alloys used alone or in combination with one another. An example of a satisfactory electrically conductive material of carbon is Conductex SC (trade name of Columbian Carbon Corporation). Conductex SC is a carbon black which has a mean particle diameter of 170 A. Extremely fine particles such as these are desirable in that they allow a more uniform conducting surface to be obtained.

Another important aspect of the conducting coating of this invention is that the outer surface of the coating is substantially smooth. There are no brittle conducting fiber ends protruding for some distance from the surface which can break off during compression or expansion of the resistance structure. Also, the conducting particles are not merely bonded onto the surface of the coating where they can abrade off during deformation. In the present invention the conducting particles which are generally very fine, are substantially, but not completely, embedded in the coating surfaces such that they will not break or abrade off. This allows resistance elements according to this invention to be used for prolonged periods of time without significant changes in resistance values or in linearity.

The amount of electrically conductive material used in the conductive coating or its "loading" and the amount of coating applied to the elastic body will be dictated by the electrical characteristics and mechanical properties desired in the final product. By electrical characteristics and mechanical properties, it is meant to refer to the sensitivity of the resistance element or the change of resistance per unit length or force, and the hysteresis behavior of the resistance element, as well as the actual resistance of the resistance element in its relaxed position. For example, where the resistance element is being used as a transducer to measure relatively high pressure, it will be desired to use a relatively high modulus element. Where pressures are low, a low modulus element having a broad range of resistance is desired to pick up slight changes in the surroundings.

The resistance of the conductive coating is readily controlled by the amount used as well as by its loading. The modulus of the elastic material can be influenced by the amount of coating used. The effect of the conductive coating on the modulus of the elastic material depends to some extent on the nature of the elastic material. The effect is more pronounced in the case of a low modulus material (e.g., elastomer foam) than it is in the case of a high modulus material (e.g., metal spring). In tailoring the properties of the resistance element to the requirements of a particular application, there will be some overlap upon adjusting the variables of loading and amount of coating. For a given loading of electrically conductive material in the coating, increased amounts of coating material increase modulus and also decrease resistance because the effective amount of electrically conductive material present in the resistance element increases. Where higher modulus is desired at a high resistance the loading of the coating should be minimized. Where low modulus is desired with low resistance, the loading of the conductive coating must be increased. The interrelationship of the variables that are adjusted in tailoring the conductive coating will become more apparent upon examination of the examples to follow.

MAKING A CONDUCTIVE COATING

One preferred method of making a conductive coating comprises forming a dispersion of particulate electrically conductive material in a liquid containing an elastic material. Conductive coating made in this manner are well suited for resistance elements according to the invention.

The preferred method of producing an elastic, nonfriable conductive coating includes the steps of:

a. heating the conductive particles under vacuum to remove impurities;

b. cooling the conductive particles to a predetermined temperature insufficient to cause vaporization of a selected liquid;

c. adding to the conductive particles, to form a paste, a liquid that does not vaporize at said temperature;

d. adding a flowable elastic material to the paste to form a conductive composition;

e. mixing the conductive composition to disperse the conductive particles uniformly therein; and

f. adding a catalyst to the mixed composition to promote cross-linking of the elastic material.

Generally, the final coating composition has a thick, pasty consistency and is therefore difficult to work into the inner cellular regions of an elastic porous mass. To facilitate penetration into these inner cellular regions it is desirable to add more liquid to the composition, preferably the same liquid as is used to form the conductive particle paste. This liquid is preferably added after the mixing step wherein the particles are uniformly distributed and serves to reduce the viscosity of the final coating, thereby enabling the coating to penetrate freely into substantially all of the open cellular regions.

Generally, the conductive particles constitute about 10 to 25 percent of the volume of the coating. When carbon particles are used, they may constitute about 20 to 50 percent of the coating by weight. It has been found that where the coating contains a very small amount of conductive particles, it will not produce the required resistance characteristics, and that where it contains too many particles, the elasticity of the coating is decreased to an extent which will undesirably affect the element as a whole. Therefore, the amount of conductive particles in the coating (also referred to as loading) must be within certain prescribed ranges to be useful.

The liquid carrier for the elastic material can be either a solvent or an emulsifying agent. In the preferred method a solvent such as naphtha, xylene or other aromatic hydrocarbon, is employed. The total amount of solvent used is dictated by the amount of coating desired for the particular application. Increased amounts of solvent cause greater dilution or lesser amounts of coating after the solvent is driven off. The solvent is driven off after the coating is applied to the elastic body by the application of moderate amounts of heat.

