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(54) **SYSTEMS AND METHODS FOR IMPLEMENTING FLEXIBLE MEMBERS INCLUDING INTEGRATED TOOLS MADE FROM METALLIC GLASS-BASED MATERIALS**

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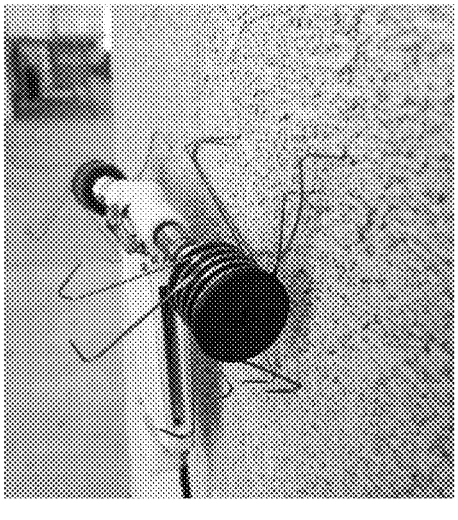
(57) **ABSTRACT**

Systems and methods in accordance with embodiments of the invention implement flexible members that include integrated tools made from metallic glass-based materials. In one embodiment, a structure includes: a flexible member characterized by an elongated geometry and an integrated tool disposed at one end of the elongated geometry; where the flexible member includes a metallic glass-based material.

10 Claims, 11 Drawing Sheets



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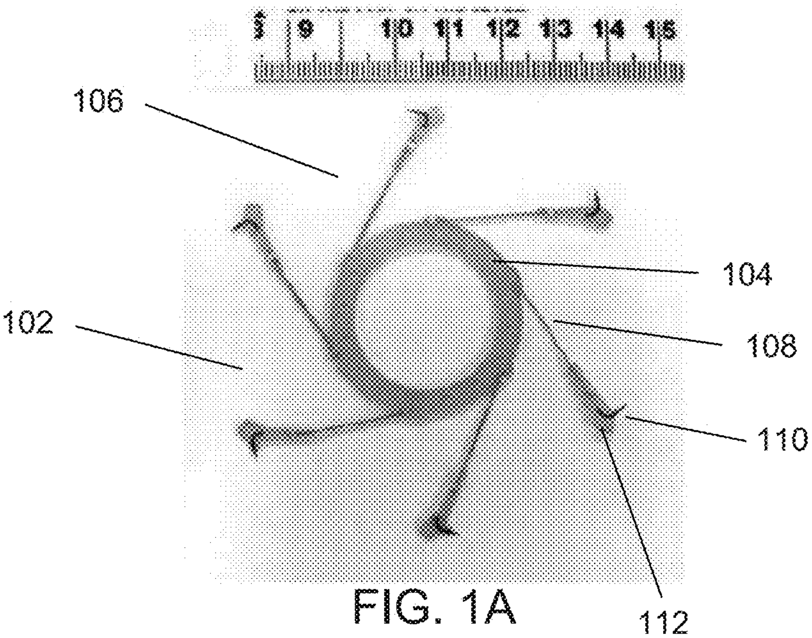

