



(51) International Patent Classification:

C22C 21/00 (2006.01) C23C 2/12 (2006.01)
C23C 10/30 (2006.01)

(21) International Application Number:

PCT/US2020/012733

(22) International Filing Date:

08 January 2020 (08.01.2020)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

62/794,509 18 January 2019 (18.01.2019) US
16/526,691 30 July 2019 (30.07.2019) US

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(54) Title: ALUMINUM ALLOYS

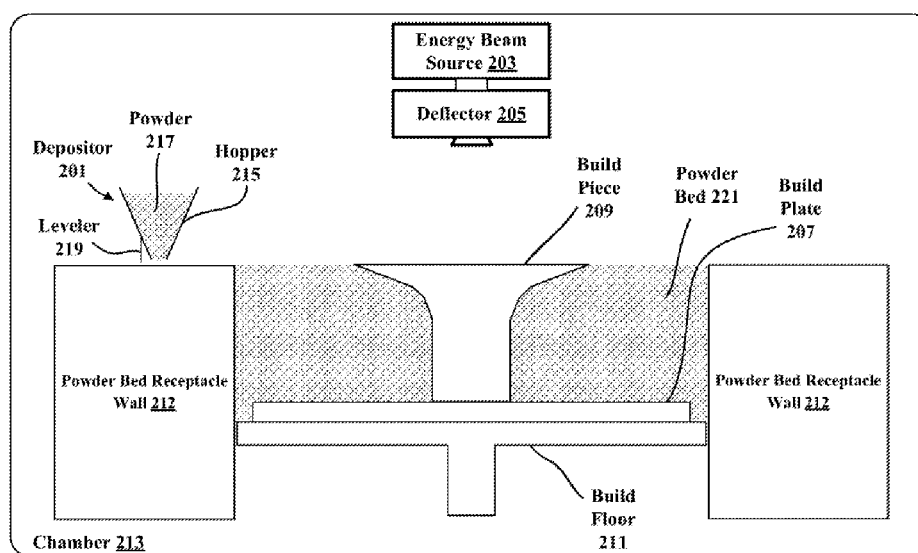


FIG. 2A

(57) Abstract: According to some configurations of the present disclosure, an alloy may include a composition that includes magnesium (Mg) that is approximately 5 to 12% by weight of the composition; manganese (Mn) that is approximately 0.1 to 2% by weight of the composition; and silicon (Si) that is approximately 0.3 to 3% by weight of the composition; and aluminum (Al) that is a balance of the composition. In one configuration, the composition may further include one or more of iron (Fe), titanium (Ti), zirconium (Zr), chromium (Cr), and/or yttrium (Y).



(84) Designated States (*unless otherwise indicated, for every kind of regional protection available*): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

ALUMINUM ALLOYS

CROSS REFERENCE TO RELATED APPLICATIONS

- [0001] This application claims the benefit of U.S. Provisional Application Serial No. 62/794509, entitled “HIGH-PERFORMANCE ALUMINUM ALLOY” and filed on January 18, 2019, and U.S. Patent Application No. 16/526,691, entitled “ALUMINUM ALLOYS” and filed on July 30, 2019, which are expressly incorporated by reference herein in their entirety.

Technical Field

- [0002] The present disclosure relates generally to alloys, and more specifically to aluminum alloys.

Description of the Related Technology

- [0003] Additive Manufacturing (AM) processes involve the use of a stored geometrical model for accumulating layered materials on a “build plate” to produce three-dimensional (3-D) objects having features defined by the model. AM techniques are capable of printing complex components using a wide variety of materials. A 3-D object is fabricated based on a computer-aided design (CAD) model. The AM process can manufacture a solid three-dimensional object directly from the CAD model without additional tooling.
- [0004] One example of an AM process is powder bed fusion (PBF), which uses a laser, electron beam, or other source of energy to sinter or melt metallic powder deposited in a powder bed, thereby consolidating powder particles together in targeted areas to produce a 3-D structure having the desired geometry. Different materials or combinations of materials, such as metals, plastics, and ceramics, may be used in PBF to create the 3-D object. Other more advanced AM techniques, including those discussed further below, are also available or under current development, and each may be applicable to the present disclosure.
- [0005] Another example of an AM process is called Binder Jet (BJ) process that uses a powder bed (similar to PBF) in which metallic powder is spread in layers and bonded by using an organic binder. The resulting part is a green part which requires burning off the binder and sintering to consolidate the layers into full density. The metallic

powder material can have the same chemical composition and similar physical characteristics as PBF powders.

[0006] Another example of an AM process is called Directed Energy Deposition (DED). DED is an AM technology that uses a laser, electron beam, plasma, or other method of energy supply, such as those in Tungsten Inert Gas (TIG), or Metal Inert Gas (MIG) welding to melt the metallic powder or wire and rod, thereby transforming it into a solid metal object. Unlike many AM technologies, DED is not based on a powder bed. Instead, DED uses a feed nozzle to propel the powder or mechanical feed system to deliver wire and rod into the laser beam, electron beam, plasma beam, or other energy stream. The powdered metal or the wire and rod are then fused by the respective energy beam. While supports or a freeform substrate may in some cases be used to maintain the structure being built, almost all the raw material (powder, wire, or rod) in DED is transformed into solid metal, and consequently, little waste powder is left to recycle. Using a layer by layer strategy, the print head, comprised of the energy beam or stream and the raw material feed system, can scan the substrate to deposit successive layers directly from a CAD model.

[0007] PBF, BJ, DED, and other AM processes may use various raw materials such as metallic powders, wires, or rods. The raw material may be made from various metallic materials. Metallic materials may include, for example, aluminum, or alloys of aluminum. It may be advantageous to use alloys of aluminum that have properties that improve functionality within AM processes. For example, particle shape, powder size, packing density, melting point, flowability, stiffness, porosity, surface texture, density electrostatic charge, as well as other physical and chemical properties may impact how well an aluminum alloy performs as a material for AM. Similarly, raw materials for AM processes can be in the form of wire and rod whose chemical composition and physical characteristics may impact the performance of the material. Some alloys may impact one or more of these or other traits that affect the performance of the alloy for AM.

[0008] One or more aspects of the present disclosure may be described in the context of the related technology. None of the aspects described herein are to be construed as an admission of prior art, unless explicitly stated herein.

