EFFECTS OF MULTIFUNCTIONAL CROSSLINKING AGENTS ON THE THERMOMECHANICAL PROPERTIES OF POLYIMIDE FILMS

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ABSTRACT

Three new polyfunctional amines were synthesized. Polyimide films containing varying amounts of the amine crosslinking agents were prepared. Their thermomechanical properties were compared with those of control film samples prepared from difunctional amines. The effect of crosslink density on isothermal weight loss, polymer softening, and glass transition temperature is discussed.
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INTRODUCTION

One of the potential applications of high temperature resistant polymers is their use as matrix resins in fiber-reinforced composites for turbojet engine components such as blades and vanes. However, the potential of high temperature resistant polymers such as polyimides (PI) and polyphenylquinoxalines (PPQ) as matrix resins in fiber-reinforced composites has not been fully realized to date. One of the problems associated with these resins is that they exhibit creep, or thermoplastic yielding under load at temperatures approaching 316°C (600°F). A commonly used method to reduce or eliminate thermoplastic behavior is to induce crosslinking into the polymer structure by post-curing the composites at temperatures up to 454°C (850°F). However, such inordinately high post-cure temperatures significantly reduce the long-term thermo-oxidative stability of the polymer by initiating reactive sites for degradation (Ref. 1). A more desirable approach for introducing cross-links is by means of chemical reactions having lower activation energies that would reduce the post-cure temperature or time. One such approach was developed by investigators at the Systems Group of TRW, Inc., using low molecular weight amide acid prepolymer end-capped with norbornene rings (Refs. 2-3). The cure proceeds by a complex set of reactions involving chain extension and some degree of crosslinking. Subsequent studies in our laboratory led to an improved method for preparing addition-cured polyimides (Refs. 4-5). In this approach in situ Polymerization of Monomer Reactants (PMR) occurs on the surface of the reinforcing fibers.

The purpose of this investigation was to further reduce thermoplastic behavior of polyimide resins by substituting a controlled amount of the diamine monomer with crosslinking agents having a higher amine functionality. The knowledge gained from a study of the thermomechanical properties of the crosslinked resins would then be used in the fabrication of fiber-reinforced polyimide composites.

This report describes the synthesis and characterization of three new polyfunctional amines. Polyimide films containing varying amounts of the crosslinking agents were prepared, and their properties compared with those of control samples prepared with difunctional amines. The effect of crosslink density on isothermal weight loss, polymer softening, and glass transition temperatures is discussed.

RESULTS AND DISCUSSION

Monomers

The monomers and crosslinking agents used in the preparation of polyimide films are shown in Fig. 1. The two dihydrides, 3,3', 4,4'-benzophenonetetra-carboxylic dianhydride (BTDA) and pyromellitic dianhydride (PMDA) were recrystallized from acetone. 4,4'-Methylenedianiline (MDA) was recrystallized from 2-propanol.

2,2', 3,3'-Tetra(p-aminophenyl)-6,6'-diquinoxaline (TABQ) was synthesized by the following method: two moles of 4,4'-diacetamidobenzil (Ref. 6)
was condensed with one mole of 3,3'-diaminobenzidine in refluxing glacial acetic acid to yield the tetraacetyl derivative of TABQ, m.p. 344-349°C. This material was hydrolyzed with conc. HCl on the steam bath. The cooled mixture was diluted with water and made basic with conc. NH₄OH. After isolation and drying, the crude material was crystallized from DMF/EtOH to give pure TABQ in 89% yield, m.p. > 360°C. Anal. - Calcd. for C₄₀H₃₀N₈: C,77.15%; H,4.86%; N,18.00%. Found: C,77.42%; H,4.47%; N,17.86%.

6,6'-Bis [2,3-di(p-aminophenyl) quinoxalyl] ketone (TABK) was synthesized by a reaction sequence analogous to that used for TABQ, with 3,3',4,4'-tetraaminobenzophenone as the tetraamine component. The intermediate tetraacetyl derivative of TABK, m.p. 231.5-233.5°C, was hydrolyzed as before. Crystallization from DMF/EtOH gave an 81% yield of pure TABK, m.p. 281-283°C. Anal. - Calcd. for C₄₁H₃₃N₈O: C,75.67%; H,4.65%; N,17.22%. Found: C,75.99%; H,4.35%; N,17.01%.

