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Benafan et al.

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(54) **SHAPE MEMORY ALLOY ROCK SPLITTERS (SMARS)**

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(52) **U.S. Cl.**
CPC ***B28D 1/327*** (2013.01); ***B28D 1/322*** (2013.01)

(58) **Field of Classification Search**
CPC B28D 1/327; B28D 1/322
USPC 125/23.01
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

1,719,257 A *	7/1929	Booth	B28D 1/221	219/200
3,580,637 A	5/1971	Itoh et al.		
4,740,036 A *	4/1988	Cerny	E21C 37/16	125/23.01
5,012,649 A	5/1991	Chevakin et al.		
5,024,388 A *	6/1991	Kaneko	E21C 37/00	125/23.01
7,624,797 B2 *	12/2009	Fay	F03G 7/065	166/134

FOREIGN PATENT DOCUMENTS

CN	101726223	6/2010
CN	201520012 U	7/2010
SU	1153061 A1	4/1985

* cited by examiner

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(74) *Attorney, Agent, or Firm* — Robert H. Earp, III

(57) **ABSTRACT**

Shape memory alloys (SMAs) may be used for static rock splitting. The SMAs may be used as high-energy multifunctional materials, which have a unique ability to recover large deformations and generate high stresses in response to thermal loads.

19 Claims, 21 Drawing Sheets

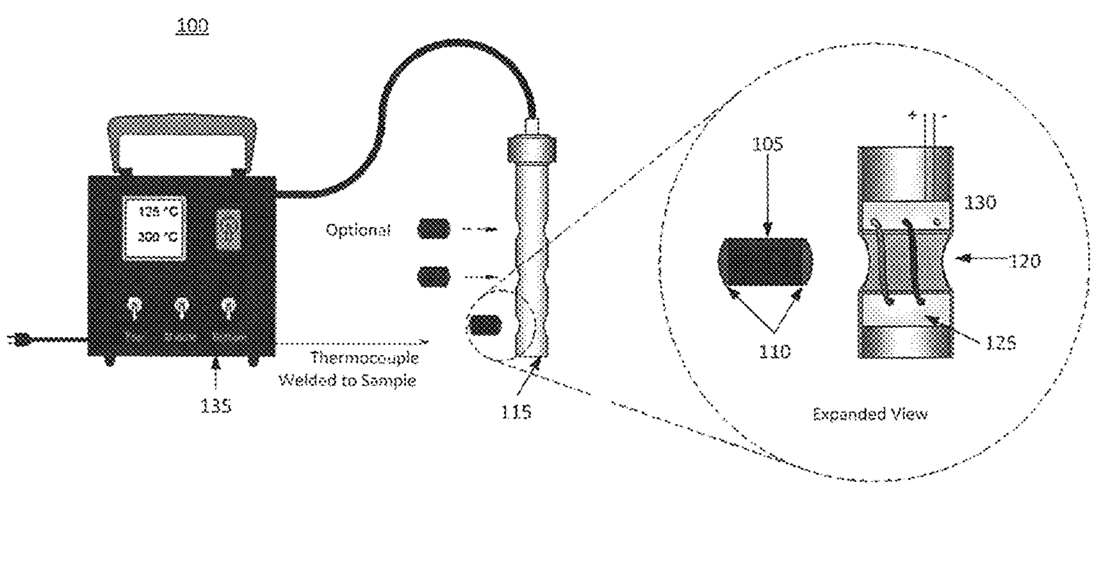


Fig. 1

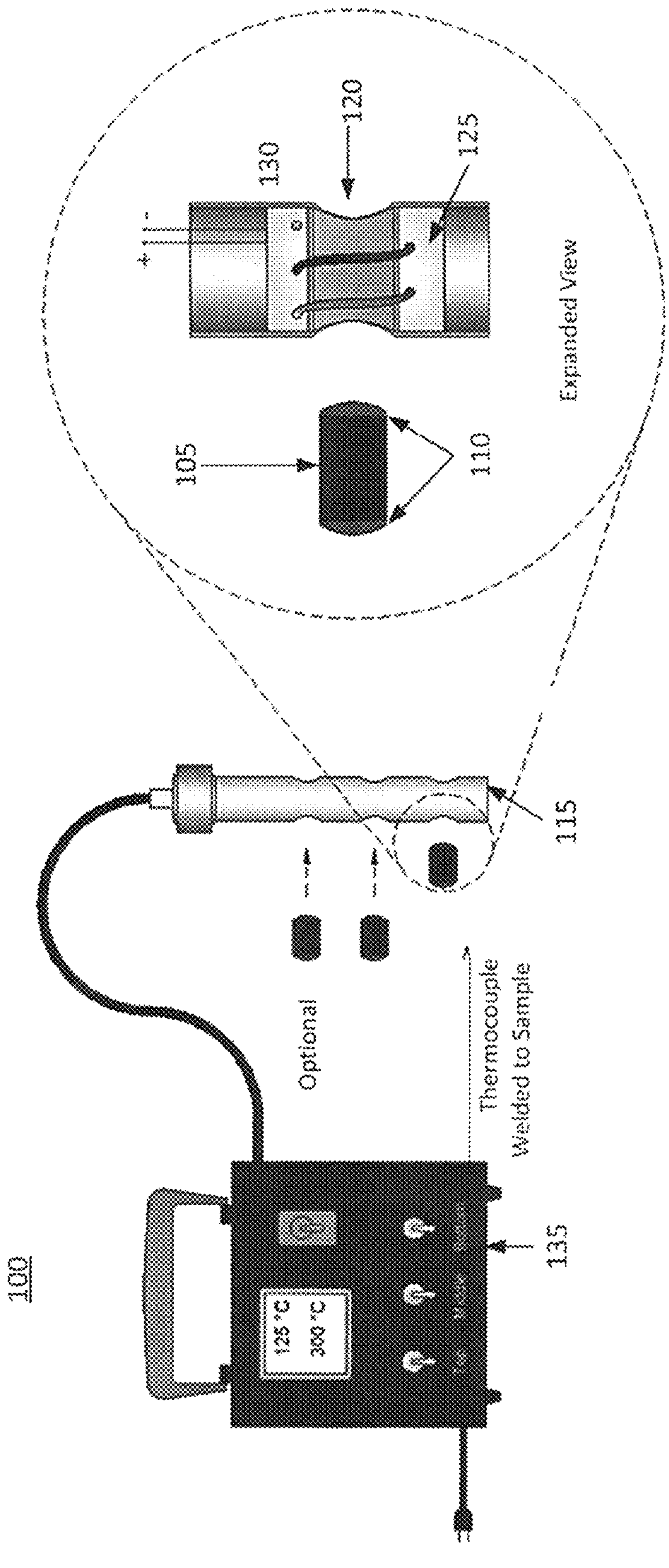
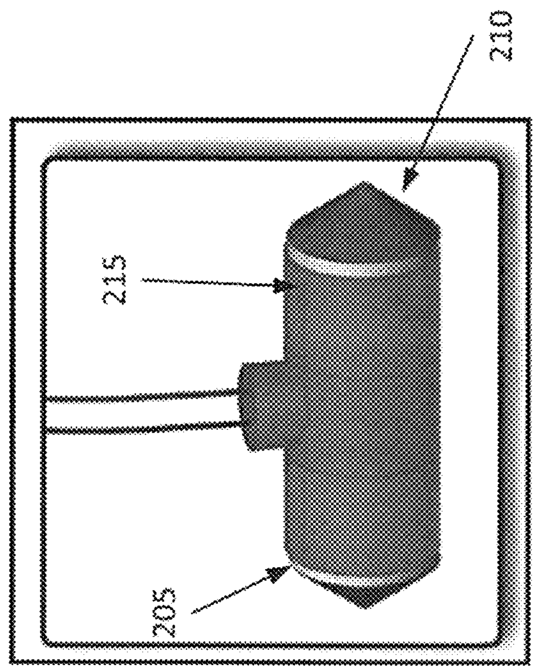

100
125 °C
300 °C
135
Optional
Thermocouple
Welded to Sample
115
105
110
Expanded View
130
120
125

