

THERMOSETTING COMPOSITIONS, CURED COMPOSITIONS, AND PREPREGS AND LAMINATES BASED ON SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of priority of U.S. Provisional Patent Application no. 63/509,663, filed June 22, 2023, which is hereby incorporated herein by reference in its entirety.

BACKGROUND OF THE DISCLOSURE

1. Field of the Disclosure

[0002] This disclosure relates to thermosetting compositions suitable for use in making electronic materials such as circuit board substrates, as well as cured compositions, prepregs and laminates based on such thermosetting compositions.

2. Technical Background

[0003] A variety of polymeric materials have been developed for use as substrates for electronics. To provide for desirably high transmission speeds, desirable properties include low dielectric constant and low dissipation factor, especially at high frequencies, as well as high glass transition temperature, low thermal expansion, and high temperature stability.

[0004] Such materials are often provided with a layer of copper foil laminated thereto. The peel strength between the copper foil and the polymeric material is an important property of such materials. During processing into devices these materials are subjected to high heat, e.g., through soldering, and insufficient adhesion between the copper and the polymer can cause in the device such as track lift, pad lift and large scale delamination. Adhesion is typically measured by the "peel strength," which quantifies the amount of force needed to peel a copper layer away from the material.

[0005] But while peel strength is important, so are the electronic and thermal properties. What are needed are new materials that have not only high peel strength with copper, but also good dielectric properties, especially at high frequencies, and good thermal properties.

SUMMARY OF THE DISCLOSURE

[0006] One aspect of the disclosure is a thermosetting composition comprising:
a poly(1,4-phenylene ether) component having at least 80% phenylene ether content, the poly(1,4-phenylene ether) component being a poly(1,4-phenylene ether) bis(meth)acrylate component, a bis(vinyl) poly(1,4-phenylene ether) component, or a bis((meth)allyl) poly(1,4-phenylene ether) component, or a combination of two or more thereof, in an amount in the range of 20-35 wt%;

an aromatic crosslinking component having a weight average molecular weight of no greater than 700 g/mol and bearing on numerical average in the range of 1.75 - 3.5 crosslinkable vinyl, (meth)allyl and/or (meth)acrylate groups per molecule, in an amount in the range of 2-15 wt%;

a butadiene/styrene copolymeric rubber component, in an amount of 5-25 wt%;

microparticulate silica, in an amount in the range of 15-50 wt%;

a halogen-free organic fire retardant component, in an amount of 15-35 wt%; and

an effective amount of a thermal free-radical initiator component.

[0007] Another aspect of the disclosure is a cured (e.g., partially cured or substantially fully cured) product of a thermosetting composition as described herein.

[0008] Another aspect of the disclosure is a method for curing a thermosetting composition as described herein, the method comprising heating the thermosetting composition at a temperature of 150-250 °C.

[0009] Another aspect of the disclosure is a prepreg comprising a mesh substrate at least partially embedded in a cured product as described herein.

[0010] Another aspect of the disclosure is a laminate of a plurality of prepregs as described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. 1 is a schematic cross-sectional view of a prepreg according to one embodiment of the disclosure.

[0012] FIG. 2 is a schematic cross-sectional view of a laminate according to one embodiment of the disclosure.

DETAILED DESCRIPTION

[0013] The present inventors have developed particular thermosetting compositions that can provide not only good peel strength to copper, but also excellent dielectric properties at high frequency and good thermal properties.

[0014] One aspect of the disclosure is a thermosetting composition comprising:

a poly(1,4-phenylene ether) component having at least 80% phenylene ether content, the poly(1,4-phenylene ether) component being a poly(1,4-phenylene ether) bis(meth)acrylate component, a bis(vinyl) poly(1,4-phenylene ether) component, or a bis((meth)allyl) poly(1,4-phenylene ether) component, or a combination of two or more thereof, in an amount in the range of 20-35 wt%;

an aromatic crosslinking component having a weight average molecular weight of no greater than 700 g/mol and bearing on numerical average in the range of 1.75 - 3.5 crosslinkable vinyl, (meth)allyl and/or (meth)acrylate groups per molecule, in an amount in the range of 2-15 wt%;

a butadiene/styrene copolymeric rubber component, in an amount of 5-25 wt%;

microparticulate silica, in an amount in the range of 15-50 wt%;

a halogen-free organic fire retardant component, in an amount of 15-35 wt%; and

an effective amount of a thermal free-radical initiator component.

[0015] As used herein, a thermosetting composition is a substantially liquid composition that cures from a liquid state to a solid state under the influence of heat. Various especially desirable thermosetting compositions are those that are "B-stageable," that is, they can be partially cured to a manipulable solid under a first heat treatment, then later fully cured under a second heat treatment. The partially cured material can be, for example, in a so-called "B-stage," and can be further cured to a so-called "C-stage." The person of ordinary skill in the art of electronic materials is familiar with the use of thermosetting compositions like those described herein in the production of a variety of products such as prepreps, resin films, resin-coated copper, laminates, and printed circuit boards.

[0016] One component of the thermosetting compositions of the disclosure is a poly(1,4-phenylene ether) component, the poly(1,4-phenylene ether) component being a poly(1,4-phenylene ether) bis(meth)acrylate component, a bis(vinyl) poly(1,4-phenylene ether) component, or a bis((meth)allyl) poly(1,4-phenylene ether) component, or a combination of two or more thereof, having at least 80 wt% phenylene ether content, in an amount in the range of 20-35 wt%. The poly(1,4-phenylene ether) component can be made of a single sample of a poly(1,4-phenylene ether) bis(meth)acrylate, bis(vinyl), or bis((meth)allyl) polymer (which itself would typically have a range of molecules of different degrees of polymerization), or a blend of multiple samples of poly(1,4-phenylene ether) bis(meth)acrylate, bis(vinyl), or bis((meth)allyl) polymers.

[0017] The poly(1,4-phenylene ether) component has at least 80 wt% phenylene ether content. This means that at least 80 wt% of the component is made up of -O-(optionally-substituted phenylene) groups. In various embodiments, the mass of the (optionally-substituted phenylene) groups of the -O-(optionally-substituted phenylene) content of the poly(1,4-phenylene ether) component is made up of at least 50% phenyl carbons and phenyl hydrogens.

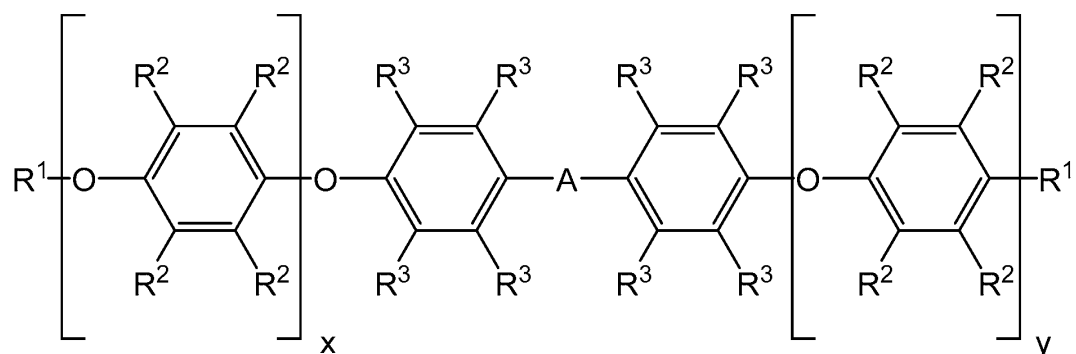
[0018] The poly(1,4-phenylene ether) component, in various desirable embodiments, is a poly(1,4-phenylene ether) bismethacrylate component, i.e., having at least 75 wt%, e.g., at least 90 wt% poly(1,4-phenylene ether) bismethacrylate.

[0019] In various embodiments, the poly(1,4-phenylene ether) component is a bis(vinyl) poly(1,4-phenylene ether) component, i.e., having at least 75 wt%, e.g., at least 90 wt% bis(vinyl) poly(1,4-phenylene ether).

[0020] In various embodiments, the poly(1,4-phenylene ether) component is a bis(allyl) poly(1,4-phenylene ether) component, i.e., having at least 75 wt%, e.g., at least 90 wt% bis(allyl) poly(1,4-phenylene ether).

[0021] In various embodiments, the poly(1,4-phenylene ether) component is a bis(methallyl) poly(1,4-phenylene ether) component, i.e., having at least 75 wt%, e.g., at least 90 wt% bis(methallyl) poly(1,4-phenylene ether).

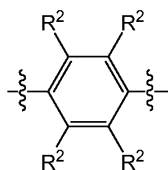
[0022] In various embodiments, the poly(1,4-phenylene ether) component has the structural formula



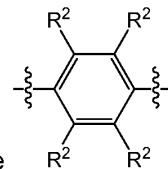
in which A is a bond, $-\text{CH}_2-$, $\text{CH}(\text{CH}_3)-$, $-\text{C}(\text{CH}_3)_2-$, $-\text{O}-$, $-\text{C}(\text{O})-$, $\text{S}(\text{O})$, or $\text{S}(\text{O})_2$; each R^1 is independently methacrylate, acrylate, vinyl, allyl or methallyl; each R^2 is independently methyl or hydrogen; and each R^3 is independently methyl or hydrogen. Mixtures of molecules having different identities of A, R^1 and R^2 are specifically contemplated within this definition. As the person of ordinary skill in the art will appreciate, values of x and y will vary depending on the molecular weight of the material.

[0023] For example, in various embodiments, A is $-\text{CH}_2-$, $\text{CH}(\text{CH}_3)-$ or $-\text{C}(\text{CH}_3)_2-$. In various embodiments, A is $-\text{C}(\text{CH}_3)_2-$.

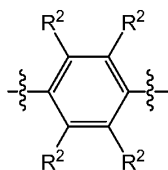
[0024] The structure of the tetra-R²-substituted moieties can vary. For example, in



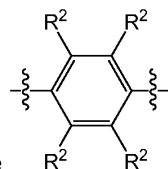
various embodiments, in at least 75% of the moieties, two R² are methyl and



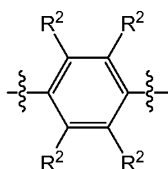
two R² are H. For example, in various embodiments, in at least 90% of the moieties two R² are methyl and two R₂ are H. in various embodiments, in at least 98% of



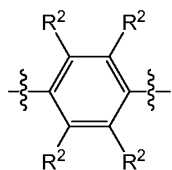
the moieties two R² are methyl and two R² are H.



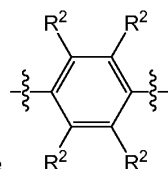
[0025] In various embodiments, in at least 75% of the moieties, two R² are methyl substituted in a meta relationship and two R² are H. For example, in various



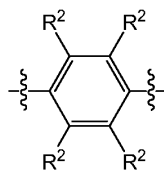
embodiments, in at least 90% of the moieties two R² are methyl substituted in a meta relationship and two R² are H. in various embodiments, in at least 98% of the



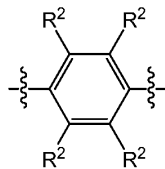
moieties two R² are methyl substituted in a meta relationship and two R² are H.



[0026] In various embodiments, in at least 75% of the moieties, two R² are methyl substituted in a meta relationship distal to the A moiety and two R² are H. For

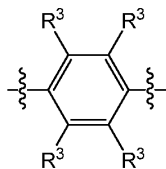


example, in various embodiments, in at least 90% of the moieties two R^2 are methyl substituted in a meta relationship distal to the A moiety and two R^2 are H. in

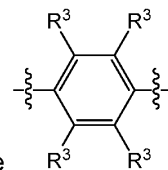


various embodiments, in at least 98% of the moieties two R^2 are methyl substituted in a meta relationship distal to the A moiety and two R^2 are H.