FIG. 1A

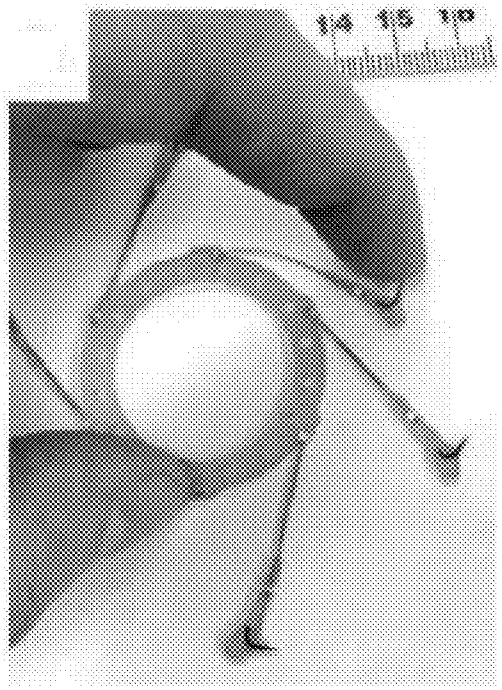

FIG. 1B

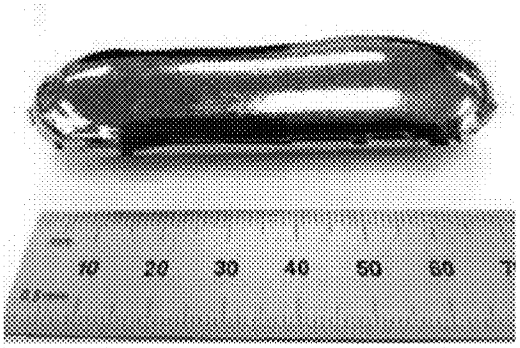

FIG. 2A

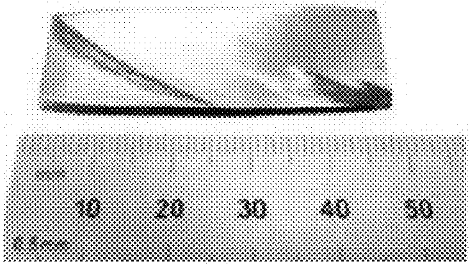

FIG. 2B

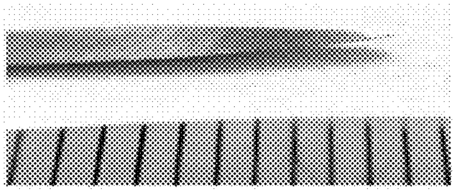

FIG. 2C

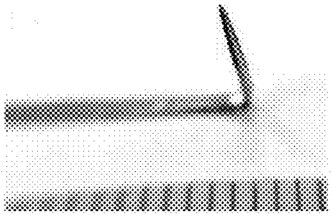

FIG. 2D

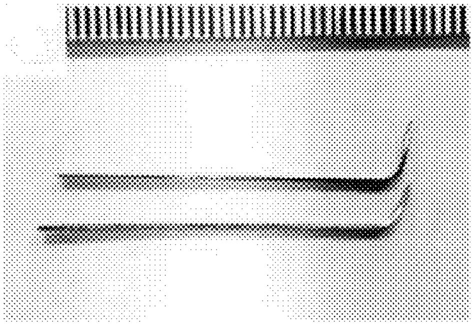

FIG. 2E

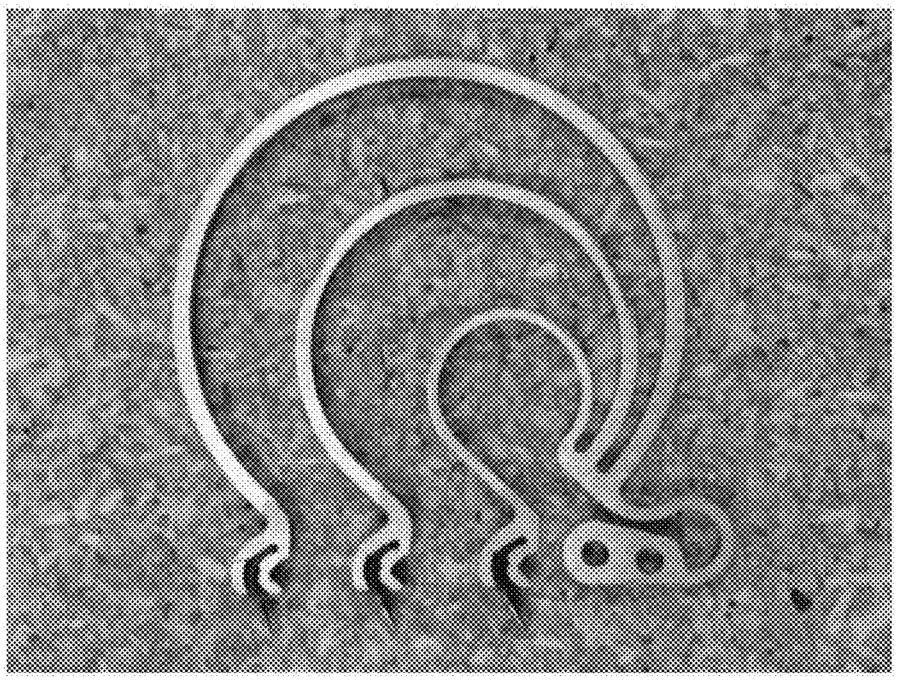

FIG. 3

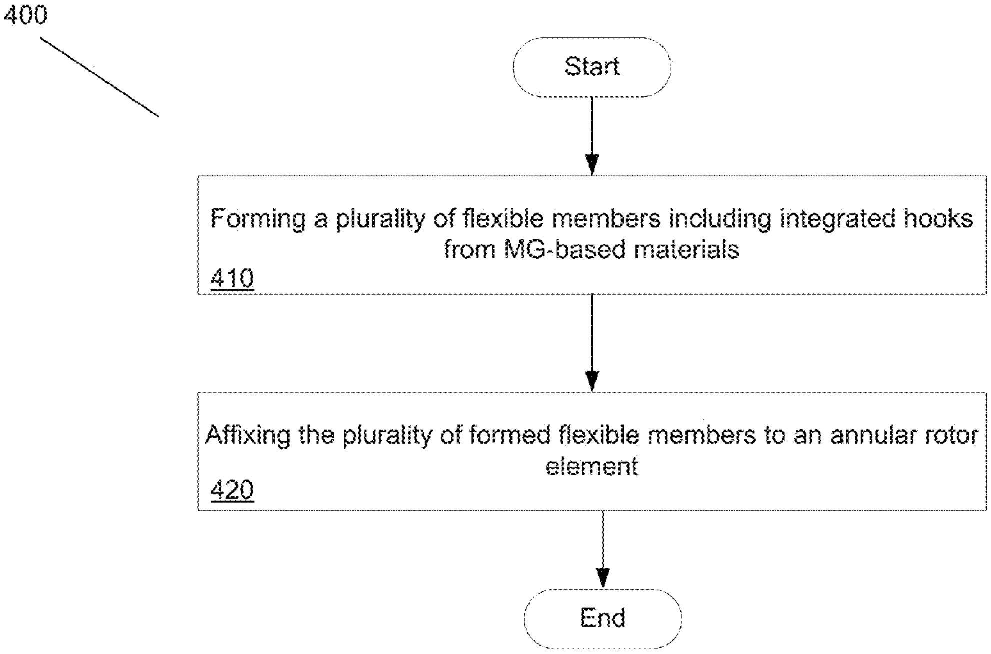
400
Start
Forming a plurality of flexible members including integrated hooks from MG-based materials
410
Affixing the plurality of formed flexible members to an annular rotor element
420
End