When using an emulsifying agent, a procedure is followed similar to that described for the solvent. In this case, however, finely divided elastic material is mixed with an emulsifying agent. The liquid containing an elastic material is then intermixed with liquid comprising a dispersion of electrically conductive material.

Instead of mixing each of the components of the conductive coating alone with a solvent prior to subsequent intermixing, it is often desirable to intermix all the components with a solvent in one batch. This procedure is enhanced when used together with ball milling or roller milling. The latter procedure insures a fine particle size of carbon and aids the uniform dispersion thereof in making a resistance element. The conductive coating should be applied to the elastic material as soon as possible after mixing and before the cross-linking of the elastic material has gone to completion. Resistance elements prepared according to the foregoing procedures appear to have improved properties in relation to those prepared from coatings prepared using separate mixing steps.

MAKING A RESISTANCE ELEMENT

Often, particularly where the configurations of FIGS. 5 through 9 are metals, the elastic structure is coated merely by dipping in the conductive coating. But where the elastic structure consists of a substantially completely open-celled, three-dimensional network of interconnecting strands, such as a reticulated elastomer foam, it is often difficult to obtain complete penetration of the coating and at the same time prevent clogging of the pores. To overcome these problems, it is preferred to apply the coating according to the method defined by the following steps:

a. applying to at least a portion of the outer surface of the network a flowable nonfriable conductive coating comprising an elastic binder and electrically conductive particles dispersed therein to form a substantially smooth outer surface at which said conductive particles are substantially, but not completely, embedded;

b. spreading the coating on the network until it is evenly distributed over the outer surface thereof;

c. centrifuging the network to remove excess coating; and

d. drying and curing the coated network to set the elastic binder.

The centrifuging step is important in that it removes any excess coating material that may be clogging the pores of the structure and also removes excess coating material of the interconnecting strands themselves such that only a thin layer of coating is left on each strand. It has been found that the coating must have an average thickness of about 0.05 to 0.25 of the thickness of the skeletal structure and that element comprising the skeletal structure with its adherent coating must fill less than about 25 percent of the volume within its (the element) outer boundary. By adjusting the duration of the centrifuging step, the thickness of the coating may be controlled within the desired limits.

When using an elastic material of elastomer foam having a large number of interconnected cells, impregnation can be difficult especially where a conductive coating of high conductivity is desired. In the latter instance, the outer cells tend to become clogged with the high viscosity coating containing a large percent of conductive material. Attempts to use greater amounts of solvent to carry the conductive coating tends to result in the formation of microcracks upon evaporation of the solvent.

It has been discovered that when the elastic material comprises an elastomer such as a foam of silicone rubber, the pretreatment thereof with a solvent such as naphtha, xylene or other aromatic hydrocarbon allows the use of coatings of high conductivity.

According to the pretreatment, a portion of the solvent used to carry the conductive coating is eliminated for use as a carrier and substituted in the pretreatment operation. The elastomer is allowed to soak in the solvent until it is saturated. In making a resistance element from an elastic material of elastomer foam, the pretreatment is observed to cause swelling of the foam. The larger pores thus formed allow easier penetration of the foam upon impregnation with conductive material immediately following the solvent pretreatment.

The solvent pretreatment is found to have advantages with regard to the electrical characteristics of the resistance element as well as its mechanical properties. The former advantage finds application in the production of resistance elements of elastomer foam whereas the latter application has even wider application.

With regard to electrical characteristics, the elimination of a portion of the solvent from the conductive coating results in a mixture of pasty consistency. Because of the decreased solvent requirement, greater amounts of coating can be used to provide a higher effective carbon content than previously available without pretreatment. Previously, the need for high solvent limited the amount of coating that could be used thereby requiring increased loading of conductive material in the coating to provide higher conductivity. It will be apparent that with the solvent pretreatment, higher conductivity coatings can be made with reduced amounts of conductive material.