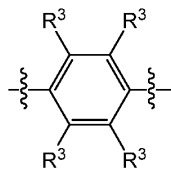
[0027] The structure of the tetra- R^3 -substituted moieties can also vary. For example, in



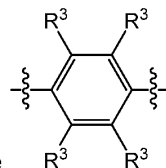
various embodiments, in at least 75% of the moieties, two R^3 are methyl and



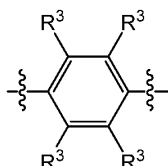
two R^3 are H. For example, in various embodiments, in at least 90% of the moieties two R^3 are methyl and two R^3 are H. in various embodiments, in at least 98% of



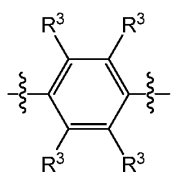
the moieties two R^3 are methyl and two R^3 are H.



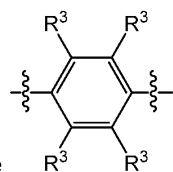
[0028] In various embodiments, in at least 75% of the moieties, two R^3 are methyl substituted in a meta relationship and two R^3 are H. For example, in various



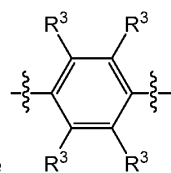
embodiments, in at least 90% of the moieties two R^3 are methyl substituted in a meta relationship and two R^3 are H. in various embodiments, in at least 98% of the



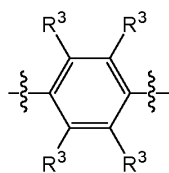
moieties two R^3 are methyl substituted in a meta relationship and two R^3 are H.



[0029] In various embodiments, in at least 75% of the moieties, two R^3 are methyl substituted in a meta relationship distal to the A moiety and two R^3 are H. For



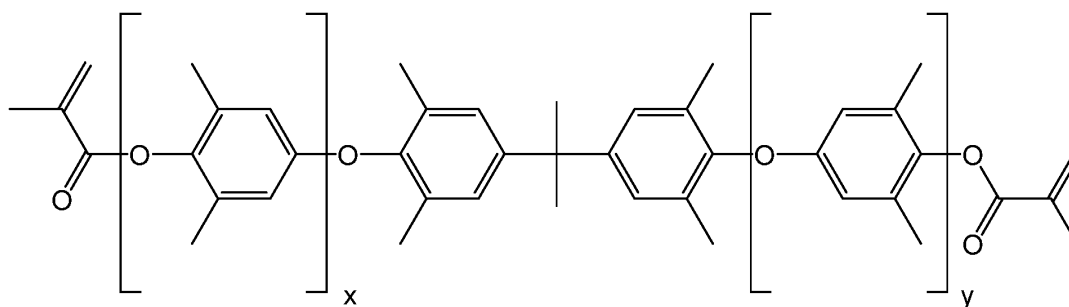
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various embodiments, in at least 98% of the moieties two R^3 are methyl substituted in a meta relationship distal to the A moiety and two R^3 are H.

[0030] As noted above, R^1 can be one or more of methacrylate, acrylate, vinyl, allyl and methallyl. In various embodiments, at least 75% of R^1 are methacrylate, e.g., at least 90%, or at least 95%. In various embodiments, at least 75% of R^1 are vinyl, e.g., at least 90%, or at least 95%. In various embodiments, at least 75% of R^1 are allyl, e.g., at least 90%, or at least 95%. In various embodiments, at least 75% of R^1 are methallyl, e.g., at least 90%, or at least 95%. In various embodiments, at least 75% of R^1 are methacrylate, vinyl, allyl or methallyl, e.g., at least 90%, or at least 95%.

[0031] In various particular embodiments, at least 75 wt% of the poly(1,4-phenylene ether) component has the formula



. In various such embodiments, at least 90 wt% of the poly(1,4-phenylene ether) component has this formula. In various such embodiments, at least 95 wt% of the poly(1,4-phenylene ether) component has this formula.

[0032] The poly(1,4-phenylene ether) component can have a variety of molecular weights. The person of ordinary skill in the art will select an appropriate molecular weight to provide the thermosetting composition with desirable properties, e.g., a desirable viscosity to allow for processing into preregs or other cured items. For example, in various embodiments, the poly(1,4-phenylene ether) component has a number-average molecular weight in the range of 1000-4000 g/mol, e.g., 1000-3500 g/mol or 1000-3000 g/mol, or 1000-2500 g/mol, or 1500-4000 g/mol, or 1500-3500 g/mol, or 1500-2500 g/mol.

[0033] As noted above, the values of x and y will depend on the molecular weight of the material. In various embodiments, the poly(1,4-phenylene ether) component has a number-average value of the sum of x+y in the range of 3-30, e.g., 3-25, or 3-20, or 3-15, or 5-30, or 5-25, or 5-20, or 5-15, or 7-30, or 7-25, or 7-20, or 7-15, or 10-30, or 10-25, or 10-20, or 10-15.

[0034] Examples of suitable materials include NORLYL SA-9000, available from SABIC; Kolon KPU-6000, available from Kolon Industries; and SP7-160, available from SilverAge Engineering Plastics Co Ltd.

[0035] As noted above, the poly(1,4-phenylene ether) component is present in the thermosetting composition in an amount in the range of 20-35 wt%. The person of ordinary skill in the art can vary the amount generally within this range. For example, in various embodiments the poly(1,4-phenylene ether) component is present in an amount of 22-35 wt%, e.g., 22-32 wt%, or 22-30 wt%. In various embodiments, the poly(1,4-phenylene ether) component is present in an amount of 25-35 wt%, e.g., 25-32 wt%, or 25-30 wt%.

[0036] As described above, the thermosetting composition also includes an aromatic crosslinking component having a weight average molecular weight of no greater than 700 g/mol and bearing on numerical average in the range of 1.75 - 3.5 crosslinkable vinyl,

(meth)allyl and/or (meth)acrylate groups per molecule, in an amount in the range of 2-15 wt%.

[0037] The person of ordinary skill in the art will appreciate that a variety of such aromatic crosslinking components may be used, alone or in combination. For example, in various desirable embodiments, the aromatic crosslinking component includes (or is) a cyanurate component. In various embodiments, the aromatic crosslinking component includes (or is) a cyanurate component that is triallylcyanurate, triallylisocyanurate, or a combination of triallylcyanurate and triallylisocyanurate. For example, in some embodiments, the aromatic crosslinking component includes (or is) triallylcyanurate. In some embodiments, the aromatic crosslinking component includes (or is) triallylisocyanurate. In some embodiments, the aromatic crosslinking component includes (or is) a combination of triallylcyanurate and triallylisocyanurate. In some embodiments, the aromatic crosslinking component includes (or is) trimethallylisocyanurate.

[0038] But the person of ordinary skill in the art will appreciate that other aromatic crosslinkers can be used, in combination with or instead of the cyanurate materials described above. For example, in various embodiments, the aromatic crosslinking component includes (or is) a divinylbenzene.

[0039] In various embodiments, the aromatic crosslinking component includes (or is) triallylcyanurate, triallylisocyanurate, trimethallylisocyanurate, divinylbenzene, or any combination thereof.

[0040] Aromatic crosslinking components such as those described above are widely available from various vendors.

[0041] The thermosetting compositions described herein can include the aromatic crosslinking component in a variety of amounts. For example, in various embodiments, the aromatic crosslinking component is present in an amount in the range of 2-11 wt%, e.g., 2-9 wt%, or 2-7 wt%. In various embodiments, the aromatic crosslinking component is present in an amount in the range of 3-15 wt%, e.g., 3-11 wt%, or 3-9 wt%, or 3-7 wt%. In various embodiments, the aromatic crosslinking component is present in an amount in the range of 4-15 wt%, e.g., 4-11 wt%, or 4-9 wt%, or 4-7 wt%. The person of ordinary skill in the art can tune the amount of aromatic crosslinking component to provide desired properties to cured materials.

[0042] The thermosetting composition also includes a butadiene/styrene copolymeric rubber component, in an amount of 5-25 wt%. As used herein, a butadiene/styrene copolymeric rubber is a polymer that is formed of at least 80 wt% butadiene and styrene

residues, and has a glass transition temperature as measured by DSC of no more than 5 °C. The corresponding component of the thermosetting composition can include one or more such samples of rubber.

[0043] In various embodiments, the butadiene/styrene copolymeric rubber component has a total content of butadiene and styrene residues in an amount of at least 90 wt%, e.g., at least 95 wt%, at least 97 wt%, at least 98 wt%, or at least 99 wt%.

[0044] In various embodiments, however, the butadiene/styrene copolymeric rubber component includes a substantial amount of other residues. For example, in some embodiments, the butadiene/styrene copolymeric rubber component includes divinylbenzene residues, e.g., grafted to a butadiene/styrene backbone. In various embodiments, the butadiene/styrene copolymeric rubber component comprises up to 5 wt% divinylbenzene residues, e.g., in the range of 0.5-5 wt%, or 0.5-3 wt%, or 1-5 wt%, or 1-3 wt%.

[0045] In various embodiments as otherwise described herein, the butadiene/styrene copolymeric rubber component has a substantially random arrangement of butadiene and styrene. The person of ordinary skill in the art will appreciate that such materials can be made by copolymerization of butadiene and styrene in a single process. However, in alternative embodiments, copolymers that have substantial block copolymer character can be used.

[0046] In various embodiments, the butadiene/styrene copolymeric rubber component has a number average molecular weight in the range of 1500-7000 g/mol, e.g., 1500-5000 g/mol, or 2500-7000 g/mol, or 2500-5000 g/mol.

[0047] The amount of 1,2-vinyl moieties of the butadiene/styrene substantially random copolymeric rubber component can vary. In various embodiments, the butadiene residues of the butadiene/styrene copolymeric rubber component have a molar fraction of 1,2-vinyl moieties in the range of 15-80 mol%, e.g., 15-70%, or 15-60%, or 20-80 mol%, or 20-70 mol%, or 20-60 mol%. In various embodiments, the butadiene residues of the butadiene/styrene copolymeric rubber component have a molar fraction of 1,2-vinyl moieties of 25-80 mol%, e.g., 25-70%, or 25-60%, or 30-80 mol%, or 30-70 mol%, or 30-60 mol%. In various embodiments, the butadiene residues of the butadiene/styrene copolymeric rubber component have a molar fraction of 1,2-vinyl moieties of 35-80 mol%, e.g., 35-70%, or 35-60%, or 40-80 mol%, or 40-70 mol%, or 40-60 mol%. In various embodiments, the butadiene residues of the butadiene/styrene copolymeric rubber component have a molar fraction of 1,2-vinyl moieties of 20-60 mol%, e.g., 20-55 mol%, or 20-50 mol%, or 20-45 mol%, or 25-60 mol%, or 25-55 mol%, or 25-50 mol%, or 25-45 mol%, or 30-60 mol%, or 30-55 mol%, or 30-50 mol%, or 30-45 mol%, or 35-60 mol%, or 35-55 mol%, or 35-50 mol%, or 35-45 mol%.

