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Continuing research at Langley Research Center on the synthesis and development of new inexpensive flexible aromatic polyimides as adhesives has resulted in a material identified as LARC-F-SO₂ with similarities to polyimidesulfone, PISO₂, and other flexible backbone polyimides recently reported by Progar and St. Clair. Also prepared and evaluated was an endcapped version of PISO₂. These two polymers were compared with LARC-TPI and LARC-STPI, polyimides researched in our laboratory and reported in the literature.

The adhesive evaluation, primarily based on lap shear strength (LSS) tests, involved preparing adhesive tapes, conducting bonding studies and exposing lap shear specimens to 204°C air for up to 1000 hrs and to a 72-hour water boil. LSS tests at RT, 177°C and 204°C were performed before (controls) and after these exposures. The type of adhesive failure as well as the T_g was determined for the fractured specimens.

The results indicate that LARC-TPI provides the highest LSSs, 33 MPa at RT, 30 MPa at 177°C, and 26 MPa at 204°C. LARC-F-SO₂, LARC-TPI and LARC-STPI all retain their strengths after thermal exposure for 1000 hrs and PISO₂ retains greater than 80% of its control strengths.

Most of the four adhesive systems showed reduced strengths for all test temperatures although still retaining a high percentage of their original strength (> 60%) except for one case.

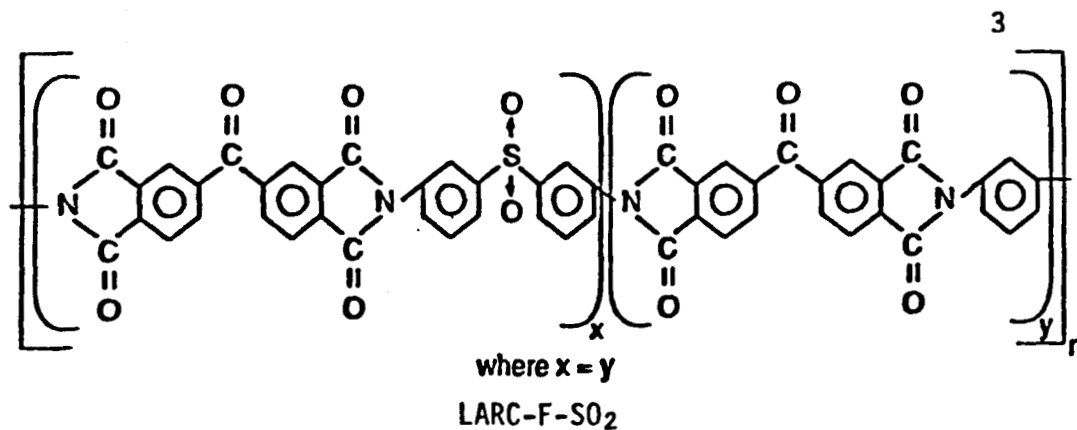
The predominant failure mode was cohesive with no significant change in the Tgs.

Although the LARC-F-SO₂ could not be prepared in diglyme alone as the solvent, the properties of the resulting adhesive were notable. The darkening of the adhesive during bonding was typical of systems which utilize amide solvents.

INTRODUCTION

During the past decade, considerable research at NASA Langley Research Center has been directed towards the synthesis of flexible aromatic polyimides.¹⁻⁷ Two notable polyimides that are now commercially available resulted from this work. They are LARC-TPI and polyimidesulfone (PISO₂).^{5,7} Both of these polyimides contain bridged aromatic diamines with meta catenation as described by Bell, et al.¹ Recently Progar and St. Clair reported on two flexible backbone copolyimides that were synthesized in an effort to develop a relatively inexpensive high temperature adhesive.^{6,8} These polymers contained the diamines 4,4'-diaminodiphenylether (commonly referred to as oxydianiline or ODA) and meta phenylenediamine (MPD). The combined use of these two compounds afforded adhesives with attractive properties. Research of a similar nature continues in our laboratory with the development of a new copolyimide with structural similarities to PISO₂. This material, designated as LARC-F-SO₂, is shown below.

This paper compares the novel LARC-F-SO₂ to its progenitors, PISO₂, LARC-STPI flexible copolyimide and LARC-TPI polymer.