FIG. 4

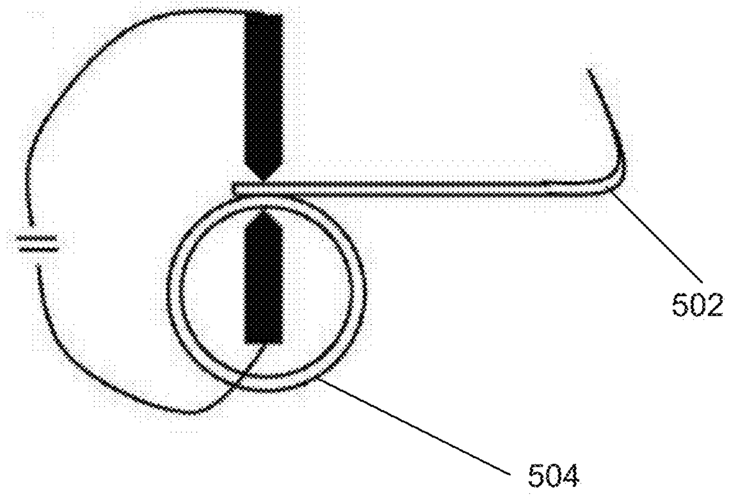

FIG. 5A

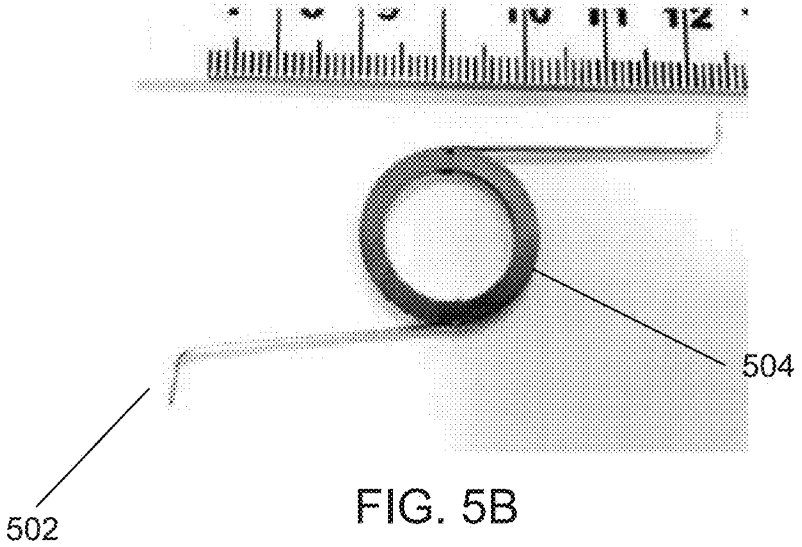

FIG. 5B

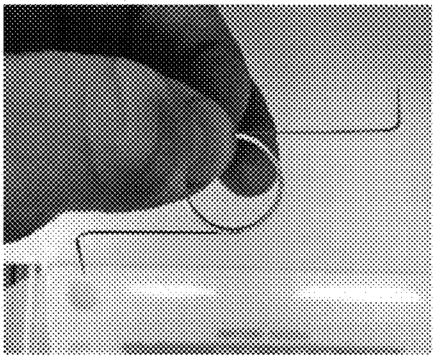

FIG. 6A

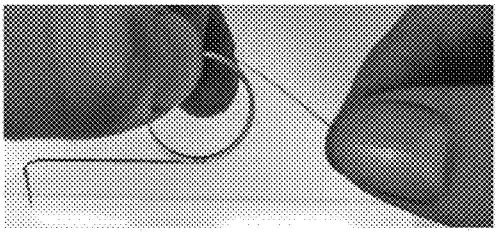

FIG. 6B

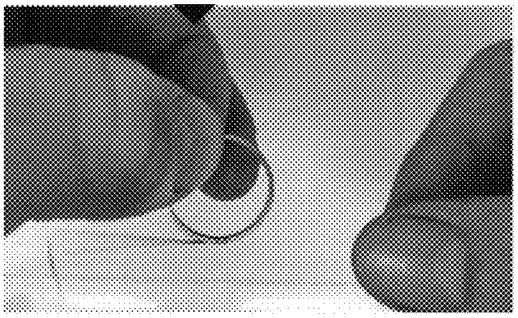

FIG. 6C

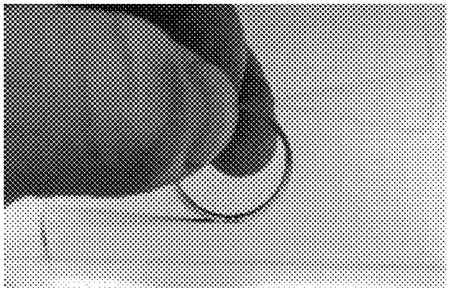

FIG. 6D

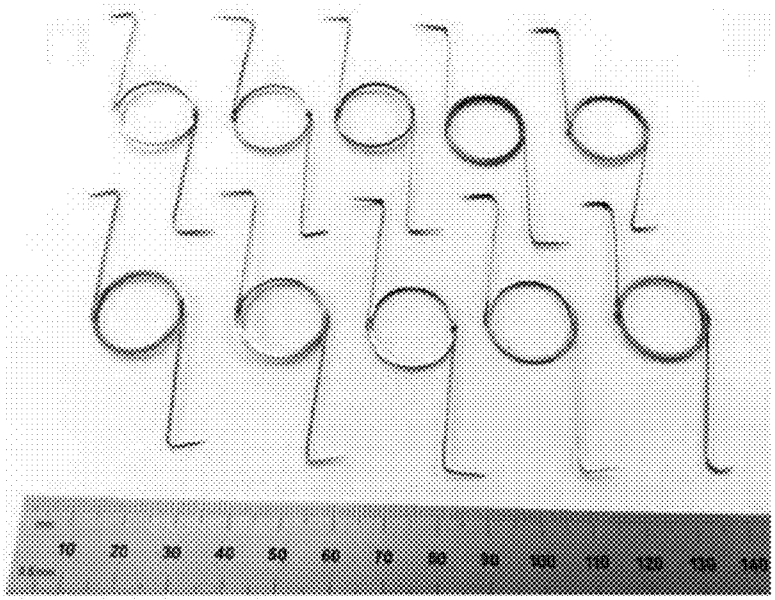

FIG. 7A

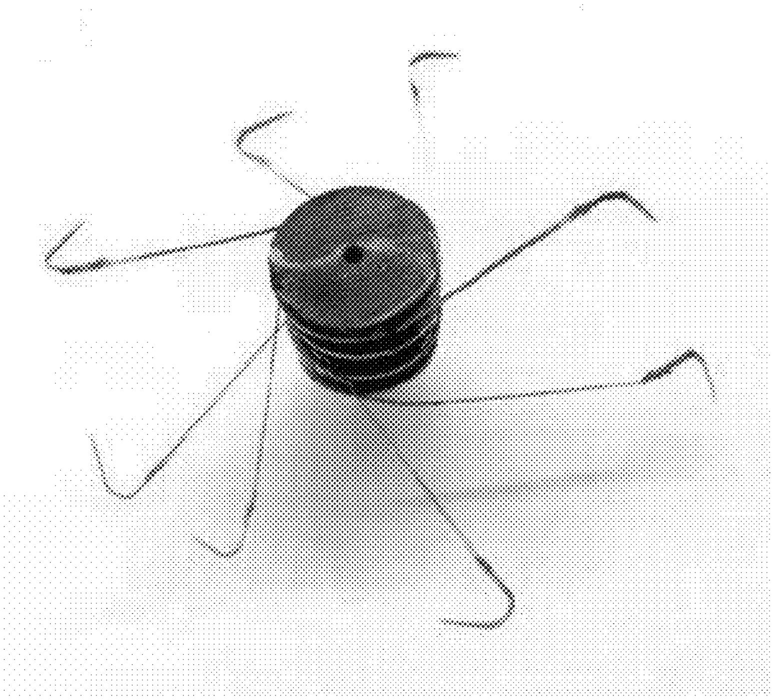

FIG. 7B

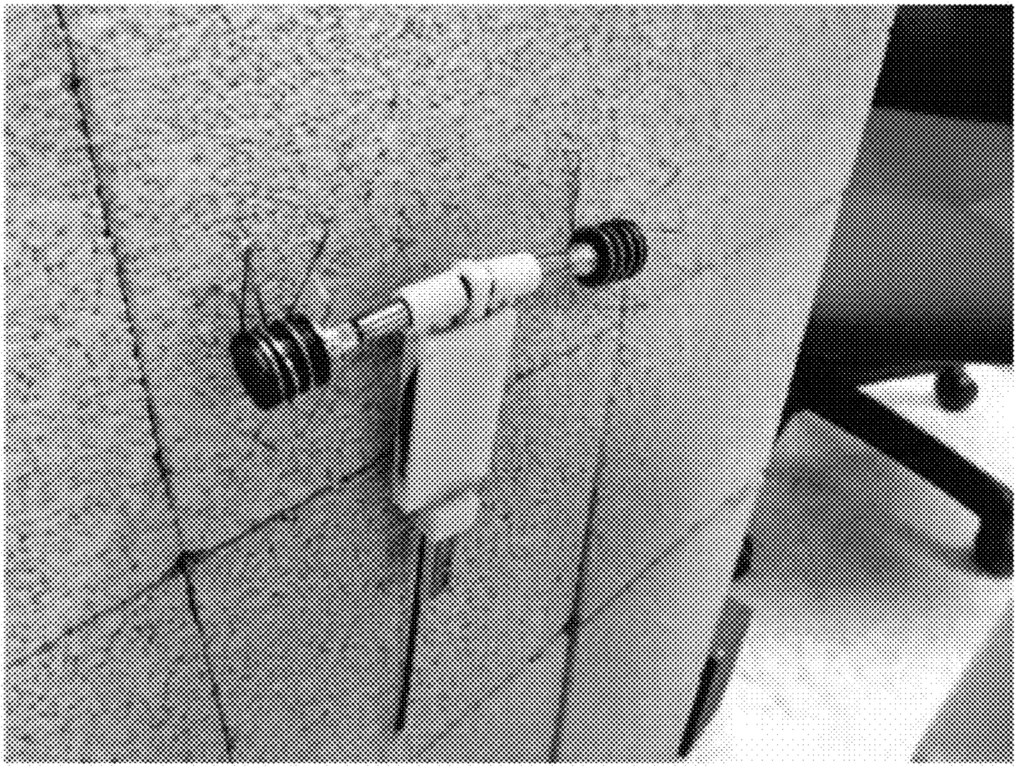

FIG. 8A

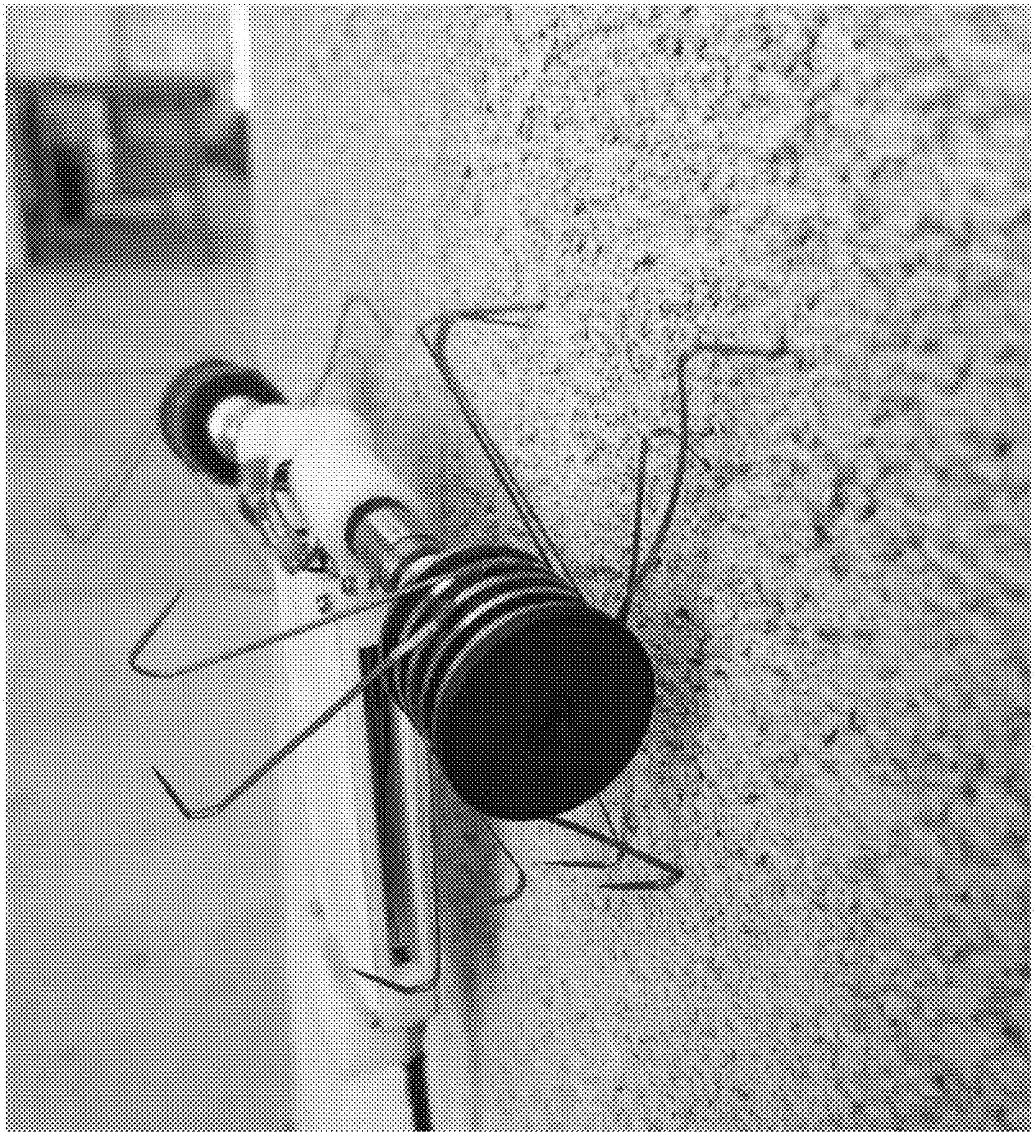

FIG. 8B

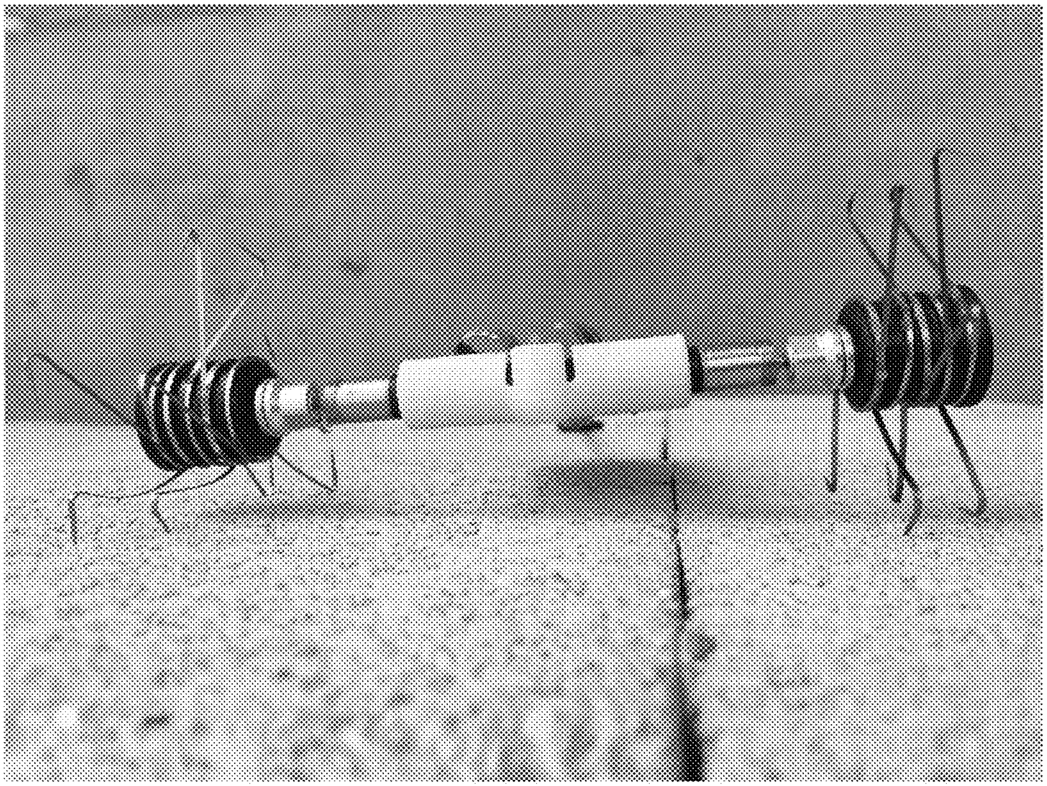

FIG. 8C

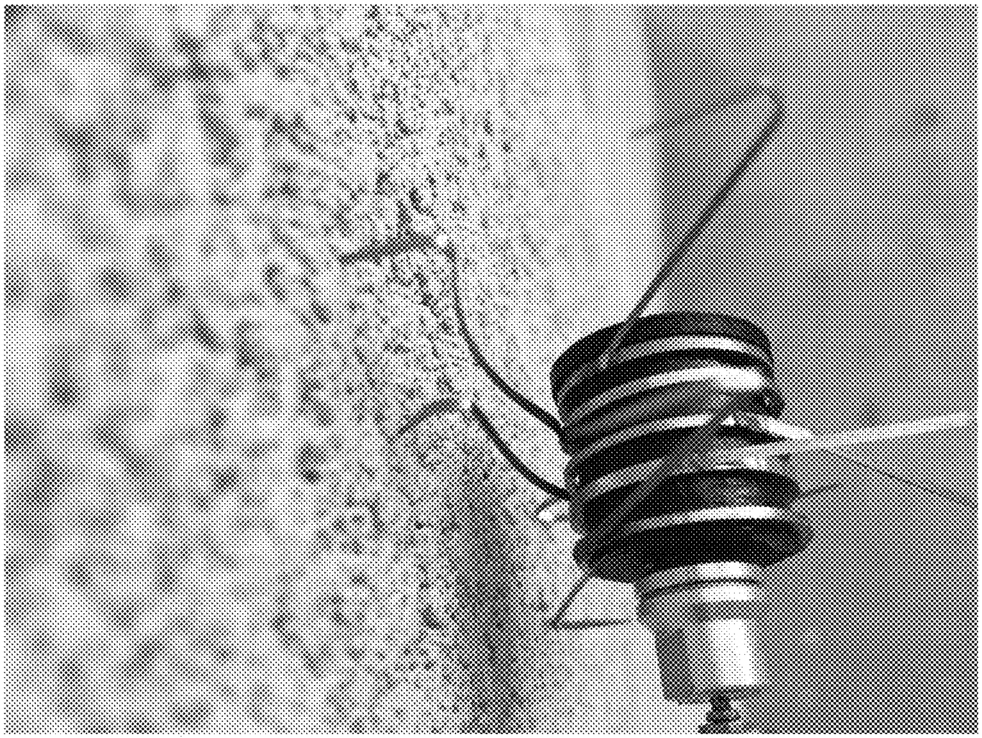

FIG. 8D

SYSTEMS AND METHODS FOR IMPLEMENTING FLEXIBLE MEMBERS INCLUDING INTEGRATED TOOLS MADE FROM METALLIC GLASS-BASED MATERIALS

CROSS-REFERENCE TO RELATED APPLICATIONS

The current application claims priority to U.S. Provisional Application No. 62/132,325, filed Mar. 12, 2015, the disclosure of which is incorporated herein by reference.

STATEMENT OF FEDERAL FUNDING

The invention described herein was made in the performance of work under a NASA contract NNN12AA01C, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the Contractor has elected to retain title.

FIELD OF THE INVENTION

The present invention generally relates to the implementation of flexible members including integrated tools made from metallic glass-based materials.

BACKGROUND

Engineered mechanisms often rely on a variety of components characterized by intentionally distinct geometries and/or mechanical properties. Thus, for instance, U.S. Pat. No. 8,789,629 (the ’629 patent) discloses terrain traversing devices having wheels with included microhooks. More specifically, the abstract of the ’629 patent reads:

> A terrain traversing device includes an annular rotor element with a plurality of co-planar microspine hooks arranged on the periphery of the annular rotor element. Each microspine hook has an independently flexible suspension configuration that permits the microspine hook to initially engage an irregularity in a terrain surface at a preset initial engagement angle and subsequently engage the irregularity with a continuously varying engagement angle when the annular rotor element is rotated for urging the terrain traversing device to traverse a terrain surface.

The ’629 patent proposes that the referenced microspine wheel assembly can be made out of any of a variety of suitable materials including, for example steel and/or a hard plastic. The disclosure of the ’629 patent is hereby incorporated by reference in its entirety.

SUMMARY OF THE INVENTION

Systems and methods in accordance with embodiments of the invention implement flexible members that include integrated tools made from metallic glass-based materials. In one embodiment, a structure includes: a flexible member characterized by an elongated geometry and an integrated tool disposed at one end of the elongated geometry; where the flexible member includes a metallic glass-based material.

In another embodiment, the integrated tool is a hook.

In yet another embodiment, the metallic glass-based material is a metallic glass matrix composite material.

In still another embodiment, the metallic glass-based material is characterized by a fracture toughness of greater than approximately 80 MPa·m$^{1/2}$.

In still yet another embodiment, flexible member is characterized in that it is fully amorphous.

In a further embodiment, the metallic glass-based material is characterized in that it has an elastic limit of greater than approximately 1%.

In a still further embodiment, the metallic glass-based material is characterized in that it has an elastic limit of greater than approximately 1.5%.

In a yet further embodiment, the metallic glass-based material is characterized in that it has an elastic limit of greater than approximately 2%.