SUMMARY

- [0009] Several aspects of one or more alloys and compositions of alloys, as well as methods of making and/or using the same, are described herein. For example, one or more alloys or compositions thereof may be aluminum alloys. The one or more alloys may be used in three-dimensional (3-D) printing and/or additive manufacturing to produce additively manufactured structures with the one of more alloys. Illustratively, an alloy may include a composition containing a plurality of materials (e.g., elements, metals, etc.).
- [0010] According to some configurations of the present disclosure, an alloy may comprise: a composition that includes: magnesium (Mg) that is approximately 5 to 12% by weight of the composition; silicon (Si) that is approximately 0.3 to 3% by weight of the composition; Manganese (Mn) that is approximately 0.1 to 2% by weight of the composition; and aluminum (Al) that is a balance of the composition. In one configuration, the composition may further include at least one of: iron (Fe), chromium (Cr); titanium (Ti); zirconium (Zr); and Yttrium (Y). In one configuration, the composition includes up to approximately 5% by weight of the include Cr. In one configuration, the composition contains up to approximately 0.25% by weight of the Fe. In one configuration, the composition includes at least 0.05% by weight of the Fe. In one configuration, the composition includes at least approximately 1% by weight of the Cr. In one configuration, the composition includes at least approximately 0.1% by weight of the Ti. In one configuration, the composition includes up to 0.6% by weight of the Ti. In one configuration, the composition includes up to approximately 2% by weight of the Zr. In one configuration, the composition includes at least 0.3% by weight of the Zr. In one configuration, the composition includes at least approximately 0.1% by weight of the Y. In one configuration, the composition includes up to 4% by weight of the Y. In one configuration, the composition includes all of the elements listed above (Al, Mg, Mn, Si, Fe, Cr, Ti, Zr, and Y). In one configuration, the balance of the Al of the composition includes up to approximately 0.1% by weight of trace impurities cumulatively and 0.01% individually.
- [0011] It will be understood that other aspects of alloys will become readily apparent to those skilled in the art from the following detailed description, wherein it is shown and described only several embodiments by way of illustration. As will be realized by those skilled in the art, the manufactured structures and the methods for manufacturing these structures are capable of other and different embodiments, and

its several details are capable of modification in various other respects, all without departing from the invention. Accordingly, the drawings and detailed description are to be regarded as illustrative in nature and not as restrictive.

BRIEF DESCRIPTION OF THE DRAWINGS

- [0012] Various aspects of alloys that may be used for additive manufacturing, for example, in automotive, aerospace, and/or other engineering contexts are presented in the detailed description by way of example, and not by way of limitation, in the accompanying drawings, wherein:
- [0013] FIGs. 1A-1B are graphs illustrating properties of alloys.
- [0014] FIGs. 2A-2D illustrate respective side views of an exemplary 3-D printer system.

DETAILED DESCRIPTION

- [0015] The detailed description set forth below in connection with the appended drawings is intended to provide a description of various exemplary embodiments of aluminum alloys are not intended to represent the only embodiments in which the invention may be practiced. The term “exemplary” used throughout this disclosure means “serving as an example, instance, or illustration,” and should not necessarily be construed as preferred or advantageous over other embodiments presented in this disclosure. The detailed description includes specific details for the purpose of providing a thorough and complete disclosure that fully conveys the scope of the invention to those skilled in the art. However, the techniques and approaches of the present disclosure may be practiced without these specific details. In some instances, well-known structures and components may be shown in block diagram form, or omitted entirely, in order to avoid obscuring the various concepts presented throughout this disclosure.
- [0016] Metal alloys, such as aluminum alloys, are often utilized in various engineering applications, such as automotive and aerospace. In many applications, these engineering applications may benefit from alloys that offer high performance and sustainability. Moreover, alloys that are economical may be more advantageous, e.g., as alloys that include rare and/or expensive elements may be impractical for relatively large-scale and/or commercial applications.
- [0017] While some alloys that fulfill the aforementioned conditions exist, these existing alloys are mostly unsuitable for additive manufacturing (AM) applications, such as

Selective Laser Melting (SLM) and/or Powder Bed Fusion (PBF). For example, AM processes with alloys commonly used for traditional manufacturing (i.e., non-AM manufacturing) may result in microstructure and/or other characteristics of these alloys that are unacceptable – e.g., by resulting in defective and/or unsafe products.

[0018] AM processes may include a very small melt pool and/or very high cooling rate from liquid to solid states for alloys, e.g., in comparison with traditional manufacturing processes. Therefore, alloys used in AM processes may be expected to develop microstructure and/or other characteristics (e.g., through the relatively small melt pool and/or relatively high cooling rate) that yield high strength, ductility, fracture toughness, fatigue strength, corrosion resistance, and/or elevated temperature strength and, therefore, result in satisfactory products.

[0019] In view of the foregoing, there exists a need for alloys that are high performance and economically feasible for AM in various automotive, aerospace, and/or other engineering applications. The present disclosure describes alloys that may be implemented in AM processes, such as SLM, PBF, DED, and others. In this way, for example, additively manufactured structures of the alloys disclosed in this invention may be produced. The alloys of the present disclosure may provide improved properties for AM in automotive, aerospace, and/or other engineering applications. The alloys may yield improved performance in AM contexts, such as one or more of high strength (e.g., yield strength), ductility, fracture toughness, fatigue strength, corrosion resistance, elevated temperature strength, percent elongation, and/or any combination thereof. Furthermore, application of the alloys of the present disclosure may be economically feasible, for example, in a commercial context and/or production scale for AM in automotive, aerospace, and/or other engineering applications.

[0020] In an aspect, high-performance aluminum alloys are described. Crashworthiness is a combination of tensile, shear, and compression strengths that make up a material's crash performance. The analytical and experimental data are utilized by a variety of industries (e.g., automotive) while designing and engineering structures incorporating the materials.

[0021] High-performance aluminum alloys processed with conventional techniques (e.g., non-AM processes) may obtain various properties through one or combination of the following processes: solid solution strengthening, strain hardening, precipitation strengthening, and/or dispersion strengthening. The processes of solid solution

strengthening, strain hardening, precipitation strengthening, grain or phase boundary strengthening, and/or dispersion strengthening may take place during solidification, subsequent thermal processing, intermediate cold working, or some combination of these.

[0022] Solidification processes and subsequent cooling in solid state in AM may differ from those processes occurring through conventional techniques. For example, the solidification in PBF processing occurs on a microscale, layer by layer, with each layer undergoing one or more melting, solidification, and cooling cycles. In such a process, melting may begin at approximately 610°C and may conclude at approximately 696°C. Due to the small size of the melt pool, the cooling rate is extremely high relative to conventional techniques – e.g., the cooling rate may be from approximately 10^3 °C/second (s) to approximately 10^6 °C/s. Therefore, non-equilibrium thermodynamics and phase transformation kinetics may become the dominate drivers during AM, thereby making alloys exhibit different properties with AM, such as through inheriting element supersaturation and alloy partitioning.

[0023] Not all alloys (e.g., AA 4046, etc.) may be suitable for the rapid solidification through AM, which may include relatively small weld pools (and may include a rate of approximately 10^3 °C/s to approximately 10^6 °C/s). The present disclosure describes alloys that may provide high performance with AM, e.g., in comparison to currently available alloys. The performance of these alloys of the present disclosure may be improved in the as-printed state, e.g., after undergoing thermal processing (post AM), or some combination of both in the as-printed state and after undergoing thermal processing.

[0024] In one exemplary configuration, one or more alloys of the present disclosure may be tailored for superior strengthening where the one or more alloys would have high ultimate and tensile strength at room and elevated temperature. In another exemplary configuration, one or more of the alloys of the present disclosure may be designed for superior ductility where the one or more alloys would have high elongation at room and elevated temperature.