3,3',5-Triaminobenzophenone (TABP) was prepared by hydrogenation of 3,3',5-trinitrobenzophenone (Ref. 7) in a Parr apparatus with Raney nickel in EtOAc at a pressure of 40-50 psi. Crystallization from water gave a 75% yield of pure TABP, m.p. 130-131.5°C. Anal. - Calcd. for C₁₃H₁₃N₃O: C,68.70%; H,5.77%; N,18.49%. Found: C,68.81%; H,5.46%; N,18.11%.

Polymer Synthesis

Two polyimides, used as control samples in this investigation, were prepared from MDA/BTDE and MDA/PMDA in a 1:1 stoichiometric ratio. The two step method of Sroog, et.al. (Ref. 8) was used. In the first step, a polyamide acid solution in dry N,N-dimethylacetamide (DMAc) was prepared under a nitrogen blanket. The solution was cast onto a glass plate, and the resulting thin film partially dried at 80°C under nitrogen for 0.5 hr. In the second step, the film was converted to the polyimide by heating to 300°C at a rate of 10°C/minute, then holding the film at 300°C for 1 hour.

In the preparation of polyamide acid solutions, the order of addition of the reactants is important. The preferred method for achieving high molecular weights is a gradual addition of the solid dianhydride to a solution of the diamine in DMAc calculated to give a total solids loading of 10-15% (Ref. 9). However, in the synthesis of polyamide acid solutions where the multifunctional amine crosslinking agents were partially substituted for the difunctional amine MDA, the order of addition had to be changed to obtain stable solutions. If the dianhydride was added to a solution of a mixture of MDA and the crosslinking agent, gelation occurred within 10-15 minutes, even at solids concentrations as low as 5%. Similar results were obtained upon addition of a mixture of MDA and the crosslinking agent to a slurry of the dianhydride in DMAc. Stable polyamide acid solutions were obtained by the following method: solid dianhydride was added during 5 minutes to a solution of MDA in DMAc. The solution was stirred for 2 hr. at temperatures up to 50°C. The crosslinking agent was added, and the mixture stirred for an additional 2 hours. In this manner 12 different polyamide acid solutions containing up to 20 mole% of the multifunctional amines were prepared. As the proportion of the crosslinking agent was increased, the solids content had to be decreased to a value of 4% in some cases. At crosslinking agent concentrations much above 20 mole%, gel formation became a serious problem even at very low solids concentrations, and synthesis of the polyamide acids was impractical.

Thermomechanical Properties of Polyimide Films

The thermo-oxidative stability of polyimide films was determined by isothermal exposure at 316°C (600°F) in a forced draft oven with an air change rate of 100 cm³/min. The film weight loss after 600 hours for the various
polyimides is summarized in Table I. Film samples 1-9 are prepared from the
dianhydride BTDA. Comparison of samples 2-4 (containing the tetraamine TABK)
with the control sample 1 shows that the weight loss of the films decreases
as the molar ratio of TABK is increased. A similar trend is apparent for
tetraamine TABQ (samples 5-7) and triamine TABP (samples 8-9). The improved
thermo-oxidative stability could perhaps be attributed to crosslinking or to
reaction with the ketone carbonyl groups. On the other hand, in the series
of film samples 10-14, made from the dianhydride PMDA, the opposite trend
prevails. As the molar ratio of the tetraamines is increased, the film
weight loss increases as well. While increasing crosslink density should
promote a higher thermo-oxidative stability, the decreasing content of the
rigid PMDA units apparently is sufficient to counteract the benefits of in-
creased crosslink density and to cause an overall increase in film weight
loss.

