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ARTICLE OF MANUFACTURE AND APPARATUS FOR PRODUCING ULTRASONIC POWER

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FIG. — 1

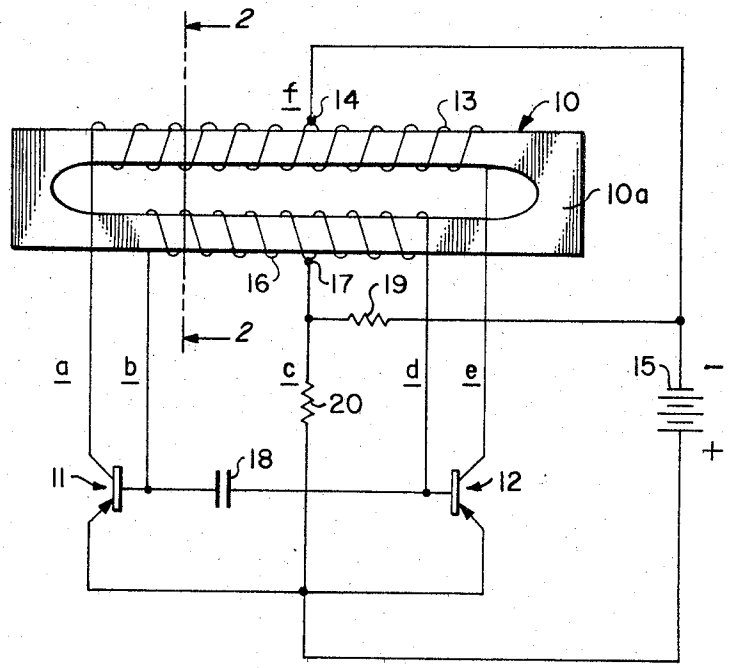
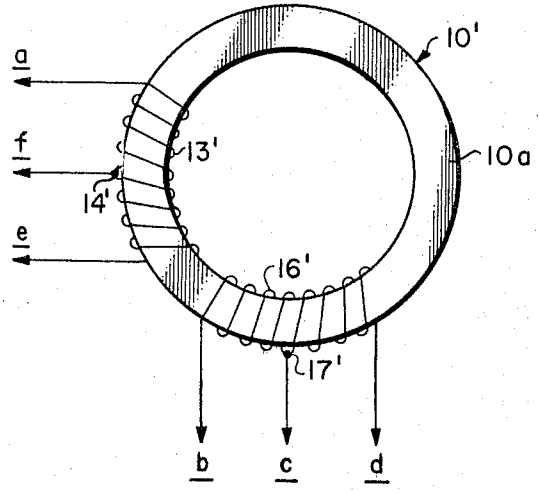


FIG. — 3



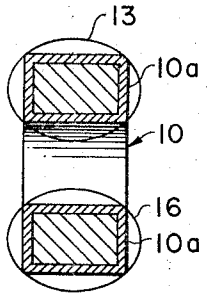


FIG. — 2

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ARTICLE OF MANUFACTURE AND APPARATUS FOR PRODUCING ULTRASONIC POWER

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ABSTRACT OF THE DISCLOSURE

An ultrasonic transducer such as a ferrite element having circuit windings has a coating of a cured solid epoxy resin about .030 inch in thickness shrunk onto it, the resin having the characteristic that its coefficient of thermal expansion in the cured solid state lies in the range of three to five times that of the transducer element. The material of the resin coating being in tension around the transducer element, pre-loads it, thereby preventing its shattering.

The present application is a continuation-in-part of our copending application, Ser. No. 503,683, now abandoned, filed Oct. 23, 1965 for Article of Manufacture and Apparatus for Producing Ultrasonic Power, which is a continuation-in-part of our copending application, Ser. No. 168,098, filed Jan. 23, 1962, now Patent No. 3,256,114.

