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(54) **Titre : COMPOSITIONS DE REVETEMENT DE SOL-GEL RENFERMANT UN HYDROXYDE DOUBLE COUCHE A INHIBITEUR DE CORROSION ENCAPSULE ET PROCEDES ASSOCIES**

(54) **Title: SOL-GEL COATING COMPOSITIONS INCLUDING CORROSION INHIBITOR-ENCAPSULATED LAYERED DOUBLE HYDROXIDE AND RELATED PROCESSES**

(57) **Abrégé/Abstract:**

A Zn-Al layered double hydroxide (LDH) composition is added to a solution including a corrosion inhibitor and stirred, and a precipitate of the solution is collected, washed, and dried to form a corrosion inhibiting material (CIM), in which the LDH composition is intercalated with the corrosion inhibitor. An inorganic CIM and/or an organic CIM may be formed. The organic CIM may be added to a sol-gel composition to form an organic CIM-containing sol-gel composition, and the inorganic CIM may be added to a sol-gel composition to form an inorganic CIM-containing sol-gel composition. Further, the organic CIM-containing sol-gel composition may be applied on a substrate (e.g., an aluminum alloy substrate) to form an organic CIM-containing sol-gel layer and cured by ultraviolet (UV) radiation, the inorganic CIM-containing sol-gel composition may be applied on the substrate to form an inorganic CIM-containing sol-gel layer and cured by UV radiation, and the sol-gel layers may be thermally cured.

ABSTRACT

A Zn-Al layered double hydroxide (LDH) composition is added to a solution including a corrosion inhibitor and stirred, and a precipitate of the solution is collected, washed, and dried to form a corrosion inhibiting material (CIM), in which
5 the LDH composition is intercalated with the corrosion inhibitor. An inorganic CIM and/or an organic CIM may be formed. The organic CIM may be added to a sol-gel composition to form an organic CIM-containing sol-gel composition, and the inorganic CIM may be added to a sol-gel composition to form an inorganic CIM-containing sol-gel composition. Further, the organic CIM-containing sol-gel
10 composition may be applied on a substrate (e.g., an aluminum alloy substrate) to form an organic CIM-containing sol-gel layer and cured by ultraviolet (UV) radiation, the inorganic CIM-containing sol-gel composition may be applied on the substrate to form an inorganic CIM-containing sol-gel layer and cured by UV radiation, and the sol-gel layers may be thermally cured.

SOL-GEL COATING COMPOSITIONS INCLUDING CORROSION INHIBITOR- ENCAPSULATED LAYERED DOUBLE HYDROXIDE AND RELATED PROCESSES

BACKGROUND

5 **1. Technical Field**

The present disclosure relates to coating compositions and processes and, more particularly, to sol-gel coating compositions including corrosion inhibitor-encapsulated layered double hydroxide and related processes.

2. Related Art

10 High strength alloys such as aluminum alloys are widely used in various industries such as the aerospace industry due to their high strength to weight ratio. However these alloys are prone to corrosion due to the presence of alloying materials.

15 In order to protect these alloys from the environment, a chrome conversion coating may be provided on a surface of an alloy followed by application of primer and a top coat. Although organic paint systems applied on the surface provide good barrier properties against corrosion, even small defects formed in the organic paint ensure pathways for the ingress of electrolyte to the metallic surface, which initiates localized corrosion. Therefore, chromium based conversion coatings have
20 been used in anti-corrosion pretreatments before application of organic coatings. However, hexavalent chromium compounds have harmful effects.

Thus, there is a need for coating compositions and processes that are chromium-free while providing a coating that is corrosion-resistant.

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SUMMARY

In accordance with embodiments of the present disclosure, various methods and formulations are provided relating to sol-gel coating of substrates such as an aluminum substrate, an aluminum alloy substrate (e.g., AA **2024**, AA**6061**, or AA**7075**), or other substrate. The sol-gel coating provided on a substrate may

provide corrosion protection. Further, the sol-gel coating provided on the substrate may provide enhanced adhesion between the substrate and a paint system (e.g., primer and paint).

In one exemplary aspect, a method for preparing a corrosion inhibiting material (CIM) includes adding a Zn-Al layered double hydroxide (LDH) composition to a solution including a corrosion inhibiting compound and stirring, collecting a precipitate of the solution, and washing and drying the precipitate of the solution to form the corrosion inhibiting material in which the corrosion inhibiting compound is intercalated in the Zn-Al LDH composition. The method may further include mixing a zinc nitrate solution and an aluminum nitrate solution and stirring under nitrogen purging to form a mixture, adding a sodium nitrate solution to the mixture while maintaining a pH ranging from about 8 to about 12 and stirring under nitrogen purging, collecting a precipitate of the mixture, and washing and drying the precipitate of the mixture to form the Zn-Al LDH composition. An organic corrosion inhibiting material may be formed by using an organic corrosion inhibiting compound (e.g., an imidazole such as 1-(3-aminopropyl)imidazole; a triazole such as 1H-1,2,3-triazole, 4-methyl-4H-1,2,4-triazole-3-thiol, 1,2,4-triazole-3-carboxylic acid, 3-amino-1,2,4-triazole-5-thiol, 4H-1,2,4-triazol-4-amine, 3-mercapto-4-methyl-4H-1,2,4-triazole, or 5-phenyl-1H-1,2,4-triazole-3-thiol; a tetrazole such as 1-methyl-1H-tetrazole-5-thiol or 1H-tetrazole-5-acetic acid; a thiazole such as 4-methyl-1,3-thiazole-5-carboxylic acid; a thiadiazole such as 1,3,4-thiadiazole-2,5-dithiol; a benzimidazole such as 1H-benzimidazole-2-carboxylic acid; a benzotriazole such as 1H-benzotriazole; a benzothiazole such as 2-mercaptobenzothiazole; a quinoline such as 8-hydroxyquinoline; phytic acid; an organophosphonic acid such as amino tris(methylenephosphonic acid), ethylenediamine tetra(methylenephosphonic acid), 1-hydroxyethylidene-1,1-diphosphonic acid, or diethylenetriamine penta(methylenephosphonic acid); a vegetable oil such as linseed oil or other vegetable oil containing saturated and/or unsaturated fatty acids such as stearic acid, palmitic acid, oleic acid, linoleic acid, or linolenic acid; and/or other organic corrosion inhibiting compound). An inorganic corrosion inhibiting material may be

formed by using an inorganic corrosion inhibiting compound (e.g., a vanadate, a molybdate, a tungstate, a phosphate, a manganate, a permanganate, an aluminate, and/or other inorganic corrosion inhibiting compound).

In an additional exemplary aspect, a method for preparing a CIM-containing sol-gel composition includes adding the corrosion inhibiting material to a sol-gel composition to form the CIM-containing sol-gel composition. The amount of the corrosion inhibiting material that is added may range from about **1** to about **10** parts by weight per **100** parts by weight of the sol-gel composition. The method may further include contacting a first alkoxysilane with water and an inorganic acid to form a first composition, contacting a zirconium alkoxide with an organic acid to form a second composition, contacting the first composition with the second composition to form a mixture, contacting one or more second alkoxysilanes and an organic acid with the mixture to form the sol-gel composition, the sol-gel composition having a ratio of a number of moles of silicon to a number of moles of zirconium (n_{Si}/n_{Zr}) ranging from about **2** to about **10**, and adding a photoinitiator to the sol-gel composition. An organic CIM-containing sol-gel composition may be formed by using an organic corrosion inhibiting material. An inorganic CIM-containing sol-gel composition may be formed using an inorganic corrosion inhibiting material.

In another exemplary aspect, a method for providing a corrosion-resistant coating on a substrate includes forming the corrosion-resistant coating including multiple sol-gel layers on the substrate using the organic CIM-containing sol-gel composition and the inorganic CIM-containing sol-gel composition. The multiple sol-gel layers may be formed by applying the organic CIM-containing sol-gel composition on the substrate to form one or more organic CIM-containing sol-gel layers, curing the one or more organic CIM-containing sol-gel layers by UV radiation, applying the inorganic CIM-containing sol-gel composition on the substrate to form one or more inorganic CIM-containing sol-gel layers, curing the one or more second sol-gel layers by the UV radiation, and thermally curing multiple sol-gel layers including the one or more organic CIM-containing sol-gel layers and

the one or more inorganic CIM-containing sol-gel layers. The method may further include applying primer and/or paint on the multiple sol-gel layers of the substrate, the multiple sol-gel layers facilitating adherence of the primer or the paint to the substrate.

5 In yet another exemplary aspect, a corrosion inhibiting material, a CIM-containing sol-gel composition, and/or a corrosion-resistant coating that includes multiple sol-gel layers may be provided by any of the above methods.

 In a further exemplary aspect, a corrosion-resistant coated product includes a plurality of sol-gel layers on a substrate, the plurality of sol-gel layers including at
10 least one organic CIM-containing sol-gel layer and at least one inorganic CIM-containing sol-gel layer. The organic CIM-containing sol-gel layer includes an organic corrosion inhibiting material and a polymer composite of one or more alkoxysilanes, a zirconium alkoxide, and an organic acid. The organic corrosion inhibiting material includes a Zn-Al layered double hydroxide (LDH) composition
15 encapsulating an organic corrosion inhibiting compound. The inorganic CIM-containing sol-gel layer includes an inorganic corrosion inhibiting material and a polymer composite of one or more alkoxysilanes, zirconium alkoxide, and an organic acid. The inorganic corrosion inhibiting material includes a Zn-Al LDH composition encapsulating an inorganic corrosion inhibiting compound.

20 In one embodiment, there is provided a method of forming a corrosion resistant coating on a substrate. The method involves adding a Zn-Al layered double hydroxide (LDH) composition to a first solution comprising a first corrosion inhibiting compound and stirring, and collecting a precipitate of the first solution. The method further involves washing and drying the precipitate of the first solution
25 to form a first corrosion inhibiting material (CIM), the first CIM comprising the first corrosion inhibiting compound intercalated in the Zn-Al LDH composition, and adding the first CIM to a first sol-gel composition to form an organic CIM-containing sol-gel composition, wherein the first corrosion inhibiting compound is an organic corrosion inhibiting compound, and wherein the first CIM is an organic CIM. The

method further involves adding the Zn-Al LDH composition to a second solution comprising an inorganic corrosion inhibiting compound and stirring, collecting a precipitate of the second solution, and washing and drying the precipitate of the second solution to form an inorganic CIM, the inorganic CIM comprising the inorganic corrosion inhibiting compound intercalated in the Zn-Al LDH composition. The method further involves adding the inorganic CIM to a second sol-gel composition to form an inorganic CIM-containing sol-gel composition, and applying the organic CIM-containing sol-gel composition on a substrate to form an organic CIM-containing sol-gel layer. The method further involves curing the organic CIM-containing sol-gel layer by UV radiation, and applying the inorganic CIM-containing sol-gel composition on the substrate to form an inorganic CIM-containing sol-gel layer. The method further involves curing the inorganic CIM-containing sol-gel layer by the UV radiation, and thermally curing a plurality of sol-gel layers comprising the organic CIM-containing sol-gel layer and the inorganic CIM-containing sol-gel layer to form a corrosion-resistant coating.

The method may involve mixing a zinc nitrate solution and an aluminum nitrate solution and stirring under nitrogen purging to form a mixture, adding a sodium nitrate solution to the mixture while maintaining a pH ranging from about 8 to about 12 and stirring under nitrogen purging, collecting a precipitate of the mixture, and washing and drying the precipitate of the mixture to form the Zn-Al LDH composition.

The method may involve contacting a first alkoxysilane with water and an inorganic acid to form a first composition, contacting a zirconium alkoxide with a first organic acid to form a second composition, and contacting the first composition with the second composition to form a mixture. The method may further involve contacting one or more second alkoxysilanes and a second organic acid with the mixture to form the sol-gel composition, the sol-gel composition having a ratio of a number of moles of silicon to a number of moles of zirconium ($n\text{Si}/n\text{Zr}$) ranging from

about 2 to about 10, adding a photoinitiator to the sol-gel composition, and diluting the sol-gel composition with a solvent.