[0025] One or more alloys of the present disclosure may be specifically designed in order to accommodate the rapid melting, solidification, and/or cooling experienced by alloys in AM (e.g., PBF process). For example, the alloying elements and concentrations thereof may be configured such that intermetallics may be formed with other alloying elements during rapid cooling. Further, the alloying elements and concentrations

thereof may be configured based on the liquid and/or solid solubilities of the alloying elements in the aluminum matrix. The alloying elements and concentrations thereof may be configured such that the alloying elements may form supersaturated solid solutions and/or nano-precipitates after rapid solidification and cooling during AM (e.g., PBF process). The alloying elements and the concentrations thereof may be configured to form intermetallics and the phases thereof during subsequent thermal processing, for example, including precipitation heat treatment and/or Hot Isostatic Pressing (HIP). Finally, the alloying elements and concentrations thereof may be configured to form targeted specific intermetallics during rapid solidification and cooling such that the phases formed thereby may enhance the performance of the one or more alloys of the present disclosure. Additionally, the configurations of the alloying elements and the concentrations thereof may result in the formation of phases during subsequent thermal processing that improves the mechanical performance of the one or more alloys of the present disclosure.

[0026] One or more alloys of the present disclosure are configured with a balance of Al. In some aspects, the balance may include at most 0.1% by weight of trace elements. The Al may be alloyed with a set of other materials, such as one or more elements. Example elements that may be used to form Al alloys in some configurations may include magnesium (Mg), manganese (Mn), silicon (Si), chromium (Cr), titanium (Ti), zirconium (Zr), Yttrium (Y), and/or some combination of all or subset of the foregoing set of elements.

[0027] One or more alloys of the present disclosure may be a composition that includes Mg, Mn, Si, and Al. According to various configurations, Mg may be approximately 5% to 12% by weight of the composition, Mn may be approximately 0.1% to 2% by weight of the composition, Si may be approximately 0.3% to 3% by weight of the composition, and Al may be a balance of the composition. According to some further configurations, compositions of the one or more alloys of the present disclosure may include at least one of Fe, Cr, Ti, Zr, and/or Y.

[0028] In alloying, various properties may be derived through different elements, e.g., when included in a solid solution with Al. For example, strengthening properties may be derived through Mg and/or Mn when included in a solid solution with Al. However, the addition of Mg and/or Mn may reduce ductility due to intermetallic compound formation based on the solubility of Mg and/or Mn. Table 1 illustrates the solid solution strengthening capabilities of various alloying elements in aluminum alloys.

As shown, the greatest solid solution strengthening capabilities may be derived through Mg and Mn, e.g., when measured on the order of thousands of pounds-force per square inch or kilopounds per square inch(ksi).

Alloying element	% difference in atomic radius	Strength increase per weight %	
		Yield (ksi)	Tensile (ksi)
Cu	-10.70	2.00	6.25
Mn	-11.30	4.40	7.80
Si	-3.80	1.33	5.75
Mg	+11.8	2.70	7.30
Zn	-6.00	0.42	2.20

TABLE 1

[0029] Some existing Al alloys (e.g., Al alloys of in the 3000 and 5000 series) produced through conventional processing are based on the addition of Mg and Mn in Al. The Mn content in Al alloys of the 3000 series may be between 0.2% and 1.2%, and the Mg content in Al alloys of the 5000 series may be between 0.5% and 5.51%. As another existing alloy, aluminum alloy (AA) 6061 may have high strength and ductility, e.g., for applications in aerospace engineering. However, AA 6061 may be unsuitable for AM applications. In particular, PBF processes using AA 6061 may produce undesirable results.

[0030] As described herein, AM may be associated with relatively high-temperature melting and relatively fast cooling, e.g., in comparison with conventional or non-AM processing techniques. The fast cooling rate associated with AM may increase the solubility limits of various elements included in one or more alloys described herein, thereby resulting in microstructures that are relatively finer in comparison with those of conventional or non-AM processing techniques.

[0031] As described above, one or more alloys of the present disclosure may include, in addition to Al, Mg that is inclusively between 5% and 12% by weight of the alloy, which may be alloyed in conjunction with Mn to derive a relative high strength and/or ductility (e.g., in comparison with Al alloys of in the 3000 and 5000 series). For example, one or more alloys of the present disclosure may include Mg that is at least 7% by weight of the alloy.

[0032] FIGs. 1A and 1B illustrate two graphs 100, 120 of properties of Al alloyed with Mg and Mn. Referring to FIG. 1A, the first graph 100 shows both the yield strength (in megapascals (MPa)) and the tensile strength (in ksi) of Al alloyed with percentages by weight of Mg and Mn. As illustrated, both the yield strength and the tensile strength of Al alloys increase for at least the percentages by weight between approximately 2% Mg and exceeding 7% Mg, which may be alloyed in combination with percentages by weight between approximately 0.0% Mn and 0.9% Mn.

[0033] Referring to FIG. 1B, the second graph 120 shows the percent elongation (in 50 millimeters (mm) / $\approx$ 2 inches (in)) of Al alloyed with percentages by weight of Mg and Mn. As illustrated, the percent elongation of Al alloys may remain relatively high (e.g., greater than 20%, but may be less than 40%) for at least the percentages by weight between approximately 2% Mg and exceeding 7% Mg, which may be alloyed in combination with percentages by weight between approximately 0.0% Mn and 0.9% Mn. Thus, as shown in FIGs. 1A and 1B, Al may be alloyed with approximately 7% by weight of Mg (e.g., potentially less than and/or potentially greater than 7% by weight of Mg) and in order to configure one or more alloys of the present disclosure with relatively high strength and ductility. As shown in Table 2, an exemplary configuration of an alloy having high strength and high ductility is illustrated.

Alloy	Mg (weight %)	Mn (weight %)	Al
Al-Mg-Mn	5.2-11.5	0.2-1.2	Balance

TABLE 2

[0034] While Al alloyed with Mg and/or Mn may provide relatively high strength and/or high ductility, the relatively high strength may be derived through solid solution strengthening, but such alloys may not be heat treatable. Thus, one or more alloys of the present disclosure may be configured for solid solution strengthening and, additionally, for precipitation hardening. In so doing, the one or more alloys of the present disclosure may be suitable for AM applications, including 3-D printing. For example, one or more alloys of the present disclosure may be configured with one or more other elements, in addition to Mg and Mn with a balance of Al. With the addition of the one or more other elements, the one or more alloys described herein may be suitable for AM applications, such as 3-D printing, while still providing relatively high strength, ductility, and/or durability.

[0035] Configuring one or more alloys of the present disclosure with Si may contribute to precipitation hardening of the one or more alloys. For example, Si may be included in an Al-Mg-Mn alloy. A configuration with Si may contribute to precipitation hardening. By way of illustration, Table 3 shows various examples of an Al-Mg-Mn-Si alloy that may be suitable for AM. According to some configurations, one or more of the alloys shown in Table 3 may be alloyed with one or more other elements, e.g., as described herein.

