US 20140147656A1

(19) United States

(12) Patent Application Publication

(10) Pub. No.: US 2014/0147656 A1

(43) Pub. Date: May 29, 2014

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(54) **APPARATUSES INCLUDING HOLLOW SHAPE MEMORY ALLOY PARTICLES**

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(21) Appl. No.: **13/954,675**

(22) Filed: **Jul. 30, 2013**

Related U.S. Application Data

(63) Continuation-in-part of application No. 13/686,849, filed on Nov. 27, 2012.

Publication Classification

(51) **Int. Cl.**

E04B 1/84 (2006.01)

E04B 1/98 (2006.01)

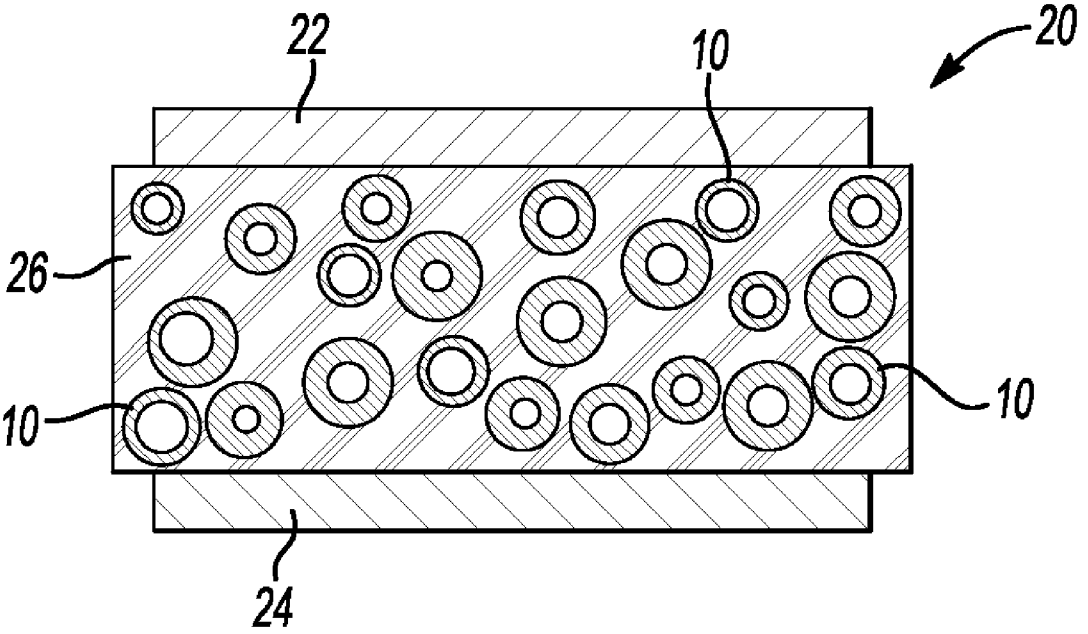
(52) **U.S. Cl.**

CPC ***E04B 1/8409*** (2013.01); ***E04B 1/84*** (2013.01); ***E04B 1/98*** (2013.01)

USPC **428/313.9**; 252/62

(57) **ABSTRACT**

An apparatus includes an elastic medium and hollow particles of a shape memory alloy (SMA) at least to dampen any of sound wave propagation through the elastic medium or vibration transmitted through the elastic medium. The hollow particles are incorporated into the elastic medium. The SMA has an Austenite finish temperature (A_f) that is lower than a temperature encountered in an application in which the apparatus is used so that the SMA exhibits stress-induced superelasticity.



