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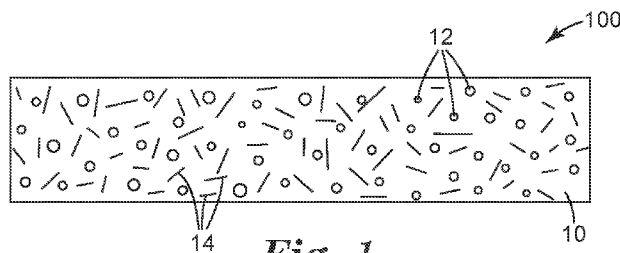
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[Continued on next page]

- (54) **Title:** METAL MATRIX COMPOSITES INCLUDING INORGANIC PARTICLES AND DISCONTINUOUS FIBERS AND METHODS OF MAKING SAME

**Fig. 1**

- (57) **Abstract:** A metal matrix composite is provided, including a metal, inorganic particles, and discontinuous fibers. The inorganic particles and the discontinuous fibers are dispersed in the metal. The metal includes aluminum, magnesium, or alloys thereof. The inorganic particles have an envelope density that is at least 30% less than a density of the metal. The metal matrix composite has a lower envelope density than the matrix metal while retaining a substantial amount of the mechanical properties of the metal.



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**METAL MATRIX COMPOSITES INCLUDING INORGANIC PARTICLES AND
DISCONTINUOUS FIBERS AND METHODS OF MAKING SAME**

Technical Field

5 **[0001]** The present disclosure relates to metal matrix composites, which include a mixture of a metal base with other materials, such as filler materials.

Background

10 **[0002]** Metal matrix composites have long been recognized as promising materials due to their combination of high strength and stiffness combined with low weight. Metal matrix composites typically include a metal matrix reinforced with fibers or other filler materials.

Summary

15 **[0003]** The present disclosure provides a lightweighted metal matrix composite. There remains a need for metal matrix composites that have a lower envelope density than the matrix metal while maintaining certain levels of physical properties.

20 **[0004]** In an aspect, the present disclosure provides a metal matrix composite. The metal matrix composite includes a metal, inorganic particles, and discontinuous fibers. The inorganic particles and the discontinuous fibers are dispersed in the metal. The metal includes aluminum, magnesium, or alloys thereof. The inorganic particles have an envelope density that is at least 30% less than a density of the metal.

[0005] In another aspect, the present disclosure provides a plurality of glass bubbles. The glass bubbles comprise glass that withstands heating to a temperature of 700 degrees Celsius for at least two hours without softening and exhibits a pouring index at 1371 degrees Celsius of 6 or less.

25 **[0006]** Various unexpected results and advantages are obtained in exemplary embodiments of the present disclosure. An advantage of at least one exemplary embodiment of the present disclosure is that a metal matrix composite containing inorganic particles and discontinuous fibers dispersed in the metal exhibits both a lower envelope density than the metal and an acceptable yield strength (e.g., plastic yielding in a tensile stress-strain curve).

30 **[0007]** The above summary of the present disclosure is not intended to describe each disclosed embodiment or every implementation of the present disclosure. The description that follows more particularly exemplifies illustrative embodiments. In several places throughout the application, guidance is provided through lists of examples, which examples can be used in various

combinations. In each instance, the recited list serves only as a representative group and should not be interpreted as an exclusive list.

Brief Description of the Drawings

5 **[0008]** The disclosure may be more completely understood in consideration of the following detailed description of various embodiments of the disclosure in connection with the accompanying figures, in which:

[0009] Figure 1 is a schematic cross-section view of a metal matrix composite according to an exemplary embodiment of the present disclosure.

10 **[0010]** Figure 2 is a graph of stress-strain curves for exemplary matrices and comparative matrices.

[0011] Figure 3 is a graph of stress-strain curves for additional exemplary matrices and comparative matrices.

15 **[0012]** Figure 4 is a graph of stress-strain curves for further exemplary matrices and comparative matrices.

[0013] Figure 5 is a graph of stress-strain curves for another exemplary matrix.

[0014] Figure 6 is a graph of stress-strain curves for still further exemplary matrices.

[0015] Figure 7 is a graph of stress-strain curves for yet another exemplary matrix.

20 **[0016]** While the above-identified drawings, which may not be drawn to scale, set forth embodiments of the present disclosure, other embodiments are also contemplated, as noted in the Detailed Description.

Detailed Description

25 **[0017]** For the following Glossary of defined terms, these definitions shall be applied for the entire application, unless a different definition is provided in the claims or elsewhere in the specification.

Glossary

[0018] Certain terms are used throughout the description and the claims that, while for the most part are well known, may require some explanation. It should be understood that, as used herein:

[0019] As used in this specification and the appended embodiments, the singular forms “a”, “an”, and “the” include plural referents unless the content clearly dictates otherwise. As used in this specification and the appended embodiments, the term “or” is generally employed in its sense including “and/or” unless the content clearly dictates otherwise.

5 [0020] As used in this specification, the recitation of numerical ranges by endpoints includes all numbers subsumed within that range (e.g. 1 to 5 includes 1, 1.5, 2, 2.75, 3, 3.8, 4, and 5).

[0021] Unless otherwise indicated, all numbers expressing quantities or ingredients, measurement of properties and so forth used in the specification and embodiments are to be understood as being modified in all instances by the term “about.” Accordingly, unless indicated
10 to the contrary, the numerical parameters set forth in the foregoing specification and attached listing of embodiments can vary depending upon the desired properties sought to be obtained by those skilled in the art utilizing the teachings of the present disclosure. At the very least, and not as an attempt to limit the application of the doctrine of equivalents to the scope of the claimed
15 embodiments, each numerical parameter should at least be construed in light of the number of reported significant digits and by applying ordinary rounding techniques.

[0022] The terms “comprises” and variations thereof do not have a limiting meaning where these terms appear in the description and claims.

[0023] The words “preferred” and “preferably” refer to embodiments of the disclosure that may afford certain benefits, under certain circumstances. However, other embodiments may also be
20 preferred, under the same or other circumstances. Furthermore, the recitation of one or more preferred embodiments does not imply that other embodiments are not useful, and is not intended to exclude other embodiments from the scope of the disclosure.

[0024] Reference throughout this specification to “one embodiment,” “certain embodiments,” “one or more embodiments” or “an embodiment,” whether or not including the term “exemplary”
25 preceding the term “embodiment,” means that a particular feature, structure, material, or characteristic described in connection with the embodiment is included in at least one embodiment of the certain exemplary embodiments of the present disclosure. Thus, the appearances of the phrases such as “in one or more embodiments,” “in certain embodiments,” “in one embodiment,” “in many embodiments” or “in an embodiment” in various places throughout this specification are
30 not necessarily referring to the same embodiment of the certain exemplary embodiments of the present disclosure. Furthermore, the particular features, structures, materials, or characteristics may be combined in any suitable manner in one or more embodiments.

[0025] The term “dispersed” with respect to one or more fillers in a metal matrix refers to the one or more fillers distributed throughout the metal matrix, for instance providing a substantially

homogeneous metal matrix composite including the metal and the filler(s). This is in contrast to areas of a metal matrix composite having a concentration of one or more fillers that is at least twice as high as an area in a different location of the metal matrix composite (e.g., layers or clusters of a filler within the metal matrix composite). Although it may be possible to observe a sufficiently small volume of a metal matrix composite in which the one or more fillers is not exactly homogenously distributed in the metal matrix, the filler(s) is still dispersed in the metal.

[0026] The term “sinter” refers to making a powdered material coalesce into a solid or porous mass by heating it without complete liquefaction. Optionally, the powdered material is also compressed during sintering.

[0027] The term “envelope density” with respect to particles refers to the mass divided by the envelope volume. The “envelope volume” refers to the sum of the volumes of the solid in each particle and any voids in the particle. Similarly, the term “envelope density” with respect to a metal matrix composite refers to the mass divided by the envelope volume, where the “envelope volume” refers to the sum of the volumes of the solid in the metal matrix composite and any voids in the metal matrix composite.

[0028] The term “skeleton density” with respect to porous particles refers to the mass divided by the skeleton volume. The “skeleton volume” refers to the sum of the volumes of the solid material and any closed pores within the particle.

[0029] The term “softening point” refers to the temperature, or range of temperatures, at which a material (e.g., in a solid phase) begins to slump under its own weight. For materials that have a definite melting point (e.g., metals), the softening point is generally regarded as being the melting point of the metal or metal alloy. However, for materials that do not have a definite melting point, the softening point may be the temperature at which elastic behavior of the material changes to plastic flow. For example, the softening point of a glass, a glass-ceramic, or a porcelain may occur at a glass-transition temperature of the material, and may be defined by a viscosity of $10^{7.65}$ poise. The softening point of glass is typically determined, for example, by the Vicat method (e.g., ASTM-D1525 or ISO 306) or by the Heat Deflection Test (e.g., ASTM-D648).

[0030] The term “strain” refers to tensile strain. The term “tensile strain” refers to deformation of a material when being stretched, bent, or pulled in tension.

[0031] The term “plastic yield” refers to the stress at which a predetermined amount of permanent deformation of a material occurs.

[0032] The term “tensile plastic yield” refers to the stress at which a predetermined amount of permanent deformation of a material occurs while the material is being subjected to a tensile force.

[0033] The term “yield strength” refers to the stress at which it is considered that plastic elongation of a material has commenced. As used herein, the yield strength is determined at an

offset of 0.2%. ASTM B557M-15 discloses “7.6 *Yield Strength*—Determine yield strength by the offset method at an offset of 0.2 %. Acceptance or rejection of material may be decided on the basis of Extension-Under-Load Method. For referee testing, the offset method shall be used. 7.6.1 *Offset Method*—To determine the yield strength by the “offset method,” it is necessary to secure data (autographic or numerical) from which a stress-strain diagram may be drawn. Then on the stress-strain diagram (Fig. 16) lay off Om equal to the specified value of the offset, draw mn parallel to OA , and thus locate r , the intersection of mn with the stress-strain diagram (Note 12). In reporting values of yield strength obtained by this method, the specified value of “offset” used should be stated in parentheses after the term yield strength. Thus: Yield strength (offset = 0.2 %) = 360 MPa”.

[0034] The term “transitional-alumina” refers to any alumina from aluminum hydroxide to alpha-alumina. Specific transitional-alumina particles include delta-alumina, eta-alumina, theta-alumina, chi-alumina, kappa-alumina, rho-alumina, and gamma-alumina. The transitional-alumina particles are generated during the heat treatment of aluminum hydroxide or aluminum oxyhydroxide. The most thermodynamically stable form is generally alpha-alumina.

[0035] Various exemplary embodiments of the disclosure will now be described. Exemplary embodiments of the present disclosure may take on various modifications and alterations without departing from the spirit and scope of the disclosure. Accordingly, it is to be understood that the embodiments of the present disclosure are not to be limited to the following described exemplary embodiments, but are to be controlled by the limitations set forth in the claims and any equivalents thereof.

[0036] In an aspect, the present disclosure provides a metal matrix composite. The metal matrix composite includes a metal, a plurality of inorganic particles, and a plurality of discontinuous fibers. The inorganic particles and the discontinuous fibers are dispersed in the metal. The inorganic particles have an envelope density that is at least 30% less than a density of the metal, at least 40%, or at least 50% less than a density of the metal. The metal comprises aluminum, magnesium, or alloys thereof.

[0037] Referring to FIG. 1, a schematic cross-section view of a metal matrix composite 100 is provided. The metal matrix composite 100 includes a metal 10, a plurality of inorganic particles 12, and a plurality of discontinuous fibers 14. The inorganic particles 12 and the discontinuous fibers 14 are dispersed in the metal 10. For simplicity, the metal matrix composite is illustrated as having a monolithic shape; however, the metal matrix composite may be formed in a number of various shapes depending on the intended application. Metal matrix composites are applicable to industries such as construction, automotive, and electronics, in which a particular metal component may be replaced with a metal matrix composite component.

[0038] In some embodiments, the metal comprises a porous matrix structure. A porous matrix structure is usually obtained from powdered metal, wherein the powder contains a metal structure in which a gas (e.g., air) is incorporated into the solid metal structure. In alternate embodiments, the metal comprises a nonporous matrix structure. A nonporous matrix structure is usually
5 obtained from molten metal.

