US 20240026499A1

(19) **United States**

(12) **Patent Application Publication**

Luo et al.

(10) **Pub. No.: US 2024/0026499 A1**

(43) **Pub. Date: Jan. 25, 2024**

(54) **MAGNESIUM ALLOYS AND METHODS OF MAKING AND USE THEREOF**

(71) Applicants: **Ohio State Innovation Foundation**, Columbus, OH (US); **Terves, Inc.**, Euclid, OH (US)

(72) Inventors: **Alan Luo**, Columbus, OH (US); **Joshua Caris**, Euclid, OH (US); **Thomas Avey**, Columbus, OH (US)

(21) Appl. No.: **18/224,247**

(22) Filed: **Jul. 20, 2023**

Related U.S. Application Data

(60) Provisional application No. 63/391,396, filed on Jul. 22, 2022.

Publication Classification

(51) **Int. Cl.**

C22C 23/02	(2006.01)
C22C 1/12	(2006.01)
C22C 23/04	(2006.01)
C22F 1/06	(2006.01)

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

CPC ***C22C 23/02*** (2013.01); ***C22C 1/12*** (2023.01); ***C22C 23/04*** (2013.01); ***C22F 1/06*** (2013.01)

(57) **ABSTRACT**

Disclosed herein are magnesium alloys and methods of making and use thereof. For example, disclosed herein are magnesium alloys comprising: from 0 to 1.5 wt. % Zn; from 0 to 1.5 wt. % Al; less than 0.2 wt. % Ca; from 0.2 to 0.4 wt. % Ce; from 0.1 to 0.8 wt. % Mn; and the balance comprising Mg. In some examples, the magnesium alloy comprises less than 1 wt. % Zn. In some examples, the magnesium alloy comprises less than 1 wt. % Al. In some examples, the magnesium alloy exhibits substantially no incipient melting when extruded with a ram speed of from 1.00 to 10.00 ipm. In some examples, the magnesium alloy is substantially free of a Mg_2Ca phase, an AlCaMg phase, an Al_2Ca phase, a $Ca_2Mg_6Zn_3$ phase, or a combination thereof. In some examples, the magnesium alloy is substantially free of a Mg_2Ca phase.

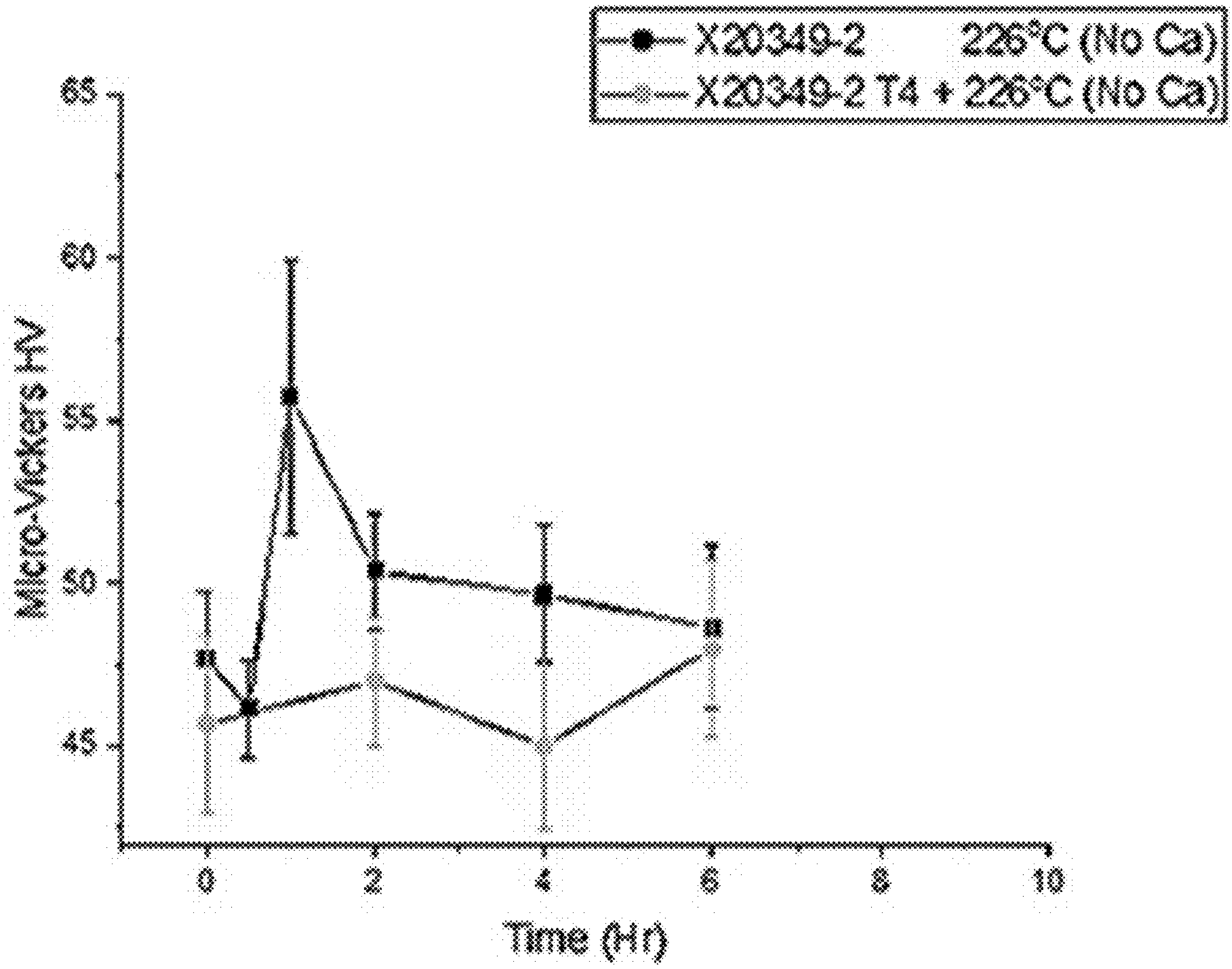

X20349-2 226°C (No Ca)
X20349-2 T4 + 226°C (No Ca)
Micro-Vickers HV
65
60
55
50
45
0
2
4
6
8
10
Time (Hr)

Figure 1

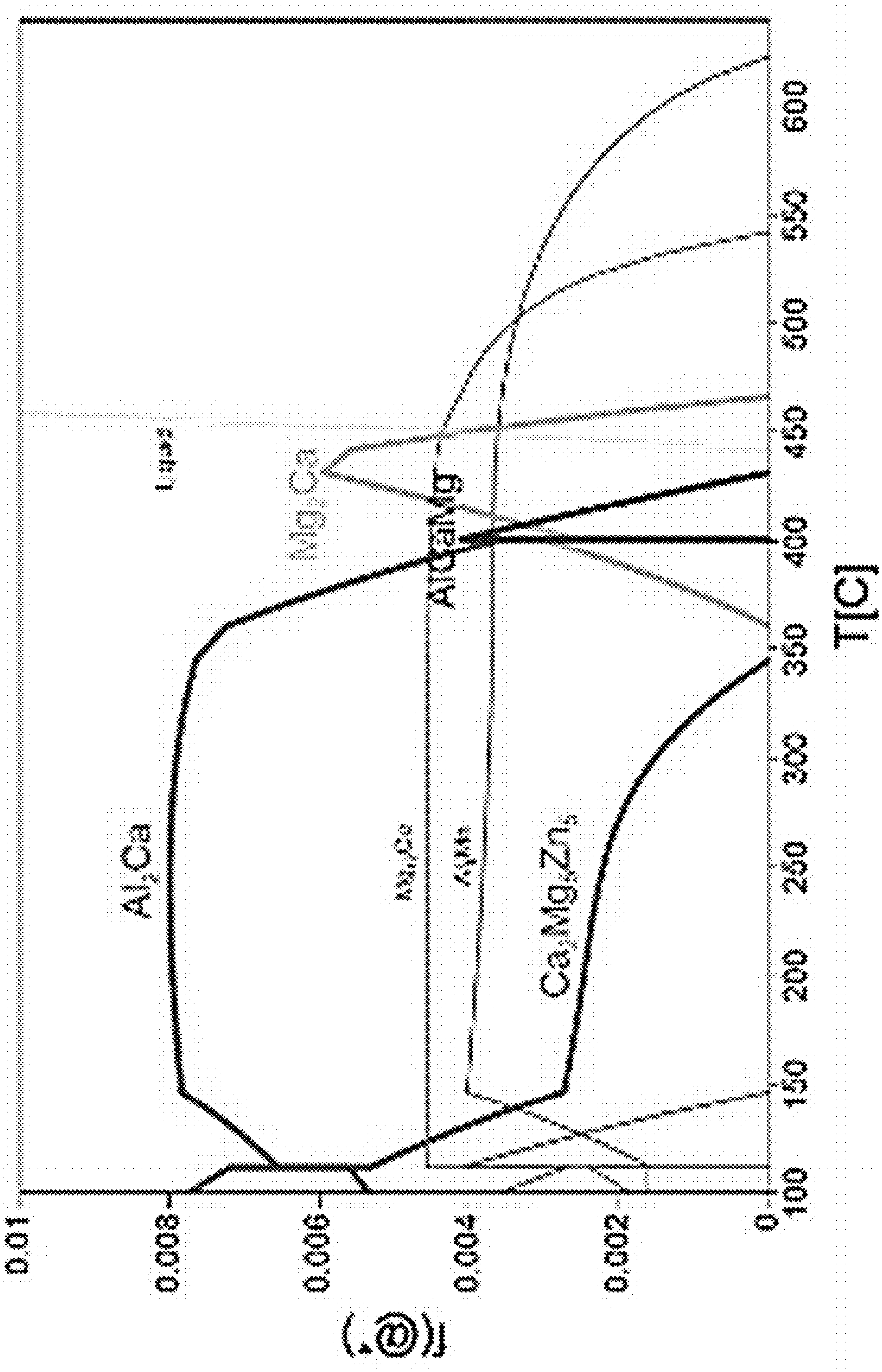
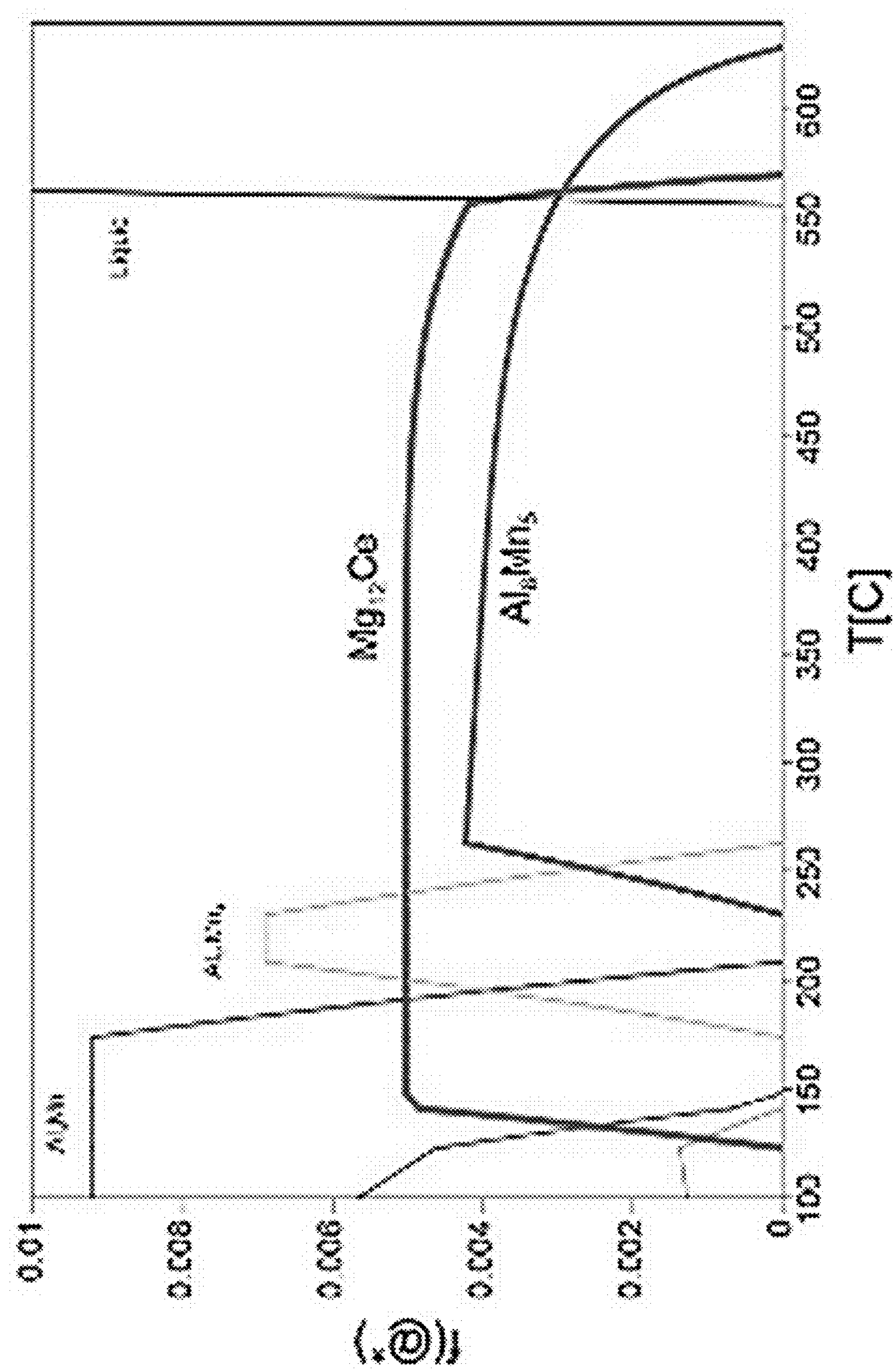