The contacting to form the first composition may involve mixing the first alkoxysilane having the formula $RA-Si-(RB)_3$ with the water and the inorganic acid, the RA may be methacryloxyalkyl or glycidyloxyalkyl, and the RB may be a methoxy or ethoxy; or the contacting to form the second composition may involve mixing the zirconium alkoxide having the formula $Zr-(RC)_4$ with methacrylic acid (MAA), and the RC may be ethoxy, n-propoxy, isopropoxy, n-butyloxy, or tert-butyloxy

The contacting to from the sol-gel composition may involve adding the one or more second alkoxysilanes each having the formula $RD-Si-(RE)_3$ to the mixture, the RD may be aryl, aminoalkyl, or glycidoxyalkyl, and the RE may be methoxy or ethoxy, and adding MAA and stirring, or the adding of the CIM may involve adding the CIM in an amount ranging from about 1 to about 10 parts by weight per 100 parts by weight of the sol-gel composition or ranging from about 1 to about 10 parts by weight per 100 parts by weight of a solid content of the sol-gel composition.

The method may involve dispersing the organic corrosion inhibiting compound comprising 1-(3-aminopropyl)imidazole, 1H-1,2,3-triazole, 4-methyl-4H-1,2,4-triazole-3-thiol, 1,2,4-triazole-3-carboxylic acid, 3-amino-1,2,4-triazole-5-thiol, 4H-1,2,4-triazol-4-amine, 3-mercapto-4-methyl-4H-1,2,4-triazole, 5-phenyl-1H-1,2,4-triazole-3-thiol, 1-methyl-1H-tetrazole-5-thiol, 1H-tetrazole-5-acetic acid, 4-methyl-1,3-thiazole-5-carboxylic acid, 1,3,4-thiadiazole-2,5-dithiol, 1H-benzimidazole-2-carboxylic acid, 1H-benzotriazole (BTA), 2-mercaptobenzothiazole (MBT), 8-hydroxyquinoline, phytic acid, an organophosphonic acid, a vegetable oil, or a combination thereof in a solvent to form the first solution.

The method may involve dissolving the inorganic corrosion inhibiting compound comprising a vanadate, a molybdate, a tungstate, a phosphate, a manganate, a permanganate, an aluminate, or a combination thereof in a solvent to form the second solution.

The substrate may involve an aluminum substrate or and aluminum alloy substrate.

The substrate may be selected from the group comprising 2024 aluminum alloy, 6061 aluminum alloy, and 7075 aluminum alloy.

5 The curing the organic CIM-containing sol-gel layer and the inorganic CIM-containing sol-gel layer by the UV radiation may involve exposing a respective one of the sol-gel layers to the UV radiation having a light dose ranging from about 500 to about 1000 mJ/cm² for a time period ranging from about 0.5 to 30 min, and the thermally curing the plurality of sol-gel layers may involve exposing the plurality of
10 sol-gel layers to infrared (IR) radiation, near IR radiation, microwave radiation, hot air having a temperature ranging from about 70 to about 90 °C, or a combination thereof.

 The method may involve applying primer and/or paint on the plurality of sol-gel layers on the substrate, the plurality of sol-gel layers facilitating adherence of
15 the primer or the paint to the substrate.

 In another embodiment, there is provided a corrosion-resistant product obtainable according to the method described above and involves a plurality of sol-gel layers on a substrate, the plurality of sol-gel layers may include at least one organic CIM-containing sol-gel layer and at least one inorganic CIM-containing sol-gel layer, the organic CIM comprising a Zn-Al layered double hydroxide (LDH) composition may involve nanocarriers of Zn-Al LDH; and an organic corrosion inhibiting compound intercalated in the nanocarriers of Zn-Al LDH, the inorganic CIM may involve a Zn-Al layered double hydroxide (LDH) composition may involve nanocarriers of Zn-Al LDH; and an inorganic corrosion inhibiting compound
20 intercalated in the nanocarriers of Zn-Al LDH.
25 intercalated in the nanocarriers of Zn-Al LDH.

 The substrate may involve an aluminum substrate or an aluminum alloy substrate.

The organic CIM may be an imidazole, a triazole, a tetrazole, a thiazole, a thiadiazole, a benzimidazole, a benzotriazole, a benzothiazole, a quinoline, phytic acid, an organophosphonic acid, or an oil.

5 The inorganic corrosion inhibiting compound may be a vanadate, a molybdate, a tungstate, a phosphate, a manganate, a permanganate, or an aluminate.

A better understanding of the methods and formulations for sol-gel coating of the present disclosure, as well as an appreciation of the above and additional advantages thereof, will be afforded to those of skill in the art by a consideration of
10 the following detailed description of one or more example embodiments thereof. In this description, reference is made to the various views of the appended sheets of drawings, which are briefly described below, and within which, like reference numerals are used to identify like ones of the elements illustrated therein.

15 **BRIEF DESCRIPTION OF THE DRAWINGS**

FIG. 1 illustrates an example process for preparing a corrosion inhibiting material in accordance with an embodiment of the present disclosure.

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FIG. 2 illustrates an example process for preparing a Zn-Al layered double hydroxide (LDH) composition in accordance with an embodiment of the present disclosure.

FIG. 3 illustrates an example process for preparing a sol-gel composition in accordance with an embodiment of the present disclosure.

FIG. 4 illustrates an example process for forming a corrosion-resistant coating that includes one or more sol-gel layers on a substrate in accordance with an embodiment of the present disclosure.

FIG. 5 illustrates an example corrosion-resistant coating that includes an inorganic CIM-containing sol-gel layer and an inorganic CIM-containing sol-gel layer formed by the process of FIG. 4 in accordance with embodiments of the present disclosure.

FIG. 6A is an SEM image of a Zn-Al layered double hydroxide (LDH) powder as prepared by the process of FIG. 2.

FIG. 6B is an energy-dispersive X-ray spectrum of the Zn-Al LDH composition of FIG. 6A.

FIG. 7A is an SEM image of a mercaptobenzothiazole-exchanged Zn-Al LDH composition as prepared by the process of FIG. 3.

FIG. 7B is an energy-dispersive X-ray spectrum of the mercaptobenzothiazole-exchanged Zn-Al LDH composition of FIG. 7A.

FIG. 8A is an SEM image of a vanadate-exchanged Zn-Al LDH composition as prepared by the process of FIG. 3.

FIG. 8B is an energy-dispersive X-ray spectrum of the vanadate -exchanged Zn-Al LDH composition of FIG. 8A.

FIGS. 9A and 9B are images of sol-gel coated substrates formed by the process of FIG. 4 after a corrosion-resistance test.

FIG. 9C is an image of a chrome conversion coated substrate after a corrosion-resistance test.

FIG. 9D is an image of an uncoated substrate after a corrosion-resistance test.

FIG. 10 is an image of a primer applied sol-gel coated substrate formed by the process of FIG. 4 after an adhesion test.

DETAILED DESCRIPTION

5 The following description is merely exemplary in nature and is not intended to limit the present disclosure, application, or uses.

The terms “substituent”, “radical”, “group”, “moiety,” and “fragment” may be used interchangeably.

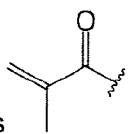
10 Singular forms “a” and “an” may include plural reference unless the context clearly dictates otherwise.

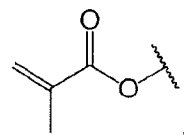
The number of carbon atoms in a substituent can be indicated by the prefix “C_{A-B}” where A is the minimum and B is the maximum number of carbon atoms in the substituent.

15 The term “alkyl” embraces a linear or branched acyclic alkyl radical containing from **1** to about **15** carbon atoms. In some embodiments, alkyl is a C₁₋₁₀ alkyl, C₁₋₆ alkyl, or C₁₋₃ alkyl radical. Examples of alkyl include, but are not limited to, methyl, ethyl, propyl, isopropyl, butyl, isobutyl, *tert*-butyl, *sec*-butyl, pentan-3-yl

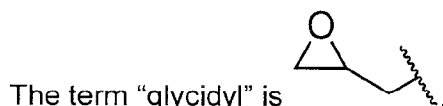
(i.e., ) , and the like.

20 The term “alkoxy” is RO– where R is alkyl. Non-limiting examples of alkoxy include methoxy, ethoxy, propoxy, n-butyloxy, and *tert*-butyloxy. The terms “alkyloxy”, “alkoxy,” and “alkyl-O-” may be used interchangeably.

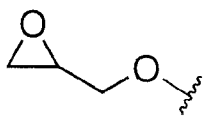
The term “methacryl” is 

The term “methacryloxy” is 

The term "methacryloxyalkyl" embraces alkyl substituted with methacryloxy. Non-limiting examples of methacryloxyalkyl include methacryloxyethyl, methacryloxypropyl, and methacryloxybutyl.



5 The term "glycidyloxy" is



The terms "glycidyloxy" and "glycidoxy" may be used interchangeably.

The term "glycidoxyalkyl" embraces alkyl substituted with glycidoxy. Non-limiting examples of glycidoxyalkyl include, glycidoxyethyl, and glycidoxypropyl, and glycidoxybutyl. The terms "glycidyloxyalkyl" and "glycidoxyalkyl" may be used

10 interchangeably.

The term "aminoalkyl" embraces an amino radical attached to a parent molecular scaffold through an alkyl radical (e.g., NH_2 -alkyl-scaffold).

The term "aryl" refers to any monocyclic, bicyclic, or tricyclic cyclized carbon radical, wherein at least one ring is aromatic. An aromatic radical may be fused to a

15 non-aromatic cycloalkyl or heterocyclyl radical. Aryl may be substituted or unsubstituted. Examples of aryl include phenyl and naphthyl.

The term "aralkyl" embraces aryl attached to a parent molecular scaffold through alkyl and may be used interchangeably with the term "arylalkyl." Examples of aralkyl include benzyl, diphenylmethyl, triphenylmethyl, phenylethyl, and

20 diphenylethyl. The terms "benzyl" and "phenylmethyl" may be used interchangeably.

The term "silane" is a compound containing silicon.

The term "organosilane" is a silane having at least one silicon to carbon bond.

25 The term "alkoxysilane" is a silane having at least one silicon to alkoxy bond.

The term "organoalkoxysilane" is a silane having at least one silicon to carbon bond and at least one silicon to alkoxy bond.

The term "about," as used herein when referring to a measurable value such as an amount, concentration, time and the like, is meant to encompass variations of $\pm 20\%$, $\pm 10\%$, $\pm 5\%$, $\pm 1\%$, $\pm 0.5\%$, or even $\pm 0.1\%$ of the specified value.

Compositions and processes relating to sol-gel coating of substrates such as metal or metal alloy substrates (e.g., aluminum substrates, aluminum alloy substrates (e.g., AA **2024**, AA**6061**, or AA**7075**), or other substrates) are provided. Sol-gel coating may be used as a chrome-free pretreatment on substrates prior to the application of organic coatings such as primer and paint. The pretreatment may be performed by applying a layer of a sol-gel composition that includes a corrosion inhibiting material (CIM). The sol-gel composition is obtained as a product of hydrolysis and condensation of a mixture of organosilanes and a metal alkoxide, along with a corrosion inhibitor (also referred to as a corrosion inhibiting compound) encapsulated in nanocarriers (also referred to as nanocontainers or nanoparticles) made up of layered double hydroxide (LDH) such as Zn-Al LDH. Nanocarriers have a size ranging from about **1** nm to about **1000** nm. Ultraviolet (UV) radiation is used to densify the sol-gel layer in addition to, or instead of, thermal curing the sol-gel layer. Thermal curing may include exposing the sol-gel layer to a high temperature (e.g., in a hot air circulated oven). Alternatively, or in addition, thermal curing may include exposing the sol-gel layer to infrared (IR) radiation or near IR radiation, which reduces curing time. The sol-gel coating composition may be low temperature curable, may provide excellent barrier protection, and may possess self-healing properties to render prolonged corrosion protection. Further, the sol-gel layers formed using the sol-gel coating composition may release corrosion inhibiting compounds on demand.

FIG. **1** illustrates an example process **100** for preparing a corrosion inhibiting material. The corrosion inhibiting material includes a layered double hydroxide (LDH) composition (e.g., a Zn-Al LDH composition) encapsulating one or more corrosion inhibiting compounds. The corrosion inhibiting material may be an organic corrosion inhibiting material that includes one or more organic corrosion inhibiting compounds, an inorganic corrosion inhibiting material that includes one or

more organic corrosion inhibiting compounds, or a combination corrosion inhibiting material that includes one or more organic corrosion inhibiting compounds and one or more inorganic corrosion inhibiting compounds.