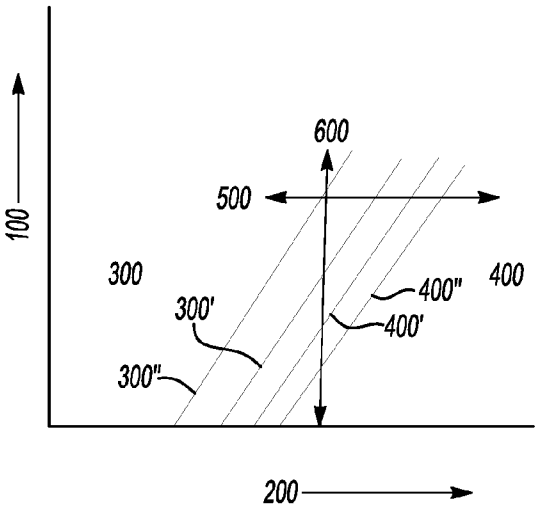


Fig-1A

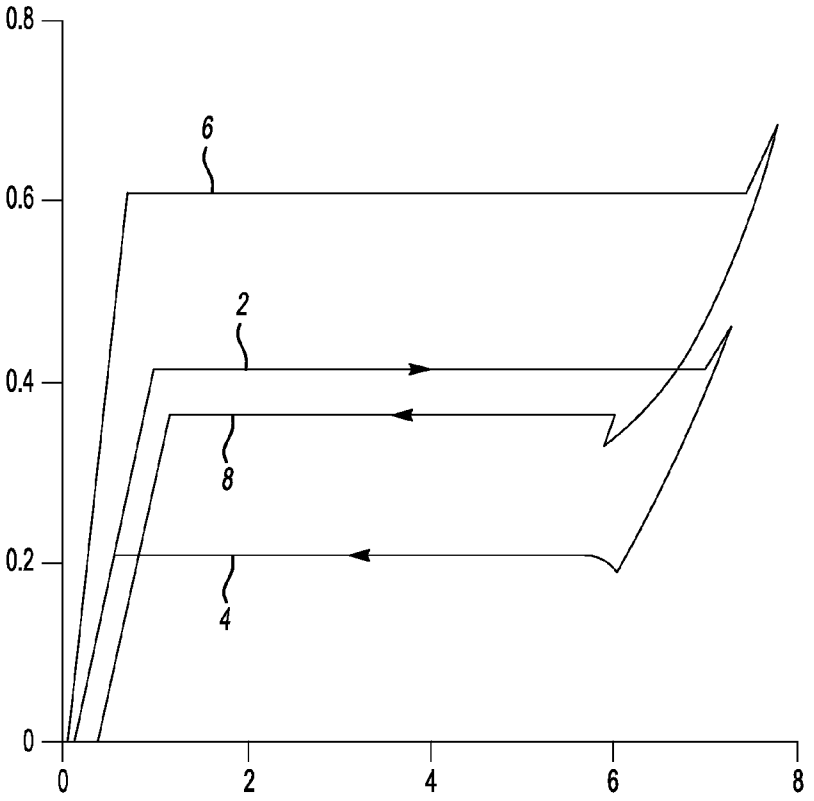


Fig-1B

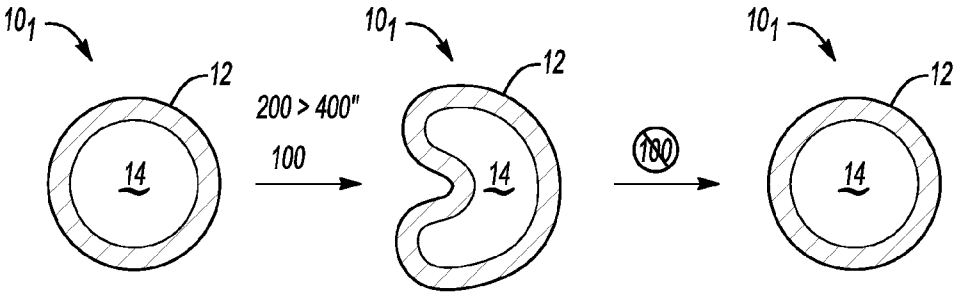


Fig-2

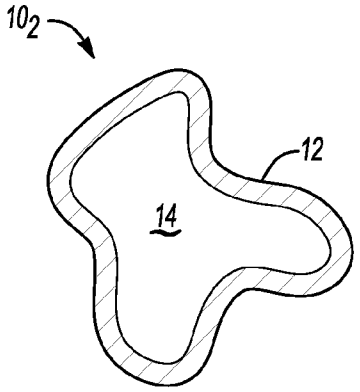


Fig-3

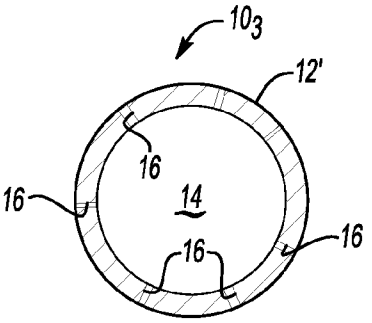


Fig-4

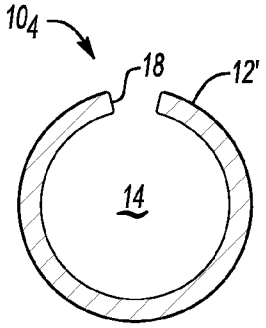


Fig-5

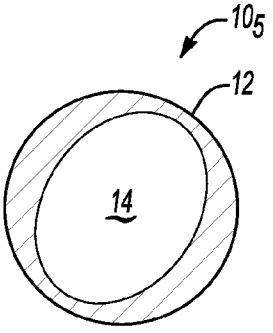


Fig-6

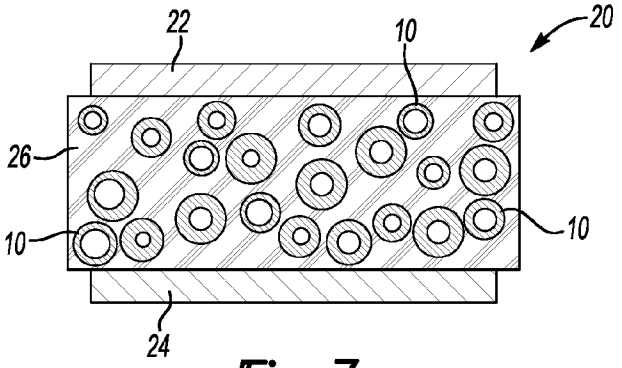


Fig-7

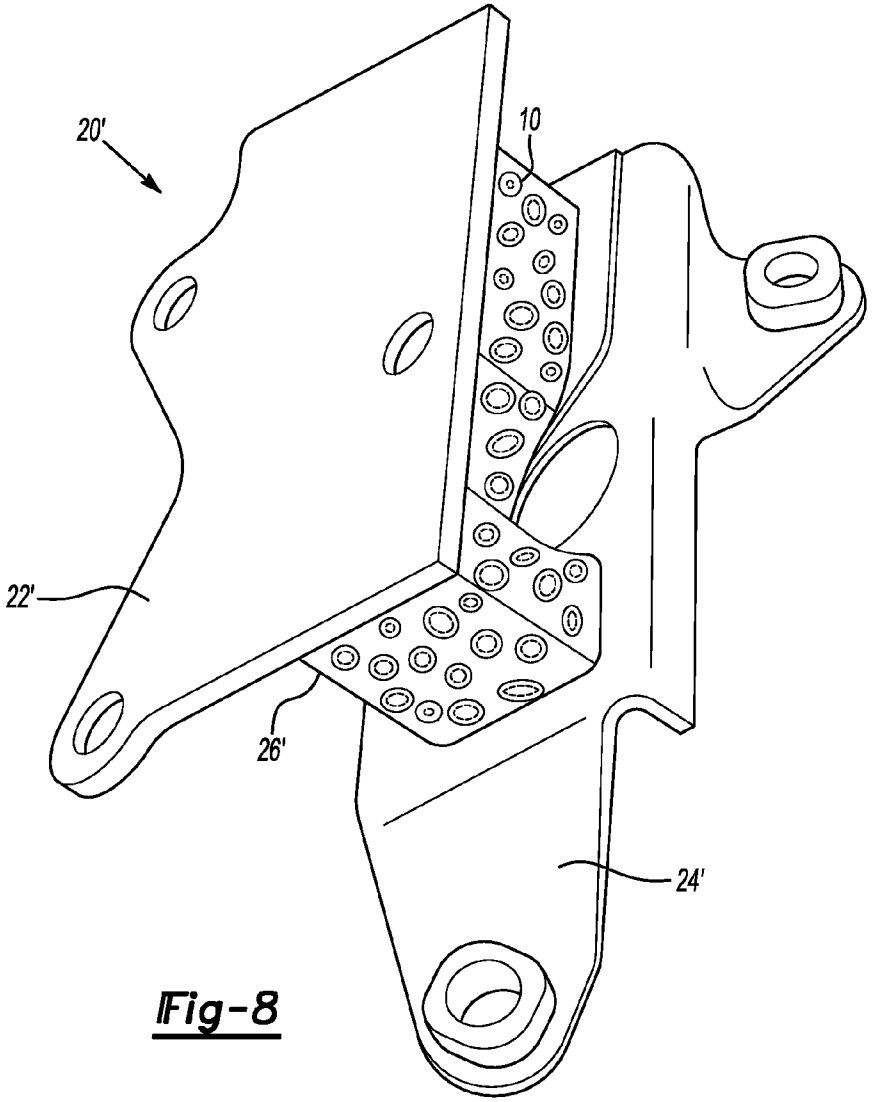
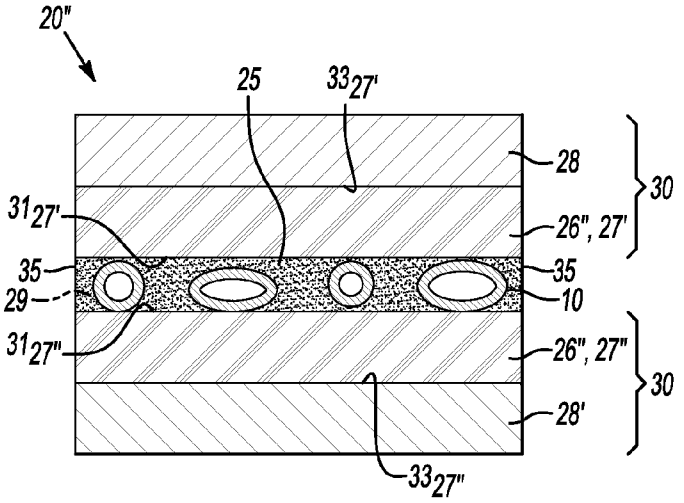


Fig-8


20"
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$33_{27'}$
28
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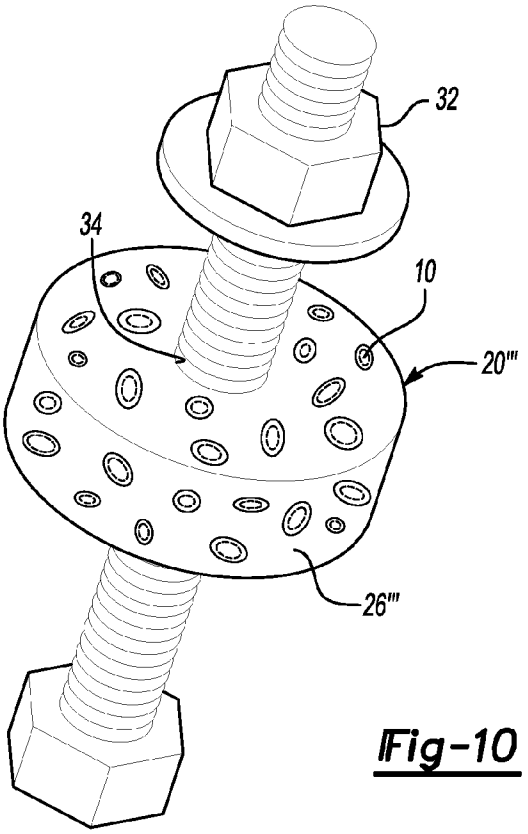
Fig-9


32
34
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20'''
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Fig-10

APPARATUSES INCLUDING HOLLOW SHAPE MEMORY ALLOY PARTICLES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part of co-pending U.S. patent application Ser. No. 13/686,849, filed Nov. 27, 2012, which itself claims the benefit of U.S. Provisional Application Ser. No. 61/576,123, filed Dec. 15, 2011, each of which is incorporated by reference herein in its entirety.