In a still yet further embodiment, the flexible member is characterized by a thickness of less than approximately three times the size of the plastic zone radius of the metallic glass-based material.

In another embodiment, the flexible member is characterized by a thickness of less than approximately 1.5 mm.

In yet another embodiment, the flexible member defines a plurality of extensions including a plurality of integrated tools disposed at one end of respective extensions.

In still another embodiment, a wheel assembly includes: at least one rotor element; a plurality of flexible members, each characterized by an elongated geometry and an integrated tool at the end of the elongated geometry; where: at least one of the plurality of flexible members includes a metallic glass-based material; and the plurality of flexible members are approximately uniformly distributed around at least one rotor element such that the aggregate of the at least one rotor element and the plurality of flexible members can viably function as a wheel.

In still yet another embodiment, the integrated tool is a hook.

In a further embodiment, the metallic glass-based material of at least one flexible member is characterized by a fracture toughness of greater than approximately 80 MPa·m$^{1/2}$.

In a yet further embodiment, a method of forming a flexible member including an integrated tool, includes: forming a metallic glass-based material into an elongated geometry; and deforming the elongated geometry to define a tool at one end of the elongated geometry when the temperature of the metallic glass-based material is lower than its respective glass transition temperature; where the metallic glass-based material is characterized by a fracture toughness of greater than approximately 80 MPa·m$^{1/2}$.

In a still further embodiment, the integrated tool is a hook.

In a still yet further embodiment, the hook is defined by an angle of greater than approximately 80° relative to the remainder of the flexible member.

In another embodiment, forming the metallic glass-based material into an elongated geometry includes shearing an elongated geometry from a sheet of the metallic glass-based material.

In still another embodiment, the thickness of the elongated geometry is less than approximately three times the size of the plastic zone radius of the metallic glass-based material.

In yet another embodiment, the thickness of the elongated geometry is less than approximately 1.5 mm.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1A-1B** illustrate a conventional wheel assembly that can be implemented within a terrain traversing device.

FIGS. **2A-2E** schematically illustrate constructing a flexible member including an integrated tool disposed at one end of the flexible member from a metallic glass-based material in accordance with certain embodiments of the invention.

FIG. **3** illustrates an alternative geometry for a flexible member including a plurality of integrated tools made from a metallic glass-based material that can be implemented in accordance with certain embodiments of the invention.

FIG. **4** illustrates a process for implementing a structure including an annular rotor element and a plurality of flexible members including integrated tools made from metallic glass-based materials in accordance with certain embodiments of the invention.

FIGS. **5**A-**5**B illustrate the incorporation of flexible members including integrated tools made from metallic glass-based materials with an annular rotor element in accordance with certain embodiments of the invention.

FIGS. **6**A-**6**D illustrate the elasticity of flexible members made from metallic glass-based materials in accordance with certain embodiments of the invention.