At block **102**, a solution of corrosion inhibiting compound is prepared. For example, an organic corrosion inhibiting compound is dissolved or dispersed in a solvent to form the solution. In another example, an inorganic corrosion inhibiting compound is dissolved in a solvent to form the solution. In a further example, an organic corrosion inhibiting compound and an inorganic corrosion inhibiting compound is dissolved in a solvent to form the solution.

In an aspect, the organic corrosion inhibiting compound is an imidazole, a triazole, a tetrazole, a thiazole, a thiadiazole, a benzimidazole, a benzotriazole, a benzothiazole, a quinoline, phytic acid, an organophosphonic acid, or an oil. The oil includes saturated and/or unsaturated fatty acids such as stearic acid, palmitic acid, oleic acid, linoleic acid, and/or linolenic acid. The oil may be a vegetable oil such as linseed oil or other vegetable oil.

Specific examples of the organic corrosion inhibiting compound include 1-(3-aminopropyl)imidazole, 1*H*-1,2,3-triazole, 4-methyl-4*H*-1,2,4-triazole-3-thiol, 1,2,4-triazole-3-carboxylic acid, 3-amino-1,2,4-triazole-5-thiol, 4*H*-1,2,4-triazol-4-amine, 3-mercapto-4-methyl-4*H*-1,2,4-triazole, 5-phenyl-1*H*-1,2,4-triazole-3-thiol, 1-methyl-1*H*-tetrazole-5-thiol, 1*H*-tetrazole-5-acetic acid, 4-methyl-1,3-thiazole-5-carboxylic acid, 1,3,4-thiadiazole-2,5-dithiol, 1*H*-benzimidazole-2-carboxylic acid, 1*H*-benzotriazole (BTA), 2-mercaptobenzothiazole (MBT), 8-hydroxyquinoline, phytic acid, amino tris(methylenephosphonic acid) (ATMP), ethylenediamine tetra(methylenephosphonic acid) (EDTMP), 1-hydroxyethylidene-1,1-diphosphonic acid (HEDP), diethylenetriamine penta(methylenephosphonic acid) (DTPMP), and linseed oil.

In an aspect, the inorganic corrosion inhibiting compound is a salt of an oxyanion of a transition metal, a post-transition metal, a metalloid, or a polyatomic non-metal.

In another aspect, the inorganic corrosion inhibiting compound is a vanadate, a molybdate, a tungstate, a phosphate, a manganate, a permanganate, or an aluminate.

Specific examples of the inorganic corrosion inhibiting compound include sodium metavanadate, potassium permanganate, sodium molybdate, and sodium tungstate.

At block **104**, a Zn-Al LDH composition is prepared. For example, the Zn-Al LDH compound may be prepared by a process **200** of FIG. 2.

At block **106**, the Zn-Al LDH composition is added to the solution of the corrosion inhibiting compound. For example, the Zn-Al LDH composition in an amount ranging from about **5** to about **100** g per **1** L of the solution is added to the solution with stirring and stirring is continued for a time period ranging from **3** to about **48** h. The amount of the Zn-Al LDH composition may be **5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, or 100** g per **1** L of the solution, where any value may form an upper end point or a lower end point, as appropriate. The time period may be about **3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 33, 36, 39, 42, 45, or 48** h, where any value may form an upper end point or a lower end point, as appropriate. A corrosion inhibitor encapsulated LDH precipitate is formed as a result of block **106**. The Zn-Al LDH is intercalated with the corrosion inhibiting compound such that the Zn-Al LDH composition functions as nanocontainers that encapsulate the corrosion inhibiting compound.

At block **108**, the precipitate of the solution of the corrosion inhibiting compound is collected, for example, by centrifugation. The precipitate is washed at block **110** and dried at block **112** to form the corrosion inhibiting material. For example, the precipitate is washed with hot water until the pH of the supernatant is neutral, and then dried in a drying oven. The corrosion inhibiting material includes a corrosion inhibiting compound-exchanged Zn-Al LDH composition (also referred to as a corrosion inhibiting compound-incorporated Zn-Al LDH composition, a corrosion inhibiting compound-intercalated Zn-Al LDH composition or a corrosion inhibiting compound-encapsulated Zn-Al LDH composition).

If an organic corrosion inhibiting compound was used in block **102**, the corrosion inhibiting material is an organic corrosion inhibiting material that includes the organic corrosion inhibiting compound encapsulated in the Zn-Al LDH composition. If an inorganic corrosion inhibiting compound was used in block **102**,
 5 the corrosion inhibiting material is an organic corrosion inhibiting material that includes the organic corrosion inhibiting compound encapsulated in the Zn-Al LDH composition. Accordingly, in embodiments in which both an inorganic corrosion inhibiting material and an organic corrosion inhibiting material are desired, process **100** may be performed twice, once using an organic corrosion inhibiting compound
 10 at block **102** and once using an inorganic corrosion inhibiting compound at block **102**.

In some embodiments, a combination corrosion inhibiting material that includes the Zn-Al LDH composition encapsulating both an organic corrosion inhibiting compound and an inorganic corrosion inhibiting compound may be formed
 15 by mixing an organic corrosion inhibiting material and an inorganic corrosion inhibiting compound each prepared by respective process **100**, or by preparing a solution including both types of corrosion inhibiting compounds at block **102** in one process **100**.

Example 1.

20 For a vanadate-based corrosion inhibiting material, **400** ml of sodium metavanadate (NaVO_3) solution having a concentration of about **0.1** M was prepared. The pH of this solution was adjusted to a pH ranging from about **8** to about **9** by addition of a NaOH solution having a concentration of about **2.0** M. To this, **10** g of a Zn-Al LDH composition was added with continuous stirring. Stirring
 25 was continued for **24** h. The powder was centrifuged after **24** h, washed with hot water until the pH of the supernatant was neutral, and followed by drying the vanadate-exchanged Zn-Al LDH composition at **60°C** for a time period ranging from about **3** to about **4** h in a drying oven. Similarly, different corrosion inhibiting materials were prepared by using a number of different molecules such as **2**-
 30 mercaptobenzothiazole, benzotriazole, **1,3,4**-thiadiazole-**2,5**-dithiol, 1-methyl-1-

tetrazole-5-thiol, 4-methyl-4H-1,2,4-triazole-3-thiol, 8-hydroxyquinoline, phytic acid, an organophosphonic acid, and linseed oil as examples. Other corrosion inhibiting materials may be prepared using other organic corrosion inhibiting compounds (e.g., imidazoles, triazoles, thiazoles, vegetable oils such as linseed oil) or inorganic corrosion inhibiting compounds in other examples.

FIG. 2 illustrates an example process 200 for preparing a Zn-Al LDH composition. For example, block 104 of FIG. 1 may be performed by process 200.

At block 202, a solution of a zinc salt (e.g., zinc nitrate or other zinc salt) and a solution of aluminum salt (e.g., aluminum nitrate or other aluminum salt) is mixed to form a solution of zinc and aluminum. For example, zinc nitrate is dissolved in a solvent, aluminum nitrate is dissolved in a solvent, and the zinc nitrate solution and the aluminum solution is mixed and stirred under nitrogen purging to form the solution of zinc and aluminum, also referred to as a mixture.

At block 204, a solution of an alkali metal salt such as a sodium salt (e.g., sodium nitrate or other sodium salt) is added to the mixture. For example, a solution of sodium nitrate is added drop-wise to the mixture while maintaining a pH ranging from about 8 to about 11 using a base solution (e.g., a 2.0 M sodium hydroxide solution or other base solution). The maintained pH may be about 8, 8.5, 9, 9.5, 10, 10.5, or 11, where any value may form an upper end point or a lower end point, as appropriate. A fluffy white precipitate is formed in the resulting mixture. At block 206, once the addition of the sodium nitrate solution is complete, the mixture is stirred vigorously under nitrogen purging for a time period ranging from about 3 hours to 24 hours. The time period may be about 3, 6, 9, 12, 15, 18, 21, or 24 h, where any value may form an upper end point or a lower end point, as appropriate.

At block 208, the precipitate of the mixture is collected, for example, by centrifugation. The precipitate is washed at block 210 and dried at block 212 to form the Zn-Al LDH composition. For example, the precipitate is washed with hot water and then dried in a drying oven.

Example 2.

A solution of **104.1** g of $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ dissolved in **25** ml water and a solution of **65.6** g of $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ dissolved in **25** ml water was mixed under vigorous stirring under N_2 purging. To this mixture, **87.5** ml of a NaNO_3 solution
 5 having a concentration of about **0.1** M, adjusted to pH **10**, was added drop-wise and maintained at a pH of about **10** by adding a NaOH having a concentration of about **2.0** M. A fluffy LDH white precipitate was formed. Once the addition was complete, the entire mixture was stirred vigorously under N_2 purging for **12** h. The precipitate was centrifuged at **6500** rpm and washed about **3** or **4** times with hot water (at
 10 **80°C**), followed by drying at **65°C** for **24** h. A Zn-Al LDH composition in the form of a powder was formed.

FIG. **3** illustrates an example process **300** for preparing a sol-gel composition. A low temperature curable matrix sol is synthesized in two parts (composition A and composition B), the two parts are mixed together, additional
 15 compounds are added and stirred, and a corrosion inhibiting material is added to obtain a sol-gel composition.

At block **302**, Composition A is prepared from an alkoxysilane such as an organoalkoxysilane. An alkoxysilane is contacted with water and an inorganic acid (e.g., HCl , HNO_3 , H_3PO_4 , or other inorganic acid) to form Composition A.

20 For example, an alkoxysilane is mixed with water and stirred, and an inorganic acid is added to the solution of the alkoxysilane and water and stirred in an ice bath until the solution turns transparent. The ratio of the number of moles of the alkoxysilane (which is equal to the number of moles of silicon from the alkoxysilane) to the number of moles of water ($n_{\text{Si}}/n_{\text{water}}$) in Composition A ranges
 25 from about **0.5** to about **2**. The ratio may be, for example, about **0.5**, **0.6**, **0.7**, **0.8**, **0.9**, **1.0**, **1.1**, **1.2**, **1.3**, **1.4**, **1.5**, **1.6**, **1.7**, **1.8**, **1.9**, or **2.0**, where any value may form an upper end point or a lower end point, as appropriate.

In an aspect, an alkoxysilane of Formula I is used as Precursor A:



30 wherein;

R_A is methacryloxyalkyl or glycidoxyalkyl; and
 R_B is alkoxy.

In another aspect, R_A is methacryloxyalkyl (e.g., methacryloxymethyl, methacryloxyethyl, methacryloxypropyl, methacryloxybutyl, or other methacryloxyalkyl) or glycidoxyalkyl (e.g., glycidoxymethyl, glycidoxyethyl, glycidoxypropyl, glycidoxybutyl); and each R_B is independently alkoxy (e.g., methoxy, ethoxy, propoxy).

Specific examples of $R_A-Si-(R_B)_3$ include 3-methacryloxypropyltrimethoxysilane, 3-methacryloxypropyltriethoxysilane, 3-glycidyloxypropyltrimethoxysilane, and 3-glycidoxypropylethoxysilane.

In some aspects, an alkoxy silane used as Precursor A of a sol-gel composition includes methacryloxyalkyl alkoxy silane (an alkoxy silane of Formula I in which R_A is methacryloxyalkyl) and/or a glycidoxyalkyl alkoxy silane (an alkoxy silane of Formula I in which the R_A is glycidoxyalkyl). The methacryloxyalkyl alkoxy silane and/or the glycidoxyalkyl alkoxy silane are used, for example, to facilitate polymerization of the sol-gel composition when exposed to UV radiation.

At block 304, Composition B is prepared from a transition metal alkoxide such as a zirconium alkoxide. A zirconium alkoxide is contacted with an organic acid such as a carboxylic acid (e.g., methacrylic acid (MAA) or other carboxylic acid) to form Composition B.

