Sept. 3, 1968 E. P. PAPADAKIS 3,400,340

ULTRASONIC WAVE TRANSMISSION DEVICES

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FIG. 1

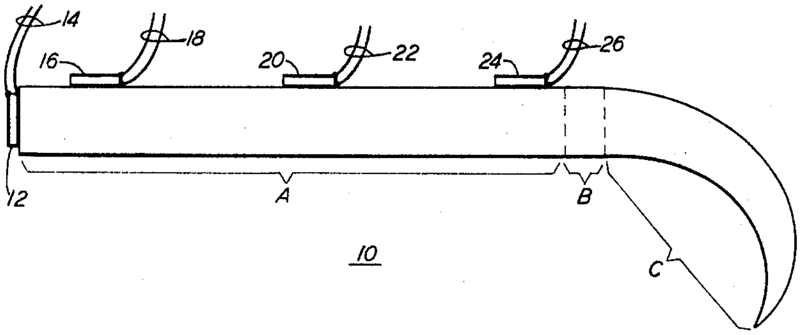
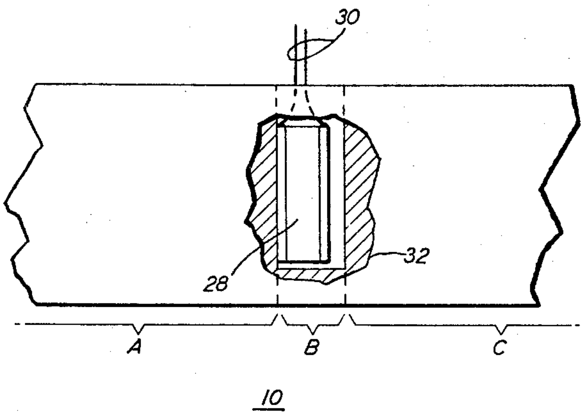


FIG. 2



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ULTRASONIC WAVE TRANSMISSION DEVICES

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This invention relates to ultrasonic and/or acoustic wave energy transmission. More particularly, it relates to methods of fabrication of structural members and to structural members of specific utility in the transmission and/or attenuation of ultrasonic and/or acoustic wave energy.

It has long been assumed that many materials including substantially all metals are not especially suitable for the transmission of ultrasonic and/or acoustic wave energy mainly because of excessive attenuation of the energy in passing through the materials.

This is usually attributed to the fact that substantially all metals and numerous other materials which are polycrystalline or pseudo-polycrystalline are of "large grain size" and the grains or particles are oriented in purely random fashion so as to cause dispersion and scattering of the energy with resultant high attenuation.

Accordingly, those skilled in the art have heretofore felt constrained to employ for low loss, ultrasonic and/or acoustic delay lines, and the like, where relatively very short delay times are sufficient, members cut from single crystals of a few substances, notably quartz, the intended path for ultrasonic and/or acoustic transmission being oriented in a prescribed manner with respect to the crystallographic axes of the single crystal from which they are cut. Where longer transmission paths having appreciably greater delay times are required, preferred materials for relatively low loss delay lines have been fused (polycrystalline) silica or, in some circumstances, drawn aluminum wire or tape. In a few instances magnetic materials have been employed principally in order to take advantage of their magnetostrictive properties but their use entails a number of disadvantages including relatively high attenuation.

A further serious and troublesome problem frequently encountered in connection with prior art ultrasonic and/or acoustic delay lines and related devices arises from the reflection of the energy from an end or other surface of such a device, the reflected energy then giving rise to misleading indications or otherwise interfering with the normal operation of the equipment. Heretofore it has been customary to attempt to eliminate reflection from specific surfaces of the delay member by bonding elements of high ultrasonic and/or acoustic absorbing or attenuating properties to the surfaces. Such arrangements, while appreciably reducing the amount of reflected energy, have, however, never proven entirely satisfactory since it is virtually impossible in most instances to provide sufficiently accurate mechanical impedance matches adjacent the bond to largely eliminate the undesirable effects of energy reflection.

Applicant has found that a large number of metal alloys and other materials can be processed to provide either very low or very high attenuation to ultrasonic and/or acoustic wave energy being transmitted through them.

He has further found that a discrete homogeneous member may have one portion thereof processed to provide low attenuation and another portion thereof processed to provide high attenuation.