TECHNICAL FIELD

[0002] The present disclosure relates generally to apparatuses including hollow shape memory alloy particles.

BACKGROUND

[0003] A shape memory alloy is an alloy material that can be deformed, and then return to its original, pre-deformed shape when exposed to a suitable stimulus (e.g., heat). Shape memory alloys may be one-way materials that remember a single shape and that require deformation to create, for example, a low-temperature shape. Shape memory alloys may also be two-way materials that remember two different shapes, for example, one at low temperatures, and one at high temperatures.

SUMMARY

[0004] An apparatus is disclosed herein. The apparatus includes an elastic medium. The apparatus further includes hollow particles of a shape memory alloy (SMA) at least to dampen any of sound wave propagation through the elastic medium or vibration transmitted through the elastic medium. The hollow particles are incorporated into the elastic medium. The SMA has an Austenite finish temperature (A_f) that is lower than a temperature encountered in an application in which the apparatus is used so that the SMA exhibits stress-induced superelasticity.

[0005] Also disclosed herein are other examples of the apparatus.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Features and advantages of examples of the present disclosure will become apparent by reference to the following detailed description and the drawings, in which like reference numerals correspond to similar, though perhaps not identical, components. For the sake of brevity, reference numerals or features having a previously described function may or may not be described in connection with other drawings in which they appear.

[0007] FIG. **1**A is a stress and temperature based phase diagram for a shape memory alloy;

[0008] FIG. **1**B is a graphical illustration of properties of a shape memory alloy in a superelastic mode;

[0009] FIG. **2** is a cross-sectional, schematic illustration of the behavior of an example of the hollow superelastic SMA particle according to the present disclosure;

[0010] FIG. **3** is a cross-sectional view of an example of the hollow superelastic SMA particle having an irregular geometric shape;

[0011] FIG. **4** is a cross-sectional view of an example of the hollow superelastic SMA particle having pores formed in the outer shell;

[0012] FIG. **5** is a cross-sectional view of an example of the hollow superelastic SMA particle having an incomplete outer shell;

[0013] FIG. **6** is a cross-sectional view of an example of the hollow superelastic SMA particle having an outer shell with a varying wall thickness;

[0014] FIG. **7** is a schematic, cross-sectional view of an example of an apparatus including examples of the hollow superelastic SMA particles according to the present disclosure;

[0015] FIG. **8** is a semi-schematic, perspective view of an example of a motor mount according to the present disclosure;

[0016] FIG. **9** is a schematic, cross-sectional view of another example of an apparatus including examples of the hollow superelastic SMA particles according to the present disclosure; and

[0017] FIG. **10** is a semi-schematic, perspective view of still another example of an apparatus including examples of the hollow superelastic SMA particles according to the present disclosure.

DETAILED DESCRIPTION

[0018] Example(s) of the apparatuses disclosed herein include an elastic medium and shape memory alloy (SMA) particles, which exhibit stress-induced superelasticity (discussed further below). For purposes of the instant disclosure, the SMA may be referred to herein as a superelastic shape memory alloy (or superelastic SMA).

[0019] The apparatus(es) may be used in a variety of applications ranging from cars, trucks, watercraft, all-terrain vehicles, aircraft, etc. Example apparatuses may serve in passively damping structurally transmitted energy, resulting, for example, from acoustic and road vibration. In these instances, the apparatuses may reduce the magnitude of sound wave propagation therethrough and/or vibrations transmitted therethrough, and thus may reduce the noise generated in the vehicles and/or the displacement of occupants and/or cargo in the vehicles. The apparatus(es) disclosed herein may also serve in damping structurally transmitted energy due to inputs of a single non-varying frequency (i.e., impact loads) or inputs of time-varying vibrations with multiple and/or varying frequencies. These apparatuses may be used in isolation and mounting elements, including powertrain mounts, bumper elements, closure stops, bushings, gaskets, snubbers, etc. As illustrated by these few examples, the apparatuses with superelastic SMA particles disclosed herein may be useful in a variety of industries, including, for example, the automotive industry, the construction industry, and the aerospace industry.

[0020] One advantage of superelastic SMA particles is that they may be suitable for long term use, even after multiple deformations. This is due to the ability of the particles to return to their original pre-deformed shape once a stimulus is removed. As such, the SMA particles are able to maintain their functionality after multiple deformations. This particular property will be discussed further below.

[0021] In plots of stress versus strain for superelastic SMA particles, any cyclic variation in stress creates a loop on the plot. The area of that loop is equal to the mechanical energy dissipated as heat. It has been found that during superelastic

deformation (discussed in detail below), internal interfaces between the Austenite and Martensite phases dissipate a substantial amount of available mechanical energy during their formation and motion. It is believed that up to 50% energy dissipation may be exhibited. The percent of the energy that is dissipated in a stress-strain cycle may be increased when the SMA hollow spheres are pre-stressed sufficiently in their packaged configuration. For example, pre-stressing may be accomplished by an external load, e.g., resulting from the packaged configuration supporting an engine block. In this configuration, the deformation cycle experienced by the SMA particle in the application of use starts beyond the small percentage deformation (approximately 1 percent) purely elastic response of the superelastic SMA. It is also believed that the dissipation of mechanical energy may impart some mechanical damping characteristics to the superelastic SMA. It is believed that the hollow superelastic SMA particles disclosed herein may advantageously be incorporated into automotive or other apparatuses for damping of sound wave propagation and/or vibrations, due, at least in part, to the presence of these damping characteristics. As an example, the hollow superelastic SMA particles may be packed in an elastic medium in order to dissipate energy.

[0022] In an example, it is believed that the SMA may dampen low frequencies, such as from about 1 hertz to about 200 hertz for vibrations (e.g., road-induced vibrations). The SMA particles are also capable of dampening higher frequency vibrations, and are not limited to the low frequencies. Damping may be achieved across such wide frequency ranges, for example, when a plurality of the hollow superelastic SMA particles having a size distribution is utilized (i.e., larger particles and smaller particles) and/or when a plurality of hollow superelastic SMA particles having a wall thickness distribution is utilized (i.e., hollow particles having thinner walls and hollow particles having thicker walls). It is to be understood that the thinner the wall thickness, the higher the frequency range for which damping can occur. It is believed that this is due to the inverse dependence—inertial effect—of the wall displacement on its thickness, and thus in SMA strain produced at any frequency. These examples are non-limiting, and it is believed that there is no upper limit on the frequency that can be dampened in impacts.

