PHENYLETHYNYL PHTHALIC ANHYDRIDE

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Abstract

Controlled molecular weight phenylethynyl terminated imide oligomers (PETIs) have been prepared by the cyclo-dehydration of precursor phenylethynyl terminated amic acid oligomers. Amino terminated amic acid oligomers are prepared from the reaction of dianhydride(s) with an excess of diamine(s) and subsequently endcapped with phenylethynyl phthalic anhydride(s) (PEPA). The polymerizations are carried out in polar aprotic solvents such as N-methyl-2-pyrrolidinone or N,N-dimethylacetamide under nitrogen at room temperature. The amic acid oligomers are subsequently cyclodehydrated either thermally or chemically to the corresponding imide oligomers. Direct preparation of PETIs from the reaction of dianhydride(s) with an excess of diamine(s) and endcapped with phenylethynyl phthalic anhydride(s) has been performed in m-cresol. Phenylethynyl phthalic anhydrides are synthesized by the palladium catalyzed reaction of phenylacetylene with bromo substituted phthalic anhydrides in triethylamine. These new materials exhibit excellent properties and are potentially useful as adhesives, coatings, films, moldings and composite matrices.

2 Claims, 2 Drawing Sheets
\[ \text{Br-W-} + \text{C≡C-H} \]

1. \( \text{N(CH}_2\text{CH}_3)_3 / \text{Benzene or Toluene} \)

2. \( \text{CuI/} (\phi_3 \text{P})_2 \text{PdCl}_2 \)

\[ \text{C≡C-W-} \]

\( W = \text{nil, } -\text{phenyl-}, -\text{phenoxide-}, -\text{biphenyl-} \), etc.

**FIG. 1**
\[ \text{FIG. 2} \]
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PHENYLETHYNYL PHTHALIC ANHYDRIDE

This application is a divisional application of application Ser. No. 08/330,773, filed Oct. 28, 1994, which issued as U.S. Pat. No. 5,567,800 on Oct. 22, 1996. +gi

ORIGIN OF THE INVENTION

The invention described herein was made jointly in the performance of work under NASA Grant NAG 1-1251 with Virginia Commonwealth University and an employee of the United States Government. In accordance with 35 USC 202, the grantee elected not to retain title.

CROSS-REFERENCE TO RELATED APPLICATION

BACKGROUND OF INVENTION

Polyimides (PI) are heterocyclic polymers commonly prepared by the condensation reaction of an aromatic diamine with an aromatic dianhydride or derivative thereof and having a repeat unit of the general structure

\[
\begin{array}{c}
\text{O} \\
\text{C} \\
\text{C} \\
\text{O} \\
\text{C} \\
\text{C} \\
\text{N} \rightarrow \text{Ar} \\
\text{O} \\
\end{array}
\]

where Ar is a tetravalent aromatic radical such as 1,2,4,5-tetrasubstituted benzene. Ar may also be a bis(diphenylene) having the general structure

\[
\begin{array}{c}
\text{O} \\
\text{C} \\
\text{C} \\
\text{O} \\
\text{C} \\
\text{C} \\
\text{N} \rightarrow \text{Ar} \\
\end{array}
\]

where Y=NH, O, S, SO₂, CO, (CH₃)₂, or any other appropriate divalent radical. Ar' is a divalent aromatic radical which may be 1,3-phenylene, 1,4-phenylene, 4,4'-biphenylene, 4,4'-oxydiphenylene, 4,4'-sulfonyldiphenylene, or any other appropriate divalent radical.


A variety of monomers, oligomers and polymers containing ethynyl (acetylenic) and substituted ethynyl (i.e. phenylethynyl) groups have been reported. The ethynyl groups in the polymer are either pendant to the chain, in the chain, or at the chain ends. Many of these materials have been used to prepare coatings, moldings, adhesives and composites [P.M. Hergenrother, “Acetylene Terminated Pre-polymers” in Encyclopedia of Polymer Science and Engineering, John Wiley and Sons, New York, Vol. 1, 61 (1965)]. Good processability by either solution casting and/or compression molding has been observed for the ethynyl and substituted ethynyl containing materials. In general, thermally cured ethynyl and substituted ethynyl containing materials exhibit a favorable combination of physical and mechanical properties. Some ethynyl endcapped materials such as the Thermody® resins are commercially available (National Starch and Chemical Co., Bridgewater, N.J. 08807).


It is a primary object of the present invention to provide novel phenylethynyl phthalic anhydrides and new imide oligomers endcapped with phenylethynyl groups, as well as polymers prepared therefrom which exhibit higher elongations, higher glass transition temperatures and higher fracture toughness, as compared to similar materials.

Another object of the present invention is to provide novel polymeric materials that are useful as adhesives, coatings, films, moldings and composite matrices.

Another object of the present invention is the composition of several new phenylethynyl phthalic anhydride (PEPA) endcapping reagents.

SUMMARY OF THE INVENTION

According to the present invention the foregoing and additional objects are obtained by synthesizing controlled molecular weight imide oligomers endcapped with phenylethynyl groups by different methods. First, amino terminated amic acid (AA) oligomers are prepared by the reaction of dianhydride(s) with an excess of diamine(s) under a nitrogen atmosphere at ambient temperature in N-methyl-2-pyrroldilnone (NMP). The endcapping reagent, a phenylethynl phthalic anhydride (PEPA), was added after the formation of the amino terminated AA oligomer. Phenylethynyl terminated amic acids have also been prepared where the PEPA endcapping reagent is added at the beginning of the reaction. The phenylethynyl terminated amide oligomers (PETI) were prepared by cyclodehydration of the precursor AA oligomers endcapped with phenylethynyl groups in NMP by azetotropic distillation with toluene.

PETIs are also prepared in N,N-dimethylacetamide containing glacial acetic acid at elevated temperature. The AA oligomer can also be converted to the corresponding PETIs by treatment with chemical cyclodehydrating agents such as acetic anhydride. The direct preparation of PETIs has been performed in m-cresol containing isquinoline at elevated temperature.

