**Liquid Crystalline Thermosets from Ester, Ester-imide, and Ester-amide Oligomers**

Inventors: Theodorus J. Dingemans, Hampton, VA (US); Erik S. Weiser, Newport News, VA (US); Terry L. St. Clair, Poquoson, VA (US)

Assignee: The United States of America as represented by the Administrator of the National Aeronautics and Space Administration, Washington, DC (US)

Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days. This patent is subject to a terminal disclaimer.

Filed: Apr. 29, 2005

**Abstract**

Main chain thermotropic liquid crystal esters, ester-imides, and ester-amides were prepared from AA, BB, and AB type monomeric materials and end-capped with phenylacetylene, phenylmaleimide, or nadimide reactive end-groups. The end-capped liquid crystal oligomers are thermotropic and have, preferably, molecular weights in the range of approximately 1000-15,000 grams per mole. The end-capped liquid crystal oligomers have broad liquid crystalline melting ranges and exhibit high melt stability and very low melt viscosities at accessible temperatures. The end-capped liquid crystal oligomers are stable for up to an hour in the melt phase. They are highly processable by a variety of melt process shape forming and blending techniques. Once processed and shaped, the end-capped liquid crystal oligomers were heated to further polymerize and form liquid crystalline thermosets (LCT). The fully cured products are rubbers above their glass transition temperatures.

7 Claims, 7 Drawing Sheets
OTHER PUBLICATIONS


* cited by examiner
FIG. 3

FIG. 4
1. Acetic Anhydride/KOAc
2. $\Delta T$
3. $\text{E} \rightarrow \text{Y}$ (End-Cap Groups)

FIG. 5

O
HO–C–Ar₁/R₁–C–OH + HO–Ar₂/R₂–OH + HO–C–Ar₃/R₃–OH

1. Acetic Anhydride/KOAc
2. $\Delta T$
3. $\text{E} \rightarrow \text{Y}$ (End-Cap Groups)

FIG. 6
1. Acetic Anhydride/KOAc
2. ΔT
3. E—Y (End-Cap Groups)

Acetic Acid

FIG. 7
**FIG. 8**

Bleeder/Breather Cloth

IM-7 Plain Weave Cloth

LaRC - (6HBA/4HNA-5PE) LCR

Release Film

**FIG. 9**

![Temperature vs. Time Graph](chart)

- 0.5 hrs @ 716°F
- 1 hrs @ 482°F
- Vacuum 5° Hg
- Vacuum 20° Hg
- Vacuum 30° Hg

![Pressure vs. Time Graph](chart)

- Temperature, °F
- Pressure, Psi

- Time, hours
FIG. 10

Temperature, °F

Pressure, Psi

Time, hours

1 hr @ 675°F
1/2 hr @ 608°F
1/2 hr @ 572°F
100 Psi
Vacuum 30" Hg
US 7,507,784 B2

1
LIQUID CRYSTALLINE THERMOSETS FROM ESTER, ESTER-IMIDE, AND ESTER-AMIDE OLGOMERS

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation of application Ser. No. 09/757,398 filed Jan. 5, 2001, now U.S. Pat. No. 6,939,940, which claims the benefit of priority from U.S. Provisional Application Ser. No. 60/232,504 filed Sep. 13, 2000.

ORIGIN OF THE INVENTION

This invention was made in part by employees of the United States Government and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

FIELD OF THE INVENTION

The present invention relates generally to liquid crystalline polymers and liquid crystal thermosets. Specifically, the invention relates to liquid crystalline ester, ester-imide, and ester-amide oligomers and the improved thermal properties of such species when they are end-capped with phenylacetylene, phenylmaleimide, or nadimide terminated monofunctional reactants. The invention also relates to the ability to process liquid crystal polymers and their use in melt process shape forming and blending techniques such as film extrusion, fiber spinning, reactive injection molding (RIM), resin transfer molding (RTM), resin film injection (RFI), powder molding, pultrusion, injection molding, blow molding, and thermo-forming.

DESCRIPTION OF THE RELATED ART

High molecular weight linear ester based thermotropic liquid crystalline polymers (TLCPs) are known in the literature. Non-end-capped TLCP copolyesters are taught by Kuhfuss and Jackson in U.S. Pat. Nos. 3,778,410 and 3,804,805. TLCP polyesters with non-reactive phenylacetylene and ethyl maleimide end-cap groups, that can only be thermoset at elevated temperatures via oxidative backbone crosslinking, are taught by Calundann in U.S. Pat. Nos. 4,067,852 and 4,161,470 and Bilow et al. in U.S. Pat. No. 5,688,895 teach high molecular weight liquid crystalline poly(ester-imide)s. Alanko et al. teach high molecular weight poly(ester-imide) oligomers. Lubowitz et al. teach end-capped backbone structures of TLCPs in order to immobilize the anisotropic melt. Lubowitz et al., however, do not teach using the claimed end-caps with liquid crystal oligomers. Lubowitz et al., further teach the use of end-cap groups that will not survive the melt condensation polymerization conditions. Finally, Lubowitz et al. do not teach materials with melt viscosities in the range of approximately 1 to approximately 250 poise at a shear rate of 100 radials/second.