[0039] Typically, the metal is present in an amount of 50 weight percent or more of the metal matrix composite, 55 weight percent or more, 60 weight percent or more, 65 weight percent or more, 70 weight percent or more, or 75 weight percent or more; and in an amount of 95 weight percent or less, 90 weight percent or less, 85 weight percent or less, or 80 weight percent or less.
10 Stated another way, the metal may be present in an amount of between 50 weight percent and 95 weight percent, inclusive, of the metal matrix composite, or between 70 weight percent and 95 weight percent, inclusive, of the metal matrix composite. The metal comprises aluminum, magnesium, or alloys thereof (i.e., an aluminum alloy or a magnesium alloy). Suitable metals include for instance and without limitation, pure aluminum (aluminum powder with purity of at
15 least 99.0%, e.g., AA1100, AA1050, AA1070 etc. , such as pure aluminum powder commercially available from Eckart (Louisville, KY)); or an aluminum alloy containing aluminum and 0.2 to 2% by mass of another metal. Such alloys include: Al—Cu alloys (AA2017 etc.), Al—Mg alloys (AA5052 etc.), Al—Mg—Si alloys (AA6061 etc.), Al—Zn—Mg alloys (AA7075 etc.) and Al—Mn alloys, either alone or as a mixture of two or more. Various suitable metal powders are
20 commercially available from Atlantic Equipment Engineers (Upper Saddle River, NJ).

[0040] Typically, when the metal is used in the form of a powder, the metal powder comprises an average particle size of 300 nanometers (nm) or more, 400 nm or more, 500 nm or more, 750 nm or more, 1 micrometer (μm) or more, 2 μm or more, 5 μm or more, 7 μm or more, 10 μm or more, 20 μm or more, 35 μm or more, 50 μm or more, or 75 μm or more; and 100 μm or less, 75 μm or less, 50 μm or less, 35 μm or less, or 25 μm or less. Stated another way, the metal powder
25 comprises an average particle size ranging between 300 nm and 100 μm, inclusive; ranging between 1 μm and 100 μm, inclusive; or ranging between 1 μm and 50 μm, inclusive. The particle size can be analyzed, for instance, using light microscopy and laser diffraction.

[0041] Suitable inorganic particles include particles having a maximum envelope density of
30 2.00 grams per cubic centimeter or less, 1.75 grams per cubic centimeter or less, 1.50 grams per cubic centimeter or less, 1.25 grams per cubic centimeter or less, or 1.00 grams per cubic centimeter or less. Typically, the plurality of inorganic particles comprises a substantially spherical shape or an acicular shape, while in some embodiments the inorganic particles comprise multicelled bubbles. The particles generally have an aspect ratio of longest axis to shortest axis of
35 2 : 1 or less.

[0042] Typically, the plurality of inorganic particles comprises an average particle size of 50 nanometers (nm) or more, 250 nm or more, 500 nm or more, 750 nm or more, 1 micrometer (μm) or more, 2 μm or more, 5 μm or more, 7 μm or more, 10 μm or more, 20 μm or more, 35 μm or more, 50 μm or more, 75 μm or more, or 100 μm or more; and 5 millimeters (mm) or less, 3 mm or less, 2 mm or less, 1 mm or less, 750 μm or less, 500 μm or less, or 250 μm or less. Stated another way, the plurality of inorganic particles comprises an average particle size ranging between 50 nm and 5 mm, inclusive; ranging between 1 μm and 1 mm, inclusive; or ranging between 10 μm and 500 μm , inclusive.

[0043] The amount of inorganic particles dispersed in the metal is not particularly limited. The plurality of inorganic particles is often present in an amount of at least 1 weight percent of the metal matrix composite, at least 2 weight percent, at least 5 weight percent, at least 8 weight percent, at least 10 weight percent, at least 15 weight percent, or at least 20 weight percent of the metal matrix composite; and up to 50 weight percent, up to 28 weight percent, up to 26 weight percent, up to 24 weight percent, or up to 22 weight percent of the metal matrix composite. In certain embodiments, the inorganic particles are present in the metal matrix composite in an amount of between 1 weight percent and 30 weight percent, or between 2 weight percent and 25 weight percent, or between 2 weight percent and 15 weight percent, inclusive, of the metal matrix composite. Including less than 1 weight percent of the inorganic particles results in a minimal decrease in envelope density of the metal matrix composite, while including more than 30 weight percent of the inorganic particles negatively impacts the mechanical properties of the metal matrix composite due to the metal matrix composite containing an insufficient amount of metal and fibers.

[0044] In certain embodiments the plurality of inorganic particles comprise porous particles. As used herein, "porous particles" refers to both particles that have pores themselves, and agglomerates of nonporous primary particles including pores between at least some of the nonporous primary particles. Examples of useful porous particles include for instance and without limitation, porous metal oxide particles, porous metal hydroxide particles, porous metal carbonates, porous carbon particles, porous silica particles, porous dehydrated aluminosilicate particles, porous dehydrated metal hydrate particles, zeolite particles, porous glass particles, expanded perlite particles, expanded vermiculite particles, porous sodium silicate particles, engineered porous ceramic particles, agglomerates of nonporous primary particles, or combinations thereof. In certain embodiments, the metal of the metal oxide, metal hydroxide, or metal carbonate is selected from aluminum, magnesium, zirconium, calcium, or combinations thereof. In select embodiments, the porous particles comprise porous alumina particles, porous carbon particles, porous silica particles, porous aluminum hydroxide particles, or combinations

thereof. The porous particles typically have had associated water removed from them, usually by heating the porous particles. Optionally, the porous particles comprise transitional-alumina particles. Suitable porous particles include for instance and without limitation, Versal 250 boehmite powder commercially available from UOP LLC (Des Plaines, IL), YH-D 16 boehmite powder, Zibo Yinghe Chemical Company, Ltd. (Shandong, China), and Alumax PB300 boehmite, PIDC International (Ann Arbor, MI).

[0045] In certain embodiments, the plurality of inorganic particles comprises ceramic bubbles or glass bubbles. Suitable materials for ceramic bubbles and glass bubbles includes, for instance and without limitation, alumina, aluminosilicate, silica, or combinations thereof. Commercially available glass bubbles include, for example, the LightStar, EconoStar, and High Alumina censopheres available from Cenostar Corporation (Amesbury, MA). Preferably, the ceramic bubbles and glass bubbles are uncoated (e.g., with a metal material, which has been used to aid in wetting of the bubbles by the metal matrix).

[0046] In some embodiments, the plurality of glass bubbles advantageously comprise glass that withstands heating to a temperature of 700 degrees Celsius for at least two hours without softening. More particularly, in certain embodiments, the glass bubbles comprise glass that has a glass softening temperature ranging from 700 degrees Celsius to 785 degrees Celsius, inclusive, or from 715 degrees Celsius to 735 degrees Celsius.

[0047] The use of high temperature resistant glass bubbles allows their incorporation in metal matrix composites that otherwise would be prepared at a temperature elevated enough to damage the glass bubbles, such as by softening at least some of the glass bubbles to the point that they deform and/or break.

[0048] Another suitable type of glass bubbles includes bubbles that leach less than 100 micrograms of sodium ion per gram of glass bubbles in deionized water when stirred with the deionized water for 2 hours. An advantage of glass bubbles with such a low sodium leaching rate is that they are useful in electronics applications where the leaching of sodium ions is often unacceptable. In an embodiment, suitable compounds used for the preparation of such low sodium glass bubbles include silica, lime, boric acid, calcium phosphate, calcined alumina silicate, and magnesium silicate. In certain embodiments, such low sodium glass bubbles exhibit a softening point between 717 °C and 735 °C, inclusive, as measured by thermal dilatometry.

[0049] It is generally known in the glass bubble art that the properties of glass bubbles can be varied by adjusting relative proportions of the components of a glass bubble composition. For example, a variety of glass bubbles differing in density, strength, softening temperature and pouring index can be prepared in a low sodium glass bubble composition including silica, lime, boric acid, calcium phosphate, calcined alumina silicate, and magnesium silicate. The pouring

index is an empirical index ranging from 1 to 10, based on judging how easy it is to pour the molten glass when the glass has been heated to a temperature of 2500 degrees Fahrenheit (1371 degrees Celsius). The pouring index is indicative of the glass viscosity at the melting temperature. A pouring index of 10 means that the glass viscosity is low enough for pouring easily. A pouring index of 1 means that the glass viscosity is very high so that the glass does not pour off (e.g., the glass is hardly moving during the attempted pouring). While not wishing to be bound by theory, it is believed that the pouring index and the softening temperature for glass bubble compositions are correlated. That is, as the pouring index of a glass composition decreases the softening temperature of the glass bubble composition increases. In other words, glass bubble compositions having similar pouring index are believed to have similar softening temperatures. Generally speaking, suitable glass bubble compositions have a pouring index of 6 or less, preferably 5 or less, 4 or less, 3 or less, or 2 or less. In certain embodiments, suitable glass bubbles have a pouring index of 1.

[0050] In some embodiments, the plurality of glass bubbles optionally comprise an average envelope density of between 0.50 and 2.30 grams per cubic centimeter, inclusive, such as between 0.50 and 1.50 grams per cubic centimeter or between 0.50 and 0.90 grams per cubic centimeter.

[0051] In certain embodiments, suitable glass bubbles may have a composition including silica, lime, boric acid, calcium phosphate, calcined alumina silicate, magnesium silicate and up to about 1 wt. % Na_2O while exhibiting a pouring index of 6 or less. In some embodiments, the glass bubbles comprise a silica to alumina weight ratio ranging from 2.5 to 7.5, inclusive, or from 5.0 to 7.5, inclusive.

Table 1, below, provides exemplary low sodium glass bubble compositions and the properties (i.e., density, strength, softening temperature and pouring index) of glass bubbles prepared therefrom.

Table 1. Exemplary glass bubble compositions

Sample#	Glass Bubble Composition (wt. %)									Density (g/cm ³)	Strength (psi)	Pouring index	Softening Temperature (°C)
	Al ₂ O ₃	B ₂ O ₃	MgO	P ₂ O ₅	SiO ₂	CaO	S	ZnO	Na ₂ O				
1	8.21	9.91	0.69	3.96	59.34	16.71	0.30	0.79		0.6942	8897.0	(1) no pour	715-735
2	8.21	9.91	1.80	2.54	59.34	16.71	0.30	1.10		0.7499	5972.1	(1) no pour	
3	8.21	9.91	1.13	2.91	59.34	16.71	0.30	1.40		0.7390	6925.1	(1) no pour	
4	8.21	9.91	0.00	3.96	59.34	16.71	0.30	1.48		0.7207	9675.0	(1) no pour	
5	8.21	9.91	1.13	2.91	59.34	16.71	0.30	1.40		0.7131	6954.1	(1) no pour	
6	8.21	9.91	2.47	0.99	59.34	16.71	0.30	1.98		0.8206	4101.5	(1) no pour	
7	8.21	9.91	1.80	1.95	59.34	16.71	0.30	1.69		0.7333	6037.3	(1) no pour	
8	8.21	9.91	2.47	2.18	59.34	16.71	0.30	0.79		0.7467	6862.2	(1) no pour	
9	8.21	9.91	1.13	2.91	59.34	16.71	0.30	1.40		0.6945	7035.5	(1) no pour	
10	9.09	7.72	3.03	3.03	59.34	16.75	0.30	0.75		0.7650	6039.5	(1) no pour	
11	11.87	7.04	1.98	1.98	59.34	16.75	0.30	0.75		0.9810	7678.3	(1) no pour	
12	18.97	4.09	3.62	2.98	52.32	16.39	0.19	0.5	0.96	2.2246		(6), very viscous	
13	20.45	4.09	3.62	2.98	52.32	14.91	0.19	0.5	0.96	2.2088		(5), very viscous	

[0052] Advantageously, suitable high temperature bubbles also have high strength. Strength can be measured according to (withdrawn) ASTM 3102-72, in which glycerol is used in place of water in the method. In some embodiments, 80 volume % of the glass bubbles withstand an isostatic pressure of 4000 psi (27.6 MPa) without fracturing, an isostatic pressure of 6000 psi (41.4 MPa) without fracturing, or an isostatic pressure of 8000 psi (55.2 MPa) without fracturing. Suitable high temperature glass bubbles are not limited to above described exemplary compositions. For example, low-sodium, high temperature resistant glass bubbles having a softening temperature of 781 °C, a density of 1.0385 grams/cm³, and a strength of 8129 psi (56 MPa) was prepared from a glass composition including SiO₂ (60.05 wt. %), CaO (3.77 wt. %), B₂O₃ (6.65 wt. %), Al₂O₃ (17.77 wt. %), MgO (3.18 wt. %), SrO (7.84 wt. %) and SO₃ (0.74 wt. %) using general methods known in the art for forming glass bubbles.