For example, the zirconium alkoxide is mixed with methacrylic acid and stirred. The ratio of the number of moles of the zirconium alkoxide (which is equal to the number of moles of zirconium from the zirconium alkoxide) to the ratio of the number of moles of methacrylic acid ((n_{Zr}/n_{MAA})) ranges from about 0.5 to about 2. The ratio may be, for example, about 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, or 2.0, where any value may form an upper end point or a lower end point, as appropriate.

In an aspect, a zirconium alkoxide of Formula II is used as Precursor B:



wherein;

R_C is alkoxy.

In another aspect, each R_C is independently alkoxy (methoxy, ethoxy, n-propoxy, isopropoxy, n-butoxy, tert-butoxy, or other alkoxy).

Specific examples of Zr-(R_C)₄ include zirconium ethoxide, zirconium n-propoxide, zirconium isopropoxide, zirconium n-butoxide, and zirconium tert-butoxide.

In some aspects, a zirconium alkoxide is used as Precursor B of a sol-gel composition, for example, to match the coefficient of thermal expansion of the sol-gel composition with a substrate. The zirconium alkoxide may be used in an amount such that the coefficient of thermal expansion of the sol-gel composition is equal to or about the coefficient of thermal expansion of the substrate.

At block **306**, Composition A and Composition B are mixed together. For example, Composition B is added to Composition A under stirring to avoid agglomeration, and the mixture of Composition A and Composition B is stirred in an ice bath and then stirred at room temperature so that the temperature of the mixture reaches room temperature.

At block **308**, one or more alkoxysilanes such as one or more organoalkoxysilanes are added to the mixture of Composition A and Composition B. One or more alkoxysilanes and an organic acid such as a carboxylic acid (e.g., methacrylic acid or other carboxylic acid) are contacted with the mixture of Composition A and Composition B to form a sol-gel composition.

For example, each of one or more alkoxysilanes are added to the mixture and stirred. Then, methacrylic acid is added to the resulting mixture and stirred. Optionally, an inorganic acid is added before, together with, or after the organic acid.

In an aspect, one or more alkoxysilane of Formula III is used as Precursor C:



wherein;

R_D is aryl, aralkyl, glycidoxyalkyl, or aminoalkyl; and

R_E is alkoxy.

In another aspect, R_D is aryl (e.g., phenyl or other aryl), aralkyl (e.g., benzyl, phenylethyl, phenylpropyl, or other aralkyl), glycidoxyalkyl (e.g., glycidomethyl, glycidoxyethyl, glycidoxypropyl, glycidoxybutyl, or other glycidoxyalkyl), or
 5 aminoalkyl (e.g., aminomethyl, aminoethyl, aminopropyl, aminobutyl, or other aminoalkyl); and each R_E is independently alkoxy (e.g., methoxy, ethoxy, propoxy).

Specific examples of R_D-Si-(R_E)₃ include phenyltrimethoxysilane, phenyltriethoxysilane, **3**-glycidoxypropyltrimethoxysilane, **3**-glycidoxypropyltriethoxysilane, **3**-aminopropyltrimethoxysilane, and
 10 **3**-aminopropyltriethoxysilane.

In some aspects, one or more alkoxysilanes used as Precursor C of a sol-gel composition include an aryl alkoxysilane (an alkoxysilane of Formula III in which R_D is aryl), a glycidylalkoxyalkyl alkoxysilane (an alkoxysilane of Formula III in which R_D is glycidoxyalkyl), and/or an aminoalkyl alkoxysilane (an alkoxysilane of Formula III in
 15 which R_D is aminoalkyl). The aryl alkoxysilane is used, for example, to improve the barrier properties of a coating formed from the sol-gel composition. The glycidylalkoxyalkyl alkoxysilane is used, for example, to generate a thick coating. The aminoalkyl alkoxysilane is used, for example, to improve the adhesion of the sol-gel composition to a substrate when deposited.

20 In an example, an aryl alkoxysilane is added to the mixture and stirred. Then, an aminoalkyl alkoxysilane is added to the mixture and stirred. Then, a glycidylalkoxyalkyl alkoxysilane is added to the mixture. Then, methacrylic acid is added and stirred. An inorganic acid may also be added. The order of the alkoxysilanes that are added may be changed in other examples.

25 The total amount of the alkoxysilanes, which includes the alkoxysilane used in block **302** and the one or more alkoxysilanes used in block **308**, and the amount of the zirconium alkoxide used in block **304** are such that the sol-gel composition has a ratio of a number of moles of alkoxysilanes (which is equal to the number of moles of silicon from the alkoxysilanes) to a number of moles of zirconium alkoxide
 30 (which is equal to the number of moles of zirconium from the zirconium alkoxide)

(n_{Si}/n_{Zr}) ranging from about **2** to about **10**. The ratio of the number of moles of silicon to the number of moles of zirconium (n_{Si}/n_{Zr}) may be about **2, 3, 4, 5, 6, 7, 8, 9, or 10**, where any value may form an upper end point or a lower end point, as appropriate.

5 In some examples, one or more of the stirring performed in blocks **302, 304, 306, and/or 308** may be performed for a time period ranging from about **10** min to about **120** min. The stirring performed in blocks **302, 304, 306, and/or 308**, may be performed for a time period of about **10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, or 120** min, where any value may form an upper end point or a lower end point, as
10 appropriate.

At block **310**, the sol-gel composition is diluted with a solvent such as alcohol (e.g., isopropanol or other solvent) and stirred. The dilution of the sol-gel composition, the stirring to age the sol-gel composition, or both (e.g., block **310** entirely) may be omitted in some embodiments.

15 For example, the sol-gel composition is diluted with isopropanol in a weight ratio of about **1:1**. The diluted sol-gel composition, or the sol-gel composition formed by block **308** if dilution is omitted, is stirred to age the sol-gel composition for a time period ranging from **1** to about **24** hours (h). The stirring to age the sol-gel composition may be performed for a time period of about **1, 2, 3, 4, 5, 6, 9, 12, 15, 18, 21, or 24** h, where any value may form an upper end point or a lower end point,
20 as appropriate.

At block **312**, a photoinitiator is added to the sol-gel composition formed by block **310** (or by block **308** for embodiments in which block **310** is omitted) and stirred.

25 For example, a photoinitiator in an amount ranging from about **0.5** to about **3** parts by weight per **100** parts by weight of the sol-gel composition (the weight of the sol-gel with the photoinitiator to be added or, alternatively, the weight of the sol-gel before adding the photoinitiator) is added, and the sol-gel composition with the photoinitiator is stirred. The amount of the photoinitiator may be about **0.5, 1, 1.5, 2, 2.5, or 3** parts by weight per **100** parts of the sol-gel composition, where any
30

value may form an upper end point or a lower end point, as appropriate. The stirring may be performed for a time period ranging from about **10** to about **60** min. The stirring may be performed for a time period of about **10, 20, 30, 40, 50, or 60** min, where any value may form an upper end point or a lower end point, as appropriate. Once the photoinitiator is added, exposure of the sol-gel composition to light may be avoided by covering a container for the sol-gel composition (e.g., using aluminum foil) and/or storing in an amber-colored container.

At block **314**, a corrosion inhibiting material is added to the sol-gel composition to form a CIM-containing sol-gel composition.

For example, a corrosion inhibiting material prepared by process **100** of FIG. **1** in an amount ranging from about **0.5** to about **10** parts by weight per **100** parts by weight of the sol-gel composition (the weight of the sol-gel with the corrosion inhibiting material to be added or, alternatively, the weight of the sol-gel before adding the corrosion inhibiting material) is added to the sol-gel composition and stirred to form a CIM-containing sol-gel composition. The amount of the corrosion inhibiting material may be about **0.5, 1, 1.5, 2, 2.5, 3, 4, 5, 6, 7, 8, 9, or 10** parts by weight per **100** parts by weight of the sol-gel composition, where any value may form an upper end point or a lower end point, as appropriate.

In another example, a corrosion inhibiting material in an amount of the sol-gel composition in an amount ranging from about **1** to about **10** parts by weight per **100** parts by weight of the solid content of the sol-gel composition is added to the sol-gel composition and stirred to form a CIM-containing sol-gel composition. The amount of the corrosion inhibiting material may be about **1, 2, 3, 4, 5, 6, 7, 8, 9, or 10** parts by weight per **100** parts by weight of the solid content of the sol-gel composition, where any value may form an upper end point or a lower end point, as appropriate. The sol-gel composition may have a solid content ranging from about **10** to about **70** parts by weight per **100** parts by weight of the sol-gel composition. The sol-gel composition may have a solid content of about **10, 20, 30, 40, 50, 60, or 70** parts by weight per **100** parts by weight of the sol-gel composition, where any value may form an upper end point or a lower end point, as appropriate.

If an organic corrosion inhibiting material is added, an organic CIM-containing sol-gel composition is formed. If an inorganic corrosion inhibiting material is added, an inorganic CIM-containing sol-gel composition is formed. Accordingly, in embodiments in which both an inorganic CIM-containing sol-gel composition and an organic corrosion inhibiting material are desired, process **300** may be performed twice, once using an organic CIM at block **314** and once using an inorganic CIM at block **314**. Alternatively, the sol-gel composition may be divided into two or more batches and block **314** may be performed for each desired CIM-containing sol-gel compositions using a respective CIM.

Blocks **302-314** of process **300** may be performed in the order presented or in a different order and/or one or more blocks may be omitted in some embodiments. For example, blocks **310**, **312**, and **314** may be performed in a different order.

Example 3.

Composition A was synthesized by mixing **171.5 g** of **3-methacryloxypropyltrimethoxysilane** and **17.0 g** of water in a glass jar loaded on a magnetic stirrer. **5.5 grams** of **0.1 N HCl** was further added to the mixture. The solution was stirred in an ice bath till the solution turned transparent. Although **3-methacryloxypropyltrimethoxysilane** was used in this example, one or more other alkoxysilanes of Formula I may be used in place of, or in addition to, **3-methacryloxypropyltrimethoxysilane** in other examples. Also, although HCl was used in this example, one or more other inorganic acids may be used in place of, or in addition to, HCl in other examples.

Composition B was synthesized by mixing **11.8 g** of methacrylic acid and **45.2 g** of zirconium n-propoxide under vigorous stirring. Stirring was continued for about **2 h**. Although zirconium n-propoxide was used in this example, one or more other zirconium alkoxides of Formula II may be used in place of, or in addition to, zirconium n-propoxide in other examples.

Composition B was added to composition A under vigorous stirring to avoid agglomeration by placing the mixture in an ice bath, and the mixture was stirred for

about 1 h. The jar containing the mixture was removed from the ice bath and stirred at room temperature for at least 1 hour for the mixture to come to room temperature.

Then 100 g of phenyltrimethoxysilane was added to the mixture of
5 Composition A and Composition B and stirred for about 1 h, and then 100 g of 3-aminopropyltrimethoxysilane was added and stirred for about 1 hour. After completion of the 1 h of stirring with 3-aminopropyltrimethoxysilane, 25 grams of 3-glycidoxypropyltrimethoxysilane was added. Finally, 10 grams of methacrylic acid was added followed by 4 g of 0.1 N HCl and stirred for a further duration of 1 h.
10 Although phenyltrimethoxysilane, 3-aminopropyltrimethoxysilane, and 3-glycidoxypropyltrimethoxysilane were used in this example, one or more other methoxysilanes of Formula III may be used in place of, or in addition to, phenyltrimethoxysilane, 3-aminopropyltrimethoxysilane, and/or 3-glycidoxypropyltrimethoxysilane in other examples.

15 The resulting mixture was diluted with isopropanol in a weight ratio of about 1:1 and stirred for about 3 hours at room temperature for aging. Although the mixture was stirred for about 3 hours, the mixture may be aged for a different time period in other examples, such as stirring overnight. Approximately 1 kg of sol-gel composition ready for coating application was formed. A photoinitiator,
20 IRGACURE® 184, in the amount of about 2 % by weight per 100 % of the sol-gel composition (including the photoinitiator) was added and stirred for 30 min. Although IRGACURE® 184 was used in this example, one or more other photoinitiators may be used in place of, or in addition to, IRGACURE® 184 in other examples. After adding IRGACURE® 184, the sol-gel composition was kept away
25 from light to avoid the sol-gel composition from interacting with light.