Improved melt processability of linear high molecular weight TLCPs was achieved by the addition of small amounts of low molecular weight organic compounds during the melt processing steps of the high molecular weight liquid crystal polymers by the teachings of Froix in U.S. Pat. No. 4,267,289 and Yoon in U.S. Pat. No. 4,581,399. Charbonneau et al. in U.S. Pat. No. 4,746,694 teach liquid crystal polymers with relatively low melt viscosities (200-1000 poise at 345°C) and a shear rate of 100 radials/sec by disrupting the linear progression of the polymer backbone. This process results in undesirable volatiles.

Thermosets have been prepared from thermotropic liquid crystalline polymers. Uruy and Kato teach, in U.S. Pat. No. 4,710,547, thermotropic liquid crystal thermosets (TLCTs) via incorporation of trifunctional cross-link units into the TLCPs in order to immobilize the anisotropic melt. Haider et al. teach, in U.S. Pat. No. 5,216,073, a moldable composition by blending a liquid crystal polyester with an epoxy-functionalized rubber. In U.S. Pat. No. 4,654,412, Calundann et al. teach incorporation of stilbene and tolane type difunctional monomers into the backbone of main chain wholly aromatic liquid crystalline polyesters in which cured shaped articles made of these polymers were prepared by backbone crosslinking using a maleic anhydride dipping procedure requiring an undesirable second process step.


Lubowitz et al. teach in U.S. Pat. Nos. 4,661,604, 4,684,714, 4,739,030, 4,851,501, and 5,550,204 self-reactive end-cap monomers to prepare oligomeric polymer resins, including polyesters. Lubowitz et al., however, do not teach using the claimed end-caps with liquid crystalline oligomers. Lubowitz et al., further teach the use of end-cap groups that will not survive the melt condensation polymerization conditions. Finally, Lubowitz et al. do not teach materials with melt viscosities in the range of approximately 1 to approximately 250 poise at a shear rate of 100 radials/second.

Bilow et al. teach in U.S. Pat. No. 3,864,309 polyimide oligomers end-capped with terminal acetylene or cyano groups. Bilow et al.’s use of the term “oligomer” is inconsistent with our present use of the term “oligomer.” Bilow et al. teach low molecular weight pure end-capped imides as opposed to low molecular weight polyimide oligomers; the Bilow et al. patent teaches end-capped backbone structures of only one unit wherein an entire sample contains only molecules of the same length and molecular weight. Bilow et al. teach the use of end-cap groups that will not survive melt condensation polymerization conditions. Finally, Bilow et al. teach materials that are neither liquid crystalline nor have melt viscosities in the range of approximately 1 to approximately 250 poise at a shear rate of 100 radials/second.

Reinhardt et al. teach, in U.S. Pat. No. 4,513,131 phenylacetylene end-capped low molecular weight poly(vinyl ethers) as opposed to the polyester, poly(ester-imide), and poly(ester-amide) oligomers. Reinhardt et al. teach materials that are
not liquid crystals. Reinhardt et al. teach pure low molecular weight polymer samples as opposed to the oligomeric mixtures.

Similarly, Sheppard et al. in U.S. Pat. No. 4,851,495, Kwiatkowski et al. in U.S. Pat. No. 3,839,287, Kovar et al. in U.S. Pat. No. 3,975,444, Baudouin et al. in U.S. Pat. No. 4,225,497, and Kumar et al. in U.S. Pat. No. 4,550,177 teach materials that are not liquid crystalline. These patents also do neither teach materials with melt viscosities in the range of approximately 1 to approximately 250 poise at a shear rate of 100 radians/second nor do they teach the use of end-cap groups that will survive melt condensation polymerization conditions.

The claimed invention of reactive end-capped liquid crystal ester, ester-imide, and ester-amide oligomers is novel and non-obvious over the prior art. The present invention was prepared via melt condensation techniques as opposed to solution chemistry and produced oligomeric mixtures as opposed to well defined pure molecular species. The present invention is oligomeric rather than pure in that they contain a mixture of varying weight and/or length TLCPs, relative to the pure analogs, and generally have molecular weight distributions of approximately 1000 to approximately 15,000 grams per mole. Linking of individual oligomers in the present invention primarily occurs via reactions only between the end-cap groups rather than backbone to backbone or backbone to end-cap group crosslinking. Finally, the present invention has unexpected and improved physical and melt processing characteristics including melt viscosities in the range of approximately 1 to approximately 250 poise at a shear rate of 100 radians/second, rubber behavior above the Tg, exhibit no exothermic behavior during batch production, and have melt process windows of up an hour at approximately 300° C.

SUMMARY OF THE INVENTION

Based on what has been stated above, it is an objective of the present invention to prepare high performance end-capped liquid crystal ester, ester-imide, and ester-amide oligomers. These end-capped liquid crystal oligomers were prepared via melt condensation techniques over a wide temperature range while maintaining the liquid crystal state and properties. The end-capped liquid crystal oligomers have greatly reduced melt flow viscosities over extended periods of time, relative to other higher molecular weight analogs, allowing for melt processing. The end-cap groups were chosen to be stable in the temperature range used for the melt condensation preparation of the liquid crystal oligomers. The end-cap groups were chosen to polymerize with each other at temperatures above the range used for the melt condensation preparation of the oligomers and above that temperature which will induce chain-extension of the liquid crystal oligomers. The melt processed end-capped liquid crystal oligomers were converted into liquid crystal thermosets by exposure to temperatures sufficiently high to cause end-cap polymerization while not inducing cross-linking of the liquid crystal backbone. The degree of end-cap polymerization was controlled through varying length and temperature of exposure.