[0053] The plurality of discontinuous fibers dispersed in the metal matrix composite is not particularly limited, and for example includes inorganic fibers, such as glass, alumina, aluminosilicate, carbon, basalt, or a combination thereof. More particularly, in certain embodiments the fibers comprise at least one metal oxide, alumina, alumina-silica, or a combination thereof. The discontinuous fibers have an average length of less than 5 centimeters, which tend to be more conducive to dispersion in a metal matrix than longer fibers. In many embodiments, the fibers have an average length that is shorter than the smallest dimension of the mold or die used to form a metal matrix composite, so that the orientation of the fibers is not restricted by the mold or die. Often, a ratio of the fiber length to the smallest dimension of the mold or die is < 1 : 1. In certain embodiments, the discontinuous fibers have an average length of less than 4 centimeters, less than 3 centimeters, or less than 2 centimeters. Discontinuous fibers may be formed from continuous fibers, for example, by methods known in the art such as chopping and milling. Typically, the plurality of discontinuous fibers comprises an aspect ratio of 10 : 1 or greater.

[0054] Suitable discontinuous fibers can have a variety of compositions, such as ceramic fibers. The ceramic fibers can be produced in continuous lengths, which are chopped or sheared, as discussed herein, to provide the ceramic fibers of the present disclosure. The ceramic fibers can be produced from a variety of commercially available ceramic filaments. Examples of filaments useful in forming the ceramic fibers include the ceramic oxide fibers sold under the trademark NEXTEL (3M Company, St. Paul, MN). NEXTEL is a continuous filament ceramic oxide fiber having low elongation and shrinkage at operating temperatures, and offers good chemical resistance, low thermal conductivity, thermal shock resistance, and low porosity. Specific examples of NEXTEL fibers include NEXTEL 312, NEXTEL 440, NEXTEL 550, NEXTEL 610

and NEXTEL 720. NEXTEL 312 and NEXTEL 440 are refractory aluminoborosilicate that includes Al_2O_3 , SiO_2 and B_2O_3 . NEXTEL 550 and NEXTEL 720 are aluminosilica and NEXTEL 610 is alumina. During manufacture, the NEXTEL filaments are coated with organic sizings or finishes which serves as aids in textile processing. Sizing can include the use of starch, oil, wax or other organic ingredients applied to the filament strand to protect and aid handling. The sizing can be removed from the ceramic filaments by heat cleaning the filaments or ceramic fibers as a temperature of 700 °C for one to four hours.

[0055] The ceramic fibers can be cut, milled, or chopped so as to provide relatively uniform lengths, which can be accomplished by cutting continuous filaments of the ceramic material in a mechanical shearing operation or laser cutting operation, among other cutting operations. Given the highly controlled nature of certain cutting operations, the size distribution of the ceramic fibers is very narrow and allow to control the composite property.

[0056] The length of the ceramic fiber can be determined, for instance, using an optical microscope (Olympus MX61, Tokyo, Japan) fit with a CCD Camera (Olympus DP72, Tokyo, Japan) and analytic software (Olympus Stream Essentials, Tokyo, Japan). Samples may be prepared by spreading representative samplings of the ceramic fiber on a glass slide and measuring the lengths of at least 200 ceramic fibers at 10X magnification.

[0057] Suitable fibers include for instance ceramic fibers available under the trade name NEXTEL (available from 3M Company, St. Paul, MN), such as NEXTEL 312, 440, 610 and 720. One presently preferred ceramic fiber comprises polycrystalline $\alpha\text{-Al}_2\text{O}_3$. Suitable alumina fibers are described, for example, in U.S. Pat. No. 4,954,462 (Wood et al.) and U.S. Pat. No. 5,185,299 (Wood et al.). Exemplary alpha alumina fibers are marketed under the trade designation NEXTEL 610 (3M Company, St. Paul, MN). In some embodiments, the alumina fibers are polycrystalline alpha alumina fibers and comprise, on a theoretical oxide basis, greater than 99 percent by weight Al_2O_3 and 0.2-0.5 percent by weight SiO_2 , based on the total weight of the alumina fibers. In other embodiments, some desirable polycrystalline, alpha alumina fibers comprise alpha alumina having an average grain size of less than one micrometer (or even, in some embodiments, less than 0.5 micrometer). In some embodiments, polycrystalline, alpha alumina fibers have an average tensile strength of at least 1.6 GPa (in some embodiments, at least 2.1 GPa, or even, at least 2.8 GPa). Suitable aluminosilicate fibers are described, for example, in U.S. Pat. No. 4,047,965 (Karst et al). Exemplary aluminosilicate fibers are marketed under the trade designations NEXTEL 440, and NEXTEL 720, by 3M Company (St. Paul, MN). Aluminoborosilicate fibers are described, for example, in U.S. Pat. No. 3,795,524 (Sowman). Exemplary aluminoborosilicate fibers are marketed under the trade designation NEXTEL 312 by 3M Company. Boron nitride fibers can be

made, for example, as described in U.S. Pat. No. 3,429,722 (Economy) and U.S. Pat. No. 5,780,154 (Okano et al.).

[0058] Ceramic fibers can also be formed from other suitable ceramic oxide filaments. Examples of such ceramic oxide filaments include those available from Central Glass Fiber Co., Ltd. (e.g., EFH75-01, EFH150-31). Also preferred are aluminoborosilicate glass fibers, which contain less than about 2% alkali or are substantially free of alkali (i.e., “E-glass” fibers). E-glass fibers are available from numerous commercial suppliers.

[0059] The amount of discontinuous fibers dispersed in the metal matrix composite is not particularly limited. The plurality of fibers is often present in an amount of at least 1 weight percent of the metal matrix composite, at least 2 weight percent, at least 3 weight percent, at least 5 weight percent, at least 10 weight percent, at least 15 weight percent, at least 20 weight percent, or at least 25 weight percent of the metal matrix composite; and up to 50 weight percent, up to 45 weight percent, up to 40 weight percent, or up to 35 weight percent of the metal matrix composite. In certain embodiments, the fibers are present in the metal matrix composite in an amount of between 1 weight percent and 50 weight percent, or between 2 weight percent and 25 weight percent, or between 5 weight percent and 15 weight percent, inclusive, of the metal matrix composite. Including less than 1 weight percent of the fibers results in a minimal increase in strength of the metal matrix composite, while including more than 50 weight percent of the fibers negatively impacts the envelope density of the metal matrix composite due to the metal matrix composite containing an insufficient amount of metal and inorganic particles. In certain embodiments, the plurality of inorganic particles and the plurality of discontinuous fibers are present in combination in an amount of between 5 weight percent and 50 weight percent, inclusive, of the metal matrix composite.

[0060] Advantageously, the metal matrix composite exhibits both a decreased envelope density (as compared to the pure metal) and acceptable mechanical properties. For instance, the metal matrix composite typically has an envelope density between 1.35 and 2.70 grams per cubic centimeter, inclusive or between 1.80 and 2.50 grams per cubic centimeter, inclusive. For example, the metal matrix composite may have an envelope density of at least 1.60 grams per cubic centimeter, at least 1.75, at least 1.90, at least 2.00, at least 2.10, or at least 2.25 grams per cubic centimeter; and an envelope density of up to 2.70, up to 2.60, up to 2.50, up to 2.40, or up to 2.30 grams per cubic centimeter.

[0061] In certain embodiments, the metal comprises aluminum or alloys thereof and the metal matrix composite has an envelope density between 1.80 and 2.50 grams per cubic centimeter,

inclusive; between 2.00 and 2.30 grams per cubic centimeter, inclusive; or between 1.80 and 2.20 grams per cubic centimeter, inclusive.

[0062] In certain embodiments, the metal comprises magnesium or alloys thereof and the metal matrix composite has an envelope density between 1.35 and 1.60 grams per cubic centimeter, inclusive; between 1.55 and 1.60 grams per cubic centimeter, inclusive; or between 1.35 and 1.50 grams per cubic centimeter, inclusive.

[0063] Advantageously, in many embodiments the metal matrix composite has an envelope density that is at least 8% less than the density of the metal (or at least 10% less, at least 12% less, at least 15% less, or at least 17% less) and can withstand a strain of 1% prior to fracture. This combination of properties provides both lightweighting of the metal and maintains some of the metal characteristics in the metal matrix composite. In particular, the metal matrix composite preferably exhibits a yield strength before failure in a tensile test. In certain embodiments the metal matrix composite has a yield strength of 50 megapascals or greater, 75 megapascals or greater, 100 megapascals or greater, or 150 megapascals or greater.

[0064] It was found that the metal matrix composite of at least certain exemplary embodiments of the present disclosure exhibits a stress-strain curve that shows a plastic yielding behavior, and the metal matrix composite of at least certain exemplary embodiments of the present disclosure exhibits a stress-strain curve that shows a tensile plastic yield behavior. That is to say, that the stress-strain curve exhibits a region of plastic flow. The plastic yield curve and tensile plastic yield curve are in contrast to a purely brittle failure mechanism. That is to say, the purely brittle behavior exhibits only an elastic region within the stress-strain curve, and no (or very little) region of plastic flow. Surprisingly, the combination of both inorganic particles and discontinuous fibers as fillers in metal matrix composites according to at least some embodiments of the disclosure provided a plastic yield curve and/or a tensile plastic yield behavior upon stress-strain testing.

[0065] For instance, referring to FIG. 3, the stress-strain curve for Example 13, containing both fibers and porous inorganic particles (described in detail below), shows a yield before a brittle failure mechanism. In certain embodiments, the metal matrix composite can withstand a strain of 0.5%, 1%, 1.5%, or even 2% prior to fracture. Moreover, it was unexpected that the metal powder remained separate from the porous inorganic particles, as opposed to being pushed into some of the pores of the porous inorganic particles during sintering (particularly sintering under applied pressure). The porous inorganic particles further, interestingly, did not tend to become damaged (e.g., crumble or crush) during sintering, but rather maintained their porous skeletal structures.

[0066] In many embodiments, the metal matrix composite exhibits an ultimate tensile strength of 25 megapascals (MPa) or greater, such as 40 MPa or greater, 50 MPa or greater, 75 MPa or greater, 100 MPa or greater, 150 MPa or greater, 200 MPa or greater, 250 MPa or greater, or 300

MPa or greater. It can further be useful to consider the tensile strength of a metal matrix composite as it relates to the envelope density of the metal matrix composite as typically tensile strength is sacrificed during lightweighting of a composite. In some embodiments, the metal matrix composite has an envelope density between 1.80 and 2.50 grams per cubic centimeter, inclusive, and an ultimate tensile strength of 50 MPa or greater, 100 MPa or greater, 150 MPa or greater, 200 MPa or greater, 250 MPa or greater, or 300 MPa or greater.

[0067] Advantageously, in certain embodiments desirable mechanical properties are obtained without requiring fillers beyond the inorganic particles and the discontinuous fibers. In such embodiments, the metal matrix composite consists essentially of a metal, a plurality of inorganic particles, and a plurality of discontinuous fibers. The metal matrix composite thus may further contain additives that do not substantially impact the mechanical properties of the metal matrix composite. In contrast, a metal matrix composite consisting essentially of a metal, a plurality of inorganic particles, and a plurality of discontinuous fibers could not further include additives such as materials used to aid dispersion of the fillers.

[0068] Methods of making a metal matrix composites of the present invention include powder metallurgy processes such as hot pressing, powder extrusion, hot rolling, heating followed by warm rolling, cold compaction and sintering, and hot isostatic pressing. Composites of the present invention could also be produced using melt or casting processes, including squeeze casting, pressure casting and stir casting, as known to the skilled practitioner.

[0069] In certain embodiments, a method of making a metal matrix composite includes mixing a metal powder, a plurality of inorganic particles, and a plurality of discontinuous fibers, thereby forming a mixture; and sintering the mixture, thereby forming the metal matrix composite. The metal powder, particles, fibers, and properties of the resulting metal matrix composite are as described above with respect to the first aspect.

[0070] In some embodiments, mixing of the metal powder, inorganic particles, and discontinuous fibers is performed manually, such as by shaking by hand a container holding the materials. Often, shaking is performed for at least 15 seconds, at least 20 seconds, at least 30 seconds, at least 45 seconds, or at least 60 seconds, and up to 2 minutes, up to 100 seconds, up to 90 seconds, or up to 70 seconds. When manually mixing the components for a metal matrix composite, optionally a container holding the materials is inverted at least once. In certain embodiments, mixing of the metal powder, inorganic particles, and discontinuous fibers is performed using an acoustic mixer, a mechanical mixer, a shaker table, or a tumbler. Mixing using an apparatus may similarly be performed for at least 15 seconds, at least 20 seconds, at least 30 seconds, at least 45 seconds, or at least 60 seconds, and up to 2 minutes, up to 100 seconds, up to

90 seconds, or up to 70 seconds. The mixture created by mixing the components comprises the particles and the fibers dispersed in the metal powder. As discussed above, having the inorganic particles and discontinuous fibers dispersed in the metal powder provides a substantially homogeneous mixture.