Fig. 2A



200

Fig. 2B

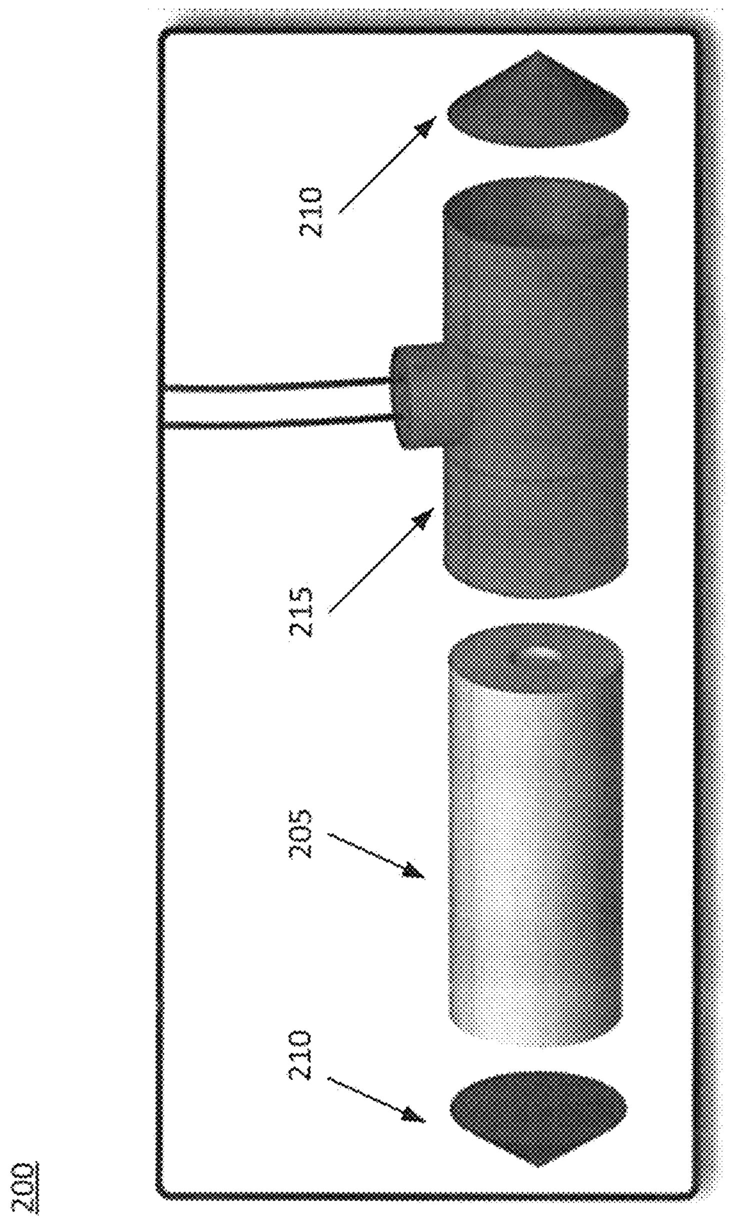


Fig. 3

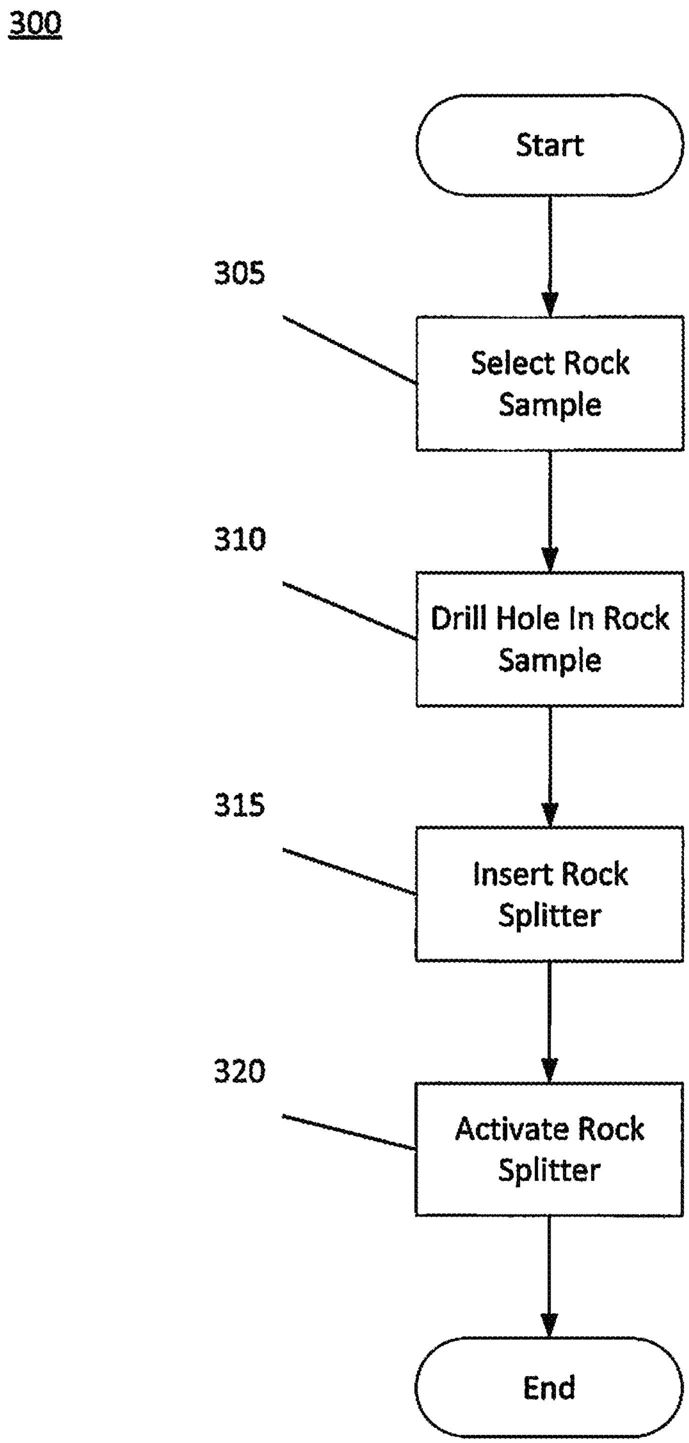

300
Start
305
Select Rock Sample
310
Drill Hole In Rock Sample
315
Insert Rock Splitter
320
Activate Rock Splitter
End

Fig. 4

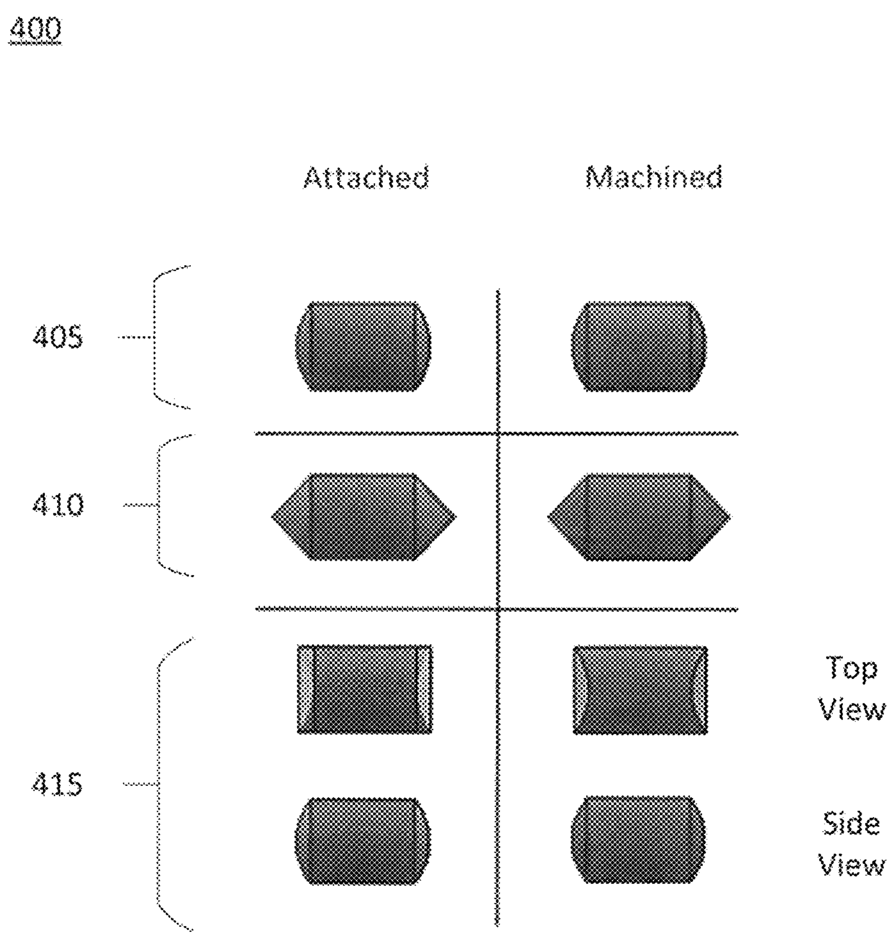


Fig. 5A

500

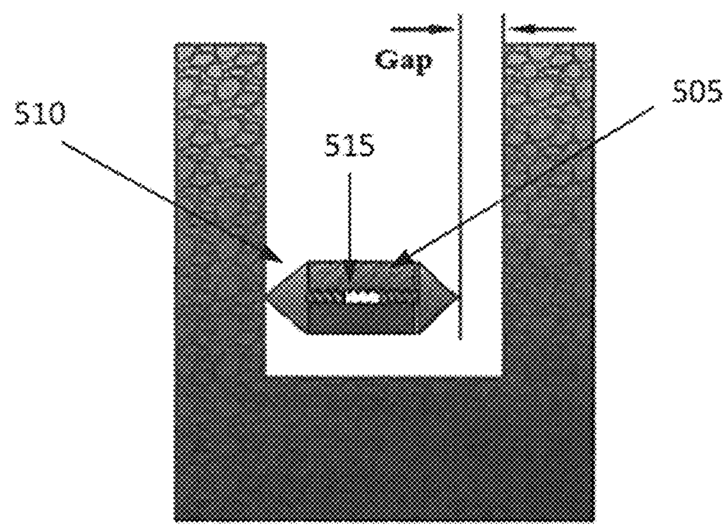


Fig. 5B

500

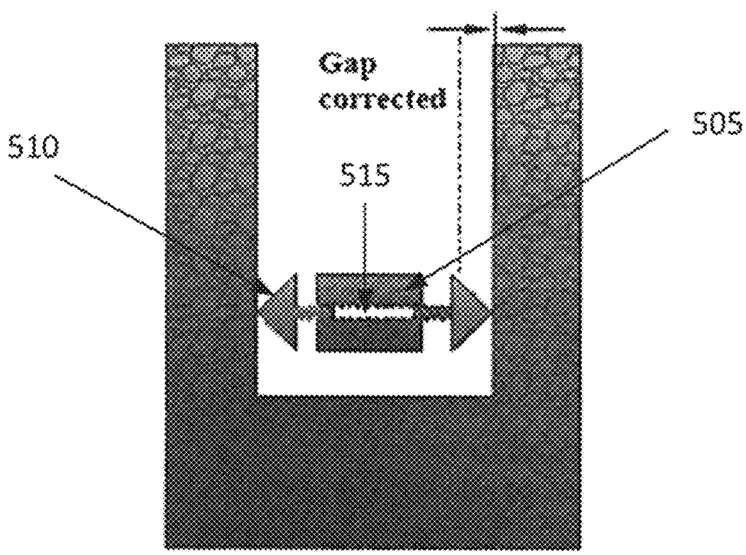


Fig. 6A

600

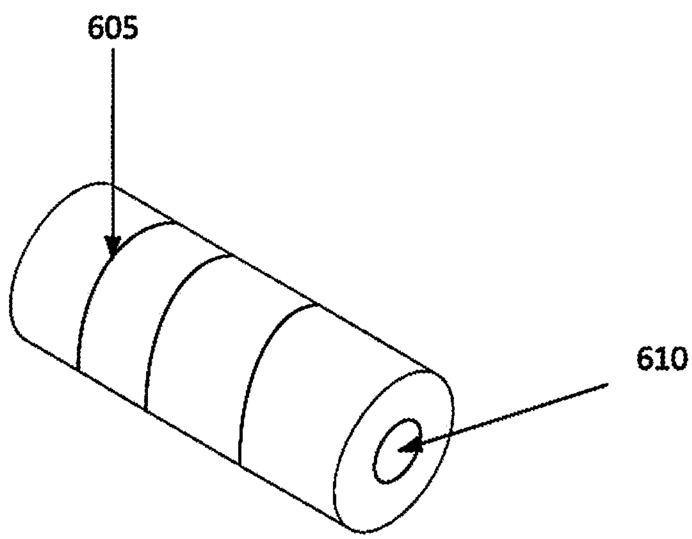


Fig. 6B

600