Phenylethynyl terminated imide oligomers are prepared by the reaction of the half alkyl ester of aromatic tetracarboxylic acids and the half alkyl ester of phenylethynyl substituted phthalic acids with aromatic diamines by heating in NMP. PETIs prepared by the alkyl ester route can also be prepared by heating neat or in solvents such as m-cresol. Phenylethynyl terminated imide oligomers are also prepared by the polymerization of monomeric reactants (PMR) approach by heating a mixture of a diamine and the ethyl ester derivatives of dianhydrides and phenylethynylphthalic anhydrides.

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In addition, the amino terminated AA oligomer can be cyclodehydrated to the corresponding amino terminated imide and the PEPA endcapper subsequently reacted with the soluble amino terminated imide oligomer. The imide oligomer must be soluble in order to perform this endcapping reaction. Upon reaction of the amino terminated imide oligomer with the PEPA endcapper, the temperature is increased to effect cyclodehydration to complete imidization.

The inherent viscosities (η\text{inh}) of the AA oligomers range from 0.16 to 0.53 dL/g. After cyclodehydration to PETIs, the η\text{inh} range from 0.12 to 0.43 dL/g. The glass transition temperatures (T_g) of the uncured as-isolated PETIs range from 208°-262° C. In some cases, a crystalline melt temperature is observed for the uncured PETIs. The temperature of onset and peak exotherm due to reaction of the phenylethynyl group range from 371°-414° C. and 419°-452° C., respectively as evidenced by heating in a sealed DSC pan at a heating rate of 20° C/minute. After curing at 350° C. for 1 h in a sealed DSC pan, the T_g of the cured polymers ranges from 237°-276° C. Thermogravimetric analysis (TGA) at a heating rate of 2.5° C/min of the uncured as-isolated PETI powders showed no weight loss occurring below 300° C. in air or nitrogen with a 5% weight loss occurring ~496° C. in air and ~512° C. in nitrogen. After a thermal cure (350° C./flowing air/1 h), TGA at a heating rate of 2.5° C/min of the cured polymers shows no weight loss occurring below 300° C. in air or nitrogen with a 5% weight loss occurring ~522° C. in air and ~525° C. in nitrogen. The average tensile strength, tensile modulus, and break elongation for unoriented thin films ranged from 15.3-20.2 ksi, 407-463 ksi, and 5-69% at 23° C. and 8.6-12.2 ksi, 293-344 ksi, and 17-83% at 177° C., respectively. The critical stress intensity factor (K_{C}) of these materials at 23° C. ranges from 2760-3529 lb/in² and the critical strain energy release rate (G_{IC}) at 23° C. ranges from 17.7-27.4 lb/in². The polymers prepared from these materials exhibit higher elongations, higher glass transition temperatures and higher fracture toughness as compared to similar materials.

**BRIEF DESCRIPTION OF THE DRAWING**

For a more complete understanding of the present invention, including its objects and attending benefits, reference should be made to the Description of the Preferred Embodiments, which is set forth in detail below. This Detailed Description should be read together with the accompanying drawing, wherein:

FIG. 1 is an equation showing the preparation of phenylethynyl substituted anhydrides according to the present invention; and

FIG. 2 is an equation showing the synthesis of controlled molecular weight phenylethynyl terminated imide oligomers (PETI) according to the present invention.

**DESCRIPTION OF THE PREFERRED EMBODIMENTS**

Phenylethynyl substituted phthalic anhydrides are prepared by the palladium catalyzed reaction of phenylethynyl-
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and Ar is a radical represented by

5

and W is a bond; Ar' is a radical represented by

10

Ar is a radical represented by

15

and W is a radical represented by

20

Wherein Y is a bond or Y is a radical selected from the group consisting of

O, CO, SO₂, C(CF₃)₂,

and

Wherein W is a bond or W is a radical selected from the group consisting of

0.75

and Ar is a radical represented by

0.25

In the general structural formula above, it is especially preferred if: Ar' is a radical represented by

0.5

and

0.5

and W is a bond; Ar' is a radical represented by

50

Ar is a radical represented by

55

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and W is a bond; Ar' is a radical represented by

and Ar is a radical represented by

and W is a bond; Ar' is a radical represented by

Ar is a radical represented by

and W is a bond; Ar' is a radical represented by

and Ar is a radical represented by

and W is a bond.

In another aspect, the present invention is a phenylethynyl phthalic anhydride having the general structural formula

Wherein W is a radical selected from the group consisting of

A particularly preferred phenylethynyl phthalic anhydride according to the present invention has the following structural formula:

In another aspect, the present invention is a phenylethynyl terminated amic acid oligomer having the general structural formula:
wherein $\text{Ar}'$ is a radical selected from the group of

\[
\begin{align*}
\text{Ar}' & \\
\text{X} & \\
\text{Y} & 
\end{align*}
\]

wherein the catenation is selected from the group consisting of

\[
\begin{align*}
2.2'; 2.3'; 2.4'; 3.3'; 3.4'; 4.4' \text{ and } X \text{ is bond or } X \text{ is a radical selected from the group consisting of }
\end{align*}
\]

\[
\begin{align*}
\text{CH}_3, \text{CO, CH(OH), C(CF}_3}_2, \text{ and }
\end{align*}
\]

Wherein $\text{Ar}$ is a radical selected from the group consisting of

\[
\begin{align*}
\text{Ar} & 
\end{align*}
\]

Especially preferred are the following specific controlled molecular weight amic acid oligomers terminated with phenylethynyl phthalimide, reference being made to the general structural formula above.

\[
\begin{align*}
(A) \text{ wherein } \text{Ar}' \text{ is a radical represented by }
\end{align*}
\]

and $\text{Ar}$ is a radical represented by

\[
\begin{align*}
\text{and } W \text{ is a bond;}
\end{align*}
\]
(B) wherein \(Ar'\) is a radical represented by

and \(Ar\) is a radical represented by

and \(W\) is a radical represented by

(C) wherein \(Ar'\) is a radical represented by

and \(Ar\) is a radical represented by

and \(W\) is a bond;

(E) \(Ar'\) is a radical represented by

\(Ar\) is a radical represented by

and \(W\) is a bond.