The present invention relates in general to piezoelectric ceramic and magnetostrictive ferrite elements used as transducers in ultrasonic oscillators and more particularly relates to special epoxy-coated transducers of the type mentioned.

Ultrasonic power is generally obtained by driving either a piezoelectric ceramic or a magnetostrictive ferrite transducer, the aforesaid drive being provided by means of an oscillator circuit of which the transducer is an inherent part. More particularly, irrespective of what kind of transducer element is used, the ultrasonic power is produced by converting electrical power to mechanical power in the form of mechanical vibrations of the transducer, the mechanical vibrations corresponding to the electrical oscillations used to produce them. Thus, for sake of example, when an oscillatorily varying magnetic field is appropriately applied to a magnetostrictive ferrite transducer, the transducer is forced to repetitively expand and contract, a well-known phenomenon, with the result that the transducer is caused to vibrate in a manner similar to the applied oscillations.

A major problem connected with power transfers of the type mentioned is that the tensile strength of these transducers is low while their compressive strength is high. This means that unless some scheme is employed to preload the transducer, a transducer will tend to crack and, therefore, fail when operated at the higher power levels. A good many schemes have been tried, probably the largest percentage of them using bolts to create the restraint. However, none of these earlier preloading schemes has proved to be entirely satisfactory for a variety of reasons. Thus, in the case of the preloading produced with the aid of bolts, the activity of the transducer has been sorely restricted due to an electromechanical phase shift created by the restraint itself. Furthermore, where the transducer element is magnetostrictive, eddy current paths are introduced which not only waste power, but also deleteriously affect the electromechanical operation of the transducer and its associated oscillator drive circuit. There has, therefore, been a long-felt need for some simple but completely effective way to provide the desired preload for these transducers.

The present invention provides the sought-after solution

to the above mentioned problem of preloading transducers, the essence of the invention residing in the discovery that when the surface of a transducer designed to deliver ultrasonic power is coated with an epoxy-resin of a particular thickness and a particular thermal expansion characteristic, and then heat-treated, the transducer becomes properly preloaded. More specifically, the epoxy-resin is applied to the transducer so that all or nearly all of its surface is substantially uniformly coated with it. Following this step the transducer is placed in an oven that has been preheated to a predetermined temperature corresponding to the kind of epoxy-resin used. The coated transducer is then baked in an oven for an interval of time also corresponding to the kind of epoxy-resin used, after which the element is taken out of the oven and permitted to slowly cool to the ambient temperature. During the cooling period, the epoxy-resin coating tends to shrink at a faster rate than the transducer material, with the result that the material of the cured solid coating is in tension around the transducer surface, and the transducer is thus uniformly and uniquely preloaded by this shrunk-on coating. The transducer may then be coupled into the oscillator drive to make the ultrasonic power available.

The cured solid epoxy resin coating should preferably be about .030 inch thick, although a tolerance between the limits of about .020 inch and .050 inch thickness is permissible. The thermal expansion characteristic of the cured solid resin should be such that its coefficient of thermal expansion in the cured solid state lies in the range of three to five times that of the transducer core to which it is applied.

Aside from the obvious advantages obtained by using an epoxy-resin technique, namely, that supporting mechanical structures and eddy paths are avoided, there is the further additional advantage that a considerable increase in power level can be obtained from this method. More particularly, the transducer will safely deliver four to five times its rated power when preloaded in accordance with the present invention. This is a significant and quite unexpected improvement in transducer development and opens up a new range of uses for them.

It is, therefore, an object of the present invention to provide a new type of preloaded ultrasonic transducer.

It is another object of the present invention to provide a method for simply and effectively preloading ultrasonic transducers.

It is a further object of the present invention to provide a method of preloading ultrasonic transducers that enables them to deliver several times their rated power without failure.

It is an additional object of the present invention to provide an ultrasonic power source capable of safely operating at relatively high power levels.