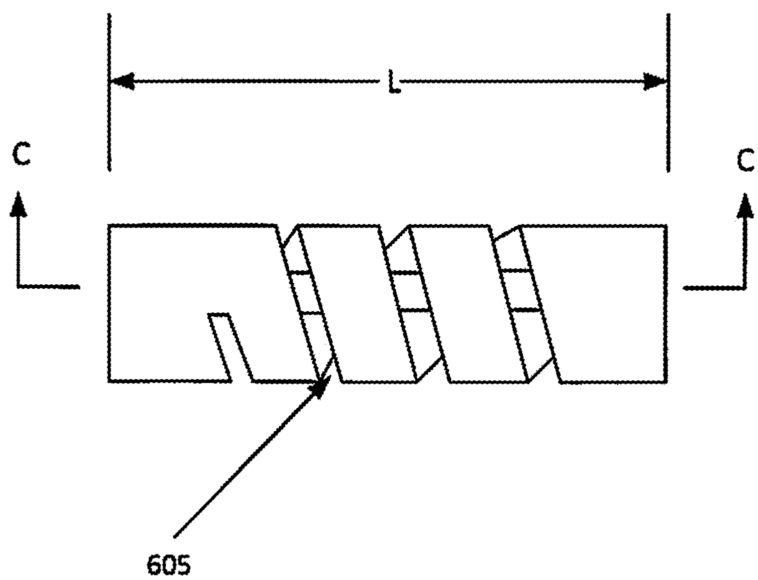


Fig. 6C

600

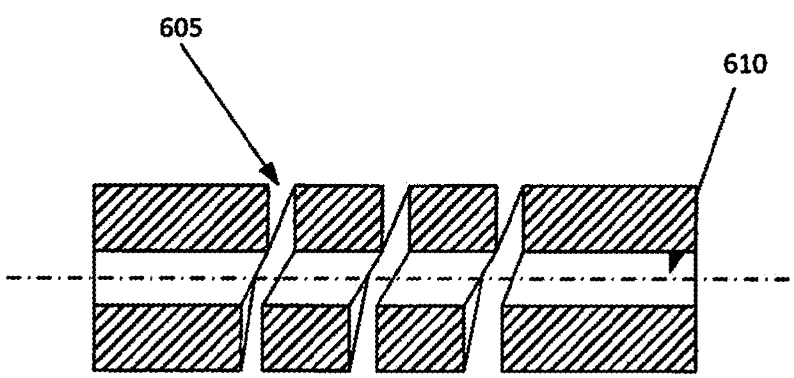


Fig. 6D

600

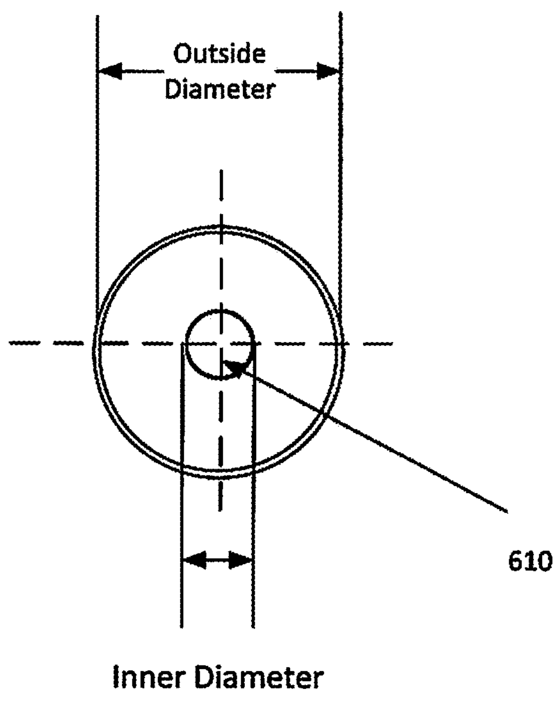


Fig. 7

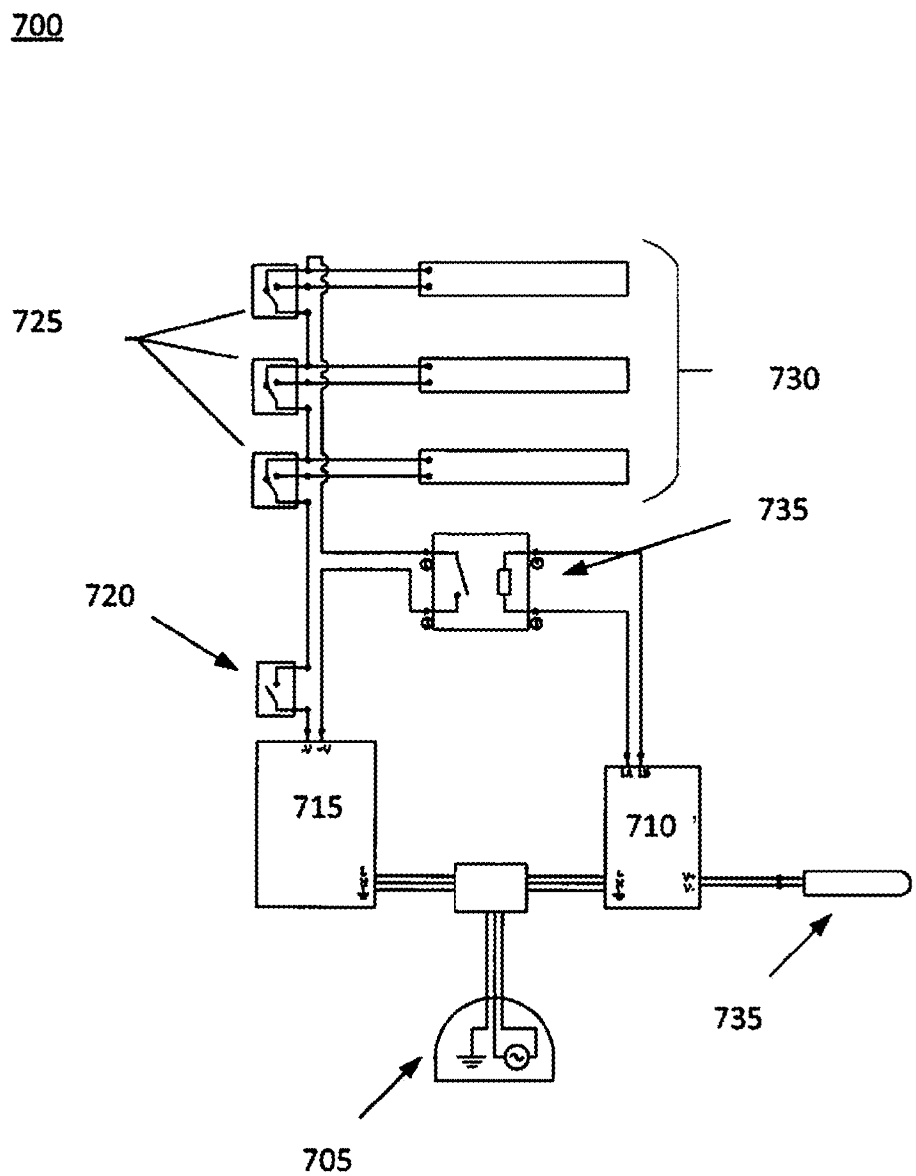


Fig. 8

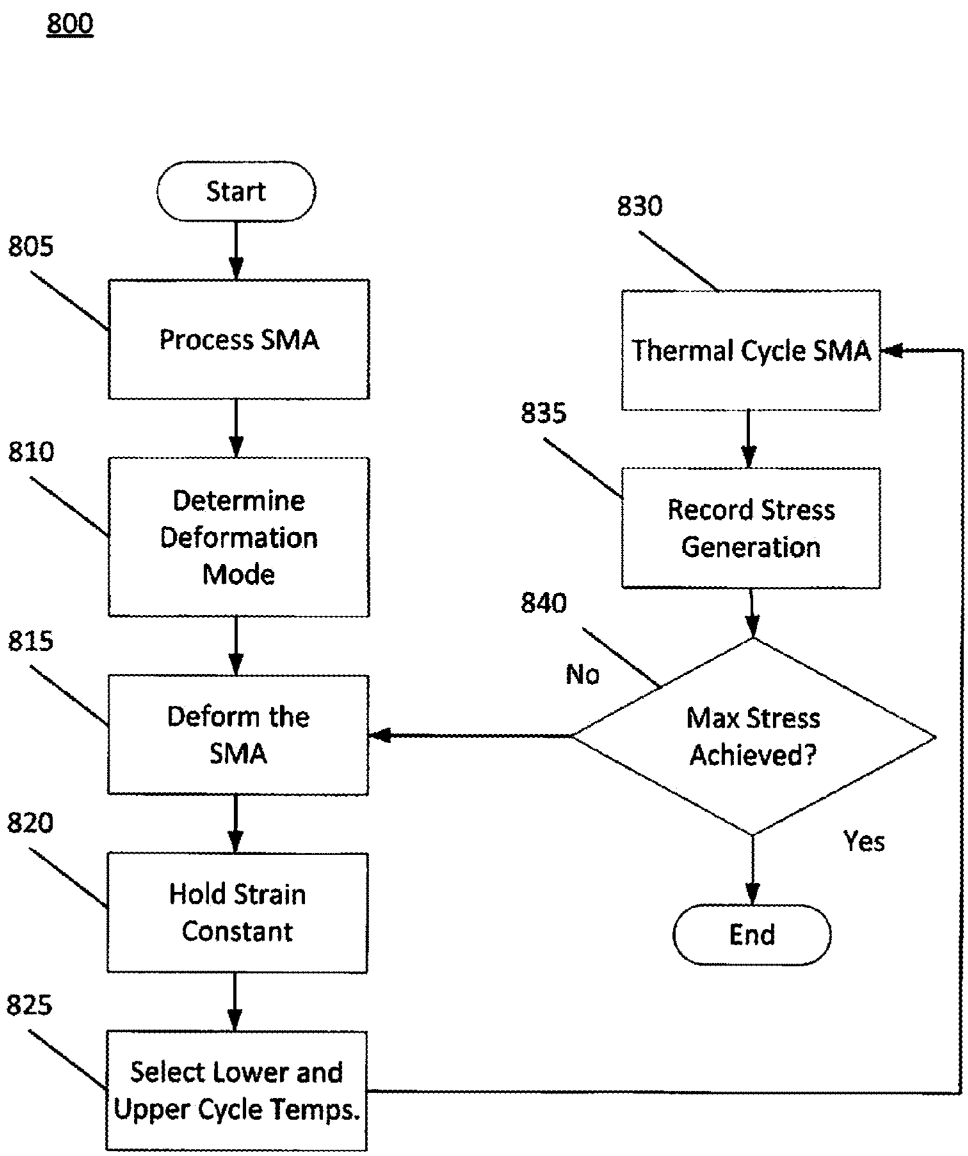

800
Start
805
Process SMA
810
Determine Deformation Mode
815
Deform the SMA
820
Hold Strain Constant
825
Select Lower and Upper Cycle Temps.
830
Thermal Cycle SMA
835
Record Stress Generation
840
No
Max Stress Achieved?
Yes
End