Accordingly, for example, the energy absorbing termination of a low loss delay member can be provided by an end portion of the member integral therewith which has been processed to impart high attenuation properties to it only. This obviously eliminates the necessity of bonding an energy absorbing member to the delay member and, furthermore, the mechanical or acoustic impedance mismatch at the transition between the low and high attenuation portions of the member can be reduced to an insignificantly small magnitude thus substantially eliminating reflection of energy from the junction between the two portions. Such arrangements can furthermore readily be adapted to effect substantially complete absorption and/or dissipation of the energy reaching the terminating end of the member.

A principal object of the invention is, accordingly, to eliminate difficulties attending the use of prior art ultrasonic and/or acoustic energy transmission devices with respect to the prevention of reflections and the complete absorption of energy reaching a terminating portion or member.

A further principal object is to substantially reduce the attenuation of ultrasonic and/or acoustic energy in many materials heretofore considered unsuitable for use as transmission devices because of high attenuation.

Other and further objects, features and advantages of the invention will become apparent from a perusal of the following detailed description of illustrative embodiments of the principles of the invention taken in conjunction with the accompanying drawing in which:

FIG. 1 illustrates a structure embodying certain of the principles of the present invention; and

FIG. 2 illustrates a second structural arrangement of the invention.

Alloys of carbon and iron containing up to two percent of carbon are known as steel. As is well known to those skilled in the art, iron may undergo four allotropic modifications. (See, for example, the book entitled "Engineering Metallurgy" by Stoughton, Butts and Bounds, fourth edition, published by McGraw-Hill Book Company, Inc., New York, 1953, concluding paragraph on p. 167.)

At temperatures from about 1400 to 1533 degrees centigrade, it is known as delta iron and has a body-centered cubic space lattice. Delta iron is mainly of scientific interest only. Upon cooling it changes to gamma iron which will hold carbon in solid solution up to a maximum of two percent at 1130 degrees centigrade. All solid solutions of carbon in gamma iron are known as austenite and have a face-centered cubic lattice.

If austenite containing substantially 0.8 percent of carbon is slowly cooled, it changes completely to a form known as pearlite which is the eutectoid of carbon and iron. If the austenite contains less than 0.8 percent of carbon and is slowly cooled, a mixture of alpha-ferrite and pearlite is obtained. If the austenite contains more than 0.8 percent of carbon and is slowly cooled, a mixture of alpha-ferrite and pearlite is obtained. If the austenite contains more than 0.8 percent of carbon and is slowly cooled, a mixture of cementite or iron carbide (Fe_3C) and pearlite is obtained.

As will be discussed in more detail hereinafter, all steels containing appreciable amounts of the pearlitic phase will exhibit high attenuation to ultrasonic wave energy.

If the austenite is cooled rapidly as by quenching in oil or water, the result will be a form of steel known as martensitic steel. Martensitic steel is a supersaturated solid solution and consists of body-centered tetragonal platelets of iron with carbon trapped interstitially. Each austenite grain transforms to many platelets. Martensitic steel so formed will have an attenuation of between one to three percent of the same steel in its pearlitic phase. Subsequent tempering of the martensitic steel at a temperature of from 400 to 700 degrees centigrade for a period of one hour and rapid cooling will then bring the carbon out as granules of iron carbide and is attenuation will undergo a further reduction of between fifty to one hundred percent.

Referring now to FIG. 1, the assembly **10** may represent, by way of a specific example, a unitary member consisting throughout of a specific alloy of iron and carbon having a carbon content not in excess of two percent. An oil-hardened die steel would, for example, be appropriate. A first portion designated A may be of martensitic steel and a second portion designated C may be of pearlitic steel. A short third portion designated B represents a transition region between portions A and C. The member may be made by heating the whole member to a temperature of 825 degrees centigrade for a period of one hour, after which portion A is rapidly cooled to room temperature but portion C is permitted to cool slowly to room temperature. Portion B as noted above will constitute a transition region varying in phase gradually from the martensitic phase of portion A to the pearlitic phase of portion C. Substantially perfect mechanical impedance matching between portions A and C is thus effected by portion B and obviously there is no discrete mechanical bond to introduce impedance discontinuities

Portion C being of pearlitic steel will rapidly attenuate any ultrasonic wave energy reaching it through portion B. Portion C may furthermore be curved and tapered to a point substantially as taught in U.S. Patent No. 2,577,500, granted Dec. 4, 1951, to D. L. Arenberg to further increase its tendency to disperse and absorb all ultrasonic energy reaching it. Ordinarily, such shaping will be necessary only in extreme cases and it is therefore suggested merely by way of indicating that additional assurance can be readily provided that no ultrasonic wave energy reaching portion C will be returned to portion A.