FIGS. **7**A-**7**B illustrate the manufacture of a wheel assembly incorporating a plurality of flexible members including integrated tools made from metallic glass-based materials in accordance with certain embodiments of the invention.

FIGS. **8**A-**8**D illustrates a terrain traversing vehicle incorporating wheel assemblies including flexible members that include integrated tools made from metallic glass-based materials in accordance with certain embodiments of the invention.

DETAILED DESCRIPTION

Turning now to the drawings, systems and methods for implementing flexible members that include integrated tools made from metallic glass-based materials are illustrated. In many embodiments of the invention, the flexible members are elongated and include tools disposed at one end of its elongated geometry. In many embodiments, the integrated tool is a hook. In a number of embodiments, flexible members that include integrated hooks are disposed around the periphery of an annular rotor element. In numerous embodiments, either one or a plurality of such annular rotor elements are configured to operate as a wheel assembly.

For context, FIGS. **1**A-**1**B illustrate a conventional wheel assembly in accordance with the disclosure of the '629 patent. In particular, FIG. **1**A illustrates a wheel assembly **102** that includes an annular rotor element **104** with attached flexible member/microspine hook assemblies **106**, which themselves each include a flexible member **108** and an attached microspine hook **110**. It is depicted that the microspine hooks **110** are attached to the flexible members **108** via a polymer **112**. The flexible member/microspine hook assemblies **106** are distributed around the periphery of the annular rotor element **104**. The flexible members **108** conventionally have been made from a flexible metal, such as spring steel or nitinol. The microspine hooks have conventionally been implemented via standard steel fishing hooks. FIG. **1**B illustrates the flexibility of the flexible suspensions **108**. As disclosed in the '629 patent, the depicted wheel assembly can be incorporated in a terrain traversing device, such that the wheels can operate to facilitate the traversal of rigorous terrain. In particular, the respective flexible suspensions permit respective microspine hooks to initially engage an irregularity in a terrain surface at a preset initial engagement angle when the annular rotor element is rotated for urging the terrain traversing device to traverse a terrain surface.

Although configurations such as those depicted in FIGS. **1**A-**1**B manufactured from combinations of steel, nitinol, and/or polymer can be effective, there exists room for improvement. For example, the bonding of a distinct hook to a typical metallic flexible member using a polymer can define a weakness within the assembly. In particular, the polymer/microspine hook bonding can be susceptible to failure in these configurations. Such assemblies can benefit from a unibody construction, and more particularly from the incorporation of metallic glass-based materials.

Metallic glasses, also known as amorphous alloys, embody a relatively new class of materials that is receiving much interest from the engineering and design communities. Metallic glasses are characterized by their disordered atomic-scale structure in spite of their metallic constituent elements—i.e. whereas conventional metallic materials typically possess a highly ordered atomic structure, metallic glass materials are characterized by their disordered atomic structure. Notably, metallic glasses typically possess a number of useful material properties that can allow them to be implemented as highly effective engineering materials. For example, metallic glasses are generally much harder than conventional metals, and are generally tougher than ceramic materials. They are also relatively corrosion resistant, and, unlike conventional glass, they can have good electrical conductivity. Importantly, metallic glass materials lend themselves to relatively easy processing in certain respects. For example, the forming of metallic glass materials can be compatible with injection molding processes. Thus, for example, metallic glass compositions can be cast into desired shapes.

Nonetheless, the practical implementation of metallic glasses presents certain challenges that limit their viability as engineering materials. In particular, metallic glasses are typically formed by raising a metallic alloy above its melting temperature, and rapidly cooling the melt to solidify it in a way such that its crystallization is avoided, thereby forming the metallic glass. The first metallic glasses required extraordinary cooling rates, e.g. on the order of 10^6 K/s, and were thereby limited in the thickness with which they could be formed. Indeed, because of this limitation in thickness, metallic glasses were initially limited to applications that involved coatings. Since then, however, particular alloy compositions that are more resistant to crystallization have been developed, which can thereby form metallic glasses at much lower cooling rates, and can therefore be made to be much thicker (e.g. greater than 1 mm). These metallic glass compositions that can be made to be thicker are known as 'bulk metallic glasses' ("BMGs"). As can be appreciated, such BMGs can be better suited for investment molding operations.

In addition to the development of BMGs, 'bulk metallic glass matrix composites' (BMGMCs) have also been developed. BMGMCs are characterized in that they possess the amorphous structure of BMGs, but they also include crystalline phases of material within the matrix of amorphous structure. For example, the crystalline phases can exist in the form of dendrites. The crystalline phase inclusions can impart a host of favorable materials properties on the bulk material. For example, the crystalline phases can allow the material to have enhanced ductility, compared to where the material is entirely constituted of the amorphous structure. BMGs and BMGMCs can be referred to collectively as BMG-based materials. Similarly, metallic glasses, metallic glasses that include crystalline phase inclusions, BMGs, and BMGMCs can be referred to collectively as metallic glass-based materials or MG-based materials.

The potential of metallic glass-based materials continues to be explored, and developments continue to emerge. For example, in U.S. patent application Ser. No. 13/928,109, D. Hofmann et al. disclose the implementation of metallic glass-based materials in macroscale gears. The disclosure of U.S. patent application Ser. No. 13/928,109 is hereby incorporated by reference in its entirety, especially as it pertains to metallic glass-based materials, and their implementation in macroscale gears. Likewise, in U.S. patent application Ser. No. 13/942,932, D. Hofmann et al. disclose the implementation of metallic glass-based materials in macroscale compliant mechanisms. The disclosure of U.S. patent application Ser. No. 13/942,932 is hereby incorporated by reference in its entirety, especially as it pertains to metallic glass-based materials, and their implementation in macroscale compliant mechanisms. Moreover, in U.S. patent application Ser. No. 14/060,478, D. Hofmann et al. disclose techniques for depositing layers of metallic glass-based materials to form objects. The disclosure of U.S. patent application Ser. No. 14/060,478 is hereby incorporated by reference especially as it pertains to metallic glass-based materials, and techniques for depositing them to form objects. Furthermore, in U.S. patent application Ser. No. 14/163,936, D. Hofmann et al., disclose techniques for additively manufacturing objects so that they include metallic glass-based materials. The disclosure of U.S. patent application Ser. No. 14/163,936 is hereby incorporated by reference in its entirety, especially as it pertains to metallic glass-based materials, and additive manufacturing techniques for manufacturing objects so that they include metallic glass-based materials. Additionally, in U.S. patent application Ser. No. 14/177,608, D. Hofmann et al. disclose techniques for fabricating strain wave gears using metallic glass-based materials. The disclosure of U.S. patent application Ser. No. 14/177,608 is hereby incorporated by reference in its entirety, especially as it pertains to metallic glass-based materials, and their implementation in strain wave gears. Moreover, in U.S. patent application Ser. No. 14/178,098, D. Hofmann et al., disclose selectively developing equilibrium inclusions within an object constituted from a metallic glass-based material. The disclosure of U.S. patent application Ser. No. 14/178,098 is hereby incorporated by reference, especially as it pertains to metallic glass-based materials, and the tailored development of equilibrium inclusions within them. Furthermore, in U.S. patent application Ser. No. 14/252,585, D. Hofmann et al. disclose techniques for shaping sheet materials that include metallic glass-based materials, including using localized thermoplastic deformation and using cold working techniques. The disclosure of U.S. patent application Ser. No. 14/252,585 is hereby incorporated by reference in its entirety, especially as it pertains to metallic glass-based materials and techniques for shaping sheet materials that include metallic glass-based materials, including using localized thermoplastic deformation and using cold-working techniques. Additionally, in U.S. patent application Ser. No. 14/259,608, D. Hofmann et al. disclose techniques for fabricating structures including metallic glass-based materials using ultrasonic welding. The disclosure of U.S. patent application Ser. No. 14/259,608 is hereby incorporated by reference in its entirety, especially as it pertains to metallic glass-based materials and techniques for fabricating structures including metallic glass-based materials using ultrasonic welding. Moreover, in U.S. patent application Ser. No. 14/491,618, D. Hofmann et al. disclose techniques for fabricating structures including metallic glass-based materials using low pressure casting. The disclosure of U.S. patent application Ser. No. 14/491,618 is hereby incorporated by reference in its entirety, especially as it pertains to metallic glass-based materials and techniques for fabricating structures including metallic glass-based materials using low pressure casting. Furthermore, in U.S. patent application Ser. No. 14/660,730, Hofmann et al. disclose metallic glass-based fiber metal laminates. The disclosure of U.S. patent application Ser. No. 14/660,730 is hereby incorporated by reference in its entirety, especially as it pertains to metallic glass-based fiber metal laminates. Additionally, in U.S. patent application Ser. No. 14/971,848, A. Kennett et al. disclose techniques for manufacturing gearbox housings made from metallic glass-based materials. The disclosure of U.S. patent application Ser. No. 14/971,848, is hereby incorporated by reference in its entirety, especially as it pertains to the manufacture of metallic glass-based gearbox housings.

