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(54) **Titre : MELANGES POLYMERE-METAL NON MISCIBLES A TROIS PHASES DESTINES A DES COMPOSITES A CONDUCTIVITE ELEVEE**

(54) **Title: THREE PHASE IMMISCIBLE POLYMER-METAL BLENDS FOR HIGH CONDUCTIVITY COMPOSITES**

(57) **Abstrégé/Abstract:**

Provided is a method of forming a conductive polymer composite. The method includes forming a mixture. The mixture includes a first thermoplastic polymer, a second thermoplastic polymer and a plurality of metal particles. The first thermoplastic polymer and the second thermoplastic polymer are immiscible with each other. The plurality of metal particles include at least one metal that is immiscible with both the first thermoplastic polymer and the second thermoplastic polymer. The method includes heating the mixture to a temperature greater than or equal to a melting point of the metal.

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ABSTRACT OF THE DISCLOSURE

Provided is a method of forming a conductive polymer composite. The method includes forming a mixture. The mixture includes a first thermoplastic polymer, a second thermoplastic polymer and a plurality of metal particles. The first

5 thermoplastic polymer and the second thermoplastic polymer are immiscible with each other. The plurality of metal particles include at least one metal that is immiscible with both the first thermoplastic polymer and the second thermoplastic polymer. The method includes heating the mixture to a temperature greater than or equal to a melting point of the metal.

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THREE PHASE IMMISCIBLE POLYMER-METAL BLENDS FOR HIGH CONDUCTIVITY COMPOSITES

DETAILED DESCRIPTION

Field of the Disclosure

- 5 **[0001]** The present disclosure is directed to three-phase immiscible polymer-metal blends for high conductivity composites.

Background

- [0002]** Additive manufacturing (also known as three dimensional printing) as practiced in industry has been, to date, mostly concerned with printing structural
- 10 features. There is a need for materials and processes that integrate functional properties (such as electronic features) into additive manufacturing. Recently, conductive materials that are potentially useful in additive manufacturing have been commercialized, but their conductivities are generally low, ranging from $\sim 10^{-3}$ S/cm to upwards of ~ 2.0 S/cm. The mechanical properties of the commercially available
- 15 materials, particularly the conductive materials such as Acrylonitrile butadiene styrene (ABS) or polylactic acid (PLA), are generally limited (e.g., are not flexible, are fairly brittle) and have limited use as a conductive component.

- [0003]** There is great interest in the field of additive manufacturing to develop improved materials that can be used to easily print completely integrated
- 20 functional objects with limited post-assembly. This would allow completely new designs in the manufacturing and consumption of everyday objects, particularly when they can be enabled with conductive materials. The capability of printing

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conductive components within an object can provide the potential for embedded sensors and electronics.

[0004] Common techniques in additive manufacturing utilize the extrusion of molten polymer through a heated nozzle. This method is used in, for example, fused
5 deposition modeling (FDM), where a filament is fed into a hot zone for continuous extrusion. The molten polymer can be deposited layer by layer onto a build plate in order to form 3D objects. There are very few filament materials currently on the market which exhibit electrical conductivity, and those which are available have relatively low conductivities, which limits the range of potential applications. The
10 materials are typically constructed such that one conductive material forms a percolating network through an insulating polymer base, such that electrons have a continuous pathway to flow. The formation of this conductive network is limited to the way the conductive particles are arranged within the polymer base. Although these materials have been extensively explored in both academia and industry, the
15 focus is typically on minimizing the amount of conductive additive required to form a percolating network, where the conductivity is relatively low. One example of a paper directed to the study of dispersion of carbon black in an immiscible polymer blend is *Feng, J. et al.*, A Method to Control the Dispersion of Carbon Black in an Immiscible Polymer Blend, *Polymer Engineering & Science* 2003, 43(5), 1058-1063,
20 which describes that the dispersion of carbon black in an immiscible polymer blend is strongly influenced by the viscosity of one of the polymers of the polymer blend. This paper does not describe techniques for increasing conductivity substantially

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beyond the percolation threshold. Nor does it discuss the use of conductive polymers for additive manufacturing. One example of a patent directed to a conductive polymer is U.S. Patent No. 6,331,586 by Thielen, A. *et al.* and published on December 18, 2001, which describes a conductive polymer blend which is
5 comprised of two immiscible polymers and a conductive material in particulate or fiber form. The patent does not describe techniques for increasing conductivity substantially beyond the percolation threshold.

[0005] Novel plastic composite materials that exhibit increased conductivity would be a welcome step forward in the art, and could have significant impacts in
10 the field of additive manufacturing.

SUMMARY

[0006] An embodiment of the present disclosure is directed to a method of forming a conductive polymer composite, comprising: forming a mixture comprising a first thermoplastic polymer, a second thermoplastic polymer and a plurality of
15 metal particles, wherein the first thermoplastic polymer and the second thermoplastic polymer are immiscible with each other, and wherein the plurality of metal particles comprise at least one metal that is immiscible with both the first thermoplastic polymer and the second thermoplastic polymer; and heating the mixture to a temperature greater than or equal to a melting point of the metal.