[0023] Superelastic SMAs, while in the superelastic state, are highly deformable, and exhibit shape memory characteristics; i.e., they have the ability to recover their original geometry after the deformation when subjected to an appropriate stimulus (i.e., when stress that causes the deformation is removed). It is believed that the hollow superelastic SMA particles in the examples disclosed herein may exhibit high wear resistance, high strength, high cycle fatigue life, high fracture toughness, and/or high mechanical hysteresis (i.e., will be effective in damping vibrations and reducing sound transmission/propagation).

[0024] It is to be understood that because the superelastic form of SMA is substantially independent of deformation rate, the apparatuses of the present disclosure are essentially totally passive devices and need no external wiring or controller.

[0025] It is further believed that the superelastic SMA particles having a hollow geometric form reduce the overall weight of the apparatus in which they are included, and may also enhance the structural life of the apparatus, e.g., in response to a physical impact. For instance, while exhibiting stress-induced superelasticity (which will be described in further detail below), the SMA enhances energy absorption (e.g., by the flexibility of the hollow SMA particles) when the apparatus is exposed to some type of physical impact. The enhancement in energy absorption may thus increase a crush efficiency of the apparatus, which may in turn increase the elastic limit and ultimate strain (i.e., the strain that the apparatus or material may be subjected to before the strain overcomes the structural integrity of the apparatus). In this way, the apparatus including the superelastic SMA may be able to dissipate and absorb energy associated with higher energy impacts than those apparatuses that do not include the superelastic SMAs.

[0026] It is generally known that SMAs are a group of metallic materials that are able to return to a defined shape, size, etc. when exposed to a suitable stimulus. SMAs undergo phase transitions in which yield strength (i.e., stress at which a material exhibits a specified deviation from proportionality of stress and strain), stiffness, dimension, and/or shape are altered as a function of temperature. In the low temperature or Martensite phase, the SMA is in a deformable phase, and in the high temperature of Austenite phase, the SMA returns to the remembered shape (i.e., prior to deformation). SMAs are also stress-induced SMAs (i.e., superelastic SMAs), which will be described further hereinbelow.

[0027] When the shape memory alloy is in the Martensite phase (shown at reference numeral **300** in FIG. **1**A) and is heated, it begins to change into the Austenite phase (shown at reference numeral **400** in FIG. **1**A). The Austenite start temperature (A_s, **400'** in FIG. **1**A) is the temperature at which this phenomenon starts, and the Austenite finish temperature (A_f, **400"** in FIG. **1**A) is the temperature at which this phenomenon is complete. When the shape memory alloy is in the Austenite phase **400** and is cooled, it begins to change into the Martensite phase **300**. The Martensite start temperature (M_s, **300'** in FIG. **1**A) is the temperature at which this phenomenon starts, and the Martensite finish temperature (M_f, **300"** in FIG. **1**A) is the temperature at which this phenomenon finishes.

[0028] FIG. **1**A illustrates a stress (shown at reference numeral **100**) and temperature (shown at reference numeral **200**) based phase diagram for a shape memory alloy. The SMA horizontal line (shown at **500** in FIG. **1**A represents the temperature based phase transition between the Martensitic state **300** and the Austenitic state **400** at an arbitrarily selected level of stress **100**. In other words, this line **500** illustrates the temperature based shape memory effect previously described herein.

[0029] Superelasticity occurs when the SMA is mechanically deformed at a temperature that is above the A_f, **400"** of the SMA. In an example, the SMA is superelastic from the A_f, **400"** of the SMA to about A_f, **400"** plus 50° C. The SMA material formulation may thus be selected so that the range in which the SMA is superelastic spans a major portion of a temperature range of interest for an application in which the hollow superelastic SMA particles (or an apparatus including the hollow superelastic SMA particles) will be used. As an example, it may be desirable to select an SMA having an A_f, **400"** of 0° C. so that the superelasticity of the material is exhibited at temperatures ranging from 0° C. to about 50° C. Other examples of suitable SMA materials have an Austenite finish temperature A_f, **400"** ranging from a cryogenic temperature (e.g., −150° C.) to in excess of 150° C.

[0030] This type of deformation (i.e., mechanical deformation at a temperature that is above the A_f, **400"** of the SMA) causes a stress-induced phase transformation from the Aus-

tenite phase **400** to the Martensite phase **300** (vertical line **600** in FIG. **1**A). Application of sufficient stress **100** when an SMA is in its Austenite phase **400** will cause the SMA to change to its lower modulus Martensite phase **300** in which the SMA can exhibit up to 8% of "superelastic" deformation (i.e., recoverable strains on the order of up to 8% are attainable). The stress **100** in the SMA particles, as well as the particle diameter and wall thickness, may contribute to how much strain the particles can undergo while retaining their superelastic ability to return to the pre-deformed shape. For most SMA particles, a stress level at least less than 100 ksi (kilo pounds per square inch) helps the particles maintain reversible deformation cycles. For example, if the stress level is below 25 ksi, the particles can undergo millions of reversible deformation cycles.

[0031] The stress-induced Martensite phase **300** is unstable at temperatures above the A_f, **400"**, so that removal of the applied stress **100** will cause the SMA to switch back to its Austenite phase **400**. The application of an externally applied stress causes the Martensite phase **300** to form at temperatures higher than the Martensite start temperature **300'** associated with a zero stress state (see FIG. **1**A). As such, the Martensite start temperature M_s, **300'** is a function of the stress **100** that is applied. Superelastic SMAs are able to be strained several times more than ordinary metal alloys without being plastically deformed. However, this characteristic is observed over a specific temperature range of A_f, **400"** to A_f, **400"**plus 50° C., and the largest ability to recover occurs within this range.

[0032] The physical properties of one SMA in superelastic mode are graphically illustrated in FIG. **1**B, and a schematic illustration of the deformation and subsequent shape recovery of one hollow superelastic SMA particle $\mathbf{10}_1$ is shown in FIG. **2** (where T, or **200**, is less than A_f, or **400"**, **100** indicates the application of stress, and the crossed out **100** indicates that the stress has been removed).

[0033] In FIG. **1**B, the SMA is a nickel titanium alloy having an Austenite finish temperature of 0° C. In FIG. **1**B the y-axis indicates stress or pressure in GPa and the x-axis indicates percentage change in strain. At an activation stress level, the SMA exhibits a stress-induced phase change from the high modulus Austenitic phase to the low modulus Martensitic phase, and an accompanying significant reversible stretching, with little further increase in stress. In other words, the SMA deforms pseudoelastically and reversibly, up to 8%, at a nearly constant stress.

[0034] More specifically, in FIG. **1**B, line **2** illustrates a 7% change in strain during deformation of the SMA under an activation stress of approximately 0.4 GPa and at a temperature of about 30° C. At line **4** in FIG. **1**B, the SMA reverses the deformation at a return stress of approximately 0.2 GPa and at a temperature of about 30° C. Also in FIG. **1**B, line **6** illustrates an almost 8% change in strain during deformation under an activation stress of approximately 0.6 GPa and at a temperature of about 50° C. Line **8** illustrates the SMA reversing the deformation at a return stress of approximately 0.36 GPa and at a temperature of about 50° C.

[0035] The example shown in FIG. **1**B is one example, and it is to be understood that the temperature at which the SMA remembers its high temperature form may be altered, for example, by changing the composition of the alloy and through heat treatment. The composition of an SMA may be controlled to provide an A_f that is below the operating temperature of the application in which the particles are being used, so that the SMA particles will behave superelastically when sufficient stress is applied. In an example, the A_f is selected to be within about 5° C. below the operating temperature of the application in which the superelastic SMA particles are being used. Suitable application temperatures vary by internal and external conditions, but may, for example, range from about −40° C. to in excess of 130° C.