It is another objective of the present invention to prepare high performance end-capped liquid crystal ester, ester-imide, and ester-amide oligomers that can be prepared using commercially available monomers in a relatively inexpensive and environmentally benign one vessel synthesis.

It is another objective of the present invention to prepare high performance end-capped liquid crystal ester, ester-imide, and ester-amide oligomers that are amenable to melt process shape forming and blending techniques such as film extrusion, fiber spinning, reactive injection molding (RIM), resin transfer molding (RTM), resin film injection (RFI), powder molding, pultrusion, injection molding, blow molding, plasma spraying, and thermo forming. More specifically, the objective is to prepare high performance end-capped liquid crystal ester, ester-imide, and ester-amide oligomers that are suitable for Resin Transfer Molding (RTM). The preferred oligomers have low melt viscosities, low dielectric constants, low moisture absorption, high solvent resistivity, and high adhesion and barrier properties. Most specifically, the oligomers have the above qualities and are able to be used as composite matrices, adhesives, high barrier coatings, low dielectric films, membranes, fibers, and moldings.

The "backbones" of the end-capped liquid crystalline ester, ester-imide, or ester-amide oligomers were prepared from the reaction between varying quantities and combinations of one or more aromatic, heterocyclic or aliphatic dicarboxylic acids, aromatic, heterocyclic or aliphatic diols aromatic, heterocyclic or aliphatic diamines, hydroxybenzoic acids and aminobenzoic acids. The preferred embodiments of the end-capped ester, ester-imide, and ester-amide oligomers backbones are depicted in FIG. 1, wherein R is the structural units depicted in FIG. 2 and Ar is the structural units depicted in FIG. 3 and X is the structural units depicted in FIG. 4. The "backbone" liquid crystal oligomers are simultaneously end-capped terminated with stoichiometric quantities of mono-functional reactants to control oligomer chain length. The end-cap units for the end-capped ester, ester-imide, and ester-amide oligomers can be prepared by methods in the art and include phenylacetylene derivatives of general formula (I)

\[
\begin{align*}
\text{I} & \quad \text{and/or phenylmaleimide of general formula (II),} \\
\text{II} & \quad \text{and/or nadimide of general formula (III),} \\
\text{III} & \quad \text{wherein Y can be a carboxy, hydroxy, amino group or any reactive analog thereof (e.g., acetoxy, propionoxy, butoxy, etc.), or an esterified carboxy group (e.g., methylbenzoate, ethylbenzoate, phenylbenzoate, etc.). The R' substituents can be identical or different on any given end-cap unit provided they do not interfere with the melt condensation synthesis of the liquid crystal oligomers or the higher temperature curing step. Possible R' substituents include hydrogen, lower alkyl}
\end{align*}
\]
polymers. Specifically, liquid crystalline polymers exhibit other polymeric species. The ability of these species to maintain molecular order in the molten state has pronounced effect on the physical properties, including melt viscosities for these weight polymer species compared to non-end-capped higher molecular weight analogs and comparable and/or superior to previously end-capped lower weight non-oligomeric species (end-capped single pure molecules), stability of melt viscosities at elevated temperatures for extended periods of time relative to previous liquid crystalline products, and reduced brittleness (i.e. rubber behavior) above the glass transition temperature. The end-capped liquid crystal oligomers exhibit lower melt viscosities than the corresponding non-end-capped high weight analogs. Being polymeric, the end-capped liquid crystal oligomers exhibit superior physical properties relative to well-defined end-capped low weight pure liquid crystal esters. This class of end-capped liquid crystal oligomers, therefore, exhibits improved melt processability relative to higher weight analogs while maintaining the benefits of being polymeric relative to well-defined end-capped low weight pure liquid crystal esters. In many instances, the lowered melt viscosity can be maintained for extended periods of time relative to the non-end-capped higher weight analogs and comparable and/or superior to the end-capped low weight pure liquid crystal esters. Lowered melt viscosities make this new class of liquid crystal polymers more amenable to melt processing. For the first time, higher weight liquid crystal oligomers can be used effectively in melt process shape forming and blending techniques.

Once melt processed and shaped, the end-capped liquid crystal oligomers were cured at elevated temperatures (temperatures above that used for the melt state condensation) resulting in liquid crystal thermosets. This second step causes the end-caps to react with one another and further increases the molecular weight of the liquid crystal polymers. Traditionally, heat curing of polymer molds is carried out at temperatures sufficiently high to induce cross-linking of the polymer backbone. Cross-linking of the backbone, however, often makes the cured product brittle. In the present invention, the reactions between the end-caps can be carried out at temperatures below that which would induce significant cross-linking within the liquid crystal oligomer backbone while the degree
of end-cap polymerization can be controlled through varying length and temperature of exposure. Unexpectedly, the lack of significant backbone cross-linking produces liquid crystalline polymers that behave as rubbers when elevated above their glass transition temperatures rather than becoming brittle.