In another aspect, the present invention is a process for synthesizing controlled molecular weight imide oligomers endcapped with phenylethynyl phthalimide and having the general structural formula

(D) \(Ar'\) is a radical represented by

60

by cyclodehydration of precursor amic acid oligomers terminated with phenylethynyl phthalimide acid and having the general structural formula
In yet another aspect, the present invention is a cured adhesive prepared from controlled molecular weight imide oligomer endcapped by phenylethynyl phthalic anhydride. Especially good results are obtained if the film is cast from a solution of a phenylethynyl terminated amic acid oligomer as specified above wherein the solution comprises polar aprotic solvent selected from the group consisting of N,N-dimethyacetamide, N-methyl-2-pyrrolidinone, N-cyclohexyl-2-pyrrolidinone, m-cresol, and dimethylsulfoxide; and wherein said reaction is carried out without the application of heat; followed by cyclodehydration of the phenylethynyl amic acid terminated imide oligomer.

Especially good results are achieved if the cyclodehydration reaction is carried out in a polar aprotic solvent such as N,N-dimethyacetamide, N-methyl-2-pyrrolidinone, N-cyclohexyl-2-pyrrolidinone, m-cresol, and dimethylsulfoxide; wherein the reaction is carried out without the application of heat, followed by cyclodehydration of the phenylethynyl amic acid terminated imide oligomer.

Especially good results are achieved if the cyclodehydration reaction is carried out in a polar aprotic solvent such as N,N-dimethyacetamide, N-methyl-2-pyrrolidinone, N-cyclohexyl-2-pyrrolidinone, m-cresol, and dimethylsulfoxide; wherein the reaction is carried out without the application of heat, followed by cyclodehydration of the phenylethynyl amic acid terminated imide oligomer.

In another aspect, the present invention is a cured composite prepared from controlled molecular weight imide oligomer endcapped with phenylethynyl phthalimide and carbon/graphite fibers. Best results are achieved if the cured composite is prepared under heat and pressure.

Having generally described the invention, a more complete understanding thereof can be obtained by reference to the following examples, which are provided herein for purposes of illustration only and do not limit the invention.

**Endcapper Synthesis**

The following example illustrates the reaction sequence of **FIG. 1** for the preparation of the endcappers.

**4-Phenylethynylphthalic Anhydride (4-PEPA)**

A mixture of triethylamine (1000 ml) and benzene (120 ml) was heated to reflux for 3 h under a nitrogen atmosphere to remove any residual water. The mixture was cooled to room temperature and 4-bromophthalic anhydride (60.7462 g, 0.2676 mol), phenylacetylene (27.3314 g, 0.2676 mol), cuprous iodide (0.1174 g, 0.6164 mmol), triphenylphosphine (0.5070 g, 1.9329 mmol), and bis(triphenylphosphine) palladium dichloride (0.1013 g, 0.1443 mmol) were added and the mixture was heated at reflux under a nitrogen atmosphere for 20 h. The cooled reaction mixture was filtered and the precipitate added to water. The crude solid was washed several times in distilled water and dried under.
vacuum at 85° C. for 1 h to afford 48.50 g (73% crude yield) of a brown powder mp (DSC, 10° C/min) 152° C. (sharp). The product was recrystallized from 1:1 toluene/hexanes to afford 41.30 g (62% yield) of an orange-brown crystalline solid, mp (DSC, 10° C/min) 151° C. (sharp). An exotherm with a peak of 389° C. had a ΔH of 390 J/g IR (KBr): 2206 cm⁻¹ (C=O); 1843 cm⁻¹ and 1771 cm⁻¹ (asymmetric and symmetric C=O stretch). Anal. calcd. for C₁₉H₁₄O₅: C, 74.2%; H, 3.14%; Found: C, 77.12%; H, 3.14%. Mass spectroscopy: m/z 248 (calcd. molecular weight: 248.2414 g/mol).

4-(Bromomphenoxo)phthalic Anhydride

A mixture of 4-bromophenol (21.7029 g, 0.1254 mol), 4-fluorophthalic anhydride (22.9027 g, 0.1379 mol), and potassium fluoride (11.1003 g, 0.1911 mol) in sulfolane (142.34 g, 21.95% w/w) was heated at 165° -170° C. for 10.5 h. The cooled light brown mixture was precipitated in water and the solid collected by filtration. The crude solid was subsequently washed in water and dried under vacuum for 24 h. The mixture was recrystallized from 4-bromophenol, mp (DSC, 10° C/min) 140° C. (broad). The crude product was recrystallized from 2:1 cyclohexane/benzene to afford 26.57 g (67% yield) of a light orange powder, mp (DSC, 10° C/min) 156° C. (sharp). IR (KBr): 1843 cm⁻¹ and 1767 cm⁻¹ (asymmetric and symmetric C=O stretch). Anal. calcd. for C₁₅H₁₀Br₂O₅: C, 52.69%; H, 2.21%; Br, 25.04%; Found: C, 52.09%; H, 2.23%; Br, 25.32%. Mass spectroscopy: m/z 319.1194 g/mol.

4-(Phenylethylenophenoxy)phthalic Anhydride (4-PEPOPA)

A mixture of triethylamine (600 ml) and benzene (100 ml) was heated to reflux for 3 h under a nitrogen atmosphere to remove any residual water. The mixture was cooled to room temperature and 4-(4-bromomphenoxo)phthalic anhydride (26.0078 g, 0.0815 mol), phenylacetylene (8.3230 g, 0.0815 mol), cuprous iodide (0.1111 g, 0.5834 mmol), triphenylphosphine (0.5493 g, 2.0942 mmol), and bis(triphenylphosphine) palladium dichloride (0.1208 g, 0.1721 mmol) were added and the mixture was heated at reflux under a nitrogen atmosphere for 24 h. The cooled reaction mixture was filtered and the precipitate added to water. The crude solid was washed several times in distilled water and dried under vacuum at 115° C. for 3 h to afford 10.49 g (33% crude yield) of a brown powder, mp (DSC, 10° C/min) 199° C. (broad). The crude product was recrystallized from 1:1 toluene/hexane and dried at 105° C. under vacuum for 2 h to afford 8.03 g (29% yield) of a yellow-tan powder, mp (DSC, 20° C/min) 202° C. (broad). An exotherm with a peak of 420° C. had a ΔH of 120 J/g IR (KBr): 1853 cm⁻¹ and 1765 cm⁻¹ (asymmetric and symmetric C=O stretch). Anal. calcd. for C₂₁H₁₄O₅: C, 77.64%; H, 3.15%; Found: C, 76.80%; H, 3.66%. Mass spectroscopy: m/z 339.9 (calcd. molecular weight: 340.3400 g/mol).