Notwithstanding all of these developments, the vast potential of metallic glass-based materials has yet to be fully appreciated. For instance, the suitability of metallic glass-based materials for implementation as flexible members that include integrated tools (e.g. the flexible suspension members—microspine assemblies discussed in the ’629 patent) has yet to be fully explored. Conventionally, the structures described in the ’629 patent have been fabricated from conventional engineering metals like steel, nitinol, and/or polymers (as depicted in FIGS. **1**A-**1**B). However, these structures can greatly benefit in a number of respects from the incorporation of metallic glass-based materials. For instance, metallic glass-based materials can imbue the wheels with improved fatigue characteristics, improved hardness, improved wear-resistance properties, improved flexibility, improved corrosion resistance, improved resilience against harsh environmental conditions, etc. Thus, for instance, the enhanced flexibility of many MG-based materials (e.g. having an elastic limit of up to 2% or more compared with steel which typically has an elastic limit of on the order of 1%) can allow better performance in terrain traversing applications. At the same time, the inherent hardness of many MG-based materials can further provide for improved hook performance; e.g. the hooks may not wear as easily as they interact with rigorous terrain. Metallic glass-based materials can also be readily cast or otherwise thermoplastically formed into any of a variety of complex geometries. Whereas conventionally, the fabrication of these structures involved adjoining various components to achieve the desired geometry, metallic glass-based materials can viably be ‘net shape’ cast (or ‘near net shape’ cast) into these structures; this can greatly enhance manufacturing efficiency. Methods for fabricating flexible members with integrated tools that include metallic glass-based materials are now discussed below.

Methods for Implementing Flexible Members Including Integral Tools from Metallic Glass-Based Materials

In many embodiments of the invention, flexible members including integral tools are fabricated from metallic glass-based materials. Any suitable manufacturing technique can be utilized to form the flexible member in accordance with embodiments of the invention. For example, in many embodiments, metallic glass-based materials are cold worked to shape them into the desired geometry—e.g. they are shaped at temperatures less than or equal to approximately room temperature (e.g. 72° F.). More broadly stated, cold-working can be said to occur when an MG-based material is shaped at a temperature less than its respective glass transition temperature. Thus for instance, FIGS. **2**A-**2**E illustrate the fabrication of a flexible member including an integrated tool from a metallic glass-based material via cold-forming in accordance with an embodiment of the invention. In particular, FIG. **2**A illustrates a metallic glass-based material to be formed into the desired structure. In the illustrated embodiment, the MG-based material is DV1.

FIG. **2**B illustrates that the metallic glass-based composition has been sliced into a thin sheet characterized by a thickness of 1 mm. FIG. **2**C illustrates that the metallic glass-based composition has been further sliced to create an elongated geometry. FIG. **2**D illustrates that the end is then bent to an angle greater than approximately 80° to create the desired geometry; more particularly, the bent end defines a hook that is the integrated tool. The inherent fracture toughness of DV1 allows it to accommodate the depicted extreme bending. FIG. **2**E illustrates the final geometry of two created structures. Thus, contrary to what may have been previously believed, it is illustrated that it is possible to bend (via cold working) an elongated geometry—made from a MG-based material—to an extreme angle without worrying about compromising the structural integrity of the piece. This is largely a function of the inherent fracture toughness of the respective metallic glass-based material. Accordingly, while cold-forming to this degree may be suitable for certain MG-based materials, it may not be suitable for all MG-based materials. A respective material must have at least a minimum fracture toughness in order to be able to withstand cold-working to this degree. Additionally, a MG-based material's ability to be cold-worked as described may be a function of the thickness of the MG-based material flexible member. Thus, for instance, in many embodiments a flexible member to be cold worked to form the integrated tool is characterized by a thickness of less than 1.5 mm. Cold forming can enable the easy manufacture of this useful geometry.

While cold-working a flexible member to form an integrated tool from a metallic glass-based material has been illustrated, it should be clear that any of a variety of processes can be implemented to form a flexible member including an integrated tool in accordance with embodiments of the invention. For example, in many embodiments, localized thermoplastic deformation processes as disclosed in U.S. patent application Ser. No. 14/252,585 incorporated by reference above are implemented, e.g. the flexible member can be bent when a region of the flexible member is above its respective glass transition temperature to define the hook. In many embodiments, direct casting techniques are utilized; casting can be a particularly efficient manufacturing strategy for the bulk fabrication of the described structures. Any suitable manufacturing technology can be implemented in accordance with embodiments of the invention.

Moreover, note that any suitable MG-based composition can be utilized to form a flexible member having an integrated tool in accordance with embodiments of the invention; embodiments of the invention are not limited to a particular composition. For example, in many instances, the utilized alloy composition is a composition that is based on one of: Ti, Zr, Cu, Ni, Fe, Pd, Pt, Ag, Au, Al, Hf, W, Ti—Zr—Be, Cu—Zr, Zr—Be, Ti—Cu, Zr—Cu—Ni—Al, Ti—Zr—Cu—Be and combinations thereof. In the instant context, the term 'based on' can be understood to mean that the specified element(s) are present in the greatest amount relative to any other present elements. Additionally, within the context of the instant application, the term "MG-based composition" can be understood reference an element, or aggregation of elements, that are capable of forming a metallic glass-based material (e.g. via being exposed to a sufficiently rapid, but viable, cooling rate). While several examples of suitable metallic glass-based materials are listed above, it should be reiterated that any suitable metallic glass-based composition can be incorporated in accordance with embodiments of the invention; for example, any of the metallic glass-based compositions listed in the disclosures cited and incorporated by reference above can be implemented. As alluded to above, in many embodiments, the implemented MG-based composition is based on the manufacturing technique to be applied. For example, where cold working will be used to shape the MG-based composition, a MG-based composition that is capable of forming a MG-based material characterized by a relatively high fracture toughness can be implemented. In a number of embodiments, the MG-based material is characterized by a fracture toughness of greater than approximately 80 MPa·m$^{1/2}$. In several embodiments, the MG-based material is characterized by a fracture toughness of greater than approximately 100 MPa·m$^{1/2}$. In many embodiments, the MG-based composition is implemented in the form of a matrix composite characterized by a particularly high fracture toughness (e.g. greater than approximately 80 MPa·m$^{1/2}$ or approximately 100 MPa·m$^{1/2}$). In a number of embodiments, the MG-based material that is to be formed into a flexible member via cold-forming is characterized by a thickness that is less than approximately three times the thickness of the plastic zone radius of the respective MG-based material. In numerous embodiments, the MG-based material that is to be formed into a flexible member via cold-forming is characterized by a thickness that is less than plastic zone radius of the respective MG-based material. In several embodiments, the MG-based material is characterized by a thickness of less than approximately 1.5 mm. These thicknesses can facilitate the desired formability. In many instances, the particular MG-based composition to be implemented is based on an assessment of the anticipated operating environment for the flexible member. For example, where it desired that the flexible member be relatively less massive, a titanium based MG-based material can be implemented. In many instances, the selection of the MG-based material to be implemented is based on the desire for one of: environmental resilience, toughness, wear resistance, hardness, density, machinability, and combinations thereof. In numerous embodiments, the MG-based material to be implemented is based on the desire to have relatively high resistance to wear (which can be correlated with hardness) and relatively high flexibility (which can be correlated with elastic strain limit). In many embodiments, the hardness of the MG-based material to be implemented is characterized by a value greater than approximately 50 Rc according to the Rockwell scale. In a number of embodiments, the MG-based material to be implemented has an elastic limit greater than approximately 1%. For reference, Tables 1-6 list materials data that can be relied on in selecting a metallic glass-based composition to be implemented. Any suitable MG-based material listed in the tables below can be implemented in accordance with various embodiments of the invention.