Method of Preparation

The "backbones" of the end-capped liquid crystalline ester, ester-imide, or ester-amide oligomers were prepared from the reaction between varying quantities and combinations of one or more aromatic, heterocyclic or aliphatic dicarboxylic acids, aromatic, heterocyclic or aliphatic diols aromatic, heterocyclic or aliphatic diamines, hydroxybenzoic acids and aminobenzoic acids. The preferred embodiments of the end-capped ester, ester-imide, and ester-amide oligomers backbones are depicted in FIG. 1 wherein R is the structural units depicted in FIG. 2 and Ar is the structural units depicted in FIG. 3 and X is the structural units depicted in FIG. 4. The preferred general methods of preparation of the end-capped ester, ester-imide, and ester-amide oligomers are presented in Figs. 5, 6, and 7 wherein R, R2, and R3 can be identical or different and are the structural units depicted in FIG. 2 and Ar1, Ar2, and Ar3 can be identical or different and are the structural units depicted in FIG. 3 and X is the structural units depicted in FIG. 4. E-Y represents end-cap units I, II, and/or III that can be prepared by methods available in the literature, wherein Y can be a carboxy, hydroxy, amino group or any reactive analog thereof (e.g., acetoxy, propionoxy, butoxy, etc.), or an esterified carboxy group (e.g., methylbenzoate, ethylbenzoate, phenylbenzoate, etc.) and the R' substituents can be identical or different on any given end-cap unit provided they do not interfere with the melt condensation curing step. Possible R' substituents include hydrogen, lower alkyl groups (preferably containing four or less carbon atoms) such as methyl, ethyl, propyl, and butyl groups, aryl groups (preferably containing six to ten carbon atoms) such as phenyl or naphthyl groups, lower alkoxy groups such as methoxy, ethoxy, and propoxy, lower arylxy groups such as phenoxo or benzyloxo, or halogen groups. The stoichiometric amounts of each reactant and end-cap group can be varied to prepare oligomers of varying size, weight, characteristic and chemical content. The reactions depicted in FIGS. 5, 6, and 7 are generally performed at between approximately 140° C. to approximately 350° C. The melt viscosities of the end-capped ester, ester-imide, and ester-amide oligomers are lower than their non-end-capped analogs.

Method of Preparation

The following specific examples are provided for illustrative purposes. These examples do not serve to limit the scope of the invention.

EXAMPLES

Preparation of Reactive End-Caps

The following examples illustrate the reaction sequence for the synthesis of the reactive end caps that were used for the preparation of end-capped ester, ester-imide, and ester-amide oligomers.

Example A (Phenylacetylene Terminated Carboxylic Acid; PE-COOH)

Into a 250 mL two-neck round bottom flask equipped with a mechanical stirrer, condenser and a nitrogen gas inlet was placed 4-aminobenzoic acid (8.0 g, 58 mmol), 4-phenylalkanhydride (14.5 g, 58 mmol) and 150 mL glacial acetic acid. This mixture was stirred at 25° C. for 1 hour after which the temperature was raised to reflux for 12 hours. The reaction mixture was cooled to 25° C. and the precipitated product was collected by filtration, washed twice with hot ethanol and dried under vacuum at 100° C. for 8 hours.

Example B (Phenylacetylene Terminated Acetoxy Phenol; PE-OAc)

Into a 250 mL two-neck round bottom flask equipped with a mechanical stirrer, condenser and a nitrogen gas inlet was placed 4-aminophenol (6.3 g, 58 mmol), 4-phenylalkanhydride (14.5 g, 58 mmol) and 200 mL glacial acetic acid. This mixture was stirred at 25° C. for 1 hour after which the temperature was raised to reflux for 12 hours. The reaction mixture was cooled to 25° C. and the precipitated product was collected by filtration, washed twice with ethanol and dried under vacuum at 50° C. for 8 hours.

The dried end-cap products were refluxed in 150 mL acetic anhydride for 5 hours. Yellow crystals precipitated upon cooling and were collected by filtration, washed with ethanol and dried under vacuum at 80° C. for 8 hours.

Other end groups were made using similar procedures. The yields and thermal analysis results (differential scanning calorimetry) of all compounds are summarized in Table 1.

<table>
<thead>
<tr>
<th>Molecular Structure</th>
<th>Name</th>
<th>Yield (%)</th>
<th>Tm (° C.)</th>
<th>ΔH_{prod} (KJ.mol⁻¹)</th>
<th>ΔH_{exotherm range (° C.)}</th>
<th>ΔH_{dehyd} (KJ.mol⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE-COOH</td>
<td>92</td>
<td>347.8</td>
<td>36.21</td>
<td>363-421</td>
<td>-67</td>
<td></td>
</tr>
</tbody>
</table>
TABLE 1-continued