Alloy	Mg (weight %)	Mn (weight %)	Si (weight %)	Al
Al-Mg-Mn-Si 1	5.0 – 7.0	0.8 – 1.2	0.8 – 1.2	Balance
Al-Mg-Mn-Si 2	6.0 – 8.0	1.0 – 1.1	1.0 – 1.2	Balance
Al-Mg-Mn-Si 3	8.0 – 10.0	0.2 – 0.5	0.8 – 1.2	Balance
Al-Mg-Mn-Si 4	8.0 – 10.0	0.2 – 0.5	1.4 – 2.0	Balance
Al-Mg-Mn-Si 5	7.0 – 9.0	0.4 – 0.8	1.4 – 2.0	Balance
Al-Mg-Mn-Si 6	6.0 – 8.0	0.9 – 1.1	0.8 – 1.2	Balance

TABLE 3

[0036] According to various configurations, one or more alloys of the present disclosure may include a set of primary elements: Al, Mg, Mn, and Si. Table 4 illustrates ranges for percentages of weights of the one or more primary elements with which one or more alloys of the present disclosure may be configured.

Al	Mg	Mn	Si
Balance	5 – 12%	0.1 – 2%	0.3 – 3%

TABLE 4

[0037] As an addition or alternative to Si, one or more alloys of the present disclosure may be configured with one or more of a set of secondary elements: Fe, Ti, Zr, Cr, and/or Y. Table 5 illustrates ranges of percentages of weights of the one or more secondary elements with which one or more alloys of the present disclosure may be configured. One or more alloys of the present disclosure may be configured with all, none, or a subset of the set of secondary elements.

	Fe	Ti	Zr	Cr	Y
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	0.05 – 0.25%	0.1 – 0.6%	0.3 – 2.0%	1 – 5%	0.1 – 4%
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TABLE 5

- [0038]** According to a first example, one configuration of the composition may include the balance of Al, the aforementioned percentages by weight of Mg, Mn, and Si, and may further include up to approximately 0.25% by weight of the Fe. In another configuration, the composition of the first example may include at least approximately 0.05% by weight of the Fe.
- [0039]** Iron is the most common impurity found in aluminum. Iron has a high solubility in molten aluminum, and is therefore easily dissolved at all molten stages of production. The solubility of iron in the solid state is very low and, depending on the cooling rate, it can precipitate by forming FeAl_3 , and more complex AlFeMgSi , in the alloy to provide additional strength if controlled in the disclosed level in the composition.
- [0040]** According to a second example, one configuration of the composition may include the balance of Al, the aforementioned percentages by weight of Mg, Mn, and Si, and may further include up to approximately 0.6% by weight of the Ti. In another configuration, the composition of the second example may include at least approximately 0.1% by weight of the Ti. Titanium can be used primarily as a grain refiner of aluminum alloys. When used alone, the effect of titanium decreases with time of holding in the molten state and with repeated re-melting. However, titanium depresses electrical conductivity and, therefore, can be used with chromium, which has a large effect on the resistivity of aluminum alloys.
- [0041]** According to a third example, one configuration of the composition may include the balance of Al, the aforementioned percentages by weight of Mg, Mn, and Si, and may further include up to approximately 2.0% by weight of the Zr. In another configuration, the composition of the third example may include at least approximately 0.3% by weight of the Zr.
- [0042]** According to a fourth example, one configuration of the composition may include the balance of Al, the aforementioned percentages by weight of Mg, Mn, and Si, and may further include up to approximately 5% by weight of the Cr. In another configuration, the composition of the fourth example may include at least approximately 1% by weight of the Cr. Chromium increases the elastic modulus in solid solution and increases the strength of the composition when in the form of submicron precipitates.

Because chromium has a slow diffusion rate, the chromium may form extremely fine dispersed phases in the composition, and may be retained in the solid solution of the composition to increase both elastic modulus and strength. Chromium also reduces stress corrosion susceptibility and improves toughness.

[0043] According to a fifth example, one configuration of the composition may include the balance of Al, the aforementioned percentages by weight of Mg, Mn, and Si, and may further include up to approximately 4% by weight of the Y. In another configuration, the composition of the fifth example may include at least approximately 0.1% by weight of the Y.

[0044] Referring to zirconium and yttrium, both elements may form complex but nano precipitates when available in small quantities. However, the present disclosure describes relatively higher amounts of both zirconium and yttrium, which may increase solid solution strength and toughness of the alloy, thereby reducing the susceptibility to cracking at high cooling rates. Yttrium may be more effective than zirconium (e.g., in increasing solid solution strengthening and/or toughness), and the inclusion of one or both of two elements in the amounts disclosure herein may balance their effects with their costs (e.g., in production of one or more of the alloys of the present disclosure).

[0045] In some exemplary applications, the one or more alloys of the present disclosure may be used for AM in automotive engineering. For example, the one or more alloys described herein may be additively manufactured for the production of nodes, joints, and/or other structures, which may be applied in vehicles (e.g., cars, trucks, etc.). For example, the one or more alloys described herein may be additively manufactured to produce all or a portion of a chassis, frame, body, etc. of a vehicle.

[0046] The characteristics of the one or more alloys described herein may contribute to the crashworthiness of structures produced from the one or more alloys described herein. Moreover, the one or more alloys of the present disclosure may be configured with the materials (e.g., elements) described herein so that products additively manufactured using at least a portion of the one or more alloys may reduce the weight of vehicles at a suitable insertion point (e.g., in comparison with existing approaches to vehicle manufacture).

[0047] The one or more alloys of the present disclosure may feature characteristics and/or properties that exceed the corresponding characteristics and/or properties of various existing alloys, e.g., in the context of AM applications. For example, Table 6 shows

exemplary compositions of alloys described in the present disclosure, with the illustrated values of the enumerated elements being the percentage by weight of each corresponding element. The values include mechanical properties of the as-printed parts, without any subsequent machining or post-processing operations. The alloys of Tables 4-6 may include resultant mechanical properties that exceed those of conventional wrought AA 6061-T6. For example, the yield strength of an alloy illustrated in Table 6 may be 266 MPa, the tensile strength of an alloy illustrated in Table 6 may be 391 MPa, and the percent elongation of the alloy illustrated in Table 6 may be 11.3%.

Aluminum alloys	Composition, weight %					Strength, MPa		Elongation
	<u>Mg</u>	<u>Si</u>	<u>Mn</u>	<u>Fe</u>	<u>Al</u>	<u>Yield</u>	<u>Tensile</u>	<u>%</u>
Alloy 1	5.64	1.21	1.02	0.16	Balance	251	385	11.3
Alloy 2	5.29	1.23	0.9	0.1	Balance	235	370	10.1
Alloy 3	6.19	1.07	1.1	0.06	Balance	266	391	9.5
Alloy 4	7.13	1.09	0.57	0.15	Balance	262	403	9

Table 6

[0048] AM processes may use various metallic powders, such as one or more alloys of the present disclosure. FIGS. 2A-2D illustrate respective side views of an exemplary 3-D printer system. In this example, the 3-D printer system is a powder-bed fusion (PBF) system 200. FIGS. 2A-2D show PBF system 200 during different stages of operation. It should also be noted that features of FIGS. 2A-2D and the other figures in this disclosure are not necessarily drawn to scale, but may be drawn larger or smaller for the purpose of better illustration of concepts described herein.