Assuming, by way of example, that portion A is intended for use as a "tapped" delay line, it is provided on its left end as shown with an input transducer **12** comprising, conventionally, a rectangular plate cut from a single crystal of quartz at a prescribed orientation with respect to the crystallographic axes of the crystal and provided with conductive electrodes on its major oppositely disposed surfaces, conductive leads **14** being electrically connected to said electrodes, respectively. Transducer **12** may then be employed to convert electrical pulses supplied through leads **14** to ultrasonic pulses which are transmitted toward the right end of portion A.

A plurality of receiving transducers, similar to transducer **12**, such as **16**, **20**, and **24** may then be mounted at spaced points along portion A as shown and portions of the ultarsonic pulses traversing portion A will cause the generation of electrical pulses in transducers **16**, **20** and **24** which will occur in successive time intervals dependent upon the travel time of the ultrasonic pulses from the input transducer **12** at the left end of the line. Electrical leads **18**, **22** and **26** may then serve to conduct the respective electrical pulses to appropriate utilization means, not shown. Energy not absorbed by receiving transducers **16**, **20** and **24** will, of course, pass via portion B to portion C where it will be absorbed.

In FIG. 2 a modification of the arrangement of FIG. 1 is illustrated and comprises the provision of a cavity in portion B in the partially cross-sectioned area **32**, with an additional receiving transducer **28** having electrical leads **30** mounted at the right end of portion A so that a portion of the ultrasonic pulses reaching the right end of portion A will cause transducer **28** to generate an electrical pulse which may be conducted over leads **30** to appropriate utilization means, not shown. The remaining ultrasonic energy reaching portion B will, of course, pass to portion C and be absorbed therein as described hereinabove.

It is obvious that, if desired, portions A, B and C can be separated from each other in which case portion A could be employed as an unterminated delay line in which the energy is reflected back and forth between its ends a number of times. Thus a single input pulse could provide several output pulses from each transducer as the energy reaches each transducer in its several trips back and forth between the end surfaces. Portion C, with or without portion B, could be employed as an absorbing termination by bonding it by prior art bonding methods to the surface of some device from which acoustic energy is to be absorbed. In other words, a member of pearlitic phase material can per se function as an otherwise conventional absorbing termination member for ultrasonic energy.

While the martensitic transformation effected by rapid cooling from the austenitic phase was first observed in connection with alloys of iron and carbon containing preferably not more than two percent of carbon, it has been found to occur also in many other alloys including the following, any one of which may, alternatively, be employed in arrangements such as those illustrated in FIGS. 1 and 2 and described above in detail for iron-carbon alloys:

Iron-nickel alloy containing up to thirty-two percent nickel; austenitic temperature range (depends on percent nickel) from minus 200 to 1000 degrees centigrade or higher;

Iron-chromium alloys containing four percent chromium; austenitic temperature range from 850 to 1350 degrees centigrade;

Iron-chromium-nickel alloys containing seventeen percent chromium and seven percent nickel;

Iron-manganese alloys containing from ten to twenty-five percent manganese; austenitic temperature range from minus 200 to 1000 degrees centigrade or higher;

Iron-osmium alloys containing from fifteen to thirty percent osmium; austenitic temperature range from minus 200 to 1000 degrees centigrade or higher;

Iron-platinum alloys containing thirty-seven percent platinum; austenitic temperature range from minus 200 to 1000 degrees centigrade or higher;

Titanium-chromium alloys containing from five to seven percent chromium; austenitic temperature range from 500 degrees centigrade and higher;

Titanium-iron alloys containing from five to six percent iron; austenitic temperature range from 300 degrees centigrade and higher;

Titanium-manganese alloys containing from five to seven percent manganese; austenitic temperature range from 200 degrees centigrade and higher;

Titanium-vanadium alloys containing from thirteen to fifteen percent of vanadium; austenitic temperature range from 300 degrees centigrade and higher;

Titanium-tungsten alloys containing from twenty-three to twenty-five percent of tungsten; austenitic temperature range from 300 degrees centigrade and higher;

Titanium-zirconium alloys containing from thirty to fifty percent zirconium; austenitic temperature range from 500 to 1600 degrees centigrade;

Zirconium-molybdenum alloys containing from two to seven percent molybdenum;

Manganese-copper alloys containing fifteen percent copper; austenitic temperature range from 100 degrees centigrade and higher;

Copper-zinc alloys containing from 39.5 to 40.3 percent zinc; austenitic temperature range from minus 100 to plus 1000 degrees centigrade;

Copper-tin alloys containing from sixteen to forty percent tin;

Copper-aluminum alloys containing from thirteen to sixteen percent aluminum; austenitic temperature range from 150 degrees centigrade and higher;

Copper-aluminum-nickel alloys containing 14.5 percent aluminum and three percent nickel;

Copper-indium alloys containing forty-three percent indium;

Indium-thallium alloys containing from twenty-eight to thirty-seven percent thallium; austenitic temperature range from 90 degrees centigrade and higher;
Indium-cadmium alloys containing 4.5 percent cadmium;
Gold-cadmium alloys containing from 47.5 to fifty-one percent cadmium.