Imide Oligomers Endcapped With Phenylethynyl Phthalic Anhydrides

EXAMPLE 1

3,4'-Oxydianiline and 4,4'-Oxydiphthalic Anhydride

Using 5 mole % Stoichiometric offset and 10 mole % 4-Phenylethynylphthalic Anhydride

The following example illustrates the reaction sequence in FIG. 2 for the preparation of the controlled molecular weight PETI where Ar' is equal to a diphenylene where X is an oxygen atom located in the 3,4'-position. Ar is equal to a bis(o-diphenylene) where Y is an oxygen atom located in the 4,4'-position, and where W is equal to a nil group. The stoichiometric imbalance is 5 mole % and the endcapping reagent is 10 mole % of 4-phenylethynylphthalic anhydride.

Into a flame dried 250 ml three necked round bottom flask equipped with nitrogen inlet, thermometer, mechanical stirrer, and drying tube were placed 3,4'-oxydianiline (6.753 g, 0.0337 mol) and 50 ml (12.5% w/w) of N,N'-dimethylacetamide (DMAC). After dissolution, 4,4'-oxydiphthalic anhydride (9.9389 g, 0.0320 mol) and 45 ml of DMAC (15.7% w/w) were added. The solution was allowed to stir for 8 h at room temperature under a nitrogen atmosphere. 4-Phenylethynylphthalic anhydride (0.8372 g, 0.0034 mol) and 3 ml of DMAC (16.0% w/w) were added and the reaction stirred at room temperature for an additional 16 h. The inherent viscosity of the amic acid oligomeric solution (0.5% in DMAC at 25° C) was 0.36 dL/g. Glacial acetic acid (9 ml) was added to the solution and the temperature increased and maintained at ~120° C. for ~16 h under a nitrogen atmosphere. As cyclodehydration to the imide occurred, a precipitate formed. The mixture was cooled, the isolated precipitate was washed with hot water and warm methanol, and dried under vacuum at 100° C. for 5 h to provide a tan powder (15.2 g, 93% yield). The inherent viscosity of a 0.5% solution in m-cresol at 25° C was 0.12 dL/g. The Tg of the uncured as-isolated oligomer was not apparent on the initial DSC scan, but Tg was observed (DSC, 20° C/min) at 254°, 285°, and 315° C. with an exothermic onset and peak at 394° C. and 434° C., respectively. The Tg of the cured polymer (cure conditions: 350° C/1 h/flowing air) was 248° C. Unoriented thin films cast from a DMAC solution of the amic acid oligomer and cured at 100°, 225°, and 350° C for 1 h each in flowing air gave tensile strength, tensile modulus, and elongation at break at 23° C of 17.3 ksi, 413 ksi, and 38% and at 177° C of 9.4 ksi, 318 ksi, and 60%, respectively. The Tg of the cured film was 251° C.

EXAMPLE 2

3,4'-Oxydianiline and 4,4'-Oxydiphthalic Anhydride

Using 5.14 mole % Stoichiometric offset and 10.28 mole % 4-Phenylethynylphthalic Anhydride

The following example illustrates the reaction sequence in FIG. 2 for the preparation of the controlled molecular weight PETI where Ar' is equal to a diphenylene where X is an oxygen atom located in the 3,4'-position. Ar is equal to a bis(o-diphenylene) where Y is an oxygen atom located in the 4,4'-position, and where W is equal to a nil group. The stoichiometric imbalance is 5.14 mole % and the endcapping reagent is 10.28 mole % of 4-phenylethynylphthalic anhydride.

Into a flame dried 250 ml three necked round bottom flask equipped with nitrogen inlet, thermometer, mechanical stirrer, and drying tube were placed 3,4'-oxydianiline (8.4413 g, 0.0422 mol) and 50 ml (16.2% w/w) of 2-pyrrolidinone (NMP). After dissolution, 4,4'-oxydiphthalic anhydride (16.2% w/w) was added and the reaction stirred at room temperature for an additional 3 h. The inherent viscosity of the amic acid oligomeric solution (0.5% in NMP at 25° C) was 0.38 dL/g. Toluene (70 ml) was added to the solution and the temperature increased and maintained at ~120° C. for ~16 h under a nitrogen atmosphere. As cyclodehydration to the imide occurred, a precipitate formed. The mixture was cooled, the isolated precipitate was washed with hot water and warm methanol, and dried under vacuum at 100° C. for 5 h to provide a tan powder (15.2 g, 93% yield). The inherent viscosity of a 0.5% solution in m-cresol at 25° C was 0.12 dL/g. The Tg of the uncured as-isolated oligomer was not apparent on the initial DSC scan, but Tg was observed (DSC, 20° C/min) at 254°, 285°, and 315° C. with an exothermic onset and peak at 394° C. and 434° C., respectively. The Tg of the cured polymer (cure conditions: 350° C/1 h/flowing air) was 248° C. Unoriented thin films cast from a DMAC solution of the amic acid oligomer and cured at 100°, 225°, and 350° C for 1 h each in flowing air gave tensile strength, tensile modulus, and elongation at break at 23° C of 17.3 ksi, 413 ksi, and 38% and at 177° C of 9.4 ksi, 318 ksi, and 60%, respectively. The Tg of the cured film was 251° C.
temperature increased and maintained at −150 °C for −16 h under a nitrogen atmosphere. As cyclodehydration to the imide occurred, a precipitate formed. The mixture was cooled, the oligomer was washed in hot water, warm methanol, and dried under vacuum at 160 °C for 5 h to provide an off-white powder (19.46 g, 97% yield). The inherent viscosity of a 0.5% solution of the imide oligomer in m-cresol at 25 °C was 0.29 dL/g. The \( T_m \) of the uncured as-isolated oligomer (DSC, 20 °C/min) was 236 °C. \( T_m \) was 323 °C and the exothermic onset and peak occurred at 397 °C and 442 °C, respectively. The \( T_g \) of the 2-pyrrolidinone Isquinohe was 0.33 dL/g and \( T_g \) at 371 °C and 425 °C, respectively. The \( T_g \) of the cured polymer (cure conditions: 350 °C/1 h/flowing oxygen atom located in the monomers (DSC, 20 °C/min) exhibited endothermic melts in 1W/m and air) was 0.0433 mol) and 50 ml absolute ethanol and the mixture stirred for −16 h at room temperature under a nitrogen atmosphere. Approximately 92 g of solution was decanted and the solvent evaporated. To the remaining solution was added 80 ml NMP and the temperature increased and maintained at −170 °C for −20 h.