[0048] The amount of styrene residues in the butadiene/styrene copolymeric rubber component can vary as well. In various embodiments, the butadiene/styrene substantially random copolymeric rubber component has in the range of 15-40 wt% styrene residues, e.g., 15-35 wt% or 15-30 wt%. In various embodiments, the butadiene/styrene copolymeric rubber component has in the range of 20-40 wt% styrene residues, e.g., 20-35 wt% or 20-30 wt%. In various embodiments, the butadiene/styrene copolymeric rubber component has in the range of 23-40 wt% styrene residues, e.g., 23-35 wt% or 23-30 wt%.

[0049] While the butadiene/styrene copolymeric rubber component can be made substantially of a single sample of butadiene/styrene copolymeric rubber, in some cases, blends can be used. For example, in various embodiments, the butadiene/styrene copolymeric rubber component is made up of a first butadiene/styrene substantially random copolymeric rubber subcomponent that has 17-27 wt% styrene residues and in which the butadiene residues have a molar fraction of 1,2-vinyl moieties of 60-80 mol%; and a second butadiene/styrene substantially random copolymeric rubber subcomponent that has 20-30 wt% styrene residues and in which the butadiene residues have a molar fraction of 1,2-vinyl moieties of 20-40 mol%. In various such embodiments, a weight ratio of the first butadiene/styrene substantially random copolymeric rubber subcomponent and the second butadiene/styrene substantially random copolymeric rubber subcomponent is in the range of 1:1.2 – 1:2.3, e.g., 1:1.5 – 1:2.3, or 1:1.2 – 1:2, or 1:1.5 – 1:2.

[0050] Butadiene/styrene substantially random copolymeric rubber materials are available from a variety of vendors, including Cray Valley (e.g., Ricon 100, Ricon 181, Ricon 184, Ricon 257) and Kuraray Co., Ltd. (L-SBR grades, including L-SBR-870, L-SBR-822 and L-SBR-841). Block copolymer materials are also widely available.

[0051] The amount of the butadiene/styrene copolymeric rubber component in the thermosetting composition can vary. For example, in various embodiments, the butadiene/styrene copolymeric rubber component is present in an amount in the range of 5-20 wt%, or 5-18 wt%, or 5-15 wt%. In various embodiments, the butadiene/styrene copolymeric rubber component is present in an amount in the range of 7-25 wt%, e.g., 7-20 wt%, or 7-18 wt%, or 7-15 wt%. In various embodiments, the butadiene/styrene substantially random copolymeric rubber component is present in an amount in the range of 9-25 wt%, e.g., 9-20 wt%, or 9-18 wt%, or 9-15 wt%.

[0052] The thermosetting composition also includes microparticulate silica, in an amount in the range of 15-50 wt%. As used herein, a microparticulate silica is a particulate material that is at least 95 wt% SiO₂ and has a d₅₀ particle size in the range of 0.1-100 microns. In various embodiments, the microparticulate silica has a d₅₀ particle size in the range of 0.5-10

microns, e.g., 0.5-7 microns, or 0.5-5 microns, or 1-10 microns, or 1-7 microns, or 1-5 microns. In various embodiments, the microparticulate silica has a d_{90} particle size in the range of 1-20 microns, e.g., 1-14 microns, or 1-8 microns, or 3-20 microns, or 3-14 microns, or 3-8 microns. In various embodiments, the microparticulate silica has a d_{10} particle size in the range of 0.1-5 microns, e.g., 0.1-3 microns, or 0.1-2 microns, or 0.5-5 microns, or 0.5-3 microns, or 0.5-2 microns. In various embodiments, the microparticulate silica has at least 99 wt% SiO_2 , e.g., at least 99.5 wt% SiO_2 .

[0053] The microparticulate silica is desirably substantially spherical. The person of ordinary skill in the art can use microscopy to confirm sphericity.

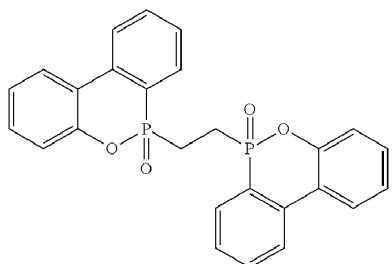
[0054] Suitable microparticulate silicas are available from a variety of vendors, including DQ-1028L, available from Novoray; SS-15V, available from Sibelco; and FB-3SDC and FB-3SDX, available from Denka Co. Ltd.

[0055] The amount of microparticulate silica can vary. For example, in various embodiments, the microparticulate silica is present in an amount in the range of 15-45 wt%, or 15-40 wt%, or 15-35 wt%. In various particular embodiments, the microparticulate silica is present in an amount in the range of 20-50 wt%, e.g., 20-45 wt%, or 20-40 wt%, or 20-35 wt%. In various particular embodiments, the microparticulate silica is present in an amount in the range of 25-50 wt%, e.g., 25-45 wt%, or 25-40 wt%, or 25-35 wt%.

[0056] The thermosetting composition also includes an organic halogen-free fire retardant component, present in an amount of 15-35 wt%. In various embodiments, the organic halogen-free fire retardant comprises phosphorus.

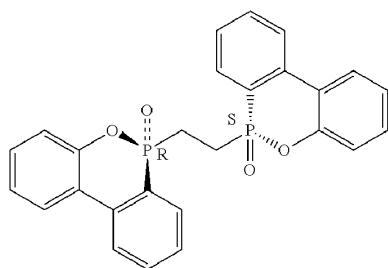
[0057] Notably, the present inventors have found that particular fire retardants described in U.S. Patents nos. 8536256, 9012546, 9522927 and 9562063 can provide especially good performance in the presently-described thermosetting compositions. Accordingly, these patents are hereby incorporated herein by reference in their entirety, and their text is copied below; the present disclosure contemplates the use of any fire retardant as generically or specifically described in any of these patents as part of the organic halogen-free fire retardant component of the thermosetting composition of the disclosure, alone or in combination. For example, in various embodiments, the organic halogen-free fire retardant component includes (or is) 6H-Dibenz[c,e][1,2]oxaphosphorin, 6,6'-(1,4-ethanediyl)bis-, 6,6'-dioxide; 6H-Dibenz[c,e][1,2]oxaphosphorin, 6,6'-(1,4-butanediyl)bis-, 6,6'-dioxide; or 6H-Dibenz[c,e][1,2]oxaphosphorin, 6,6'-(p-xylenediyl)bis-, 6,6'-dioxide; or any combination thereof. In various embodiments, the fire retardant component includes (or is) 6H-Dibenz[c,e][1,2]oxaphosphorin, 6,6'-(1,4-ethanediyl)bis-, 6,6'-dioxide. In various

embodiments, the fire retardant component includes (or is) a compound having the structure:
having the following structure:



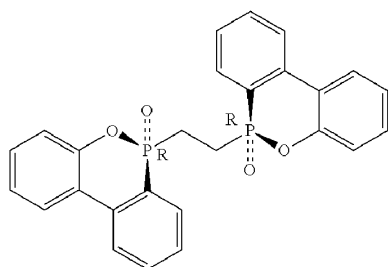
In various embodiments, the fire retardant component includes (or is) composition comprising the high melting point isomer of Formula IIa:

Formula IIa

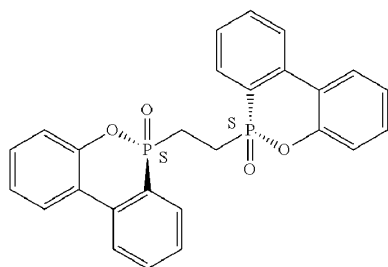


and the low melting point isomers of Formula IIb and IIc having the Formulas:

Formula IIb



Formula IIc



wherein said composition has an Isomer Ratio of greater than about 0.5 utilizing the ^{31}P NMR method and wherein said Isomer Ratio = $A_h/(A_h + A_l)$, wherein A_h : area of high melting point isomer peak and A_l : area of low melting point isomers peak.

[0058] But in other embodiments, other halogen-free flame retardants can be used. In various embodiments, the organic halogen-free fire retardant is a phosphorus-containing fire retardant, e.g., selected from FRM 6300 (Qingdao) and Mosaflam 615 (UFC).

[0059] The organic halogen-free fire retardant component can be provided in the thermosetting composition in a variety of amounts within the broader range of 15-35 wt%. For example, in various embodiments, the organic halogen-free fire retardant component is present in an amount of 15-30 wt%, e.g., 15-25 wt%. In various embodiments, the organic halogen-free fire retardant component is present in an amount of 20-35 wt%, e.g., 20-30 wt%, or 20-25 wt%. In various embodiments, the organic halogen-free fire retardant component is present in an amount of 25-35 wt%, e.g., 25-30 wt%.

[0060] As noted above, the thermosetting composition also includes an effective amount of a thermal free-radical initiator component. The person of ordinary skill in the art will identify a desirable thermal free-radical initiator or combination thereof, in desirable amount(s) to provide initial polymerization of the thermosetting composition to a B-staged composition, and to further polymerize the B-staged composition to a substantially-polymerized composition, e.g., in laminate form. Suitable initiators include, without limitation, benzoyl peroxide, dicumyl peroxide, methyl ethyl ketone peroxide, lauryl peroxide, cyclohexanone peroxide, t-butyl hydroperoxide, t-butyl benzene hydroperoxide, acetyl isobutyryl peroxide, diacetyl peroxide, t-butyl peroctoate, α,α' -bis(t-butylperoxy-m-isopropyl)benzene, 2,3-dimethyl-2,3-diphenylbutane, di(trimethylsilyl)peroxide, 5-dimethyl-2,5-di(benzoylperoxy)hexane, 2,5-dimethylhexane-2,5-dihydroperoxide, 2,5-dimethyl-2,5-di(t-butylperoxy)-hex-3-yne, di-t-butylperoxide, t-butylcumyl peroxide, 2,5-dimethyl-2,5-di(t-butylperoxy)hexane, t-butylperoxy benzoate, 2,2-bis(t-butylperoxy)butane, 2,2-bis(t-butylperoxy)octane, 2-trimethylsilylphenyltriphenylsilyl peroxide, 2,3-trimethylsilyloxy-2,3-diphenylbutane, di(t-butylperoxy) isophthalate, azobisisobutyronitrile (AIBN), azobis(2-isopropyl)butyronitrile, 2,2'-azobis(2,4-dimethyl)valeronitrile (AVBN), (2,4-dichlorobenzoyl) peroxide, (2-dimethylbenzoyl) peroxide, and dodecanoyl peroxide. The person of ordinary skill in the art can provide the initiator component with a single initiator or a combination of initiators. The one or more initiators can be provided in some embodiments with a carrier; the person of ordinary skill in the art will appreciate that the mass of the thermal free-radical initiator component is calculated as the mass of the initiator compound(s) themselves, omitting the mass of any carriers.

[0061] The person of ordinary will determine an effective amount of the thermal free-radical initiator component. For example, in various embodiments, the thermal free-radical initiator component is present in an amount in the range of 0.05-4 wt%, e.g., 0.05-2 wt%, or 0.05-1 wt%, or 0.05-0.7 wt%. In various embodiments, the thermal free-radical initiator component is present in an amount in the range of 0.07-4 wt%, e.g., 0.07-2 wt%, or 0.07-1 wt%, or 0.07-0.7 wt%. In various embodiments, the thermal free-radical initiator component is present in an amount in the range of 0.1-4 wt%, e.g., 0.1-2 wt%, or 0.1-1 wt%, or 0.1-0.7 wt%. In various embodiments, the thermal free-radical initiator component is present in an amount in the range of 0.2-4 wt%, e.g., 0.2-2 wt%, or 0.2-1 wt%, or 0.2-0.7 wt%.