The novel features which are believed to be characteristic of the invention, both as to its organization and method of operation together with further objects and advantages thereof, will be better understood from the following description considered in connection with the accompanying drawing in which an embodiment of the invention is illustrated by way of example. It is to be expressly understood, however, that the drawing is for the purpose of illustration and description only and is not intended as a definition of the limits of the invention.

FIG. 1 is a schematic circuit of an ultrasonic power source that includes a transducer prepared in accordance with the present invention;

FIG. 2 is a cross-sectional view of the transducer element in FIG. 1 taken along the line 2—2; and

FIG. 3 illustrates a transducer of different configuration or design than the transducer element of FIG. 1.

Referring now to the drawing, the circuit arrangement shown in FIG. 1 is of an ultrasonic power source and includes a magnetostrictive transducer **10** in the shape of a core and a pair of transistors generally designated **11** and **12**. Transducer element **10** is coated with an epoxy-resin material **10***a* and is suitably biased by means of either a coil or a permanent magnet, the biasing requirement being so well known and so standardized that it is not shown in the figure. As previously mentioned, the epoxy-resin coating is an important feature of the invention. The collector elements of transistors **11** and **12** are coupled to each other through a winding **13** which is center-tapped at **14**. Winding **13** is wound on core **10** over epoxy-resin coating **10***a* and is to be considered a primary winding. The emitter elements, on the other hand, are shorted or connected directly to each other and also to the positive terminal of a voltage source such as battery **15**.

A secondary winding **16**, center-tapped at **17**, is also wound on core **10** over epoxy-resin coating **10***a*, the two ends of this secondary winding respectively being connected directly to the base elements of transistors **11** and **12**. Also connected between the ends of secondary winding **16** and, therefore, between the base elements of the transistors, is a capacitor **18** whose function in the circuit is to reject unwanted modes of oscillation. Accordingly, the value of capacitance of capacitor **18** is selected so that the capacitor will resonate with secondary winding **16** at the same frequency as magnetostrictive transducer **10**. Finally, the circuit includes a voltage divider comprising a pair of resistors **19** and **20** connected in series across voltage source **15**. More specifically, resistor **19** is connected between center-tap **17** and the negative terminal of voltage source **15** while resistor **20** is connected between center-tap **17** and the positive terminal of the same voltage source. It should be mentioned that the values of resistance of resistors **19** and **20** are chosen so as to establish the proper operating bias for transistors **11** and **12**.

Transducer **10** in cross-section is clearly shown in FIG. 2, the epoxy-resin material **10***a* with which the transducer is coated as well as primary and secondary windings **13** and **16**, respectively, also being clearly shown.

Considering now the circuit operation, when the power is turned on, one of the two transistors, either transistor **11** or transistor **12**, conducts more than the other. This is due to the fact that the two transistors are not perfectly identical. Assuming initially that transistor **11** conducts more than transistor **12**, an unbalanced current flows in primary winding **13**. It will be recognized by those skilled in the arts involved, that the resulting unbalanced current causes or produces a change in dimension of magnetostrictive element **10**. The dimensional change in turn induces a current in secondary winding **16**, the windings being phased in such a manner that, under the circumstances mentioned, the secondary winding causes transistor **11** to go into full conduction while at the same time cutting off transistor **12**. As a result, a square current wave and, therefore, a like kind of magnetic field, is applied to the transducer, that is, to magnetostrictive element **10**, and since it is itself a resonant element it therefore vibrates at its natural frequency. As it does vibrate, the transducer returns from its initial displacement to its original dimension, then displaces in the opposite direction. It will be recognized that as it displaces in the opposite direction, it induces a reserve current in secondary winding **16**. By so doing, transistor **11** is cut off and therefore no longer conducts current, transistor **12** simultaneously being caused to go into full conduction. Thus, the resonant cycle is completed and will continuously be repeated since the circuit oscillation is self-sustained by the magnetostrictive feedback.