A corrosion inhibiting material that includes a vanadate-encapsulated Zn-Al LDH composition was added to one batch of the sol-gel composition to form an inorganic CIM-containing sol-gel composition. Although vanadate was used in this example, other inorganic corrosion inhibiting compounds may be used in other
30 examples. A corrosion inhibiting material that includes a mercaptobenzothiazole-

encapsulated Zn-Al LDH composition was added to another batch of the sol-gel composition to form an organic CIM-containing sol-gel composition. Although 2-mercaptobenzothiazole was used in this example, other inorganic corrosion inhibiting compounds may be used in other examples. The solid content of the sol-gel composition was about **28** parts by weight per **100** parts by weight of the sol-gel composition (including the photoinitiator). To add **5** parts by weight of the corrosion inhibiting material per **100** parts by weight of the solid content of the sol-gel composition, **1.4 g** of the respective corrosion inhibiting compound was added per **100 g** of each batch of the sol-gel composition and stirred overnight. Although the stirring was carried out overnight in this example, other time periods may be used in other examples (e.g., **2** hours may be sufficient for uniform dispersion).

FIG. 4 illustrates an example process **400** for forming a corrosion-resistant coating that includes one or more sol-gel layers (e.g., one or more sol-gel coatings) on a substrate such as a panel (e.g., an aluminum substrate, an aluminum alloy substrate, or other substrate). One or more layers of the sol-gel composition are applied to a substrate, each of the one or more layers is cured by UV light, and then the one or more layers of the sol-gel composition are thermally cured.

At block **402**, an organic CIM sol-gel composition prepared by process **300** of FIG. 3 is applied to a substrate. For example, the organic CIM sol-gel composition is contacted with the substrate to form an organic CIM-containing sol-gel layer such as by dipping the substrate in the organic CIM sol-gel composition, by immersing the substrate in the organic CIM sol-gel composition, by spraying the organic CIM sol-gel composition on the substrate, and/or by other methods of applying the organic CIM sol-gel composition to the substrate. If dip coating is used, the organic CIM-containing sol-gel layers can be deposited using a withdrawals speed ranging from about **1** to about **15** mm/s (e.g., about **5** to about **12** mm/s, about **10** mm/s, or other withdrawal speed). The withdrawal speed may be about **1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, or 15** mm/s, where any value may form an upper end point or a lower end point, as appropriate.

At block **404**, the organic CIM-containing sol-gel layer formed by block **402** is cured by UV radiation. For example, the UV radiation has a light dose ranging from about **500** to about **1000** mJ/cm². The UV radiation may have a light dose of about **500, 550, 600, 650, 700, 750, 800, 850, 900, 950, or 1000** mJ/cm², where any value
 5 may form an upper end point or a lower end point, as appropriate. The curing by UV radiation may be performed for a time period ranging from about **0.5** to about **30** min. The time period may be about **0.5, 1, 2, 3, 4, 5, 10, 15, 20, 25, or 30** min, where any value may form an upper end point or a lower end point, as appropriate.

At block **406**, an inorganic CIM sol-gel composition prepared by process **300**
 10 of FIG. **3** is applied to a substrate. For example, the inorganic CIM sol-gel composition is contacted with the substrate to form an inorganic CIM-containing sol-gel layer such as by dipping the substrate in the inorganic CIM sol-gel composition, by immersing the substrate in the inorganic CIM sol-gel composition, by spraying the inorganic CIM sol-gel composition on the substrate, and/or by other methods of
 15 applying the inorganic CIM sol-gel composition to the substrate. If dip coating is used, the inorganic CIM-containing sol-gel layers can be deposited using a withdrawals speed ranging from about **1** to about **15** mm/s (e.g., about **5** to about **12** mm/s, about **10** mm/s, or other withdrawal speed). The withdrawal speed may be about **1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, or 15** mm/s, where any value
 20 may form an upper end point or a lower end point, as appropriate.

At block **408**, the inorganic CIM-containing sol-gel layer formed by block **402** is cured by UV radiation. For example, the UV radiation has a light dose ranging from about **500** to about **1000** mJ/cm². The UV radiation may have a light dose of about **500, 550, 600, 650, 700, 750, 800, 850, 900, 950, or 1000** mJ/cm², where
 25 any value may form an upper end point or a lower end point, as appropriate. The curing by UV radiation may be performed for a time period ranging from about **0.5** to about **30** min. The time period may be about **0.5, 1, 2, 3, 4, 5, 10, 15, 20, 25, or 30** min, where any value may form an upper end point or a lower end point, as appropriate.

Blocks **402-404** are performed before blocks **406-408**, but the order may be reversed in other embodiments. In some embodiments, blocks **402-404** are repeated to form one or more additional organic CIM-containing sol-gel layers and/or blocks **406-408** are repeated to form one or more additional inorganic CIM-
 5 containing sol-gel layers. Blocks **402-404** and/or blocks **406-408** may be repeated until the desired number of respective sol-gel layers is formed, in an order corresponding to the desired order of the respective CIM-containing sol-gel layers. In some embodiments, blocks **404** and/or **408** may be omitted for at least one of the sol-gel layers (e.g., at least one of the sol-gel layers may be air dried or thermally
 10 cured instead of curing using UV radiation). For example, curing using UV radiation may be omitted for the final, top-most sol-gel layer among the desired sol-gel layers.

At block **410**, the sol-gel layers are thermally cured. For example, the multiple sol-gel layers including an organic CIM-containing sol-gel layer and an
 15 inorganic CIM-containing sol-gel layer are thermally cured at a temperature ranging from about **70** to about **90** °C. The multiple sol-gel layers may be thermally cured at about **70, 75, 80, 85, or 90** °C, where any value may form an upper end point or a lower end point, as appropriate. The thermal curing may be performed for a time period ranging from about **40** to about **120** minutes. The time period may be **40,**
 20 **50, 60, 70, 80, 90, 100, 110, or 120** min, where any value may form an upper end point or a lower end point, as appropriate. In an example, the thermal curing is performed in a hot air circulated oven. Alternatively, or in addition to, thermal curing at a high temperature, the thermal curing includes exposing the sol-gel layers to infrared (IR) radiation, near IR radiation, and/or microwave radiation. For example,
 25 the sol-gel layers are exposed to IR and/or near IR radiation for a time period ranging from about **10** to about **60** min (e.g., **30** min or other time period). The time period of exposure to IR and/or near IR may be about **10, 15, 20, 25, 30, 35, 40, 45, 50, 55, or 60** min, where any value may form an upper end point or a lower end point, as appropriate.

At block **412**, primer and/or paint is applied on the sol-gel layers of the substrate. For example, the primer is applied on the top-most sol-gel layer, and the paint is applied on the primer. The cured sol-gel layers may not only provide corrosion resistance to the substrate but may also facilitate adherence of the primer and/or paint to the substrate.

Example 4.

Each sol-gel layer of a substrate was UV cured using a conveyORIZED UV curing unit. UV curing was performed on both sides of the substrate using three-medium-pressure-mercury lamp conveyORIZED UV curing unit. The lamps provided an output of about **120 W/cm** with a total wattage/lamp (**1 m** long) = **12 kW**. The belt speed was maintained at about **2 m/min** during curing. The light dose as measured by a UV radiometer was **871 mJ/cm²** in the UV-C region. After UV curing for about **5 minutes**, the sol-gel layer coated substrate was subjected to thermal curing in an air circulated oven at **80°C** for an hour.

FIG. **5** illustrates an example corrosion-resistant coating that includes an inorganic CIM-containing sol-gel layer and an inorganic CIM-containing sol-gel layer formed by process **400** of FIG. **4**. An organic CIM-containing sol-gel composition is contacted with substrate **502** to provide organic CIM-containing sol-gel layer **504**, and sol-gel layer **504** is UV cured. Then, an inorganic CIM-containing sol-gel composition is contacted with sol-gel layer **504** to provide an inorganic CIM-containing sol-gel layer **506** on sol-gel layer **504**, and sol-gel layer **506** is UV cured. Sol-gel layer **506** is not UV cured in other examples. Then, sol-gel layers **504** and **506** are thermally cured. The order of sol-gel layers **504** and **506** may be reversed in other examples. Further, although sol-gel layers including one organic CIM-containing sol-gel layer and one inorganic CIM-containing sol-gel layer is shown in FIG. **5**, the corrosion-resistant coating may include more than one of each type of sol-gel layer in other examples.

FIG. **6A** is a scanning electron microscopy (SEM) image of a Zn-Al LDH composition as prepared by process **200** of FIG **2**, and FIG. **6B** is an energy-dispersive X-ray spectra of the Zn-Al LDH composition. FIG. **7A** is an SEM image

of a mercaptobenzothiazole-exchanged LDH composition as prepared by process 300 of FIG. 3 (e.g., as described in Example 3), and FIG. 7B is an energy-dispersive X-ray spectra of the mercaptobenzothiazole-exchanged Zn-Al LDH composition. FIG. 8A is an SEM image of a vanadate-exchanged LDH composition as prepared by process 300 of FIG. 3 (e.g., as described in Example 3), and FIG. 8B is an energy-dispersive X-ray spectra of the vanadate -exchanged Zn-Al LDH composition.

FIG. 9A is an image of a sol-gel coated substrate 900, formed by the process of FIG. 4, after a corrosion-resistance test. Sol-gel coated substrate 900 has an organic CIM-containing sol-gel layer that includes a mercaptobenzothiazole-exchanged LDH composition as its organic corrosion inhibiting material formed on a substrate, and an inorganic CIM-containing sol-gel layer that includes a vanadate-exchanged LDH composition as its inorganic corrosion inhibiting material formed on the organic CIM-containing sol-gel layer. Sol-gel coated substrate 900 was exposed to a 5% salt spray. FIG. 9A shows sol-gel coated substrate 900 after 336 h of the salt spray test.

FIG. 9B is an image of a sol-gel coated substrate 910, formed by the process of FIG. 4, after a corrosion-resistance test. Sol-gel coated substrate 910 has an organic CIM-containing sol-gel layer that includes a phytic acid-exchanged LDH composition as its organic corrosion inhibiting material formed on a substrate, and an inorganic CIM-containing sol-gel layer that includes a vanadate-exchanged LDH composition as its inorganic corrosion inhibiting material formed on the organic CIM-containing sol-gel layer. Sol-gel coated substrate 910 was exposed to a 5% salt spray. FIG. 9B shows sol-gel coated substrate 910 after 336 h of the salt spray test.

FIG. 9C is an image of a chromated substrate 920, formed by chrome conversion coating, after a corrosion-resistance test. Chrome conversion coated substrate 920 was exposed to a 5% salt spray. FIG. 9C shows chrome conversion coated substrate 920 after 336 h of the salt spray test.

FIG. 9D is an image of an uncoated aluminum alloy substrate **930** after a corrosion-resistance test. Uncoated substrate **930** was exposed to a **5%** salt spray. FIG. 9D shows uncoated substrate **930** after **336** h of the salt spray test, which was severely corroded.

5 Sol-gel coated substrate **900** shown in FIG. 9A and sol-gel coated substrate **910** shown in FIG. 9B had no corrosion. Chrome conversion coated substrate **920** shown in FIG. 9C, although not corroded, had discolored. Chrome conversion coating followed by applying a primer and paint is currently considered the state of the art for corrosion-resistant coatings for metal or metal alloy substrates.
10 Accordingly, sol-gel coated substrates **900** and **910** shown in FIGS. 9A and 9B, respectively, may have a corrosion resistance that is comparable or better than that of chrome conversion coated substrate **920**.