For convenience in the remainder of this application and the appended claims, the above listed materials including alloys of iron and carbon which transform upon suitable heat treatment from the austenitic to the martensitic or pearlitic phases will be referred to as "List A."

In accordance with the teachings of the present invention, it has been found that alloys in the martensitic phase can be rendered relatively free from attenuation to ultrasonic and/or acoustic wave energy and those in the pearlitic phase will very effectively attenuate and absorb such energy.

By way of a specific example, the alloy of iron containing 0.5 percent carbon when austenitized by heating for a period of one hour per inch of thickness at a temperature of substantially 825 degrees centigrade within the range in which austenite is formed, but near the lower limit of the range, and then rapidly cooled to cause transformation to the martensitic phase will have an attenuation to ultrasonic wave energy of substantially one percent of that which it would have if permitted to cool slowly. Slow cooling will, of course, result in a pearlitic transformation having high attenuation.

If austenitized at a higher temperature than suggested above and then rapidly cooled, although martensite will be produced, its attenuation will not be as low. This is believed to result from the formation of larger grain sizes as the austenitizing temperature is increased. In a specific instance, for example, an increase of 100 degrees Fahrenheit in the austenitizing temperature resulted in an increase of one hundred fifty percent in the attenuation of the martensitic phase of the material at a frequency of fifty megacycles per second.

In accordance with a further feature of the invention, slow cooling from the austenitic phase of the abovementioned 0.5 percent carbon steel will result in the pearlitic phase having an attenuation substantially one hundred times as great as for suitably prepared martensite. This attenuation can also be further increased by austenitizing at a temperature of substantially 1000 degrees centigrade and slowly cooling to the pearlitic phase. Steel members so treated obviously can serve as very effective absorbers of ultrasonic energy.

Comparable results can be obtained both with respect to low attenuation in the martensitic phase and high attenuation in the pearlitic phase for the additional materials of List A given hereinabove.

Furthermore, if an elongated member of an alloy selected from those mentioned in List A as given above is treated throughout the major portion of its length as taught in the present application to induce the martensitic phase and thus impart low attenuating properties to it so that it can, for example, be employed as a delay line, but an end portion is treated to induce the pearlitic phase and thus impart very high attenuating properties to the end portion only, the end portion can then serve as an energy absorbing termination for the major or delay line portion of the member.

Normally, a short section between the two abovementioned portions will provide a relatively gradual transition between the phases of the portions and no large or abrupt mechanical impedence discontinuities will therefore be encountered.

Obviously, no bonding of the energy absorbing portion to the major portion is necessary since they are integral parts of a unitary member. Acordingly, this arrangement of the present invention is seen to eliminate the prior art problem of obtaining an efficient bond between an absorbing member and a transmission member (delay line, for example) and thus no problems resulting from impedance mismatches and the reflection of energy at bonded surfaces are encountered.

As a further feature of the invention, applicant has found that the attenuation of a large number of metals to ultrasonic wave energy can be substantially reduced by mechanically working or deforming the materials in addition to and in conjunction with treatments including (in appropriate cases) those described in detail hereinabove.

Mechanical working or deforming in specific manners, as will be described in more detail hereinunder, is believed to result in decreased attenuation to ultrasonic wave energy by effecting preferred orientations of the grain structures which largely reduce the scattering of the wave energy.

Probably the most convenient method of working or deforming metals is by rolling them into plates or strips, though forging and other well known methods can obviously effect similar structural changes in many instances.

Rolling in conjunction with recrystallization by tempering in plates or strips is particularly effective in three cases enumerated below.