Compression properties of the polyimide films such as softening and
penetration under load were determined with a DuPont 942 Thermomechanical
Analyzer (TMA) using a penetration probe. The TMA runs were conducted on
4 x 4 mm film samples, 0.0254-0.0508 mm (1-2 mils) thick, at a heating
rate of 10°C/min. under a load of 10 g. The sensitivity of the probe dis-
placement was 4.6x10^-4 cm/cm of chart paper. Figure 2 shows the TMA curves
for the linear MDA/BTDA polyimide (sample 1) and two polyimides containing
various mole fractions of the tetraamine TABK (samples 3 and 4). As the
temperature is increased, all curves show an initial upward displacement of
the probe due to thermal expansion of the films. The temperature at which
the probe has reached its maximum upward deflection on the ordinate scale
is arbitrarily defined as the onset of penetration temperature. This tem-
perature of course depends on variables such as film thickness, heating rate
and applied load. However, since all TMA runs were performed under identical
conditions, this permits one to make at least qualitative comparisons of film
softening and creep characteristics. It is seen in Fig. 2 that the onset of
penetration temperature increases from 275°C for the MDA/BTDA film (sam-
ple 1) to 295°C for sample 3 (containing 8 mole% of TABK) and to 307°C
for sample 4 (containing 16 mole% of TABK). The glass transition tempera-
tures (Tg) correspond to the point where the penetration curve exhibits a
change of slope. The Tg values were determined from a separate first de-
rivative plot of the TMA curve, where the second derivative is zero. Com-
pared with a value of 300°C for sample 1, the Tg also increased signifi-
cantly with increasing crosslink density: to 327°C for sample 3, and to 342°C
for sample 4.

Figure 3 shows the TMA curves for the control sample 10 (MDA/PMDA film),
sample 11 (containing 8 mole% TABK), and sample 12 (containing 16 mole%
TABK). Here the onset of penetration temperature increases even more dra-
matically than in the MDA/BTDA polymer series, from 285°C in the control sam-
ple to 385°C in sample 12. While sample 10 exhibits a discrete Tg value
of 362°C, the Tg values of the crosslinked film samples 11 and 12 were not
observed in the temperature range investigated. It should be noted that none
of the film samples used in the TMA studies were subjected to an elevated
temperature post-cure. It can also be seen in Figs. 2 and 3 that the depth
of penetration decreases as the crosslink density of the film samples is in-
creased.

Table II summarizes the onset of penetration temperatures and Tg values
for all polyimide films investigated. It can be seen that in the series
based on the MDA/BTDA polyimide a significant increase of both Tg and onset
of penetration is obtained with increasing crosslink density, although films
with a low tetraamine content (samples 2 and 5) exhibited only a small Tg
increase (5°C) compared with control sample 1. Film samples 8 and 9, con-
taining the triamine TABP, exhibited considerably lower Tg values compared to
the films containing the tetraamines TABK and TABQ with a comparable mole percent of MDA.

In the MDA/PMDA polymer series, films prepared using the tetraamine TABQ (samples 13 and 14) showed a very pronounced increase in the onset of penetration temperature with increasing tetraamine content, up to 435°C for sample 14.

In summary, this investigation has shown that substitution of polyfunctional amines into the polyimide structure significantly decreases thermoplasticity without subjecting the polymers to an elevated temperature post-cure. These polyfunctional amines are currently being investigated as crosslinking agents in graphite fiber/PMR polyimide composites.

CONCLUSIONS

The results of this investigation show that the use of tetrafunctional amines for introducing crosslinks into the BTDA/MDA polyimide structure resulted in a significantly higher thermo-oxidative stability. Substitution of tetraamines in the PMDA/MDA polyimide had an adverse effect on the polymer thermo-oxidative stability. The substitution of tri- and tetra-functional amines into the polymer molecular structure significantly increased the polyimide softening temperature and glass transition temperature. The increases were obtained without subjecting the polymers to an elevated temperature post-cure. This suggests that incorporation of the tetrafunctional crosslinking agents in the polyimide matrix of graphite fiber-reinforced composites would significantly increase the creep resistance of the composites without the need for long-time elevated temperature postcure schedules.