[0036] As mentioned above (and as shown in FIG. **1**B), the hollow superelastic SMA particles exhibit stress-induced superelasticity when at temperatures greater than the Austenite finish temperature (A_f) of the particular SMA. Some examples of the superelastic SMA that may be used herein include nickel-titanium based alloys, indium-titanium based alloys, nickel-aluminum based alloys, nickel-gallium based alloys, copper based alloys (e.g., copper-zinc alloys, copper-aluminum alloys, copper-gold, and copper-tin alloys), gold-cadmium based alloys, silver-cadmium based alloys, indium-cadmium based alloys, manganese-copper based alloys, iron-platinum based alloys, iron-palladium based alloys, and the like. Some specific examples include alloys of copper-zinc-aluminum-nickel, copper-aluminum-nickel, nickel-titanium, zinc-copper-gold-iron, gold-cadmium, iron-platinum, titanium-niobium, gold-copper-zinc, iron-manganese, zirconium-cobalt, zinc-copper, and titanium-vanadium-palladium. Examples of nickel-titanium based alloys include alloys of nickel and titanium, alloys of nickel, titanium, and platinum, alloys of nickel, titanium, and palladium, or alloys of nickel, titanium and at least one other metal.

[0037] As shown in all of FIGS. **2** through **6**, the hollow superelastic SMA particles $\mathbf{10}_1$, $\mathbf{10}_2$, $\mathbf{10}_3$, $\mathbf{10}_4$, $\mathbf{10}_5$ include an outer shell **12** fully or partially surrounding a hollow interior **14**. The outer shell **12** may be complete (shown as **12**) or incomplete (**12'**). A complete shell **12** has a continuous, non-porous exterior. The surface of the complete shell **12** may be smooth or may have surface irregularities, such as protrusions, bumps, indentations, dimples, or cavities, formed therein. The surface irregularities of the complete shell **12** may be protrusions, bumps, etc. extending out of the surface of the complete shell or dents, cavities, dimples, etc. formed in the surface of the complete shell **12**, but these irregularities do not extend through the shell **12** to the interior **14**. It is believed that the presence of surface irregularities may help produce an enhanced mechanical component of interaction (mechanical interlock), which allows force to transfer between individual particles as well as the particles and the surrounding material in which they are embedded more easily. Examples of complete shells **12** are shown in FIGS. **2**, **3** and **6**. The example shown in FIG. **3** has a deeply curved, but complete surface.

[0038] An incomplete shell **12'** may include pore(s), hole (s), crack(s), void(s), gap(s), etc. that extend from the surface of the outer shell **12'** through the thickness of the outer shell **12'** so that the hollow interior **14** of the particle is exposed. An incomplete shell **12'** may include a single pore, hole, crack, etc., or may include a plurality of pores, holes, cracks, etc. Examples of incomplete shells **12'** are shown in FIGS. **4** and **5**. In particular, FIG. **4** illustrates a plurality of pores **16**, and FIG. **5** illustrates a single crack, break, gap, etc. **18** in the outer shell **12'**.

[0039] The superelastic SMA may have any regular geometric shape (e.g., including regular three-dimensional shapes) or any irregular geometric shape (including irregular three-dimensional shapes). As examples, the hollow superelastic SMA particles may be perfectly or imperfectly shaped

hollow spheres, hollow prisms, hollow pyramids, hollow cylinders, etc. As other examples, the exterior surface of the particles may be curved, angular, or combinations thereof. An example of a hollow particle $\mathbf{10}_1$ having a regular geometric shape is shown in FIG. **2** while an example of a hollow particle $\mathbf{10}_2$ having an irregular geometric shape is shown in FIG. **3**. In some cases, the hollow particles within a plurality of particles include at least some different and random shapes (e.g., some particles are spheres, some are cylinders, some particles are irregularly shaped, etc.).

[0040] It is believed that hollow particles have a relatively low mass due to a relatively thin wall (i.e., shell) thickness and a lower net density of the individual SMA particles $\mathbf{10}_1$, $\mathbf{10}_2$, $\mathbf{10}_3$, $\mathbf{10}_4$, $\mathbf{10}_5$. In an example, if the wall thickness is less than 5% of the radius of the particle $\mathbf{10}_1$, $\mathbf{10}_2$, $\mathbf{10}_3$, $\mathbf{10}_4$, $\mathbf{10}_5$, the mass/weight of the particle $\mathbf{10}_1$, $\mathbf{10}_2$, $\mathbf{10}_3$, $\mathbf{10}_4$, $\mathbf{10}_5$ will be less than the mass/weight of an equivalent volume of a typical lubricating oil. As such, the hollow superelastic SMA particles $\mathbf{10}_1$, $\mathbf{10}_2$, $\mathbf{10}_3$, $\mathbf{10}_4$, $\mathbf{10}_5$ may impart little weight to the object, material, etc. in which the particles are included.

[0041] While the desirable wall thickness of the hollow superelastic SMA particles $\mathbf{10}_1$, $\mathbf{10}_2$, $\mathbf{10}_3$, $\mathbf{10}_4$, $\mathbf{10}_5$ may vary depending upon the application in which the particles $\mathbf{10}_1$, $\mathbf{10}_2$, $\mathbf{10}_3$, $\mathbf{10}_4$, $\mathbf{10}_5$ are used, as an example, the wall thickness may range from about 1 μm to about 500 μm. This range may vary depending upon the total size (e.g., the diameter measured from one side of the exterior surface to another side of the exterior surface, or the average diameter calculated using a plurality of diameter measurements) of the particle $\mathbf{10}_1$, $\mathbf{10}_2$, $\mathbf{10}_3$, $\mathbf{10}_4$, $\mathbf{10}_5$. The lower limit of wall thickness may range from about 5% of the radius of the particle to less than 100% of the radius of the particle. When the wall thickness exceeds 20% of the radius, the particles tend to exhibit more stiffness. In general, stiffness approaches its greatest value when the radius of the interior **14** shrinks to nearly zero. As such, the wall thickness may be varied depending upon a desirable stiffness of the hollow superelastic SMA particles. A varying wall thickness is shown in FIG. **6**, where some portions of the outer shell **12** are thicker than other portions of the outer shell **12**.

[0042] It is to be understood that the size of the superelastic SMA particles **10** (i.e., SMA particles $\mathbf{10}_1$, $\mathbf{10}_2$, $\mathbf{10}_3$, $\mathbf{10}_4$, $\mathbf{10}_5$) used in a single application may be relatively consistent or may vary (i.e., a distribution of particle sizes may be used). The particle size generally refers to the diameter of the particle **10** measured from one point on the exterior surface of the outer shell **12**, **12'** to another point on the exterior surface of the outer shell **12**, **12'**. When the particle has an irregular shape, an average diameter may be taken to determine the size of the particle. For prism shaped and pyramid shaped particles, the size may be determined using the volume. As an example, the particles **10** disclosed herein may have a size or an average size ranging from about 20 μm to about 20 mm. The size of the particles **10** may also depend upon the application in which the particles **10** are to be used.

[0043] While a variety of different shapes and configurations of the particles **10** have been described, it is to be understood that the form of the particle **10** may be dictated by the application in which the particle **10** is to be used. For example, superelastic SMA particles having a complete shell **12** may be desirable in applications where light weight is desirable. For another example, SMA particles **10** having varying sizes and wall thicknesses may be desirable in applications in which it is desirable to dampen multiple forcing frequencies, such as multiple acoustic frequencies.