The benefits of pretreatment on mechanical properties relates to the interaction of the conductive coating with the elastomer wall. The advantage derived renders the pretreatment suitable for preparing resistance elements from a composite of solid elastomer and conductive coating as well as from an elastomer foam. The solvent used for pretreatment apparently does not evaporate until after vulcanization of the elastomer of the conductive coating thereby minimizing the possibility of microcracking. The reduced amount of solvent needed to carry the conductive coating also reduces the possibility of microcracking from this source. Another surprising advantage relating to mechanical characteristics is found to result upon evaporation of the absorbed solvent. The elastomer body shrinks to compress the coating and in effect prestresses the coating. As stated previously, the latter advantage makes the pretreatment process especially useful for resistance elements comprising a solid elastic substrate coated with a conductive coating wherein expansion or contraction of the composite causes the resistance of the conductive coating to change proportionally.

THE TRANSDUCER

Where the elastic material is a metal such as in FIGS. 6, 7, or 8, a transducer is provided by affixing electrical leads to the top and bottom metal portions and including the resistance element in a suitable electrical circuit. In the embodiment selected for illustration in FIG. 10, an elastic foam body 80 has an interconnected cellular portion 82 coated with a conductive coating 85. While an elastic material of nonconductive foam is shown in FIG. 10, it is not meant to be limited thereto. Any of the elastic materials of FIGS. 3 to 5 or FIG. 9 may be used. Contacts 89 are affixed to the longitudinal ends of foam 80 by means of an electrically conductive cement 88. A satisfactory cement comprises equal proportions by volume of a solvent release cement having the ability to shrink upon curing and a mixture of silver flake and silver powder. Wolfson et al. (U.S. Pat. No. 2,774,747) described a typical conductive cement. Leads affixed to contacts **89** connect transducer **84** in an electrical circuit comprising a power source and electrical readout device. As explained in connection with FIGS. **1** and **2**, when foam **80** changes dimension by reason of physical force applied thereto, there is a corresponding change in the current path or electrical resistance measured by the electrical readout device.

Although an elastic material can be used alone as in FIG. **10**, the use of a solid elastic material such as liver rubber in combination therewith relieves a portion of the stress. In addition, foam **80** of FIG. **10** can be impregnated to a limited depth only so that only a portion of the foam is axially traversed by conductive material.

Referring to FIG. **11**, the axial core **96** of foam **90** having a conductive coating on the interconnected cell walls thereof receives a solid elastic material **97**. Contacts (not shown) are affixed to ends of the composite body as described in connection with FIG. **10**. The solid elastic material **97** of FIG. **11** may comprise live rubber or any other highly resilient material such as a fiberglass spring or metal spring insulated from the conductive coating. In addition to the core of FIG. **11**, solid elastic material may be a coaxial portion such as a sleeve surrounding the foam body. The solid elastic material may be combined with any of the coated elastic materials such as those illustrated in FIGS. **1** through **9**.

Referring to FIG. **12**, a load cell **110** comprises a transducer **104** inside of a bellows **108** having the ability to deform elastically uniformly in a longitudinal direction with applied pressure. The contacts **106** of transducer **104** are insulated from bellows **108** by insulating discs **109**. Leads **101** from a power source (not shown) carry current to the transducer and are insulated from bellows **108**. By enclosing transducer **104** within load cell **110** to measure fluid pressure, the transducer is left unaffected by the presence of the fluid. Further, the deformation of the transducer can be controlled by the elastic properties of the bellows. Thus, FIG. **12** provides a method of controlling the modulus of the elastic material in addition to the previously described method of adjusting the amount of conductive coating.

A further application for the transducer of this invention includes the Bourdon tube **120** of FIG. **13** wherein a transducer **124** is grasped between the opposing faces **116** and **118** of Bourdon tube **120**. Insulating plates **125** serve to insulate the contact caps **127** from faces **116** and **118**. Transducer **124** is connected to a power source (not shown) by leads **121**. Fluid enters faces **116** and **114** and flows to closed face **118** whereby pressure in tube **120** causes face **118** to move outwardly to release force on transducer **124** in an amount proportional to the fluid pressure. In turn, force released from the transducer causes the length of the current path flowing in the transducer circuit to change. When fluid pressure decreases, the faces move inwardly and force is exerted on the transducer. Where desired, the mechanical arrangement normally used in the Bourdon tube to transmit the changes of tube geometry to a pointer or readout device can be included with the arrangement of FIG. **13**. In this manner, two types of readout are provided.