EXPERIMENTAL

Materials and polymer synthesis

The experimental procedures for the synthesis of the polyimides, except for LARC-F-SO₂ and endcapped PISO₂, have been reported previously. The procedure for the synthesis of LARC-F-SO₂ involved the use of reagent grade monomers and solvents that are commercially available. The list of chemicals, abbreviations, their source and m.p. or b.p. follows: benzophenonetetracarboxylic acid dianhydride (BTDA), Allco Company, Pittsburg, KA, m.p. 224-226°C; meta-phenylenediamine (MPD), purissimus grade from Fluka Chemical Company, Hauppauge, NY, m.p. 61-63°C; 3,3'-diaminodiphenylsulfone (3,3'-DDSO₂), FIC Corporation, San Francisco, CA, m.p. 165-167°C; bis-2-methoxyethylether (diglyme), Fluka Chemical Company, b.p. 60-62°C; N,N-dimethylacetamide (DMAc), Fluka Chemical Company, b.p. 165-167°C.

The preparation of the polymers was carried out at room temperature in a 1000 ml cylindrical flask with a removable, four-neck top. Stirring of the mixture was accomplished using an impeller blade driven by a constant-torque, overhead motor equipped with a variable speed control.

The BTDA (16.273 g, 0.505 M) was slurried in 135 g of diglyme at ambient temperature ($\sim 20^{\circ}\text{C}$). Next the 3,3'-DDS O_2 (6.20 g, 0.0250 M) was added and the mixture was allowed to stir for approximately one hour. At this point the materials were all in solution as the 3,3'-DDS O_2 and the BTDA had reacted as evidenced by a slight increase in temperature. The MPD (2.704 g, 0.0250 M) was added to the reaction vessel, the polymerization reaction continued rapidly and a precipitation of the polyamide-acid copolymer occurred within 15 min. In order to redissolve the polymer, 55 g of DMAc was added and stirring continued overnight. The polymer redissolved and was used as a 11.6 wt% solid solution to prepare the adhesive scrim cloth and for priming. The inherent viscosity (η_{inh}) of the polymer, as determined at 0.5 wt% solids in DMAc at 35°C , was 0.724 dl/g.

The monomers used in the preparation of endcapped PISO $_2$ were BTDA, 3,3'-DDS O_2 , and phthalic anhydride (PA) obtained from Eastman Kodak Company, Rochester, NY, m.p. 131°C w/ 3°C range. The polymer was prepared as a 20 wt% solids solution in a mixed solvent of diglyme and tetrahydrofuran (THF). The THF was obtained from Aldrich Chemical Company, Inc., Milwaukee, Wisconsin, Gold label (99.9%), b.p. 67°C .

The BTDA (193.2 g, 0.6 M) and 3,3'-DDS O_2 (148.8 g, 0.6 M) were dissolved at ambient conditions in the diglyme/THF (1410 g/90 g) mixed solvent and stirred for 16 hours. Most of the solids, approximately 90 percent, dissolved initially with the rest of the BTDA dissolving over the remaining reaction time. The solution was amber-orange in color. The PA (1.2 g, 0.008 M) was dissolved in 8 ml of DMAc and added to the polyamic-acid solution. Some precipitation occurred initially but

cleared up within one minute. The inherent viscosity was determined to be 0.589 dl/g.

Characterization

Lap shear strength (LSS) was obtained according to ASTM D-1002 using a Model TT Instron Universal Testing Machine. The LSSs reported represent an average of four lap shear specimens per test condition except as noted in the tables. The range of LSSs is indicated by dashed lines in the bar graph figures and is listed in the tables. Elevated temperature tests were conducted in a clam-shell, quartz-lamp oven with temperatures controlled to within $\pm 3^\circ\text{C}$ for all tests. Specimens were held 10 min at temperature prior to testing except for the water-boil test specimens for which the tests were conducted as soon as the test temperature was reached (approximately 1-2 min).

Bondline thickness is defined as the difference between the total joint thickness measured with a micrometer and the sum of the adherend thicknesses. The average bondline thickness for the thermally aged and water-boil specimens was 0.025 cm for PISO₂, 0.015 cm for LARC-F-SO₂, 0.009 cm for LARC-TPI, and 0.017 cm for LARC-STPI.

Glass transition temperatures (T_g) of the adhesive from the fractured lap shear specimens were determined by thermomechanical analysis (TMA) on a DuPont 943 Analyzer.* TMAs were run on the fractured

*Use of trade names or company names does not constitute an official endorsement by NASA, either expressed or implied.

lap shear specimens in static air at a heating rate of 5°C/min using a hemispherical probe with a 15 g load.