[0044] In one example, the hollow SMA particles $\mathbf{10}_1$, $\mathbf{10}_2$, $\mathbf{10}_3$, $\mathbf{10}_4$, $\mathbf{10}_5$ are prepared by obtaining hollow sacrificial substrates, which are commercially available, such as hollow aluminum oxide or glass spheres. Then, SMA materials may be spray deposited on the hollow sacrificial substrates. In an example, the SMA materials may be composed of nickel and titanium powders (or other SMA material powders, such as indium and titanium, nickel and aluminum, etc.) present in about an equal mass percentage and having a size of less than or equal to about 2 microns to 3 microns. The SMA material may also be a powdered nickel-titanium alloy containing about an equal atomic proportion (within 1% to 0.1% depending on the desired phase transition temperature) of two or more materials (e.g., Ni and Ti). Then, an annealing step is performed by heating the spheres. For nickel-titanium spheres, the temperature for annealing is at least 400° C.

[0045] In another example of making the hollow particles $\mathbf{10}_1$, $\mathbf{10}_2$, $\mathbf{10}_3$, $\mathbf{10}_4$, $\mathbf{10}_5$, a core material may be used that is a sacrificial scaffolding/template. The template enables the formation of the outer shell **12**, **12'**. For example, the shell **12**, **12'** may be deposited on the core using any suitable technique. In this example, if the outer shell is an incomplete outer shell **12'**, then the sacrificial scaffolding/template may be removed through the pore(s), hole(s), etc. to obtain the hollow particle. Removal of the sacrificial scaffolding/template may depend upon the material of which the scaffolding/template is formed. As an example, removal may be accomplished if the sacrificial scaffolding/template is a brittle material, such as a ceramic. In this case, deforming the shell **12'** will cause the scaffolding/template to break. Performing deformation multiple times may break the scaffolding/template into small particles that can be removed through the pore(s), hole(s), etc. The sacrificial scaffolding/template may also be made of a material that can be dissolved by a suitable chemical. For example, a scaffolding/template made of iron could be dissolved by adding cola and then pouring the dissolved contents out of the pore(s), hole(s), etc. to obtain the hollow interior **14**.

[0046] FIGS. **7** through **10** illustrate different examples of an apparatus **20**, **20'**, **20"**, **20'"**. In each example of the apparatus **20**, **20'**, **20"**, **20'"** described below, it is to be understood that an excitation source (not shown) may transfer energy into the apparatus **20**, **20'**, **20"**, **20'"**. The excitation source may be energy resulting from an impulse/impact, acoustic vibrations, noise, or road-induced periodic vibrations as discussed above. Upon exposure of the apparatus **20**, **20'**, **20"**, **20'"** to the excitation source, an elastic medium of the apparatus **20**, **20'**, **20"**, **20'"** forcefully communicates with, or otherwise transfers forces to the SMA particles **10**, which are present in or are at least partially surrounded by the elastic medium. When exposed to the force, the SMA particles **10** exhibit superelastic deformation, and thus serve as an energy dissipating element of the apparatus **20**, **20'**, **20"**, **20'"**.

[0047] Various configurations and combinations of SMA particles **10** may be used in the apparatuses **20**, **20'**, **20"**, **20'"** disclosed herein. In an example, the SMA particles **10** may be uniform in size and/or shape, or may have a distribution of wall thicknesses and/or sizes as discussed above. In particular, FIG. **7** shows a cross-sectional view of an example of hollow SMA particles **10** having a variety of sizes and a variety of wall thicknesses. In each of the examples disclosed herein, it is to be understood that the SMA particles **10** have an Austenite finish temperature (A_f) that is lower than a tem-

perature encountered in an application in which the apparatus **20**, **20'**, **20"**, **20'"** is used so that the SMA particles **10** exhibit stress-induced superelasticity as discussed above. It is to be further understood that any of the examples of the SMA particles (e.g., $\mathbf{10}_1$, $\mathbf{10}_2$, $\mathbf{10}_3$, $\mathbf{10}_4$, $\mathbf{10}_5$, or combinations thereof) previously described may be used in the apparatuses **20**, **20'**, **20"**, **20'"**.

[0048] With further reference to FIG. **7**, an example of the apparatus **20** is shown. The apparatus **20** includes the elastic medium **26** with the SMA particles **10** incorporated therein.

[0049] It is to be understood that the elastic medium **26** (as well as the elastic medium **26'** shown in FIG. **8**, the elastic medium **26"** shown in FIG. **9**, and the elastic medium **26'"** shown in FIG. **10**) has an elasticity that allows the elastic medium **26**, **26'**, **26"**, **26'"** to be substantially self-restoring (i.e., without exposure to some external stimulus). Further, the elastic medium **26**, **26'**, **26"**, **26'"** may reversibly stretch several times (i.e., stretching from and returning to an original dimension), depending, for example, on the particular material and geometry of the elastic medium **26**, **26'**, **26"**, **26'"**. The flexibility of the elastic medium **26**, **26'**, **26"**, **26'"** does not constrain deformation and energy dissipation of the SMA particles **10** as much as, for example, a more rigid material, such as a thermoset composite panel. In this way, it is believed that the elastic medium **26**, **26'**, **26"**, **26'"** may serve to decrease the amplitude and lengthen the period of a vibration or impact pulse input, while also allowing the SMA particles **10** to dissipate energy from the apparatus **20**, **20'**, **20"**, **20'"**.

[0050] The elastic medium **26**, **26'**, **26"**, **26'"** may be a natural or synthetic rubber. Some examples of the elastic medium **26**, **26'**, **26"**, **26'"** include cis-polyisoprene, cis-polybutadiene, poly(butadiene-styrene), poly(isobutylene-isoprene), chlorinated poly(isobutylene-isoprene), brominated poly(isobutylene-isoprene), poly(ethylene-propylene), poly (ethylene-propylenediene), chloro-sulfonyl-polyethylene, polychloroprene, poly(butadiene-acrylonitrile), hydrogenated poly(butadiene-acrylonitrile), polyethylacrylate, poly (ethylacrylateacrylonitrile), ethylene acrylic, polysulfides, fluoro compounds (e.g., fluoroelastomers (FKM), perfluoroelastomers (FFKM), or tetrafluoro ethylene/propylene rubbers (FEPM)), fluoro-vinyl polysiloxane, poly(dimethylsiloxane), poly(methylphenyl-siloxane), poly(oxydimethyl silylene), poly(polyoxymethylphenylsilylene), polyester urethane, polyether urethane, polypropylene oxide-allyl glycidyl ether), polyether block amides, polyepichlorohydrin, poly(epichlorohydrin-ethylene oxide), and ethylene vinylacetate.

[0051] As shown in FIG. **7**, the elastic medium **26** has the SMA particles **10** incorporated directly within the medium **26**. In this example, the SMA particles **10** may be present in any suitable amount so long as the SMA particles are surrounded by the medium **26** material. The percentage of particles **10** incorporated into the elastic medium **26** may depend upon the particle size(s). Smaller particles will allow for more particles to be packed into the medium **26**, and will reduce the interstitial spaces between the particles **10**.

[0052] In the example shown in FIG. **7**, the elastic medium **26** is also operatively connected to structural members **22**, **24**. In an example, the structural members **22**, **24** are adhered or otherwise secured to opposed sides of the elastic medium **26**. In another example, the structural members **22**, **24** may form a housing for the elastic medium **26** of the apparatus **20**. When the structural members **22**, **24** form the housing, it is to be understood that the elastic medium **26** may be partially or completely surrounded by the structural members **22**, **24**. In an example, the structural members **22**, **24** may be made of any material having sufficient rigidity so that the members **22**, **24** do not deform appreciably under the forces that are transmitted therethrough.