For many applications, the transducer according to this invention shows remarkably little change in properties when subjected to varying temperatures. However, where close accuracy is needed, temperature compensation is usually desired. Referring to FIGS. **14** and **15**, The outer resistance elements **135** and **136** surround the shorter inner resistance elements **131** and **132**. The upper end of inner resistance elements **131** and **132** and outer resistance elements **135** and **136** are affixed to an insulating plate **138**. Insulating plate **139** is affixed to the lower ends of outer resistance elements **135** and **136**. Leads **141** from a power source (not shown) are attached to resistance elements **135** and **136**. Outer resistance elements **135** and **136** are responsive to pressure whereas inner resistance elements **131** and **132** are not. Leads **142** through **146** interconnect the resistance elements so that each element comprises one arm of a Wheatstone Bridge circuit. Each of the inner elements **131** and **132** is connected to one of the outer elements **135** and **136** so that an inner element and an outer element comprise alternate arms in the bridge circuit. Because the voltage drop across them is equal to the applied voltage, their outputs are added and the output is doubled. Although wires can be used to interconnect the resistance elements in the bridge circuit, some leads can be printed on the inner face of the contacts by conventional techniques. To insure maximum output on the bridge circuit, the resistance of all the resistance elements should be equal. In other words, the fixed resistance of the elements not responsive to pressure should be equal to the normal resistance of the elements responsive to pressure. By normal resistance, it is meant the resistance of the responsive elements prior to being placed in the environment in which the transducer operates. This is done according to the invention by varying the composition and amount of conductive coating applied to the resistance element. The inner elements do not have to comprise resistance elements according to the invention so long as their resistance is equal to the normal resistance of the outer elements and they respond to temperature in the same manner as the outer elements. A load cell can be made by including the temperature-compensated transducer of FIGS. **14** and **15** within the bellows of FIG. **12**.

Referring to FIG. **16**, a temperature-compensated transducer has four times the output of a transducer comprising one element alone. The transducer comprises the upper resistance elements **161** and **162** and the lower resistance elements **168** and **169** affixed to the end caps **159** and **171**, respectively, at one end and affixed at their opposing ends to an insulating plate **165** having a pressure applying disc **166** affixed to its rim. The transducer assembly **180** is disposed inside of a bellows assembly **179** and separated therefrom at the longitudinal ends by the insulating discs **157** and **173**. At a point about midway along the bellows, pressure applying disc **166** is affixed to the bellows assembly **179** to define an upper bellows portion **155** and lower bellows portion **177**. The tabs **153** are affixed to the upper and lower faces of bellows **179**. The resistance elements are connected by electrical leads **175** so that each resistance element comprises one arm of a Wheatstone Bridge arranged with upper and lower resistance elements as alternate arms. In actual use, spaced rods are run through the openings in tabs **153** so that the position of the transducer is fixed and pressure of the surrounding environment is transmitted solely to pressure applying disc **166**. Leads from a power source (not shown) are connected to end caps **159** and **171**. Upon application of pressure to pressure applying disc **166** in a direction shown by the arrows, the lower bellows portion **177** and lower resistance elements **168** and **169** are compressed while the upper bellows portion **155** and upper elements **161** and **162** are placed in tension. Preferably, the normal resistance of the resistance elements of FIG. **16** is about equal.

Referring to FIG. **17**, a modification of the transducer of FIG. **16** comprises the transducer assembly **195** enclosed within a rigid container **198** and insulated therefrom by the insulating plates **191** and **199**. A rod **192** extends through an opening in the top of the rigid container **198** and is affixed at its base to insulator plate **193**. Pressure responsive means **189** are provided on the portion of rod **192** outside of rigid container **198**. Upon application of force to the pressure applying means **189**, the transducer assembly **195** responds in the manner described for FIG. **16**. The resistance elements of FIGs. **16** and **17** that are stressed in tension may initially be in the relaxed state or compressed (prestressed). The latter alternative is useful where the resistance material has a low tensile strength. The most useful resistance element of FIGS. **1** through **9** for the transducers of FIGS. **12** through **17** will be determined by the properties sought to be measured and the accuracy desired.