[0049] The particular embodiments illustrated in FIGS. 2A-D are some suitable examples of a PBF system employing principles of the present disclosure. Specifically, one or more of the aluminum alloys described herein may be used in at least one PBF system 200 described in FIGS. 2A-D. While one or more aluminum alloys described in the present disclosure may be suitable for various AM processes (e.g., using a PBF system, as shown in FIGS. 2A-D), it will be appreciated that one or more aluminum alloys of the present disclosure may be suitable for other applications, as well. For example, one or more aluminum alloys described herein may be used in other fields

or areas of manufacture without departing from the scope of the present disclosure. Accordingly, AM processes employing the one or more aluminum alloys of the present disclosure are to be regarded as illustrative, and are not intended to limit the scope of the present disclosure.

[0050] According to some examples of the present disclosure, an aluminum alloy used in PBF system 200 may be a composition that includes a balance of Al, Mg that is at least 2% by weight of the composition, Mn that is up to 2.5% by weight of the composition, and Si that is up to 4% by weight of the composition. In a specific configuration, Mg may be 5 to 12% by weight of the composition, Mn may be 0.1 to 2% by weight of the composition, and Si may be 0.3 to 3% by weight of the composition.

[0051] In some further configurations, the composition may further include at least one element selected from a group of Fe, Ti, Zr, Cr, and/or Y. In one example, the composition may include Fe that is up to 1% by weight of the composition – e.g., the composition may include Fe that is inclusively between 0.05% to 0.25% by weight of the composition. In another example, the composition may include Ti that is 0 to 1% by weight of the composition – e.g., the composition may include Ti that is inclusively between 0.1% to 0.6% by weight of the composition. In a further example, the composition may include Zr that is 0.15-5% by weight of the composition – e.g., the composition may include Zr that is inclusively between 0.3% to 2% by weight of the composition. In still another example, the composition may include Cr that is at least 1% by weight of the composition – e.g., the composition may include Cr that is inclusively between 1% to 5% by weight of the composition. In yet another example, the composition may include Y that is at least 0.1% by weight of the composition – e.g., the composition may include Y that is inclusively between 0.1% to 4% by weight of the composition. In one configuration, the composition includes all of the elements listed above (Al, Mg, Mn, Si, Fe, Cr, Ti, Zr, and Y). In one configuration, the composition includes up to approximately 0.1% by weight of trace impurities cumulatively, and 0.01% individually (e.g., in each individual element that is alloyed with the balance of Al).

[0052] Prior to use in PBF system 200, the elements of an aluminum alloy may be combined into a composition according to one of the examples/configurations described herein. For example, the elements in respective concentrations described in one of the examples/configurations of the present disclosure may be combined when the

elements are molten. The composition may be mixed while the elements are molten, e.g., in order to promote even distribution of each element with the balance of Al. The molten composition may be cooled and atomized. Atomization of the composition may yield a metallic powder that includes the elements of the one of the examples/configurations of the present disclosure, and can be used in additive manufacturing systems such as PBF system 200.

[0053] PBF system 200 can include a depositor 201 that can deposit each layer of metal powder, an energy beam source 203 that can generate an energy beam, a deflector 205 that can apply the energy beam to fuse the powder material, and a build plate 207 that can support one or more build pieces, such as a build piece 209. PBF system 200 can also include a build floor 211 positioned within a powder bed receptacle. The walls 212 of the powder bed receptacle generally define the boundaries of the powder bed receptacle, which is sandwiched between the walls 212 from the side and abuts a portion of the build floor 211 below. Build floor 211 can progressively lower build plate 207 so that depositor 201 can deposit a next layer. The entire mechanism may reside in a chamber 213 that can enclose the other components, thereby protecting the equipment, enabling atmospheric and temperature regulation and mitigating contamination risks. Depositor 201 can include a hopper 215 that includes a powder 217, such as a metal powder, and a leveler 219 that can level the top of each layer of deposited powder.

[0054] Referring specifically to FIG. 2A, this figure shows PBF system 200 after a slice of build piece 209 has been fused, but before the next layer of powder has been deposited. In fact, FIG. 2A illustrates a time at which PBF system 200 has already deposited and fused slices in multiple layers, e.g., 150 layers, to form the current state of build piece 209, e.g., formed of 150 slices. The multiple layers already deposited have created a powder bed 221, which includes powder that was deposited but not fused.

[0055] FIG. 2B shows PBF system 200 at a stage in which build floor 211 can lower by a powder layer thickness 223. The lowering of build floor 211 causes build piece 209 and powder bed 221 to drop by powder layer thickness 223, so that the top of the build piece and powder bed are lower than the top of powder bed receptacle wall 212 by an amount equal to the powder layer thickness. In this way, for example, a space with a consistent thickness equal to powder layer thickness 223 can be created over the tops of build piece 209 and powder bed 221.

- [0056] FIG. 2C shows PBF system 200 at a stage in which depositor 201 is positioned to deposit the powder 217 in a space created over the top surfaces 226 of build piece 209 and powder bed 221 and bounded by powder bed receptacle walls 212. In this example, depositor 201 progressively moves over the defined space while releasing the powder 217 from hopper 215. Leveler 219 can level the released powder to form a powder layer 225 that has a thickness substantially equal to the powder layer thickness 223 (see, e.g., FIG. 2B). Thus, the powder in a PBF system can be supported by a powder material support structure, which can include, for example, a build plate 207, a build floor 211, a build piece 209, walls 212, and the like. It should be noted that the illustrated thickness of powder layer 225 (i.e., powder layer thickness 223 (FIG. 2B) is greater than an actual thickness used for the example involving 150 previously-deposited layers discussed above with reference to FIG. 2A.
- [0057] FIG. 2D shows PBF system 200 at a stage in which, following the deposition of powder layer 225 (FIG. 2C), energy beam source 203 generates an energy beam 227 and deflector 205 applies the energy beam to fuse the next slice in build piece 209. In various exemplary embodiments, energy beam source 203 can be an electron beam source, in which case, energy beam 227 constitutes an electron beam. Deflector 205 can include deflection plates that can generate an electric field or a magnetic field that selectively deflects the electron beam to cause the electron beam to scan across areas designated to be fused. In various embodiments, energy beam source 203 can be a laser, in which case, the energy beam 227 is a laser beam. Deflector 205 can include an optical system that uses reflection and/or refraction to manipulate the laser beam to scan selected areas to be fused.
- [0058] In various embodiments, the deflector 205 can include one or more gimbals and actuators that can rotate and/or translate the energy beam source to position the energy beam. In various embodiments, energy beam source 203 and/or deflector 205 can modulate the energy beam, e.g., turn the energy beam on and off as the deflector scans so that the energy beam is applied only in the appropriate areas of the powder layer. For example, in various embodiments, the energy beam can be modulated by a digital signal processor (DSP).
- [0059] An alloy may be a substance composed of two or more materials (e.g., metals or nonmetals). The two or more materials may be combined together by being merged together, for example, when molten.

[0060] In some configurations, one or more alloys of the present disclosure may be a composition that may be mixed to include a balance of Al and the following materials: (1) Mg that is approximately 5-12% by weight of the composition; (2) Mn that is approximately 0.1-2% by weight of the composition; (3) Si that is 0.3-3% by weight of the composition. In some configurations, the balance of Al may include up to 0.1% of trace elements.