A set of parameters for a specific circuit arrangement is presented below where the various sub-numerals refer to the circuit elements in the figure. The parameters are as follows:

R_{19}—120 ohms;
R_{20}—5 ohms;
C_{18}—4 microfarads;
Transistors **11** and **12** are 2N441P-N-P transistors;
E_{15}—12 volts;
Primary winding **13** contains a total of 14 turns;
Secondary winding **16** contains a total of 8 turns.

Magnetostrictive core member **10** is a magnetostrictive ferrite 7A2 material manufactured and sold by the Ferroxcube Corporation of America, 50 East Ridge Street, Saugerties, New York; and

Epoxy-resin material **10***a* may be any one of a number of epoxy-resin materials that are presently commercially available. It should, however, have a coefficient of thermal expansion in the solid cured state which is in the range of three to five times that of the transducer core.

It should be mentioned at this point that the circuit shown in FIG. 1 may be modified in several respects. Thus, for example, it will be obvious to those skilled in the ultrasonic art that capacitor **18** may be eliminated from the circuit. However, without the capacitor, transducer **10** tends to oscillate at its lowest mode which is determined by the dimensions of the transducer. Again, the circuit would operate just as effectively by reversing the polarity of the applied voltage and by substituting N-P-N transistors for P-N-P transistors **11** and **12**. Finally, it will also be recognized that vacuum tubes of the triode type are equivalent in this case to the transistors and may be substituted for them.

The present invention has many applications, and one is in an ultrasonic cleaner system. The special transducer and circuitry is utilized in an ultrasonic generator, the generator utilizing a plurality of modules mounted inside the ultrasonic cleaner console. Each module contains two circuits which drive each transducer separately, thus insuring optimum drive for individual transducers. In the application described, each module converts ordinary line current to a high frequency, on the order of 21 kilocycles.

As utilized, the circuitry is completely self-tuning and operates each transducer separately, assuring constant optimum performance. The electrical resonant frequency automatically adjusts to match the mechanical resonant frequency, which is a function of the load.

The phenomenon of operation can be explained as follows: when the mass of a vibrating mechanical system is increased, the frequency of vibration is reduced. Loading the ultrasonic transducer by pressing on its end or immersing the end in a liquid has the same effect as an increase in mass. The electromechanical characteristic of the transducer at resonance displays a negative impedance-frequency relation, that is, as frequency drops, the electrical impedance, which is herein largely inductive reactance, rises. Thus the effective inductance in the output coil displays an increase, which lowers the resonant frequency of the electrical circuit until a new equilibrium is reached.

Reference is now made to the method by means of which the epoxy-resin coating is provided on the transducer. In preparation, the curing oven is preheated to a temperature that is between 210° C. and 220° C. At the same time, the transducer is cleaned, two steps being involved. First, the surface of the transducer is sandblasted, thereby providing a smooth, substantially dirt-free surface. Second, following the sandblasting, the transducer is ultrasonically cleansed by immersing it in a liquid solvent to which ultrasonic power is applied. As is well known, the utrasonic vibrations of the solvent cause the dirt to be dislodged from the transducer surface, with the result that for all practical purposes, the transducer is then perfectly clean. Of course, other cleansing techniques are available and may be used, but the cleansing steps mentioned above have been found to be most expeditious and effective.

After the transducer has been cleaned in the manner described and then dried in air, the epoxy-resin material is applied to its entire surface area and this is accomplished by painting it on with an ordinary paint brush, the transducer being held during this period by means of a clamp or other device. In completing the paint job, the transducer is placed on prongs or minimum surface areas so that the epoxy-resin can be applied to those areas that have not yet received it, because of interference by the holding clamp or device or for other reasons. The prongs or minimum surface areas that come into contact with the transducer and the epoxy-resin thereon are pre-treated with a release agent that keeps the epoxy-resin from adhering to them. An example of such a release agent is silicone grease.