As cyclodehydration to the imide occurred, a precipitate formed. The mixture was cooled, the oligomer was washed in hot water, warm methanol, and dried under vacuum at 240 °C for 4 h to provide a brown powder (11.90 g). The \( T_m \) of the uncured as-isolated oligomer (DSC, 20 °C/min) was 226 °C. \( T_m \) of the uncured oligomer (DSC, 20 °C/min) exhibited endothermic melts at 124 °C, 132 °C, 144 °C, and 155 °C. The \( T_g \) of the cured polymer (cure conditions: 350 °C/1 h/DSC pan) was 235 °C.

**EXAMPLE 5**

3,4'-Oxydianiline and 4,4'-Oxydiphthalic Anhydride. Using 5.14 mole % Stoichiometric offset and 10.28 mole % 4-(4-Phenylethynylphenoxy)phthalic Anhydride

The following example illustrates the reaction sequence in FIG. 2 for the preparation of the controlled molecular weight PBTI where \( \text{Ar}' \) is equal to a diphenylene where \( X \) is an oxygen atom located in the 3,4'-position, \( \text{Ar}' \) is equal to a bis(o-diphenylene) where \( Y \) is an oxygen atom located in the monomers (DSC, 20 °C/min) was 235 °C. The \( T_g \) of the cured polymer (cure conditions: 350 °C/1 h/DSC pan) was 235 °C.

**EXAMPLE 4**

3,4'-Oxydianiline and 4,4'-Oxydiphthalic Anhydride. Using 5.14 mole % Stoichiometric offset and 10.28 mole % 4-Phenylethynlyphthalic Anhydride

The following example illustrates the reaction sequence in FIG. 2 for the preparation of the controlled molecular weight PBTI where \( \text{Ar}' \) is equal to a diphenylene where \( X \) is an oxygen atom located in the 3,4'-position, \( \text{Ar}' \) is equal to a bis(o-diphenylene) where \( Y \) is an oxygen atom located in the 4,4'-position, and where \( W \) is equal to a nil group. The stoichiometric imbalance is 5.14 mole % and the endcapping reagent is 10.28 mole % of 4-phenylethynlyphthalic anhydride.

Into a flame dried 250 ml three necked round bottom flask equipped with nitrogen inlet, thermometer, mechanical stirrer, and drying tube were placed 3,4'-oxydianiline (8.4413 g, 0.0422 mol) and 50 ml (14.0% w/w) of m-cresol. After dissolution, 4,4'-oxydiphthalic anhydride (12.0405 g, 0.0400 mol), 4-phenylethynlyphthalic anhydride (1.0758 g, 0.0043 mol) and 60 ml of m-cresol (15.0% w/w) were added and the reaction stirred at room temperature for −16 h. Isoquinoline (5 drops) was added to the mixture. The temperature was increased and maintained at −200 °C for −6.5 h under a nitrogen atmosphere. The mixture was cooled, the oligomer precipitated in methanol, washed in warm methanol, and dried at 150 °C under vacuum for 5 h to provide an off-white powder (20.0 g, 100% yield). The inherent viscosity of a 0.5% solution of the imide oligomer in m-cresol at 25 °C was 0.29 dL/g and in NMP at 25 °C was 0.33 dL/g. The \( T_m \) of the uncured as-isolated oligomer (DSC, 20 °C/min) was 219 °C with an exothermic onset and peak at 371 °C and 425 °C, respectively. The \( T_g \) of the cured polymer (cure conditions: 350 °C/1 h/flowing air) was 246 °C. A sample compression molded at 350 °C/200 psi/1 h had a \( G_{ic} \) (critical strain energy release rate) of 19.72 in lb/in² and a \( T_g \) of 234 °C.

**EXAMPLE 3**

3,4'-Oxydianiline and 4,4'-Oxydiphthalic Anhydride. Using 5.14 mole % Stoichiometric offset and 10.28 mole % 4-Phenylethynlyphthalic Anhydride

The following example illustrates the reaction sequence in FIG. 2 for the preparation of the controlled molecular weight PBTI where \( \text{Ar}' \) is equal to a diphenylene where \( X \) is an oxygen atom located in the 3,4'-position, \( \text{Ar}' \) is equal to a bis(o-diphenylene) where \( Y \) is an oxygen atom located in the 4,4'-position, and where \( W \) is equal to a nil group. The stoichiometric imbalance is 5.14 mole % and the endcapping reagent is 10.28 mole % of 4-(4-phenylethynlyphenoxy)phthalic anhydride.

Into a 250 ml three necked round bottom flask equipped with nitrogen inlet, thermometer, mechanical stirrer, and condenser were placed 4,4'-oxydiphthalic anhydride (16.6081 g, 0.0600 mol), 4-phenylethynlyphthalic anhydride (1.1637 g, 0.0065 mol), and 130 ml absolute ethanol. The mixture was brought to reflux and maintained for −4.5 h. As the anhydrides were converted to the corresponding ester derivatives, the solution cleared. To the cooled solution was added 3,4'-oxydianiline (12.6620 g, 0.0632 mol) and 50 ml absolute ethanol and the mixture stirred for −16 h at room temperature under a nitrogen atmosphere. Approximately 92 g of solution was decanted and the solvent evaporated. To the remaining solution was added 80 ml NMP and the temperature increased and maintained at −170 °C for −20 h.

As cyclodehydration to the imide occurred, a precipitate formed. The mixture was cooled, the oligomer was washed in hot water, warm methanol, and dried under vacuum at 240 °C for 4 h to provide a brown powder (11.90 g). The \( T_m \) of the uncured as-isolated oligomer (DSC, 20 °C/min) was 226 °C. \( T_m \) of the uncured as-isolated oligomer (DSC, 20 °C/min) exhibited endothermic melts at 124 °C, 132 °C, 144 °C, and 155 °C. The \( T_g \) of the cured polymer (cure conditions: 350 °C/1 h/DSC pan) was 235 °C.