[0061] In some other configurations, one or more alloys of the present disclosure may be the aforementioned composition of Al, Mg, Mn, and Si, and the composition may include at least one of the following other materials: Fe, Ti, Zr, Cr, and/or Y. When an alloy of the present disclosure is a composition that includes Fe, Fe may be 0.05-0.25% by weight of the composition. When an alloy of the present disclosure is a composition that includes Ti, Ti may be 0.1-0.6% by weight of the composition. When an alloy of the present disclosure is a composition that includes Zr, Zr may be 0.3-2% by weight of the composition. When an alloy of the present disclosure is a composition that includes Cr, Cr may be 1-5% by weight of the composition. When an alloy of the present disclosure is a composition that includes Y, Y may be 0.1-4% by weight of the composition. In various configurations, the one or more alloys of the present disclosure may include all, none, or some of the other materials Fe, Ti, Zr, Cr, and/or Y.

[0062] An example alloy of the present disclosure may be processed with the L-PBF method to print test bars. Tensile properties may be obtained from the example alloy.

[0063] AM raw materials can be manufactured by powder making processes as well as other methods such as Ingot Metallurgy (I/M) in which a solid ingot is manufactured by melting the metal along with added alloying elements and solidifying in a mold such as ingot. The molded solid or the ingot is then deformed by various wrought material production methods such as rolling, extrusion, drawing etc. The ingots, wires and rods are either melted and atomized to make powders or fed directly into the laser, electron, plasma beams, or electrical arc such as TIG, MIG, to melt the metal layer by layer manufacture AM products.

[0064] Powder characteristics may be important for successful fusion within an AM machine such as PBF and/or DED. Some aspects of alloy powders that may be advantageous for use with AM may include but are not limited to, good flow, close packing of particles and spherical particle shape. These aspects may lead to consistent and predictable layers.

[0065] The previous description is provided to enable any person skilled in the art to practice the various aspects described herein. Various modifications to these exemplary embodiments presented throughout this disclosure will be readily apparent to those skilled in the art, and the concepts disclosed herein may be applied to aluminum alloys. Thus, the claims are not intended to be limited to the exemplary embodiments presented throughout the disclosure but are to be accorded the full scope consistent with the language claims. All structural and functional equivalents to the elements of the exemplary embodiments described throughout this disclosure that are known or later come to be known to those of ordinary skill in the art are intended to be encompassed by the claims. Moreover, nothing disclosed herein is intended to be dedicated to the public regardless of whether such disclosure is explicitly recited in the claims. No claim element is to be construed under the provisions of 35 U.S.C. §112(f), or analogous law in applicable jurisdictions, unless the element is expressly recited using the phrase “means for” or, in the case of a method claim, the element is recited using the phrase “step for.”

WHAT IS CLAIMED IS:

1. An alloy comprising:
a composition that includes:
magnesium (Mg) that is at least 2% by weight of the composition;
manganese (Mn) that is up to 2.5% by weight of the composition;
silicon (Si) that is up to 4% by weight of the composition; and
aluminum (Al) that is a balance of the composition.
2. The alloy of claim 1, wherein the composition includes:
Mg that is 5 to 12% by weight of the composition;
Mn that is 0.1 to 2% by weight of the composition;
Si that is 0.3 to 3% by weight of the composition.
3. The alloy of claim 1, wherein the composition further includes at least one of:
iron (Fe),
titanium (Ti),
zirconium (Zr),
chromium (Cr), or
yttrium (Y).
4. The alloy of claim 3, wherein the composition includes:
Fe that is up to 1% by weight of the composition;
Ti that is 0 to 1% by weight of the composition;
Zr that is 0.15-5% by weight of the composition;
Cr that is at least 1% by weight of the composition; and
Y that is at least 0.1% by weight of the composition.
5. The alloy of claim 3, wherein composition includes up to 0.25% by weight of the Fe.
6. The alloy of claim 5, wherein the composition includes at least 0.05% by weight of the Fe.

7. The alloy of claim 3, wherein composition includes up to 0.6% by weight of the Ti.
8. The alloy of claim 7, wherein the composition includes at least 0.1% by weight of the Ti.
9. The alloy of claim 3, wherein composition includes up to 2.0% by weight of the Zr.
10. The alloy of claim 9, wherein the composition includes at least 0.3% by weight of the Zr.
11. The alloy of claim 3, wherein composition includes up to 5% by weight of the Cr.
12. The alloy of claim 11, wherein the composition includes at least 1% by weight of the Cr.
13. The alloy of claim 3, wherein composition includes up to 4% by weight of the Y.
14. The alloy of claim 13, wherein the composition includes at least 0.1% by weight of the Y.
15. The alloy of claim 1, wherein the balance of the Al of the composition includes up to 0.1% by weight of trace impurities.

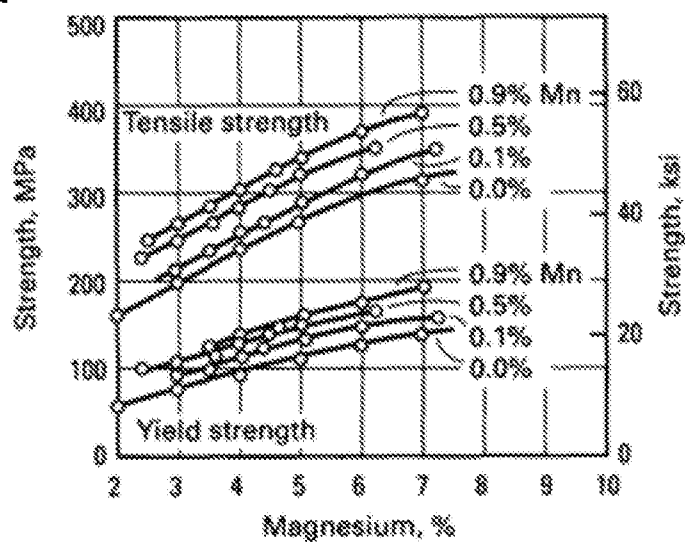
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FIG. 1A

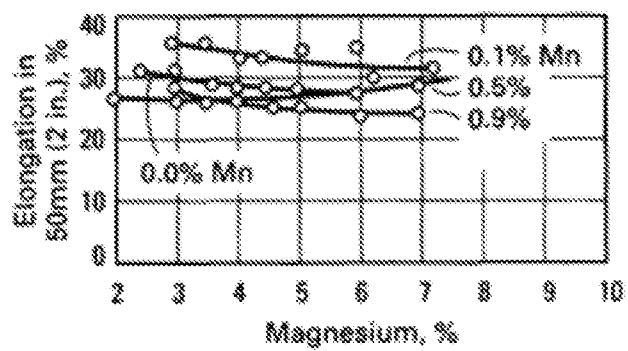
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FIG. 1B