FIG. 10 is an image of a primer applied sol-gel coated substrate **1000** formed by process **400** of FIG. 4 after an adhesion test. A scribed wet tape adhesion test
15 on primer applied sol-gel coated substrate **1000** was performed as follows. Primer applied sol-gel coated substrate **1000** was immersed in tap water for **24** hours. After **24** hours, primer applied sol-gel coated substrate **1000** was removed and blot dry with cheesecloth. Using a metal cutting tool (e.g., a razor blade, a scalpel, a knife, or other cutting tool), two parallel **2** inch long scratches were made, **3/4** to **1**
20 inch apart, through the coating and to the substrate. The parallel scratches were joined with two intersecting lines, or an "X" pattern. An adhesive tape was applied over the scratched pattern, and the tape was pressed against the test surface with firm hand pressure. (Alternatively, adhesive tape may be applied using a roller). One end of the tape was lifted such that a length of about **2** inches on that end of
25 the tape was not in contact with the test surface. The minimum remaining length of the tape in contact with the test surface was approximately **4** inches. The lifted-up **2** inch segment of the tape was positioned to create an approximate **45** degree angle with the test surface. The remainder of the tape was removed by pulling up and back with an abrupt motion. For this adhesion test, if the primer comes off the
30 substrate, it implies poor adhesion. If the primer does not come off the substrate, it

implies good adhesion. As shown by the result in FIG. 10, the primer of sol-gel coated substrate **1000** did not come off. Thus, the sol-gel layers formed by process **400** of FIG. 4 may have good adhesion to organic paint such as primer and/or paint.

When introducing elements of the embodiments described or exemplary
5 aspects thereof, the articles “a,” “an,” “the,” and “said” are intended to mean that there are one or more of the elements. The terms “comprising,” “including,” and “having” are intended to be inclusive and mean that there may be additional elements other than the listed elements. Although specific embodiments have been described, the details of these embodiments are not to be construed as limitations.
10 Different aspects, embodiments and features are defined in detail herein. Each aspect, embodiment or feature so defined may be combined with any other aspect(s), embodiment(s) or feature(s) (preferred, advantageous or otherwise) unless clearly indicated to the contrary.

**EMBODIMENTS IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS
CLAIMED ARE DEFINED AS FOLLOWS:**

1. A method of forming a corrosion resistant coating on a substrate, the
5 method comprising:

adding a Zn-Al layered double hydroxide (LDH) composition to a first
solution comprising a first corrosion inhibiting compound and stirring;

10 collecting a precipitate of the first solution;

washing and drying the precipitate of the first solution to form a first
corrosion inhibiting material (CIM), the first CIM comprising the first
corrosion inhibiting compound intercalated in the Zn-Al LDH
15 composition;

adding the first CIM to a first sol-gel composition to form an organic
CIM-containing sol-gel composition, wherein the first corrosion
inhibiting compound is an organic corrosion inhibiting compound, and
20 wherein the first CIM is an organic CIM;

adding the Zn-Al LDH composition to a second solution comprising an
inorganic corrosion inhibiting compound and stirring;

25 collecting a precipitate of the second solution;

washing and drying the precipitate of the second solution to form an
inorganic CIM, the inorganic CIM comprising the inorganic corrosion
inhibiting compound intercalated in the Zn-Al LDH composition;

30 adding the inorganic CIM to a second sol-gel composition to form an
inorganic CIM-containing sol-gel composition;

applying the organic CIM-containing sol-gel composition on a substrate to form an organic CIM-containing sol-gel layer;

5 curing the organic CIM-containing sol-gel layer by UV radiation;
applying the inorganic CIM-containing sol-gel composition on the substrate to form an inorganic CIM-containing sol-gel layer;

10 curing the inorganic CIM-containing sol-gel layer by the UV radiation;
and

thermally curing a plurality of sol-gel layers comprising the organic CIM-containing sol-gel layer and the inorganic CIM-containing sol-gel layer to form a corrosion-resistant coating.

15

2. The method of claim 1, further comprising:

mixing a zinc nitrate solution and an aluminum nitrate solution and stirring under nitrogen purging to form a mixture;

20

adding a sodium nitrate solution to the mixture while maintaining a pH ranging from about 8 to about 12 and stirring under nitrogen purging;

collecting a precipitate of the mixture; and

25

washing and drying the precipitate of the mixture to form the Zn-Al LDH composition.

3. The method of claims 1 or 2, further comprising:

30

contacting a first alkoxysilane with water and an inorganic acid to form a first composition;

contacting a zirconium alkoxide with a first organic acid to form a second composition;

contacting the first composition with the second composition to form a mixture;

contacting one or more second alkoxysilanes and a second organic acid with the mixture to form the sol-gel composition, the sol-gel composition having a ratio of a number of moles of silicon to a number of moles of zirconium (n_{Si}/n_{Zr}) ranging from about 2 to about 10;

adding a photoinitiator to the sol-gel composition; and

diluting the sol-gel composition with a solvent.

4. The method of any one of claims 1 – 3, wherein the contacting to form the first composition comprises mixing the first alkoxysilane having the formula $R_A-Si-(R_B)_3$ with the water and the inorganic acid, wherein the R_A is methacryloxyalkyl or glycidyoxyalkyl, and wherein the R_B is a methoxy or ethoxy; or

wherein the contacting to form the second composition comprises mixing the zirconium alkoxide having the formula $Zr-(R_C)_4$ with methacrylic acid (MAA), and wherein the R_C is ethoxy, n-propoxy, isopropoxy, n-butyloxy, or tert-butyloxy

5. The method of any one of claims 1 – 4, wherein the contacting to form the sol-gel composition comprises:

adding the one or more second alkoxysilanes each having the formula $R_D-Si-(R_E)_3$ to the mixture, wherein the R_D is aryl, aminoalkyl, or glycidyoxyalkyl, and wherein the R_E is methoxy or ethoxy; and

adding MAA and stirring; or

5 wherein the adding of the CIM comprises adding the CIM in an amount ranging from about **1** to about **10** parts by weight per **100** parts by weight of the sol-gel composition or ranging from about **1** to about **10** parts by weight per **100** parts by weight of a solid content of the sol-gel composition.

10 **6.** The method of any one of claims **1 – 5**, further comprising:

dispersing the organic corrosion inhibiting compound comprising **1**-(3-aminopropyl)imidazole, **1H-1,2,3**-triazole, **4**-methyl-**4H-1,2,4**-triazole-**3**-thiol, **1,2,4**-triazole-**3**-carboxylic acid, **3**-amino-**1,2,4**-triazole-**5**-thiol, **4H-1,2,4**-triazol-**4**-amine, **3**-mercapto-**4**-methyl-**4H-1,2,4**-triazole, **5**-phenyl-**1H-1,2,4**-triazole-**3**-thiol, **1**-methyl-**1H**-tetrazole-**5**-thiol, **1H**-tetrazole-**5**-acetic acid, **4**-methyl-**1,3**-thiazole-**5**-carboxylic acid, **1,3,4**-thiadiazole-**2,5**-dithiol, **1H**-benzimidazole-**2**-carboxylic acid, **1H**-benzotriazole (BTA), **2**-mercaptobenzothiazole (MBT), **8**-hydroxyquinoline, phytic acid, an organophosphonic acid, a vegetable oil, or a combination thereof in a solvent to form the first solution.

7. The method of any one of claims **1 – 6**, further comprising:

25 dissolving the inorganic corrosion inhibiting compound comprising a vanadate, a molybdate, a tungstate, a phosphate, a manganate, a permanganate, an aluminate, or a combination thereof in a solvent to form the second solution.

30 **8.** The method of any one of claims **1 – 7**, wherein the substrate comprises an aluminum substrate or and aluminum alloy substrate.

9. The method of any one of claims **1 – 8**, wherein the substrate is selected from the group comprising **2024** aluminum alloy, **6061** aluminum alloy, and **7075** aluminum alloy.

5 **10.** The method of any one of claims **1 – 9**, wherein:

the curing the organic CIM-containing sol-gel layer and the inorganic CIM-containing sol-gel layer by the UV radiation comprises exposing a respective one of the sol-gel layers to the UV radiation having a light
10 dose ranging from about **500** to about **1000** mJ/cm² for a time period ranging from about **0.5** to **30** min; and

the thermally curing the plurality of sol-gel layers comprise exposing the plurality of sol-gel layers to infrared (IR) radiation, near IR
15 radiation, microwave radiation, hot air having a temperature ranging from about **70** to about **90** °C, or a combination thereof.

11. The method of any one of claims **1 – 10**, further comprising applying primer and/or paint on the plurality of sol-gel layers on the substrate, the plurality of
20 sol-gel layers facilitating adherence of the primer or the paint to the substrate.

12. A corrosion-resistant product obtained according to the method of claim **1** and comprising a plurality of sol-gel layers on a substrate,
25

the plurality of sol-gel layers including at least one organic CIM-containing sol-gel layer and at least one inorganic CIM-containing sol-gel layer,

the organic CIM comprising a Zn-Al layered double hydroxide (LDH) composition comprising nanocarriers of Zn-Al LDH; and an organic
30 corrosion inhibiting compound intercalated in the nanocarriers of Zn-Al LDH;

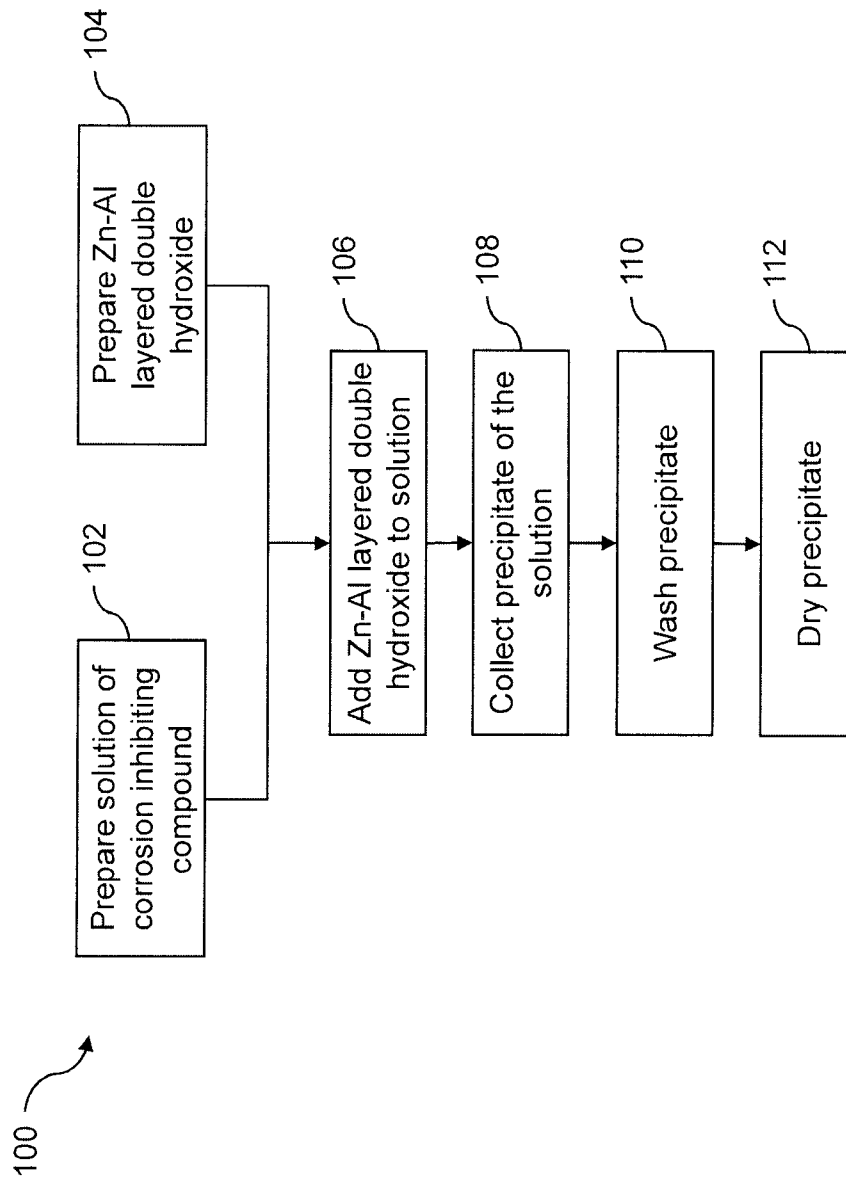
the inorganic CIM comprising a Zn-Al layered double hydroxide (LDH) composition comprising nanocarriers of Zn-Al LDH; and an inorganic corrosion inhibiting compound intercalated in the nanocarriers of Zn-Al LDH.