Now that the transducer surface is completely covered with the epoxy-resin material, the combination of the pronged mechanism and the transducer resting thereon are placed in the oven which, it will be remembered, has been preheated to and is at a temperature of approximately 220° C. The transducer remains in the oven and is cured for several hours, the actual number of hours depending on the particular epoxy-resin used. By the end of the curing time, the epoxy-resin is hard. Consequently, the coated transducer is taken out of the oven and allowed to slowly cool in air for a period of from two or three hours. The transducer is now ready for use and can be expected as a result of this coating technique to deliver four to five times the rated power of the transducer. As a concrete example of the improvement that can be achieved in this way, if the rated power is less than 50 watts, then the transducer will produce 200 watts.

It was mentioned earlier that a number of different epoxy-resins are commercially available. However, whichever one is selected for the purposes of the present invention, it should be an epoxy-resin having a high coefficient of thermal expansion in the cured solid state. Stated differently and more specifically, the epoxy-resin should be one that experiences very little shrinkage during the curing step, less than one percent (1%), that is, less than one hundredth ($\frac{1}{100}$) inch per inch. On the other hand, the epoxy-resin material should possess the quality of shrinking at a much more rapid rate during the cooling step than the ferrite constituting the magnetostrictive transducer, and within the range of three to five times that of the ferrite as stated before. When the epoxy-resin has this quality, the desired preload can be uniformly applied throughout the transducer so that it will then be capable of operating at greatly increased power levels as set forth above. An example of an epoxy-resin that may be used is known as Stycast No. 2651, manufactured by Emerson and Cumming, Inc. of Canton, Massachusetts. The cure time for Stycast No. 2651 is two hours at the oven temperature mentioned, namely, from 210° C. to 220° C.

To obtain the desired preload and absence of shattering, the thickness of the cured solid epoxy-resin should be about .030 inch, and not outside the critical range of .020 inch to .050 inch. It has been found that if the thickness is less than about .020 inch, shattering will occur on preloading, and if greater than about .050 inch the core will be too damped for proper operation. Furthermore, it has been found by tests of numerous cured epoxy-resins of different coefficients of thermal expansion that when the coefficient of thermal expansion of the cured resin is outside the critical range of three to five times that of the core, shattering would occur.

Having described the manner in which the transducer is coated, it should next be mentioned that transducer **10** or its associated drive circuit in FIG. 1 may be modified in several respects. One such modification was indicated earlier when it was stated that capacitor **18** could be eliminated from the circuit. Another modification could be made in the shape or configuration of the transducer as is shown in FIG. 3 wherein a ring or annular shaped

transducer **10'** is shown that may be substituted for the transducer of FIG 1. Transducer **10'** is also covered with an epoxy-resin coating **10***a* and, because of its shape, is designed to oscillate or vibrate radially rather than longitudinally when power is applied to it. A primary winding **13'** and a secondary winding **16'** are also wound on transducer **10'**, the lines leading from primary winding **13'** being designated *a*, *e* and *f* and the lines leading from secondary winding **16'** being designated *b*, *c* and *d*. In substituting transducer **10'** for transducer **10**, lines *a–f* in FIG. 3 are connected to those points in the drive circuit to which the similarly designated lines in FIG. 1 are connected.

Again, the ultrasonic power source of FIG. 1 may be adapted to use a magnetostrictive ceramic transducer that has been epoxy-resin coated rather than a magnetostrictive transducer.