TABLE 1

Material Properties of MG-Based Materials relative to Heritage Engineering Materials

Material	Density (g/cc)	Stiffness, E (GPa)	Tensile Yield (MPa)	Tensile UTS (MPa)	Elastic Limit (%)	Specific Strength	Hardness (HRC)
SS 15500 H1024	7.8	200	1140	1170	<1	146	36
Ti—6Al—4V STA	4.4	114	965	1035	<1	219	41
Ti—6Al—6V—4Sn STA	4.5	112	1035	1100	<1	230	42
Nitronic 60 CW	7.6	179	1241	1379	<1	163	40
Vascomax C300	8.0	190	1897	1966	<1	237	50
Zr-BMG	6.1	97	1737	1737	>1.8	285	60
Ti-BMGMC	5.2	94	1362	1429	>1.4	262	51
Zr-BMGMC	5.8	75	1096	1210	>1.4	189	48

TABLE 2

Material Properties of Select MG-Based Materials as a function of Composition

name	atomic %	weight %	BMG (%)	bcc (%)	ρ (g/cm^3)	σ_y (MPa)	σ_{max} (MPa)	ε_y (%)	E (GPa)	T_s (K)
DV2	$Ti_{44}Zr_{20}V_{12}Cu_5Be_{19}$	$Ti_{41.9}Zr_{36.3}V_{12.1}Cu_{6.3}Be_{3.4}$	70	30	5.13	1597	1614	2.1	94.5	956
DV1	$Ti_{48}Zr_{20}V_{12}Cu_5Be_{15}$	$Ti_{44.3}Zr_{35.2}V_{11.8}Cu_{6.1}Be_{2.6}$	53	47	5.15	1362	1429	2.3	94.2	955
DV3	$Ti_{56}Zr_{18}V_{10}Cu_4Be_{12}$	$Ti_{51.6}Zr_{31.6}V_{9.8}Cu_{4.9}Be_{2.1}$	46	54	5.08	1308	1309	2.2	84.0	951
DV4	$Ti_{62}Zr_{15}V_{10}Cu_4Be_9$	$Ti_{57.3}Zr_{26.4}V_{9.8}Cu_{4.9}Be_{1.6}$	40	60	5.03	1086	1089	2.1	83.7	940
DVAI1	$Ti_{60}Zr_{16}V_9Cu_3Al_3Be_9$	$Ti_{55.8}Zr_{28.4}V_{8.9}Cu_{3.7}Al_{1.6}Be_{1.6}$	31	69	4.97	1166	1189	2.0	84.2	901
DVAI2	$Ti_{67}Zr_{11}V_{10}Cu_5Al_2Be_5$	$Ti_{62.4}Zr_{19.5}V_{9.9}Cu_{6.2}Al_1Be_{0.9}$	20	80	4.97	990	1000	2.0	78.7	998
Ti-6-4a	$Ti_{86.1}Al_{10.3}V_{3.6}$	$Ti_{90}Al_6V_4$ (Grade 5 Annealed)	na	na	4.43	754	882	1.0	113.8	1877
Ti-6-4s	$Ti_{86.1}Al_{10.3}V_{3.6}$ [Ref]	$Ti_{90}Al_6V_4$ (Grade 5 STA)	na	na	4.43	1100	1170	~1	114.0	1877
CP-Ti	Ti_{100}	Ti_{100} (Grade 2)	na	na	4.51	380	409	0.7	105.0	~1930

TABLE 3

Material Properties of Select MG-Based Materials as a function of Composition

Alloy	σ_{max} (MPa)	ε_{tot} (%)	σ_y (MPa)	ε_y (%)	E (GPa)	ρ (g/cm^3)	G (GPa)	CIT (J)	RoA (%)	υ
$Zr_{36.6}Ti_{31.4}Nb_7Cu_{5.9}Be_{19.1}$ (DH1)	1512	9.58	1474	1.98	84.3	5.6	30.7	26	44	0.371
$Zr_{38.3}Ti_{32.9}Nb_{7.3}Cu_{6.2}Be_{15.3}$ (DH2)	1411	10.8	1367	1.92	79.2	5.7	28.8	40	50	0.373
$Zr_{39.6}Ti_{33.9}Nb_{7.6}Cu_{6.4}Be_{12.5}$ (DH3)	1210	13.10	1096	1.62	75.3	5.8	27.3	45	46	0.376
$Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ (Vitreloy 1)	1737	1.98	—	—	97.2	6.1	35.9	8	0	0.355
$Zr_{56.2}Ti_{13.8}Nb_{5.0}Cu_{6.9}Ni_{5.6}Be_{12.5}$ (LM 2)	1302	5.49	1046	1.48	78.8	6.2	28.6	24	22	0.375

TABLE 4

Material Properties as a Function of Composition and Structure, where A is Amorphous, X, is Crystalline, and C is Composite

	A/X/C	2.0 Hv	E (GPa)
(CuZr42Al7Be10)Nb3	A	626.5	108.5
(CuZr46Al5Y2)Nb3	A	407.4	76.9
(CuZrAl7Be5)Nb3	A	544.4	97.8
(CuZrAl7Be7)Nb3	A	523.9	102.0
Cu40Zr40Al10Be10	A	604.3	114.2
Cu41Zr40Al7Be7Co5	C	589.9	103.5
Cu42Zr41Al7Be7Co3	A	532.4	101.3
Cu47.5Zr48Al4Co0.5	X	381.9	79.6
Cu47Zr46Al5Y2	A	409.8	75.3
Cu50Zr50	X	325.9	81.3
CuZr41Al7Be7Cr3	A	575.1	106.5
CuZrAl5Be5Y2	A	511.1	88.5
CuZrAl5Ni3Be4	A	504.3	95.5
CuZrAl7	X	510.5	101.4
CuZrAl7Ag7	C	496.1	90.6
CuZrAl7Ni5	X	570.0	99.2
Ni40Zr28.5Ti16.5Be15	C	715.2	128.4
Ni40Zr28.5Ti16.5Cu5Al10	X	627.2	99.3
Ni40Zr28.5Ti16.5Cu5Be10	C	668.2	112.0
Ni56Zr17Ti13Si2Sn3Be9	X	562.5	141.1
Ni57Zr18Ti14Si2Sn3Be6	X	637.3	139.4
Ti33.18Zr30.51Ni5.33Be22.88Cu8.1	A	486.1	96.9
Ti40Zr25Be30Cr5	A	465.4	97.5
Ti40Zr25Ni8Cu9Be18	A	544.4	101.1
Ti45Zr16Ni9Cu10Be20	A	523.1	104.2
Vit 1	A	530.4	95.2
Vit105 (Zr52.5Ti5Cu17.9Ni14.6Al10)	A	474.4	88.5
Vit 106	A	439.7	83.3
Zr55Cu30Al10Ni5	A	520.8	87.2
Zr65Cu17.5Al7.5Ni10	A	463.3	116.9
DH1	C	391.1	84.7
GHDT (Ti30Zr35Cu8.2Be26.8)	A	461.8	90.5

TABLE 5

Fatigue Characteristics as a Function of Composition

Material	Fracture strength (MPa)	Geometry (mm)	Loading mode^a	Frequency (Hz)	R-ratio	Fatigue, limit (MPa)	Fatigue ratio^b
$Zr_{56.2}Cu_{6.9}Ni_{5.6}Ti_{13.8}Nb_{5.0}Be_{12.5}$ Composites [62]	1480	3 × 3 × 30	4PB	25	0.1	~296	0.200
$Zr_{41.2}Cu_{12.5}Ni_{10}Ti_{13.8}Be_{22.5}$ [49]	1900	3 × 3 × 50	4PB	25	0.1	~152	0.080
$Zr_{41.2}Cu_{12.5}Ni_{10}Ti_{13.8}Be_{22.5}$ [74]	1900	2 × 2 × 60	3PB	10	0.1	768	0.404
$Zr_{41.2}Cu_{12.5}Ni_{10}Ti_{13.8}Be_{22.5}$ [74]	1900	2 × 2 × 60	3PB	10	0.1	359	0.189
$Zr_{44}Ti_{11}Ni_{10}Cu_{10}Be_{25}$ [75]	1900	2.3 × 2.0 × 85	4PB	5-20	0.3	550	0.289
$Zr_{44}Ti_{11}Ni_{10}Cu_{10}Be_{25}$ [75]	1900	2.3 × 2.0 × 85	4PB	5-20	0.3	390	0.205
$Zr_{52.5}Cu_{17.9}Al_{10}Ni_{14.5}Ti_5$ [77]	1700	3.5 × 3.5 × 30	4PB	10	0.1	850	0.500
$(Zr_{58}Ni_{13.5}Cu_{18}Al_{10.4})_{99}Nb_1$ [76]	1700	2 × 2 × 25	4PB	10	0.1	559	0.329
$Zr_{55}Cu_{30}Ni_5Al_{10}$ [78]	1560	2 × 20 × 50	Plate bend	40	0.1	410	0.263