20 **[0007]** In another embodiment, there is a conductive polymer composite, comprising: a first thermoplastic polymer; a second thermoplastic polymer; and plurality of metal particles, wherein the first thermoplastic polymer and the second

thermoplastic polymer are immiscible with each other, and wherein the plurality of metal particles comprise at least one metal that is immiscible with both the first thermoplastic polymer and the second thermoplastic polymer.

[0008] In another embodiment, there is a polymer composite filament, comprising: a first thermoplastic polymer defining a first continuous domain; a second thermoplastic polymer defining a second continuous domain, wherein the second thermoplastic is immiscible with the first thermoplastic; and a continuous metal trace disposed at an interface of the first continuous phase and the second continuous phase.

10 **[0009]** The compositions of the present application exhibit one or more of the following advantages: improved conductivity of filaments for 3D printing applications, such as fused deposition modeling (FDM); an unexpected, a phase separation of an alloy at its melting point which can be utilized in a two-phase immiscible polymer system to form a continuous conductive trace; or an improved
15 method for increasing the electrical conductivity in composites while retaining material properties suitable for additive manufacturing.

[0009a] In accordance with another aspect, there is provided a method of forming a conductive polymer composite, comprising:

forming a mixture comprising a first thermoplastic polymer, a second
20 thermoplastic polymer and a plurality of metal particles, wherein the first thermoplastic polymer and the second thermoplastic polymer are immiscible with each other, and wherein the plurality of metal particles comprise at least one metal

that is immiscible with both the first thermoplastic polymer and the second thermoplastic polymer;

wherein forming the mixture comprises melting the first thermoplastic polymer and the second thermoplastic polymer such that they form two co-
5 continuous immiscible phases separated by an interface, and

wherein the melting comprises melting the first thermoplastic polymer and the second thermoplastic polymer at a temperature below a melting point of the plurality of metal particles;

heating the mixture to a temperature greater than or equal to the
10 melting point of the plurality of metal particles, and

forming a composite by cooling the heated mixture,

wherein the composite comprises a continuous metal trace,

wherein the first thermoplastic polymer comprises one or more of polycaprolactone, polylactic acid (PLA), copolymers thereof, or mixtures thereof.

15 **[0009b]** In accordance with an aspect, there is provided a conductive polymer composite, comprising:

a first thermoplastic polymer;

a second thermoplastic polymer; and

a plurality of metal particles,

20 wherein the first thermoplastic polymer and the second thermoplastic polymer are immiscible with each other, and

wherein the plurality of metal particles comprise at least one metal that is immiscible with both the first thermoplastic polymer and the second thermoplastic polymer;

5 wherein the first thermoplastic polymer comprises one or more of polycaprolactone, polylactic acid (PLA), copolymers thereof, or mixtures thereof.

[0009c] In accordance with an aspect, there is provided a polymer composite filament, comprising:

10 a first thermoplastic polymer defining a first continuous domain; and
a second thermoplastic polymer defining a second continuous domain,
wherein the second thermoplastic polymer is immiscible with the first thermoplastic polymer;

wherein a continuous metal trace is disposed at an interface of the first continuous domain and the second continuous domain; and

15 wherein the first thermoplastic polymer comprises one or more of polycaprolactone, polylactic acid (PLA), copolymers thereof, or mixtures thereof.

[0009d] In accordance with an aspect, there is provided a conductive polymer composite, comprising:

20 a first thermoplastic polymer;
a second thermoplastic polymer; and
a plurality of metal particles,

wherein the first thermoplastic polymer and the second thermoplastic polymer are immiscible with each other,

wherein the plurality of metal particles comprise at least one metal that is immiscible with both the first thermoplastic polymer and the second thermoplastic polymer, wherein the first thermoplastic polymer defines a first continuous domain;

the second thermoplastic polymer defines a second continuous domain;

wherein a continuous metal trace is disposed at an interface of the first continuous domain and the second continuous domain and wherein the plurality of metal particles comprises BiSnAg and at least one of BiSnPb, BiSn, SbPbBi, SnBi, InSn, SnInAg, SnAgCu, SnAg, SnCu, SnSb, SnAgSb or mixtures thereof.

[0010] 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 present teachings, as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrates embodiments of the present teachings and

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together with the description, serve to explain the principles of the present teachings.

[0012] FIG. 1 is a flowchart showing the steps of a method of an embodiment.

5 **[0013]** FIG. 2 is a photograph showing an example of BiSnAg alloy phase separation in poly(styrene-isoprene-styrene) block copolymer to the surface of a filament during extrusion.

[0014] FIGS. 3A-3B are scanning electron micrographs of a filament comprising BiSnAg particles in polycaprolactone extruded below the melting point of BiSnAg (FIG. 3A), and above the melting point of BiSnAg and showing the phase separation and coalescence into larger domains (FIG. 3B).

[0015] It should be noted that some details of the figure have been simplified and are drawn to facilitate understanding of the embodiments rather than to maintain strict structural accuracy, detail, and scale.

15 **DESCRIPTION OF THE EMBODIMENTS**

[0016] Reference will now be made in detail to embodiments of the present teachings, examples of which are illustrated in the accompanying drawings. In the drawings, like reference numerals have been used throughout to designate identical elements. In the following description, reference is made to the accompanying drawing that forms a part thereof, and in which is shown by way of illustration a specific exemplary embodiment in which the present teachings may be practiced. The following description is, therefore, merely exemplary.