Al2Ca
Mg2Ca
AlCaMg
CaMgZn
T[C]
f(@*)
0.01
0.008
0.006
0.004
0.002
0
100
150
200
250
300
350
400
450
500
550
600

Figure 2



Mg12Ce
Al8Mn5
T[C]
f(@*)
0.01
0.008
0.006
0.004
0.002
0
100
150
200
250
300
350
400
450
500
550
600

Figure 3

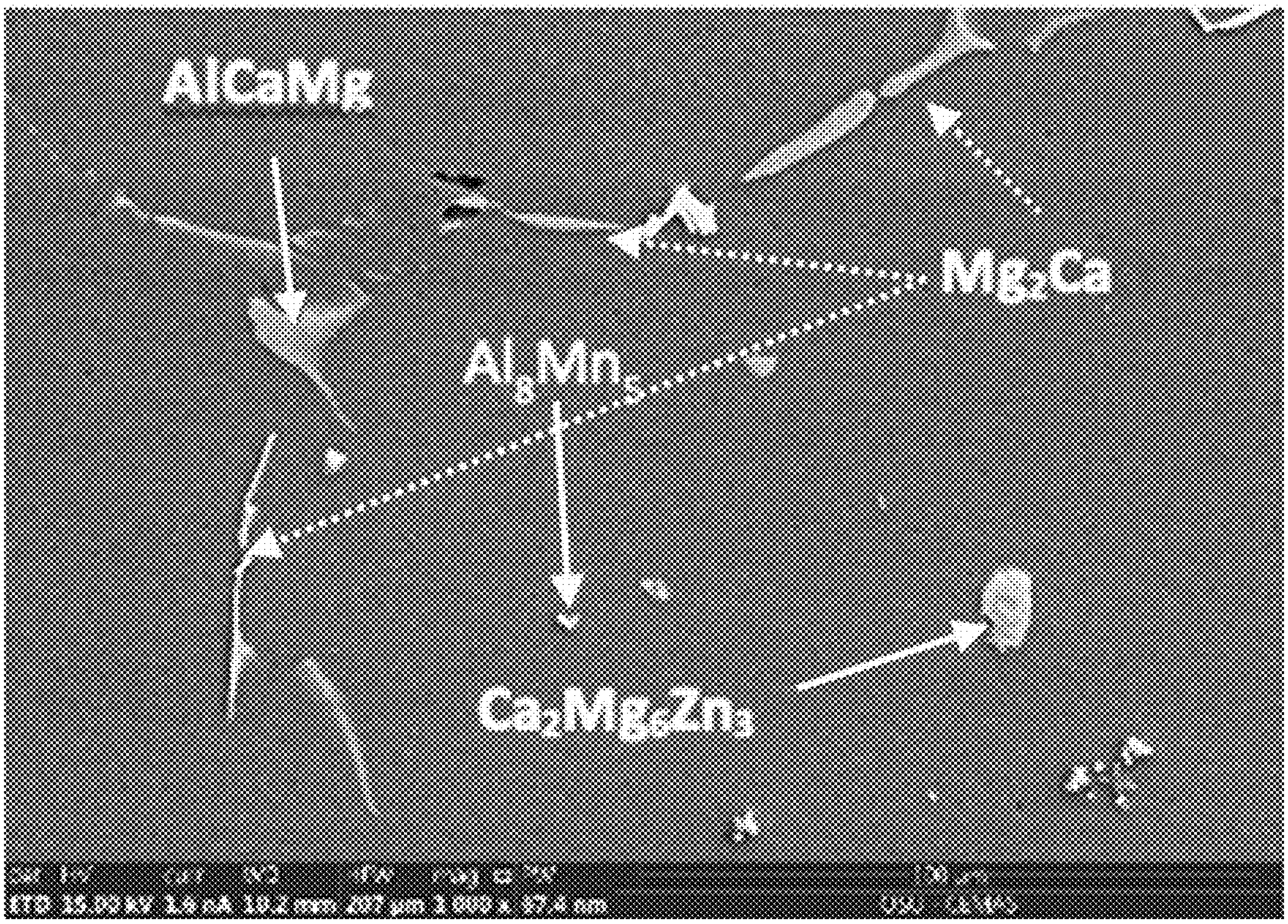


Figure 4

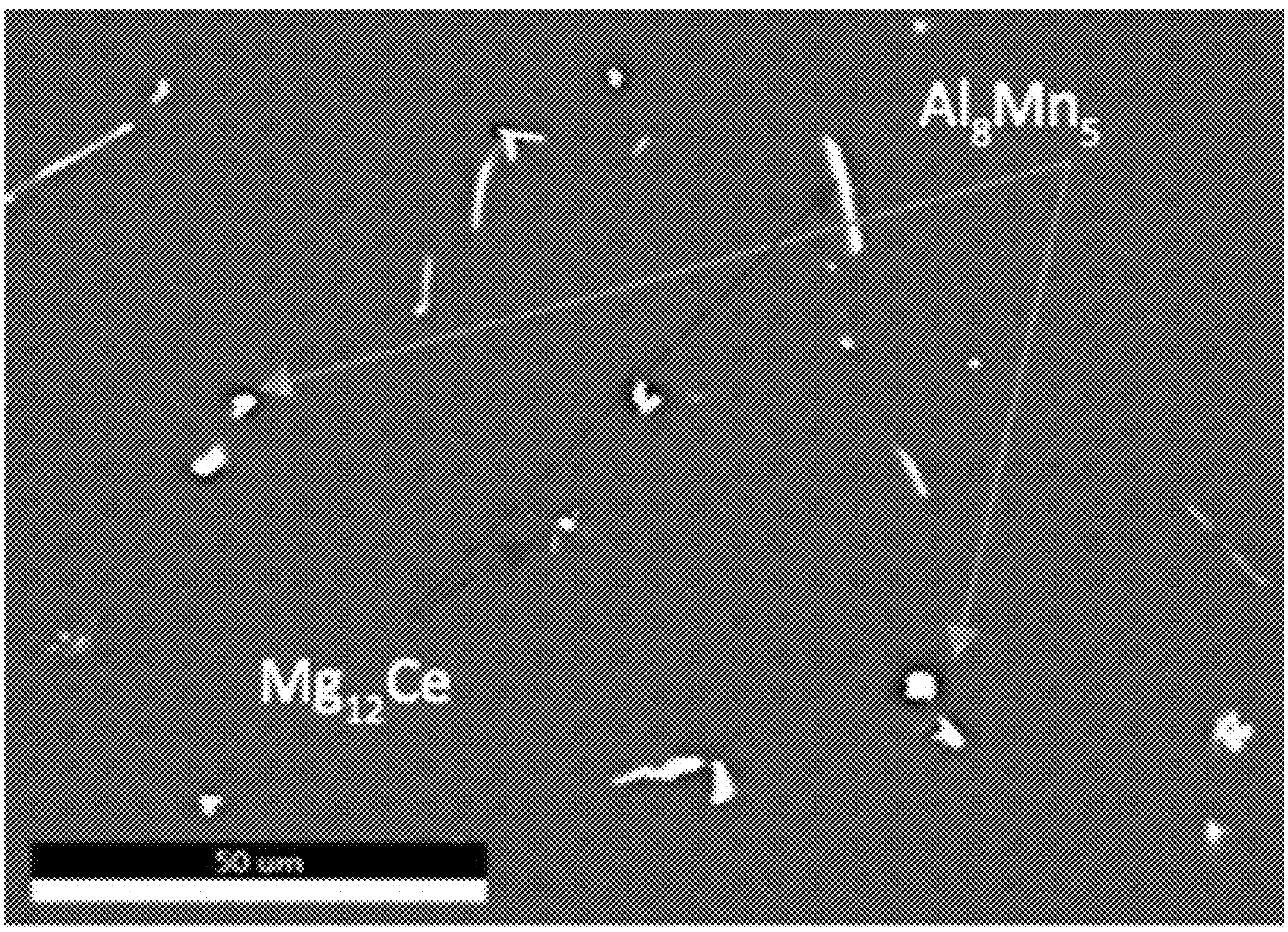


Figure 5

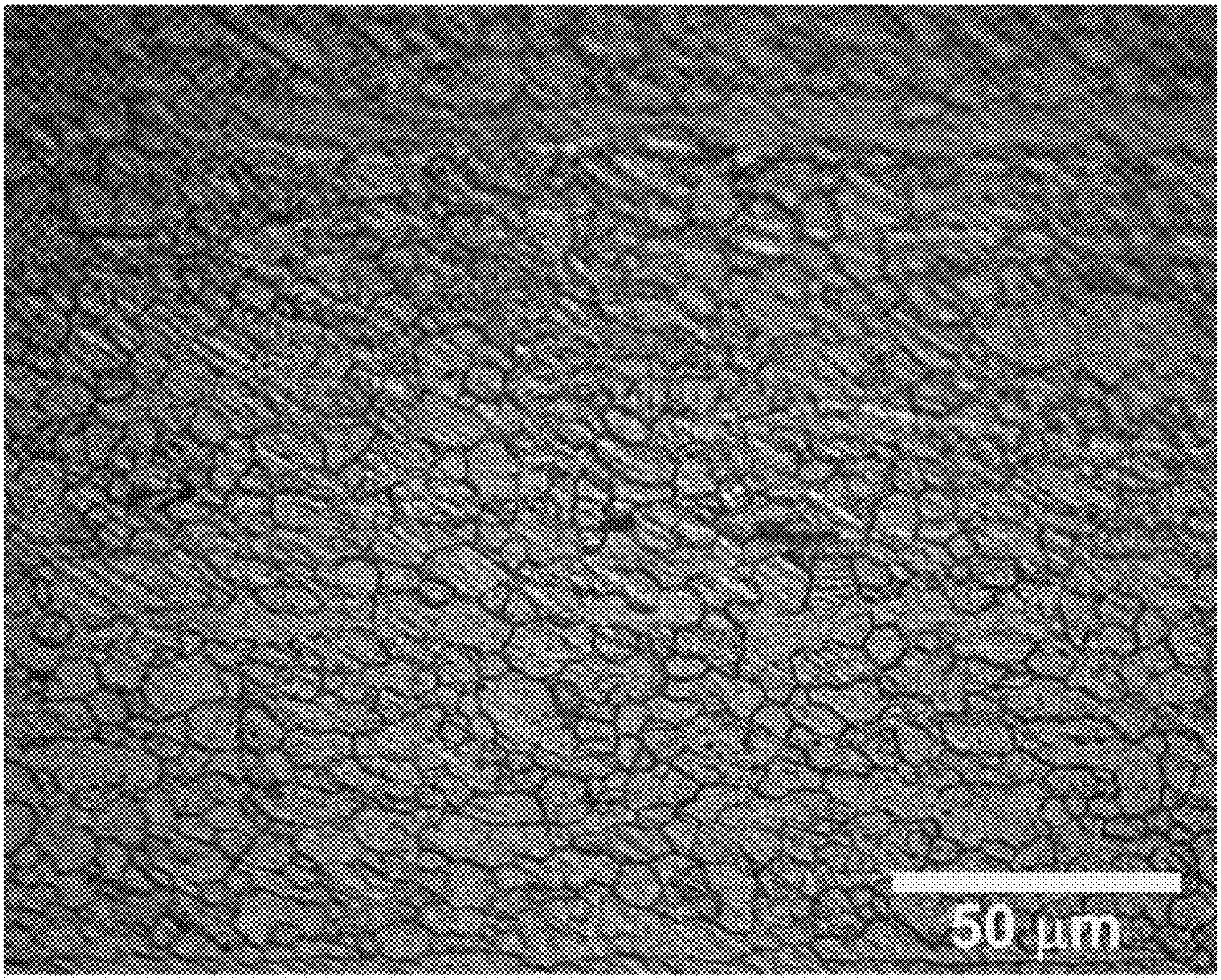


Figure 6

MAGNESIUM ALLOYS AND METHODS OF MAKING AND USE THEREOF

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority to U.S. Provisional Application No. 63/391,396 filed Jul. 22, 2022, which is hereby incorporated herein by reference in its entirety.

STATEMENT OF GOVERNMENT SUPPORT

[0002] This invention was made with government support under grant/contract number DE-SC0020806 awarded by the U.S. Department of Energy. The government has certain rights in the invention.

BACKGROUND

[0003] Magnesium (Mg), the lightest structural metal, and its alloys with high specific strength and low density are promising lightweight materials for industrial applications in automotive, aerospace, and electronic sectors. However, compared to commercial aluminum alloys and steels, there are only limited applications of Mg alloys owing to their low strength, poor ductility, and poor formability at room temperature. Thus, there is an urgent need to improve the mechanical performance of Mg extrusion alloys at room temperature, especially for high-volume industrial applications such as the automotive market. The compositions, methods, and systems discussed herein addresses these and other needs.

SUMMARY

[0004] In accordance with the purposes of the disclosed compositions, methods, and systems as embodied and broadly described herein, the disclosed subject matter relates to magnesium alloys and methods of making and use thereof.

[0005] For example, disclosed herein are magnesium alloys comprising: from 0 to 1.5 wt. % Zn; from 0 to 1.5 wt. % Al; less than 0.2 wt. % Ca; from 0.2 to 0.4 wt. % Ce; from 0.1 to 0.8 wt. % Mn; and the balance comprising Mg.

[0006] In some examples, the magnesium alloy comprises less than 1 wt. % Zn. In some examples, the magnesium alloy comprises less than 1 wt. % Al. In some examples, the magnesium alloy comprises from 0 to 0.15 wt. % Ca. In some examples, the magnesium alloy comprises from 0 to 0.1 wt. % Ca. In some examples, the magnesium alloy is substantially free of Ca. In some examples, the magnesium alloy comprises 0.2 wt. % Ce. In some examples, the magnesium alloy comprises 0.4 wt. % Mn.