<table>
<thead>
<tr>
<th>Molecular Structure</th>
<th>Name</th>
<th>Yield (%)</th>
<th>Tm (° C.)</th>
<th>ΔHαex (KJ.mol⁻¹)</th>
<th>Exotherm range (° C.)</th>
<th>ΔHαex (KJ.mol⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM-CoOH</td>
<td>92</td>
<td>261.2</td>
<td>30.2</td>
<td>311-407</td>
<td>-23</td>
<td></td>
</tr>
<tr>
<td>PM-OAc</td>
<td>94</td>
<td>155.6</td>
<td>29.3</td>
<td>302-421</td>
<td>-54</td>
<td></td>
</tr>
<tr>
<td>NOR-CoOH</td>
<td>77</td>
<td>233.1</td>
<td>30.61</td>
<td>290-360</td>
<td>-21</td>
<td></td>
</tr>
<tr>
<td>NOR-OAc</td>
<td>90</td>
<td>191.4</td>
<td>27.2</td>
<td>310-388</td>
<td>-32</td>
<td></td>
</tr>
</tbody>
</table>

Preparation of End-Capped Liquid Crystal Oligomers

**Example 1**

A 100 mL 3-neck round bottom flask was charged with 4-hydroxybenzoic acid (20.72 g, 0.15 mol), 6-hydroxy-2-naphtoic acid (38.4 g, 0.17 mol), PE-COOH (2.43 g, 6.6 mmol), PE-OAc (2.52 g, 6.6 mmol) and 4 mg potassium acetate. The flask was equipped with a sealed glass paddle stirrer, a nitrogen inlet tube and an insulated distillation head. The flask was purged with nitrogen gas, and the reaction mixture was heated over a 3 hour period on a water metal bath, under a slow stream of nitrogen, with the reaction temperature being increased from 150° C. to 300° C. At this point the temperature was increased to 310° C. over 30 minutes and a vacuum was slowly applied for 25 min. The opaque melt was cooled to room temperature and the product (6HBA/4HNA-9PE) was broken from the flask and ground into a fine powder.

**Example II**

A 100 mL 3-neck round bottom flask was charged with 4-hydroxybenzoic acid (20.72 g, 0.15 mol), 6-hydroxy-2-naphtoic acid (18.82 g, 0.15 mol), NOR-COOH (1.13 g, 4 mmol), NOR-OAc (1.19 g, 4 mmol), acetic anhydride (28.1 g, 0.275 mol), and 4 mg potassium acetate. The flask was equipped with a sealed glass paddle stirrer, a nitrogen inlet tube and an insulated distillation head. The flask was purged with nitrogen gas, and the reaction mixture was heated over a 1 hour period on a water metal bath, under a slow stream of nitrogen, to 140° C. and held for 1 hour at this temperature. The reaction temperature was increased to 250° C. in 100 min. and held at this temperature for 50 min. The reaction temperature was increased from 250° C. to 275° C. in 30 min. and a vacuum was slowly applied for 20 min. The opaque melt was cooled to room temperature and the product (6HBA/4HNA-9NOR) was broken from the flask and ground into a fine powder.
Example III

A 100 mL 3-neck round bottom flask was charged with 4-hydroxybenzoic acid (20.72 g, 0.15 mol), 6-hydroxy-2-naphtoic acid (11.33 g, 0.06 mol), PM-COOH (1.17 g, 2.21 mmol), PM-OAc (1.23 g, 4 mmol), 4-acetoxybenzoic acid (28.1 g, 0.275 mol), and 5 mg potassium acetate. The flask was equipped with a sealed glass paddle stirrer, a nitrogen inlet tube and an insulated distillation head. The flask was purged with nitrogen gas, and the reaction mixture was heated over a 3 hour period on a woods metal bath, under a slow stream of nitrogen, with the reaction temperature being increased from 150° C. to 300° C. After three hours a vacuum was slowly applied for 25 min. The opaque melt was cooled to room temperature and the product (6HBA/4HNA-9PM) was broken from the flask and ground into a fine powder.

Example IV

A 100 mL 3-neck round bottom flask was charged with 4-acetoxybenzoic acid (19.8 g, 0.11 mol), 6-acetoxy-2-naphtoic acid (2.3 g, 0.01 mol), 2,6-diaceotynaphthalene (9.77 g, 0.04 mol), terephthalic acid (7.62 g, 0.046 mol), ethylene bis(4-acetoxyanilide) (18.85 g, 0.049 mol), PE-COOH (2.32 g, 6.3 mmol), and 4 mg potassium acetate. The flask was equipped with a sealed glass paddle stirrer, a nitrogen inlet tube and an insulated distillation head. The flask was purged with nitrogen gas, and the reaction mixture was heated over a 3 hour period on a woods metal bath, under a slow stream of nitrogen, with the reaction temperature being increased from 150° C. to 300° C. After three hours the temperature was increased to 250° C. over 30 minutes and a vacuum was slowly applied for 20 min. The opaque melt was cooled to room temperature and the product (6HBA/4HNA-9PM) was broken from the flask and ground into a fine powder.

Example V

A 100 mL 3-neck round bottom flask was charged with terephthalic acid (8.31 g, 0.05 mol), ethylene bis(4-hydroxybenzoate) (13.33 g, 0.044 mol), 4-acetoxyphenylethynyl (2.77 g, 0.012 mol), and 4 mg potassium acetate. The flask was equipped with a sealed glass paddle stirrer, a nitrogen inlet tube and an insulated distillation head. The flask was purged with nitrogen gas, and the reaction mixture was heated over a 3 hour period on a woods metal bath, under a slow stream of nitrogen, with the reaction temperature being increased from 150° C. to 260° C. After three hours the temperature was increased to 310° C. over 30 minutes and a vacuum was slowly applied for 15 min. The opaque melt solidified and was cooled to room temperature. The product (6HBA/4HNA-9PM) was broken from the flask and ground into a fine powder.