**EXAMPLE 5**

3,4'-Oxydianiline and 4,4'-Oxydiphthalic Anhydride. Using 5.14 mole % Stoichiometric offset and 10.28 mole % 4-(4-Phenylethynlyphenoxy)phthalic Anhydride

The following example illustrates the reaction sequence in FIG. 2 for the preparation of the controlled molecular weight PBTI where \( \text{Ar}' \) is equal to a diphenylene where \( X \) is an oxygen atom located in the 3,4'-position, \( \text{Ar}' \) is equal to a bis(o-diphenylene) where \( Y \) is an oxygen atom located in the 4,4'-position, and where \( W \) is equal to a 4-phenyl group. The stoichiometric imbalance is 5.14 mole % and the endcapping reagent is 10.28 mole % of 4-(4-phenylethynlyphenoxy)phthalic anhydride.

Into a flame dried 300 ml three necked round bottom flask equipped with nitrogen inlet, thermometer, mechanical stirrer, and drying tube were placed 3,4'-oxydianiline (7.2371 g, 0.0361 mol) and 50 ml (12.3% w/w) N-Methyl-2-pyrrolidinone (NMP). After dissolution, 4,4'-oxydiphthalic anhydride (10.6358 g, 0.0343 mol), 4-(4-phenylethynlyphenoxy)phthalic anhydride (1.2645 g, 0.0037 mol) and 45 ml NMP (14.9% w/w) were added and the reaction stirred at room temperature for 24 h. The inherent viscosity of the amic acid oligomeric solution (0.5% in NMP at 25 °C) was 0.53 dL/g. Approximately 30 g of amic acid oligomeric solution was used to cast an unoriented thin film. Toluene (70 ml) was added to the remaining amic acid oligomeric solution and the temperature increased and maintained at −150 °C for −16 h under a nitrogen atmosphere. As cyclodehydration to the imide occurred, a precipitate formed. The mixture was cooled, the oligomer was washed in hot water, warm methanol, and dried under vacuum at 210 °C for 3 h to provide an off-white powder (13.05 g, 100% yield). The \( T_g \) of the uncured as-isolated oligomer (DSC, 20 °C/min) was 216 °C. \( T_g \) was 273 °C and 323 °C and the exothermic onset and peak occurred at 414 °C and 452 °C, respectively. The \( T_g \) of the cured polymer (cure conditions: 350 °C/1 h/static air) was 246 °C. Unoriented thin films cast from a NMP solution
of the amic acid oligomer cured at 100°, 225°, and 350°C. For 1 h each in flowing air gave tensile strength, tensile modulus, and elongation at break at 23° C. of 16.9 ksi, 408 ksi, and 35% and at 177° C. of 8.6 ksi, 293 ksi, and 56%, respectively. The Tg of the cured film was 257° C. A sample compression molded at 350° C./200 psi/h had a Gvc (critical strain energy release rate) of 25.7 in lb/in2. Mixtures of dihydrides have been used to alter properties as illustrated in Examples 6 and 7.

EXAMPLE 6

3,4'-Oxydianiline and 1,1:1,4,4'-Oxydiphthalic Anhydride, and 3:3,4,4'-Biphenyl Tetracarboxylic Dianhydride. Using 5.14 mole % Stoichiometric offset and 10.28 mole % 4-Phenylenyophthalic Anhydride

The following example illustrates the reaction sequence in FIG. 2 for the preparation of the controlled molecular weight PETI where Ar' is equal to a diphenylene where X is an oxygen atom located in the 3,4'-position; Ar (1) is equal to a bis(o-diphenylene) where Y is a nil group located in the 4,4'-position and Ar (2) is equal to a bis(o-diphenylene) where Y is a nil group located in the 4,4'-position, and where W is equal to a nil group. The ratio of dihydrides [Ar (1):Ar (2)] is 1:1. The stoichiometric imbalance is 7.635 mole % and the endcapping reagent is 15.27 mole % of 4-phenylenyophthalic anhydride.

Into a flame dried 500 ml three necked round bottom flask equipped with nitrogen inlet, thermometer, mechanical stirrer, and drying tube were placed 3.4'-oxydianiline (18.0309 g, 0.0900 mol) and 100 ml of NMP (14.9% w/w). After dissolution, 4,4'-oxydiphthalic anhydride (12.9223 g, 0.0417 mol) and 3,3,4,4'-biphenyl tetracarboxylic dianhydride (12.2558 g, 0.0417 mol) and 100 ml of NMP (17.3% w/w) were added and the reaction stirred for 8 h at room temperature under a nitrogen atmosphere. 4-Phenylenyophthalic anhydride (3.3440 g, 0.0135 mol) and 50 ml of NMP (15.3% w/w) were added and the reaction stirred at room temperature for an additional 16 h. The inherent viscosity of the amic acid oligomeric solution (0.5% in NMP at 25°C) was 0.32 dl/g. Approximately 28 g of amic acid oligomeric solution was used to cast an oriented thin film. Toluene (100 ml) was added to the remaining amic acid oligomeric solution and the temperature increased and maintained at 160°C for 24 h under a nitrogen atmosphere. As the amic acid oligomer was cyclodehydrated to the imide, the imide oligomer remained in solution. The mixture was cooled, the polymer precipitated in water, washed with hot 15% oxygen atom located in the 4,4'-position and where Y is a nil group located in the 4,4'-position, and where W is equal to a nil group. The ratio of dihydrides [Ar (1):Ar (2)] is 1:1. The stoichiometric imbalance is 7.635 mole % and the endcapping reagent is 15.27 mole % of 4-phenylenyophthalic anhydride.