[0007] In some examples, the magnesium alloy comprises from 0 to 1.5 wt. % Zn, from 0 to 1.5 wt. % Al, less than 0.2 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg. In some examples, the magnesium alloy comprises less than 1 wt. % Zn, from 0 to 1.5 wt. % Al, less than 0.2 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg. In some examples, the magnesium alloy comprises from 0 to 1.5 wt. % Zn, less than 1 wt. % Al, less than 0.2 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg. In some examples, the magnesium alloy comprises less than 1 wt. % Zn, less than 1 wt. % Al, less than 0.2 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg. In some examples, the magnesium alloy comprises less than 1 wt. % Zn, less than 1 wt. % Al, from 0 to 0.15 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg. In some examples, the magnesium alloy comprises less than 1 wt. % Zn, less than 1 wt. % Al, from 0 to 0.1 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg. In some examples, the magnesium alloy comprises less than 1 wt. % Zn, less than 1 wt. % Al, 0 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg.

[0008] In some examples, the Zn, Al, Ca, Ce, and Mn, when present, are substantially dissolved in the magnesium alloy. In some examples, the magnesium alloy is microalloyed.

[0009] In some examples, the magnesium alloy has a high strength. In some examples, the magnesium alloy has a yield strength of 20 ksi or more, 25 ksi or more, 30 ksi or more, 35 ksi or more, 40 ksi or more, or 45 ksi or more.

[0010] In some examples, the magnesium alloy has an ultimate tensile strength of 20 ksi or more, 25 ksi or more, 30 ksi or more, 35 ksi or more, 40 ksi or more, or 45 ksi or more.

[0011] In some examples, the magnesium alloy has a high ductility.

[0012] In some examples, the magnesium alloy has an elongation to failure of 10% or more, 15% or more, 20% or more, 25% or more, or 30% or more.

[0013] In some examples, the magnesium alloy is formable at room temperature.

[0014] In some examples, the magnesium alloy has a solidus temperature of from 500° C. to 625° C.

[0015] In some examples, the magnesium alloy exhibits substantially no incipient melting when extruded with a ram speed of from 1.00 to 10.00 ipm.

[0016] In some examples, the magnesium alloy is substantially free of a Mg_2Ca phase, an AlCaMg phase, an Al_2Ca phase, a $Ca_2Mg_6Zn_3$ phase, or a combination thereof. In some examples, the magnesium alloy is substantially free of a Mg_2Ca phase.

[0017] Also disclosed herein are objects comprising any of the magnesium alloys described herein. Also disclosed herein are sheets comprising any of the magnesium alloys described herein. Also disclosed herein are articles of manufacture comprising any of the magnesium alloys, objects, or sheets disclosed herein.

[0018] Also disclosed herein are methods of use of any of the magnesium alloys, objects, sheets, or articles of manufacture described herein, the methods comprising using the magnesium alloy, the object, or the sheet in an automotive, aerospace, or electronic application.

[0019] Also disclosed herein are methods of making a magnesium alloy based object comprising any of the magnesium alloys described herein, the methods comprising: heating an object comprising a preliminary magnesium alloy at a first temperature for a first amount of time; wherein the preliminary magnesium alloy comprises a first intermetallic phase having a first melting temperature and an alloy phase having a solidus temperature; wherein the melting temperature of the first intermetallic phase is lower than the solidus temperature of the alloy phase; wherein the first temperature is above the melting temperature of the first intermetallic phase and below the solidus temperature of the alloy phase; thereby substantially dissolving the first intermetallic phase into the alloy phase.

[0020] In some examples, the preliminary magnesium alloy further comprises: a second intermetallic phase having a second melting temperature; wherein the first melting temperature (e.g., of the first intermetallic phase) is lower than the second melting temperature (e.g., of the second intermetallic phase), and the solidus temperature of the alloy phase; wherein the second melting temperature (e.g., of the second intermetallic phase) is lower than the solidus temperature of the alloy phase; wherein the first temperature is above the first melting temperature (e.g., of the first intermetallic phase), below the second melting temperature (e.g., of the second intermetallic phase), and below the solidus temperature of the alloy phase; such that heating the object comprising the preliminary magnesium alloy at the first temperature for the first amount of time thereby substantially dissolves the first intermetallic phase into the alloy phase to form an object comprising a first intermediate magnesium alloy, the first intermediate magnesium alloy comprising the second intermetallic phase and the alloy phase; and wherein the method further comprises: heating the object comprising the first intermediate magnesium alloy at a second temperature for a second amount of time; wherein the second temperature is above the second melting temperature (e.g., of the second intermetallic phase) and below the solidus temperature of the alloy phase; thereby substantially dissolving the second intermetallic phase into the alloy phase.

[0021] In some examples, the preliminary magnesium alloy further comprises: a third intermetallic phase having a third melting temperature; wherein the first melting temperature (e.g., of the first intermetallic phase) is lower than the second melting temperature (e.g., of the second intermetallic phase), the third melting temperature (e.g., of the third intermetallic phase), and the solidus temperature of the alloy phase; wherein the second melting temperature (e.g., of the second intermetallic phase) is lower than the third melting temperature (e.g., of the third intermetallic phase) and the solidus temperature of the alloy phase; wherein the third melting temperature (e.g., of the third intermetallic phase) is lower than the solidus temperature of the alloy phase; wherein the first temperature is above the first melting temperature (e.g., of the first intermetallic phase), below the second melting temperature (e.g., of the second intermetallic phase), below the third melting temperature (e.g., of the third intermetallic phase), and below the solidus temperature of the alloy phase; and wherein the second temperature is above the second melting temperature (e.g., of the second intermetallic phase), below the third melting temperature (e.g., of the third intermetallic phase), and below the solidus temperature of the alloy phase; such that: heating the object comprising the preliminary magnesium alloy at the first temperature for the first amount of time thereby substantially dissolves the first intermetallic phase into the alloy phase to form an object comprising a first intermediate magnesium alloy, the first intermediate magnesium alloy comprising the second intermetallic phase, the third intermetallic phase, and the alloy phase; and heating the object comprising the first intermediate magnesium alloy at the second temperature for the second amount of time thereby substantially dissolves the second intermetallic phase into the alloy phase to form an object comprising a second intermediate magnesium alloy, the second intermediate magnesium alloy comprising the third intermetallic phase and the alloy phase; and wherein the method further comprises: heating the object comprising the second intermediate magnesium alloy at a third temperature for a third amount of time; wherein the third temperature is above the melting temperature of the third intermetallic phase; thereby substantially dissolving the third intermetallic phase into the alloy phase.

[0022] In some examples, the first temperature is from 10° C. to 200° C. above the first melting temperature (e.g., of the first intermetallic phase). In some examples, the first temperature is from 200° C. to 375° C. In some examples, the first temperature is from 350° C. to 375° C. In some examples, the first temperature is 360° C.

[0023] In some examples, the first amount of time is from 1 hour to 24 hours, or from 4 hours to 8 hours.

[0024] In some examples, the second temperature is from 10° C. to 120° C. above the melting temperature of the second intermetallic phase. In some examples, the second temperature is from 375° C. to 450° C. In some examples, the second temperature is from 430° C. to 450° C. In some examples, the second temperature is 440° C.

[0025] In some examples, the second amount of time is from 1 hour to 48 hours, or from 22 hours to 26 hours.

[0026] In some examples, the third temperature is from 10° C. to 50° C. above the melting temperature of the third intermetallic phase. In some examples, the third temperature is from 450° C. to 500° C. In some examples, the third temperature is from 460° C. to 500° C. In some examples, the third temperature is 480° C.

[0027] In some examples, the third amount of time is from 0.1 hours to 6 hours, 0.5 hours to 1.5 hours, or from 2.5 hours to 3.5 hours.

[0028] In some examples, the methods further comprise determining the first temperature, the first amount of time, the second temperature, the second amount of time, the third temperature, the third amount of time, or a combination thereof.

[0029] In some examples, the first intermetallic phase comprises $Ca_2Mg_6Zn_3$. In some examples, the second intermetallic phase comprises Al_2Ca. In some examples, the third intermetallic phase comprises AlCaMg.

[0030] In some examples, the magnesium alloy based object comprises a substantially homogeneous matrix comprising the alloy phase.

[0031] In some examples, the methods further comprise thermomechanically treating the magnesium alloy based object by heating the magnesium alloy based object at a fourth temperature for a fourth amount of time and, subsequently, mechanically treating the magnesium alloy based object.

[0032] In some examples, the fourth temperature is above room temperature and below the solidus temperature. In some examples, the fourth temperature is from 10° C. to 250° C. below the solidus temperature. In some examples, the fourth temperature is from 275° C. to 525° C.

[0033] In some examples, the fourth amount of time is from 1 minute to 1 hour.

[0034] In some examples, the methods further comprise determining the fourth temperature and/or the fourth amount of time.

[0035] In some examples, mechanically treating the magnesium alloy based object comprises rolling the magnesium alloy based object. In some examples, the magnesium alloy based object has an average thickness and rolling the magnesium alloy based object reduces the average thickness of the magnesium alloy based object.

[0036] In some examples, mechanically treating the magnesium alloy based object comprises extrusion and/or forging. In some examples, mechanically treating the magnesium alloy based object comprises extrusion. In some examples, the extrusion uses a ram speed of from 1.00 to 10.00 ipm.

[0037] In some examples, the methods further comprise repeating the thermomechanical treatment.

[0038] In some examples, the magnesium alloy based object exhibits improved mechanical properties after thermomechanical treatment.

[0039] In some examples, the methods further comprise casting the object comprising the preliminary magnesium alloy.

[0040] In some examples, the methods further comprise determining the composition of the preliminary magnesium alloy and/or the magnesium alloy.

[0041] In some examples, the methods further comprise determining the amount of Zn to include in the magnesium alloy, the amount of Al to include in the magnesium alloy, the amount of Ca to include in the magnesium alloy, the amount of Ce to include in the magnesium alloy, the amount of Mn to include in the magnesium alloy, or a combination thereof.

[0042] Also disclosed herein are magnesium alloy based objects made by any of the methods disclosed herein. In some examples, the magnesium alloy based object has a yield strength of 20 ksi or more, 25 ksi or more, 30 ksi or more, 35 ksi or more, 40 ksi or more, or 45 ksi or more. In some examples, the magnesium alloy has an ultimate tensile strength of 20 ksi or more, 25 ksi or more, 30 ksi or more, 35 ksi or more, 40 ksi or more, or 45 ksi or more. In some examples, the magnesium alloy has a high ductility. In some examples, the magnesium alloy an elongation to failure of 10% or more, 15% or more, 20% or more, 25% or more, or 30% or more. Also disclosed herein are methods of use of any of the magnesium alloy based objects disclosed herein, the methods comprising using the magnesium alloy based object in an automotive, aerospace, or electronic application. Also disclosed herein are articles of manufacture comprising any of the magnesium alloy based objects disclosed herein.

[0043] Additional advantages of the disclosed compositions, systems, and methods will be set forth in part in the description which follows, and in part will be obvious from the description. The advantages of the disclosed compositions, systems, and methods will be realized and attained by means of the elements and combinations particularly pointed out in the appended claims. It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the disclosed systems and methods, as claimed.

[0044] The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF THE FIGURES

[0045] The accompanying figures, which are incorporated in and constitute a part of this specification, illustrate several aspects of the disclosure, and together with the description, serve to explain the principles of the disclosure.

[0046] FIG. **1**. Age hardening results (Micro-Vickers HV) for samples X20349-2 aged from the as extruded (A.E.) condition as well as after heat treatment at 480° C./1 h/WQ (T4).

[0047] FIG. **2**. Equilibrium Phase fraction vs Temperature plot of ZAXEM11100.

[0048] FIG. **3**. Equilibrium Phase fraction vs Temperature plot of Ca modified ZAEM1100.

[0049] FIG. **4**. SEM micrograph of ZAXEM11100 composition.

[0050] FIG. **5**. SEM micrograph of Ca modified ZAEM1100 composition.

[0051] FIG. **6**. Image of bumper beam X22278-3, which had a very fine grain structure in the longitudinal direction.

DETAILED DESCRIPTION

[0052] The compositions, methods, and systems described herein may be understood more readily by reference to the following detailed description of specific aspects of the disclosed subject matter and the Examples included therein.

[0053] Before the present compositions, methods, and systems are disclosed and described, it is to be understood that the aspects described below are not limited to specific synthetic methods or specific reagents, as such may, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular aspects only and is not intended to be limiting.

[0054] Also, throughout this specification, various publications are referenced. The disclosures of these publications in their entireties are hereby incorporated by reference into this application in order to more fully describe the state of the art to which the disclosed matter pertains. The references disclosed are also individually and specifically incorporated by reference herein for the material contained in them that is discussed in the sentence in which the reference is relied upon.

General Definitions

[0055] In this specification and in the claims that follow, reference will be made to a number of terms, which shall be defined to have the following meanings.

[0056] Throughout the description and claims of this specification the word "comprise" and other forms of the word, such as "comprising" and "comprises," means including but not limited to, and is not intended to exclude, for example, other additives, components, integers, or steps.

[0057] As used in the description and the appended claims, the singular forms "a," "an," and "the" include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to "a composition" includes mixtures of two or more such compositions, reference to "an agent" includes mixtures of two or more such agents, reference to "the component" includes mixtures of two or more such components, and the like.

[0058] "Optional" or "optionally" means that the subsequently described event or circumstance can or cannot occur, and that the description includes instances where the event or circumstance occurs and instances where it does not.