[0062] Additional components than those outlined above can be present in some embodiments. For example, in various embodiments, the thermosetting composition can also include a silane coupling agent, e.g., to provide bonding to the microparticulate silica filler and/or to a glass material used in making a prepreg or laminate. The person of ordinary skill in the art is familiar with silane coupling agents, and can select a suitable one based on the description herein. For example, the silane coupling agent can in some embodiments be selected from one or more of (meth)acryl-functional silanes (e.g., 3-(meth)acryloxy)propyltrimethoxysilane), vinyl-functional silanes (e.g., vinyltriethoxysilane), allyl-functional silanes (e.g., allyltrimethoxysilane), and other reactive carbon-carbon double-bond-bearing silanes (e.g., styryltrimethoxysilane, 3-butenyltriethoxysilane, 7-octenyltriethoxysilane). The silane coupling agent can be present in an amount, e.g., up to 5 wt%, e.g., in the range of 0.1-5 wt%. However, the present inventors have noted that a silane coupling agent in many embodiments is not necessary for good performance, and so in various embodiments, there is no more than 0.01 wt% of a silane coupling agent present.

[0063] The amounts described herein for components of the thermosetting composition are on a dry solids basis, i.e., with 100 wt% being the total of the non-volatile (i.e., boiling point less than 200 °C at atmospheric pressure) components of the composition. In various embodiments, the thermosetting composition is provided in substantially non-volatile form, i.e., without a substantial amount of a solvent. The present inventors have noted that thermosetting compositions as described here can in many embodiments be provided with desirable viscosities without the use of large amounts of solvent. Accordingly, in various embodiments, the thermosetting compositions as described herein can be provided with no more than 10 wt% material having a boiling point at atmospheric pressure of less than 200 °C, e.g., no more than 5 wt%, or no more than 3 wt%, or no more than 1 wt%, all calculated with the non-volatile content being 100 wt% as described above.

[0064] However, the present inventors note that a solvent can be useful to provide the material with a lower viscosity for processing, especially in the impregnation of a glass or polymer fabric for making a prepreg. Accordingly, in various embodiments, the thermosetting composition also includes a solvent having a boiling point at atmospheric pressure of less than 200 °C. The person of ordinary skill in the art will appreciate that a variety of solvents could be used, alone or in combination, and will determine an appropriate solvent in which to suspend the various components of the composition. Potential examples include γ -butyrolactone, cyclohexanone, butanone, methyl isobutyl ketone, N,N-dimethylformamide, propylene glycol monomethyl ether, N,N-dimethylacetamide, ethylene glycol monomethyl ether, methoxy ethyl acetate, ethoxy ethyl acetate, propoxy ethyl acetate, diisobutyl ketone (DIBK), N-methyl-pyrrolidone, xylene, ethyl acetate, toluene, trichloroethane, dibutyl ether, methyl ethyl ketone, and acetone. Similarly, the person of ordinary skill in the art will appreciate that the amount of solvent can be varied to provide a desired viscosity; in various embodiments, the amount of solvent is up to 60 wt%, e.g., in the range of 20-60 wt%, in excess of the non-volatile components of the thermosetting composition (i.e., taken together as 100 wt%).

[0065] Another aspect of the disclosure is a cured product of a thermosetting composition as described herein. As the person of ordinary skill in the art will appreciate, the cured product can in some embodiments be only partially-cured, e.g., to an extent to form a solid form, such that it is handleable but can be more fully cured by further processing. This partial curing can be to a so-called "B-stage," or to a lesser or further extent. In other embodiments, the cured product can be substantially fully cured, so that it is substantially stable to further processing. A variety of curing conditions may be used, but typically curing temperatures are in the range of 100-250 °C, for a time sufficient to arrive at a desired degree of cure.

[0066] Another aspect of the disclosure is a prepreg comprising a mesh substrate at least partially embedded in a cured product of the disclosure, desirably a partially-cured product that can be further cured by further heating at a later time. One embodiment is shown in schematic cross-sectional view in FIG. 1. Here, prepreg 100 comprises mesh substrate 110, embedded in a cured product of the disclosure 120.

[0067] The person of ordinary skill in the art can use a variety of mesh substrates. For example, in various embodiments, the mesh substrate is a fabric (woven or non-woven), e.g., made from glass fiber, carbon fiber, or various polymer fibers such as aramid fiber such as the material available under the trade name KEVLAR. In particular desirable embodiments, the substrate is a borosilicate glass fabric. In some such embodiments, the

glass is formed, on an oxide basis, of SiO_2 (50-80 wt%), B_2O_3 (5-25 wt%), with optional components including without limitation CaO (up to 30 wt%) Al_2O_3 (up to 20 wt%) and MgO (up to 5 wt%). Examples of suitable glass fabrics include electronic grade E-glass fabric, NE-glass fabric, D-glass fabric, and S-glass fabric. In various embodiments, the mesh substrate is substantially embedded in the cured product. As the person of ordinary skill in the art will appreciate, prepregs can be made of a variety of overall thicknesses, but in some embodiments, the prepreg is in the range of 10-300 microns in thickness, e.g., 10-200 microns, or 10-150 microns, or 10-100 microns. In some embodiments, the prepreg is in the range of 25-300 microns in thickness, e.g., 25-200 microns, or 25-150 microns, or 25-100 microns. In some embodiments, the prepreg is in the range of 50-300 microns in thickness, e.g., 50-200 microns, or 50-150 microns. The prepreg desirably includes at least 30 wt% of the cured product of the disclosure, e.g., at least 50 wt%.

[0068] The person of ordinary skill in the art is familiar with methods for making prepregs, and will adapt such methods for use with the thermosetting composition of the disclosure. The thermosetting composition can be contacted with the mesh substrate, dried as necessary to remove any volatiles, and cured by heating to cause the thermosetting composition to at least partially cure it to provide the prepreg.

[0069] Another aspect of the disclosure is a laminate of a plurality of prepregs of the present disclosure. One example is shown in schematic perspective view in FIG. 2. Here, laminate 230 includes a laminate of a plurality of prepregs 200. The laminate can be made by heat-pressing a plurality of prepregs as described herein to cause softening and further curing of partially-cured material of the prepregs to fuse them together into a laminate structure. Heat pressing conditions can vary, but can generally be in the range of 150-250 °C and 1-10 MPa. The further curing in many embodiments can substantially fully cure the material. As used herein, substantial full curing can be determined using a delta T_g measurement, in which a material is run to 250 °C in a differential scanning calorimeter and a first T_g determined. The sample is then cooled to room temperature, and a T_g measurement up to 250 °C is repeated to provide a second T_g . If the difference between the first T_g and the second T_g is no more than 10 °C, the material is said to be substantially fully cured. Here, too, the person of ordinary skill in the art is familiar with techniques for forming laminates from prepregs, and will adapt them for use with the prepregs of the disclosure.

[0070] The laminates of the disclosure can include one or more layers of metal, such as copper. The one or more layers of metal can be disposed, e.g., on one or both major surfaces of the laminate, and/or laminated in between layers of prepregs. Each layer of

metal can be substantially uniform, or can be provided in the form of circuits, e.g., by etching. As the person of ordinary skill in the art will appreciate, a circuit board laminate can be built in a plurality of steps, e.g., by providing a first laminate with metal on one or both surfaces thereof, then forming a circuit out of such metal, then further laminating the so-processed first laminate with additional layers of prepreg and metal to form a multilayer laminate.

[0071] The present inventors have found that the materials described herein can provide good peel strength, even when used with thin, low-roughness copper. Such copper is available under the designation “BF-NN.” In various embodiments, the one or more layers of copper are in the range of 15-50 microns in thickness, e.g., in the range of 17-37 microns in thickness. In various embodiments, each of the one or more layers of copper have an outer surface facing away from the prepreg to which the layer is laminated, having one or more of a surface roughness Ra (measured by contact, ISO 4287) of no more than 0.3 microns, and/or a surface roughness Sa (measured contactless, ISO 25178) in the range of 0.1-0.3 microns, e.g., 0.15-0.25 microns. In various embodiments, each of the one or more layers of copper have an inner surface contacting one of the prepreps having one or more of a surface roughness Sa in the range of 0.1-0.4 microns (e.g., 0.12-0.3 microns; a surface roughness Sz in the range of 1-5 microns (e.g., 1.2-4 microns); and/or a surface roughness Sdr in the range of 0.5-3 microns (e.g., 0.7-2 microns), each measured contactless, ISO 25178).

[0072] The present inventors have found that the materials described herein have a variety of desirable properties, including low Df values, good peel strength, and high glass transition temperature. For example, in various embodiments, the laminate has a Df value in the range of 0.0015 to 0.003, e.g., 0.0015 to 0.0025, as measured by IPC-TM-650 2.5.5.5. In various embodiments, the laminate has a peel strength of at least 2.5 lb/in as measured by IPC-TM-650 2.4.8 (e.g., in the range of 2.5-5 lb/in, or 2.5-4.5 lb/in, or 2.5-4 lb/in, or 3-5 lb/in, or 3-4.5 lb/in, or 3-4 lb/in). In various embodiments, the laminate has a Tg as measured by DSC in the range of 180-240 °C, e.g., 180-230 °C, or 180-220 °C, or 190-240 °C, or 190-230 °C, or 190-220 °C.

[0073] Various aspects and embodiments of the disclosure are further provided by the following non-limiting examples.

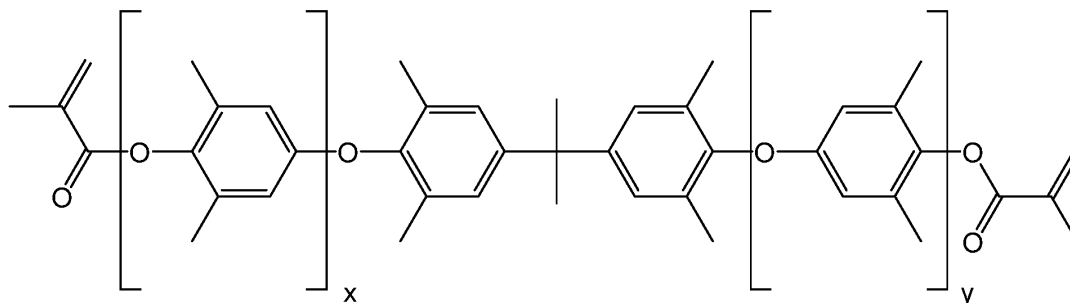
EXAMPLE 1

[0074] Various aspects and embodiments of the disclosure are further provided by the following non-limiting examples.