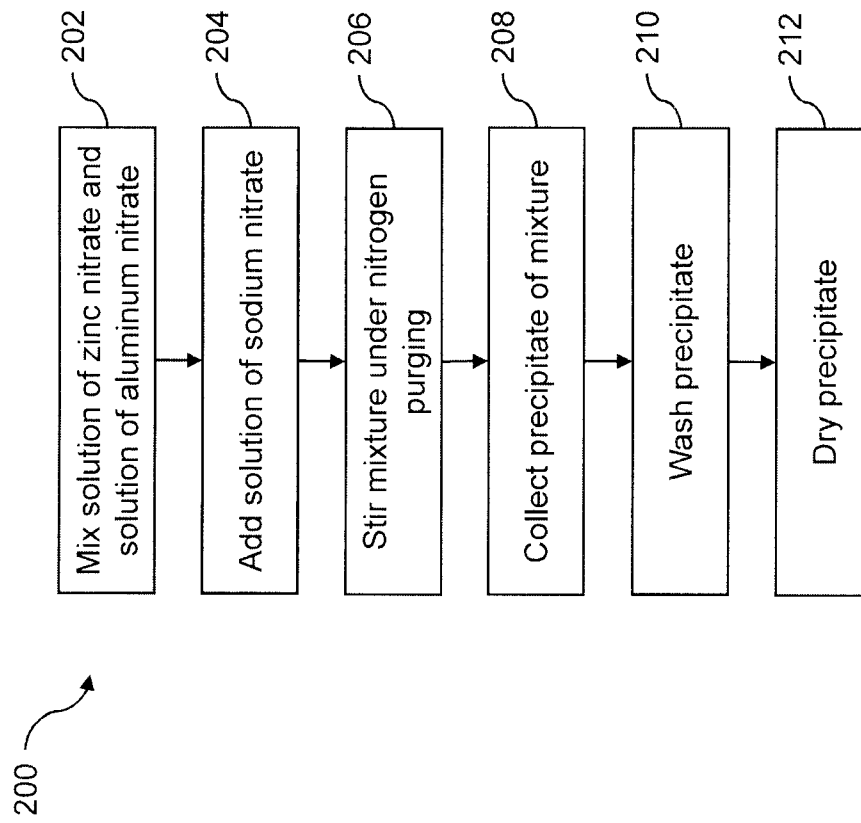
5

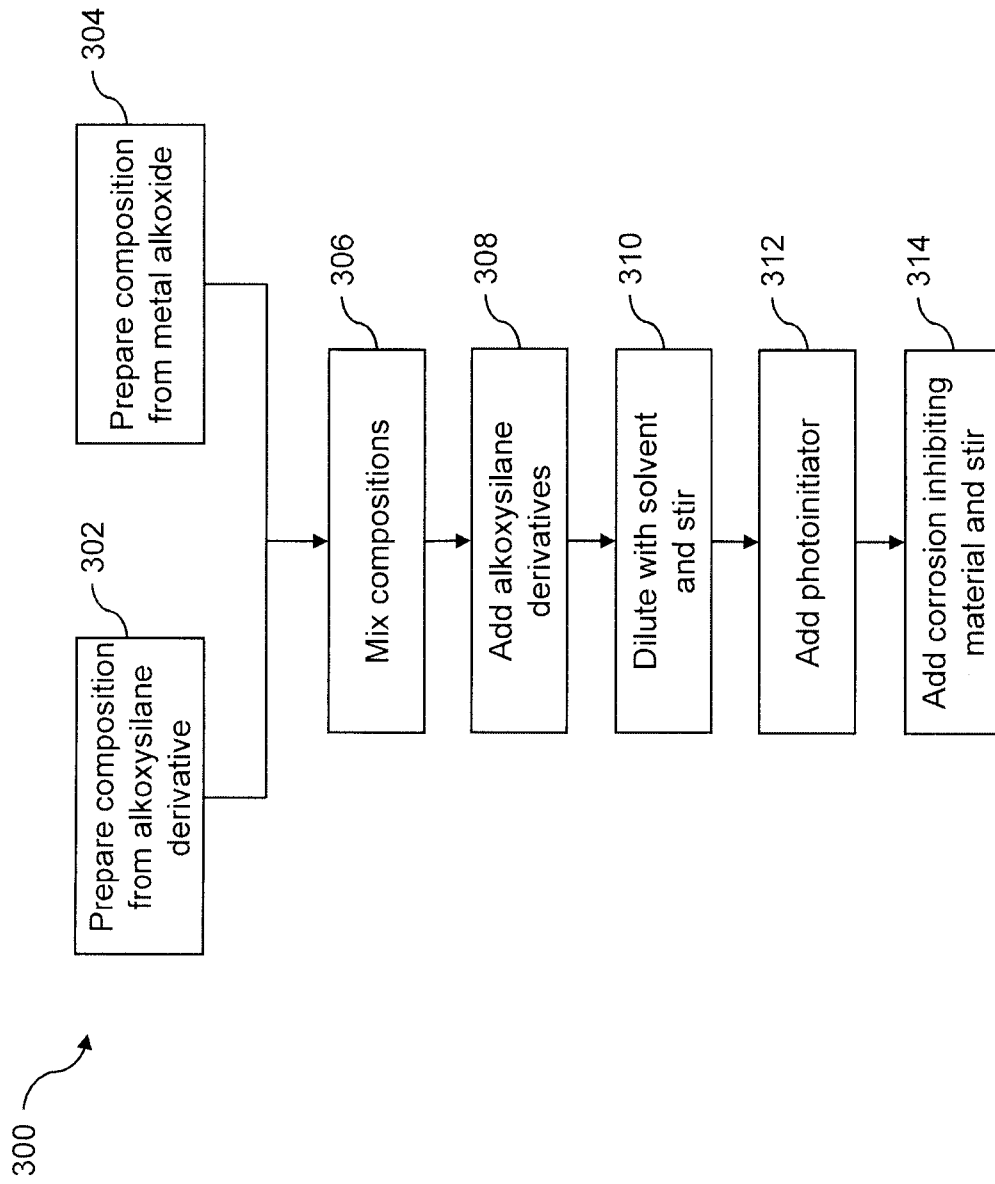
13. The corrosion resistant product of claim **12**, wherein the substrate comprises an aluminum substrate or an aluminum alloy substrate.

10 **14.** The corrosion resistant product of claim **12** or claim **13**, wherein the organic CIM is an imidazole, a triazole, a tetrazole, a thiazole, a thiadiazole, a benzimidazole, a benzotriazole, a benzothiazole, a quinoline, phytic acid, an organophosphonic acid, or an oil.

15 **15.** The corrosion resistant product of any one of claims **12** - **14**, wherein the inorganic corrosion inhibiting compound is a vanadate, a molybdate, a tungstate, a phosphate, a manganate, a permanganate, or an aluminate.

**FIG. 1**

**FIG. 2**

**FIG. 3**

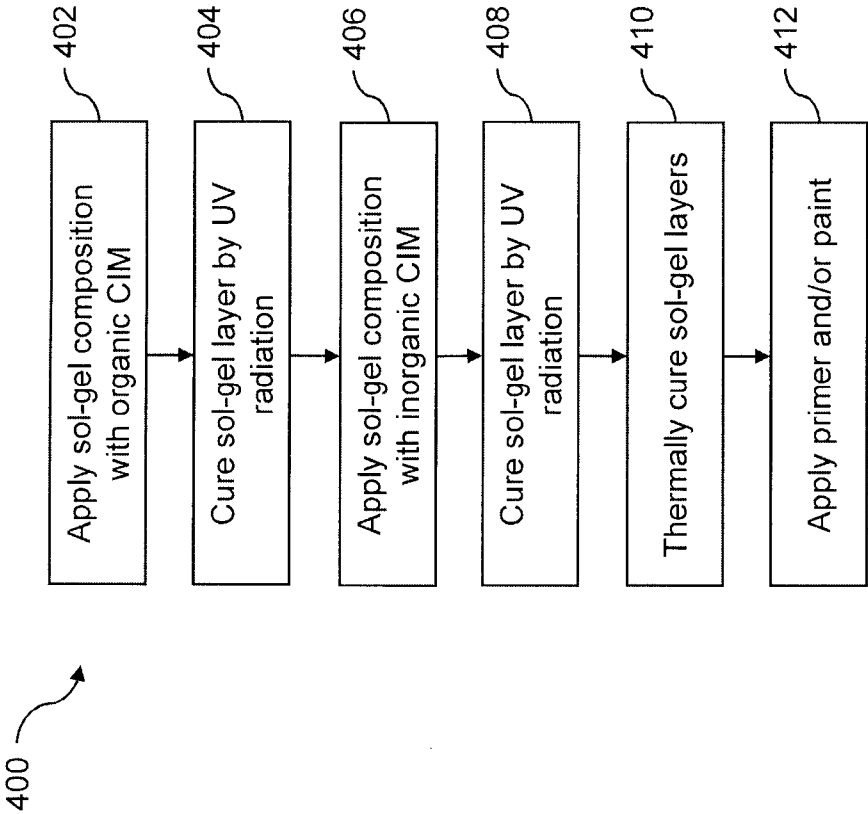


FIG. 4

<u>506</u>
<u>504</u>
<u>502</u>

FIG. 5

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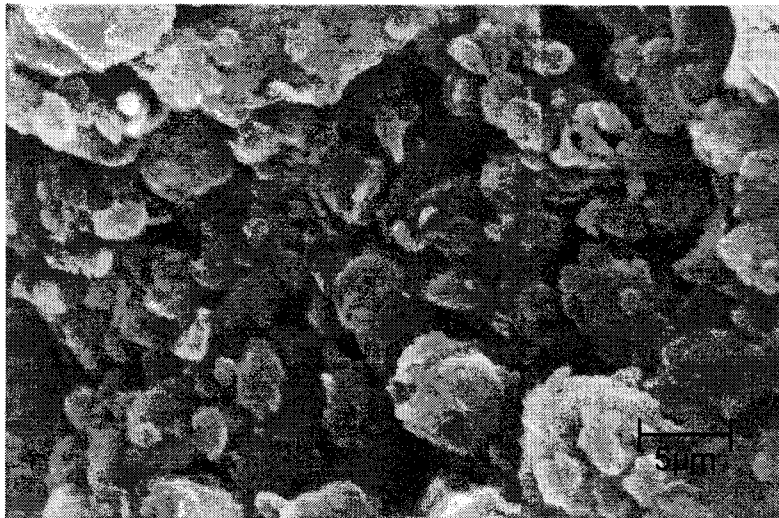