Fig. 9

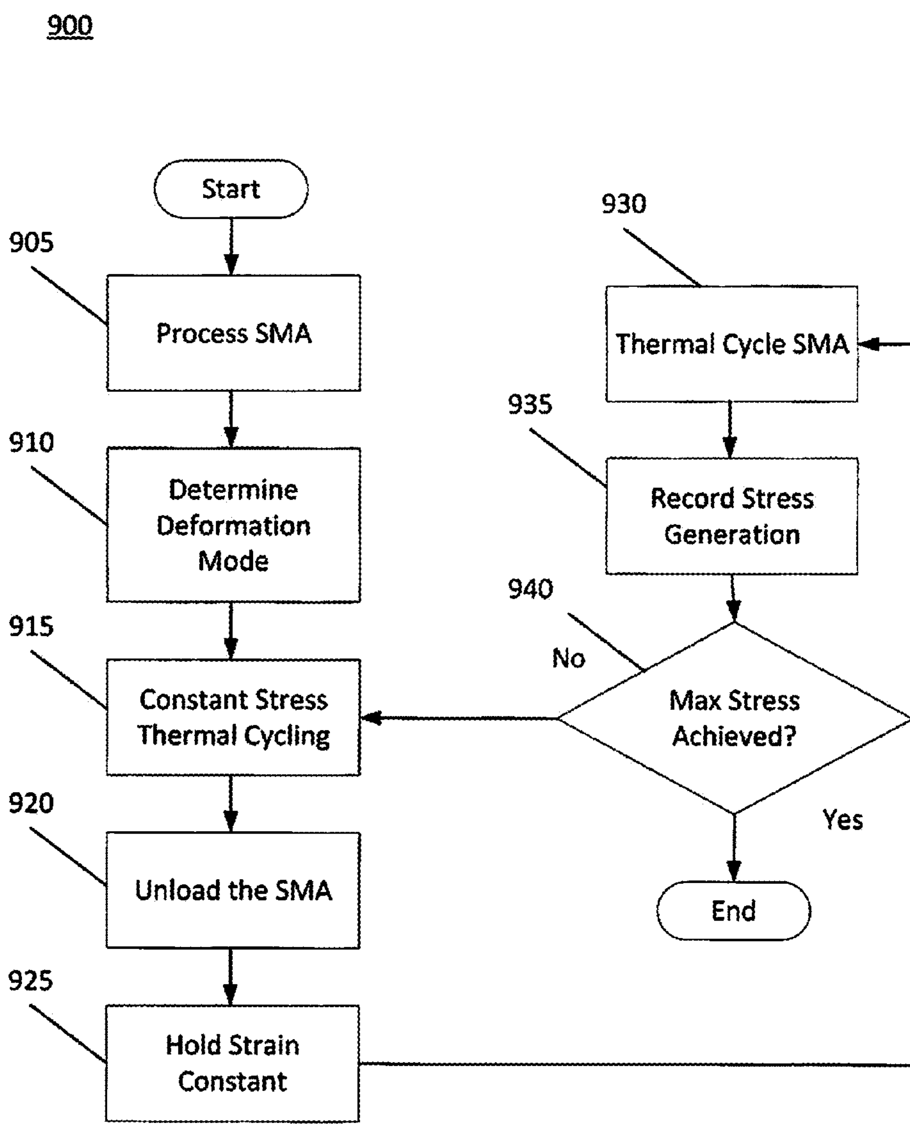

900
Start
905
Process SMA
910
Determine Deformation Mode
915
Constant Stress Thermal Cycling
920
Unload the SMA
925
Hold Strain Constant
930
Thermal Cycle SMA
935
Record Stress Generation
940
No
Max Stress Achieved?
Yes
End

Fig. 10

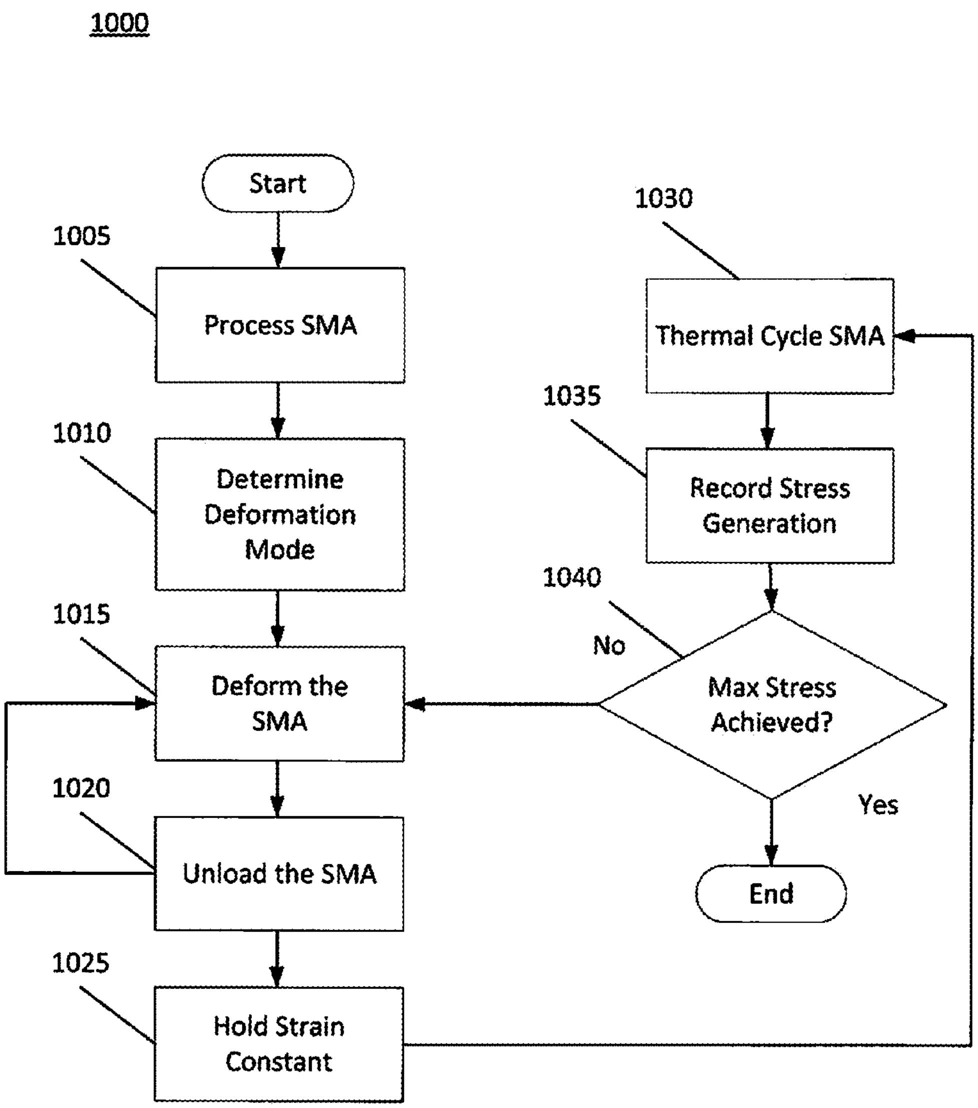

1000
Start
1005
Process SMA
1010
Determine Deformation Mode
1015
Deform the SMA
1020
Unload the SMA
1025
Hold Strain Constant
1030
Thermal Cycle SMA
1035
Record Stress Generation
1040
No
Max Stress Achieved?
Yes
End