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[0017] An embodiment of the present disclosure is directed to a conductive polymer composite. Generally, the conductive composite material comprises three immiscible phases which provide for the formation of a continuous conductive domain to be formed from one of the immiscible phases. That is, the composite
5 comprises a three-phase composite material which contains a continuous metal trace, allowing for higher conductivity applications in additive manufacturing. The three-phase composite material comprises at least three components: first thermoplastic polymer, a second thermoplastic polymer, and a metal. These components are immiscible in order to form the three co-continuous domains.
10 These domains can be formed at any point during processing: melt mixing, extrusion into filament, or extrusion during 3D printing.

[0018] The composites of the embodiments and methods of making such composites as described herein offer significant improvement over current composite materials. For example, as a result of the first thermoplastic polymer and
15 the second thermoplastic polymer being immiscible with one another, melt-mixing the first thermoplastic polymer, the second thermoplastic polymer and the metal at a temperature below the melting point of the metal causes the metal to localize at an interface of the two co-continuous phases of the immiscible first and second thermoplastic polymers. After localization, the melt-mix can be heated above the
20 melting point of the metal in order to form a larger, continuous domain. Alternatively, all three of the first thermoplastic polymer, the second thermoplastic polymer and the metal can be processed above the melting point of the metal to

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form three immiscible phases, each of which forms a co-continuous domain with the other. As a result of either of these processes, the conductivity of filaments formed by extrusion of such melt-mixtures does not depends on the metal/conductor forming a percolation network between particles thereof. Instead, for the

5 embodiments described herein, the conductivity of the conductive composite filaments, for example, as measured between two ends thereof, comprises the conductivity of the metal itself, which is orders of magnitude higher than what's typically achieved in a percolating network. Accordingly, the embodiments described herein provide for conductive polymer composites to comprise any metals

10 having low-melting temperature, including alloys and nanoparticles.

[0019] As shown in FIG. 1, in an embodiment a method 100 for forming a conductive polymer composite comprises forming a mixture at 101. The mixture can include a first thermoplastic polymer 11, a second thermoplastic polymer 13 and a plurality of metal particles 15. The first thermoplastic polymer and the second

15 thermoplastic polymer may be selected such that they are immiscible with each other. The plurality of metal particles may comprise at least one metal that is immiscible with both the first thermoplastic polymer and the second thermoplastic polymer. The method continues with heating the mixture at 103, for example, to a temperature greater than or equal to a melting point of the metal. In an

20 embodiment, upon heating the mixture, the plurality of metal particles undergo a phase separation comprising coalescing of at least two of the plurality of metal particles. While not limited to any particular theory it is believed that the plurality of

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metal particles preferentially localize at an interface between the first thermoplastic polymer and the second thermoplastic polymer. Such an interface may be the result of an interfacial tension between two co-continuous polymer phases forming a boundary where the particles preferentially localize as a result of a predetermined
5 ratio of viscosities between the first and second thermoplastic polymers.

[0020] The mixture of the first thermoplastic polymer, the second thermoplastic polymer and the plurality of metal particles can be formed by melting the first thermoplastic polymer and the second thermoplastic polymer such that they form two co-continuous immiscible phases separated by an interface. Accordingly,
10 melting can include melting the first thermoplastic polymer and the second thermoplastic polymer at a temperature below the melting point of the at least one metal. As a result, the mixture can, therefore, include a first domain that includes first thermoplastic polymer, a second domain that includes the second thermoplastic polymer, and a third domain that includes the metal. In an embodiment, mixing may
15 include melt-mixing the first thermoplastic polymer and the second thermoplastic polymer. In an embodiment, the method 100 can include extruding the mixture at 105 and forming a conductive polymer composite filament at 107.

[0021] The method can further include forming a composite by cooling the heated mixture, wherein the composite comprises a continuous metal trace. The
20 method can further include providing the composite to a three-dimensional-printer, heating the composite, and extruding the heated composite onto a substrate to form a three-dimensional object. In an embodiment, the mixing step can include

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providing the first thermoplastic polymer, the second thermoplastic polymer and the metal to a three-dimensional printer followed by melting the first thermoplastic polymer and the second thermoplastic polymer and extruding the heated mixture onto a substrate to form a three-dimensional object.

5 **[0022]** THERMOPLASTIC POLYMERS

[0023] Any suitable thermoplastic polymer useful in three-dimensional printing can be employed as the first and the second thermoplastic polymers in the composites of the present disclosure. In an example, the first and second thermoplastic polymers are immiscible with each other. Accordingly, the first
10 thermoplastic polymer may be different than the second thermoplastic polymer. While not limited to any particular theory, it is believed that hydrophobic/hydrophilic characteristic of a thermoplastic polymer is a physical property that provides for the immiscibility between different thermoplastic polymers. Accordingly, in an embodiment, the first thermoplastic polymer is more hydrophobic than the second
15 thermoplastic polymer. Alternatively, in an embodiment, the second thermoplastic polymer is more hydrophobic than the first thermoplastic polymer. Meanwhile, in an embodiment, the first thermoplastic polymer is more hydrophilic than the second thermoplastic polymer. Alternatively, in an embodiment, the second thermoplastic is more hydrophilic than the first thermoplastic polymer. In another embodiment,
20 the first thermoplastic polymer is hydrophobic and the second thermoplastic polymer is hydrophilic. Alternatively, in an embodiment, the second thermoplastic polymer is hydrophobic and the first thermoplastic polymer is hydrophilic.