Example VI

A 100 mL 3-neck round bottom flask was charged with 6-acetoxy-2-naphtoic acid (11.51 g, 0.05 mol), terephthalic acid (2.77 g, 0.017 mol), 4-acetoxyacetanilide (3.22 g, 0.017 mol), PE-COOH (0.49 g, 1.3 mmol), PE-OAc (0.5 g, 1.3 mmol) and 3 mg potassium acetate. The flask was equipped with a sealed glass paddle stirrer, a nitrogen inlet tube and an insulated distillation head. The flask was purged with nitrogen gas, and the reaction mixture was heated over a 3 hour period on a woods metal bath, under a slow stream of nitrogen, with the reaction temperature being increased from 150° C. to 300° C. After three hours a vacuum was slowly applied for 25 min. The opaque melt was cooled to room temperature and the product (6HBA/2TA/2AP-9PE) was broken from the flask and ground into a fine powder.

Example VII

A 100 mL 3-neck round bottom flask was charged with terephthalic acid (7.62 g, 0.046 mol), ethylene bis(4-acetoxyanilide) (18.85 g, 0.049 mol), PE-COOH (2.32 g, 6.3 mmol), and 4 mg potassium acetate. The flask was equipped with a sealed glass paddle stirrer, a nitrogen inlet tube and an insulated distillation head. The flask was purged with nitrogen gas, and the reaction mixture was heated over a 3 hour period on a woods metal bath, under a slow stream of nitrogen, with the reaction temperature being increased from 150° C. to 300° C. At this point the temperature was increased to 310° C. over 30 minutes and a vacuum was slowly applied for 15 min. The opaque melt solidified and was cooled to room temperature. The product (50TA/50EAA-9PE) was broken from the flask and ground into a fine powder.

Example VIII

A 100 mL 3-neck round bottom flask was charged with 4-acetoxybenzoic acid (10.81 g, 0.06 mol), N-(3-acetoxynaphthyl)trimellitimide (11.33 g, 0.4 mol), PE-COOH (0.58 g, 1.6 mmol), PE-OAc (0.61 g, 1.6 mmol) and 2 mg potassium acetate. The flask was equipped with a sealed glass paddle stirrer, a nitrogen inlet tube and an insulated distillation head. The flask was purged with nitrogen gas, and the reaction mixture was heated over an 3 hour period on a woods metal bath, under a slow stream of nitrogen, with the reaction temperature being increased from 150° C. to 300° C. At this point the temperature was increased to 310° C. and a vacuum was slowly applied for 20 min. The opaque melt was cooled to room temperature and the product (6HBA/4IM-9PE) was broken from the flask and ground into a fine powder.

Characterization of End-Capped Liquid Crystal Oligomers

The end-capped liquid crystal oligomers were characterized using melt rheology, thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). All results are summarized in Tables 2 and 3.

### TABLE 2

<table>
<thead>
<tr>
<th>Example</th>
<th>Name</th>
<th>Phase Behavior at 250° C.</th>
<th>Phase type after 1 h. hold at 370° C.</th>
<th>(γ(P) at 100 rad·s⁻¹·°C⁻¹) for 1 h.</th>
</tr>
</thead>
<tbody>
<tr>
<td>6HBA/4HNA</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>(1E5-9E5)250</td>
</tr>
<tr>
<td>6HBA/4HNA-1PE</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>(2E4-5E5)250</td>
</tr>
<tr>
<td>6HBA/4HNA-5PE</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>(3-10)-250</td>
</tr>
<tr>
<td>6HBA/4HNA-9PE</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>(2-25)250</td>
</tr>
<tr>
<td>6HBA/4HNA-13PE</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>(4E4-1E5)250</td>
</tr>
</tbody>
</table>
TABLE 2-continued

Optical microscopy and melt rheology results.

<table>
<thead>
<tr>
<th>Example</th>
<th>Name</th>
<th>Phase Behavior at 250° C.</th>
<th>Phase type after 1 h. hold at 370° C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>6HBA/4HNA-9NOR</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>III</td>
<td>6HBA/4HNA-9PM</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>IV</td>
<td>5HBA/2O/SA/2IA/2ND-9PE</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>V</td>
<td>50TA/100HEB-5PE</td>
<td>N</td>
<td>I</td>
</tr>
<tr>
<td>VI</td>
<td>6HNA/2TA/1AP-9PE</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>VII</td>
<td>50TA/50EA-9PE</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>VIII</td>
<td>6HBA/4IM-9PE</td>
<td>N</td>
<td>N</td>
</tr>
</tbody>
</table>

N = nematic
I = isotropic

TABLE 3

Thermal properties of the LC oligomers.