Fig. 11

1100

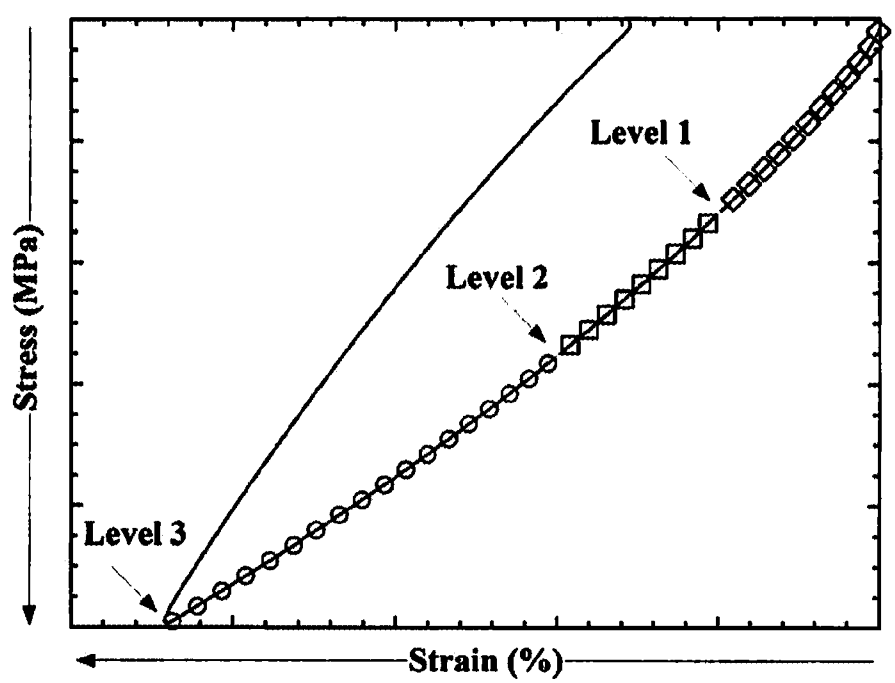
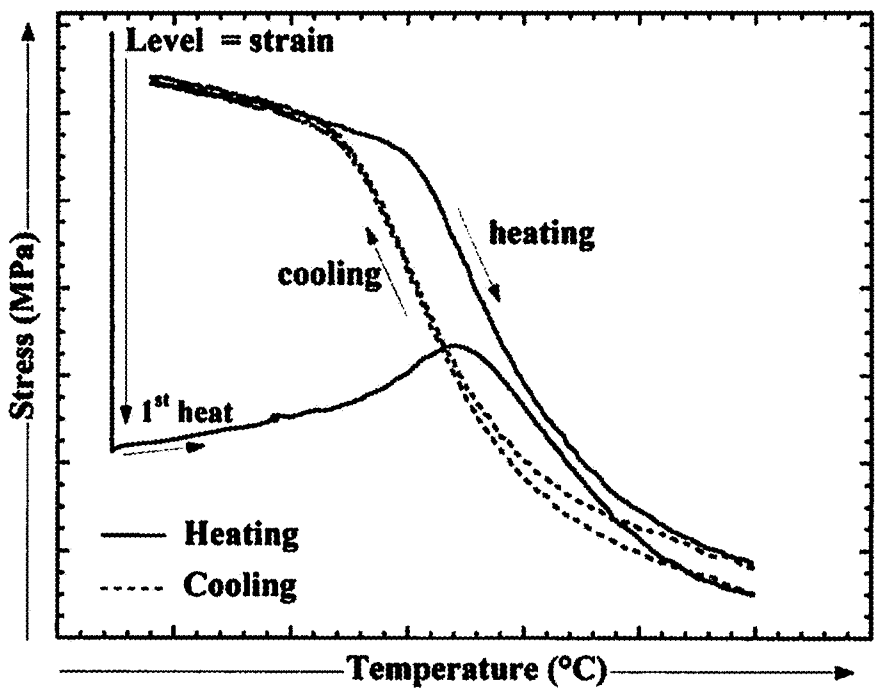


Fig. 12

1200



Level = strain
heating
cooling
1st heat
Heating
Cooling
Stress (MPa)
Temperature (°C)

Fig. 13

1300

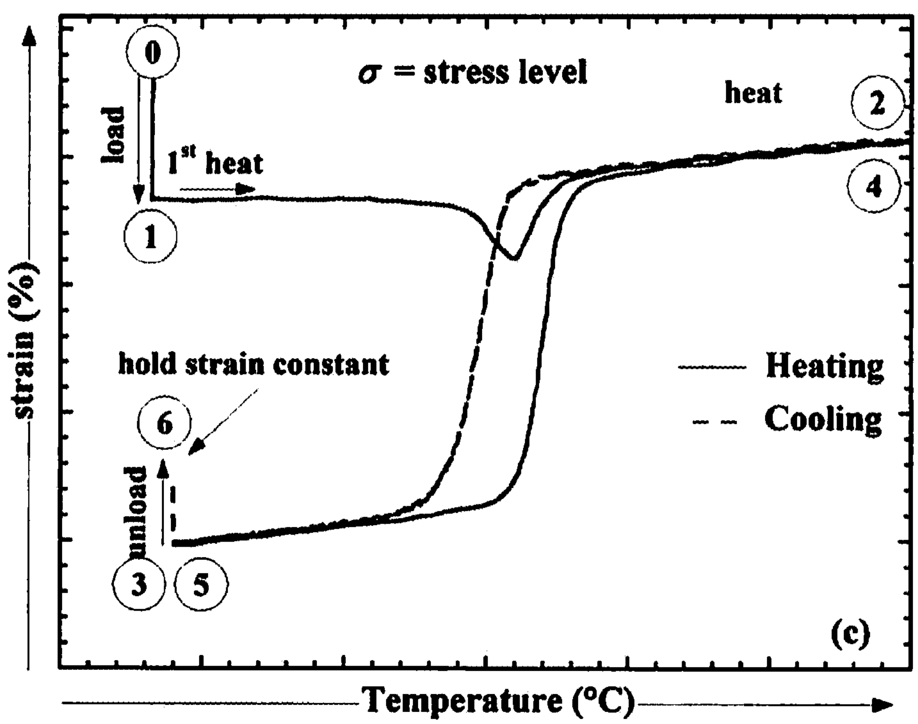

σ = stress level
heat
0
load
1st heat
1
2
4
hold strain constant
6
unload
3
5
Heating
Cooling
(c)
strain (%)
Temperature (°C)

Fig. 14

1400

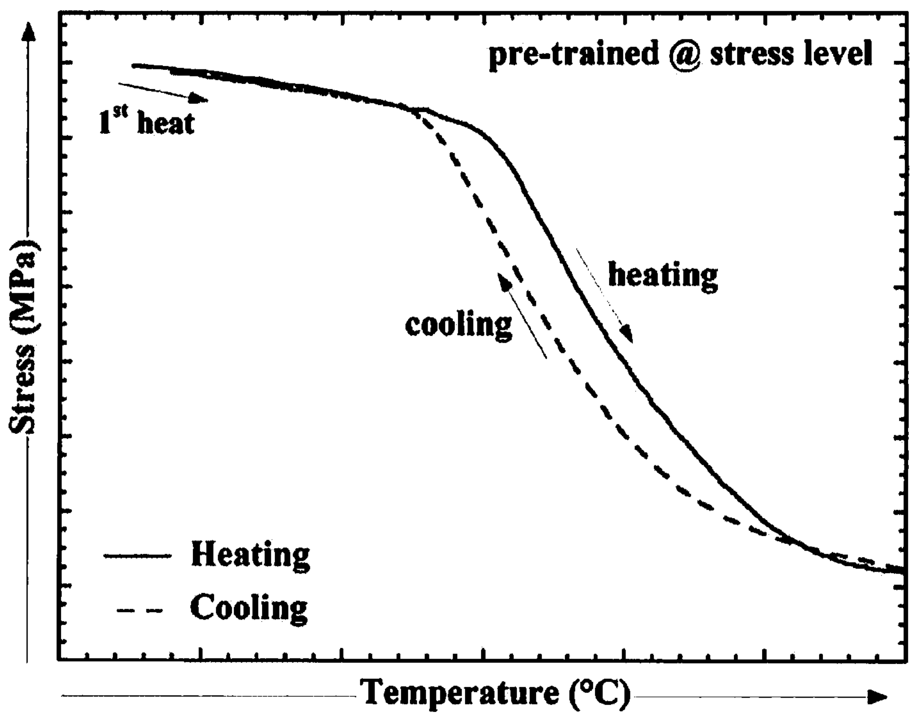
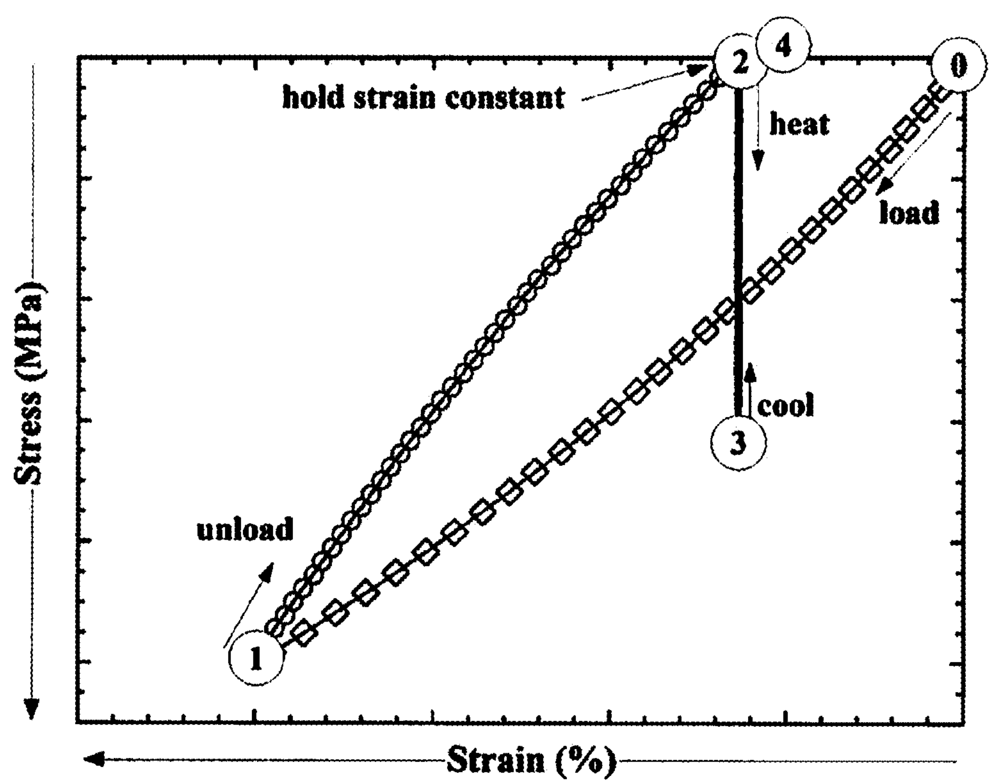

pre-trained @ stress level
1st heat
heating
cooling
Heating
Cooling
Stress (MPa)
Temperature (°C)