[0059] Ranges can be expressed herein as from "about" one particular value, and/or to "about" another particular value. By "about" is meant within 5% of the value, e.g., within 4, 3, 2, or 1% of the value. When such a range is expressed, another aspect includes from the one particular value and/or to the other particular value. Similarly, when values are expressed as approximations, by use of the antecedent "about," it will be understood that the particular value forms another aspect. It will be further understood that the endpoints of each of the ranges are significant both in relation to the other endpoint, and independently of the other endpoint.

[0060] Values can be expressed herein as an "average" value. "Average" generally refers to the statistical mean value.

[0061] By "substantially" is meant within 5%, e.g., within 4%, 3%, 2%, or 1%.

[0062] "Exemplary" means "an example of" and is not intended to convey an indication of a preferred or ideal embodiment. "Such as" is not used in a restrictive sense, but for explanatory purposes.

[0063] It is understood that throughout this specification the identifiers "first" and "second" are used solely to aid in distinguishing the various components and steps of the disclosed subject matter. The identifiers "first" and "second" are not intended to imply any particular order, amount, preference, or importance to the components or steps modified by these terms.

[0064] References in the specification and concluding claims to parts by weight of a particular element or component in a composition denotes the weight relationship between the element or component and any other elements or components in the composition or article for which a part by weight is expressed. Thus, in a compound containing 2 parts by weight of component X and 5 parts by weight component Y, X and Y are present at a weight ratio of 2:5, and are present in such ratio regardless of whether additional components are contained in the compound.

[0065] A weight percent (wt. %) of a component, unless specifically stated to the contrary, is based on the total weight of the formulation or composition in which the component is included.

[0066] The term "or combinations thereof" as used herein refers to all permutations and combinations of the listed items preceding the term. For example, "A, B, C, or combinations thereof" is intended to include at least one of: A, B, C, AB, AC, BC, or ABC, and if order is important in a particular context, also BA, CA, CB, CBA, BCA, ACB, BAC, or CAB. Continuing with this example, expressly included are combinations that contain repeats of one or more item or term, such as BB, AAA, AB, BBC, AAABCCCC, CBBAAA, CABABB, and so forth. The skilled artisan will understand that typically there is no limit on the number of items or terms in any combination, unless otherwise apparent from the context.

Compositions and Methods

[0067] Disclosed herein are magnesium alloys. The magnesium alloys comprise Mg and optionally further comprise Zn, Al, Ca, Ce, Mn, or a combination thereof. The Zn, Al, Ca, Ce, and Mn, when present, can, in some examples, be substantially dissolved in the magnesium alloy. In some examples, the magnesium alloy is microalloyed. The magnesium alloy can, for example, comprise: from 0 to 1.5 wt. % Zn, from 0 to 1.5 wt. % Al, less than 0.2 wt. % Ca, from to 0.4 wt. % Ce, from 0.1 to 0.8 wt. % Mn, and the balance comprising Mg.

[0068] The magnesium alloy can, for example, comprise 0 wt. % or more Zn (e.g., 0.1 wt. % or more, 0.2 wt. % or more, 0.3 wt. % or more, 0.4 wt. % or more, 0.5 wt. % or more, 0.6 wt. % or more, 0.7 wt. % or more, 0.8 wt. % or more, 0.9 wt. % or more, 1.0 wt. % or more, 1.1 wt. % or more, 1.2 wt. % or more, 1.3 wt. % or more, or 1.4 wt. % or more). In some examples, the magnesium alloy can comprise 1.5 wt. % or less Zn (e.g., 1.4 wt. % or less, 1.3 wt. % or less, 1.2 wt. % or less, 1.1 wt. % or less, 1.0 wt. % or less, 0.9 wt. % or less, 0.8 wt. % or less, 0.7 wt. % or less, 0.6 wt. % or less, 0.5 wt. % or less, 0.4 wt. % or less, 0.3 wt. % or less, 0.2 wt. % or less, or 0.1 wt. % or less). The amount of Zn in the magnesium alloy can range from any of the minimum values described above to any of the maximum values described above. For example, the magnesium alloy can comprise from 0 to 1.5 wt. % Zn (e.g., from 0 wt. % to 0.75 wt. %, from 0.75 wt. % to 1.5 wt. %, from 0 wt. % to 0.5 wt. %, from 0.5 wt. % to 1 wt. %, from 1 wt. % to 1.5 wt. %, from 0 wt. % to 1.4 wt. %, from 0.1 wt. % to 1.5 wt. %, from 0.1 wt. % to 1.4 wt. %, from 0 wt. % to 1 wt. %, or from 0.1 wt. % to 1 wt. %). In some examples, the magnesium alloy can comprise less than 1 wt. % Zn.

[0069] The magnesium alloy can, for example, comprise 0 wt. % or more Al (e.g., 0.1 wt. % or more, 0.2 wt. % or more, 0.3 wt. % or more, 0.4 wt. % or more, 0.5 wt. % or more, 0.6 wt. % or more, 0.7 wt. % or more, 0.8 wt. % or more, 0.9 wt. % or more, 1.0 wt. % or more, 1.1 wt. % or more, 1.2 wt. % or more, 1.3 wt. % or more, or 1.4 wt. % or more). In some examples, the magnesium alloy can comprise 1.5 wt. % or less Al (e.g., 1.4 wt. % or less, 1.3 wt. % or less, 1.2 wt. % or less, 1.1 wt. % or less, 1.0 wt. % or less, 0.9 wt. % or less, 0.8 wt. % or less, 0.7 wt. % or less, 0.6 wt. % or less, 0.5 wt. % or less, 0.4 wt. % or less, 0.3 wt. % or less, 0.2 wt. % or less, or 0.1 wt. % or less). The amount of Al in the magnesium alloy can range from any of the minimum values described above to any of the maximum values described above. For example, the magnesium alloy can comprise from 0 to 1.5 wt. % Al (e.g., from 0 wt. % to 0.75 wt. %, from 0.75 wt. % to 1.5 wt. %, from 0 wt. % to 0.5 wt. %, from 0.5 wt. % to 1 wt. %, from 1 wt. % to 1.5 wt. %, from 0 wt. % to 1.4 wt. %, from 0.1 wt. % to 1.5 wt. %, from 0.1 wt. % to 1.4 wt. %, from 0 wt. % to 1 wt. %, or from 0.1 wt. % to 1 wt. %). In some examples, the magnesium alloy can comprise less than 1 wt. % Al.

[0070] The magnesium alloy can, for example, comprise less than 0 2 wt. % Ca (e.g., 0.19 wt. % or less, 0.18 wt. % or less, 0.17 wt. % or less, 0.16 wt. % or less, 0.15 wt. % or less, 0.14 wt. % or less, 0.13 wt. % or less, 0.12 wt. % or less, 0.11 wt. % or less, 0.10 wt. % or less, 0.09 wt. % or less, 0.08 wt. % or less, 0.07 wt. % or less, 0.06 wt. % or less, 0.05 wt. % or less, 0.04 wt. % or less, 0.03 wt. % or less, 0.02 wt. % or less, or 0.01 wt. % or less). In some examples, the magnesium alloy can comprise 0 wt. % or more Ca (e.g., 0.01 wt. % or more, 0.02 wt. % or more, 0.03 wt. % or more, 0.04 wt. % or more, 0.05 wt. % or more, 0.06 wt. % or more, 0.07 wt. % or more, 0.08 wt. % or more, 0.09 wt. % or more, 0.10 wt. % or more, 0.11 wt. % or more, 0.12 wt. % or more, 0.13 wt. % or more, 0.14 wt. % or more, 0.15 wt. % or more, 0.16 wt. % or more, 0.17 wt. % or more, 0.18 wt. % or more, or 0.19 wt. % or more). The amount of Ca in the magnesium alloy can range from any of the minimum values described above to any of the maximum values described above. For example, the magnesium alloy can comprise from 0 to less than 0.2 wt. % Ca (e.g., from 0 wt. % to 0.1 wt. %, from 0.1

wt. % to less than 0.2 wt. %, from 0.01 wt. % to less than 0.2 wt. %, from 0 wt. % to 0.19 wt. %, from 0 wt. % to 0.15 wt. %, from 0 wt. % to 0.1 wt. %, or from 0 wt. % to 0.05 wt. %). In some examples, the magnesium alloy is substantially free of Ca.

[0071] The magnesium alloy can, for example, comprise 0.2 wt. % or more Ce (e.g., 0.25 wt. % or more, 0.3 wt. % or more, or 0.35 wt. % or more). In some examples, the magnesium alloy can comprise 0.4 wt. % or less Ce (e.g., 0.35 wt. % or less, 0.3 wt. % or less, or 0.25 wt. % or less). The amount of Ce in the magnesium alloy can range from any of the minimum values described above to any of the maximum values described above. For example, the magnesium alloy can comprise from 0.2 to 0.4 wt. % Ce (e.g., from 0.2 wt. % to 0.35 wt. %, from 0.2 wt. % to 0.3 wt. %, or from 0.2 wt. % to 0.25 wt. %). In some examples, the magnesium alloy can comprise 0.2 wt. % Ce.

[0072] The magnesium alloy can, for example, comprise 0.1 wt. % or more Mn (e.g., 0.15 wt. % or more, 0.2 wt. % or more, 0.25 wt. % or more, 0.3 wt. % or more, 0.35 wt. % or more, 0.4 wt. % or more, 0.45 wt. % or more, 0.5 wt. % or more, 0.55 wt. % or more, 0.6 wt. % or more, 0.65 wt. % or more, or 0.7 wt. % or more). In some examples, the magnesium alloy can comprise 0.8 wt. % or less Mn (e.g., 0.75 wt. % or less, 0.7 wt. % or less, 0.65 wt. % or less, 0.6 wt. % or less, 0.55 wt. % or less, 0.5 wt. % or less, 0.45 wt. % or less, 0.4 wt. % or less, 0.35 wt. % or less, 0.3 wt. % or less, 0.25 wt. % or less, 0.2 wt. % or less, or 0.15 wt. % or less). The amount of Mn in the magnesium alloy can range from any of the minimum values described above to any of the maximum values described above. For example, the magnesium alloy can comprise from 0.1 to 0.8 wt. % Mn (e.g., from 0.15 wt. % to 0.75 wt. %, from 0.2 wt. % to 0.6 wt. %, or from 0.3 wt. % to 0.5 wt. %). In some examples, the magnesium alloy comprises 0.4 wt. % Mn.

[0073] The magnesium alloy, can, for example, comprise from 0 to 1.5 wt. % Zn, from 0 to 1.5 wt. % Al, less than 0.2 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg. In some examples, the magnesium alloy comprises less than 1 wt. % Zn, from 0 to 1.5 wt. % Al, less than 0.2 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg. In some examples, the magnesium alloy comprises from 0 to 1.5 wt. % Zn, less than 1 wt. % Al, less than 0.2 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg. In some examples, the magnesium alloy comprises less than 1 wt. % Zn, less than 1 wt. % Al, less than 0.2 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg. In some examples, the magnesium alloy comprises less than 1 wt. % Zn, less than 1 wt. % Al, from 0 to 0.15 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg. In some examples, the magnesium alloy comprises less than 1 wt. % Zn, less than 1 wt. % Al, from 0 to 0.1 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg. In some examples, the magnesium alloy comprises less than 1 wt. % Zn, less than 1 wt. % Al, 0 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg.

[0074] The magnesium alloys described herein can, for example, have a high strength. For example, the magnesium alloy can have a yield strength of 20 kilopound force per square inch (ksi) or more (e.g., 21 ksi or more, 22 ksi or more, 23 ksi or more, 24 ksi or more, 25 ksi or more, 26 ksi or more, 27 ksi or more, 28 ksi or more, 29 ksi or more, 30 ksi or more, 31 ksi or more, 32 ksi or more, 33 ksi or more, 34 ksi or more, 35 ksi or more, 36 ksi or more, 37 ksi or more, 38 ksi or more, 39 ksi or more, 40 ksi or more, 41 ksi or more, 42 ksi or more, 43 ksi or more, 44 ksi or more, or 45 ksi or more).

[0075] In some examples, the magnesium alloy can have an ultimate tensile strength of 20 kilopound force per square inch (ksi) or more (e.g., 21 ksi or more, 22 ksi or more, 23 ksi or more, 24 ksi or more, 25 ksi or more, 26 ksi or more, 27 ksi or more, 28 ksi or more, 29 ksi or more, 30 ksi or more, 31 ksi or more, 32 ksi or more, 33 ksi or more, 34 ksi or more, 35 ksi or more, 36 ksi or more, 37 ksi or more, 38 ksi or more, 39 ksi or more, 40 ksi or more, 41 ksi or more, 42 ksi or more, 43 ksi or more, 44 ksi or more, or 45 ksi or more).

[0076] In some examples, the magnesium alloy has a high ductility.

[0077] In some examples, the magnesium alloy can have an elongation to failure of 15% or more (e.g., 11% or more, 12% or more, 13% or more, 14% or more, 15% or more, 16% or more, 17% or more, 18% or more, 19% or more, 20% or more, 21% or more, 22% or more, 23% or more, 24% or more, 25% or more, 26% or more, 27% or more, 28% or more, 29% or more, or 30% or more).

[0078] In some examples, the magnesium alloy can have an elongation to failure of 15% or more (e.g., 11% or more, 12% or more, 13% or more, 14% or more, 15% or more, 16% or more, 17% or more, 18% or more, 19% or more, 20% or more, 21% or more, 22% or more, 23% or more, 24% or more, 25% or more, 26% or more, 27% or more, 28% or more, 29% or more, or 30% or more) at a low strain rate (e.g., a strain rate of from 1×10^{-4} per second (s^{-1}) to 1×10^{-3} s^{-1}).