[0075] Various particular example formulations include the following components, on a solids basis:

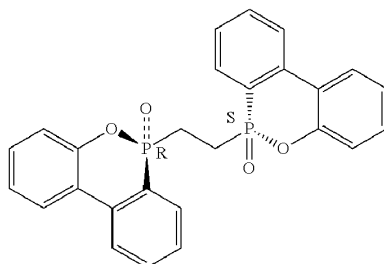
Component	A (wt%)	B (wt%)	C (wt%)	D (wt%)	E (wt%)
PPO bismethacrylate	27.4	31.4	28.2	25.0	26.1
Triallyl cyanurate	5.0	5.8	6.2	-	-
Triallyl isocyanurate	-	-	-	4.8	5.6
Styrene-butadiene rubber (70% 1,2 vinyl, 17-27 wt% styrene)	4.8	5.5	15.1	-	-
Styrene-butadiene rubber (20-40% 1,2-vinyl, 20-30 wt% styrene)	8.7	9.9	-	15.9	-
Styrene-butadiene rubber (30% 1,2-vinyl, 28 wt% styrene)	-	-	-	-	16.0
Microparticulate spherical silica	30.9	26.2	29.1	31.5	31.0
Halogen-free flame retardant	22.8	20.7	21.0	22.3	20.9
Thermal free-radical initiator	0.4	0.5	0.4	0.5	0.4

[0076] The PPO methacrylate is the poly(phenylene oxide) bismethacrylate available under the trade name NORLYL 900, having the nominal structural formula



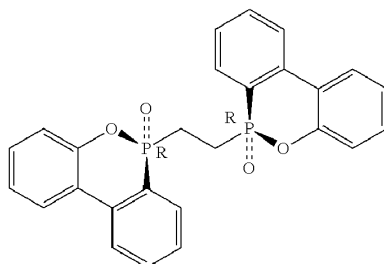
. The styrene-butadiene rubber (70% 1-2 vinyl, 17-27 wt% styrene) is the material available under the trade name RICON® 100. The styrene-butadiene rubber (20-40% 1,2-vinyl, 20-30 wt% styrene) is the material available under the trade name RICON® 181. The styrene-butadiene rubber (30% 1,2-vinyl), 28% styrene) is the material available under the trade name RICON® 184. The microparticulate silica is DQ-1028L, available from Novoray. The halogen-free flame retardant is a composition comprising the high melting point isomer of Formula IIa:

Formula IIa

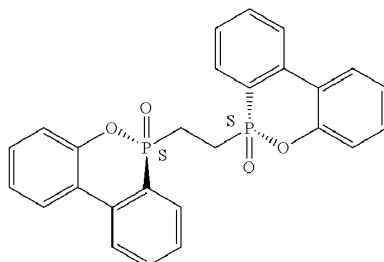


and the low melting point isomers of Formula IIb and IIc having the Formulas:

Formula IIb



Formula IIc



wherein said composition has an Isomer Ratio of greater than about 0.5 utilizing the ^{31}P NMR method and wherein said Isomer Ratio = $A_h / (A_h + A_l)$, wherein A_h : area of high melting point isomer peak and A_l : area of low melting point isomers peak.

[0077] The thermosetting compositions are formed into 6-ply laminates. The thermosetting composition is charged into a dip pan, and woven glass fabric (2116, low Dk glass, 0.10 mm thick, 105 g/m²) is drawn through the dip pan and then between rollers having 0.012 gap thickness. The resin-coated glass fabric is dried in an oven to substantially remove solvent (i.e., less than 1% solvent remaining). This provides a prepreg material with 57% resin on glass, about 0.005" in thickness.

[0078] Six layers of this prepreg are plied up between two sheets of copper (BF-NN grade, super flat profile, "1oz," 35 microns nominal thickness), with the treated side of the copper contacting the prepreg material, and the assembly is then placed between two

stainless steel press platens, and loaded into a hot oil vacuum press. Pressure (200-500 psi) and vacuum (2-5 mbar) are applied, and the temperature of the load is brought to the dwell temp (210 °C) at a defined heat rise rate (2.5 °C/min) and held there for a defined time (120 min), after which the press is allowed to cool at about 5°C/min, until the resulting laminate is cool enough to remove.

[0079] Data for two example formulations are provided in the Table below:

Property	Test method	A	B
Tg (by DSC)	-	204 °C	210 °C
Tg (by DMA)	-	223 °C	216 °C
Tg (by TMA)	-	186 °C	183 °C
CTE : α_1 (z-axis)	IPC TM-650 2.4.24.5	65 ppm/°C	65 ppm/°C
CTE : α_2 (z-axis)	IPC TM-650 2.4.24.5	228 ppm/°C	176 ppm/°C
Time to delamination (260 C)	IPC TM-650 2.4.24.1	60 min	60 min
Time to delamination (288 C)	IPC TM-650 2.4.24.1	60 min	60 min
Dk	IPC TM-650 2.5.59	3.45	3.41
Df	IPC TM-650 2.5.59	0.0018	0.0021
Peel strength	IPC TM-650 2.4.8	3.7 lb/in	3.5 lb/in
Flammability	UL94VO	V0	V0

[0080] The use of thin, high-flatness copper is especially challenging from the standpoint of peel strength. The formulations described herein are demonstrated to provide good peel strength, even to BF-NN grade copper.

[0081] Various aspects of the disclosure are illustrated by the following enumerated embodiments, which can be combined in any number and in any combination not technically or logically inconsistent:

Embodiment 1. A thermosetting composition comprising:

a poly(1,4-phenylene ether) component having at least 80% phenylene ether content, the poly(1,4-phenylene ether) component being a poly(1,4-phenylene ether) bis(meth)acrylate component, a bis(vinyl) poly(1,4-phenylene ether) component, or a bis((meth)allyl) poly(1,4-phenylene ether) component, or a combination of two or more thereof, in an amount in the range of 20-35 wt%;

an aromatic crosslinking component having a weight average molecular weight of no greater than 700 g/mol and bearing on numerical average in the range of 1.75 - 3.5 crosslinkable vinyl, (meth)allyl and/or (meth)acrylate groups per molecule, in an amount in the range of 2-15 wt%;

a butadiene/styrene copolymeric rubber component, in an amount of 5-25 wt%;

microparticulate silica, in an amount in the range of 15-50 wt%;

an organic halogen-free fire retardant component, in an amount of 15-35 wt%; and

a thermal free-radical initiator component, in an amount of 0.1-3 wt%.

Embodiment 2. The thermosetting composition of embodiment 1, wherein the mass of the (optionally-substituted phenylene) groups of the -O-(optionally-substituted phenylene) content of the poly(1,4-phenylene ether) component is made up of at least 50% phenyl carbons and phenyl hydrogens.

Embodiment 3. The thermosetting composition of embodiment 1 or embodiment 2, wherein the poly(1,4-phenylene ether) bis(meth)acrylate component is a poly(1,4-phenylene ether) bismethacrylate component, i.e., having at least 75 wt%, e.g., at least 90 wt% poly(1,4-phenylene ether) bismethacrylate.

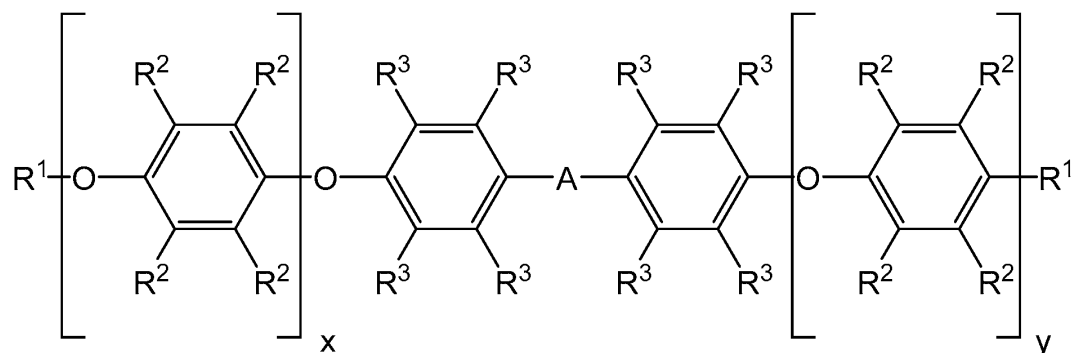
Embodiment 4. The thermosetting composition of embodiment 1 or embodiment 2, wherein the poly(1,4-phenylene ether) component is a bis(vinyl) poly(1,4-phenylene ether) component, i.e., having at least 75 wt%, e.g., at least 90 wt% bis(vinyl) poly(1,4-phenylene ether).

Embodiment 5. The thermosetting composition of embodiment 1 or embodiment 2, wherein the poly(1,4-phenylene ether) component is a bis(allyl) poly(1,4-phenylene ether) component, i.e., having at least 75 wt%, e.g., at least 90 wt% bis(allyl) poly(1,4-phenylene ether).

Embodiment 6. The thermosetting composition of embodiment 1 or embodiment 2, wherein the poly(1,4-phenylene ether) component is a bis(methallyl) poly(1,4-phenylene ether)

component, i.e., having at least 75 wt%, e.g., at least 90 wt% bis(methallyl) poly(1,4-phenylene ether).

Embodiment 7. The thermosetting composition of any of embodiments 1-6, wherein the poly(1,4-phenylene ether) component has the formula

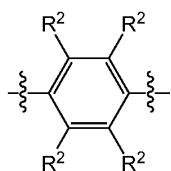


wherein A is a bond, $-\text{CH}_2-$, $\text{CH}(\text{CH}_3)-$, $-\text{C}(\text{CH}_3)_2-$, $-\text{O}-$, $-\text{C}(\text{O})-$, $\text{S}(\text{O})$, or $\text{S}(\text{O})_2$; each R^1 is independently methacrylate, acrylate, vinyl, allyl or methallyl; each R^2 is independently methyl or hydrogen; and each R^3 is independently methyl or hydrogen.

Embodiment 8. The thermosetting composition of embodiment 7, wherein A is $-\text{CH}_2-$, $\text{CH}(\text{CH}_3)-$ or $-\text{C}(\text{CH}_3)_2-$.

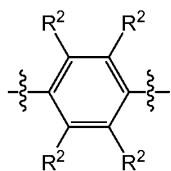
Embodiment 9. The thermosetting composition of embodiment 7, wherein A is $-\text{C}(\text{CH}_3)_2-$.

Embodiment 10. The thermosetting composition of any of embodiments 7-9, wherein in at



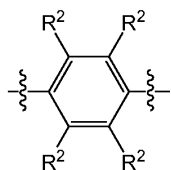
least 75% of the R^2 moieties (e.g., at least 90% or at least 98%), two R^2 are methyl and two R_2 are H.

Embodiment 11. The thermosetting composition of any of embodiments 7-9, wherein in at



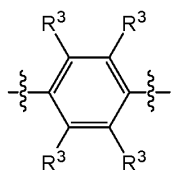
least 75% of the R^2 moieties (e.g., at least 90% or at least 98%), two R^2 are methyl substituted in a meta relationship and two R^2 are H.

Embodiment 12. The thermosetting composition of any of embodiments 7-9, wherein in at



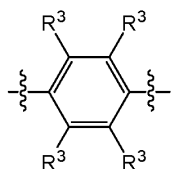
least 75% of the R^2 moieties (e.g., at least 90% or at least 98%), two R^2 are methyl substituted in a meta relationship distal to the A moiety, and two R^2 are H.

Embodiment 13. The thermosetting composition of any of embodiments 7-12, wherein in at



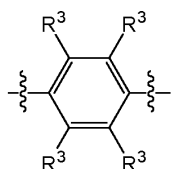
least 75% of the R^3 moieties (e.g., at least 90% or at least 98%), two R^3 are methyl and two R^3 are H.

Embodiment 14. The thermosetting composition of any of embodiments 7-13, wherein in at



least 75% of the R^3 moieties (e.g., at least 90% or at least 98%), two R^3 are methyl substituted in a meta relationship and two R^3 are H.

Embodiment 15. The thermosetting composition of any of embodiments 7-14, wherein in at



least 75% of the R^3 moieties (e.g., at least 90% or at least 98%), two R^3 are methyl substituted in a meta relationship distal to the A moiety, and two R^3 are H.

Embodiment 16. The thermosetting composition of any of embodiments 7-15, wherein at least 75% of R^1 are methacrylate, e.g., at least 90%, or at least 95%.