[0053] In one example, the apparatus **20** may be made by first embedding the SMA particles **10** in the elastic medium **26** while the elastic medium **26** is uncured and viscous. When the elastic medium **26** is uncured and viscous, it includes unlinked polymer chains. After the SMA particles **10** are embedded, the next step includes mechanically working the uncured elastic medium **26**, for example, by stirring or kneading, to evenly distribute the particles **10** throughout the uncured elastic medium **26**. The final step involves crosslinking by polymerizing the long polymer chains. For example, uncured natural rubber may be crosslinked by vulcanization. Vulcanizing a rubber elastic medium may be accomplished by adding sulfur and other additives to the uncured medium and heating at 170° C. while under pressure for about ten minutes.

[0054] FIG. **8** semi-schematically depicts a specific example of the apparatus **20**, namely a motor mount **20'**. The motor mount **20'** includes the elastic medium **26'** with the SMA particles **10** embedded therein. It is to be understood that the elastic medium **26'** may be any isolating material that is suitable for use in the motor mount **20'**. For example, the elastic medium **26'** in the motor mount **20'** may be chloroprene rubber, butadiene-acrylonitrile rubber, ethylene-propylene-diene rubber, and natural rubber. It is believed that other elastic medium materials may also be used.

[0055] The elastic medium **26'** may be operatively connected (e.g., bonded, fastened, etc.) to structural members **22'**, **24'**. In the example of the motor mount **20'** shown in FIG. **8**, the structural members **22'**, **24'** are a pair of mounting brackets. In particular, the mounting brackets include a vehicle frame mounting bracket **22'** and an engine mounting bracket **24'**. The brackets **22'** and **24'** may be composed of a metal, such as steel or titanium with some other suitable material with similar strength and stiffness.

[0056] It is to be understood that while the motor mount **20'** is shown in FIG. **8**, the elastic medium **26**, **26'** and SMA particles **10** may be incorporated into various other damping elements in accordance with the present disclosure. As examples, the apparatus **20** may be a bumper element, a closure stop, a bushing, a gasket, a snubber, etc. In one example, another apparatus according to the present disclosure may be a bushing with a metal sleeve serving as a housing that surrounds the elastic medium **26** with SMA particles **10** incorporated therein.

[0057] While FIGS. **7** and **8** illustrate example apparatuses **20**, **20'** with a single elastic medium **26**, **26'**, it is to be understood that other examples of the apparatus **20"** may include two layers **27'**, **27"** of an elastic medium **26"** or a housing (not shown) made of the elastic medium **26"**. An example of the apparatus **20"** including the two elastic medium layers **27'**, **27"** is shown in FIG. **9**. In this example, the elastic medium **26"** may be any of the materials previously described.

[0058] As illustrated in FIG. **9**, the layers **27'**, **27"** of the elastic medium **26"** are separated from one another so that a space **25** is defined between respective interior surfaces $\mathbf{31}_{27'}$, $\mathbf{31}_{27''}$ of the two layers **27'**, **27"** and between end(s) **35** of the apparatus **20"**. The end(s) **35** may be a resilient material, which is sufficiently flexible to elastically deform under vertical loads in the orientation shown, but which also maintains

integrity to constrain the particles **10** within the end(s) **35** while the particles **10** are being deformed in response to forces transmitted through the particles **10** under the impact loading. An example of a suitable resilient material is a spring steel. In some examples, the end(s) **35** may be defined by a continuous wall around the apparatus **20"** that operatively connects the two layers **27'**, **27"** of elastic medium **26"** (e.g., at or near the perimeter of the layers **27'**, **27"**). In other examples, the end(s) E may be defined by a multi-faceted wall with two or more surfaces sealingly connected together. The multi-faceted wall may operatively connect the two layers **27'**, **27"** of elastic medium **26"** together at or near the perimeter of the layers **27'**, **27"**. An adhesive or another securing mechanism may be used to operatively connect the material (s) that define the end(s) **35** to the two layers **27'**, **27"** of elastic medium **26"**.

[0059] In still other examples, the elastic medium **26"** may be a housing that defines the space **25**. As an example, the elastic medium **26"** may be formed as two pieces of material that are secured directly together to form a desirable shape (e.g., an enclosed cylinder) having the space **25** defined therein.

[0060] The layers **27'**, **27"** are part of a structure **30** that at least partially surrounds the space **25**. The structure **30** may also include additional layers **28**, **28'** positioned on respective outer-facing surfaces $\mathbf{33}_{27'}$, $\mathbf{33}_{27''}$ of the layers **27'**, **27"**, which are secured via a suitable adhesive or other securing mechanism. In some instances, the additional layers **28**, **28'** are configured to form a housing for the apparatus **20"**, and thus cover the end(s) in addition to the outer-facing surfaces $\mathbf{33}_{27'}$, $\mathbf{33}_{27''}$. In an example, the additional layers **28**, **28'** are adhered or otherwise secured together to form this housing. Each of the outer layers **28**, **28'** may be formed of any suitable material, including, for example, fabrics, metals, steel or other metal alloys, plastics, or composite materials.

[0061] Other layers (not shown) of the same or different materials may also be included in addition to the layers **28**, **28'**.

[0062] The layers **27'**, **27"** of elastic medium **26"** and the outer layers **28**, **28'** may be distinct layers (as shown in FIG. **9**) or may be integrated into a single layer. For example, one layer may include a mesh layer (e.g., a fabric mesh) with the elastic medium **26"** intermixed therein.

[0063] In the apparatus **20"**, the SMA particles **10** are provided in the space **25**. It is to be understood that the space **25** may be completely full of tightly packed SMA particles **10**, where the volume percentage of particles **10** corresponds to the particle size. The smaller particle size allows for more particles **10** to be packed within the space **25**, at least in part because interstitial spaces (i.e., voids) between the particles **10** are reduced. As an example, the space **25** being completely full of SMA particles **10** means that without external pressure, the SMA particle volume percentage is as high as possible without deforming the SMA particles **10**. In the example of FIG. **9**, the particles **10** are loosely packed within the space **25**.

[0064] In the apparatus **20"**, the SMA particles **10** alone may occupy the space **25**, or the SMA particles **10** may be suspended in a fluid that is incorporated into the space **25**. The fluid may assist in more uniformly loading the SMA particles **10** so that their deformation may be more global, as opposed to local deformation resulting from direct contact with neighboring particles **10**. An example of the fluid is shown in FIG. **9** by the speckles labeled **29**. Examples of the fluid include a magnetorheological fluid, water, oil, gas or any other type of fluid.

[0065] It is to be understood that the apparatus **20"** may be vented or sealed with respect to an external environment (i.e., an ambient space outside of the apparatus **20"**). In these examples, the SMA particles **10** are retained within the apparatus **20"** while air may be vented out to an environment outside of the apparatus **20"**.

[0066] FIG. **10** illustrates still another example of the apparatus **20'"**. In this example, the SMA particles **10** are embedded in the elastic medium **26"**, which has an aperture **34** defined at or near a center of the elastic medium **26'"** that extends through a thickness of the elastic medium **26'"**. Any of the materials previously described may be used for the particles **10** and the medium **26'"**. In this example, a through bolt **32** may be used to mount and hold the apparatus **20'"** to another component. As illustrated, this example of the apparatus **20'"** does not include additional structural members, ends, or housings.

[0067] It is to be understood that deformation of SMA particles **10** within the apparatus **20**, **20'**, **20"**, **20'"** may be due to direct contact with a component of the apparatus **20**, **20'**, **20"**, **20'"** or may be due to indirect contact with forces (e.g., resulting from sound waves or vibrations) exerted upon the apparatus **20**, **20'**, **20"**, **20'"**. An example of direct contact is when the elastic medium **26**, **26'**, **26"**, **26'"** of the apparatus **20**, **20'**, **20"**, **20'"** directly contacts and deforms one or more of the SMA particles **10**. Additionally, deformation of the SMA particles **10** may occur indirectly by pressurization of the SMA particles **10** within the apparatus **20**, **20'**, **20"**, **20'"**. Further, the SMA particles **10** may contact each other upon exposure of the apparatus **20**, **20'**, **20"**, **20'"** to an excitation source, which results in the deformation.