[0079] In some examples, the magnesium alloy can have an elongation to failure of 15% or more (e.g., 11% or more, 12% or more, 13% or more, 14% or more, 15% or more, 16% or more, 17% or more, 18% or more, 19% or more, 20% or more, 21% or more, 22% or more, 23% or more, 24% or more, 25% or more, 26% or more, 27% or more, 28% or more, 29% or more, or 30% or more) at a high strain rate (e.g., a strain rate of from 100 per second (s^{-1}) to 200 s^{-1}). In some examples, the magnesium alloy can have a 10-15% increase (e.g., 10% or more, or 15% or less) in a property (e.g., yield strength, ultimate tensile strength, elongation to failure, or a combination thereof) at intermediate strain rates (e.g., a strain rate of from 1×10^{-3} per second (s^{-1}) to 100 s^{-1}) relative to the same property at a low strain rate.

[0080] In some examples, the strength of the magnesium alloy can have a positive strain rate dependence.

[0081] The magnesium alloys described herein can be formable at room temperature. As used herein, room temperature is meant to include temperatures of 20-30° C.

[0082] The magnesium alloy can, for example, have a solidus temperature of 500° C. or more (e.g., 510° C. or more, 520° C. or more, 530° C. or more, 540° C. or more, 550° C. or more, 560° C. or more, 570° C. or more, 580° C. or more, 590° C. or more, 600° C. or more, 610° C. or more, or 620° C. or more). In some examples, the magnesium alloy can have a solidus temperature of 625° C. or less (e.g., 620° C. or less, 610° C. or less, 600° C. or less, 590° C. or less, 580° C. or less, 570° C. or less, 560° C. or less, 550° C. or less, 540° C. or less, 530° C. or less, 520° C. or less, or 510° C. or less). The solidus temperature of the magnesium alloy can range from any of the minimum values described above to any of the maximum values described above. For example, the magnesium alloy can have a solidus temperature of from 500° C. to 625° C. (e.g., from 500° C. to 560° C., from 560° C. to 625° C., from 500° C. to 525° C., from 525° C. to 550° C., from 550° C. to 575° C., from 575° C. to 600° C., from 600° C. to 625° C., from 500° C. to 600° C., from 500° C. to 575° C., from 500° C. to 550° C., from 525° C. to 625° C., from 550° C. to 625° C., from 575° C. to 625° C., from 600° C. to 625° C., or from 525° C. to 600° C.).

[0083] In some examples, the magnesium alloy exhibits substantially no incipient melting when extruded with a ram speed of 1.00 inches per minute (ipm) or more (e.g., 1.50 ipm or more, 2.00 ipm or more, 2.50 ipm or more, 3.00 ipm or more, 3.50 ipm or more, 4.00 ipm or more, 4.50 ipm or more, 5.00 ipm or more, 5.50 ipm or more, 6.00 ipm or more, 6.50 ipm or more, 7.00 ipm or more, 7.50 ipm or more, 8.00 ipm or more, 8.50 ipm or more, 9.00 ipm or more, or 9.50 ipm or more). In some examples, the magnesium alloy exhibits substantially no incipient melting when extruded with a ram speed of 10.00 ipm or less (e.g., 9.50 ipm or less, 9.00 ipm or less, 8.50 ipm or less, 8.00 ipm or less, 7.50 ipm or less, 7.00 ipm or less, 6.50 ipm or less, 6.00 ipm or less, 5.50 ipm or less, 5.00 ipm or less, 4.50 ipm or less, 4.00 ipm or less, 3.50 ipm or less, 3.00 ipm or less, 2.50 ipm or less, 2.00 ipm or less, or 1.50 ipm or less). The ram speed can range from any of the minimum values described above to any of the maximum values described above. For example, the magnesium alloy can exhibit substantially no incipient melting when extruded with a ram speed of from 1.00 to 10.00 ipm (e.g., from 1.00 to 5.00, from 5.00 to 10.00, from 1.00 to 2.50, from 2.50 to 5.00, from 5.00 to 7.50, from 7.50 to 10.00, from 2.00 to 10.00, from 3.00 ipm to 10.00 ipm, from 4.00 ipm to 10.00 ipm, from 6.00 ipm to 10.00 ipm, from 7.00 ipm to 10.00 ipm, from 8.00 ipm to 10.00 ipm, from 9.00 ipm to 10.00 ipm, from 1.00 ipm to 9.00 ipm, from 1.00 ipm to 8.00 ipm, from 1.00 ipm to 7.00 ipm, from 1.00 ipm to 6.00 ipm, from 1.00 ipm to 4.00 ipm, from 1.00 ipm to 3.00 ipm, from 1.00 ipm to 2.00 ipm, from 2.00 ipm to 9.00 ipm, or from 3.00 ipm to 8.00 ipm).

[0084] As used herein, substantially no incipient melting of the magnesium alloy means that 5% or less of the alloy phase melts (e.g., 4.5% or less, 4% or less, 3.5% or less, 3% or less, 2.5% or less, 2% or less, 1.5% or less, 1% or less, 0.5% or less, or 0.1% or less).

[0085] In some examples, the magnesium alloy is substantially free of a Mg_2Ca phase, an AlCaMg phase, an Al_2Ca phase, a $Ca_2Mg_6Zn_3$ phase, or a combination thereof. In some examples, the magnesium alloy is the magnesium alloy is substantially free of a Mg_2Ca phase.

[0086] Also described herein are objects, sheets, and articles of manufacture comprising any of the magnesium alloys described herein. Also described herein are methods of use of the magnesium alloys, objects, sheets, and articles of manufacture described herein, the methods comprising using the magnesium alloys, objects, sheets, or articles of manufacture in an automotive, aerospace, or electronic application. Also described herein are methods of use of the magnesium alloys described herein, the methods comprising using the magnesium alloys in plate, forging and extrusion applications, e.g., for a variety of industries.

[0087] Also described herein are methods of making a magnesium alloy based object comprising any of the magnesium alloys described herein, the method comprising heating an object comprising a preliminary magnesium alloy. The term "preliminary magnesium alloy" is used herein to refer to a magnesium alloy before it has undergone a heat treatment as disclosed herein. It is not meant to imply that the preliminary magnesium alloy is not yet a magnesium alloy (e.g., a metal element). Rather, a preliminary magnesium alloy is meant to refer to a magnesium alloy that has intermetallic phases present (e.g., 2 or more intermetallic phases, 3 or more intermetallic phases, etc.).

[0088] In some examples, the preliminary magnesium alloy comprises a first intermetallic phase and an alloy phase. The first intermetallic phase has a first melting temperature and the alloy phase has a solidus temperature; wherein the first melting temperature (e.g., of the first intermetallic phase) is lower than the solidus temperature of the alloy phase.

[0089] "Phase," as used herein, generally refers to a region of a material which is a distinct and physically separate portion of a heterogeneous system. The term "phase" does not imply that the material making up a phase is a chemically pure substance, but merely that the chemical and/or physical properties of the material making up the phase are essentially uniform throughout the material, and that these chemical and/or physical properties differ significantly from the chemical and/or physical properties of another phase within the material. Examples of physical properties include density, thickness, aspect ratio, specific surface area, porosity, dimensionality, and melting temperature. Examples of chemical properties include chemical composition.

[0090] In some examples, the first intermetallic phase can comprise a plurality of intermetallic compounds wherein each of the plurality of intermetallic compounds have a melting temperature that is distinct the solidus temperature of the alloy phase. In some examples, the first intermetallic phase can comprise a plurality of intermetallic compounds wherein each of the plurality of intermetallic compounds have a melting temperature that is substantially the same.

[0091] The methods disclosed herein can comprise heating an object comprising a preliminary magnesium alloy at a first temperature for a first amount of time; wherein the first temperature is above the first melting temperature (e.g., of the first intermetallic phase) and below the solidus temperature of the alloy phase.

[0092] In some examples, the first intermetallic phase can comprise $Ca_2Mg_6Zn_3$.

[0093] The first temperature can, for example, be above the melting temperature of the first intermetallic phase by 10° C. or more (e.g., 20° C. or more, 30° C. or more, 40° C. or more, 50° C. or more, 60° C. or more, 70° C. or more, 80° C. or more, 90° C. or more, 100° C. or more, 110° C. or more, 120° C. or more, 130° C. or more, 140° C. or more, 150° C. or more, 160° C. or more, 170° C. or more, or 180° C. or more). In some examples, the first temperature can be above the melting temperature of the first intermetallic phase by 200° C. or less (e.g., 190° C. or less, 180° C. or less, 170° C. or less, 160° C. or less, 150° C. or less, 140° C. or less, 130° C. or less, 120° C. or less, 110° C. or less, 100° C. or less, 90° C. or less, 80° C. or less, 70° C. or less, 60° C. or less, 50° C. or less, 40° C. or less, or 30° C. or less). The first temperature can be above the melting temperature of the first intermetallic phase by an amount that ranges from any of the minimum values described above to any of the maximum values described above. For example, the first temperature can be from to 200° C. above the melting temperature of the first intermetallic phase (e.g., from 10° C. to 100° C., from 100° C. to 200° C., from 10° C. to 50° C., from 50° C. to 100° C., from 100° C. to 150° C., from 150° C. to 200° C., from 10° C. to 190° C., from 20° C. to 200° C., or from 20° C. to 190° C.).

[0094] In some examples, the first temperature can be 200° C. or more (e.g., 205° C. or more, 210° C. or more, 215° C. or more, 220° C. or more, 225° C. or more, 230° C. or more, 235° C. or more, 240° C. or more, 245° C. or more, 250° C. or more, 255° C. or more, 260° C. or more, 265° C. or more, 270° C. or more, 275° C. or more, 280° C. or more, 285° C. or more, 290° C. or more, 295° C. or more, 300° C. or more, 305° C. or more, 310° C. or more, 315° C. or more, 320° C. or more, 325° C. or more, 330° C. or more, 335° C. or more, 340° C. or more, 345° C. or more, 350° C. or more, 355° C. or more, 360° C. or more, 365° C. or more, or 370° C. or more). In some examples, the first temperature can be 375° C. or less (e.g., 370° C. or less, 365° C. or less, 360° C. or less, 355° C. or less, 350° C. or less, 345° C. or less, 340° C. or less, 335° C. or less, 330° C. or less, 325° C. or less, 320° C. or less, 315° C. or less, 310° C. or less, 305° C. or less, 300° C. or less, 295° C. or less, 290° C. or less, 285° C. or less, 280° C. or less, 275° C. or less, 270° C. or less, 265° C. or less, 260° C. or less, 255° C. or less, 250° C. or less, 245° C. or less, 240° C. or less, 235° C. or less, 230° C. or less, 225° C. or less, 220° C. or less, 215° C. or less, 210° C. or less, or 205° C. or less). The first temperature can range from any of the minimum values described above to any of the maximum values described above. For example, the first temperature can be from 200° C. to 375° C. (e.g., from 275° C. to 375° C., from 300° C. to 375° C., or from 350° C. to 375° C.). In some examples, the first temperature is 360° C.

[0095] The first amount of time can, for example, be 1 hour or more (e.g., 2 hours or more, 3 hours or more, 4 hours or more, 5 hours or more, 6 hours or more, 7 hours or more, 8 hours or more, 9 hours or more, 10 hours or more, 11 hours or more, 12 hours or more, 13 hours or more, 14 hours or more, 15 hours or more, 16 hours or more, 17 hours or more, 18 hours or more, 19 hours or more, 20 hours or more, 21 hours or more, 22 hours or more, or 23 hours or more). In some examples, the first amount of time can be 24 hours or less (e.g., 23 hours or less, 22 hours or less, 21 hours or less, 20 hours or less, 19 hours or less, 18 hours or less, 17 hours or less, 16 hours or less, 15 hours or less, 14 hours or less, 13 hours or less, 12 hours or less, 11 hours or less, 10 hours or less, 9 hours or less, 8 hours or less, 7 hours or less, 6 hours or less, 5 hours or less, 4 hours or less, or 3 hours or less). The first amount of time can range from any of the minimum values described above to any of the maximum values described above. For example, the first amount of time can be from 1 hour to 24 hours (e.g., from 1 hour to 12 hours, from 12 hours to 24 hours, from 1 hour to 6 hours, from 6 hours to 12 hours, from 12 hours to 18 hours, from 18 hours to 24 hours, from 1 hour to 18 hours, from 3 hours to 24 hours, from 2 hours to 20 hours, from 3 hours to 8 hours, from 4 hours to 16 hours, or from 4 hours to 8 hours).

[0096] The first temperature and/or the first amount of time can be selected in view of a variety of factors. For example, the first temperature and the first amount of time can be selected such that heating the object comprising the preliminary magnesium alloy at the first temperature for the first amount of time substantially dissolves the first intermetallic phase into the alloy phase. In some examples, the methods can further comprise determining the first temperature and/or the first amount of time at which to heat the object comprising the preliminary magnesium alloy to thereby substantially dissolve the first intermetallic phase into the alloy phase.

[0097] In some examples, the preliminary magnesium alloy further comprises a second intermetallic phase having a second melting temperature; wherein the first melting temperature (e.g., of the first intermetallic phase) is lower than the second melting temperature (e.g., of the second intermetallic phase), and the solidus temperature of the alloy phase; wherein the second melting temperature (e.g., of the second intermetallic phase) is lower than the solidus temperature of the alloy phase; and wherein the first temperature is above the first melting temperature (e.g., of the first intermetallic phase), below the second melting temperature (e.g., of the second intermetallic phase), and below the solidus temperature of the alloy phase; such that heating the object comprising the preliminary magnesium alloy at the first temperature for the first amount of time thereby substantially dissolves the first intermetallic phase into the alloy phase to form an object comprising a first intermediate magnesium alloy, the first intermediate magnesium alloy comprising the second intermetallic phase and the alloy phase.