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[0024] The first and the second thermoplastic polymer may be selected from high density polyethylene (HDPE), metallocene catalyzed linear low density polyethylene (mLLDPE), polypropylene (PP) thermoplastic urethane (TPU), ethylene propylene rubber (EPR), ethylene propylene diene rubber (EPDM),

5 Poly(styrene-isoprene-styrene), polycaprolactone, acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), copolymers thereof such as block copolymers thereof, or any combinations thereof.

[0025] Exemplary combinations of first and second thermoplastic polymer (e.g., first thermoplastic polymer / second thermoplastic polymer) include:

10 HDPE/EPR, HDPE/EPDM, HDPE/ mLLDPE, PP/EPDM, PP/EPR, PP/mLLDPE, and mLLDPE/EPR.

[0026] The amounts of the first and second thermoplastic polymer may be selected such that the first and second thermoplastic polymers form co-continuous domains when mixed together. In an example, the polymeric content of a

15 composite of the embodiments can be selected such that the first thermoplastic polymer comprises from about 10% to about 90% by weight relative to the total weight of the conductive polymer composite., and the second thermoplastic polymer comprises from about 10% to about 90% by weight relative to the total weight of the conductive polymer composite. In an example, the polymeric content of a

20 composite of the embodiments can be selected such that the first thermoplastic polymer comprises from about 2.5% to about 67.5% by weight relative to the total weight of the conductive polymer composite, for example 5% to about 67.5% by

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weight relative to the total weight of the conductive polymer composite.; and the second thermoplastic polymer comprises from about 2.5% to about 67.5% by weight relative to the total weight of the conductive polymer composite, for example, from about 5% to about 67.5% by weight relative to the total weight of the
5 conductive polymer composite.

[0027] The composite can include three immiscible components. The components may include two polymers (i.e., the first thermoplastic polymer and the second thermoplastic polymer and one metal or metal alloy. In other words, the composite can comprise a first thermoplastic polymer, a second thermoplastic
10 polymer and at least one metal.

METAL

[0028] For the metal, any suitable metal useful in three-dimensional printing can be employed in the composites of the present disclosure. The metal may be selected from any metal and may include metal alloys. Any suitable metal can be
15 employed, for example, in particular form. Examples of suitable metals include Bi, Sn, Sb, Pb, Ag, In, Cu, or alloys thereof. For example, alloys may include at least one of the following, BiSnPb, BiSn, BiSnAg, SbPbBi, SnBi, InSn, SnInAg, SnAgCu, SnAg, SnCu, SnSb, SnAgSb, or mixtures thereof.

[0029] The metal may be selected based on its melting temperature, for
20 example, in ambient environments. For example, metals comprising a melting temperature (T_m) in the range of from about 100 °C to about 250 °C may be

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selected. The metal may be immiscible with the first thermoplastic polymer and the second thermoplastic polymer.

[0030] Example amounts of metal include a range of from 10 % to about 75% by weight, such as from about 25% to about 75% by weight, or from about 50% to about 75% by weight relative to the total weight of the conductive polymer composite.

[0031] The conductive polymer composites of the present disclosure can include any other suitable ingredients in any desired amounts, although not required. Alternatively, ingredients not expressly recited in the present disclosure can be limited and/or excluded from the conductive polymer composites disclosed herein. Thus, the amounts of the thermoplastic polymer, metal, first polymer and second polymer as recited herein, can add up to from about 90% to about 100% by weight of the total ingredients employed in the composites of the present disclosure, such as from about 95% to about 100% by weight, or from about 98% to about 100% by weight, or from about 99% to about 100% by weight, or about 100% by weight of the total ingredients.

[0032] Because of the continuous metal domains that form at an interface between immiscible thermoplastic polymers, the composite of the embodiments also has a bulk conductivity of the bulk metal of the selected metal. Bulk conductivity is calculated using the formula,

$$\sigma = L/(R \cdot A) \quad (1)$$

Where:

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σ is bulk electrical conductivity;

L is length of the filament;

R is measured resistance of an extruded filament;

A is the cross-sectional area (πr^2) of the filament, where r is

5 the radius of the filament.

The resistance, R, can be measured by forming an extruded filament made from the composite. The tips of the filament are painted with silver to provide good electrical connections with the testing equipment (e.g., a digital multimeter), but would not necessarily be painted if the filaments were to be used in additive manufacturing.

10 Resistance can then be measured across the length of the filament. The dimensions of the filament and the measured value for R can then be used to calculate bulk conductivity (σ) of the composite.

[0033] The composites of the present disclosure can be made by any suitable method. For example, the thermoplastic polymer can be combined with the
15 first polymer, the second polymer and the metal particles using melt mixing techniques. Other suitable techniques for mixing such compositions are well known in the art.

[0034] The present disclosure is also directed to a method of three dimensional printing. The method includes providing any of the conductive polymer
20 composites of the present disclosure to a three dimensional printer. The composite can be in any suitable form useful in three dimensional printing, such as a filament. The conductive polymer is generally heated to a molten state suitable for extrusion.