[0068] In some applications, the apparatus **20**, **20'**, **20"**, **20'"** may generate sufficient heat over multiple deformation events to raise the temperature to a high level (e.g., above 200° C. for NiTi SMA particles, although higher temperatures are contemplated for other SMAs). In such cases, the high temperature may decrease the life cycle of the SMA particles **10**. In these situations, the apparatus **20**, **20'**, **20"**, **20'"** can be surrounded by or immersed in a fluid bath (or other common heat sink) to help directly, e.g., through conductive heat transfer, cool the particles **10**.

[0069] It is to be understood that the terms "connect/connected/connection" and/or the like are broadly defined herein to encompass a variety of divergent connected arrangements and assembly techniques. These arrangements and techniques include, but are not limited to (1) the direct communication between one component and another component with no intervening components therebetween; and (2) the communication of one component and another component with one or more components therebetween, provided that the one component being "connected to" the other component is somehow in operative communication with the other component (notwithstanding the presence of one or more additional components therebetween).

[0070] Additionally, reference throughout the specification to "one example", "another example", "an example", and so forth, means that a particular element (e.g., feature, structure, and/or characteristic) described in connection with the example is included in at least one example described herein, and may or may not be present in other examples. In addition, it is to be understood that the described elements for any

example may be combined in any suitable manner in the various examples unless the context clearly dictates otherwise.

[0071] It is to be understood that the ranges provided herein include the stated range and any value or sub-range within the stated range. For example, a range from about 0° C. to about 50° C. should be interpreted to include not only the explicitly recited limits of about 0° C. to about 50° C., but also to include individual values, such as 25° C., 33° C., 43.5° C., 48° C., etc., and sub-ranges, such as from about 15° C. to about 45° C., from about 18° C. to about 35° C., etc. Furthermore, when "about" is utilized to describe a value, this is meant to encompass minor variations (up to +/−10%) from the stated value.

[0072] In describing and claiming the examples disclosed herein, the singular forms "a", "an", and "the" include plural referents unless the context clearly dictates otherwise.

[0073] While several examples have been described, it will be apparent to those skilled in the art that the disclosed examples may be modified. Therefore, the foregoing description is to be considered non-limiting.

1. An apparatus, comprising:
an elastic medium; and
hollow particles of a shape memory alloy at least to dampen any of sound wave propagation through the elastic medium or vibration transmitted through the elastic medium, the hollow particles being incorporated into the elastic medium, and the shape memory alloy having an Austenite finish temperature (A_f) that is lower than a temperature encountered in an application in which the apparatus is used so that the shape memory alloy exhibits stress-induced superelasticity.

2. The apparatus as defined in claim **1** wherein the hollow particles of the shape memory alloy have a distribution of wall thicknesses.

3. The apparatus as defined in claim **1** wherein the hollow particles of the shape memory alloy are spherical, randomly shaped, or combinations thereof.

4. The apparatus as defined in claim **1** wherein the hollow particles of the shape memory alloy have a distribution of sizes.

5. The apparatus as defined in claim **1** wherein the hollow particles of the shape memory alloy have a distribution of wall thicknesses and a distribution of sizes.

6. The apparatus as defined in claim **1** wherein the vibration is periodic and is within a range from about 1 hertz to about 200 hertz.

7. The apparatus as defined in claim **1** wherein the vibration is random.

8. The apparatus as defined in claim **1** wherein the elastic medium is selected from the group consisting of cis-polyisoprene, cis-polybutadiene, poly(butadiene-styrene), poly (isobutylene-isoprene), chlorinated poly(isobutylene-isoprene), brominated poly(isobutylene-isoprene), poly (ethylene-propylene), poly(ethylene-propylenediene), chloro-sulfonyl-polyethylene, polychloroprene, poly(butadiene-acrylonitrile), hydrogenated poly(butadiene-acrylonitrile), polyethylacrylate, poly(ethylacrylateacrylonitrile), ethylene acrylic, polysulfides, fluoro compounds (e.g., fluoroelastomers (FKM), perfluoro-elastomers (FFKM), or tetrafluoro ethylene/propylene rubbers (FEPM)), fluoro-vinyl polysiloxane, poly(dimethylsiloxane), poly(methylphenylsiloxane), poly(oxydimethyl silylene), poly(polyoxymethylphenylsilylene), polyester urethane, polyether urethane, poly(propylene oxide-allyl glycidyl ether), polyether block amides, polyepichlorohydrin, poly(epichlorohydrin-ethylene oxide), and ethylene vinyl-acetate.

9. The apparatus as defined in claim **1**, further comprising a housing surrounding at least a portion of the elastic medium.

10. An apparatus, comprising:
a structure including two elastic medium layers;
hollow particles of a shape memory alloy at least to dampen any of sound wave propagation through the structure or vibration transmitted through the structure, the hollow particles being positioned in a space defined between the two elastic medium layers, and the shape memory alloy having an Austenite finish temperature (A_f) that is lower than a temperature encountered in an application in which the apparatus is used so that the shape memory alloy exhibits stress-induced superelasticity.

11. The apparatus as defined in claim **10** wherein the hollow particles of the shape memory alloy have a distribution of wall thicknesses.

12. The apparatus as defined in claim **10** wherein the hollow particles of the shape memory alloy are spherical, randomly shaped, or combinations thereof.

13. The apparatus as defined in claim **10** wherein the hollow particles of the shape memory alloy have a distribution of sizes.

14. The apparatus as defined in claim **10** wherein the hollow particles of the shape memory alloy have a distribution of wall thicknesses and a distribution of sizes.

15. The apparatus as defined in claim **10** wherein the vibration is periodic and is within a range from about 1 hertz to about 200 hertz.

16. The apparatus as defined in claim **10** wherein the two elastic medium layers are selected from the group consisting of cis-polyisoprene, cis-polybutadiene, poly(butadiene-styrene), poly(isobutylene-isoprene), chlorinated poly(isobutylene-isoprene), brominated poly(isobutylene-isoprene), poly (ethylene-propylene), poly(ethylene-propylenediene), chloro-sulfonyl-polyethylene, polychloroprene, poly(butadiene-acrylonitrile), hydrogenated poly(butadiene-acrylonitrile), polyethylacrylate, poly(ethylacrylateacrylonitrile), ethylene acrylic, polysulfides, fluoro compounds (e.g., fluoroelastomers (FKM), perfluoro-elastomers (FFKM), or tetrafluoro ethylene/propylene rubbers (FEPM)), fluoro-vinyl polysiloxane, poly(dimethylsiloxane), poly(methylphenylsiloxane), poly(oxydimethyl silylene), poly(polyoxymethylphenylsilylene), polyester urethane, polyether urethane, poly(propylene oxide-allyl glycidyl ether), polyether block amides, polyepichlorohydrin, poly(epichlorohydrin-ethylene oxide), and ethylene vinyl-acetate.

17. The apparatus as defined in claim **10** wherein the vibration is random.

18. The apparatus as defined in claim **10** wherein each of the two elastic medium layers has an outer-facing surface, and wherein the structure further includes an outer layer positioned on each of the outer-facing surfaces.

19. The apparatus as defined in claim **10**, further comprising a fluid disposed in the space defined between the two elastic medium layers, wherein the hollow particles of the shape memory alloy are within the fluid.

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