5 [0071] Following mixing, the mixture is sintered. In most embodiments, the sintering is performed for a time of at least 30 minutes, at least 60 minutes, at least 90 minutes, or at least 2 hours, and up to 3 hours or up to 24 hours; such as between 30 minutes and 3 hours, inclusive. Typically, the mixture is sintered in a die (e.g., a mold). The sintering is usually performed in a hot press or a furnace at a temperature of at least 250 degrees Celsius (°C), at least 300 °C, at least
10 400 °C, at least 500 °C, or at least 600 °C, and up to 1,000 °C, up to 900 °C, up to 800 °C, or up to 700 °C; such as between 250 °C and 1,000 °C, inclusive, or between 400 °C and 900 °C, or between 600 °C and 800 °C. In many embodiments, the temperature is increased at a steady rate until a desired maximum temperature is reached.

[0072] In certain embodiments, the sintering further comprises applying pressure to the
15 mixture in the die. For instance, sintering is optionally performed at a pressure of at least 4 megapascals (MPa), at least 5 MPa, at least 7 MPa, at least 10 MPa, at least 12 MPa, at least 15 MPa, or at least 20 MPa; and up to 200 MPa, up to 150 MPa, up to 100 MPa, up to 75 MPa, up to 50 MPa, or up to 25 MPa; such as between 4 MPa and 200 MPa, inclusive, between 4 MPa and 50 MPa, inclusive, or between 15 MPa and 200 MPa, inclusive. In certain embodiments, the die is
20 flushed with an inert gas (e.g., nitrogen or argon) following the release of applied pressure.

[0073] Following the sintering process, the metal matrix composite can be allowed to cool (e.g., within or outside the hot press or furnace). In some embodiments, the metal matrix composite is allowed to furnace cool (i.e., by turning off the furnace and waiting for the metal matrix composite to cool down on its own). In other embodiments, a coolant, for instance and
25 without limitation, an inert gas (e.g., nitrogen, argon, etc.), is passed through the hot press or furnace to help the metal matrix composite to cool down faster.

[0074] Exemplary Embodiments

[0075] Embodiment 1 is a metal matrix composite. The metal matrix composite includes a
30 metal; a plurality of inorganic particles; and a plurality of discontinuous fibers. The inorganic particles and the discontinuous fibers are dispersed in the metal. The metal comprises aluminum, magnesium, or alloys thereof and the inorganic particles have an envelope density that is at least 30% less than a density of the metal.

[0076] Embodiment 2 is the metal matrix composite of embodiment 1, wherein the metal matrix composite has an envelope density that is at least 8% less than the density of the metal and can withstand a strain of 1% prior to fracture.

[0077] Embodiment 3 is the metal matrix composite of embodiment 2, wherein the metal matrix composite can withstand a strain of 2% prior to fracture.

[0078] Embodiment 4 is the metal matrix composite of any of embodiments 1 to 3, wherein the metal matrix composite has a yield strength of 50 megapascals or greater.

[0079] Embodiment 5 is the metal matrix composite of any of embodiments 1 to 4, wherein the metal matrix composite has a yield strength of 100 megapascals or greater.

[0080] Embodiment 6 is the metal matrix composite of any of embodiments 1 to 5, wherein the metal matrix composite has an ultimate tensile strength of 100 megapascals or greater.

[0081] Embodiment 7 is the metal matrix composite of any of embodiments 1 to 6, wherein the metal matrix composite has an ultimate tensile strength of 200 megapascals or greater.

[0082] Embodiment 8 is the metal matrix composite of any of embodiments 1 to 7, wherein the metal matrix composite has an ultimate tensile strength of 300 megapascals or greater.

[0083] Embodiment 9 is the metal matrix composite of any of embodiments 1 to 8, wherein the plurality of inorganic particles comprises porous particles.

[0084] Embodiment 10 is the metal matrix composite of embodiment 9, wherein the porous particles have a maximum envelope density of 2 grams per cubic centimeter or less.

[0085] Embodiment 11 is the metal matrix composite of embodiment 9 or embodiment 10, wherein the porous particles comprise porous metal oxide particles, porous metal hydroxide particles, porous metal carbonates, porous carbon particles, porous silica particles, porous dehydrated aluminosilicate particles, porous dehydrated metal hydrate particles, zeolite particles, porous glass particles, expanded perlite particles, expanded vermiculite particles, porous sodium silicate particles, engineered porous ceramic particles, agglomerates of nonporous primary particles, or combinations thereof.

[0086] Embodiment 12 is the metal matrix composite of any of embodiments 9 to 11, wherein the porous particles comprise porous alumina particles, porous carbon particles, porous silica particles, porous aluminum hydroxide particles, or combinations thereof.

[0087] Embodiment 13 is the metal matrix composite of embodiment 12, wherein the porous particles comprise transitional-alumina particles.

[0088] Embodiment 14 is the metal matrix composite of any of embodiments 1 to 8, wherein the plurality of inorganic particles comprises ceramic bubbles or glass bubbles.

[0089] Embodiment 15 is the metal matrix composite of embodiment 14, wherein the plurality of inorganic particles has a maximum envelope density of 2 grams per cubic centimeter or less.

5 [0090] Embodiment 16 is the metal matrix composite of embodiment 14 or embodiment 15, wherein the glass bubbles comprise glass that withstands heating to a temperature of 700 degrees Celsius for at least two hours without softening.

[0091] Embodiment 17 is the metal matrix composite of any of embodiments 14 to 16, wherein the glass bubbles are bubbles that leach less than 100 micrograms of sodium ion per gram of glass
10 bubbles in deionized water when stirred with the deionized water for 2 hours.

[0092] Embodiment 18 is the metal matrix composite of embodiment 14 or embodiment 15, wherein the plurality of inorganic particles comprises alumina, aluminosilicate, silica, or combinations thereof.

[0093] Embodiment 19 is the metal matrix composite of any of embodiments 11 to 15 or 18,
15 wherein the inorganic particles comprise multicelled bubbles.

[0094] Embodiment 20 is the metal matrix composite of any of embodiments 1 to 19, wherein the plurality of inorganic particles has a substantially spherical shape or an acicular shape.

[0095] Embodiment 21 is the metal matrix composite of any of embodiments 1 to 20, wherein the plurality of inorganic particles has an average particle size ranging between 50 nanometers
20 (nm) and 5 millimeters (mm), inclusive.

[0096] Embodiment 22 is the metal matrix composite of any of embodiments 1 to 21, wherein the plurality of inorganic particles has an average particle size ranging between 1 micrometer (μm) and 1 mm, inclusive.

[0097] Embodiment 23 is the metal matrix composite of any of embodiments 1 to 22, wherein
25 the plurality of inorganic particles has an average particle size ranging between 10 μm and 500 μm , inclusive.

[0098] Embodiment 24 is the metal matrix composite of any of embodiments 1 to 23, wherein the plurality of discontinuous fibers comprises glass, alumina, aluminosilicate, carbon, basalt, or a combination thereof.

30 [0099] Embodiment 25 is the metal matrix composite of any of embodiments 1 to 24, wherein the plurality of discontinuous fibers has an aspect ratio of 10 : 1 or greater.

[00100] Embodiment 26 is the metal matrix composite of any of embodiments 1 to 25, wherein the metal comprises a porous matrix structure.

[00101] Embodiment 27 is the metal matrix composite of any of embodiments 1 to 26, wherein the metal comprises aluminum or alloys thereof.

5 [00102] Embodiment 28 is the metal matrix composite of any of embodiments 1 to 27, wherein the metal matrix composite has an envelope density between 1.80 and 2.50 grams per cubic centimeter, inclusive.

[00103] Embodiment 29 is the metal matrix composite of any of embodiments 1 to 28, wherein the metal matrix composite has an envelope density between 2.00 and 2.30 grams per cubic
10 centimeter, inclusive.

[00104] Embodiment 30 is the metal matrix composite of any of embodiments 1 to 28, wherein the metal matrix composite has an envelope density between 1.80 and 2.20 grams per cubic centimeter, inclusive.

[00105] Embodiment 31 is the metal matrix composite of any of embodiments 1 to 26, wherein
15 the metal comprises magnesium or alloys thereof.

[00106] Embodiment 32 is the metal matrix composite of embodiment 31, wherein the metal matrix composite has an envelope density between 1.35 and 1.60 grams per cubic centimeter, inclusive.

[00107] Embodiment 33 is the metal matrix composite of embodiment 31 or embodiment 32,
20 wherein the metal matrix composite has an envelope density between 1.55 and 1.60 grams per cubic centimeter, inclusive.

[00108] Embodiment 34 is the metal matrix composite of embodiment 31 or embodiment 32, wherein the metal matrix composite has an envelope density between 1.35 and 1.50 grams per cubic centimeter, inclusive.

25 [00109] Embodiment 35 is the metal matrix composite of any of embodiments 1 to 34, wherein the metal matrix composite exhibits a yield strength before failure in a tensile test.

[00110] Embodiment 36 is the metal matrix composite of any of embodiments 1 to 35, wherein the metal is present in an amount of between 50 weight percent and 95 weight percent, inclusive, of the metal matrix composite.

30 [00111] Embodiment 37 is the metal matrix composite of any of embodiments 1 to 36, wherein the plurality of inorganic particles is present in an amount of between 2 weight percent and 25 weight percent, inclusive, of the metal matrix composite.

[00112] Embodiment 38 is the metal matrix composite of any of embodiments 1 to 37, wherein the plurality of discontinuous fibers is present in an amount of between 2 weight percent and 25 weight percent, inclusive, of the metal matrix composite.

5 [00113] Embodiment 39 is the metal matrix composite of any of embodiments 1 to 38, wherein the plurality of inorganic particles and the plurality of discontinuous fibers are present in combination in an amount of between 5 weight percent and 50 weight percent, inclusive, of the metal matrix composite.

[00114] Embodiment 40 is the metal matrix composite of any of embodiments 1 to 39, wherein the envelope density of the inorganic particles is at least 40% less than the density of the metal.

10 [00115] Embodiment 41 is the metal matrix composite of any of embodiments 1 to 40, wherein the envelope density of the inorganic particles is at least 50% less than the density of the metal.

[00116] Embodiment 42 is the metal matrix composite of any of embodiments 1 to 41, wherein the metal matrix composite consists essentially of the metal; the plurality of inorganic particles; and the plurality of discontinuous fibers.

15 [00117] Embodiment 43 is a number of glass bubbles. The glass bubbles comprise glass that withstands heating to a temperature of 700 degrees Celsius for at least two hours without softening and exhibits a pouring index at 1371 degrees Celsius of 6 or less.

[00118] Embodiment 44 is the glass bubbles of embodiment 43, exhibiting a pouring index at 1371 degrees Celsius of 5 or less, 4 or less, 3 or less, or 2 or less.

20 [00119] Embodiment 45 the glass bubbles of embodiment 43 or embodiment 44, exhibiting a pouring index at 1371 degrees Celsius of 1.

[00120] Embodiment 46 is the glass bubbles of any of embodiments 43 to 45, comprising glass that has a glass softening temperature ranging from 700 degrees Celsius to 785 degrees Celsius, inclusive.

25 [00121] Embodiment 47 is the glass bubbles of any of embodiments 43 to 46, comprising glass that has a glass softening temperature ranging from 715 degrees Celsius to 735 degrees Celsius.

[00122] Embodiment 48 is the glass bubbles of any of embodiments 43 to 47, comprising glass which leaches less than 100 micrograms of sodium ion per gram of glass bubbles in deionized water when stirred with the deionized water for 2 hours.

30 [00123] Embodiment 49 is the glass bubbles of any of embodiments 43 to 48, comprising an envelope density of 0.5 to 2.3 grams per cubic centimeter (g/cc), 0.5 to 1.5 g/cc, or 0.5 to 0.9 g/cc.

[00124] Embodiment 50 is the glass bubbles of any of embodiments 43 to 49, wherein 80 volume % of the glass bubbles withstand an isostatic pressure of 4000 psi (27.6 MPa) without fracturing.

[00125] Embodiment 51 is the glass bubbles of any of embodiments 43 to 50, wherein 80 volume % of the glass bubbles withstand an isostatic pressure of 6000 psi (41.4 MPa) without fracturing.