FIG. 6A

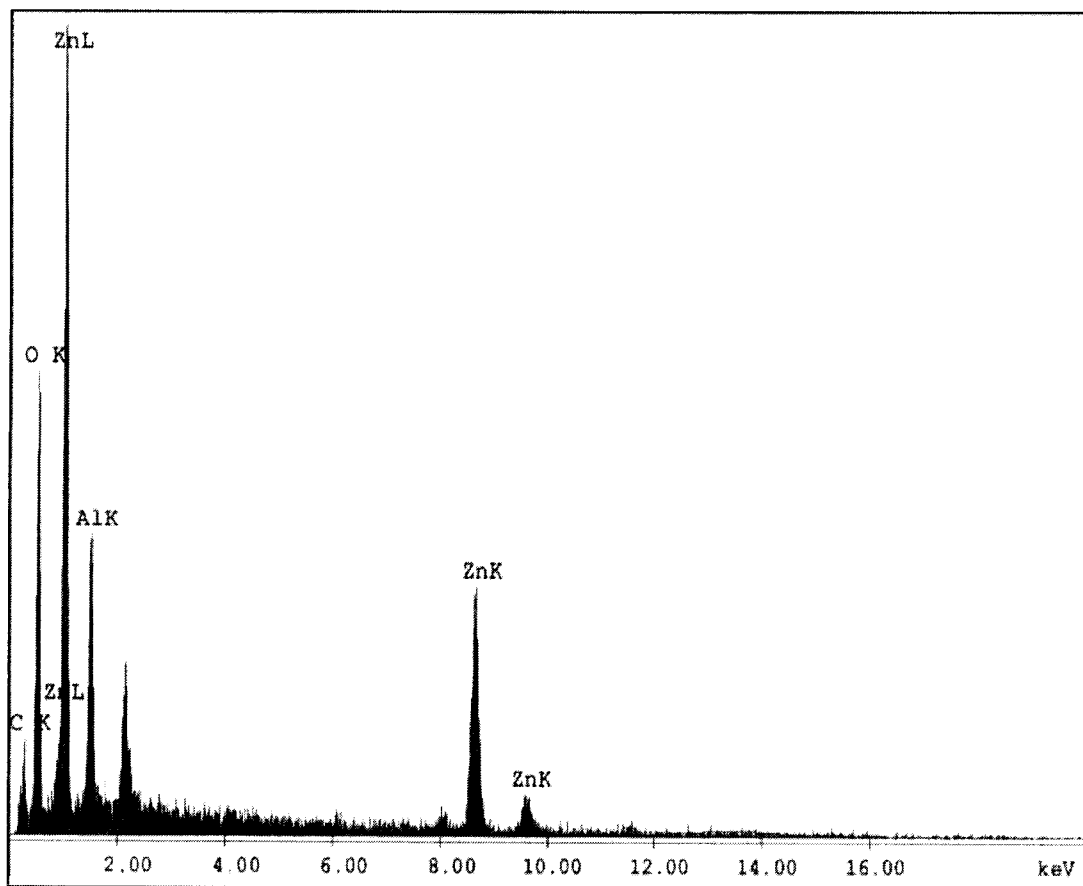


FIG. 6B

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FIG. 7A

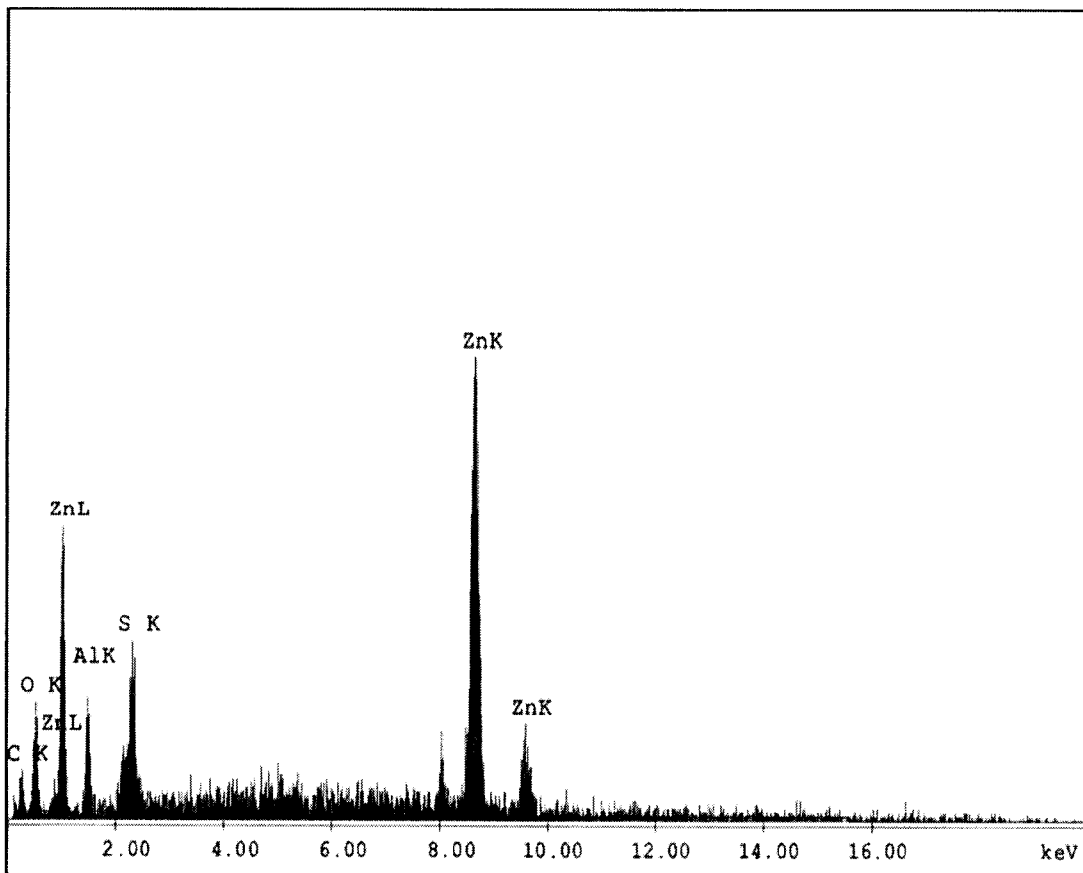


FIG. 7B

7/8

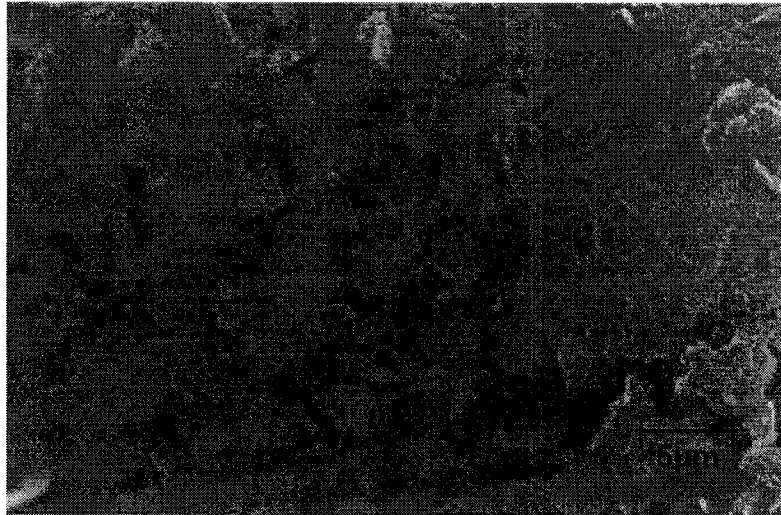


FIG. 8A

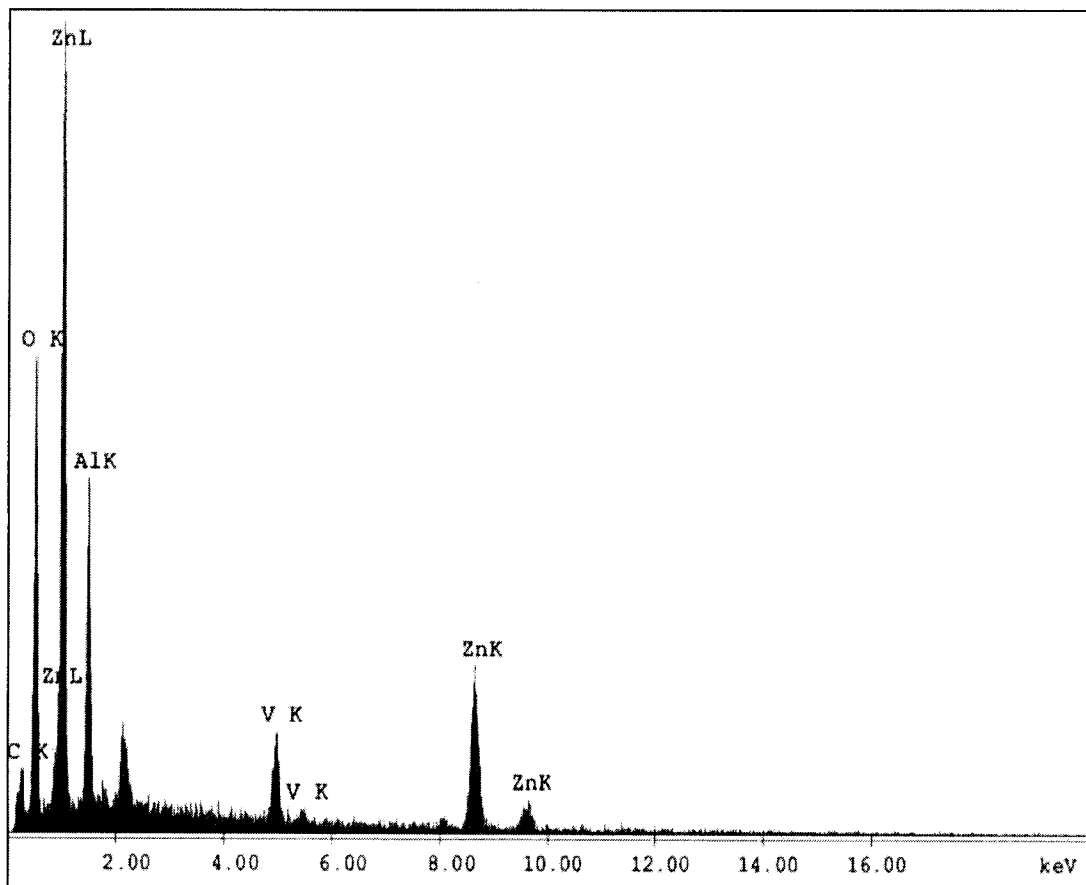


FIG. 8B

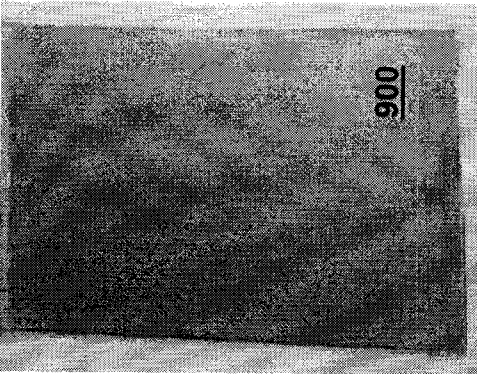


FIG. 9A

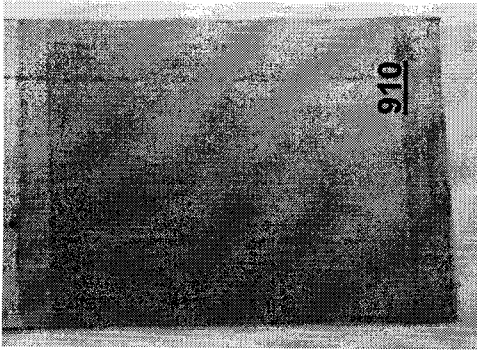


FIG. 9B

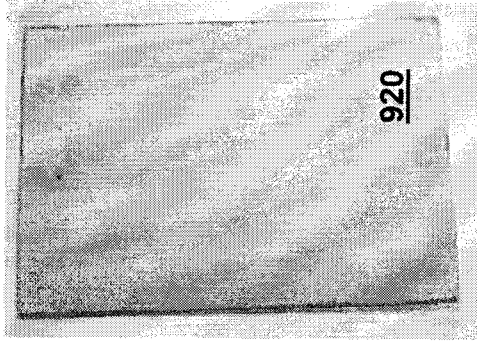


FIG. 9C



FIG. 9D

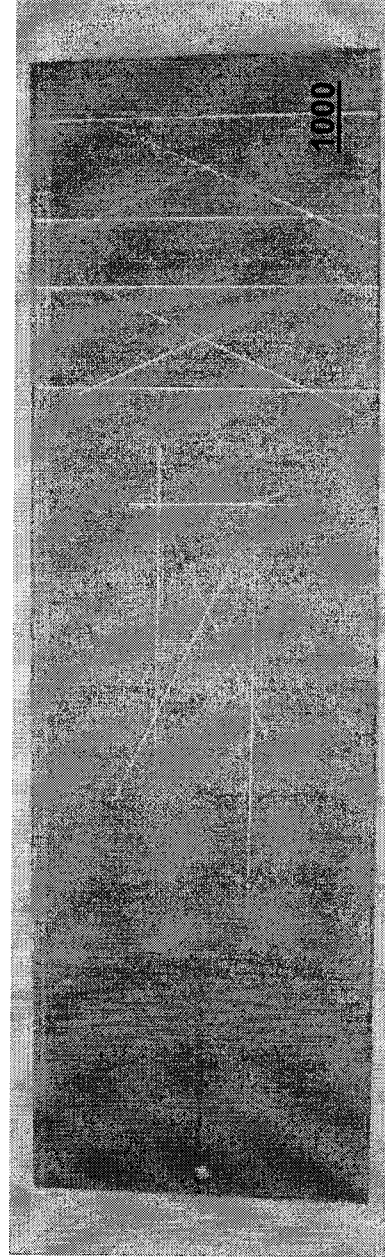


FIG. 10