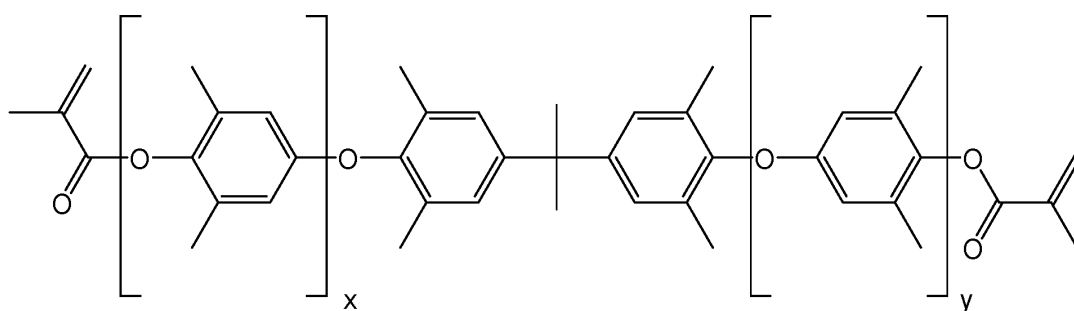
Embodiment 17. The thermosetting composition of any of embodiments 4-15, wherein at least 75% of R^1 are vinyl, e.g., at least 90%, or at least 95%.

Embodiment 18. The thermosetting composition of any of embodiments 4-15, wherein at least 75% of R^1 are allyl, e.g., at least 90%, or at least 95%.

Embodiment 19. The thermosetting composition of any of embodiments 4-15, wherein at least 75% of R¹ are methallyl, e.g., at least 90%, or at least 95%.

Embodiment 20. The thermosetting composition of any of embodiments 4-15, wherein at least 75% of R¹ are methacrylate, vinyl, allyl or methallyl, e.g., at least 90%, or at least 95%.

Embodiment 21. The thermosetting composition of any of embodiments 7-20 wherein at least 75 wt%, e.g., at least 90 wt% or at least 95 wt%, of the poly(1,4-phenylene ether) component has the formula



Embodiment 22. The thermosetting composition of any of embodiments 7-21, wherein the poly(1,4-phenylene ether) component has a number-average value of the sum of x+y in the range of 3-30, e.g., 3-25, or 3-20, or 3-15, or 5-30, or 5-25, or 5-20, or 5-15, or 7-30, or 7-25, or 7-20, or 7-15, or 10-30, or 10-25, or 10-20, or 10-15.

Embodiment 23. The thermosetting composition of any of embodiments 1-22, wherein the poly(1,4-phenylene ether) component has a number-average molecular weight in the range of 1000-4000 g/mol, e.g., 1000-3500 g/mol or 1000-3000 g/mol, or 1000-2500 g/mol, or 1500-4000 g/mol, or 1500-3500 g/mol, or 1500-2500 g/mol.

Embodiment 24. The thermosetting composition of any of embodiments 1-23, wherein the poly(1,4-phenylene ether) component is present in an amount of 22-35 wt%, e.g., 22-32 wt%, or 22-30 wt%.

Embodiment 25. The thermosetting composition of any of embodiments 1-24, wherein the poly(1,4-phenylene ether) component is present in an amount of 25-35 wt%, e.g., 25-32 wt%, or 25-30 wt%.

Embodiment 26. The thermosetting composition of any of embodiments 1-25, wherein the aromatic crosslinking component includes (or is) a cyanurate component.

Embodiment 27. The thermosetting composition of any of embodiments 1-26, wherein the aromatic crosslinking component is a cyanurate component that is triallylcyanurate, triallylisocyanurate, or a combination of triallylcyanurate and triallylisocyanurate.

Embodiment 28. The thermosetting composition of any of embodiments 1-27, wherein the aromatic crosslinking component includes (or is) triallylcyanurate.

Embodiment 29. The thermosetting composition of any of embodiments 1-28, wherein the aromatic crosslinking component includes (or is) triallylisocyanurate.

Embodiment 30. The thermosetting composition of any of embodiments 1-29, wherein the aromatic crosslinking component includes (or is) a combination of triallylcyanurate and triallylisocyanurate.

Embodiment 31. The thermosetting composition of any of embodiments 1-30, wherein the aromatic crosslinking component includes (or is) trimethallylisocyanurate.

Embodiment 32. The thermosetting composition of any of embodiments 1-30 wherein the aromatic crosslinking component includes (or is) a divinylbenzene.

Embodiment 33. The thermosetting composition of any of embodiments 1-30, wherein the aromatic crosslinking component includes (or is) triallylcyanurate, triallylisocyanurate, trimethallylisocyanurate, divinylbenzene, or any combination thereof.

Embodiment 34. The thermosetting composition of any of embodiments 1-33, wherein the aromatic crosslinking component is present in an amount in the range of 2-11 wt%, e.g., 2-9 wt%, or 2-7 wt%

Embodiment 35. The thermosetting composition of any of embodiments 1-33, wherein the aromatic crosslinking component is present in an amount in the range of 3-15 wt%, e.g., 3-11 wt%, or 3-9 wt%, or 3-7 wt%.

Embodiment 36. The thermosetting composition of any of embodiments 1-33, wherein the aromatic crosslinking component is present in an amount in the range of 4-15 wt%, e.g., 4-11 wt%, or 4-9 wt%, or 4-7 wt%.

Embodiment 37. The thermosetting composition of any of embodiments 1-36, wherein the butadiene/styrene copolymeric rubber component has a total content of butadiene and styrene residues in an amount of at least 90 wt%, e.g., at least 95 wt%, at least 97 wt%, at least 98 wt%, or at least 99 wt%.

Embodiment 38. The thermosetting composition of any of embodiments 1-37, wherein the butadiene/styrene copolymeric rubber component comprises up to 5 wt% divinylbenzene residues, e.g., in the range of 0.5-5 wt%, or 0.5-3 wt%, or 1-5 wt%, or 1-3 wt%.

Embodiment 39. The thermosetting composition of any of embodiments 1-38, wherein the butadiene/styrene copolymeric rubber component has a substantially random arrangement of butadiene and styrene.

Embodiment 40. The thermosetting composition of any of embodiments 1-39, wherein the butadiene/styrene copolymeric rubber component has a number average molecular weight in the range of 1500-7000 g/mol, e.g., 1500-5000 g/mol, or 2500-7000 g/mol, or 2500-5000 g/mol.

Embodiment 41. The thermosetting composition of any of embodiments 1-40, wherein the butadiene residues of the butadiene/styrene copolymeric rubber component have a molar fraction of 1,2-vinyl moieties in the range of 15-80 mol%, e.g., 15-70%, or 15-60%, or 20-80 mol%, or 20-70 mol%.

Embodiment 42. The thermosetting composition of any of embodiments 1-40, wherein the butadiene residues of the butadiene/styrene copolymeric rubber component have a molar fraction of 1,2-vinyl moieties of 25-80 mol%, e.g., 25-70%, or 25-60%, or 30-80 mol%, or 30-70 mol%.

Embodiment 43. The thermosetting composition of any of embodiments 1-40, wherein the butadiene residues of the butadiene/styrene copolymeric rubber component have a molar fraction of 1,2-vinyl moieties of 20-60 mol%, e.g., 20-55 mol%, or 20-50 mol%, or 20-45 mol%, or 25-60 mol%, or 25-55 mol%, or 25-50 mol%, or 25-45 mol%, or 30-60 mol%, or 30-55 mol%, or 30-50 mol%, or 30-45 mol%, or 35-60 mol%, or 35-55 mol%, or 35-50 mol%, or 35-45 mol%.

Embodiment 44. The thermosetting composition of any of embodiments 1-43, wherein the butadiene/styrene copolymeric rubber component has in the range of 15-40 wt% styrene residues, e.g., 15-35 wt% or 15-30 wt%.

Embodiment 45. The thermosetting composition of any of embodiments 1-43, wherein the butadiene/styrene copolymeric rubber component has in the range of 20-40 wt% styrene residues, e.g., 20-35 wt% or 20-30 wt%.

Embodiment 46. The thermosetting composition of any of embodiments 1-43, wherein the butadiene/styrene copolymeric rubber component has in the range of 23-40 wt% styrene residues, e.g., 23-35 wt% or 23-30 wt%.

Embodiment 47. The thermosetting composition of any of embodiments 1-46, wherein the butadiene/styrene copolymeric rubber component is made up of a first butadiene/styrene substantially random copolymeric rubber subcomponent that has 17-27 wt% styrene residues and in which the butadiene residues have a molar fraction of 1,2-vinyl moieties of 60-80 mol%; and a second butadiene/styrene substantially random copolymeric rubber subcomponent that has 20-30 wt% styrene residues and in which the butadiene residues have a molar fraction of 1,2-vinyl moieties of 20-40 mol%.

Embodiment 48. The thermosetting composition of embodiment 47, wherein a weight ratio of the first butadiene/styrene substantially random copolymeric rubber subcomponent and the second butadiene/styrene substantially random copolymeric rubber subcomponent is in the range of 1:1.2 – 1:2.3, e.g., 1:1.5 – 1:2.3, or 1:1.2 – 1:2, or 1:1.5 – 1:2.

Embodiment 49. The thermosetting composition of any of embodiments 1-48, wherein the butadiene/styrene copolymeric rubber component is present in an amount in the range of 5-20 wt%, or 5-18 wt%, or 5-15 wt%.

Embodiment 50. The thermosetting composition of any of embodiments 1-48, wherein the butadiene/styrene copolymeric rubber component is present in an amount in the range of 7-25 wt%, e.g., 7-20 wt%, or 7-18 wt%, or 7-15 wt%.

Embodiment 51. The thermosetting composition of any of embodiments 1-48, wherein the butadiene/styrene copolymeric rubber component is present in an amount in the range of 9-25 wt%, e.g., 9-20 wt%, or 9-18 wt%, or 9-15 wt%.

Embodiment 52. The thermosetting composition of any of embodiments 1-51, wherein the microparticulate silica has a d_{50} particle size in the range of 0.5-10 microns, e.g., 0.5-7 microns, or 0.5-5 microns, or 1-10 microns, or 1-7 microns, or 1-5 microns.

Embodiment 53. The thermosetting composition of any of embodiments 1-52, wherein the microparticulate silica has a d_{90} particle size in the range of 1-20 microns, e.g., 1-14 microns, or 1-8 microns, or 3-20 microns, or 3-14 microns, or 3-8 microns.

Embodiment 54. The thermosetting composition of any of embodiments 1-53, wherein the microparticulate silica has a d_{10} particle size in the range of 0.1-5 microns, e.g., 0.1-3 microns, or 0.1-2 microns, or 0.5-5 microns, or 0.5-3 microns, or 0.5-2 microns.

Embodiment 55. The thermosetting composition of any of embodiments 1-54, wherein the microparticulate silica is substantially spherical.

Embodiment 56. The thermosetting composition of any of embodiments 1-55, wherein the microparticulate silica has at least 99 wt% SiO_2 , e.g., at least 99.5 wt% SiO_2 .

Embodiment 57. The thermosetting composition of any of embodiments 1-56, wherein the microparticulate silica is present in an amount in the range of 15-45 wt%, or 15-40 wt%, or 15-35 wt%.

Embodiment 58. The thermosetting composition of any of embodiments 1-57, wherein the microparticulate silica is present in an amount in the range of 20-50 wt%, e.g., 20-45 wt%, or 20-40 wt%, or 20-35 wt%.