It should be recognized that while substantially all, if not absolutely all, of the transducer surface should receive the coating, the desired result according to this invention is obtainable in instances where a minor part of the surface is uncoated, or contains less coating than the major part. For example, in the structure of FIG. 1, the ends of element **10** have less need for the coating than do the arms which carry the windings, and even if coating on an end be absent, the high performance in accordance with this invention is obtainable. For this reason, in the use of a transducer such as that of FIG 1, an end of the transducer core is frequently a place chosen for attachment to another body. For example, where it is desired to introduce ultrasonic energy into liquid in a tank by means of a transducer such as that of FIG. 1, it has been a practise to grind off the cured coating from an end of the core, and then attach it to a tank by applying to the end from which the cured resin has been ground off, a liquid coating of epoxy-resin of the same character as that constituting the cured coating over the major surface of the transducer. This liquid epoxy-coated end is held against the tank until its curing has occurred, which results in a secure bonding of the transducer to the tank. Although the transducer will be completely coated even at its butt end in this instance, the layer of resin used to create the adherence between the transducer core and the tank will ordinarily be thinner, for example, about .05 inch, than that of the resin coating around the major surface of the transducer.

Having thus described the invention, what is claimed as new is:

We claim:

1. The article of manufacture comprising: an ultrasonic transducer; and a shrunk-on coating of cured solid epoxy-resin material surrounding in tension, and in contacting relation with, at least the major part of the surface of said transducer, said coating being within the range of .020 to .050 inch in thickness and formed so as to preload in compression said transducer throughout its major surface area, said cured solid epoxy-resin coating having a coefficient of thermal expansion of three to five times that of the transducer.

2. In an ultrasonic power source, the subcombination comprising: a magnetostrictive transducer; a shrunk-on cured solid coating of epoxy-resin material contactingly encasing said transducer in tension, said coating being within the range of .020 to .050 inch in thickness and formed so as to exert a compressive force on said transducer over at least the major part of its surface area; said epoxy-resin coating having a coefficient of thermal expansion of three to five times that of the transducer; and first and second windings wound on said transducer over said epoxy-resin coating.

3. An ultrasonic power source comprising: a magnetostrictive transducer; a shrunk-on coating of cured solid epoxy-resin material in tensile contacting relationship to substantially the entire surface areas of said transducer, said coating being within the range of .020 to

.050 inch in thickness and formed so as to substantially uniformly compressively preload said transducer over substantially its entire surface area, said epoxy-resin coating having a coefficient of thermal expansion of three to five times that of the transducer element; primary and secondary windings wound on said transducer over said epoxy resin coating; and an oscillator drive circuit coupled to said primary winding for exciting dimensional variations in said transducer, said drive circuit including a feedback circuit coupled to said secondary winding for returning a portion of the power applied to said transducer to said drive circuit to sustain the dimensional variations.

4. The power source defined in claim 3 wherein said drive circuit includes a voltage source; a pair of transistors, the collector elements thereof respectively being connected to the ends of said primary winding, the base elements thereof respectively being connected to the ends of said secondary winding, and the emitter elements thereof being connected to one end of said voltage source; and means for applying a substantially equal voltage bias to said transistors.

5. The power source defined in claim 4 wherein said means includes center-taps on said primary and secondary windings, the center-tap on said primary winding being connected to the other end of said voltage source, and a voltage-divider connected across said voltage source and to the center-tap of said secondary winding.

6. A circuit for producing ultrasonic vibrations when a suitable voltage source is connected between the input terminals thereof, said circuit comprising: a magnetostrictive core; a substantially uniformly thick epoxy-resin coating .020 to .050 inch thick shrunk over said core which exerts a compressive force on the core; first and

second center-tapped windings respectively constituting primary and secondary windings wound on said core over the cured epoxy-resin coating, the center-tap of said primary winding being connected to one of the input terminals; a pair of transistors, each of them having first, second and third elements, said first elements being connected to the other of the input terminals, said second elements respectively being connected to the ends of said secondary winding, and said third elements respectively being connected to the ends of said primary winding; means coupled to the center-tap of said secondary winding for applying a substantially equal voltage bias to said transistors; and a capacitor connected between the ends of said secondary winding, the capacitance of said capacitor being of such value that said capacitor will resonate with said secondary winding at substantially the frequency of vibration of said magnetostrictive transducer.

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