[00126] Embodiment 52 is the glass bubbles of any of embodiments 43 to 51, wherein 80 volume % of the glass bubbles withstand an isostatic pressure of 8000 psi (55.2 MPa) without fracturing.

[00127] Embodiment 53 is the glass bubbles of any of embodiments 43 to 52, comprising silica, lime, boric acid, calcium phosphate, calcined alumina silicate, magnesium silicate and up to about 1 wt. % Na_2O .

[00128] Embodiment 54 is the glass bubbles of any of embodiments 43 to 53, comprising a silica to alumina weight ratio ranging from 2.5 to 7.5, inclusive.

[00129] Embodiment 55 is the glass bubbles of any of embodiments 43 to 54, comprising a silica to alumina weight ratio ranging from 5.0 to 7.5, inclusive.

EXAMPLES

[00130] These Examples are merely for illustrative purposes and are not meant to be overly limiting on the scope of the appended claims. Notwithstanding that the numerical ranges and parameters setting forth the broad scope of the present disclosure are approximations, the numerical values set forth in the specific examples are reported as precisely as possible. Any numerical value, however, inherently contains certain errors necessarily resulting from the standard deviation found in their respective testing measurements. At the very least, and not as an attempt to limit the application of the doctrine of equivalents to the scope of the claims, each numerical parameter should at least be construed in light of the number of reported significant digits and by applying ordinary rounding techniques.

Summary of Materials

[00131] Unless otherwise noted, all parts, percentages, ratios, etc. in the Examples and the rest of the specification are by weight. Table 2 provides a description and a source for materials used in the Examples below:

Table 2: summary of materials

Name	Description	Source
Al 6063 powder	Gas atomized aluminum 6063 powder	The Aluminium Powder Company, Sutton Coldfield, UK
Al 1-511 powder	Eckart 1-511 gas atomized 99.5% aluminum powder	Eckart America Corp, Louisville, KY
Al 1-131 powder	Eckart 1-131 gas atomized 99.5% aluminum powder	Eckart America Corp, Louisville, KY
Ceramic Fibers	Chopped alumina NEXTEL 610 fibers, 180 micrometers long	3M Company, St. Paul, MN
Glass Fibers	1/32" milled glass fibers	Fibre Glast Developments Corp, Brookville, OH
Cenospheres	Cenostar cenospheres Econostar, Lightstar, and High Alumina, grade 106	Cenostar Corp, Amesbury, MA
Glass bubbles	High temperature glass bubbles	Preparatory Example 1
Alumina particles	Versal 250 boehmite powder, heat treated to 600 °C	UOP LLC, Des Plaines, IL
Silicon carbide	Silicon carbide, partially sintered agglomerate	3M Company, St. Paul, MN
Silica	SiO ₂	US Silica, Frederick, MD
Lime	CaCO ₃	Imerys, Roswell, GA
Boric Acid	B(OH) ₃	US Borax, Boron, CA
Calcium phosphate	Ca(H ₂ PO ₄) ₂ ·H ₂ O	Spectrum, New Brunswick, NJ
Alumina silicate	Calcined Al ₂ Si ₂ O ₇	Gelest, Morrisville, PA
Magnesium silicate	3MgO ₄ SiO ₂ ·2H ₂ O	Alfa Aesar, Ward Hill, MA
Zinc sulfate	ZnSO ₄ ·7H ₂ O	Spectrum, New Brunswick, NJ
CMC	Carboxymethyl cellulose	Ashland Inc., Covington, KY

Test Method 1. Three-Point Bend Test

[00132] The stress and strain of metal matrix composites was determined using a three-point bend test. In the three-point bend test, a sample was placed lengthwise between two cylindrical supports spaced apart by 32 millimeters (mm). A third loading cylinder suspended from the load cell of the testing apparatus was lowered so as to touch the sample at its midpoint. A software-controlled load frame provided by MTS Systems Corporation (Eden Prairie, MN) fitted with a 100 kilonewton (KN) load cell was used to apply a load to the center of the sample via the middle loading cylinder. The system measured the force being applied to the sample and the displacement of the middle loading cylinder from its starting position for each timepoint. These values were converted to stress and strain, respectively, using standard force equations.

Test Method 2. Acoustic Dispersion Method

[00133] To homogeneously disperse one or more filler materials in a metal, all materials were poured into a 50 milliliter (mL) glass vial, which was then capped securely. Next, the vial was loaded in a Resodyn LabRAM acoustic mixer (Resodyn Corporation, Butte, MT), and shaken at 70% intensity using automatic frequency adjustment for 3 minutes, after which point it was tapped against a hard surface 3-5 times to allow all materials to settle at the bottom on the vial.

Test Method 3. Ion Leaching Test

[00134] A sample of 100 g glass bubbles were stirred with 1000 g deionized (DI) water in a sonicator for approximately 2 hours. Then the glass bubbles were separated from the DI water by centrifuging at 10,000 rotations per minute (rpm) for 10 minutes. The ion concentrations in the resulting leachate solutions were measured by ion chromatography. Individual calibration curves for each ion were prepared by plotting the area of each ion in the standards versus the concentration of that ion in the standard. The concentration of each ion that leached from the samples was determined using the measured area of each ion. The identity of each ion was achieved through retention matching only.

Preparatory Example 1

[00135] The amount of each material listed in Table 3 below was mixed and placed into a fused silica crucible. Then the mixture was heated in a furnace at 2320 degrees Fahrenheit (1271 degrees Celsius) for 4 hours. Next, the material was cooled to room temperature (e.g., about 23 degrees Celsius). The material was chiseled out from the crucible and crushed to frit particles by a disk mill (BICO Inc., Burbank, CA). The maximum size of the frit was less than 5 millimeters (mm). The frit particles were then jet-milled to powder with a particle size mass-median-diameter (D50) of 20 micrometers (μm) using a jet mill (Hosokawa Alpine, Augsburg, Germany). 1000 g of the powder was then mixed with 1100 g of water, 2 weight percent additional boric acid, and 0.3 weight percent of sulfur from Zinc sulfate, as well as 1 weight percent CMC, each based on the total weight of the glass powders. The total solid of the slurry was made to 48 weight percent. The water/frit powder slurry was milled down to D50 of 1.4 μm primary particle size by a LabStar mill (NETZSCH Premier Technologies, LLC, Exton, PA). The slurry from the milling was spray dried to form agglomerated feed particles. The glass bubbles were produced through a natural gas flame from the spray dried feed. The total glass bubble density and flame conditions were as listed in Table 4 below. The resulting bubbles had a D5 of 7 micrometers, a D50 of 35 micrometers, and a D90 of 60 micrometers.

Table 3. Materials and amounts, in grams, for mixing and melting.

Sample	Silica	Lime	Boric Acid	calcium phosphate	Alumina silicate, calcined	Magnesium silicate
B-1	301.3	185.9	89.4	49.5	94.8	87.5
B-2	292.4	190.7	81.0	37.4	136.3	66.1

Table 4. Flame forming conditions and glass bubble density.

Sample	Flame Flows (SLPM)			Density (g/cm ³)
	Air	Natural Gas	oxygen	
B-1A	265	30	-	0.8249
B-1B	285	30	-	0.8878
B-1C	241	30	5	0.8180
B-2A	265	30	-	0.7650
B-2B	285	30	-	0.7960
B-2C	241	30	5	0.8553

5 **Table 5.** Ion chromatography results.

Ion	Concentration ion in B-1 Glass Bubbles (µg ion/g bubble)
Cations	
Sodium	53 ± 7
Potassium	23 ± 13
Calcium	190 ± 36
Anions	
Fluoride	Below LOD, ≤ 4
Chloride	Below LOD, ≤ 9
Nitrite	13 ± 2
Bromide	24 ± 4
Sulfate	240 ± 12
Nitrate	22 ± 3
Phosphate	260 ± 4

Comparative Example 1

[00136] 10 grams (g) of Al 1-511 powder was poured into a circular graphite die with 1.5 inch (3.81 centimeter) inner diameter. The Al 1-511 powder was sintered as follows: The die was loaded into an HP50-7010 hot press (Thermal Technology LLC, Santa Rosa, CA), and the setup was pumped down to vacuum. The die was heated from room temperature at 25 degrees Celsius per minute (deg C/min) to 600 degrees Celsius, where it was held for 15 minutes (min). After the 15 min hold at temperature, 640 kilograms (kg) of force (800 pounds per square inch of pressure

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for this sized die) was applied at 600 degrees Celsius for 1 hour (hr). The pressure was then released, the chamber was flooded with nitrogen, and the die was allowed to furnace cool back down to room temperature. The dimensions of the resulting sintered disk, as well as its mass, were measured to calculate an envelope density of 1.91 grams per cubic centimeter (g/cc), which is 29% lower than that of fully dense pure aluminum. A strip was cut out of the middle of the disk having a width of approximately 0.5 inches (1.27 centimeters) and a length of 1.5 inches (3.81 centimeters), and this strip was subjected to the Three-Point Bend Test described above. The sample had an ultimate tensile strength of 31 megapascals (MPa). The results are shown in Table 6 below and in Figure 2.

Comparative Example 2

[00137] 10 g of Al 1-511 powder and 1 g of glass bubbles were mixed via the Manual Dispersion Method described above, and the mixture was poured into the same graphite die as in Comparative Example 1. The setup then underwent the same sintering procedure described in Comparative Example 1 above. The resulting sintered disk had an envelope density of 1.58 g/cc. The results of the Three-Point Bend Test are shown in Table 6 below and in Figure 2.

Comparative Example 3

[00138] 10 g of Al 1-511 powder and 1 g of ceramic fibers were mixed via the Manual Dispersion Method described above, and the mixture was poured into the same graphite die as in Comparative Examples 1 and 2. The setup then underwent the same sintering procedure described in Comparative Example 1 above. The resulting disk had an envelope density of 2.11 g/cc. The results of the Three-Point Bend Test are shown in Table 6 below and in Figure 2.

Comparative Example 4

[00139] 9 g of Al 1-511 powder, 0.3 g of glass bubbles, and 1.7 g of ceramic fibers were loosely stirred, and the mixture was poured into the same graphite die as in Comparative Examples 1-3. The setup then underwent the same sintering procedure described in Comparative Example 1 above. The resulting disk had an envelope density of 1.72 g/cc. The results of the Three-Point Bend Test are shown in Table 6 below and in Figure 2.

Example 5

[00140] 9 g of Al 1-511 powder, 0.3 g of glass bubbles, and 1.7 g of ceramic fibers were mixed via the Manual Dispersion Method described above, and the mixture was poured into the same graphite die as in Comparative Examples 1-4. The setup then underwent the same sintering procedure described in Comparative Example 1 above. The resulting disk had an envelope density of 1.83 g/cc. The results of the Three-Point Bend Test are shown in Table 6 below in Figure 2.

Example 6

[00141] 10 g of Al 1-511 powder, 0.5 g of glass bubbles, and 0.5 g of ceramic fibers were mixed via the Manual Dispersion Method described above, and the mixture was poured into the same graphite die as in Comparative Examples 1-4 and Example 5. The setup then underwent the same sintering procedure described in Comparative Example 1 above. The resulting disk had an envelope density of 1.71 g/cc. The results of the Three-Point Bend Test are shown in Table 6 below.

Example 7

[00142] 8 g of Al 1-511 powder, 0.45 g of glass bubbles, and 2.55 g of ceramic fibers were mixed via the Manual Dispersion Method described above, and the mixture was poured into the same graphite die as in Comparative Examples 1-4 and Examples 5-6. The setup then underwent the same sintering procedure described in Comparative Example 1 above. The resulting disk had an envelope density of 1.78 g/cc. The results of the Three-Point Bend Test are shown in Table 6 below.

Example 8

[00143] 7 g of Al 1-511 powder, 0.6 g of glass bubbles, and 3.4 g of ceramic fibers were mixed via the Manual Dispersion Method described above, and the mixture was poured into the same graphite die as in Comparative Examples 1-4 and Examples 5-7. The setup then underwent the same sintering procedure described in Comparative Example 1 above. The resulting disk had an envelope density of 1.63 g/cc. The results of the Three-Point Bend Test are shown in Table 6 below.

Table 6.