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Then the heated conductive polymer is extruded onto a substrate to form a three dimensional object.

EXAMPLES

Example 1

5 **[0035]** Poly(styrene-isoprene-styrene) block copolymer was melt mixed with BiSnAg metal alloy (Indalloy #282, available from INDIUM CORPORATION®, United States) for 30 minutes at 30rpm in a twin screw extruder. Filaments were extruded on a melt flow indexer to form filaments 1.75mm in diameter with a custom designed die and 19.66 kg weight. During processing, the metal alloy phase
10 separated to areas of lower surface tension. While melt mixing above the melting point of BiSnAg alloy on the twin screw extruder, the alloy phase separated to the edges of the chamber. When melt mixed below the melting point of the metal alloy and extruded above the melting temperature, filament extruded from the melt flow indexer was observed as having phase separated alloy on the surface of the
15 filament as shown in FIG. 2.

[0036] In addition to phase separation, the alloy particles were unexpectedly observed to have undergone a phase change as evidenced by larger domains shown between FIGS. 3A-3B. While not limited to any particular embodiment, it is believed that the alloy phase separated to areas of lower surface tension.

20 **[0037]** Notwithstanding that the numerical ranges and parameters setting forth the broad scope of the disclosure are approximations, the numerical values set forth in the specific examples are reported as precisely as possible. Any numerical

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value, however, inherently contains certain errors necessarily resulting from the standard deviation found in their respective testing measurements. Moreover, all ranges disclosed herein are to be understood to encompass any and all sub-ranges subsumed therein.

- 5 **[0038]** While the present teachings have been illustrated with respect to one or more implementations, alterations and/or modifications can be made to the illustrated examples without departing from the spirit and scope of the appended claims. In addition, while a particular feature of the present teachings may have been disclosed with respect to only one of several implementations, such feature
- 10 may be combined with one or more other features of the other implementations as may be desired and advantageous for any given or particular function. Furthermore, to the extent that the terms “including,” “includes,” “having,” “has,” “with,” or variants thereof are used in either the detailed description and the claims, such terms are intended to be inclusive in a manner similar to the term “comprising.” Further, in the
- 15 discussion and claims herein, the term “about” indicates that the value listed may be somewhat altered, as long as the alteration does not result in nonconformance of the process or structure to the illustrated embodiment. Finally, “exemplary” indicates the description is used as an example, rather than implying that it is an ideal.
- 20 **[0039]** It will be appreciated that variants of the above-disclosed and other features and functions, or alternatives thereof, may be combined into many other different systems or applications. Various presently unforeseen or unanticipated

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alternatives, modifications, variations, or improvements therein may be subsequently made by those skilled in the art which are also intended to be encompassed by the following claims.

WHAT IS CLAIMED IS:

1. A method of forming a conductive polymer composite, comprising:
 - forming a mixture comprising a first thermoplastic polymer, a second thermoplastic polymer and a plurality of metal particles, wherein the first thermoplastic polymer and the second thermoplastic polymer are immiscible with each other, and wherein the plurality of metal particles comprise at least one metal that is immiscible with both the first thermoplastic polymer and the second thermoplastic polymer;
 - wherein forming the mixture comprises melting the first thermoplastic polymer and the second thermoplastic polymer such that they form two co-continuous immiscible phases separated by an interface, and
 - wherein the melting comprises melting the first thermoplastic polymer and the second thermoplastic polymer at a temperature below a melting point of the plurality of metal particles;
 - heating the mixture to a temperature greater than or equal to the melting point of the plurality of metal particles, and
 - forming a composite by cooling the heated mixture,
 - wherein the composite comprises a continuous metal trace,
 - wherein the first thermoplastic polymer comprises one or more of polycaprolactone, polylactic acid (PLA), copolymers thereof, or mixtures thereof.

2. The method of claim 1, wherein the mixture comprises a first domain consisting essentially of the first thermoplastic polymer, a second domain consisting essentially of the second thermoplastic polymer, and a third domain consisting essentially of the at least one metal.

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3. The method of claim 1 or 2, wherein the forming of the mixture comprises melt-mixing the first thermoplastic polymer and the second thermoplastic polymer.

4. The method of claim 1 or 2, wherein the forming of the mixture comprises
10 providing the first thermoplastic polymer, the second thermoplastic polymer and the plurality of metal particles to a three-dimensional printer; melting the first thermoplastic polymer and the second thermoplastic polymer; and extruding the heated mixture onto a substrate to form a three-dimensional object.

15 5. The method of any one of claims 1 to 3, further comprising extruding the mixture to form a conductive polymer composite filament.

6. The method of any one of claims 1 to 3, further comprising providing the composite to a three-dimensional-printer, heating the composite, and extruding the
20 heated composite onto a substrate to form a three-dimensional object.