<table>
<thead>
<tr>
<th>Example</th>
<th>Name</th>
<th>5% wt. loss in N₂ (°C.)</th>
<th>5% wt. loss in air (°C.)</th>
<th>Tg (°C.) Heat 1</th>
<th>Tm (°C.) Heat 1</th>
<th>Tg (°C.) Heat 2</th>
<th>Tm (°C.) Heat 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>6HBA/4HNA</td>
<td>414</td>
<td>401</td>
<td>91</td>
<td>—</td>
<td>91</td>
<td>—</td>
</tr>
<tr>
<td>II</td>
<td>6HBA/4HNA-1PE</td>
<td>431</td>
<td>411</td>
<td>100</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>II</td>
<td>6HBA/4HNA-3PE</td>
<td>438</td>
<td>454</td>
<td>85</td>
<td>—</td>
<td>84</td>
<td>—</td>
</tr>
<tr>
<td>II</td>
<td>6HBA/4HNA-9PE</td>
<td>454</td>
<td>440</td>
<td>80</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>II</td>
<td>6HBA/4HNA-13PE</td>
<td>409</td>
<td>393</td>
<td>—</td>
<td>245</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>III</td>
<td>6HBA/4HNA-9NOR</td>
<td>433</td>
<td>401</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>IV</td>
<td>6HBA/4HNA-9PM</td>
<td>394</td>
<td>361</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>V</td>
<td>5HBA/2O/SA/2IA/2ND-9PE</td>
<td>438</td>
<td>400</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>VI</td>
<td>50TA/50EA-9PE</td>
<td>368</td>
<td>333</td>
<td>56</td>
<td>185</td>
<td>65</td>
<td>—</td>
</tr>
<tr>
<td>VII</td>
<td>50TA/50EA-9PE</td>
<td>427</td>
<td>400</td>
<td>—</td>
<td>—</td>
<td>139</td>
<td>—</td>
</tr>
<tr>
<td>VIII</td>
<td>6HBA/4IM-9PE</td>
<td>385</td>
<td>408</td>
<td>138</td>
<td>317</td>
<td>210</td>
<td>204</td>
</tr>
</tbody>
</table>

Note: The heating rate for TGA experiments was 2.5° C. min⁻¹ and a heating rate of 10° C. min⁻¹ was used for the DSC experiments. The TGA samples were cured at 350° C. for 1 h. prior to the measurement. The DSC samples were heated to 350° C. and held for 1 h. prior to the second heat.

TABLE 4

Film tensile test results at room temperature

<table>
<thead>
<tr>
<th>THBA/3HNA-9PE</th>
<th>Strain at break (%)</th>
<th>Modulus (GPa)</th>
<th>Yield stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>2.635</td>
<td>2.700</td>
<td>55.187</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>0.088</td>
<td>0.144</td>
<td>2.760</td>
</tr>
</tbody>
</table>

TABLE 5

Film 3-point bending test results (ASTM D790) at room temperature

<table>
<thead>
<tr>
<th>THBA/3HNA-9PE</th>
<th>Strain at peak (%)</th>
<th>Modulus (GPa)</th>
<th>Max stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>3.215</td>
<td>3.925</td>
<td>91.3</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>0.757</td>
<td>0.409</td>
<td>10.0</td>
</tr>
</tbody>
</table>
Example IX (Composite Laminate Film)

One ply of KAPTON® film was placed on a metal plate and 25 grams of (6HBA/4HNA-9PE) was spread evenly on top of the KAPTON® film. Four plies of plain weave IM-7 graphite cloth was placed above the powder, followed by two plies of 0.0025" THFLO® bleed/breather cloth. FIG. 8 is a composites laminate lay-up configuration of the end-capped liquid crystal oligomers. The entire lay-up was contained in a metal dam and was vacuum bagged utilizing a standard vacuum bagging process for high temperature polyimides. The (6HBA/4HNA-9PE)/IM-7 cloth was heated to 482° F. with 5" Hg of vacuum and held for one hour. During the hour hold, the viscosity of the resin increased and was forced up through the plain weave cloth via the 5" Hg of vacuum. After 60 minutes at 482° F., the vacuum was increased to 20" Hg and the temperature was ramped to the final cure temperature of 700° F. As the temperature reached 600° F., full vacuum was applied (30" Hg) to allow increased consolidation pressure and to ensure resin infusion into the IM-7 fibers. When the final hold temperature was reached (700° F.) the part was held for 30 minutes to allow the reactive end groups (PE) to react and then the laminate was cooled to ambient temperature while maintaining full vacuum. At ambient temperature, the mold was removed from the vacuum bag and the laminate was removed from the metal dam. FIG. 9 is schematic of the cure cycle for the melt processing of 6HBA/4HNA-5PE into laminate graphite cloth ((6HBA/4HNA-5PE)/IM-7). Upon visual and ultrasonic examination, the laminate was determined to be of good quality. This result indicates that the low zero shear melt-viscosity of the thermotropic LC precursors leads to excellent wet-out of the carbon fiber reinforcement.