Fig. 15

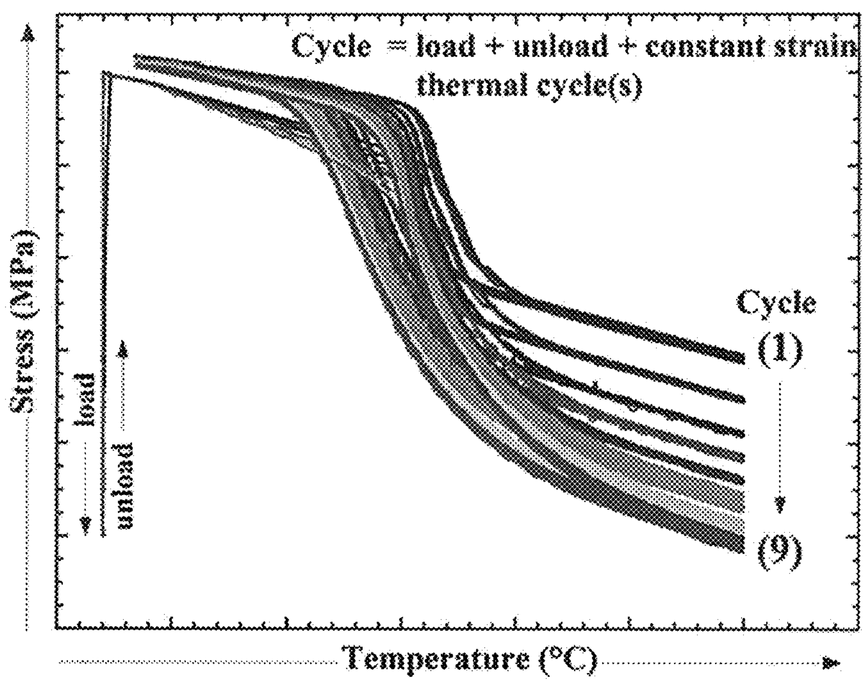
1500



2
4
0
hold strain constant
heat
load
cool
3
unload
1
Stress (MPa)
Strain (%)

Fig. 16

1600


Cycle = load + unload + constant strain thermal cycle(s)
Stress (MPa)
load
unload
Cycle
(1)
(9)
Temperature (°C)

SHAPE MEMORY ALLOY ROCK SPLITTERS (SMARS)

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Patent Application No. 61/993,622, filed on May 15, 2014. The subject matter thereof is hereby incorporated herein by reference in its entirety.

ORIGIN OF THE INVENTION

The invention described herein was made by employees of the United States Government and may be manufactured and used by or for the Government for Government purposes without the payment of any royalties thereon or therefore.

FIELD

The present invention relates to rock splitters, and, more particularly, to a non-explosive process for fracturing planetary rocklike materials and minerals.

BACKGROUND

Solar system exploration has been reliant on state-of-the-art space technologies ranging from navigation systems to propulsion systems, and also, to scientific instruments. These missions often require close contact with planetary bodies, such as the moon, planet Mars, asteroids and comets, where in-situ environmental sampling is sought. In these cases, scientific instruments are built to detect, collect, and characterize samples from the atmosphere, dust particles, soil, rock samples, or aeolian deposits, for example. This provides researchers with geologic and climate history for a better understanding of near-Earth planets, asteroids, and the evolution of the objects as a whole.

Based on revolutionary discoveries by previous missions, it is of interest not only to analyze matter on the planetary bodies, but also to return the soil and rock samples to Earth for more detailed studies and investigations. However, limitations exist preventing large rocks, such as ledges and boulders, from being sampled. For example, limited tools allowed onboard a space vehicle or restrictions in physical space and weight or safety reasons prevent these rock formations from being sampled. In many cases, it would be beneficial to break the rock formation in the region of interest to examine the internal structures or compositions, and determine whether the region of interest is appropriate to transfer the sample back to Earth.

While rock breaking and splitting is a common task here on Earth, and is accomplished using many different methods, breaking and splitting rock outside of Earth is difficult. On Earth, dynamically, explosive and blasting methods are being used to break large rock formations in mines and drilling operations. Static methods, such as fluid pressure cells, agents, and hydraulic wedges, are also being employed. Most of these methods, however, are not suitable for space applications due to the large size and weight of the equipment used. Moreover, demolition techniques generate dust, noise, vibrations and flying debris that can interfere with the space vehicle components, such as sensors, detectors, and cameras, and pose safety concerns. Even in the case when agents and pressure fluids are used, these methods are time consuming, carry the risk of contaminating the environment, and do not guarantee chemical reactions with certain rocks, especially unknown rock structures on foreign planets. Furthermore, simply transporting the active agents for these last two processes (i.e., explosive agents and corrosive fluids) poses significant ricks for crews and spacecraft.

Thus, an alternative approach for rock splitting on foreign planets and objects may be beneficial.

SUMMARY

Certain embodiments of the present invention may provide solutions to the problems and needs in the art that have not yet been fully identified, appreciated, or solved by current rock splitting techniques. For example, a compact, reliable, non-explosive, and cost effective technique for static rock splitting using shape memory alloys (SMAs) is provided. This is demonstrated through the capability of SMAs as high-energy multifunctional materials, which have a unique ability to recover large deformations and generate high stresses in response to thermal loads. This may allow SMA rock splitter (SMARS) to become part of a basic multifunctional scientific package (e.g., robotic sampling, propping, and structure reinforcement) onboard rovers or spacecraft.

In one embodiment, an apparatus for splitting rocks includes one or more SMA expanding elements, which include nickel titanium hafnium (NiTiHf), nickel titanium zirconium (NiTiZr), or nickel titanium hafnium zirconium (NiTiHfZr). When the one or more SMA expanding elements reach a predefined temperature within a predefined borehole of the rock, the one or more SMA expanding elements may exert force on walls of the borehole for splitting the rock.

In another embodiment, a process includes determining a deformation mode of the SMA material. The process also includes based on the deformation mode, isothermally training the SMA material to a predefined strain level required to obtain a desired stress and displacement, isobaric training the SMA material to the predefined stress level, or cyclic training the SMA material to the predefined stress levels.

BRIEF DESCRIPTION OF THE DRAWINGS

In order that the advantages of certain embodiments of the invention will be readily understood, a more particular description of the invention briefly described above will be rendered by reference to specific embodiments that are illustrated in the appended drawings. While it should be understood that these drawings depict only typical embodiments of the invention and are not therefore to be considered to be limiting of its scope, the invention will be described and explained with additional specificity and detail through the use of the accompanying drawings, in which:

FIG. **1** is a diagram illustrating a SMARS system, according to an embodiment of the present invention.

FIGS. **2**A and **2**B illustrate components of SMARS, according to an embodiment of the present invention.

FIG. **3** is a flow diagram illustrating a process for activating SMARS, according to an embodiment of the present invention.

FIG. **4** illustrates SMARS end caps, according to an embodiment of the present invention.

FIGS. **5**A and **5**B illustrate adjustable tips for SMARS, according to an embodiment of the present invention.

FIGS. **6**A-**6**D illustrates SMARS pusher, according to an embodiment of the present invention.

FIG. **7** is a circuit diagram illustrating a control system for SMARS, according to an embodiment of the present invention.

FIG. **8** is a flow diagram illustrating a process for isothermally training SMA material and verifying the stress capability, according to an embodiment of the present invention.

FIG. **9** is a flow diagram illustrating a process for isobarically training SMA material and verifying the stress capability, according to an embodiment of the present invention.

FIG. **10** is a flow diagram illustrating a process for cyclically training SMA material and verifying the stress capability, according to an embodiment of the present invention.

FIG. **11** is a graph illustrating the isothermal training method where the SMA material is deformed in the martensite phase at room temperature to a specific strain level, according to an embodiment of the present invention.

FIG. **12** is a graph illustrating the resultant stress generation after the isothermal training method, according to an embodiment of the present invention.

FIG. **13** is a graph illustrating the isobaric training method where the SMA material is thermomechanically cycled under a constant stress, according to an embodiment of the present invention.

FIG. **14** is a graph illustrating the resultant stress generation after the isobaric training method, according to an embodiment of the present invention.

FIG. **15** is a graph illustrating the cyclic training method where the SMA material is deformed in the martensite phase and unloaded to zero stress, according to an embodiment of the present invention.

FIG. **16** is a graph illustrating the resultant stress generation after the cyclic training method, according to an embodiment of the present invention.

DETAILED DESCRIPTION OF THE EMBODIMENTS

Embodiments of the present invention pertain to the implementation of SMAs as a driving member of a non-explosive, static rock splitter device for space exploration with an extension to ground-based applications. The actuating member fabricated from SMA compositions, such as NiTiHf, NiTiZr, and other alloys with ternary and quaternary additions and specialized aging and heat treatments, may generate stresses in excess of 800 MPa, and in some embodiments, in excess of 1000 MPa. The SMAs may also have temperature capabilities of 100 degrees Celsius or more. These stresses are much higher than the stress that the commercial binary nickel titanium (NiTi) alloys generate. These high stresses allow construction of instruments based on SMA technology that are reliable for flight missions with reduced cost from launch to operation costs.

It should be appreciated that SMAs have the ability to recover large deformations and generate high stresses in response to thermal or mechanical loads. This behavior may occur by virtue of a crystallographically reversible martensitic phase transformation between a high symmetry parent austenite phase and a low symmetry martensite phase. In general, when the SMA is deformed in the martensitic condition, the induced deformation can be recovered by applying heat above certain temperature. However, as long as the critical temperature is not reached, the SMA retains the deformed condition indefinitely until actuated, i.e., heated. When the SMA is heated above the transformation temperature, but is constrained from moving, the SMA may generate extremely large forces. This high power and weight ratio characteristic makes this technology suitable for large force applications, hence SMARS.

SMARS may include SMA material that acts as the actuating member, a casing heater placed around the SMA material, and a power source to provide a current through the heaters. In some embodiments, end caps may be used for acute penetration into rocks, and in further embodiments, a hand-press may be used to reset the SMA material after each usage.

Also, in some embodiments, the SMA material may include nickel-rich (Ni-rich) compositions of ternary NiTiHf and NiTiZr. The SMA material are precipitation strengthened through metallurgical techniques involving a solution anneal or hot working above the solvus temperature. This is then followed by an aging treatment used to form the precipitate structure. The aging treatment provides strength and dimensional stability to the SMA material, while still allowing the transformation to occur. The SMA material may span from Ni-rich, heat treatable precipitation strengthened Ni—Ti—Hf and Ni—Ti—Zr alloys with 3 to 30 atomic percent hafnium (Hf) or Zirconium (Zr), or some combination thereof, in some embodiments.