7. The method of any one of claims 1 to 6, wherein upon heating the mixture, the plurality of metal particles undergo a phase separation comprising coalescing of at least two of the plurality of metal particles.
- 5 8. The method of any one of claims 1 to 7, wherein the plurality of metal particles preferentially localize at an interface between the first thermoplastic polymer and the second thermoplastic polymer.
9. The method of any one of claims 1 to 8, wherein the second thermoplastic
10 polymer is different than the first thermoplastic polymer.
10. The method of any one of claims 1 to 9, wherein the second thermoplastic polymer comprises high density polyethylene (HDPE), metallocene catalyzed linear low density polyethylene (mLLDPE), polypropylene (PP) thermoplastic urethane
15 (TPU), ethylene propylene rubber (EPR), ethylene propylene diene rubber (EPDM), polycaprolactone, acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), copolymers thereof, or mixtures thereof, and wherein the first thermoplastic polymer is different than the second thermoplastic polymer.
- 20 11. The method of any one of claims 1 to 10, wherein the metal particles comprise Bi, Sn, Sb, Pb, Ag, In, Cu, or alloys thereof.

12. The method of any one of claims 1 to 10, wherein the metal particles comprise BiSnPb, BiSn, BiSnAg, SbPbBi, SnBi, InSn, SnInAg, SnAgCu, SnAg, SnCu, SnSb, SnAgSb, or mixtures thereof.
- 5 13. The method of any one of claims 1 to 10, wherein the metal particles comprise a mixture of more than one of BiSnPb, BiSn, BiSnAg, SbPbBi, SnBi, InSn, SnInAg, SnAgCu, SnAg, SnCu, SnSb, and SnAgSb.
14. The method of any one of claims 1 to 10, wherein the metal particles
10 comprise BiSnAg and at least one of BiSnPb, BiSn, SbPbBi, SnBi, InSn, SnInAg, SnAgCu, SnAg, SnCu, SnSb, SnAgSb, or mixtures thereof.
15. The method of any one of claims 1 to 14, wherein the mixing comprises providing the plurality of metal particles in an amount ranging from about 10% to
15 about 75% by weight, relative to the total weight of the mixture.
16. A conductive polymer composite, comprising:
a first thermoplastic polymer;
a second thermoplastic polymer; and
20 a plurality of metal particles,
wherein the first thermoplastic polymer and the second thermoplastic polymer are immiscible with each other, and

wherein the plurality of metal particles comprise at least one metal that is immiscible with both the first thermoplastic polymer and the second thermoplastic polymer;

wherein the first thermoplastic polymer comprises one or more of
5 polycaprolactone, polylactic acid (PLA), copolymers thereof, or mixtures thereof.

17. The conductive polymer composite of claim 16, wherein the metal particles comprise Bi, Sn, Sb, Pb, Ag, In, Cu, or alloys thereof.

10 18. The conductive polymer composite of claim 16, wherein the metal particles comprise BiSnPb, BiSn, BiSnAg, SbPbBi, SnBi, InSn, SnInAg, SnAgCu, SnAg, SnCu, SnSb, SnAgSb, or mixtures thereof.

19. The conductive polymer composite of any one of claims 16 to 18, wherein
15 the composite is formed by a method comprising the steps of:

forming a mixture comprising the first thermoplastic polymer, the second thermoplastic polymer and the plurality of metal particles,

wherein the forming the mixture comprises melting the first thermoplastic polymer and the second thermoplastic polymer such that they form two co-
20 continuous immiscible phases separated by an interface,

wherein the melting comprises melting the first thermoplastic polymer and the second thermoplastic polymer at a temperature below the melting point of the plurality of metal particles;

heating the mixture to a temperature greater than or equal to a melting point
5 of the plurality of metal particles; and

forming the composite by cooling the heated mixture,

wherein the composite comprises a continuous metal trace.

20. The conductive polymer composite of any one of claims 16 to 19, wherein
10 the plurality of metal particles is localized at an interface between the first thermoplastic polymer and the second thermoplastic polymer.

21. The conductive polymer composite of any one of claims 16 to 20, wherein at least two of the plurality of metal particles are coalesced.

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22. The conductive polymer composite of any one of claims 16 to 21, wherein the first thermoplastic polymer defines a first continuous domain; the second thermoplastic polymer defines a second continuous domain; and a continuous metal trace is disposed at an interface of the first continuous
20 domain and the second continuous domain.

23. A polymer composite filament, comprising:

a first thermoplastic polymer defining a first continuous domain; and
a second thermoplastic polymer defining a second continuous domain,
wherein the second thermoplastic polymer is immiscible with the first thermoplastic
polymer;

5 wherein a continuous metal trace is disposed at an interface of the first
continuous domain and the second continuous domain; and

 wherein the first thermoplastic polymer comprises one or more of
polycaprolactone, polylactic acid (PLA), copolymers thereof, or mixtures thereof.

10 24. The polymer composite filament of claim 23, wherein the plurality of metal
particles comprise Bi, Sn, Sb, Pb, Ag, In, Cu, or alloys thereof.

 25. The polymer composite filament of claim 23, wherein the plurality of metal
particles comprise a mixture of more than one of BiSnPb, BiSn, BiSnAg, SbPbBi,
15 SnBi, InSn, SnInAg, SnAgCu, SnAg, SnCu, SnSb, SnAgSb.

 26. The polymer composite filament of claim 23, wherein the plurality of metal
particles comprise BiSnAg.

20 27. The polymer composite filament of claim 23, wherein the plurality of metal
particles comprises BiSnAg and at least one of BiSnPb, BiSn, SbPbBi, SnBi, InSn,
SnInAg, SnAgCu, SnAg, SnCu, SnSb, SnAgSb or mixtures thereof.