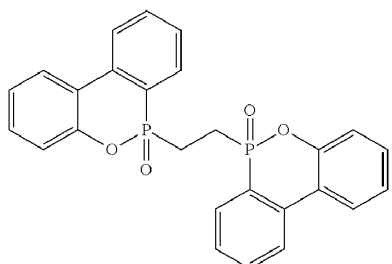
Embodiment 59. The thermosetting composition of any of embodiments 1-58, wherein the microparticulate silica is present in an amount in the range of 25-50 wt%, e.g., 25-45 wt%, or 25-40 wt%, or 25-35 wt%.

Embodiment 60. The thermosetting composition of any of embodiments 1-59, wherein the organic halogen-free fire-retardant component is a fire retardant as described in any of U.S. Patents nos. 8536256, 9012546, 9522927 and 9562063.

Embodiment 61. The thermosetting composition of any of embodiments 1-59, wherein the organic halogen-free fire retardant component includes (or is) 6H-Dibenz[c,e][1,2]oxaphosphorine, 6,6'-(1,4-ethanediyl)bis-, 6,6'-dioxide; 6H-Dibenz[c,e][1,2]oxaphosphorine, 6,6'-(1,4-butanediyl)bis-, 6,6'-dioxide; or 6H-Dibenz[c,e][1,2]oxaphosphorine, 6,6'-(p-xylenediyl)bis-, 6,6'-dioxide; or any combination thereof.

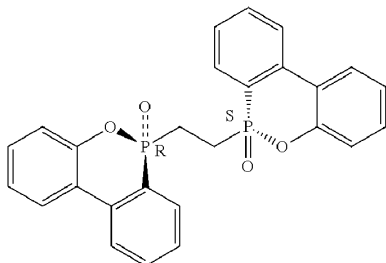
Embodiment 62. The thermosetting composition of any of embodiments 1-59, wherein the organic halogen-free fire retardant component includes (or is) 6H-Dibenz[c,e][1,2]oxaphosphorin, 6,6'-(1,4-ethanediyl)bis-, 6,6'-dioxide.

Embodiment 63. The thermosetting composition of any of embodiments 1-59, wherein the organic halogen-free fire retardant component includes (or is) a compound having the structure: having the following structure:



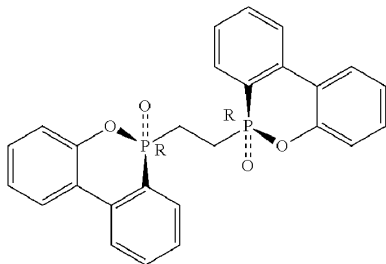
Embodiment 64. The thermosetting composition of any of embodiments 1-59, wherein the organic halogen-free fire retardant component includes (or is) composition comprising the high melting point isomer of Formula IIa:

Formula IIa

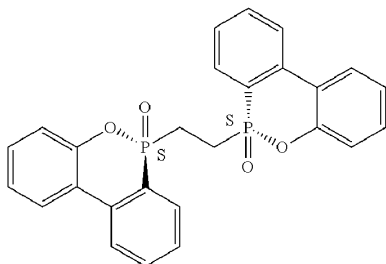


and the low melting point isomers of Formula IIb and IIc having the Formulas:

Formula IIb



Formula IIc



wherein said composition has an Isomer Ratio of greater than about 0.5 utilizing the ^{31}P NMR method and wherein said Isomer Ratio = $A_h / (A_h + A_l)$, wherein A_h : area of high melting point isomer peak and A_l : area of low melting point isomers peak.

Embodiment 65. The thermosetting composition according to any of embodiments 1-64, wherein the organic halogen-free fire retardant component is present in an amount of 15-30 wt%, e.g., 15-25 wt%.

Embodiment 66. The thermosetting composition according to any of embodiments 1-64, wherein the organic halogen-free fire retardant component is present in an amount of 20-35 wt%, e.g., 20-30 wt%, or 20-25 wt%.

Embodiment 67. The thermosetting composition according to any of embodiments 1-64, wherein the organic halogen-free fire retardant component is present in an amount of 25-35 wt%, e.g., 25-30 wt%.

Embodiment 68. The thermosetting composition according to any of embodiments 1-67, wherein the thermal free-radical initiator component is one or more of benzoyl peroxide, dicumyl peroxide, methyl ethyl ketone peroxide, lauryl peroxide, cyclohexanone peroxide, t-butyl hydroperoxide, t-butyl benzene hydroperoxide, acetyl isobutyryl peroxide, diacetyl peroxide, t-butyl peroctoate, α, α' -bis(t-butylperoxy-m-isopropyl)benzene, 2,3-dimethyl-2,3-

diphenylbutane, di(trimethylsilyl)peroxide, 2,5-dimethyl-2,5-di(benzoylperoxy)hexane, 2,5-dimethylhexane-2,5-dihydroperoxide, 2,5-dimethyl-2,5-di(t-butylperoxy)-hex-3-yne, di-t-butylperoxide, t-butylcumyl peroxide, 2,5-dimethyl-2,5-di(t-butylperoxy)hexane, t-butylperoxy benzoate, 2,2-bis(t-butylperoxy)butane, 2,2-bis(t-butylperoxy)octane, 2-trimethylsilylphenyltriphenylsilyl peroxide, 2,3-trimethylsilyloxy-2,3-diphenylbutane, di(t-butylperoxy) isophthalate, azobisisobutyronitrile (AIBN), azobis(2-isopropyl)butyronitrile, 2,2'-azobis(2,4-dimethyl)valeronitrile (AVBN), (2,4-dichlorobenzoyl) peroxide, (2-dimethylbenzoyl) peroxide, and dodecanoyl peroxide.

Embodiment 69. The thermosetting composition according to any of embodiments 1-68, wherein the thermal free-radical initiator component is present in an amount in the range of 0.05-4 wt%, e.g., 0.05-2 wt%, or 0.05-1 wt%, or 0.05-0.7 wt%.

Embodiment 70. The thermosetting composition according to any of embodiments 1-68, wherein the thermal free-radical initiator component is present in an amount in the range of 0.07-4 wt%, e.g., 0.07-2 wt%, or 0.07-1 wt%, or 0.07-0.7 wt%.

Embodiment 71. The thermosetting composition according to any of embodiments 1-68, wherein the thermal free-radical initiator component is present in an amount in the range of 0.1-4 wt%, e.g., 0.1-2 wt%, or 0.1-1 wt%, or 0.1-0.7 wt%.

Embodiment 72. The thermosetting composition according to any of embodiments 1-68, wherein the thermal free-radical initiator component is present in an amount in the range of 0.2-4 wt%, e.g., 0.2-2 wt%, or 0.2-1 wt%, or 0.2-0.7 wt%.

Embodiment 73. The thermosetting composition according to any of embodiments 1-72, further comprising a silane coupling agent, e.g., in an amount up to 5 wt%.

Embodiment 74. The thermosetting composition according to any of embodiments 1-73, comprising no more than 0.01 wt% of a silane coupling agent.

Embodiment 75. The thermosetting composition according to any of embodiments 1-74, provided in substantially non-volatile form, i.e., without a substantial amount of a solvent.

Embodiment 76. The thermosetting composition according to any of embodiments 1-74, comprising no more than 10 wt% material having a boiling point at atmospheric pressure of

less than 200 °C, e.g., no more than 5 wt%, or no more than 3 wt%, or no more than 1 wt%, all calculated with the non-volatile content being 100 wt%.

Embodiment 77. The thermosetting composition according to any of embodiments 1-74, further comprising a solvent having a boiling point at atmospheric pressure of less than 200 °C.

Embodiment 78. The thermosetting composition according to embodiment 77, wherein the solvent is one or more of γ -butyrolactone, cyclohexanone, butanone, methyl isobutyl ketone, N,N-dimethylformamide, propylene glycol monomethyl ether, N,N-dimethylacetamide, ethylene glycol monomethyl ether, methoxy ethyl acetate, ethoxy ethyl acetate, propoxy ethyl acetate, diisobutyl ketone (DIBK), N-methyl-pyrrolidone., xylene, ethyl acetate, toluene, trichloroethane, dibutyl ether, methyl ethyl ketone, and acetone.

Embodiment 79. The thermosetting composition according to embodiment 77 or embodiment 78, wherein an amount of solvent is in the range of 20-60 wt% in excess of the non-volatile components of the thermosetting composition (i.e., taken together as 100 wt%).

Embodiment 80. A cured product of a thermosetting composition according to any of embodiments 1-79.

Embodiment 81. A method for curing the thermosetting composition according to any of embodiments 1-79, comprising heating the thermosetting composition at a temperature of 150-250 °C.

Embodiment 82. A prepreg comprising a mesh substrate at least partially embedded in a cured product of embodiment 80 or a cured product made by the method of embodiment 81.

Embodiment 83. The prepreg according to embodiment 82, wherein the cured product is a partially-cured product.

Embodiment 84. The prepreg according to embodiment 82 or embodiment 83, wherein, the mesh substrate is a fabric (woven or non-woven).

Embodiment 85. The prepreg according to embodiment 84, wherein the fabric made from glass fiber, e.g., as a borosilicate glass fabric.

Embodiment 86. The prepreg according to embodiment 82 or embodiment 83, wherein, the mesh substrate is electronic grade E-glass fabric, NE-glass fabric, D-glass fabric, or S-glass fabric.

Embodiment 87. The prepreg according to any of embodiments 82-86, that is in the range of 10-300 microns in thickness, e.g., 10-200 microns, or 10-150 microns, or 10-100 microns.

Embodiment 88. The prepreg according to any of embodiments 82-86, that is in the range of 25-300 microns in thickness, e.g., 25-200 microns, or 25-150 microns, or 25-100 microns.

Embodiment 89. The prepreg according to any of embodiments 82-86, that is in the range of 50-300 microns in thickness, e.g., 50-200 microns, or 50-150 microns.

Embodiment 90. The prepreg according to any of embodiments 82-89, comprising at least 30 wt% of the cured product of the disclosure, e.g., at least 50 wt%.

Embodiment 91. A laminate of a plurality of prepregs according to any of embodiments 82-89.

Embodiment 92. A laminate according to embodiment 91, wherein the cured product of the prepregs in the laminate is substantially fully cured.

Embodiment 93. A laminate according to embodiment 91 or embodiment 92, further comprising one or more layers of metal, e.g., at one or more opposing major surfaces of the laminate.

Embodiment 94. A laminate according to embodiment 93, wherein the one or more layers of metal are layers of copper.

Embodiment 95. A laminate according to embodiment 94, wherein the one or more layers of copper are in the range of 15-50 microns in thickness, e.g., in the range of 17-37 microns in thickness.

Embodiment 96. A laminate according to embodiment 94 or embodiment 95, wherein each of the one or more layers of copper have an outer surface facing away from the prepreg to which the layer is laminated, having one or more of a surface roughness Ra (measured by

contact, ISO 4287) of no more than 0.3 microns, and/or a surface roughness Sa (measured contactless, ISO 25178) in the range of 0.1-0.3 microns, e.g., 0.15-0.25 microns.

Embodiment 97. A laminate according to any of embodiments 94-96, wherein each of the one or more layers of copper have an inner surface contacting one of the prepregs having one or more of a surface roughness Sa in the range of 0.1-0.4 microns (e.g., 0.12-0.3 microns; a surface roughness Sz in the range of 1-5 microns (e.g., 1.2-4 microns); and/or a surface roughness Sdr in the range of 0.5-3 microns (e.g., 0.7-2 microns), each measured contactless, ISO 25178).