Composite	Al (weight%)	Bubble (weight%)	Ceramic Fiber (weight %)	Ultimate strength (MPa)	Envelope density (g/cc)
CE-1	100	0	0	31	1.91
CE-2	91	9	0	18	1.58
CE-3	91	0	9	57	2.11
CE-4	82	3	15	18	1.72
EX-5	82	3	15	54	1.83
EX-6	91	4.5	4.5	28	1.71
EX-7	73	4	23	43	1.78
EX-8	64	5	31	32	1.63

Comparative Example 9

[00144] 10.8 grams (g) of Al 6063 powder was poured into a circular graphite die with a 1.575 inch (4.00 centimeter) inner diameter. The Al 6063 powder was sintered as follows: The die was loaded into a Toshiba Machine GMP-411VA glass mold press machine (Toshiba Machine Co., Numazu-shi, Japan), and the setup was flooded with nitrogen for 60 seconds, then pumped down to vacuum. The die was heated from 40 degrees Celsius at 28 degrees Celsius per minute (deg C/min) to 600 degrees Celsius. Once the die reached 600 degrees C, it was held at that temperature while the force on the die was gradually increased from zero applied force to 21,000 Newtons (2400 psi (or 16.55 MPa) of pressure for this sized die). The gradual increase in force occurred approximately linearly over the course of 20 minutes. Once the full force of 21,000 N was reached, the die was held in this state at 600 degrees C for 1 hour. The pressure was then released, and the die was allowed to furnace cool down to room temperature. The dimensions of the resulting sintered disk, as well as its mass, were measured to calculate an envelope density of 2.51 grams per cubic centimeter (g/cc), which is 7% lower than that of fully dense aluminum 6063. A strip was cut out of the middle of the disk having a width of approximately 0.5 inches (1.27 centimeters) and a length of 1.5 inches (3.81 centimeters), and this strip was subjected to the Three-Point Bend Test described above. The sample had an ultimate tensile strength of 203 megapascals (MPa). The results are shown in Table 7 below and in Figure 3.

Comparative Example 10

[00145] 8.64 g of Al 6063 powder and 0.48 g of alumina powder were mixed via the Acoustic Dispersion Method described above, and the mixture was poured into the same graphite die as in Comparative Example 9. The setup then underwent the same sintering procedure described in Comparative Example 9 above. The resulting sintered disk had an envelope density of 2.34 g/cc. The results of the Three-Point Bend Test are shown in Table 7 below and in Figure 3.

Comparative Example 11

[00146] 9.72 g of Al 6063 powder and 1.56 g of ceramic fibers were mixed via the Acoustic Dispersion Method described above, and the mixture was poured into the same graphite die as in Comparative Examples 9-10. The setup then underwent the same sintering procedure described in Comparative Example 9 above. The resulting disk had an envelope density of 2.65 g/cc. The results of the Three-Point Bend Test are shown in Table 7 below and in Figure 3.

Example 12

[00147] 7.56 g of Al 6063 powder, 0.48 g of alumina powder, and 1.56 g of ceramic fibers were mixed via the Acoustic Dispersion Method described above, and the mixture was poured into the same graphite die as in Comparative Examples 9-11. The setup then underwent the same sintering procedure described in Comparative Example 9 above. The resulting disk had an envelope density of 2.45 g/cc. The results of the Three-Point Bend Test are shown in Table 7 below and in Figure 3.

Example 13

[00148] 5.4 g of Al 6063 powder, 0.96 g of alumina powder, and 1.56 g of ceramic fibers were mixed via the Acoustic Dispersion Method described above, and the mixture was poured into the same graphite die as in Comparative Examples 9-11 and Example 12. The setup then underwent the same sintering procedure described in Comparative Example 9 above. The resulting disk had an envelope density of 2.11 g/cc. The results of the Three-Point Bend Test are shown in Table 7 below and in Figure 3.

Example 14

[00149] 5.4 g of Al 6063 powder, 0.96 g of alumina powder, and 1.56 g of ceramic fibers were mixed via the Acoustic Dispersion Method described above, and the mixture was poured into the same graphite die as in Comparative Examples 9-11 and Examples 12-13. The die was loaded into a Toshiba Machine GMP-411VA glass mold press machine (Toshiba Machine Co., Numazu-shi, Japan), and the setup was flooded with nitrogen for 60 seconds, then pumped down to vacuum. The die was heated from 40 degrees Celsius at 30 deg C/min to 630 degrees Celsius. Once the die reached 630 degrees Celsius, it was held at that temperature while the force on the die was gradually increased from zero applied force to 34,664 Newtons (4000 psi (or 27.58 MPa) of pressure for this sized die). The gradual increase in force occurred approximately linearly over the course of 20 minutes. Once the full force of 34,664 N was reached, the die was held in this state at

630 degrees C for 1 hour. The pressure was then released, and the die was allowed to furnace cool down to room temperature. The resulting disk had an envelope density of 2.19 g/cc. The results of the Three-Point Bend Test are shown in Table 7 below and in Figure 3.

5 **Table 7:** Compositions and mechanical properties of examples.

Composite	Al (weight%)	Alumina (weight%)	Ceramic Fiber (weight%)	Ultimate strength (MPa)	Envelope density (g/cc)	Strain-to- Failure (%)
CE-9	100	0	0	203	2.51	>4% (max measurable)
CE-10	95	5	0	132	2.34	1.3
CE-11	86	0	14	279	2.65	>4% (max measurable)
EX-12	79	5	16	182	2.45	1.2
EX-13	68	12	20	106	2.11	0.8
EX-14	68	12	20	186	2.19	0.9

Comparative Example 15

10 [00150] 10.8 grams (g) of Al 6063 powder was poured into a circular graphite die with 1.575 inch (4.00 centimeter) inner diameter. The Al 6063 powder was sintered as follows: The die was loaded into a Toshiba Machine GMP-411VA glass mold press machine (Toshiba Machine Co., Numazu-shi, Japan), and the setup was flooded with nitrogen for 60 seconds, then pumped down to vacuum. The die was heated from 40 degrees Celsius at 28 degrees Celsius per minute (deg C/min) to 615 degrees Celsius. Once the die reached 615 deg C, it was held at that temperature while the force on the die was gradually increased from zero force to 21,000 Newtons (1600 psi of pressure for this sized die). The gradual increase in force occurred approximately linearly over the course of 20 minutes. Once the full force of 21,000 N was reached, the die was held in this state at 600 deg C for 1 hour. The pressure was then released, and the die was allowed to furnace cool down to room temperature. The dimensions of the resulting sintered disk, as well as its mass, were measured to calculate an envelope density of 2.51 grams per cubic centimeter (g/cc), which is 7% lower than that of fully dense aluminum 6063. A strip was cut out of the middle of the disk having a width of approximately 0.5 inches (1.27 centimeters) and a length of 1.575 inches (4.00 centimeters), and this strip was subjected to the Three-Point Bend Test described above. The

sample had an ultimate tensile strength of 203 megapascals (MPa). The results are shown in Table 8 below and Figure 4.

Example 16

5 [00151] 5.4 g of Al 1-511 powder, 0.96 g of glass bubbles, and 0.78 g of ceramic fibers were mixed via the Acoustic Dispersion Method described above, and the mixture was poured into the same graphite die as in Comparative Example 15. The die was loaded into a Toshiba Machine GMP-411VA glass mold press machine (Toshiba Machine Co., Numazu-shi, Japan), and the setup was flooded with nitrogen for 60 seconds, then pumped down to vacuum. The die was heated from 10 40 degrees Celsius at 30 degrees Celsius per minute (deg C/min) to 615 degrees Celsius. Once the die reached 615 deg C, it was held at that temperature while the force on the die was gradually increased from zero force to 13,954 Newtons (1600 psi of pressure for this sized die). The gradual increase in force occurred approximately linearly over the course of 20 minutes. Once the full force of 13,954 N was reached, the die was held in this state at 615 deg C for 1 hour. The pressure 15 was then released, and the die was allowed to furnace cool down to room temperature. The resulting disk had an envelope density of 1.93 g/cc. The results of the Three-Point Bend Test are shown in Table 8 below and Figure 4.

Example 17

20 [00152] 5.4 g of Al 1-511 powder, 0.96 g of glass bubbles, and 0.78 g of ceramic fibers were mixed via the Acoustic Dispersion Method described above, and the mixture was poured into the same graphite die as in Example 16. The setup then underwent the same sintering procedure described in Example 16 above. The resulting disk had an envelope density of 1.91 g/cc. The results of the Three-Point Bend Test are shown in Table 8 below and Figure 4.

Example 18

25 [00153] 5.4 g of Al 1-511 powder, 0.96 g of Lightstar 106 cenospheres, and 0.78 g of ceramic fibers were mixed via the Acoustic Dispersion Method described above, and the mixture was poured into the same graphite die as in Example 16. The setup then underwent the same sintering 30 procedure described in Example 16 above. The resulting disk had an envelope density of 1.93 g/cc. The results of the Three-Point Bend Test are shown in Table 8 below and Figure 4.

Example 19

[00154] 5.4 g of Al 1-511 powder, 0.96 g of High Alumina 106 cenospheres, and 0.78 g of ceramic fibers were mixed via the Acoustic Dispersion Method described above, and the mixture was poured into the same graphite die as in Example 16. The setup then underwent the same sintering procedure described in Example 16 above. The resulting disk had an envelope density of 1.95 g/cc. The results of the Three-Point Bend Test are shown in Table 8 below and Figure 4.

Example 20

[00155] 5.4 g of Al 1100 powder, 0.96 g of Econostar 106 cenospheres, and 0.78 g of ceramic fibers were mixed via the Acoustic Dispersion Method described above, and the mixture was poured into the same graphite die as in Example 16. The setup then underwent the same sintering procedure described in Example 16 above. The resulting disk had an envelope density of 1.93 g/cc. The results of the Three-Point Bend Test are shown in Table 8 below and Figure 4.

Table 8: Compositions and mechanical properties of examples.

Composite	Al (weight%)	Bubble (weight%)	Ceramic Fiber (weight%)	Ultimate strength (MPa)	Envelope density (g/cc)	Strain-to- Failure (%)
CE-15	100	0	0	203	2.51	>4% (max measurable)
EX-16	76	13	11	153	1.93	1.1%
EX-17	76	13	11	150	1.91	1.3%
EX-18	76	13	11	149	1.93	1.6%
EX-19	76	13	11	157	1.95	1.8%
EX-20	76	13	11	149	1.93	1.6%

Example 21

[00156] 5.4 g of Al 1-511 powder, 0.96 g of partially sintered silicon carbide agglomerate particles, and 0.78 g of ceramic fibers were mixed via the Acoustic Dispersion Method described

above, and the mixture was poured into the same graphite die as in Example 16. The setup then underwent the same sintering procedure described in Example 16 above. The resulting disk had an envelope density of 2.28 g/cc, an ultimate tensile strength of 190 MPa, and a strain-to-failure of 3.4%. The results of the Three-Point Bend Test are shown in Figure 5.

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Example 22

[00157] 5.94 g of Al 1-131 powder, 0.96 g of Lightstar 106 cenospheres, and 0.78 g of ceramic fibers were mixed via the Acoustic Dispersion Method described above, and the mixture was poured into the same graphite die as in Example 16. The setup then underwent the same sintering procedure described in Example 16 above. The resulting disk had an envelope density of 1.98 g/cc. The results of the Three-Point Bend Test are shown in Table 9 below and in Figure 6.

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Example 23

[00158] 7.56 g of Al 1-131 powder, 0.6 g of Lightstar 106 cenospheres, and 0.78 g of ceramic fibers were mixed via the Acoustic Dispersion Method described above, and the mixture was poured into the same graphite die as in Example 16. The setup then underwent the same sintering procedure described in Example 16 above. The resulting disk had an envelope density of 2.21 g/cc. The results of the Three-Point Bend Test are shown in Table 9 and in Figure 6.

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Example 24

7.02 g of Al 1-131 powder, 0.72 g of Lightstar 106 cenospheres, and 0.78 g of ceramic fibers were mixed via the Acoustic Dispersion Method described above, and the mixture was poured into the same graphite die as in Example 16. The setup then underwent the same sintering procedure described in Example 16 above. The resulting disk had an envelope density of 2.12 g/cc. The results of the Three-Point Bend Test are shown in Table 9 and in Figure 6.

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Example 25

[00159] 7.02 g of Al powder, 0.72 g of Lightstar 106 cenospheres, and 0.78 g of ceramic fibers were mixed via the Acoustic Dispersion Method described above, and the mixture was poured into the same graphite die as in Example 16. The setup then underwent the same sintering procedure described in Example 16 above. The resulting disk had an envelope density of 2.00 g/cc. The results of the Three-Point Bend Test are shown in Table 9 and in Figure 6.

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Table 9: Compositions and mechanical properties of examples.