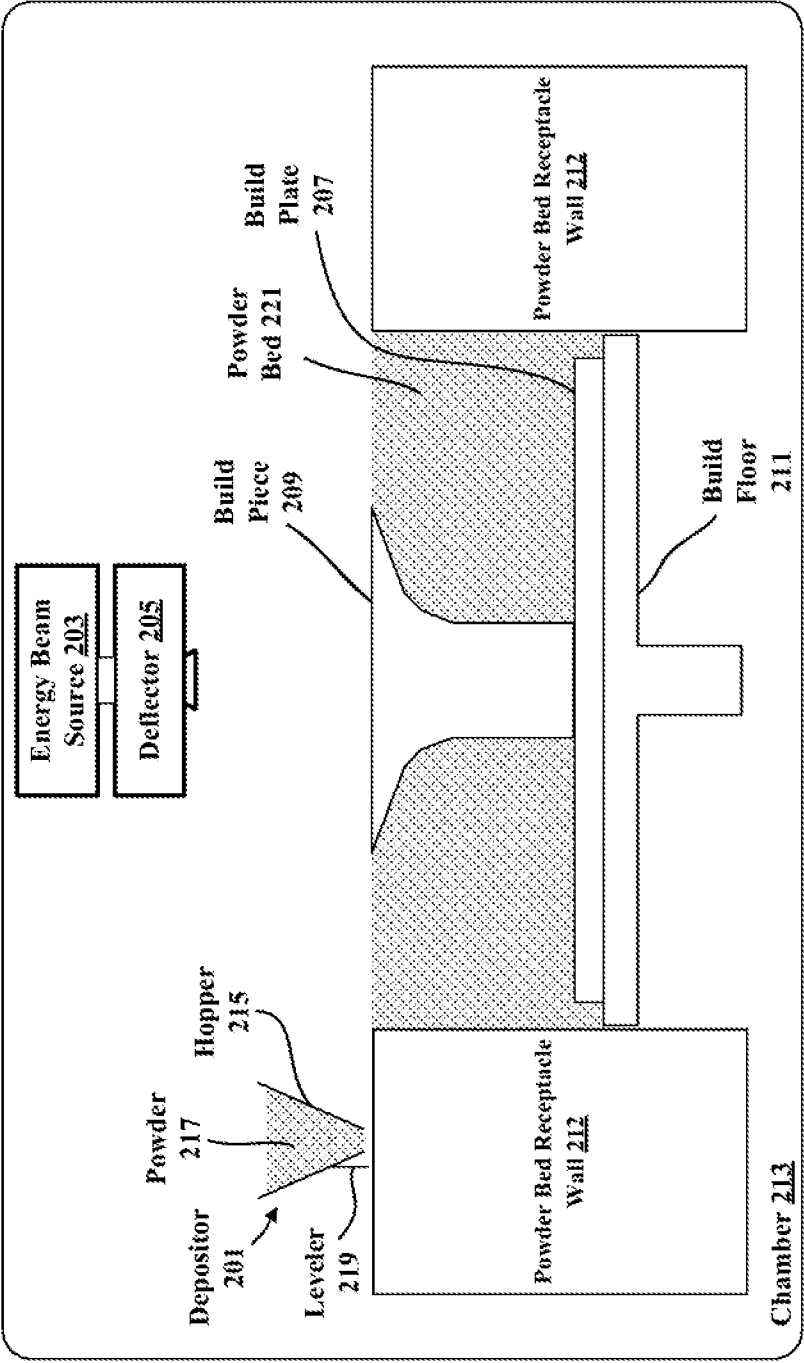
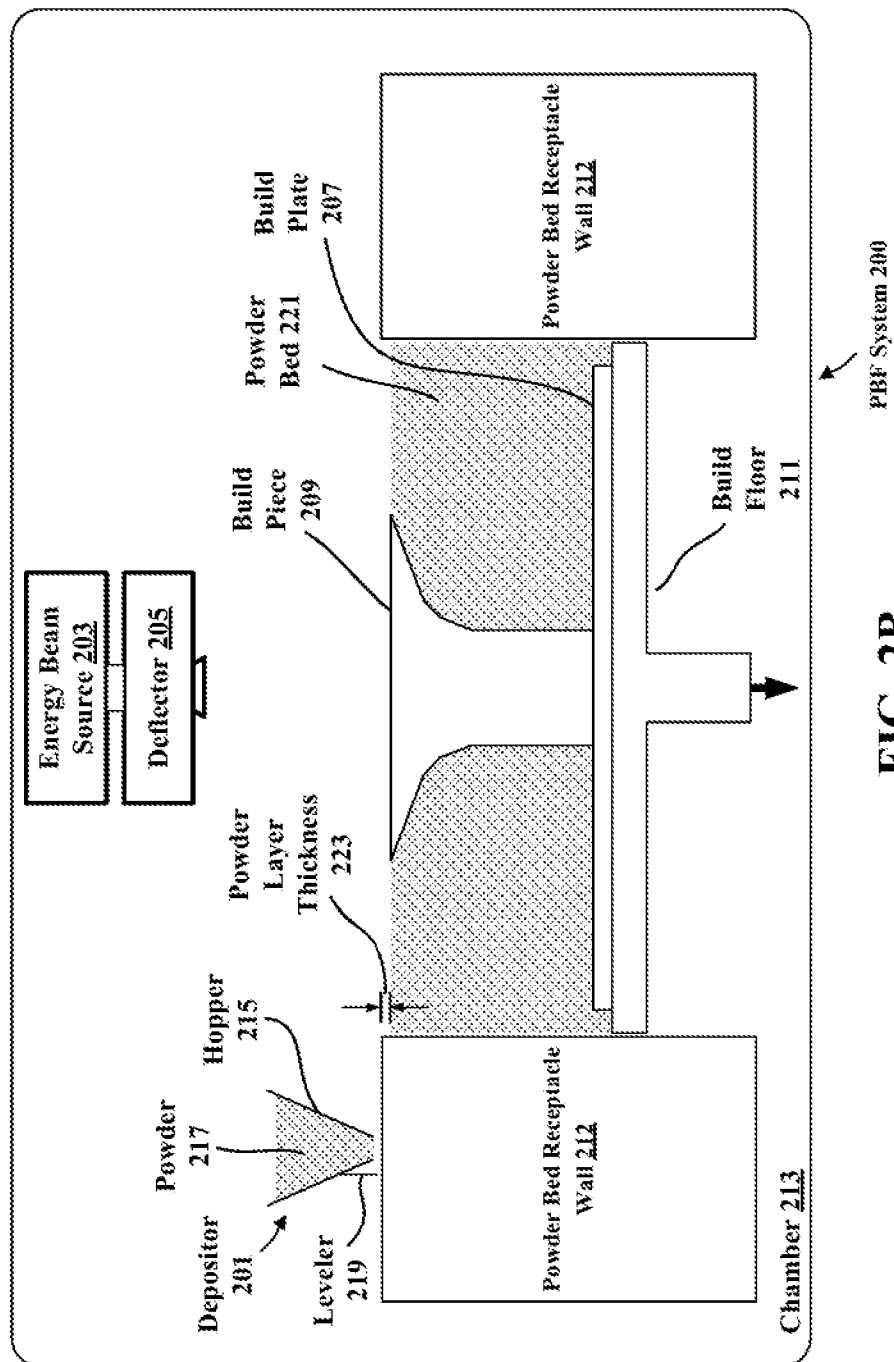