The SMA material in certain embodiments may be produced by vacuum induction melting, followed by casting into ingots. The ingots may then be homogenized, i.e., heat treated at high temperature to ensure uniform composition throughout the ingot. Finally, the homogenized SMA material may then be sealed into steel cans and extruded into a rod. In some embodiments, the SMA material may be heat treated between 400° C. and 550° C. for various times to form the precipitate structure and strengthen the SMA material.

FIG. **1** is a diagram illustrating a SMARS system **100**, according to an embodiment of the present invention. In FIG. **1**, SMARS system **100** is configured to provide controllable rock splitting without any demolition damage to the surrounding environment. SMARS system **100** includes a SMA expanding element (hereinafter "expanding element") **105** with end caps **110**. See, for example, FIGS. **2**A and **2**B, which illustrate components of SMARS **200**, according to an embodiment of the present invention. In some embodiments, SMARS **200** includes an expanding element **205**, such as an SMA, made of NiTiHf alloys, a heater **215** that fits over expanding element **205**, and end caps **210** at both ends of expanding element **205**. Depending on the embodiment, end caps **210** may be conical, spherical, cylindrical, helical, or flat.

Returning to FIG. **1**, SMARS expanding elements **105** (i.e., the NiTiHf alloy) in the form of cylindrical pellet may be initially conditioned (or trained) to produce desirable forces upon activation. The training process of expanding elements **105** used is described in more detail below.

In order to achieve the anticipated forces and displacements necessary, several training processes may be used. The training process described herein may produce a desirable material response after performing selected mechanical, thermal, and/or thermomechanical loading. In the case of SMARS, training may attain the highest possible blocking forces (i.e., the forces generated during the constrained heating, also known as recovery forces) with the highest possible displacements. For purpose of explanation, the following training methods may be used, e.g., isothermal, isobaric, and cyclic training routines.

Turning to FIG. **8**, for example, a flow diagram **800** illustrating a process to isothermally train SMA material (or expanding element), according to an embodiment of the present invention, is shown. In this embodiment, the process begins at **805** with processing of the bulk SMA material in an acceptable form (e.g., rods, bars, billets, tubes, etc.), ageing times and temperatures, surface finish, and any other SMA material preparation requirement. At **810**, the deformation mode is determined, i.e., tension, compression, torsion, or some combination thereof, and an element of appropriate geometry for the selected mode of use is prepared. At **815**, the SMA material is deformed in the martensite phase at room temperature to a specific strain level. See, for example, graph **1100** of FIG. **11**. At **820**, strain level from step **815** is held constant before unloading.

The effect of this training procedure on the blocking stress, which simulates the operation of the SMARS device after isothermal training, is determined by thermal cycling once the strain imposed at room temperature is held constant. At **825**, for thermal cycling purposes, a lower cycle and upper cycle temperature is selected, e.g., 30° C. and 300° C. At **830**, the SMA material is thermal cycled under the constant strain level between the lower and upper cycle temperatures. In some embodiments, the constant-strain thermal cycling portion may be repeated for multiple cycles. At **835**, the stress generated with temperature is recorded, as shown, for example, in graph **1200** of FIG. **12**. At **840**, a determination is made as to whether maximum stress is achieved during temperature cycling (or sufficient for the desired applications). If not, the process returns to step **815**; otherwise, the process is complete and the training is deemed appropriate for application in SMARS.

This process depends on the strain level reached in step **815** in order to achieve the desired microstructure (e.g., reoriented martensite phase) that yields optimum stresses when thermally cycled under constant-strain conditions. The strain levels also dictate the amount of displacement generated when the material is used in the SMARS application.

FIG. **9** is a flow diagram **900** illustrating a process to isobarically train SMA material, according to an embodiment of the present invention. In this embodiment, the process begins at **905** with bulk processing of the SMA material in an appropriate form (e.g., rods, bars, billets, tubes, etc.), and at **910**, the deformation mode is determined, i.e., tension, compression, torsion, or some combination thereof, and an element of appropriate geometry for the selected mode of use is prepared. At **915**, the SMA material is thermomechanically cycled for one or more cycles under a constant stress, as shown, for example, in graph **1300** of FIG. **13**. At **920**, the SMA material may be unloaded to zero stress.

The effect of this training procedure on the blocking stress, which simulates the operation of the SMARS device after isobaric training, is determined by thermal cycling once the SMA material is fixed in strain at its new shape. At **925**, the remnant strain on the SMA material is held constant while thermal cycling under constant strain condition. At **930**, the SMA material is thermally cycled under a constant strain between a selected lower cycle temperature and upper cycle temperature, e.g., 30° C. and 300° C. At **935**, the stress generation and the temperature are recorded, as shown in, for example, graph **1400** of FIG. **14**. At **940**, a determination is made as to whether maximum stress is achieved during temperature cycling. If not, the process returns to step **915**; otherwise, the process is complete and the training is deemed appropriate for application in SMARS.

This process serves to texture the material at much lower training stresses when compared to the isothermal training. This is advantageous in cases where resetting or retraining the SMA material in the field of operations where large force equipment cannot be used.

FIG. **10** is a flow diagram **1000** illustrating a process to cyclically train SMA material, according to an embodiment of the present invention. It should be appreciated that this process relates to the ability to reuse or retrain the SMA materials for SMARS operation. In this embodiment, the process begins at **1005** with processing the SMA material in an appropriate form (e.g., rods, bars, billets, tubes, etc.), and at **1010**, determining the deformation mode of the SMA material, i.e., tension, compression, torsion, or some combination thereof, and an material of appropriate geometry for the selected mode of use is prepared. At **1015**, the SMA material is deformed in the martensite phase at room temperature to a specific stress value. At **1020**, the SMA material is unloaded to zero stress, as shown in, for example, graph **1500** of FIG. **15**. At this point, the SMA material may be reloaded, such that step **1015** is repeated.

The effect of this training procedure on the blocking stress, which simulates the operation of the SMARS device after cyclic training, is determined by thermal cycling once the SMA material is fixed in strain. At **1025**, the remnant strain may be held constant, and at **1030**, the SMA material is thermally cycled under the constant strain. At **1035**, the stress generation and the temperature are recorded, as shown in, for example, graph **1600** of FIG. **16**. At **1040**, a determination is made as to whether maximum stress is achieved. If not, the process returns to step **1015**; otherwise, the process is complete and the training is deemed appropriate for application in SMARS. This process is more applicable to resetting the SMA material after use and still obtaining similar or even higher stresses.

It should be appreciated that the training process may be applied not only to NiTiHf or NiTiZr alloys, but also apply to other SMA material and other compounds and formulations.

Upon completion of the training or conditioning of SMA material, the SMA material may exist in a low temperature martensite phase. Returning back to FIG. **1**, during the martensite phase, end caps **110** may be mechanically attached or directly machined on trained expanding element **105**, i.e., the SMA material. In certain embodiments, the effective length of end caps **110** from tip to tip is made equal to a pre-drilled borehole diameter for proper operation. In other words, the width of expanding element **105** including end caps **110** is the same size as the pre-drilled hole in the rock, for example.

SMARS system **100** may also include a heater **115** that includes one or more expanding elements **105**. Heater **115** may include one or more sleeves **120** allowing one or more SMA expanding element **105** to be inserted within each sleeve **120**. In some embodiments, sleeve **120** may be made of metal. An adhesive cement **125** may surround sleeve **120** to prevent heater **115** from degradation. Power, such as direct current (DC) or alternating current (AC), may be connected to a heater **130**, which are wrapped around metal sleeve **120**. When heater **115** is inserted into a pre-drilled hole within a rock or a crack, theheater **130** in some embodiments may supply heat to expanding elements **105** causing expanding elements **105** to expand after reaching certain temperatures.

It should be appreciated that various types of heating systems may be used for SMARS system **100**. As discussed above, in one embodiment, a metallic sleeve **120**, adhesive cement **125**, and conductive wires **130** may be housed within in heater **115**. This may provide a compact heater capable of heating to temperatures exceeding 400° C. in a relatively short period of time. In some embodiments, this may be seconds to one minute. In another embodiment, heaters may be wrapped around and bonded to the expanding elements **105**. In a further embodiment, induction heating may be used to heat expanding elements **105**. This may be used for large, dry boreholes. Induction heating may yield fast heating rates, but may require a much higher power consumption (e.g., 120 VAC) and footprint (a separate power supply is needed to power the induction unit).

In some embodiments, a control box **135** may deliver a power signal to the heater **115**. During operation, expanding elements **105** may undergo a phase transformation to the high temperature austenite phase. In this phase, expanding element may go to an unconstrained condition, i.e., expansion in this case. However, since expanding elements **105** are confined by the wall constraints within the borehole, expanding elements **105** may not initially expand, and instead exert forces at the contact area resulting in rock fracture. After the rock is split, expanding elements **105** may be retrained to the constrained condition. Expanding elements **105** may be reused for successive employments in some embodiments given that new expanding elements **105** may be used, or in other embodiments, same expanding elements **105** may be re-trained.

It should be appreciated that control box **135** in this embodiment may include a temperature indicator with retransmission, a power supply, selector switches to trigger the individual heaters either simultaneously or sequentially, connectivity for type-K thermocouples, and a main power switch to activate the chosen heaters. See, for example, FIG. **7**, which is a circuit diagram **700** illustrating a control box for the SMARS system, according to an embodiment of the present invention.

The control box includes a power input **705** to energize a temperature controller **710** that monitors the temperature of heaters **730**. The control box also includes a direct current (DC) power supply **715** to energize the main power switch **720**, and to provide heating to the SMA elements. The control box in some embodiments includes heater selecting switches **725** that activates one or more heaters **730**.

Temperature controller **710** and thermocouples **740** may monitor the temperature of heaters **730**. Solid-state relay **735** may be used to modulate or regulate the power coming out of power supply **715**.

Turning to FIG. **3**, a flow diagram **300** illustrating a process for activating SMARS is shown, according to an embodiment of the present invention. In this embodiment, the process begins at **305** with a rock sample or crack being selected. This rock sample or crack may be on Earth, on another planet, asteroid, etc. At **310**, the bore hole is drilled in the selected rock sample, and at **315**, the rock splitter is inserted in the bore hole. At **320**, the rock splitter, which includes the expanding elements, is activated causing the expanding elements to split the rock.