Composite	Al (weight%)	Bubble (weight%)	Ceramic Fiber (weight%)	Maximum strength (MPa)	Envelope density (g/cc)	Strain-to- Failure (%)
EX-22	77	13	10	189	1.98	1.7%
EX-23	84	7	9	185	2.21	2.8%
EX-24	82.5	8.5	9	179	2.12	2.3%
EX-25	82.5	8.5	9	160	2.00	2.4%

Example 26

5 **[00160]** 5.94g of Al 1-131 powder, 0.84 g of Lightstar 106 cenospheres, and 1.016 g of glass fibers were mixed via the Acoustic Dispersion Method described above, and the mixture was poured into the same graphite die as in Example 16. The setup then underwent the same sintering procedure described in Example 16 above. The resulting disk had an envelope density of 2.00 g/cc, an ultimate tensile strength of 159 MPa, and a strain-to-failure of 1.8%. The results of the Three-
10 Point Bend Test are shown in Figure 7.

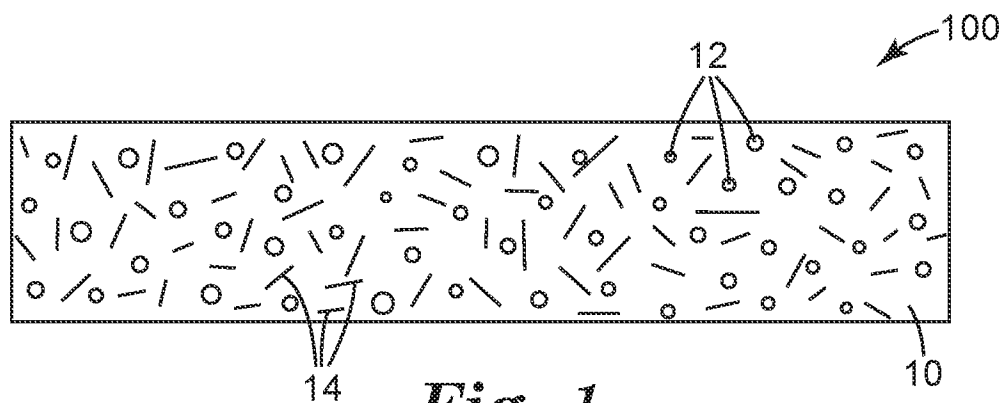
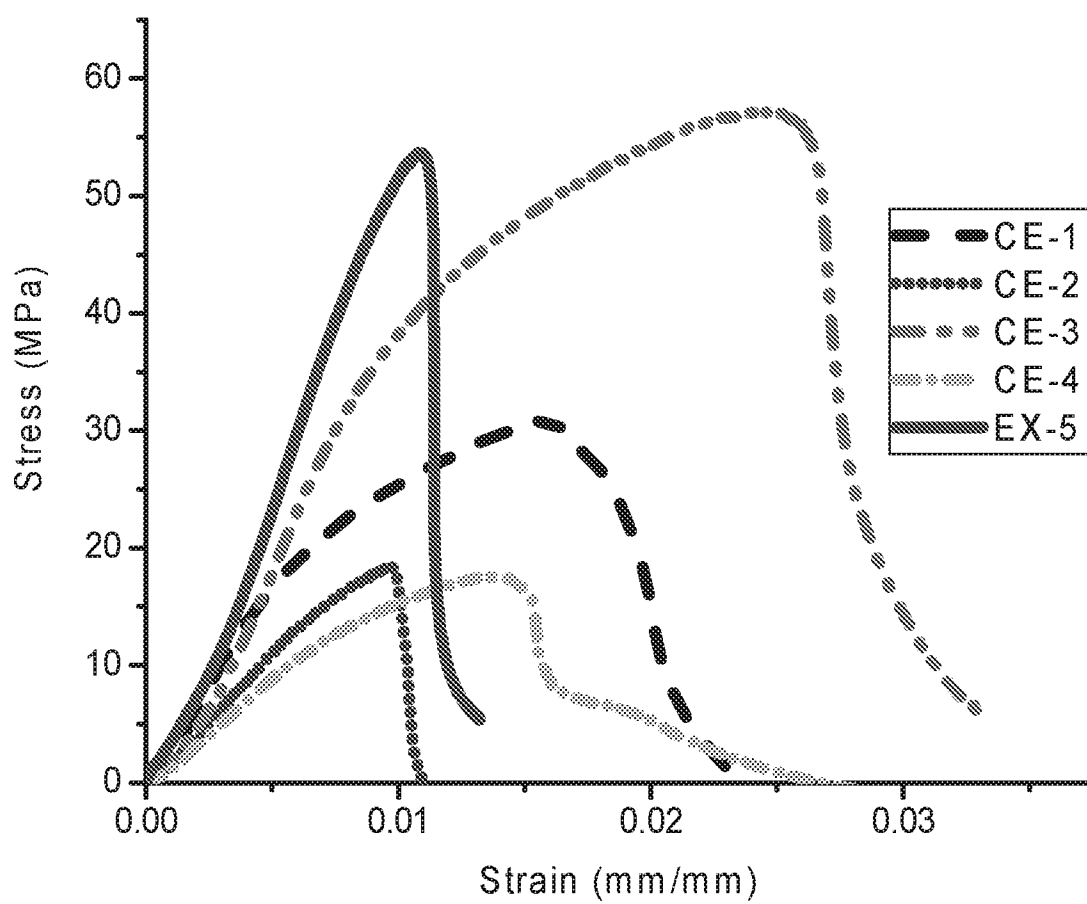
[00161] While the specification has described in detail certain exemplary embodiments, it will be appreciated that those skilled in the art, upon attaining an understanding of the foregoing, may readily conceive of alterations to, variations of, and equivalents to these embodiments. Furthermore, all publications and patents referenced herein are incorporated by reference in their
15 entirety to the same extent as if each individual publication or patent was specifically and individually indicated to be incorporated by reference. Various exemplary embodiments have been described. These and other embodiments are within the scope of the following claims.

What is claimed is:

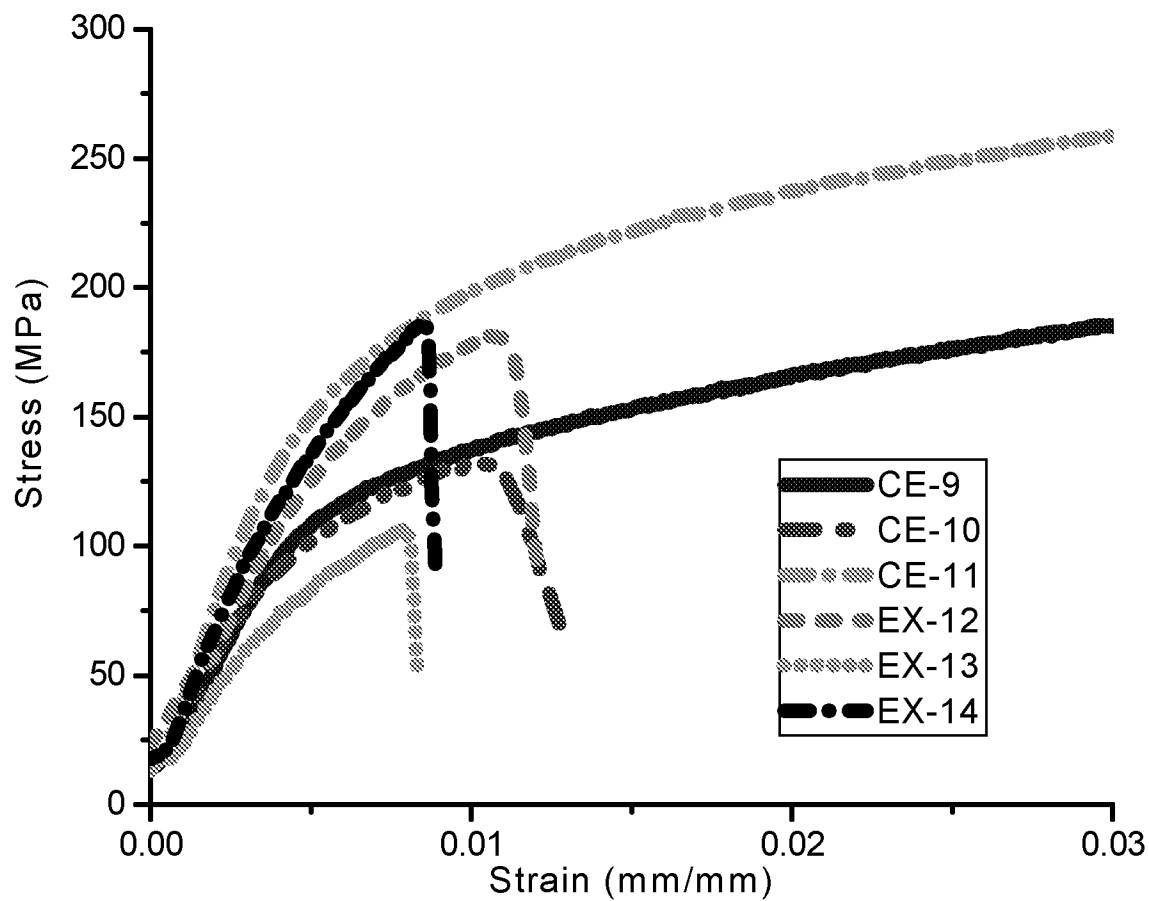
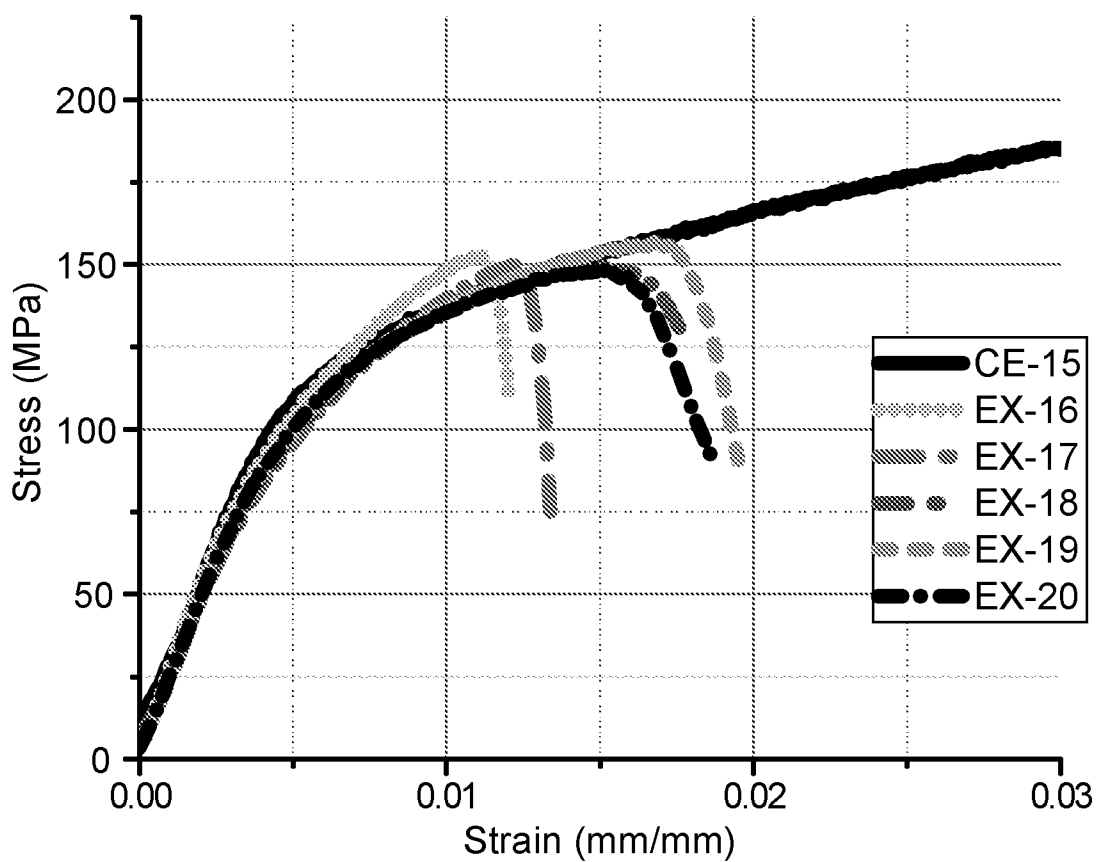
1. A metal matrix composite, comprising:
 - a. a metal, the metal comprising aluminum, magnesium, or alloys thereof;
 - b. a plurality of inorganic particles, the inorganic particles having an envelope density that is at least 30% less than a density of the metal; and
 - c. a plurality of discontinuous fibers,wherein the inorganic particles and the discontinuous fibers are dispersed in the metal.
2. The metal matrix composite of claim 1, wherein the metal matrix composite has an envelope density that is at least 8% less than the density of the metal and can withstand a strain of 1% prior to fracture.
3. The metal matrix composite of claim 2, wherein the metal matrix composite can withstand a strain of 2% prior to fracture.
4. The metal matrix composite of any of claims 1 to 3, wherein the metal matrix composite has a yield strength of 50 megapascals or greater.
5. The metal matrix composite of any of claims 1 to 4, wherein the plurality of inorganic particles comprises porous particles comprising porous metal oxide particles, porous metal hydroxide particles, porous metal carbonates, porous carbon particles, porous silica particles, porous dehydrated aluminosilicate particles, porous dehydrated metal hydrate particles, zeolite particles, porous glass particles, expanded perlite particles, expanded vermiculite particles, porous sodium silicate particles, engineered porous ceramic particles, agglomerates of nonporous primary particles, or combinations thereof.
6. The metal matrix composite of any of claims 1 to 4, wherein the plurality of inorganic particles comprises ceramic bubbles or glass bubbles.
7. The metal matrix composite of claim 6, wherein the plurality of inorganic particles comprises alumina, aluminosilicate, silica, or combinations thereof.
8. The metal matrix composite of any of claims 1 to 7, wherein the plurality of inorganic particles comprises an average particle size ranging between 1 μm and 1 mm, inclusive.