FIG. 2A



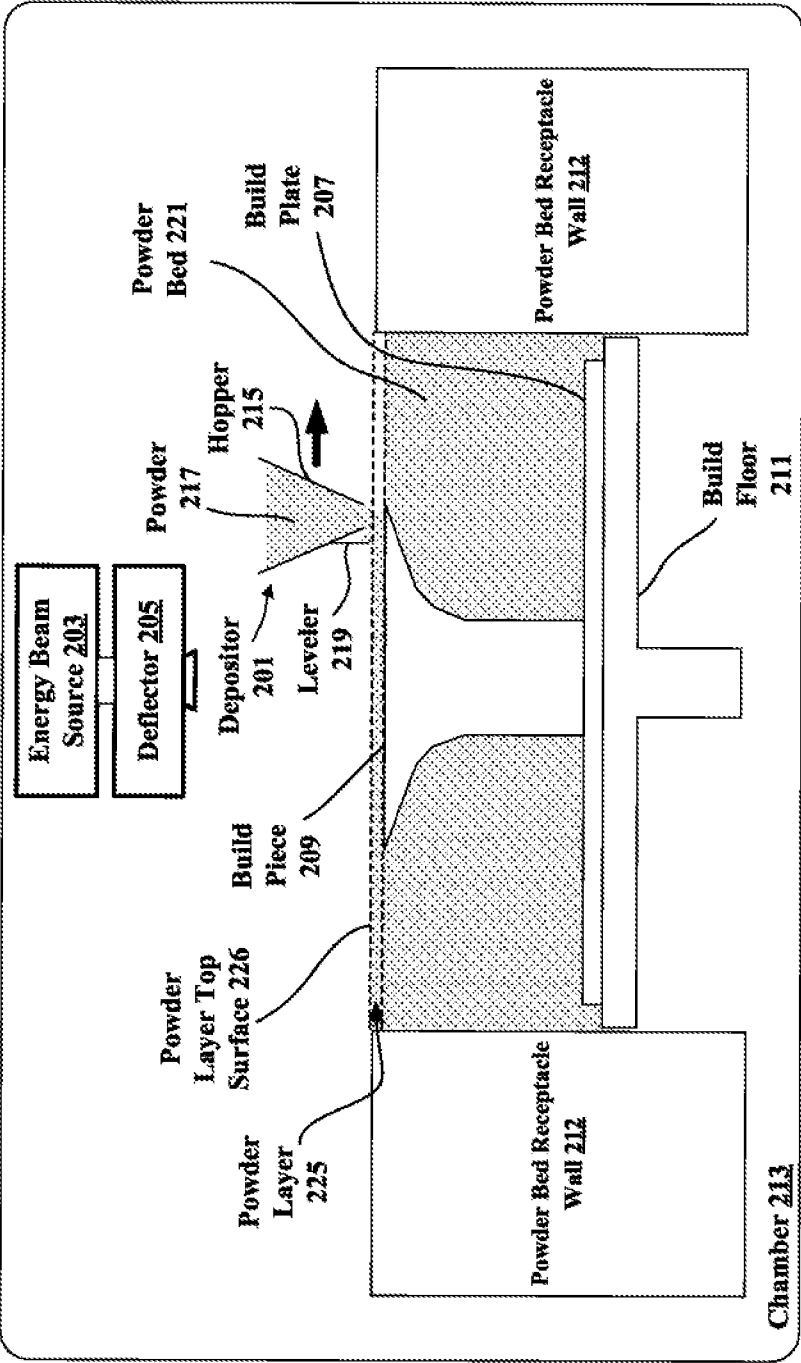


FIG. 2C

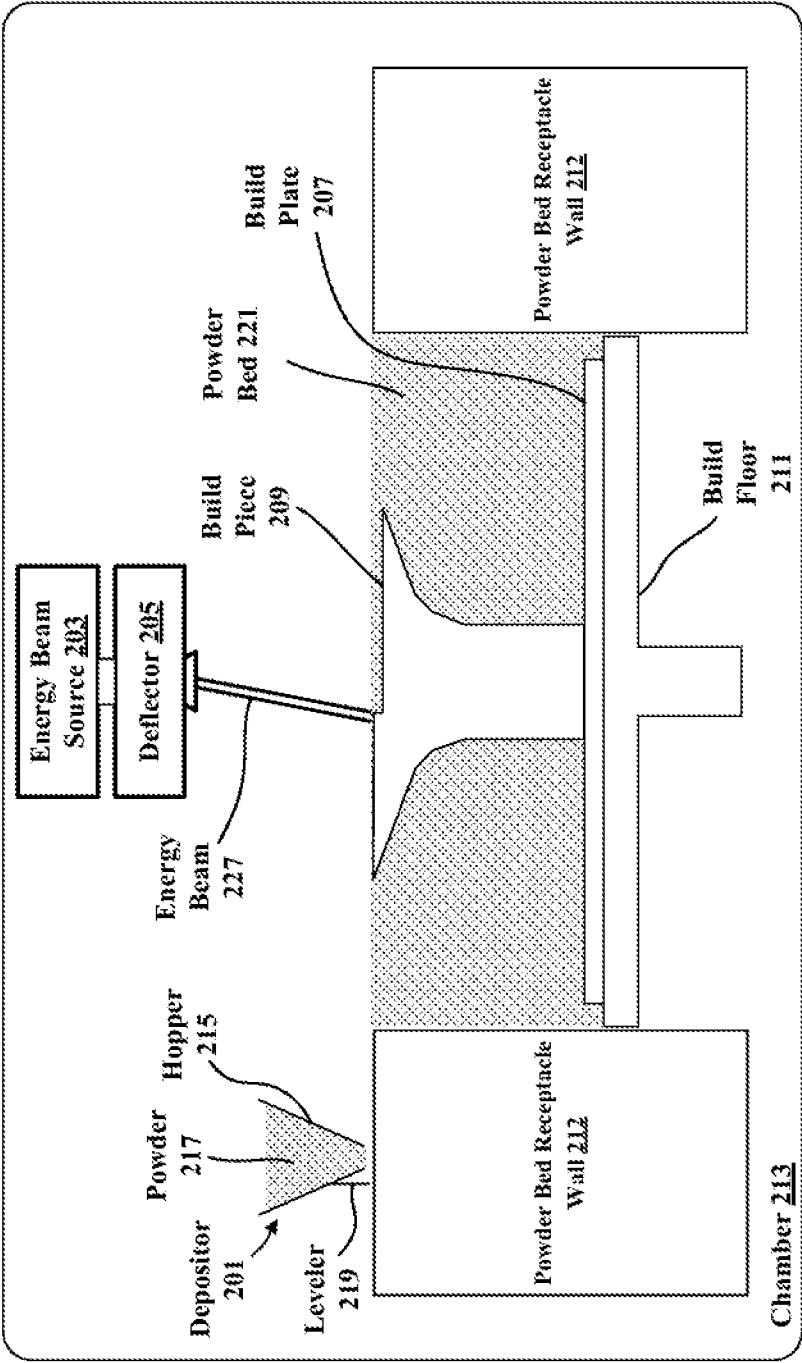


FIG. 2D