28. The polymer composite filament of any one of claims 23 to 27, wherein the composite is formed by a method comprising the steps of:

forming a mixture comprising the first thermoplastic polymer, the second
5 thermoplastic polymer and the plurality of metal particles,

wherein the forming of the mixture comprises melting the first thermoplastic polymer and the second thermoplastic polymer such that they form two co-continuous immiscible phases separated by an interface, and

wherein the melting comprises melting the first thermoplastic polymer and
10 the second thermoplastic polymer at a temperature below the melting point of the plurality of metal particles;

heating the mixture to a temperature greater than or equal to a melting point of the plurality of metal particles, and

forming the composite by cooling the heated mixture; and
15 wherein the composite comprises a continuous metal trace.

29. A conductive polymer composite, comprising:

a first thermoplastic polymer;
a second thermoplastic polymer; and
20 a plurality of metal particles,

wherein the first thermoplastic polymer and the second thermoplastic polymer are immiscible with each other,

wherein the plurality of metal particles comprise at least one metal that is immiscible with both the first thermoplastic polymer and the second thermoplastic polymer, wherein the first thermoplastic polymer defines a first continuous domain;

the second thermoplastic polymer defines a second continuous domain;

- 5 wherein a continuous metal trace is disposed at an interface of the first continuous domain and the second continuous domain and wherein the plurality of metal particles comprises BiSnAg and at least one of BiSnPb, BiSn, SbPbBi, SnBi, InSn, SnInAg, SnAgCu, SnAg, SnCu, SnSb, SnAgSb or mixtures thereof.

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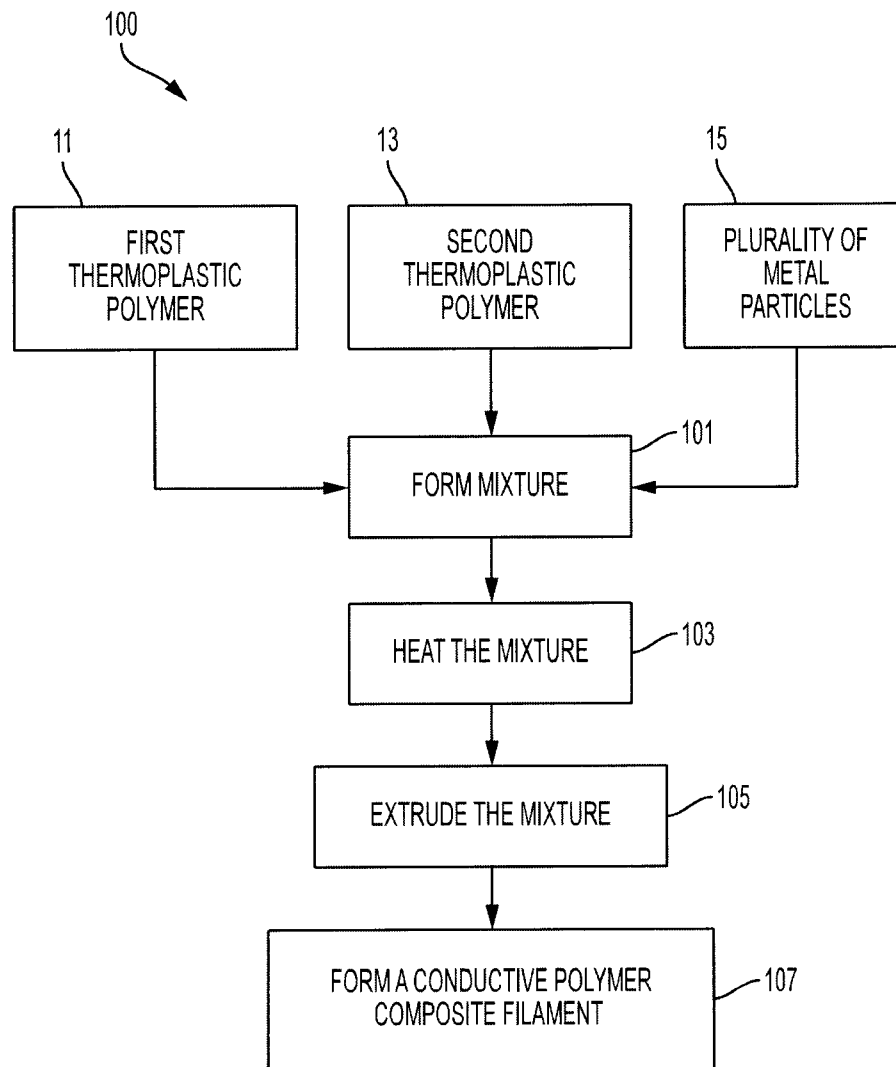