9. The metal matrix composite of any of claims 1 to 8, wherein the plurality of discontinuous fibers comprises glass, alumina, aluminosilicate, carbon, basalt, or a combination thereof.
- 5 10. The metal matrix composite of any of claims 1 to 9, wherein the metal comprises a porous matrix structure.
11. The metal matrix composite of any of claims 1 to 10, wherein the metal comprises aluminum or alloys thereof and wherein the metal matrix composite has an envelope
10 density between 1.80 and 2.50 grams per cubic centimeter, inclusive.
12. The metal matrix composite of any of claims 1 to 10, wherein the metal comprises magnesium or alloys thereof and wherein the metal matrix composite has an envelope
15 density between 1.35 and 1.60 grams per cubic centimeter, inclusive.
13. The metal matrix composite of any of claims 1 to 12, wherein the metal matrix composite exhibits a yield strength before failure in a tensile test.
14. The metal matrix composite of any of claims 1 to 13, wherein the metal is present in an
20 amount of between 50 weight percent and 95 weight percent, inclusive, of the metal matrix composite.
15. The metal matrix composite of any of claims 1 to 14, wherein the metal matrix composite consists essentially of the metal; the plurality of inorganic particles; and the plurality of
25 discontinuous fibers.

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*Fig. 1**Fig. 2*

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*Fig. 3**Fig. 4*

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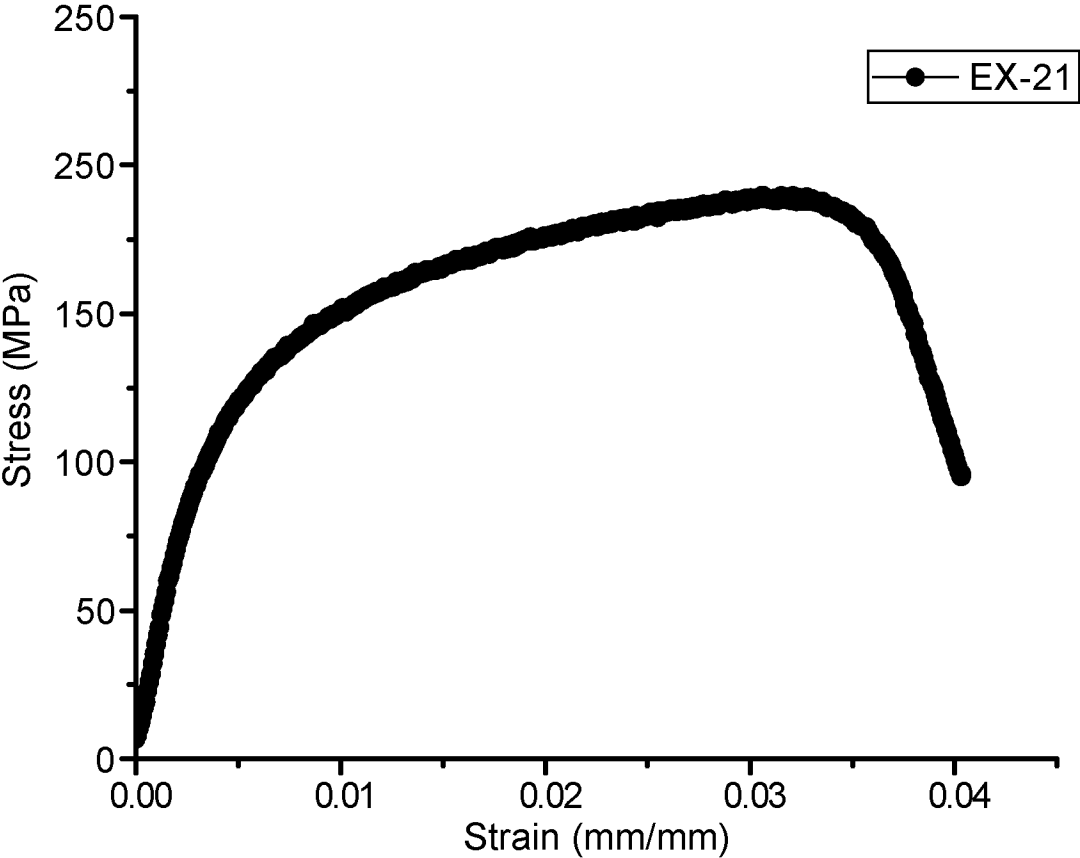


Fig. 5

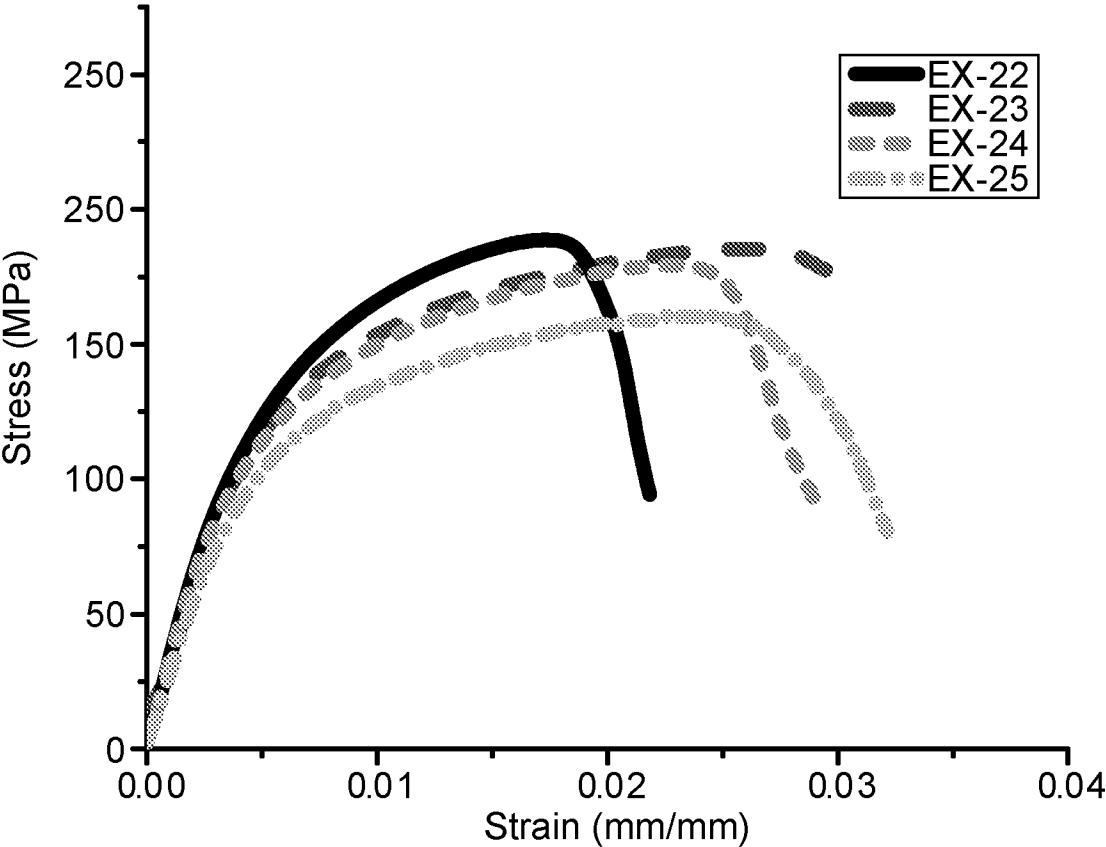


Fig. 6

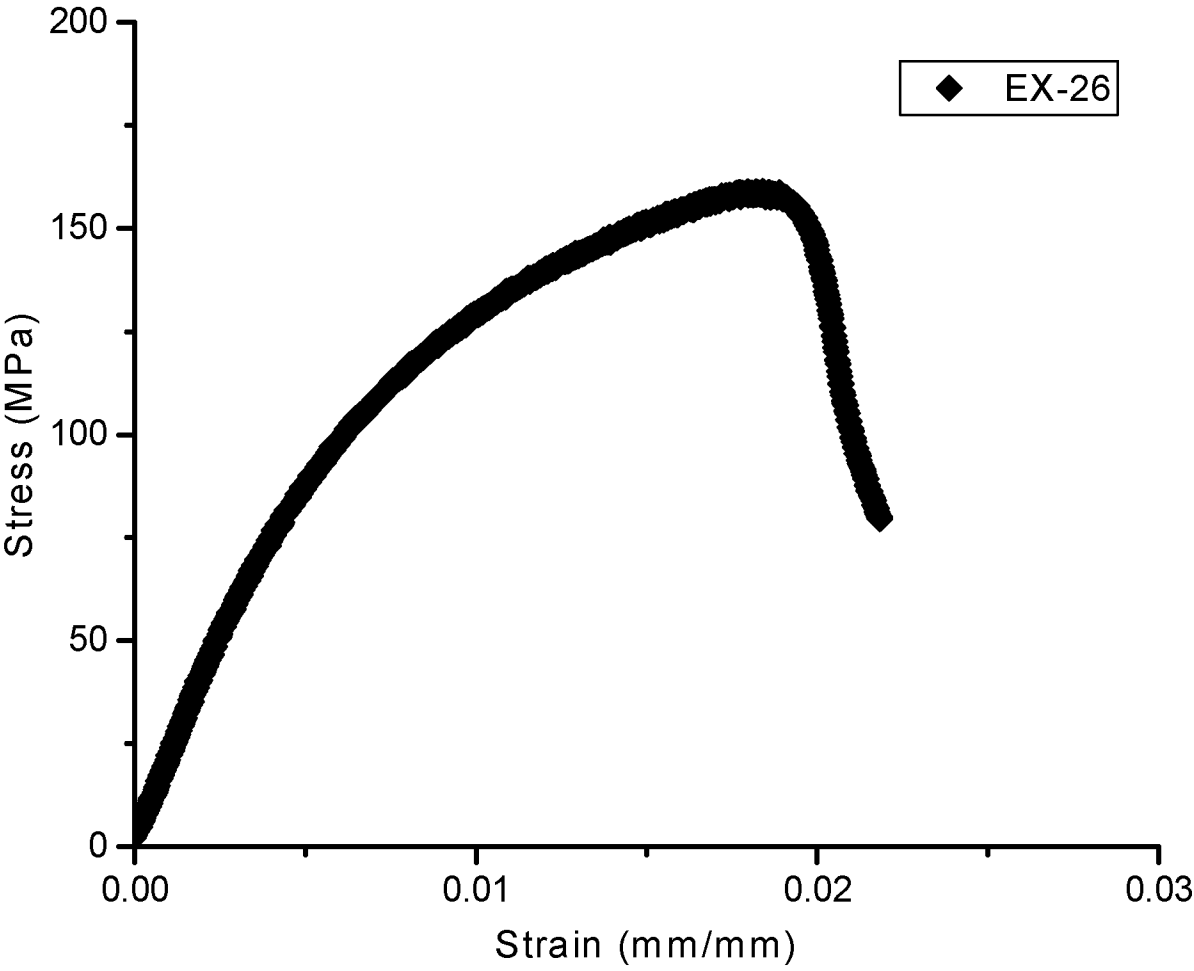


Fig. 7