TABLE 6

Fatigue Characteristics as a Function of Composition

Material	Fracture strength (MPa)	Geometry (mm)	Loading mode^a	Frequency (Hz)	R-ratio	Fatigue limit (MPa)	Fatigue ratio^b
$Zr_{56.2}Cu_{6.9}Ni_{5.6}Ti_{13.8}Nb_{5.0}Be_{12.5}$ Composites [56]	1480	Ø2.98	TT	10	0.1	239	0.161
$Zr_{55}Cu_{30}Al_{10}Ni_5$ Nano [85]	1700	2 × 4 × 70	TT	10	0.1	~340	0.200
$Zr_{41.2}Cu_{12.5}Ni_{10}Ti_{13.8}Be_{22.5}$ [55]	1850	Ø2.98	TT	10	0.1	703	0.380
$Zr_{41.2}Cu_{12.5}Ni_{10}Ti_{13.8}Be_{22.5}$ [55]	1850	Ø2.98	TT	10	0.1	615	0.332
$Zr_{41.2}Cu_{12.5}Ni_{10}Ti_{13.8}Be_{22.5}$ [56]	1850	Ø2.98	TT	10	0.1	567	0.306
$Zr_{41.2}Cu_{12.5}Ni_{10}Ti_{13.8}Be_{22.5}$ [80]	1900	—	CC	5	0.1	~1050	0.553
$Zr_{41.2}Cu_{12.5}Ni_{10}Ti_{13.8}Be_{22.5}$ [80]	1900	—	TC	5	−1	~150	0.079
$Zr_{50}Cu_{40}Al_{10}$ [53]	1821	Ø2.98	TT	10	0.1	752	0.413
$Zr_{50}Cu_{30}Al_{10}Ni_{10}$ [53]	1900	Ø2.98	TT	10	0.1	865	0.455
$Zr_{50}Cu_{37}Al_{10}Pd_3$ [57]	1899	Ø2.98	TT	10	0.1	983	0.518
$Zr_{50}Cu_{37}Al_{10}Pd_3$ [81]	1899	Ø5.33	TT	10	0.1	~900	0.474
$Zr_{52.5}Cu_{17.9}Al_{10}Ni_{14.6}Ti_5$ [82]	1660	6 × 3 × 1.5	TT	1	0.1	—	—
$Zr_{52.5}Cu_{17.9}Al_{10}Ni_{14.6}Ti_5$ [51]	1700	Ø2.98	TT	10	0.1	907	0.534
$Zr_{50}Cu_{20}Al_{10}Ni_8Ti_3$ [82]	1580	6 × 3 × 1.5	TT	1	0.1	—	—
$Zr_{55}Cu_{15}Al_{10}Ni_{10}$ [84]	1300	3 × 4 × 16	TT	20	0.1	~280	0.215
$Zr_{55}Cu_{30}Al_{10}Ni_5$ [83]	1560	1 × 2 × 5	TT	0.13	0.5	—	—

Furthermore, although a particular geometry for a flexible member with an integrated tool is illustrated and described with respect to FIGS. **2**A-**2**E, it should be clear that any suitable geometry for a flexible member including an integrated tool can be incorporated in accordance with embodiments of the invention. For example, in many embodiments, a flexible member includes a plurality of extensions and a plurality of integrated tools. Thus, for instance, FIG. **3** illustrates a geometry for a flexible member including a plurality of extensions with a plurality of integrated tools in accordance with certain embodiments of the invention. As can be appreciated from the discussion above, any suitable manufacturing techniques can be used to implement the depicted geometry. For example, the depicted geometry could be cast from a MG-based composition in accordance with embodiments of the invention.

In many embodiments, the flexible members described above are incorporated within the context of a terrain traversing vehicle as disclosed in the terrain traversing devices disclosed in the ’629 application. Thus, for example, FIG. **4** illustrates a process for implementing a wheel including microhooks that can be incorporated within a terrain traversing device as disclosed in the ’629 patent. In particular, FIG. **4** illustrates that the process **400** includes forming **410** a plurality of flexible members that include integrated hooks from metallic glass-based materials. As before, any suitable metallic glass-based material can be incorporated in accordance with embodiments of the invention, including any material referenced above. Additionally, any suitable manufacturing technique can be used to form the flexible members from the metallic glass-based materials, e.g. cold forming or direct casting. The method **400** further includes affixing **420** the plurality of formed flexible members to an annular rotor element. Any suitable affixing technique can be implemented in accordance with embodiments of the invention. For example, in many embodiments, the flexible member is welded to the annular rotor element. In a number of embodiments, a rapid capacitive discharge technique is utilized to affix the flexible member to the annular rotor element. FIGS. **5**A-**5**B schematically illustrate using a rapid capacitive discharge technique to affix the flexible member to an annular rotor element in accordance with certain embodiments of the invention. In particular, FIG. **5**A diagrams using rapid capacitive discharge to affix a flexible member **502** to an annular rotor element **504** in accordance with an embodiment of the invention. FIG. **5**B illustrates an annular rotor element including a plurality of flexible members in accordance with an embodiment of the invention.

Notably, metallic glass-based materials are often characterized by their high elastic limits. For example, whereas conventional metals have elastic limits on the order of 1%, metallic glass-based materials can have elastic limits as high as 2% or more. This high elasticity can allow them to be viably implemented within the terrain traversing devices disclosed in the ’629 patent. FIGS. **6**A-**6**D visually illustrate the flexibility that flexible members made from metallic glass-based materials can be made to possess.

FIGS. **7**A-**7**B illustrate the formation of a wheel including a plurality flexible members with integrated hooks made from metallic glass-based materials in accordance with embodiments of the invention. In particular, FIG. **7**A illustrates a plurality of annular rotor elements including a plurality of flexible members made from metallic glass-based materials. FIG. **7**B illustrates an assembled wheel incorporated the plurality of annular rotor elements and associated flexible members. In particular, the annular rotor elements can be adjoined such that flexible members are evenly distributed around the adjoined annular rotor elements such that the assembly can operate as a wheel.

FIGS. **8**A-**8**D illustrates a terrain traversing device that incorporates wheels including flexible members with integrated hooks made from metallic glass-based materials in accordance with embodiments of the invention. In particular, FIG. **8**A illustrates an isometric view of the device; FIG. **8**B illustrates a view looking down on the device; FIG. **8**C illustrates a side-view of the device; and FIG. **8**D illustrates a close up of the wheel assembly. Notably, the flexible members and integrated hooks made from MG-based materials were sufficiently structurally integral to allow the device to crawl vertically up a cinder block.

As can be inferred from the above discussion, the above-mentioned concepts can be implemented in a variety of arrangements in accordance with embodiments of the invention. For example, while a hook has been given as the example of an integrated tool, any suitable integrated tool can be implemented in accordance with embodiments of the invention. For instance, any implement configured to facilitate mobility or grip/engage a surface can be implemented. Accordingly, although the present invention has been described in certain specific aspects, many additional modifications and variations would be apparent to those skilled in the art. It is therefore to be understood that the present invention may be practiced otherwise than specifically described. Thus, embodiments of the present invention should be considered in all respects as illustrative and not restrictive.

What claimed is:

1. A terrain traversing device comprising:

a device body;

at least one rotor element rotatably interconnected with said device body and configured to provide a propulsive force thereto;

a plurality of elongated flexible members, each having a first end and a second end and formed of a metallic glass-based material having a thickness of less than approximately three times the size of the plastic zone radius of the metallic glass-based material and an elastic limit of at least 1.0%;

an integrated tool disposed at the first end of each of the elongated flexible members, wherein the integrated tool is at least one hook formed by a bend in the elongated flexible member;

wherein the elongated flexible member and the integrated tool comprise a unitary body; and

wherein only the second end of each of the elongated flexible members is attached to the at least one rotor element, such that each elongated flexible member is configured to at least partially wrap about the at least one rotor element during operation; and

wherein the plurality of elongated flexible members are distributed around the at least one rotor element such that the aggregate of the plurality of elongated flexible members form an outer wheel of integrated tools about the at least one rotor element.

2. The terrain traversing device of claim **1**, wherein the integrated tool comprises a plurality of hooks.

3. The terrain traversing device of claim **1**, wherein the metallic glass-based material is a metallic glass matrix composite material.

4. The terrain traversing device of claim **1**, wherein the metallic glass-based material is characterized by a fracture toughness of greater than approximately 80 MPa·m$^{1/2}$.

5. The terrain traversing device of claim **1**, wherein the metallic glass-based material is fully amorphous.

6. The terrain traversing device of claim **1**, wherein the metallic glass-based material is characterized in that it has an elastic limit of greater than approximately 1.5%.

7. The terrain traversing device of claim **1**, wherein the metallic glass-based material is characterized in that it has an elastic limit of greater than approximately 2%.

8. The terrain traversing device of claim **1**, wherein the elongated flexible member is characterized by a thickness of less than approximately 1.5 mm.

9. The terrain traversing device of claim **1**, wherein the elongated flexible member defines a plurality of extensions including a plurality of integrated tools disposed at one end of the respective extensions.

10. A terrain traversing device comprising:

a device body;

at least one rotor element rotatably interconnected with the device body, and configured to provide a propulsive force thereto;

a plurality of elongated flexible members, each having a first end and a second end with an integrated tool disposed at the first end, wherein each of the elongated flexible members comprises a unitary body with the integrated tool formed of a metallic glass-based material;

wherein the metallic glass-based material has a fracture toughness of at least 80 MPa·m$^{1/2}$, an elastic limit of at least 1.0%, and allows bending by cold working of the elongated flexible member with a thickness of less than approximately three times the size of the plastic zone radius of the respective metallic glass-based material to an angle as small as 80° without compromising the structural integrity of the elongated flexible member;

wherein the integrated tool is a hook formed by a bend in the elongated flexible member, and wherein the bend forms an angle with the elongated flexible member of greater than 80°; and

wherein only the second end of each of the elongated flexible members is attached to the at least one rotor element, such that each elongated flexible member is configured to at least partially wrap about the at least one rotor element during operation; and

wherein the plurality of elongated flexible members are distributed around the at least one rotor element such that the aggregate of the plurality of elongated flexible members form an outer wheel of integrated tools about the at least one rotor element.

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