[0098] In some examples, the methods further comprise heating the object comprising the first intermediate magnesium alloy at a second temperature for a second amount of time; wherein the second temperature is above the second melting temperature (e.g., of the second intermetallic phase) and below the solidus temperature of the alloy phase.

[0099] In some examples, the second intermetallic phase comprises Al_2Ca.

[0100] The second temperature can, for example, be above the melting temperature of the second intermetallic phase by 10° C. or more (e.g., 20° C. or more, 30° C. or more, 40° C. or more, 50° C. or more, 60° C. or more, 70° C. or more, 80° C. or more, 90° C. or more, or 100° C. or more). In some examples, the second temperature can be above the melting temperature of the second intermetallic phase by 120° C. or less (e.g., 110° C. or less, 100° C. or less, 90° C. or less, 80° C. or less, 70° C. or less, 60° C. or less, 50° C. or less, 40° C. or less, or 30° C. or less). The second temperature can be above the melting temperature of the second intermetallic phase by an amount that range from any of the minimum values described above to any of the maximum values described above. For example, the second temperature can be from 10° C. to 120° C. above the melting temperature of the second intermetallic phase (e.g., from 10° C. to 60° C., from 60° C. to 120° C., from 10° C. to 40° C., from 40° C. to 80° C. from 80° C. to 120° C., from 10° C. to 100° C., from 20° C. to 120° C., or from 20° C. to 100° C.).

[0101] In some examples, the second temperature can be 375° C. or more (e.g., 380° C. or more, 385° C. or more, 390° C. or more, 395° C. or more, 400° C. or more, 405° C. or more, 410° C. or more, 415° C. or more, 420° C. or more, 425° C. or more, 430° C. or more, 435° C. or more, 440° C. or more, or 445° C. or more). In some examples, the second temperature can be 450° C. or less (e.g., 445° C. or less, 440° C. or less, 435° C. or less, 430° C. or less, 425° C. or less, 420° C. or less, 415° C. or less, 410° C. or less, 405° C. or less, 400° C. or less, 395° C. or less, 390° C. or less, 385° C. or less, or 380° C. or less). The second temperature can range from any of the minimum values described above to any of the maximum values described above. For example, the second temperature can be from 375° C. to 450° C. (e.g., from 400° C. to 450° C., from 425° C. to 450° C., or from 430° C. to 450° C.). In some examples, the second temperature is 440° C.

[0102] The second amount of time can, for example, be 1 hour or more (e.g., 2 hours or more, 3 hours or more, 4 hours or more, 5 hours or more, 6 hours or more, 7 hours or more, 8 hours or more, 9 hours or more, 10 hours or more, 11 hours or more, 12 hours or more, 13 hours or more, 14 hours or more, 15 hours or more, 16 hours or more, 17 hours or more, 18 hours or more, 19 hours or more, 20 hours or more, 21 hours or more, 22 hours or more, 23 hours or more, 24 hours or more, 26 hours or more, 28 hours or more, 30 hours or more, 32 hours or more, 34 hours or more, 36 hours or more, 38 hours or more, 40 hours or more, 42 hours or more, 44 hours or more, or 46 hours or more). In some examples, the second amount of time can be 48 hours or less (e.g., 46 hours or less, 44 hours or less, 42 hours or less, 40 hours or less, 38 hours or less, 36 hours or less, 34 hours or less, 32 hours or less, 30 hours or less, 28 hours or less, 26 hours or less, 24 hours or less, 23 hours or less, 22 hours or less, 21 hours or less, 20 hours or less, 19 hours or less, 18 hours or less, 17 hours or less, 16 hours or less, 15 hours or less, 14 hours or less, 13 hours or less, 12 hours or less, 11 hours or less, 10 hours or less, 9 hours or less, 8 hours or less, 7 hours or less, 6 hours or less, 5 hours or less, 4 hours or less, or 3 hours or less). The second amount of time can range from any of the minimum values described above to any of the maximum values described above. For example, the second amount of time can be from 1 hour to 48 hours (e.g., from 1 hour to 24 hours, from 24 hours to 48 hours, from 1 hour to 12 hours, from 12 hours to 24 hours, from 24 hours to 36 hours, from 36 hours to 48 hours, from 2 hours to 46 hours, from 3 hours to 36 hours, from 12 hours to 30 hours, or from 22 hours to 26 hours).

[0103] The second temperature and/or the second amount of time can be selected in view of a variety of factors. For example, the second temperature and the second amount of time can be selected such that heating the object comprising the first intermediate magnesium alloy at the second temperature for the second amount of time substantially dissolves the second intermetallic phase into the alloy phase. In some examples, the methods can further comprise determining the second temperature and/or the second amount of time at which to heat the object comprising the first intermediate magnesium alloy to thereby substantially dissolve the second intermetallic phase into the alloy phase.

[0104] In some examples, the preliminary magnesium alloy further comprises a third intermetallic phase having a third melting temperature; wherein the first melting temperature (e.g., of the first intermetallic phase) is lower than the second melting temperature (e.g., of the second intermetallic phase), the third melting temperature (e.g., of the third intermetallic phase), and the solidus temperature of the alloy phase; wherein the second melting temperature (e.g., of the second intermetallic phase) is lower than the third melting temperature (e.g., of the third intermetallic phase) and the solidus temperature of the alloy phase; wherein the third melting temperature (e.g., of the third intermetallic phase) is lower than the solidus temperature of the alloy phase; and wherein the first temperature is above the first melting temperature (e.g., of the first intermetallic phase), below the second melting temperature (e.g., of the second intermetallic phase), below the third melting temperature (e.g., of the third intermetallic phase), and below the solidus temperature of the alloy phase; such that: heating the object comprising the preliminary magnesium alloy at the first temperature for the first amount of time thereby substantially dissolves the first intermetallic phase into the alloy phase to form an object comprising a first intermediate magnesium alloy, the first intermediate magnesium alloy comprising the second intermetallic phase, the third intermetallic phase, and the alloy phase; and heating the object comprising the first intermediate magnesium alloy at the second temperature for the second amount of time thereby substantially dissolves the second intermetallic phase into the alloy phase to form an object comprising a second intermediate magnesium alloy, the second intermediate magnesium alloy comprising the third intermetallic phase and the alloy phase

[0105] In some examples, the methods further comprise heating the object comprising the second intermediate magnesium alloy at a third temperature for a third amount of time; wherein the third temperature is above the melting temperature of the third intermetallic phase; thereby substantially dissolving the third intermetallic phase into the alloy phase.

[0106] In some examples, the third intermetallic phase comprises AlCaMg.

[0107] The third temperature can, for example, be above the melting temperature of the third intermetallic phase by 10° C. or more (e.g., 15° C. or more, 20° C. or more, 25° C. or more, 30° C. or more, 35° C. or more, or 40° C. or more). In some examples, the third temperature can be above the melting temperature of the third intermetallic phase by 50° C. or less (e.g., 45° C. or less, 40° C. or less, 35° C. or less, 30° C. or less, 25° C. or less, or 20° C. or less). The third temperature can be above the melting temperature of the third intermetallic phase by an amount that ranges from any of the minimum values described above to any of the maximum values described above. For example, the third temperature can be from 10° C. to 50° C. above the melting temperature of the third intermetallic phase (e.g., from 10° C. to 30° C., from 30° C. to 50° C., from 10° C. to 20° C., from 20° C. to 30° C., from 30° C. to 40° C., from 40° C. to 50° C., from 10° C. to 40° C., from 20° C. to 50° C., or from 20° C. to 40° C.).

[0108] In some examples, the third temperature can be 450° C. or more (e.g., 455° C. or more, 460° C. or more, 465° C. or more, 470° C. or more, 475° C. or more, 480° C. or more, 485° C. or more, 490° C. or more, or 495° C. or more). In some examples, the third temperature can be 500° C. or less (e.g., 495° C. or less, 490° C. or less, 485° C. or less, 480° C. or less, 475° C. or less, 470° C. or less, 465° C. or less, 460° C. or less, or 455° C. or less). The third temperature can range from any of the minimum values described above to any of the maximum values described above. For example, the third temperature can be from 450° C. to 500° C. (e.g., from 460° C. to 500° C., from 470° C. to 490° C., or from 475° C. to 485° C.). In some examples, the third temperature is 480° C. The third amount of time can, for example, be 0.1 hours or more (e.g., 0.2 hours or more, 0.3 hours or more, 0.4 hours or more, 0.5 hours or more, 0.6 hours or more, 0.7 hours or more, 0.8 hours or more, 0.9 hours or more, 1 hours or more, 1.25 hours or more, 1.5 hours or more, 1.75 hours or more, 2 hours or more, 2.25 hours or more, 2.5 hours or more, 2.75 hours or more, 3 hours or more, 3.25 hours or more, 3.5 hours or more, 4 hours or more, 4.5 hours or more, 5 hours or more, or 5.5 hours or more). In some examples, the third amount of time can be 6 hours or less (e.g., 5.5 hours or less, 5 hours or less, 4.5 hours or less, 4 hours or less, 3.5 hours or less, 3.25 hours or less, 3 hours or less, 2.75 hours or less, 2.5 hours or less, 2.25 hours or less, 2 hours or less, 1.75 hours or less, 1.5 hours or less, 1 hour or less, 0.9 hours or less, 0.8 hours or less, 0.7 hours or less, 0.6 hours or less, 0.5 hours or less, 0.4 hours or less, or 0.3 hours or less). The third amount of time can range from any of the minimum values described above to any of the maximum values described above. For example, the third amount of time can be from 0.1 hours to 6 hours (e.g., from 0.1 hours to 3 hours, from 3 hours to 6 hours, from 0.1 hours to 1.5 hours, from 1.5 hours to 3 hours, from 3 hours to 4.5 hours, from 4.5 hours to 6 hours, from 0.2 hours to 5.5 hours, from 0.5 hours to 1.5 hours, or from 2.5 hours to 3.5 hours).

[0109] The third temperature and/or the third amount of time can be selected in view of a variety of factors. For example, the third temperature and the third amount of time can be selected such that heating the object comprising the second intermediate magnesium alloy at the third temperature for the third amount of time substantially dissolves the third intermetallic phase into the alloy phase and minimizes incipient melting of the alloy phase. In some examples, the methods can further comprise determining the third temperature and/or the third amount of time at which to heat the object comprising the second intermediate magnesium alloy to thereby substantially dissolve the third intermetallic phase into the alloy phase and minimize incipient melting of the alloy phase.

[0110] In some examples, the magnesium alloy based object can comprise a substantially homogeneous matrix comprising the alloy phase.

[0111] In some examples, the methods can further comprise thermomechanically treating the magnesium alloy based object by heating the magnesium alloy based object at a fourth temperature for a fourth amount of time and, subsequently, mechanically treating the magnesium alloy based object. In some examples, mechanically treating the magnesium alloy based object comprises rolling the magnesium alloy based object, extrusion, forging (e.g., open-die forging and/or closed-die forging), or a combination thereof. In some examples, mechanically treating the magnesium alloy based object comprises rolling the magnesium alloy based object. In some examples, mechanically treating the magnesium alloy based object comprises extrusion. In some examples, mechanically treating the magnesium alloy comprises extrusion with a ram speed of from 1.00 to 10.00 ipm. In some examples, mechanically treating the magnesium alloy based object comprises forging (e.g., open-die forging and/or closed-die forging). In some examples, the methods can further comprise repeating the thermomechanical treatment.

[0112] The fourth amount of time can, for example, be 1 minute or more (e.g., 2 minutes or more, 3 minutes or more, 4 minutes or more, 5 minutes or more, 6 minutes or more, 7 minutes or more, 8 minutes or more, 9 minutes or more, 10 minutes or more, 11 minutes or more, 12 minutes or more, 13 minutes or more, 14 minutes or more, 15 minutes or more, 16 minutes or more, 17 minutes or more, 18 minutes or more, 19 minutes or more, 20 minutes or more, 25 minutes or more, 30 minutes or more, 35 minutes or more, 40 minutes or more, 45 minutes or more, or 50 minutes or more). In some examples, the fourth amount of time can be 1 hour or less (e.g., 55 minutes or less, 50 minutes or less, 45 minutes or less, 40 minutes or less, 35 minutes or less, 30 minutes or less, 25 minutes or less, 20 minutes or less, 19 minutes or less, 18 minutes or less, 17 minutes or less, 16 minutes or less, 15 minutes or less, 14 minutes or less, 13 minutes or less, 12 minutes or less, 11 minutes or less, 10 minutes or less, 9 minutes or less, 8 minutes or less, 7 minutes or less, 6 minutes or less, 5 minutes or less, 4 minutes or less 3 minutes or less, or 2 minutes or less). The fourth amount of time can range from any of the minimum values described above to any of the maximum values described above. For example, the fourth amount of time can be from 1 minute to 1 hour (e.g., from 1 minute to 30 minutes, from 1 minute to 60 minutes, from 1 minute to 20 minutes, from 20 minutes to 40 minutes, from 40 minutes to 60 minutes, from 1 minute to 50 minutes, from 2 minutes to 60 minutes, or from 2 minutes to 50 minutes).