FIG. **4** illustrates SMARS end caps **400**, according to an embodiment of the present invention. As discussed above, end caps may be attached to SMA expanding elements. Depending on the configuration, the end caps may be mechanically attached, machined on, or bonded to, the SMA expanding element. For example, different types of end caps may directly attach to the SMA expanding element depending on the rock types or the hardness of the rock, and also to compensate for any gaps between SMA expanding element and the rock surface. As shown in FIG. **4**, several types of end caps may be used, e.g., spherical **405**, conical **410**, and cylindrical **415**. In some embodiments, flat ends may also be attached to SMA expanding element.

The flat ends may be utilized for plane borehole walls or pre-existing cracks in the vicinity of the rock of interest. The conical ends may be used for acute penetration into the rocks to help with the crack initiation and ultimately propagation to fracture. Both the spherical and cylindrical ends may be used for maximizing the contact surface area within the borehole. In these cases, the end tip forms may be machined to match the borehole diameter.

FIGS. **5**A and **5**B illustrate adjustable tips for SMARS **500**, according to an embodiment of the present invention. In this embodiment, a SMA expanding element **505** with end caps **510** is inserted within a hole. As shown in FIG. **5**A, a gap exists between one end cap **510** and the wall of the hole in the rock. To compensate for this gap, or to provide a gap correction, cap **510** may be unscrewed. SMA expanding element **505** may then be activated to expand and exert force on the wall of the hole in order to split the rock.

FIGS. **6**A-**6**D illustrates SMARS pusher **600**, according to an embodiment of the present invention. In some embodiments where complete splitting is required, SMA pusher **600** can provide additional displacement after the SMA expanding element has been activated. Pusher **600** may be made in the form of helical springs, which includes grooves **605**, and may be placed on the top position of the sample holder **115**. See, for example, FIG. **1**. In one embodiment, pusher **600** may be heated sequentially after the bottom and/or middle SMA expanding member in the heater is fully expanded to completely split the fractured rock. In other words, pushers **600** may provide additional displacements to fully split the rock in additional embodiments.

Pusher **600** may have a predefined length L, and include an inner hole **610** to allow an end cap (not shown) to be inserted within pusher **600**. See, for example, FIGS. **6**A-**6**D. As shown in FIG. **6**D, rod **600** has an outer diameter OD and an inner diameter ID for inner hole **605**.

Pusher **600** provides additional displacement, but at generally lower stresses than the expanding elements. Its purpose is to finish fracturing the rock once the expanding elements have initiated fracture. Thus, if the displacements (or strains) imparted by the training methods are not sufficient to completely split the rock, SMA pushers **600**, which can also be trained using the aforementioned methods, may provide additional controlled displacement for a compete rock splitting.

SMARS, in one or more embodiments, is a static device that provides controllable motion without any demolition damage to the surrounding environment, compared to the alternative dynamic explosive, blasting approaches, or high impact approaches. This characteristic makes the SMARS ideal for critical planetary rock breaking and/or sampling operations, where flying debris from blasts/explosion methods can destruct the rock formation of interest, pose safety concerns to the crew, and cause damage to the costly nearby equipment, e.g., rover mirrors and sensors. In addition, static SMARS may require little setup and activation time compared to other static methods, such as chemical agents, that can take up to days to react with some hard rocks. Mission reliability is another benefiting factor since SMARS operate based on a material response and may only require heat input to activate without the need for complex valve systems and hydraulic fluids. This makes SMARS extremely simple and essentially user friendly during operation. The small volume and extremely low weight of the SMARS reduces payload launch costs and transportation hazards when compared to heavy hydraulic wedges and dangerous explosive materials and chemicals. SMARS may also be dust and vibration free during operation, and further does not disturb nearby instruments conducting simultaneous tasks.

Although the SMARS device is targeted for static rock breaking in space related explorations, it is readily understood that SMARS can also be used in non-rock related applications such as a proppant or spacers to unjam a trapped component. The SMARS device development can also be extended in some embodiments to the applicability of ground-based systems such as oil drilling, mining, fossil collecting and retrieval of other fragile geologic samples, proppants, civil engineering and other fields requiring compact but large static forces. The SMARS device can also be used for structure reinforcement and corrective force applications to structural members and other engineering components. The SMARS device is also envisioned for applications requiring smooth and controlled cracking and/or splitting such as in the military applications where quiet and explosive free operation is generally sought.

It will be readily understood that the components of various embodiments of the present invention, as generally described and illustrated in the figures herein, may be arranged and designed in a wide variety of different configurations. Thus, the detailed description of the embodiments, as represented in the attached figures, is not intended to limit the scope of the invention as claimed, but is merely representative of selected embodiments of the invention.

The features, structures, or characteristics of the invention described throughout this specification may be combined in any suitable manner in one or more embodiments. For example, reference throughout this specification to "certain embodiments," "some embodiments," or similar language means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrases "in certain embodiments," "in some embodiment," "in other embodiments," or similar language throughout this specification do not necessarily all refer to the same group of embodiments and the described features, structures, or characteristics may be combined in any suitable manner in one or more embodiments.

It should be noted that reference throughout this specification to features, advantages, or similar language does not imply that all of the features and advantages that may be realized with the present invention should be or are in any single embodiment of the invention. Rather, language referring to the features and advantages is understood to mean that a specific feature, advantage, or characteristic described in connection with an embodiment is included in at least one embodiment of the present invention. Thus, discussion of the features and advantages, and similar language, throughout this specification may, but do not necessarily, refer to the same embodiment.

Furthermore, the described features, advantages, and characteristics of the invention may be combined in any suitable manner in one or more embodiments. One skilled in the relevant art will recognize that the invention can be practiced without one or more of the specific features or advantages of a particular embodiment. In other instances, additional features and advantages may be recognized in certain embodiments that may not be present in all embodiments of the invention.

One having ordinary skill in the art will readily understand that the invention as discussed above may be practiced with steps in a different order, and/or with hardware elements in configurations which are different than those which are disclosed. Therefore, although the invention has been described based upon these preferred embodiments, it would be apparent to those of skill in the art that certain modifications, variations, and alternative constructions would be apparent, while remaining within the spirit and scope of the invention. In order to determine the metes and bounds of the invention, therefore, reference should be made to the appended claims.

The invention claimed is:

1. An apparatus for splitting rock, comprising:

one or more shape memory alloy expanding elements comprising nickel titanium hafnium (NiTiHf), nickel titanium zirconium (NiTiZr), or nickel titanium hafnium zirconium (NiTiHfZr), wherein

when the one or more shape memory alloy expanding elements reach a predefined temperature within a predefined borehole of the rock, the one or more shape memory alloy expanding elements are configured to exert force on walls of the borehole for splitting the rock; and

adjustable end tips configured to enhance cracking of the rock and compensate for irregularity in a borehole diameter.

2. The apparatus of claim **1**, wherein the one or more shape memory alloy expanding elements comprise a temperature capability of at least 100 degrees Celsius.

3. The apparatus of claim **1**, wherein the one or more shape memory alloy expanding elements comprise a stress capability of at least 800 MPa.

4. The apparatus of claim **1**, wherein the one or more shape memory alloy expanding elements comprise a stress capability of at least 1000 MPa.

5. The apparatus of claim **1**, wherein the adjustable end tips comprises one or more shapes depending on rock type being explored.

6. The apparatus of claim **1**, wherein the adjustable end tips are machined directly onto the shape memory alloy expanding elements.

7. The apparatus of claim **1**, wherein the adjustable end tips are independent to the shape memory alloy expanding elements.

8. The apparatus of claim **1**, further comprising:

one or more pushers configured to provide additional displacement at a relatively lower stress after the shape memory alloy expanding elements have been activated.

9. The apparatus of claim **8**, wherein the one or more pushers comprise a specific amount of weight required to deflect the material per unit length, or spring rate, to achieve a desired final splitting.

10. The apparatus of claim **1**, further comprising:

a heater housing the one or more shape memory alloy expanding elements is configured to heat the one or more shape memory alloy expanding elements within the predefined borehole of the rock.

11. The apparatus of claim **10**, wherein the heater comprises one or more sleeves to house the one or more shape memory alloy expanding elements.

12. The apparatus of claim **11**, wherein the heater comprises adhesive cement surrounding the one or more sleeves.

13. The apparatus of claim **11**, wherein the heater comprises heater wrapped around the one or more sleeves.

14. The apparatus of claim **10**, wherein, when the heater is placed within the predefined borehole of the rock, the heaters are configured to supply heat to the one or more shape memory alloy expanding elements causing the one or more shape memory alloy expanding elements to expand after reaching predefined temperature.

15. A process for training shape memory alloy material, comprising:

determining a deformation mode of the shape memory alloy material; and

based on the deformation mode, isothermally training the shape memory alloy material to a predefined strain level required to obtain a desired stress and displacement, isobaric training the shape memory alloy material to the predefined stress level, or cyclic training the shape memory alloy material to the predefined stress levels.

16. The process of claim **15**, wherein the shape memory alloy material comprises nickel titanium hafnium (NiTiHf), nickel titanium zirconium (NiTiZr), or nickel titanium hafnium zirconium (NiTiHfZr).

17. The process of claim **15**, wherein the isothermally training of the shape memory alloy material comprises:

deforming the shape memory alloy material to the predefined strain level;

maintaining the predefined strain level of the shape memory alloy material; and

thermal cycling the shape memory alloy material under the predefined strain level between a lower temperature cycle and an upper temperature cycle.

18. The process of claim **15**, wherein the isobaric training the shape memory alloy material comprises:

thermomechanically cycling the shape memory alloy material for one or more cycles at a constant stress;

unloading the thermomechanically cycled shape memory alloy material to zero stress;

holding a remnant strain constant on the unloaded shape memory alloy material; and

thermal cycling the shape memory alloy material under the constant remnant strain between a lower temperature cycle and an upper temperature cycle.

19. The process of claim **15**, wherein the cyclic training of the shape memory alloy material comprises:

deforming the shape memory alloy material in a martensite phase to the predefined stress level;

unloading the shape memory alloy material to zero stress;

holding constant a remnant strain level on the shape memory alloy material; and

thermally cycling the shape memory alloy material under the constant remnant strain level.

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