Into a flame dried 500 ml three necked round bottom flask equipped with nitrogen inlet, thermometer, mechanical stirrer, and drying tube were placed 3,4'-oxydianiline (17.1723 g, 0.0858 mol) and 100 ml of NMP (14.3% w/w). After dissolution, 4,4'-oxydiphthalic anhydride (12.6288 g, 0.0407 mol) and 3,3,4,4'-biphenyl tetracarboxylic dianhydride (11.9775 g, 0.0407 mol) and 100 ml of NMP (16.8% w/w) were added and the solution stirred for 8 h at room temperature under a nitrogen atmosphere. 4-Phenylenyophthalic anhydride (2.1501 g, 0.0087 mol) and 15 ml of NMP (16.5% w/w) were added and the reaction stirred at room temperature for an additional 16 h. The inherent viscosity of the amic acid oligomeric solution (0.5% in NMP at 25°C) was 0.43 dl/g. Approximately 30 g of amic acid oligomeric solution was used to cast an unoriented thin film. Toluene (100 ml) was added to the remaining amic acid oligomeric solution and the temperature increased and maintained at 150°C for 16 h under a nitrogen atmosphere. As the amic acid oligomer was cyclodehydrated to the imide, the imide oligomer remained in solution. The solution was heated for an additional 5 h at 175°C under a nitrogen atmosphere. The mixture was cooled, the polymer precipitated in water, washed in hot water, warm methanol, and dried under vacuum at 160°C for 3 h to provide an off-white powder (35.1 g, 88% yield). The inherent viscosity of a 0.5% solution of the imide oligomer in NMP at 25°C was 0.38 dl/g. The Tg of the uncured as-isolated imide oligomer (DSC, 20°C/min) was 222°C. with an exothermic onset and peak at 372°C and 419°C, respectively. The Tg of the cured polymer (cure conditions: 350°C/1 h/static air) was 267°C. Unoriented thin films cast from a NMP solution of the amic acid oligomer cured at 100°, 225°, and 350°C for 1 h each in flowing air gave tensile strength, tensile modulus, and elongation at break at 23°C of 20.2 ksi, 431 ksi, and 69% and at 177°C of 10.7 ksi, 341 ksi, and 70%, respectively. The Tg of the cured film was 267°C. A sample compression molded at 350° C./200 psi/h had a Gvc (critical strain energy release rate) of 17.68 in lb/in2 and a Tg of 248°C.

EXAMPLE 7

3,4'-Oxydianiline and 1:1,4,4'-Oxydiphthalic Anhydride, and 3:3,4,4'-Biphenyl Tetracarboxylic Dianhydride. Using 7.635 mole % Stoichiometric offset and 15.27 mole % 4-Phenylenyophthalic Anhydride

The following example illustrates the reaction sequence in FIG. 2 for the preparation of the controlled molecular weight PETI where Ar' is equal to a diphenylene where X is an oxygen atom located in the 3,4'-position; Ar (1) is equal to a bis(o-diphenylene) where Y is a nil group located in the 4,4'-position and Ar (2) is equal to a bis(o-diphenylene) where Y is a nil group located in the 4,4'-position, and where W is equal to a nil group. The ratio of dihydrides [Ar (1):Ar (2)] is 1:1. The stoichiometric imbalance is 7.635 mole % and the endcapping reagent is 15.27 mole % of 4-phenylenyophthalic anhydride.

Into a flame dried 250 ml three necked round bottom flask equipped with nitrogen inlet, thermometer, mechanical stirrer, and drying tube were placed 3,4'-oxydianiline (10.8126 g, 0.0540 mol), 1.3-bis-(3-aminoophenoxy)benzene (2.7857 g, 0.0095 mol) and 90 ml of NMP (12.8% w/w).
After dissolution, 3,3',4,4'-biphenyl tetracarboxylic dianhydride (17.0649 g, 0.0578 mol), 4-phenylethynylphthalic anhydride (2.8449 g, 0.0115 mol) and 90 ml of NMP (15.3% w/w) were added and the reaction stirred at room temperature for 20 h. The inherent viscosity of the amic acid oligomeric solution (0.5% in NMP at 25°C) was 0.27 dL/g. Approximately 25 g of amic acid oligomeric solution was used to cast an unoriented thin film. Toluene (70 ml) was added to the remaining amic acid oligomeric solution and the temperature increased and maintained at ~180°C for ~24 h under a nitrogen atmosphere. As the amic acid oligomer was cyclodehydrated to the imide, a precipitate formed. The mixture was cooled, the oligomer washed in hot water, warm methanol, and dried under vacuum at 25°C for 4 h to provide a yellow powder (24.2 g, 78% yield). The inherent viscosity of a 0.5% solution of the imide oligomer in m-cresol at 25°C was 0.28 dL/g. The Tg of the uncured as-isolated oligomer (DSC, 20°C/min) was 262°C and the Tg of the cured polymer (cure conditions: 200°C/2 h N2 static) was 249°C. Unoriented thin films cast from a NMP solution of the amic acid oligomer cured at 100°C, 225°C, and 350°C for 1 h each in flowing air gave tensile strength, tensile modulus and elongation at break at 23°C of 18.8 ksi, 455 ksi, and 32% and at 177°C of 12.2 ksi, 332 ksi, and 83%, respectively. The Tg of the cured film was 270°C. A sample compression molded at 350°C/150 psi/1 h had a Gc (critical strain energy release rate) of 27.4 in lb/in².

EXAMPLE 9

0.75:0.25 3,4'-Oxydianiline and 1,3-bis(3-aminophenoxy)benzene, and 3,3',4,4'-Benzophenone Tetracarboxylic Dianhydride, Using 29.03 mole Tetracarboxylic Dianhydride, Using 29.03 mole

The following example illustrates the reaction sequence in FIG. 2 for the preparation of the controlled molecular weight PETI where Ar' (1) is equal to a diphenylene where X is an oxygen atom located in the 3,4'-position and Ar' (2) is equal to a diphenylene where X is a 1,3-dioxynaphthalene and Ar' is equal to a bis(o-diphenylene) where X is a carbonyl group located in the 4,4'-position, and where W is equal to a naphthyl group. The ratio of diamines [Ar' (1):Ar' (2)] is 0.75:0.25. The stoichiometric imbalance is 29.03 mole % and the endcapping reagent is 58.06 mole % of 4-phenylethynylphthalic anhydride.