EXAMPLE 1

The hysteresis behavior of a transducer according to the invention was studied by measurements of change of resistance with force upon application of a load to a given load of force and upon release of the load to a relaxed state. Resistance elements for the transducer were made using a silicone rubber foam having a density of 8.5 lb./ft.³and a length of one-half inch and a diameter of one-half inch. Conductive coating was prepared by mixing VM&P (Varnish Makers and Painters) naphtha (Standard Oil Company of Ohio) with silicone rubber (GE Clear Seal) and particular carbon (Conductex SC Beads) respectively in separate containers. The total amount of naphtha used was governed by the amount of coating desired. The respective solutions were mixed, stirred thoroughly, and resistance elements were prepared by dipping foam bodies in the solutions described below:

Sample	Carbon, p.p.h., by Weight	Coating Weight % of orig Foam Weight
301	50	143
307	50	55.1
311	100	113

Following application of the conductive coating, the resistance elements were placed in a warm oven until the solvent was driven off. Electrically conductive cement was used to affix brass contacts having a diameter of about five-eighths inch and a thickness of about 0.050inch to each end of the resistance element. Leads were affixed to the electrodes so as to complete an electrical circuit including a power source and electrical readout device. Load was applied to each transducer and the electrical resistance measured at various deflections. Upon full compression of the resistance element, load was gradually released in small increments so that deflection and resistance could be recorded. The graph of FIG. **18** shows the hysteresis behavior of the three transducers. Excellent reliability is shown for the numerous ranges of resistance that are covered.

EXAMPLE 2

The useful resistance ranges of resistance elements made in the manner of the transducers of example 1 silicone foams of two different densities were determined in relation to the conductivity of the coating and amount of conductive coating used. Measurements of electrical resistance were made in the relaxed state and in the fully compressed state. The tabulation below compares the resistance ranges with the amount and conductivity of the conductive coating.

Sample*	Carbon p.p.h., by Weight	Coating Weight, % of orig. Foam Weight	Resistance Range, ohms
321	150	225	16–20.5
221	150	149	14.5–17.0
317	150	159	26–56
217	150	91	20–32
319	150	116	25–110
219	150	63.5	27–62
323	150	103	36–280
223	150	47.3	28–162
309	100	205	36–52
209	100	142	28–40
311	100	113	47–120
211	100	60.8	70–120
313	100	108	72–400
213	100	45.5	52–230
315	100	78	200–2,000
215	100	33.2	120–670
301	50	143	100–300
201	50	77.3	320–355
303	50	100	175–710
203	50	38	263–595
305	50	72.3	230–1,500
205	50	41.3	130–600
307	50	55.1	1,300–6,700
207	50	23.4	560–2,500

200—Density of Foam equals 10.9 lb./ft.³
300—Density of Foam equals 8.5 lb./ft.³

From the above, it is apparent that a wide variety of ranges of electrical resistance are available by adjusting the amount of conductive material in the coating and the amount of coating used.

EXAMPLE 3

Transducers were made in the manner described for example 1and the relationship of force to change of resistance per unit of force applied and change of resistance per change of unit length were studied for various amounts and conductivities of conductive coatings. In this way, the effect of the latter variables on sensitivity could be studied. Referring to FIGs. **19** and **20**, the sensitivity of the resistance elements varies within a wide range depending on the amount and type of conductive coating that is used. This allows conductive elements to be tailored for specific environments.

EXAMPLE 4

The useful resistance ranges of resistance elements were studied as a function of the manner of applying a conductive coating. Resistance elements were made from an elastic material of silicone rubber foam having a density of 8.5 lb./ft.³ and a length of three-eighths inch and a diameter of 1⅛ inch. Conductive coating for sample **101** was prepared by mixing xylene with silicone rubber (GE Clear Seal) and particular carbon (Conductex SC Beads) and ball milling for 5minutes. Immediately following ball milling, the resistance element was prepared by dipping the foam body in the coating solution. For sample **103**, 80 percent of xylene that was used for the conductive coating of sample **101** was used to impregnate the foam body prior to dipping it in a coating solution containing 80 percent less xylene than was used for the conductive coating of sample **101**. Transducers were prepared in the manner described for example 1and measurements of electrical resistance made in the relaxed state and with an applied force of 50 grams.

The formulations and electrical properties of the transducers are given below:

Sample	Carbon, p.p.h., by weight	Coating Weight % of original Foam Weight	Resistance ohms 0.0 g.	Resistance ohms 50.0 g.
101	40	90	60	20
103	40	100	10	4

The use of solvent pretreatment for sample **103** provided a resistance element having improved conductivity in relation to sample **101**. Sample **103** was cycled several times with no change in the resistance from that shown above. The ball milling procedure is also shown to provide higher conductivity as evidenced by comparing sample **303** of example 2 with sample **101**.