(1) Face-centered cubic metals and alloys such as copper, gold, iridium, nickel, platinum, rhodium, silver, alloys of iron and nickel containing at least thirty percent of nickel, alloys of copper and zinc containing up to one percent of zinc, alloys of copper and aluminum containing 0.2 percent of aluminum, alloys of copper and cadmium containing 0.1 percent of cadmium, alloys of copper and oxygen containing 0.1 percent of oxygen, alloys of nickel and manganese containing one percent of manganese, trimetallic alloys of iron and nickel with copper or other metals as the third member in numerous combinations such as those well known to those skilled in the art by the trade names "Elinvar" (comprising thirty-six percent nickel, twelve percent chromium, fifty-two percent iron), "Invar" (comprising thirty-six percent nickel, sixty-four percent iron), "Ni-Span-C" (comprising forty-two percent nickel, 5.5 percent chromium, 2.2 percent titanium, 50.1 percent iron), "Iso-Elastic" (comprising thirty-six percent nickel, eight percent chromium, some molybdenum, manganese, copper and vanadium, fifty-two percent iron), and numerous others.

These metals and alloys develop the so-called "cube texture" designated by the symbols (100)[001] in the conventional "Miller Crystallographic Indices," well known to those skilled in the art. The cube edge will have the same direction as that of the rolling operation, and a cube face will be in the rolling plane. They require cold-rolling with a reduction in thickness of eighty-five to ninety-five percent followed by high temperature annealing. The annealing temperature should be between 650 to 980 degrees centigrade for a period of eight hours for copper as an example.

The above list of face-centered cubic materials will be referred to hereinafter as "List B."

(2) Body-centered cubic metals such as steel (alloy of iron and carbon), molybdenum, iron, chromium, tantalum, rubidium, tungsten and others.

The above materials develop the texture designated by the symbols (001)[110] when cross-rolled to a reduction of fifty to ninety-five percent and then annealed so as to produce recrystallization. The annealing temperature should be 600 degrees centigrade (iron and steel), 1315 degrees centigrade (molybdenum), for a period of one to twenty-four hours. Cross-rolling consists of rolling a sheet of metal in one direction and then in a direction at ninety degrees to the first direction. The reversal of directions is repeated frequently during the rolling. (See F. Bitter, United States Patent No. 2,046,717).

The above list of body-centered cubic metals will be referred to hereinafter as "List C."

(3) Hexagonal close-packed metals and alloys such as zinc, manganese and alloys of zinc and copper and zinc and cadmium.

The C axes of the grains are aligned with the direction of rolling. A reduction in thickness of eighty-five to ninety-five percent is required. Recrystallization must then be effected by heating to a temperature of 500 degrees centigrade (titanium) for a period of one to twenty-four hours.

The above list of hexagonal close-packed materials will be referred to hereinafter as "List D."

Attenuation to ultrasonic wave energy in the above indicated classes of materials may be reduced by a factor of from ten to one hundred.

Conversely, the attenuation to ultrasonic wave energy may be increased by the mechanical working of specific materials as described in detail hereinunder. Working of a random nature such as to cause multiplication of dislocation loops and create microcracks should increase the attenuation.

By combining the above heat and mechanical treatments for materials which may be transformed to martensitic and pearlitic phases, the properties of low attenuation or high attenuation, respectively, may be further enhanced.

Numerous and varied modifications and rearrangements in accordance with the principles of the invention will readily occur to those skilled in the art. Accordingly, it is to be distinctly understood that the foregoing suggested structures and descriptive matter are illustrative but should in no way be taken as limiting the scope of the invention.

What is claimed is:

1. An ultrasonic delay line comprising a delay medium having an electromechanical input transducer for generating an ultrasonic wave in the delay medium and at least one electromechanical output transducer attached to a transmitting portion of the delay medium for detecting said wave, said delay medium comprising an elongated integral member having a first portion of a phase which is freely transmitting, a second portion of a phase which, relative to the first portion, is highly absorbing of acoustic energy, and a transition portion varying in phase gradually from the phase of the first portion to the phase of the second portion and intermediate said first and second portions, whereby the second portion substantially reduces reflection of acoustic energy back into the first portion.

2. The ultrasonic delay line of claim **1** characterized in that said member is of a composition which consists essentially of a metallic alloy capable of undergoing a martensitic transformation from an austenitic phase, said first portion is substantially of the martensitic phase and said second portion is substantially of the austenitic phase.

3. The ultrasonic delay line of claim **1** characterized in that said member is of a composition which consists essentially of an alloy of carbon-iron, said first portion is substantially of the martensitic phase and said second portion is substantially of the pearlitic phase.

4. The ultrasonic delay line of claim **3** characterized in that the attenuation of said first portion is about one to three percent that of said second portion.

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