FIG. 1

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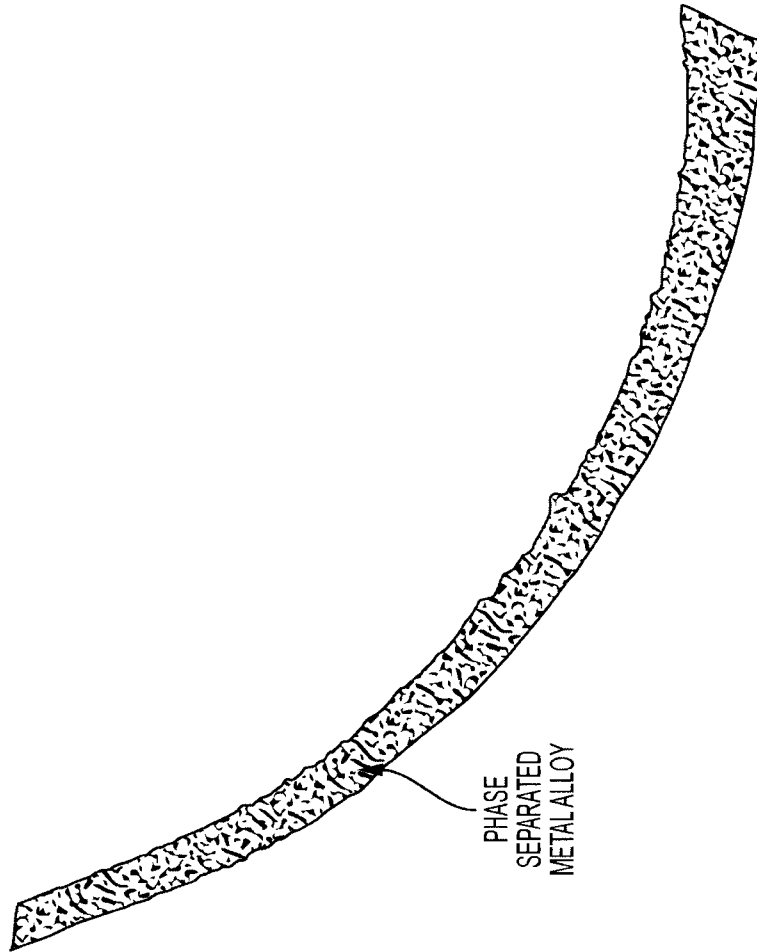


FIG. 2

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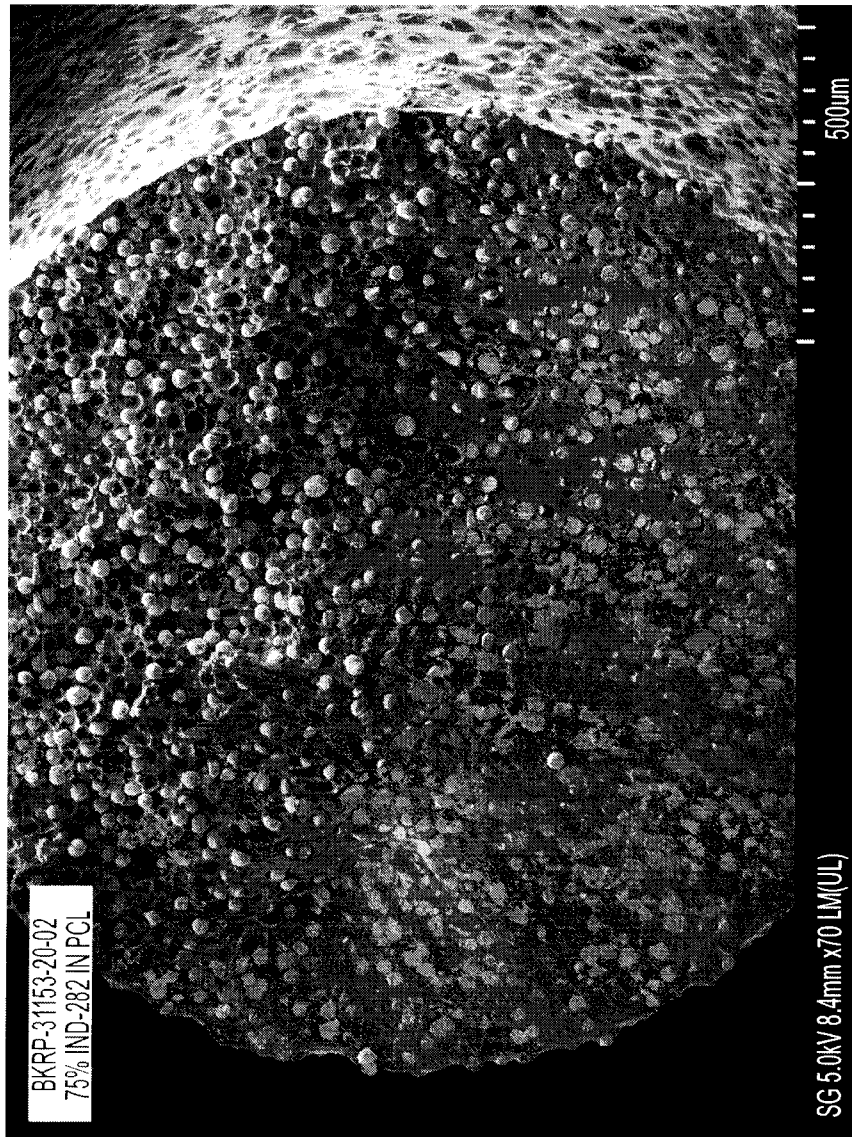


FIG. 3A

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FIG. 3B