Often it is desirable to provide a transducer having a variable modulus so that the electrical resistance characteristics of the transducer upon deformation can be closely controlled. This allows adjustment of the sensitivity of the transducer within various deformation ranges. Referring to FIG. **21** a pair of stacked vertical resistance elements **212** and **214** to form the resistance element **216** are provided between the electrical contacts **219** affixed to each of the longitudinal ends of the resistance element **216**. The elements **212** and **214** are affixed to one another and to the contacts **219** by means of electrically conductive cement **218**. Where resistance elements **212** and **214** are of different modulus, the lower modulus material collapses rapidly upon initial compression of the transducers to cause an immediate change of resistance. The element of higher modulus collapses more slowly and causes a further change of resistance with deformation after the lower modulus element has ceased to be effective.

Referring of FIG. **22**, a transducer **225** having controlled resistance change with deformation comprises a resistance element **227** of elastomer foam between electrical contacts **237** forming a central opening **229** provided with an insulated spring **231** and a resilient stop **233**. Initial deformation of the transducer **225** causes a change of resistance dictated by the characteristics of the resistance element **227**. Upon further deformation, the upper contact **237** strikes spring **231** whereby it controls additional deformation of the resistance element **227**. When deformation equals the distance between the end of stop **233** and the lower electrical contact **237**, the stop controls further deformation. At each of the latter two stages, the transducer can be subjected to higher deformation thereby extending its useful pressure operating range.

A preferred embodiment of the variable resistance element according to the present invention is shown in FIGS. **23** to **26**. This embodiment comprises a commercial polyurethane foam having a first coating of silicone rubber which is in turn coated with an elastic electrically conductive material. FIGS. **23** to **26** are photomicrographs of increasing magnification which show in greater detail the structure of the element.

FIG. **23** shows the cellular structure of a reticulated polyurethane foam coated with a conductive coating according to this invention. It is clear from this photomicrograph that the coated foam is a substantially open celled structure and that the greater portion of its volume is void space. FIG. **24** shows a cross section of one of the interconnecting strands of the coated structure. The dark triangular portion the center of the strand is the reticulated polyurethane foam structure. Reticulated or "dewindowed" foam structures such as these are commercially available from Scott Paper Company and are more fully described in U.S. Pat. No. 3,171,820, Volz. The light portion immediately surrounding the triangular polyurethane core is the first coating of silicone rubber. Coating the polyurethane core with silicone rubber in this manner greatly improves the mechanical properties of the cellular structure. The first silicone coating is preferably dried and cured before applying the conductive coating.

As shown in FIG. **24** and in more detail in FIG. **25** the thin layer of dark material surrounding the light silicone rubber portion is the conductive coating. FIG. **25** shows that the outer surface of the coating is substantially smooth and free from protruding particles on fiber ends. It is also apparent from FIG. **25** that the carbon particles are uniformly distributed, over the surface of the coating. FIG. **26** is photomicrograph of a portion of the surface of the coating taken normal to the surface and magnified to 5,000 X. The white fibers in FIGS. **26** are a filler material in the silicone rubber elastic binder. The carbon particles are still too small to be visible but they are substantially embedded in the silicone rubber in the evenly distributed dark areas to the photo. Resistance elements such as the one shown in FIGS. **23** to **26** have been cycled as many as one million times in a fixture designed to compress the element 42 percent of its original height and then pull the element back to its original size with only minor decreases of 2 to 3 percent in hysteresis and linearity. It is obvious from these figures that an elastic resistance element according to this invention is far superior than any similar devices to date.

The preferred reticulated foam structures comprise a three-dimensional network of interconnecting strands of elastic material integrally interconnected by nexuses at spaced points to form a skeletal outline of a multitude of polyhedrons each face of which is polygonal and common to a pair of adjacent polyhedrons, substantially all of the faces being open and free from membranous elastic material. Structures having 10 to 100 faces per lineal inch (commonly referred to as pores per lineal inch) are preferable. The reticulated foam structure may be made of silicone rubber, thus eliminating the intermediate silicone rubber layer. More than one intermediate layer may be used where desirable.