Thermomechanical spectra of the polymers were obtained on a torsional braid analysis (TBA) system interfaced with an IBM PC. Individual glass braids were coated with a 11.6 wt% solids LARC-F-SO₂ polyamic acid solution and a 5 wt% solids PISO₂ solution and precured in air for one hour at each of three temperatures: 100°C, 200°C and 300°C. Tests were conducted by heating in a nitrogen atmosphere to 400°C at 3°C/min. T_g was determined as the extrapolated maximum peak height of the damping versus temperature curve.

Inherent viscosity was determined using a Cannon-Ubbelohde viscometer in a 35°C water bath controlled to within ± 0.01°C. A 10 ml solution of 0.5 wt% solids in N,N-dimethylacetamide (DMAc) was made and filtered. The average of three runs of the solution was reported.

Adhesive tape preparation

Adhesive tape for the PISO₂ was prepared by brush coating a primer solution of polyamic-acid, diluted to approximately 5 wt% solids in diglyme/THF, onto 112 E-glass cloth with A-1100 finish (γ-aminopropylsilane). The glass cloth had been tightly mounted on a metal frame and dried in a forced-air oven for 30 min at 100°C prior to coating. The 0.01 cm thick glass cloth served as a carrier for the adhesive as well as for bondline control and an escape channel for solvent. The coated cloth was then air-dried for 1 hr at ambient temperature and heated for 1 hr at each of three temperatures: 100°C, 150°C and 175°C. Subsequently, each

application of a 20 wt% solids solution, η_{inh} 0.589 dl/g, was brush coated onto the cloth and exposed to the following schedule until a thickness of 0.025 - 0.027 cm was obtained:

- (1) Room temperature (RT), held 1 hr
- (2) RT \rightarrow 100°C, held 1 hr
- (3) 100°C \rightarrow 150°C, held 1 hr
- (4) 150°C \rightarrow 175°C, held 1 hr

Adhesive tape for LARC-F-SO₂ was prepared in a similar manner in an attempt to standardize the tape preparations. An approximately 5 wt% solids solution of polyamic-acid in diglyme/DMAc was used to prime coat the oven-dried glass cloth. The prime coated cloth was air-dried for 1 hr at ambient temperature and heated for 1 hr at each of three temperatures: 100°C, 150°C and 175°C. Subsequently, after each application of an 11.6 wt% solids solution onto the cloth, the tape was exposed to the following schedule until a thickness of 0.018 - 0.023 cm was obtained:

- (1) RT, held 1 hr
- (2) RT \rightarrow 100°C, held 1 hr
- (3) 100°C \rightarrow 150°C, held 2 hrs
- (4) 150°C \rightarrow 175°C, held 3 hrs

The involved procedure to prepare the tapes was necessary to drive-off solvent and reaction product volatiles when converting the polyamic-acid resin to the polyimide. Imidization of polyamic-acids to polyimides generally occurs above 160°C with the degree of conversion being a function of time and temperature.

Adhesive bonding

The prepared adhesive tapes were used to bond titanium alloy adherends (Ti-6Al-4V, per Mil-T-9046E, Type III Comp. C) with a nominal thickness of 0.13 cm. The Ti-6Al-4V panels were grit blasted with 120 grit aluminum oxide, washed with methanol, and treated with Pasa Jell 107* to form a stable oxide on the surface. The adherends were washed with water and dried in a forced-air oven at 100°C for 5 min. The treated adherends were primed within two hours of the surface treatment by applying a thin coat of the polyamic-acid solution of the respective adhesive on the surfaces to be bonded. After air drying in a forced-air oven for 30 min, they were heated for 15 min at 100°C and 15 min at 150°C. The primed adherends were placed in a polyethylene bag and stored in a desiccator until needed. Lap shear specimens were prepared by inserting the adhesive tape between the primed adherends using a 1.27 cm overlap (ASTM D-1002) and applying 2.07 MPa pressure in a hydraulic press during the heating schedule. Bonding temperature was monitored using a type K thermocouple spot-welded to the titanium adherend at the edge of the bondline.

Several bonding cycles for the LARC-F-SO₂ adhesive were investigated during this study to determine a bonding process which produced good strengths. The cycle selected was as follows:

*Trade name for a titanium surface treatment available from Semco, Glendale, CA.