[0113] The fourth temperature can, for example, be above room temperature and below the solidus temperature. In some examples, the fourth temperature can be below the solidus temperature by 10° C. or more (e.g., 20° C. or more, 30° C. or more, 40° C. or more, 50° C. or more, 60° C. or more, 70° C. or more, 80° C. or more, 90° C. or more, 100° C. or more, 110° C. or more, 120° C. or more, 130° C. or more, 140° C. or more, 150° C. or more, 160° C. or more, 170° C. or more, 180° C. or more, 190° C. or more, 200° C. or more, 210° C. or more, 220° C. or more, or 230° C. or more,). In some examples, the fourth temperature can be below the solidus temperature by 250° C. or less (e.g., 240° C. or less, 230° C. or less, 220° C. or less, 210° C. or less, 200° C. or less, 190° C. or less, 180° C. or less, 170° C. or less, 160° C. or less, 150° C. or less, 140° C. or less, 130° C. or less, 120° C. or less, 110° C. or less, 100° C. or less, 90° C. or less, 80° C. or less, 70° C. or less, 60° C. or less, 50° C. or less, 40° C. or less, or 30° C. or less). The fourth temperature can be below the solidus temperature by an amount that range from any of the minimum values described above to any of the maximum values described above. For example, the fourth temperature can be from 10° C. to 250° C. below the solidus temperature (e.g., from 10° C. to 130° C., from 130° C. to 250° C., from 10° C. to 50° C., from 50° C. to 100° C., from 100° C. to 150° C., from 150° C. to 200° C., from 200° C. to 250° C., from 10° C. to 200° C., from 20° C. to 250° C., or from 20° C. to 200° C.).

[0114] The fourth temperature can, for example, be 275° C. or more (e.g., 280° C. or more, 290° C. or more, 300° C. or more, 310° C. or more, 320° C. or more, 330° C. or more, 340° C. or more, 350° C. or more, 360° C. or more, 370° C. or more, 380° C. or more, 390° C. or more, 400° C. or more, 410° C. or more, 420° C. or more, 430° C. or more, 440° C. or more, 450° C. or more, 460° C. or more, 470° C. or more, 480° C. or more, 490° C. or more, 500° C. or more, 510° C. or more, or 520° C. or more). In some examples, the fourth temperature can be 525° C. or less (e.g., 520° C. or less, 510° C. or less, 500° C. or less, 490° C. or less, 480° C. or less, 470° C. or less, 460° C. or less, 450° C. or less, 440° C. or less, 430° C. or less, 420° C. or less, 410° C. or less, 400° C. or less, 390° C. or less, 380° C. or less, 370° C. or less, 360° C. or less, 350° C. or less, 340° C. or less, 330° C. or less, 320° C. or less, 310° C. or less, 300° C. or less, 290° C. or less, or 280° C. or less). The fourth temperature can range from any of the minimum values described above to any of the maximum values described above. For example, the fourth temperature can be from 275° C. to 525° C. (e.g., from 275° C. to 400° C., from 400° C. to 525° C., from 275° C. to 325° C., from 325° C. to 375° C., from 375° C. to 425° C., from 425° C. to 475° C., from 475° C. to 525° C., from 300° C. to 525° C., from 275° C. to 500° C., or from 300° C. to 500° C.).

[0115] In some examples, the methods can further comprise determining the fourth temperature and/or the fourth amount of time.

[0116] In some examples, mechanically treating the magnesium alloy based object comprises rolling the magnesium alloy based object. For example, the magnesium alloy based object can have an average thickness and rolling the magnesium alloy based object reduces the average thickness of the magnesium alloy based object.

[0117] In some examples, the magnesium alloy based object exhibits improved mechanical properties (e.g., improved yield strength and/or ductility) after thermomechanical treatment.

[0118] In some examples, the methods can further comprise determining the first temperature, the first amount of time, the second temperature, the second amount of time, the third temperature, the third amount of time, the fourth temperature, the fourth amount of time, or a combination thereof. For example, determining the first temperature, the first amount of time, the second temperature, the second amount of time, the third temperature, the third amount of time, or a combination thereof can be carried out in whole or in part on one or more computing device(s).

[0119] In some examples, the methods can further comprise casting the object comprising the preliminary magnesium alloy. In some examples, the methods can further comprise determining the composition of the preliminary magnesium alloy and/or the magnesium alloy. For example, the composition of the preliminary magnesium alloy and/or the magnesium alloy can be based on the characteristics of the alloying elements to provide the maximum benefit of each alloying element to the alloy. For example, the methods can further comprise determining the amount of Zn to include in the magnesium alloy, the amount of Al to include in the magnesium alloy, the amount of Ca to include in the magnesium alloy, the amount of Ce to include in the magnesium alloy, the amount of Mn to include in the magnesium alloy, or a combination thereof. For example, determining the amount of Zn to include in the magnesium alloy, the amount of Al to include in the magnesium alloy, the amount of Ca to include in the magnesium alloy, the amount of Ce to include in the magnesium alloy, the amount of Mn to include in the magnesium alloy, or a combination thereof can be carried out in whole or in part on one or more computing device(s). For example, the methods can further comprise optimizing the addition of each alloying element to achieve the best performance via controlling solute concentration and precipitates in magnesium matrix.

[0120] Also disclosed herein are magnesium alloy based objects made by any of the methods described herein. In some examples, the magnesium alloy based objects can comprise a substantially homogeneous matrix comprising the alloy phase.

[0121] In some examples, the magnesium alloy based object exhibits a yield strength of 20 kilopound force per square inch (ksi) or more (e.g., 21 ksi or more, 22 ksi or more, 23 ksi or more, 24 ksi or more, 25 ksi or more, 26 ksi or more, 27 ksi or more, 28 ksi or more, 29 ksi or more, 30 ksi or more, 31 ksi or more, 32 ksi or more, 33 ksi or more, 34 ksi or more, 35 ksi or more, 36 ksi or more, 37 ksi or more, 38 ksi or more, 39 ksi or more, 40 ksi or more, 41 ksi or more, 42 ksi or more, 43 ksi or more, 44 ksi or more, or 45 ksi or more).

[0122] In some examples, the magnesium alloy based object can have an ultimate tensile strength of 20 kilopound force per square inch (ksi) or more (e.g., 21 ksi or more, 22 ksi or more, 23 ksi or more, 24 ksi or more, 25 ksi or more, 26 ksi or more, 27 ksi or more, 28 ksi or more, 29 ksi or more, 30 ksi or more, 31 ksi or more, 32 ksi or more, 33 ksi or more, 34 ksi or more, 35 ksi or more, 36 ksi or more, 37 ksi or more, 38 ksi or more, 39 ksi or more, 40 ksi or more, 41 ksi or more, 42 ksi or more, 43 ksi or more, 44 ksi or more, or 45 ksi or more).

[0123] In some examples, the magnesium alloy based object has a high ductility.

[0124] In some examples, the magnesium alloy based object has an elongation to failure of 15% or more (e.g., 11% or more, 12% or more, 13% or more, 14% or more, 15% or more, 16% or more, 17% or more, 18% or more, 19% or more, 20% or more, 21% or more, 22% or more, 23% or more, 24% or more, 25% or more, 26% or more, 27% or more, 28% or more, 29% or more, or 30% or more). Also described herein are methods of use of the magnesium alloy based objects described herein, the methods comprising using the magnesium alloy based object in an automotive, aerospace, or electronic application. Also described herein are articles of manufacture comprising the magnesium alloy based objects described herein. Also described herein are methods of use of the magnesium alloys described herein, the methods comprising using the magnesium alloys in plate, forging and extrusion applications, e.g., for a variety of industries

[0125] A number of embodiments of the invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope of the invention. Accordingly, other embodiments are within the scope of the following claims.

[0126] The examples below are intended to further illustrate certain aspects of the systems and methods described herein, and are not intended to limit the scope of the claims.

EXAMPLES

[0127] The following examples are set forth below to illustrate the methods and results according to the disclosed subject matter. These examples are not intended to be inclusive of all aspects of the subject matter disclosed herein, but rather to illustrate representative methods and results. These examples are not intended to exclude equivalents and variations of the present invention which are apparent to one skilled in the art.

[0128] Efforts have been made to ensure accuracy with respect to numbers (e.g., amounts, temperature, etc.) but some errors and deviations should be accounted for. Unless indicated otherwise, parts are parts by weight, temperature is in ° C. or is at ambient temperature, and pressure is at or near atmospheric. There are numerous variations and combinations of measurement conditions, e.g., component concentrations, temperatures, pressures and other measurement ranges and conditions that can be used to optimize the described process.

Example 1—Formable Magnesium Alloys Amendable to Extrusion Processing

[0129] Magnesium (Mg), the lightest structural metal, and its alloys with high specific strength and low density are promising lightweight materials for industrial applications in automotive, aerospace, and electronic sectors. However, compared to commercial aluminum alloys and steels, there are only limited applications of Mg alloys owing to their low strength, poor ductility, and poor formability at room temperature. Thus, there is an urgent need to improve the mechanical performance of Mg extrusion alloys at room temperature, especially for high-volume industrial applications such as the automotive market.

[0130] Alloy Design. Based on CALPHAD (CALculation of PHAse Diagrams) simulation (Table 1), the following alloys are designed to provide a minimum of 550° C. solidus to enable high extrusion exit temperature (and a corresponding high extrusion exit speed). This is based on the work of Atwell where the measured cracking limit temperature (onset of incipient melting) is linked in a 1:1 correlation with the solidus temperature for the alloy (Atwell et al. *Metallurgical and Materials Transactions A,* 2007, 38(12), 3032-3041). Experimental alloys (Table 2, heat chemistry) have been cast.

TABLE 1

CALPHAD modeling of solidus of Mg—Zn—Al—Ca—Ce—Mn system.

Mg (wt. %)	Zn (wt. %)	Al (wt. %)	Ca (wt. %)	Ce (wt. %)	Mn (wt. %)	$T_{solidus}$ (° C.)
99.4	0	0	0	0.2	0.4	584
98.9	0	0	0.5	0.2	0.4	540
98.4	0	1	0	0.2	0.4	607
97.9	0	1	0.5	0.2	0.4	516
98.4	1	0	0	0.2	0.4	412
97.9	1	0	0.5	0.2	0.4	410
97.4	1	1	0	0.2	0.4	570
97.2	1	1	0.2	0.2	0.4	451
96.9	1	1	0.5	0.2	0.4	442
99.2	0	0	0.2	0.2	0.4	587
98.2	0	1	0.2	0.2	0.4	557
98.9	0.5	0.0	0	0.2	0.4	600
98.7	0.5	0.0	0.2	0.2	0.4	536
98.4	0.5	0.5	0	0.2	0.4	590
98.2	0.5	0.5	0.2	0.2	0.4	524

TABLE 2

Experimental alloy design: Lot chemistry (wt. %) for cast 9" diameter, 30" length extrusion billets.

Lot #	Comp	Mg	Zn	Al	Ca	Ce	Mn
X20245-2	ZAXEM11100	96.19	1.36	1.17	0.541	0.221	0.405
X20274-1	ZAXEM11100	96.19	1.35	1.21	0.402	0.214	0.517
X20274-2	ZAXEM11100	96.14	1.37	1.28	0.462	0.232	0.405
X20274-3	ZAXEM11100	96.18	1.34	1.23	0.431	0.203	0.479
X20350-1	ZAXEM11100	96.65	0.969	1.16	0.442	0.228	0.435
X20350-2	ZAXEM11100	96.78	0.948	1.10	0.403	0.251	0.414
X20350-3	ZAXEM11100	96.84	0.942	1.05	0.408	0.222	0.431
X20349-1	AEM100	98.17	0.003	1.11	0.003	0.193	0.415
X20349-2	ZAE1100	97.21	1.010	1.05	0.002	0.194	0.423
X20349-3	ZAXEM11100	97.05	0.978	1.07	0.181	0.197	0.412

[0131] Extrusion Conditions. Example extrusion conditions for the billets are presented below (Table 3). Billets (Chemistry from Table 2) were solutionized (Sol) with one of three heat treatment (HT) schedules. Prior to extrusion, the billet was furnace heated to the extrusion temperature (T_{billet}) and an extrusion die (extrusion cross section 0.4"×5.5" was heated—T_{die}). The extrusion ratio for all experiments was 28.9 (corresponding to a 9" D container and 0.4"×5.5" cross section extrusion). All billets were initially extruded at a ram speed (v_{RAM}) of 1.00 ipm which corresponds to an extrusion exit speed (v_{ex}) of 0.73 m/min. The corresponding average strain rate (e') and flow stress (s) as predicted through slab analysis (with measured breakout pressure) are presented along with the temperature of the extruded product—T_{exit} (measured 3 ft from the die exit).

TABLE 3

Example extrusion conditions for billets with chemistry shown in Table 2.

Lot #	Sol HT	T_{billet} (° C.)	T_{die} (° C.)	v_{RAM} (ipm)	v_{ex} (m/min)	e' (s^{-1})	σ (MPa)	T_{exit} (° C.)
X20245-2	A	364	393	1.00	0.73	0.04	62	410
X20274-1	A	357	370	1.00	0.73	0.04	66	393
X20274-2	A	346	369	1.00	0.73	0.04	59	393
X20274-3	A	291	368	1.00	0.73	0.04	66	396
X20350-1	A	311	375	1.00	0.73	0.04	67	396
X20350-2	B	301	366	1.00	0.73	0.04	60	391
X20350-3	C	302	373	1.00	0.73	0.04	62	391
X20349-1	A	306	369	1.00	0.73	0.04	52	402
X20349-2	B	304	369	1.00	0.73	0.04	54	384
X20349-3	C	302	372	1.00	0.73	0.04	63	393

[0132] Sol HT Schedule A: The furnace temperature was set to 360° C. (680° F.). Billet placed in furnace and allowed to heat for 6 hours. Furnace temperature was then raised to 440° C. (824° F.). Once the furnace reached temperature, the billet was allowed to soak for 24 hours. The furnace temperature was raised to 480° C. (896° F.). Once the furnace reached temperature, the billet was allowed to soak for 1 hour. Finally, the billet was removed and forced air cooled.