Example X (RESIN PLAQUE)

6HBA/4HNA-9PE) was fabricated into a neat resin plaque by the process shown in FIG. 10. The neat resin plaques were fabricated in order to test mechanical properties such as; K1C (opening mode fracture toughness), flexure strength and modulus, and compressive strength and modulus. A conceptual drawing of the mold that was used to fabricate the neat resin plaques is depicted in FIG. 11. The mold was 3.5" x 3.5" and was restricted to a maximum height of 0.5". The height was restricted by placing steel spacers in the mold to ensure the final dimensions of the plaque were at least 3" x 3" x 0.5". Two steel spacers with dimension, 1.5" x 0.25" x 0.5", were placed in the mold. A piece of KAPTON® film was placed into the base of the mold and onto the film was poured 100 grams of (6HBA/4HNA-9PE). This material was compacted in a hydraulic press and another piece of KAPTON® film and the steel plunger were inserted into the mold. The entire mold was placed in a vacuum hydraulic press. The (6HBA/4HNA-9PE) was heated to 572° F. with no pressure or vacuum and held for 30 min. During this hold, the (6HBA/4HNA-9PE) began to react which was evident by a increase in viscosity and the production of acetic acid. After 30 min. at 572° F., the temperature was increased to 608° F. and 30" Hg of vacuum was applied. The polymer was held at 608° F. for 30 min. and the temperature was increased to its final hold temperature of 675° F. As the temperature approached 675° F., pressure (100 psi) was applied. The plaque was held at 675° F. for 1 hr. and was cooled to room temperature under full vacuum and pressure. The plaque was removed from the mold and visual inspection indicated a well consolidated neat resin plaque with a density of 0.86 g/cm³.

Example XI (Foam Structure)

A foamed structure was fabricated using (6HBA/4HNA-9PE) that was not fully polymerized. The process was the same as described in Example X. During the high temperature vacuum step the released acetic acid acts as a blowing agent and a plaque was obtained that has a well defined porous density (0.43 g/cm³) and shows good mechanical properties.

Example XII (Adhesive Resin)

To test adhesive bonding, an adhesive scrim cloth was saturated with molten (6HBA/4HNA-9PE) at 280° C. The resulting cloth contained 28 wt % resin and was placed between two titanium coupons to form a lap joint with a surface area of 2.34x1.27 cm (1x0.5 inch). The titanium coupons were sand blasted, treated with Pasa-Gel 107, washed, and dried prior to use. The lap joints were bonded in a heated press for 1 h. at 350° C. and 15 psi. The resulting bonded lap joints were tested at room temperature according to ASTM D 1002. The results are summarized in Table 6.

TABLE 6

<table>
<thead>
<tr>
<th>Sample set</th>
<th>Bond Press (MPa)</th>
<th>Bondline overlap (mils)</th>
<th>Area of overlap (inch²)</th>
<th>Length of overlap (inch)</th>
<th>Shear Str. (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1 (15)</td>
<td>28 (1.1)</td>
<td>0.5</td>
<td>0.5</td>
<td>1998</td>
</tr>
<tr>
<td>2</td>
<td>0.1 (15)</td>
<td>20 (0.8)</td>
<td>0.5</td>
<td>0.5</td>
<td>1863</td>
</tr>
</tbody>
</table>

We claim:

1. An oligomer mixture with self-reactive end-caps comprising the general structure:

2. wherein Z is a liquid crystal backbone of the oligomer mixture selected from the group consisting of an ester, an ester-imide and an ester-amide, the liquid crystal backbone of the oligomer mixture being entirely aromatic in composition, wherein E and E' are selected from the group consisting of:  

![Chemical Structure]
wherein X is selected from the group consisting of hydrogen, alkyl groups containing six or less carbon atoms, aryl groups containing less than ten carbon atoms, lower alkoxy groups containing six or less carbons, lower arylxy groups containing ten or less carbon atoms, fluorine, chlorine, bromine, and iodine.

2. An oligomer mixture with self-reactive end-caps as claimed in claim 1, wherein Z is an entirely aromatic liquid crystal backbone of the oligomer mixture having at least one structural repeat unit selected from the group consisting of

wherein Ar is selected from the group consisting of

wherein n is a number less than 500,

wherein E and E' are selected from the group consisting of

wherein R' is selected from the group consisting of hydrogen, alkyl groups containing six or less carbon atoms, aryl groups containing less than ten carbon atoms, lower alkoxy groups containing six or less carbons, lower arylxy groups containing ten or less carbon atoms, fluorine, chlorine, bromine, and iodine.
and wherein \( R' \) is selected from the group consisting of hydrogen, alkyl groups containing six or less carbon atoms, aryl groups containing less than ten carbon atoms, lower alkoxy groups containing six or less carbons, lower aryloxy groups containing ten or less carbon atoms, fluorine, chlorine, bromine, and iodine.

3. A polymer product comprising an oligomer mixture with self-reactive end-caps according to claim 2 wherein said product is prepared by a process selected from the group consisting of melt processing, molding, fiber spinning, reactive injection molding, resin transfer molding, resin film injecting, powder molding, injection molding, blow molding, thermo-forming, plasma spraying, and pultrusion molding.

4. The polymer product of claim 3 wherein said product is in the form from the group consisting of a fibre, filament, coating, film, lining, tube, pipe, sheath, sheet, and panel.

5. An oligomer mixture with self-reactive end-caps as claimed in claim 2, wherein \( E \) and \( E' \) are identical.

6. An oligomer mixture with self-reactive end-caps as claimed in claim 2, wherein the molecular weight range of the oligomers is between approximately 1000 and approximately 15,000 grams per mole.

7. An oligomer mixture with self-reactive end-caps as claimed in claim 2, wherein the melt viscosity of the oligomer mixtures is between approximately 1 and approximately 250 poise at approximately 200° C. to approximately 350° C.