Into a flame dried 250 ml three necked round bottom flask equipped with nitrogen inlet, thermometer, mechanical stirrer, and drying tube were placed 3,4'-oxydianiline (10.5323 g, 0.0526 mol), 1,3-bis(3-aminophenoxy)benzene (5.1256 g, 0.0175 mol) and 25 ml of NMP (37.8% w/w). After dissolution, a slurry of 3,3',4,4'-benzophenone tetracarboxylic dianhydride (16.0382 g, 0.0498 mol) and 4-phenylethynylphthalic anhydride (10.1079 g, 0.0407 mol) in 50 ml of NMP (33.6% w/w) were added to the stirred solution. An additional 45 ml of NMP was used to rinse in the anhydrides. The solids content was 25.2% w/w (120 ml total NMP). The mixture was stirred overnight at room temperature under nitrogen. The inherent viscosity of the amic acid oligomeric solution (0.5% in NMP at 25°C) was 0.16 dL/g. Toluene (70 ml) was added to the amic acid oligomeric solution and the temperature increased and maintained at ~180°C for ~24 h under a nitrogen atmosphere. As the amic acid oligomer was cyclodehydrated to the imide, a precipitate formed. The mixture was cooled, the oligomer washed in hot water, warm methanol, and dried under vacuum at 25°C for 4 h to provide a yellow powder (38.4 g, 98% yield). The Tg of the uncured as-isolated oligomer (DSC, 20°C/min) was 262°C and the Tg of the cured polymer (cure conditions: 360°C/1 h static air) was 276°C.

In the tables which follow, oligomer and polymer characterization is presented in Table 1; unoriented thin film properties are presented in Table 2; adhesive properties are presented in Table 3; and composite properties are presented in Table 4.

**Table 1: Oligomer and Polymer Characterization**

<table>
<thead>
<tr>
<th>No.</th>
<th>M (g/mol)</th>
<th>Inside (Mg/100ml)</th>
<th>Amic</th>
<th>Tg (Tg), °C</th>
<th>Temp. of % Wt. Loss, °C</th>
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<td></td>
<td></td>
<td>Inside¹</td>
<td>Inside²</td>
</tr>
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<td>9000</td>
<td>0.38 0.2a</td>
<td>256</td>
<td>(323)</td>
<td>243 489</td>
</tr>
<tr>
<td>2</td>
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<td>0.31 0.1a²</td>
<td>211</td>
<td>(268, 320)</td>
<td>237 508</td>
</tr>
<tr>
<td>3</td>
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<td>0.47 0.43³</td>
<td>232</td>
<td>(277)</td>
<td>256 493</td>
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<td></td>
<td>267 505</td>
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<td>250 513</td>
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<td>6</td>
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<td>0.49 0.36⁴</td>
<td>225</td>
<td>(323)</td>
<td>264 486</td>
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<tr>
<td>7</td>
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<td>216</td>
<td>(273, 323)</td>
<td>246 487</td>
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<tr>
<td>8</td>
<td>5000</td>
<td>0.27 0.28³</td>
<td>208</td>
<td>(288)</td>
<td>249 505</td>
</tr>
<tr>
<td>9</td>
<td>1500</td>
<td>0.16</td>
<td>262</td>
<td>(341)</td>
<td>276 451</td>
</tr>
</tbody>
</table>

¹Inside-1: ODPA/3,4'-ODA/PEPA
²Inside-2: 3:1 ODPA-BPDA/3,4'-ODA/PEPA
³Inside-3: 1:1 ODPA-BPDA/3,4'-ODA/PEPA
⁴Inside-4: 1:3 ODPA-BPDA/3,4'-ODA/PEPA
⁵Inside-5: ODPA/3,4'-ODA/PEPA
⁶Inside-6: BPDA/(85:3,4'-ODA/(15)AP/PEPA
⁷Inside-7: BTDA/3:1 3,4'-ODA/AB/PEPA

²Inherent viscosity determined on 0.5% (v/v) NMP solution at 25°C.
²Inherent viscosity determined on 0.5% (v/v) m-cresol solution at 25°C.
²Powdered samples after hold at 350°C/1 h static air, C-inside: cured inside powder.
TABLE 2

<table>
<thead>
<tr>
<th></th>
<th>Calc'd ( \text{g/mol} )</th>
<th>( T_c )</th>
<th>Test Temp.</th>
<th>Strength</th>
<th>Modulus</th>
<th>Elongation at Break, %</th>
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</thead>
<tbody>
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<td>274</td>
<td>23</td>
<td>15.3</td>
<td>407</td>
<td>5</td>
</tr>
</tbody>
</table>

\( ^* \) Determined by DSC at 20°C/min on film samples cured at 100, 225, 350°C for 1 h each in flowing air.

TABLE 3

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Test Temp., °C</th>
<th>Strength, psi</th>
<th>Cohesive Failure, %</th>
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</thead>
<tbody>
<tr>
<td>Control</td>
<td>23</td>
<td>7100</td>
<td>100</td>
</tr>
<tr>
<td>Jet Fuel(^1)</td>
<td>23</td>
<td>7200</td>
<td>95</td>
</tr>
<tr>
<td>Hydraulic Fluid(^2)</td>
<td>23</td>
<td>4500</td>
<td>90</td>
</tr>
<tr>
<td>Water ( \text{Oil} )(^3)</td>
<td>23</td>
<td>4400</td>
<td>75</td>
</tr>
<tr>
<td>Water ( \text{Beer} )(^3)</td>
<td>23</td>
<td>6600</td>
<td>85</td>
</tr>
<tr>
<td>Water ( \text{Oil} )(^3)</td>
<td>23</td>
<td>4400</td>
<td>90</td>
</tr>
<tr>
<td>Water ( \text{Beer} )(^3)</td>
<td>23</td>
<td>4800</td>
<td>90</td>
</tr>
</tbody>
</table>

\( ^* \) at 350°C/100 psi, tape -1% volatiles

\( ^1 \) Unstressed samples aged in flowing air

We claim:
1. A phenylethynyl phthalic anhydride having the general structural formula

\[ \text{C}_4\text{H}_2\text{C}_6=\text{W} \]

Wherein \( W \) is a radical selected from the group consisting of

\[ \text{C}_4\text{H}_2\text{C} \quad \text{O} \quad \text{O} \quad \text{O} \quad \text{O} \quad \text{O} \]

2. A phenylethynyl phthalic anhydride according to claim 1 having the following structural formula:

\[ \text{C}_4\text{H}_2\text{C} \quad \text{C} = \text{W} \quad \text{O} \quad \text{O} \quad \text{O} \]

TABLE 4

<table>
<thead>
<tr>
<th>Property</th>
<th>Layup</th>
<th>Test Temp., °C</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexural Strength, ksi</td>
<td>Unidirectional</td>
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<td>310</td>
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<tr>
<td>Flexural Modulus, ksi</td>
<td>Unidirectional</td>
<td>23</td>
<td>20.4</td>
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* * * * *