[0133] Sol HT Schedule B: The furnace temperature was set to 360° C. (680° F.). Billet placed in furnace and allowed to heat for 6 hours. Furnace temperature was then raised to 440° C. (824° F.). Once the furnace reached temperature, the billet was allowed to soak for 24 hours. The furnace temperature was raised to 480° C. (896° F.). Once the furnace reached temperature, the billet was allowed to soak for 3 hours. Finally, the billet was removed and forced air cooled.

[0134] Sol HT Schedule C: The furnace temperature was set to 440° C. (824° F.). Billet placed in furnace and allowed to heat 24 hours. The furnace temperature was raised to 480° C. (896° F.). Once the furnace reached temperature, the billet was allowed to soak for 3 hours. Finally, the billet was removed and forced air cooled.

[0135] All extrusions exhibited no incipient melting with a ram speed of 1.00 ipm. The ram speed was incremented by 0.25 ipm until incipient melting was observed. Billets containing a significant fraction of Calcium (X20245, X20274, and X20350) were all observed to exhibit incipient melting with a ram speed 1.00-2.00 ipm. As an example, Billet X20245-2 was observed to have an extrusion exit temperature of 391° C. with a ram speed of 1.00 ipm. With an increase in ram speed to 2.00 ipm, the extrusion exit temperature raised to 432° C. with a corresponding observation of incipient melting. The CALPHAD predicted solidus temperature for the X20245-2 composition is presented below (Table 4) in comparison to the nominal ZAXEM11100 composition. The predicted solidus ($T_{Solidus}$) of 418° C. for X20245-2 is lower than the observed extrusion exit temperature of 432° C. with a ram speed of 2.00 ipm, confirming the observation of incipient melting.

TABLE 4

CALPHAD predicted solidus temperature presented for the nominal ZAXEM11100 alloy composition as well as that for billet X20245-2.							
Alloy	Mg (wt. %)	Zn (wt. %)	Al (wt. %)	Ca (wt. %)	Ce (wt. %)	Mn (wt. %)	$T_{Solidus}$ (° C.)
Nominal	Bal.	1.00	1.00	0.50	0.20	0.40	442
X20245-2	Bal.	1.36	1.17	0.54	0.22	0.41	418

[0136] Only billets X20349-1, -2, and -3 were observed without incipient melting at a ram speed of 4.00 ipm. At a ram speed of 4.00 ipm, the exit speed for the extrusion was 2.94 m/min with an average strain rate (e') of 0.15 s^{-1}. The temperature of the extruded product for all three billets X20349-1, -2, and -3 with a ram speed of 4.00 ipm were 430° C. The observed extrusion exit temperature is significantly lower than the CALPHAD predicted solidus temperature for any of the three alloys (as presented below, Table 5, in comparison with the nominal ZAXEM11100 composition). Generally, alloys with lower Ca and Zn content have significantly higher solidus temperature (enabling a higher extrusion exit temperature and extrusion exit speed).

TABLE 5

CALPHAD predicted solidus temperature presented for the nominal ZAXEM11100 alloy composition as well as that for billets X20349-1, -2, and -3.							
Alloy	Mg (wt. %)	Zn (wt. %)	Al (wt. %)	Ca (wt. %)	Ce (wt. %)	Mn (wt. %)	$T_{Solidus}$ (° C.)
Nominal	Bal.	1.00	1.00	0.50	0.20	0.40	442
X20349-1	Bal.	—	1.11	—	0.193	0.415	607
X20349-2	Bal.	1.01	1.05	—	0.194	0.423	570
X20349-3	Bal.	0.978	1.07	0.181	0.197	0.412	451

[0137] Mechanical properties. Tensile properties were measured for the resulting as extruded (A.E.) product in the direction parallel to extrusion direction. Three tensile samples (ASTM E8) with dimensions 0.25"×0.5" cross section and gage length 2.25" were machined from the extruded 0.4"×5.5" plate. Tensile properties from extrusions processed with a ram speed of 1 ipm are presented below (Table 6). Average tensile properties (in the direction of extrusion) for as extruded (A.E.) materials with an extrusion speed of 4.00 ipm are shown in Table 7.

TABLE 6

As extruded (A.E.), longitudinal tensile properties for extrusions with ram speed of 1.00 ipm.							
ID	Alloy	n	V_{RAM} (ipm)	Cond.	YS (ksi)	UTS (ksi)	ef (%)
X20245-2	ZAXEM11100	3	1.00	A.E.	28.6	37.5	16.0
X20274-2	ZAXEM11100	3	1.00	A.E.	27.9	35.9	17.6
X20349-1	AEM100	3	1.00	A.E.	29.6	35.1	10.6
X20349-2	ZAEM1100	3	1.00	A.E.	25.0	31.8	12.7
X20349-3	ZAXEM11100	3	1.00	A.E.	27.7	34.9	16.4

TABLE 7

As extruded (A.E.), longitudinal tensile properties for extrusions with ram speed of 4.00 ipm.							
ID	Alloy	n	V_{RAM} (ipm)	Cond.	YS (ksi)	UTS (ksi)	ef (%)
X20349-1	AEM100	3	4.00	A.E.	29.2	35.3	11.7
X20349-2	ZAEM1100	3	4.00	A.E.	26.3	34.7	15.1
X20349-3	ZAXEM11100	3	4.00	A.E.	22.4	35.1	15.7

[0138] Simple aging studies (Micro Vickers, HV) were performed on the transverse cross section from samples of X20349-2, extruded at 4.00 ipm. Hardness was performed on samples after aging at 226° C. and after heat treatment (T4−480° C./1 h/WQ) with subsequent aging at 226° C., results presented in FIG. **1**. The sample heat treated and aged (T4+226° C., green) did not exhibit age hardening whereas the sample simply aged at 226° C. did exhibit age hardening with a peak observed at 1 hour. This indicates that composition X20349-2 enables both high extrusion exit speed and the possibility of age hardening.

[0139] Microstructure changes. In ZAXEM11100, the 0.5 wt. % of Ca resulted in the formation of four different Ca-containing phases seen in FIG. **2**: Mg_2Ca, AlCaMg, Al_2Ca, and $Ca_2Mg_6Zn_3$. The Laves phases: C14-Mg_2Ca, C15-Al_2Ca, and C36-AlCaMg have been shown to improve creep resistance but are very brittle at lower temperatures (Zehnder et al. *Mater. Sci. Eng. A,* 2019, 759, 754; Zhong et al. Laves Phases in Mg—Al—Ca Alloys. Magnesium Technology 2004, pages 317-323; Luo et al. *Metall. Mater. Trans. A,* 2002, 33(3), 567). The presence of Laves phases are an issue for the target of room temperature properties, particularly formability.

[0140] Of these phases, Mg_2Ca is of greatest concern because of its stability above the solidus. While a multistage heat treatment has been shown to help lower the fraction of Mg_2Ca, the phase is stable, and therefore could reform in the 350-450° C. extrusion temperature range (Shi et al. *Sci. Rep.* 2020, 10(1), 1). This phase begins melting at 440° C. which dramatically reduces grain boundary strength leading to the cracking that was observed during extrusion. With the modification of Ca, the Mg_2Ca phase and the other Ca Laves phases, are no longer predicted (as seen in FIG. **3** for ZAEM1100). Without the Ca Laves phases, the first phase to melt would be $Mg_{12}Ce$ at 570° C. This is confirmed with SEM microstructures (FIG. **4**-FIG. **5**). Mg_2Ca forms as a long and semi continuous phase along the edge of grains (FIG. **4**). In contrast, the phases formed in the modified Ca alloy (FIG. **5**) are distributed in the grains and will better accommodate stresses experienced during extrusion.

[0141] Benefits/Advantages. The new extrusion alloy has improved formability for subsequent bending and forming and crash energy absorption. Lightweight magnesium alloys compared with commercial aluminum alloys/steel. Excellent combination of mechanical properties surpassing those of the existing magnesium extrusion alloys reported so far.

Example 2

[0142] Data was collected for ZAXEM type alloys in comparison with AZ31C and AZ61A extruded into the same die. The results are shown in Table 8 and Table 9. Bumper beam X22278-3 had a very fine grain structure in the longitudinal direction (FIG. **6**).

TABLE 8

Tensile properties for plates (0.4" × 5.5").

Composition	1Zn—1Al—0.5Ca—0.2Ce—0.5Mn	1Zn—1Al—0.5Ca—0.2Ce—0.5Mn	1Zn—1Al—0.2Ce—0.5Mn	AZ31C
Lot(s)	X20245-2, X20274-1, X20274-2, X20350-3	X20274-2	X20349-2	Q23058-2
Condition	As extruded	T6	As extruded	As extruded
n	18	3	6	3
Yield Strength (ksi)	28.5	33.6	25.6	24.7
Ultimate Tensile Strength (ksi)	36.3	41.2	33.2	36.5
Elongation to Failure (%)	16.7	21.6	13.9	8.2

TABLE 9

Tensile properties for bumper beams.

Composition	0.5Zn—0.5Al—0.2Ca—0.2Ce—0.7Mn	1Zn—1Al—0.2Ce—0.5Mn	AZ61A	AZ31C
Lot(s)	X22278-3	X22052-2, X22052-4	R20162-6	Q23058-4
Condition	As extruded	As extruded	As extruded	As extruded
n	6	12	3	6
Yield Strength (ksi)	34.4	23.8	27.8	22.0
Ultimate Tensile Strength (ksi)	39.2	32.6	37.7	34.9
Elongation to Failure (%)	5.0	9.3	9.3	14.7

[0143] Other advantages which are obvious and which are inherent to the invention will be evident to one skilled in the art. It will be understood that certain features and sub-combinations are of utility and may be employed without reference to other features and sub-combinations. This is contemplated by and is within the scope of the claims. Since many possible embodiments may be made of the invention without departing from the scope thereof, it is to be understood that all matter herein set forth or shown in the accompanying drawings is to be interpreted as illustrative and not in a limiting sense.

[0144] The methods of the appended claims are not limited in scope by the specific methods described herein, which are intended as illustrations of a few aspects of the claims and any methods that are functionally equivalent are intended to fall within the scope of the claims. Various modifications of the methods in addition to those shown and described herein are intended to fall within the scope of the appended claims. Further, while only certain representative method steps disclosed herein are specifically described, other combinations of the method steps also are intended to fall within the scope of the appended claims, even if not specifically recited. Thus, a combination of steps, elements, components, or constituents may be explicitly mentioned herein or less, however, other combinations of steps, elements, components, and constituents are included, even though not explicitly stated.

What is claimed is:

1. A magnesium alloy comprising:

from 0 to 1.5 wt. % Zn,

from 0 to 1.5 wt. % Al,

less than 0.2 wt. % Ca,

from 0.2 to 0.4 wt. % Ce,

from 0.1 to 0.8 wt. % Mn, and

the balance comprising Mg.

2. The magnesium alloy of claim **1**, wherein the magnesium alloy comprises less than 1 wt. % Zn.

3. The magnesium alloy of claim **1**, wherein the magnesium alloy comprises less than 1 wt. % Al.

4. The magnesium alloy of claim **1**, wherein the magnesium alloy comprises from 0 to 0.15 wt. % Ca.

5. The magnesium alloy of claim **1**, wherein the magnesium alloy comprises from 0 to 0.1 wt. % Ca.

6. The magnesium alloy of claim **1**, wherein the magnesium alloy is substantially free of Ca.

7. The magnesium alloy of claim **1**, wherein the magnesium alloy comprises less than 1 wt. % Zn, less than 1 wt. % Al, less than 0.2 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg.

8. The magnesium alloy of claim **1**, wherein the magnesium alloy comprises less than 1 wt. % Zn, less than 1 wt. % Al, from 0 to 0.15 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg.

9. The magnesium alloy of claim **1**, wherein the magnesium alloy comprises less than 1 wt. % Zn, less than 1 wt. % Al, from 0 to 0.1 wt. % Ca, 0.2 wt. % Ce, 0.4 wt. % Mn, and the balance comprising Mg.

10. The magnesium alloy of claim **1**, wherein the Zn, Al, Ca, Ce, and Mn, when present, are substantially dissolved in the magnesium alloy.

11. The magnesium alloy of claim **1**, wherein the magnesium alloy is microalloyed.

12. The magnesium alloy of claim **1**, wherein the magnesium alloy has a yield strength of 20 ksi or more.

13. The magnesium alloy of claim **1**, wherein the magnesium alloy has an ultimate tensile strength of 20 ksi or more.

14. The magnesium alloy of claim **1**, wherein the magnesium alloy has an elongation to failure of 10% or more.

15. The magnesium alloy of claim **1**, wherein the magnesium alloy is formable at room temperature.

16. The magnesium alloy of claim **1**, wherein the magnesium alloy has a solidus temperature of from 500° C. to 625° C.

17. The magnesium alloy of claim **1**, wherein the magnesium alloy is substantially free of a Mg_2Ca phase, an AlCaMg phase, an Al_2Ca phase, a $Ca_2Mg_6Zn_3$ phase, or a combination thereof.

18. An object comprising the magnesium alloy of claim **1**.

19. A method of use of the magnesium alloy of claim **1**, the method comprising using the magnesium alloy in an automotive, aerospace, or electronic application.

20. A method of making a magnesium alloy based object comprising the magnesium alloy of claim **1**, the method comprising:

heating an object comprising a preliminary magnesium alloy at a first temperature for a first amount of time;

wherein the preliminary magnesium alloy comprises a first intermetallic phase having a first melting temperature and an alloy phase having a solidus temperature;

wherein the melting temperature of the first intermetallic phase is lower than the solidus temperature of the alloy phase; and

wherein the first temperature is above the melting temperature of the first intermetallic phase and below the solidus temperature of the alloy phase;

thereby substantially dissolving the first intermetallic phase into the alloy phase.

* * * * *