Resistance elements as illustrated by the invention characterized by an elastic material defining a collapsible structure having at least an interconnected portion bonded with a conductive coating have many uses and advantages. The uses of the resistance element include measurements of torsion, strain, and angular displacement as well as low-level acoustical pickups. Transducers according to the invention find uses including the measurement of force, pressure and torsion. Temperature-compensated transducers find use for measurements above room temperature where the combined factors of low cost and accuracy are relevant.

One advantage of this invention is that a resistance element is provided having an electrical resistivity varying in a simple functional relation with the state of tension or compression of the resistance element.

Another advantage of this invention is that a low-cost resistance element is provided having an electrical resistivity and sensitivity tailored to its environment and providing a reliable variation of electrical resistivity with continued application of tension or compression to the resistance element.

Still another advantage of this invention is that a low-cost transducer is provided having a high output.

It will be understood that various changes in the details, materials, steps and arrangements of parts, which have been herein described and illustrated may be made within the principles and scope of the invention.

I claim:

1. A resistance element comprising an elastic material having a progressively collapsible solvent-impregnated and swollen then dried and unswollen skeletal structure and a nonfriable elastic electrically conductive continuous coating adherent to at least an interconnected portion of said progressively collapsible structure,

said coating having an average thickness of about 0.05 to 0.25 of the thickness of said skeletal structure,

said element filling less than about 25 percent of the volume within its outer boundary, and

said coating comprising an elastic binder and electrically conductive particles dispersed therein and having been applied to the structure in its solvent-swollen condition and prestressed by the subsequent drying and shrinking to form a substantially smooth outer surface at which said conductive particles are substantially, but not completely, embedded.

2. A resistance element as in claim **1**, wherein said conductive particles comprise about 10 to 25 percent of the volume of said coating.

3. A resistance element as in claim **1**, wherein said elastic binder consists essentially of silicone rubber.

4. A resistance element as in claim **1**, wherein said conductive particles consist essentially of carbon.

5. A resistance element as in claim **1**, wherein said elastic material consists essentially of a nonconductive elastomer foam having an interconnected cellular network.

6. A resistance element as in claim **1**, wherein said elastic material consists essentially of a porous mass of particles of elastomer foam adherent at their contact points, each said particle having an interconnected cellular network.

7. A progressively collapsible variable resistance element comprising

a three-dimensional network of interconnecting strands of solvent-impregnated and swollen then dried and unswollen elastic material integrally interconnected by nexuses at spaced points to form a multitude of reticulated cells substantially all faces of which are open and free from membranous elastic material; and

a nonfriable elastic coating, substantially covering said interconnecting strands and nexuses without substantially filling said open faces, comprising an elastic binder and electrically conductive particles dispersed therein and having been applied to the network in its solvent-swollen condition and prestressed by the subsequent drying and shrinking to form a substantially smooth outer surface at which said conductive particles are substantially, but not completely, embedded in said binder.

8. A resistance element as in claim 7, wherein the average thickness of said coating is less than about 0.5 of the radius of said interconnecting strands.

9. A resistance element as in claim 7, wherein said network has about 10 to 100 faces per lineal inch.

10. A resistance element as in claim 7, comprising also an intermediate layer of elastic material between the skeletal network and said coating.

11. A resistance element as in claim 10, wherein said intermediate layer consists essentially of silicone rubber.

12. A resistance element as in claim 7, wherein the skeletal network consists essentially of polyurethane resin.

13. A resistance element as in claim 7, wherein the particulate conductive material consists essentially of carbon.

14. A progressively collapsible variable resistance element comprising:

an interwoven structure of fibrous strands;

a layer of elastic material substantially covering said strands and bonding them at spaced points of intersection to form a three-dimensional interconnected solvent-impregnated and swollen then dried and unswollen network substantially free of membranous material in the areas between strands, said elastic layer imparting elasticity to the structure as a whole; and

a nonfriable elastic coating substantially covering said network without substantially filling said areas between strands comprising an elastic binder and electrically conductive particles dispersed therein and having been applied to the network in its solvent-swollen condition and prestressed by the subsequent drying and shrinking to form a substantially smooth outer surface at which said conductive particles are substantially, but not completely, embedded in said binder.

15. A resistance element as in claim 14, wherein said layer of elastic material consists essentially of silicone rubber.

16. A resistance element as in claim 14, wherein the particulate conductive material consists essentially of carbon.

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