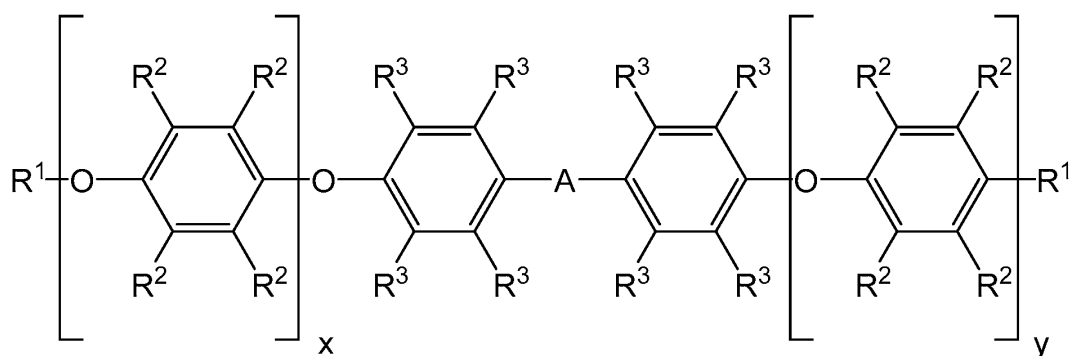
Embodiment 98. A laminate according to any of embodiments 93-97, having a peel strength of at least 2.5 lb/in as measured by IPC-TM-650 2.4.8 (e.g., in the range of 2.5-5 lb/in, or 2.5-4.5 lb/in, or 2.5-4 lb/in, or 3-5 lb/in, or 3-4.5 lb/in, or 3-4 lb/in).

Embodiment 99. A laminate according to any of embodiments 93-98, having a Df value of in the range of 0.0015 to 0.003, e.g., 0.0015 to 0.0025, as measured by IPC-TM-650 2.5.5.5.

Embodiment 100. A laminate according to any of embodiments 93-99, having a Tg as measured by DSC in the range of 180-240 °C, e.g., 180-230 °C, or 180-220 °C, or 190-240 °C, or 190-230 °C, or 190-220 °C.

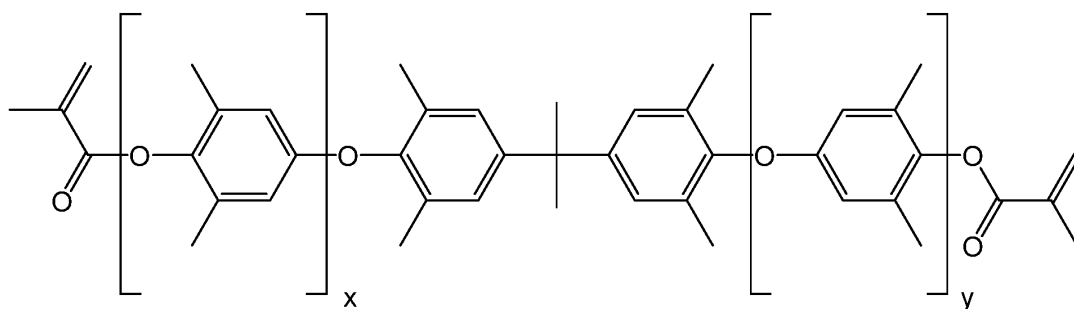
Claims

1. A thermosetting composition comprising:
 - a poly(1,4-phenylene ether) component having at least 80% phenylene ether content, the poly(1,4-phenylene ether) component being a poly(1,4-phenylene ether) bis(meth)acrylate component, a bis(vinyl) poly(1,4-phenylene ether) component, or a bis((meth)allyl) poly(1,4-phenylene ether) component, or a combination of two or more thereof, in an amount in the range of 20-35 wt%;
 - an aromatic crosslinking component having a weight average molecular weight of no greater than 700 g/mol and bearing on numerical average in the range of 1.75 - 3.5 crosslinkable vinyl, (meth)allyl and/or (meth)acrylate groups per molecule, in an amount in the range of 2-15 wt%;
 - a butadiene/styrene copolymeric rubber component, in an amount of 5-25 wt%;
 - microparticulate silica, in an amount in the range of 15-50 wt%;
 - an organic halogen-free fire retardant component, in an amount of 15-35 wt%; and
 - a thermal free-radical initiator component, in an amount of 0.1-3 wt%.
2. The thermosetting composition of claim 1, wherein the mass of the (optionally-substituted phenylene) groups of the -O-(optionally-substituted phenylene) content of the poly(1,4-phenylene ether) component is made up of at least 50% phenyl carbons and phenyl hydrogens.
3. The thermosetting composition of claim 1 or claim 2, wherein the poly(1,4-phenylene ether) bis(meth)acrylate component is a poly(1,4-phenylene ether) bismethacrylate component, i.e., having at least 75 wt%, e.g., at least 90 wt% poly(1,4-phenylene ether) bismethacrylate.
4. The thermosetting composition of any of claims 1-3, wherein the poly(1,4-phenylene ether) component has the formula



wherein A is a bond, -CH₂-, CH(CH₃)-, -C(CH₃)₂-, -O-, -C(O)-, S(O), or S(O)₂; each R¹ is independently methacrylate, acrylate, vinyl, allyl or methallyl; each R² is independently methyl or hydrogen; and each R³ is independently methyl or hydrogen.

5. The thermosetting composition of claim 4 wherein at least 75 wt%, e.g., at least 90 wt% or at least 95 wt%, of the poly(1,4-phenylene ether) component has the formula



6. The thermosetting composition of any of claims 1-5, wherein the poly(1,4-phenylene ether) component is present in an amount of 25-35 wt%.

7. The thermosetting composition of any of claims 1-6, wherein the aromatic crosslinking component is a cyanurate component that is triallylcyanurate, triallylisocyanurate, or a combination of triallylcyanurate and triallylisocyanurate.

8. The thermosetting composition of any of claims 1-6, wherein the aromatic crosslinking component includes (or is) triallylcyanurate.

9. The thermosetting composition of any of claims 1-8, wherein the aromatic crosslinking component is present in an amount in the range of 4-15 wt%, e.g., 4-11 wt%, or 4-9 wt%, or 4-7 wt%.

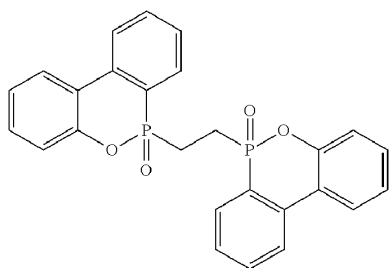
10. The thermosetting composition of any of claims 1-9, wherein the butadiene/styrene copolymeric rubber component has a total content of butadiene and styrene residues in an amount of at least 95 wt%.
11. The thermosetting composition of any of claims 1-10, wherein the butadiene/styrene copolymeric rubber component has a substantially random arrangement of butadiene and styrene.
12. The thermosetting composition of any of claims 1-11, wherein the butadiene/styrene copolymeric rubber component has a number average molecular weight in the range of 1500-7000 g/mol.
13. The thermosetting composition of any of claims 1-12, wherein the butadiene residues of the butadiene/styrene copolymeric rubber component have a molar fraction of 1,2-vinyl moieties in the range of 15-80 mol%.
14. The thermosetting composition of any of claims 1-12, wherein the butadiene residues of the butadiene/styrene copolymeric rubber component have a molar fraction of 1,2-vinyl moieties 30-60 mol%.
15. The thermosetting composition of any of claims 1-13, wherein the butadiene/styrene copolymeric rubber component has in the range of 23-40 wt% styrene residues.
16. The thermosetting composition of any of claims 1-15, wherein the butadiene/styrene copolymeric rubber component is made up of a first butadiene/styrene substantially random copolymeric rubber subcomponent that has 17-27 wt% styrene residues and in which the butadiene residues have a molar fraction of 1,2-vinyl moieties of 60-80 mol%; and a second butadiene/styrene substantially random copolymeric rubber subcomponent that has 20-30 wt% styrene residues and in which the butadiene residues have a molar fraction of 1,2-vinyl moieties of 20-40 mol%, wherein a weight ratio of the first butadiene/styrene substantially random copolymeric rubber subcomponent and the second butadiene/styrene substantially random copolymeric rubber subcomponent is in the range of 1:1.2 – 1:2.3.
17. The thermosetting composition of any of claims 1-16, wherein the butadiene/styrene copolymeric rubber is present in an amount in the range of 9-25 wt%.

18. The thermosetting composition of any of claims 1-17, wherein the microparticulate silica has a d_{10} particle size in the range of 0.1-5 microns.

19. The thermosetting composition of any of claims 1-18, wherein the microparticulate silica is substantially spherical.

20. The thermosetting composition of any of claims 1-19, wherein the microparticulate silica is present in an amount in the range of 20-45 wt%.

21. The thermosetting composition of any of claims 1-20, wherein the organic halogen-free fire retardant component includes (or is) a compound having the structure: having the following structure:



22. The thermosetting composition according to any of claims 1-21, wherein the organic halogen-free fire retardant component is present in an amount of 20-35 wt%.

23. The thermosetting composition according to any of claims 1-22, wherein the thermal free-radical initiator component is one or more of benzoyl peroxide, dicumyl peroxide, methyl ethyl ketone peroxide, lauryl peroxide, cyclohexanone peroxide, t-butyl hydroperoxide, t-butyl benzene hydroperoxide, acetyl isobutyryl peroxide, diacetyl peroxide, t-butyl peroctoate, α,α' -bis(t-butylperoxy-m-isopropyl)benzene, 2,3-dimethyl-2,3-diphenylbutane, di(trimethylsilyl)peroxide, 2,5-dimethyl-2,5-di(benzoylperoxy)hexane, 2,5-dimethylhexane-2,5-dihydroperoxide, 2,5-dimethyl-2,5-di(t-butylperoxy)-hex-3-yne, di-t-butylperoxide, t-butylcumyl peroxide, 2,5-dimethyl-2,5-di(t-butylperoxy)hexane, t-butylperoxy benzoate, 2,2-bis(t-butylperoxy)butane, 2,2-bis(t-butylperoxy)octane, 2trimethylsilylphenyltriphenylsilyl peroxide, 2,3-trimethylsilyloxy-2,3-diphenylbutane, di(t-butylperoxy) isophthalate, azobisisobutyronitrile (AIBN), azobis(2-isopropyl)butyronitrile, 2,2'-azobis(2,4-dimethyl)valeronitrile (AVBN), (2,4-dichlorobenzoyl) peroxide, (2-dimethylbenzoyl) peroxide, and dodecanoyl peroxide.

24. The thermosetting composition according to any of claims 1-23, wherein the thermal free-radical initiator component is present in an amount in the range of 0.2-2 wt%.
25. A cured product of a thermosetting composition according to any of claims 1-24.
26. A method for curing the thermosetting composition according to any of claims 1-24, comprising heating the thermosetting composition at a temperature of 150-250 °C.
27. A prepreg comprising a mesh substrate at least partially embedded in a cured product of claim 25 or a cured product made by the method of claim 26.
28. A laminate of a plurality of prepregs according to claim 27.
29. A laminate according to claim 28, having
- a peel strength of at least 2.5 lb/in as measured by IPC-TM-650 2.4.8;
 - a Df value of in the range of 0.0015 to 0.003, as measured by IPC-TM-650 2.5.5.5;
 - and
 - a Tg as measured by DSC in the range of 180-240 °C.