REFERENCES

TABLE I. - PERCENT WEIGHT LOSS OF POLYIMIDE FILMS

<table>
<thead>
<tr>
<th>Film sample</th>
<th>Monomer stoichiometry</th>
<th>Percent weight loss after 600 hr at 316° C (600° F)\textsuperscript{a}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00 MDA/1.00 BTDA</td>
<td>17.1</td>
</tr>
<tr>
<td>2</td>
<td>0.92 MDA/0.04 TABK/1.00 BTDA</td>
<td>17.0</td>
</tr>
<tr>
<td>3</td>
<td>0.84 MDA/0.08 TABK/1.00 BTDA</td>
<td>13.6</td>
</tr>
<tr>
<td>4</td>
<td>0.68 MDA/0.16 TABK/1.00 BTDA</td>
<td>10.6</td>
</tr>
<tr>
<td>5</td>
<td>0.92 MDA/0.04 TABQ/1.00 BTDA</td>
<td>16.5</td>
</tr>
<tr>
<td>6</td>
<td>0.84 MDA/0.08 TABQ/1.00 BTDA</td>
<td>12.5</td>
</tr>
<tr>
<td>7</td>
<td>0.68 MDA/0.16 TABQ/1.00 BTDA</td>
<td>11.9</td>
</tr>
<tr>
<td>8</td>
<td>0.85 MDA/0.10 TABP/1.00 BTDA</td>
<td>13.7</td>
</tr>
<tr>
<td>9</td>
<td>0.70 MDA/0.20 TABP/1.00 BTDA</td>
<td>11.2</td>
</tr>
<tr>
<td>10</td>
<td>1.00 MDA/1.00 PMDA</td>
<td>15.0</td>
</tr>
<tr>
<td>11</td>
<td>0.84 MDA/0.08 TABK/1.00 PMDA</td>
<td>15.2</td>
</tr>
<tr>
<td>12</td>
<td>0.68 MDA/0.16 TABK/1.00 PMDA</td>
<td>19.8</td>
</tr>
<tr>
<td>13</td>
<td>0.84 MDA/0.08 TABQ/1.00 PMDA</td>
<td>16.8</td>
</tr>
<tr>
<td>14</td>
<td>0.68 MDA/0.16 TABQ/1.00 PMDA</td>
<td>20.0</td>
</tr>
</tbody>
</table>

\textsuperscript{a}In circulating air; flow rate 100 ml/min.

TABLE II. - THERMOMECHANICAL ANALYSIS OF POLYIMIDE FILMS\textsuperscript{a}

<table>
<thead>
<tr>
<th>Film sample</th>
<th>Monomer stoichiometry</th>
<th>Onset of penetration, °C</th>
<th>Tg, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00 MDA/1.00 BTDA</td>
<td>275</td>
<td>300</td>
</tr>
<tr>
<td>2</td>
<td>0.92 MDA/0.04 TABK/1.00 BTDA</td>
<td>275</td>
<td>305</td>
</tr>
<tr>
<td>3</td>
<td>0.84 MDA/0.08 TABK/1.00 BTDA</td>
<td>295</td>
<td>327</td>
</tr>
<tr>
<td>4</td>
<td>0.68 MDA/0.16 TABK/1.00 BTDA</td>
<td>307</td>
<td>342</td>
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<tr>
<td>5</td>
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<td>275</td>
<td>305</td>
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<td>321</td>
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<tr>
<td>7</td>
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<td>310</td>
<td>335</td>
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<td>8</td>
<td>0.85 MDA/0.10 TABP/1.00 BTDA</td>
<td>283</td>
<td>305</td>
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<tr>
<td>9</td>
<td>0.70 MDA/0.20 TABP/1.00 BTDA</td>
<td>297</td>
<td>317</td>
</tr>
<tr>
<td>10</td>
<td>1.00 MDA/1.00 PMDA</td>
<td>285</td>
<td>362</td>
</tr>
<tr>
<td>11</td>
<td>0.84 MDA/0.08 TABK/1.00 PMDA</td>
<td>315</td>
<td>&gt;450</td>
</tr>
<tr>
<td>12</td>
<td>0.68 MDA/0.16 TABK/1.00 PMDA</td>
<td>385</td>
<td>&gt;450</td>
</tr>
<tr>
<td>13</td>
<td>0.84 MDA/0.08 TABQ/1.00 PMDA</td>
<td>325</td>
<td>&gt;450</td>
</tr>
<tr>
<td>14</td>
<td>0.68 MDA/0.16 TABQ/1.00 PMDA</td>
<td>435</td>
<td>&gt;450</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Penetration probe; 10 g load; heating rate 10° C/min; sample size 4 x 4 mm.
Figure 1. - Monomers used for polyimide synthesis.

Figure 2. - Thermomechanical analysis of polyimide films. Penetration probe; 10g load; heating rate 10°C/min.; sample size 4x4 mm.

Figure 3. - Thermomechanical analysis of polyimide films. Penetration probe; 10g load; heating rate 10°C/min.; sample size 4x4 mm.