- (1) 2.07 MPa pressure, heating rate $\approx 8.2^{\circ}\text{C}/\text{min}$, RT \rightarrow 343°C
- (2) Held 1 hr at 343°C
- (3) Cool under pressure to $\approx 150^{\circ}\text{C}$ and remove from bonding press

Past experience with these types of thermoplastic polyimides had shown a beneficial affect when heating the adhesive tape to higher temperatures for a period of time.⁹ The adhesive tape heat treatment selected was that which gave the best lap shear strengths and involved an additional heat treatment of 1 hr each at 200°C , 225°C and 250°C . The color of the tape changed from a straw yellow to amber. The heat treated LARC-F-SO₂ adhesive tape which was stiff and boardy was used to prepare lap shear specimens for thermal exposure and water boil tests. LSS tests were conducted at RT, 177°C and 204°C .

A similar procedure was used to determine the best heat treatment for the PISO₂ adhesive tape. The same bonding cycle that was used for LARC-F-SO₂ was used for PISO₂. The heat treatment chosen for the PISO₂ included additional heating for 1 hr at each temperature from 200°C to 275°C in 25°C increments. Some foaming of the tape resulted due to the heat treatment and the adhesive was stiff and boardy with no tack or drape. Specimens were prepared with this tape for thermal exposure and water boil.

Thermal exposures at 204°C for 500 hrs and 1000 hrs were performed in a forced-air oven controlled within $\pm 2^{\circ}\text{C}$. Lap shear tests were conducted at RT, 177°C and 204°C before (controls) and after thermal exposure.

In order to determine the effects of humidity (moisture) on an adhesive, a 72-hr water boil was conducted in laboratory glassware

containing distilled boiling water. The bonded area of the lap shear specimens was immersed during a 72-hr period. LSSs were subsequently determined at RT, 177°C and 204°C.

These two adhesive systems, LARC-F-SO₂ and PSIO₂ were compared with results previously reported for LARC-TPI and LARC-STPI.¹⁰

RESULTS AND DISCUSSION

Resin chemistry

The proposed general reaction scheme for the formation of the polyimide polymers to be evaluated is shown in Figure 1. A discussion of the reactions to form LARC-F-SO₂ and PISO₂, in this case a PA endcapped version, is given since the reaction scheme of LARC-TPI and the random copolymer, LARC-STPI, is reported in the literature.^{5,10}

The structure of LARC-F-SO₂ formed from the monomer BTDA, 3,3'-DDSO₂ and MPD is shown in Figure 2. The copolymer contains bridged, aromatic diamines with meta catenation. Meta-oriented diamines were shown to have improved processability and improved adhesive strength when compared to para-oriented diamines.⁷ The meta linkages, as in both amine-derived moieties, should introduce thermoplasticity because of the inherent flexibility of these units of the polymer chain. The use of mixed solvents, as in the preparation of LARC-F-SO₂, is not preferred. Data from our laboratory has shown that the use of diglyme is preferred over amide solvents such as DMAc.⁴ However, in the present study the use of a mixed solvent system was necessitated by the insolubility of the

polyamic acid of LARC-F-SO₂ in diglyme. We feel that the ultimate adhesive properties of this copolymer are lower than would be expected if only diglyme were the solvent. Some of the darkening of the adhesive during bonding might be attributable to the presence of DMAc since this phenomenon was noted in adhesives reported in reference 4.

The structure of PISO₂ formed from BTDA and 3,3'-DDS₂ with PA end caps is shown in Figure 2. The formation of PISO₂ without end capping had been discussed in references 7 and 9. The purpose of endcapping this polymer was to control the molecular weight of the polymer chains allowing greater flow during processing and to prevent chain extension during cure which creates volatiles and foaming. Again, the meta-oriented diamine, 3,3'-DDS₂, allows flexibility in the polymer chain and is partially responsible for some of the thermoplasticity of the polymer.

Also shown in Figure 2 are the structures of LARC-TPI and LARC-STPI.

LSS and durability comparison

Test results from this study for LARC-F-SO₂ and PISO₂ are compared with data reported for PISO₂ in Table I and Figure 3. Figure 3 shows the LSSs for non-exposed specimens for tests conducted at RT, 177°C, 204°C and 232°C where Table 1 includes processing information and thermal aging data. LARC-F-SO₂ and PISO₂ each have BTDA and the diamine, 3,3'-DDS₂, in common. The strength test results of the present study indicate the PISO₂ adhesive system provides significantly higher strengths at RT, 177°C and 204°C than the LARC-F-SO₂ adhesive system: RT, 27.5 MPa compared to 17.9 MPa; 177°C, 27.5 MPa compared to 18.8 MPa; and 204°C,

20.4 MPa compared to 19.6 MPa. PISO₂ also had a LSS of 23.1 MPa at 232°C. Slight differences in the bonding process, the adhesive resin, the preparation of the adhesive tape, and surface treatment may account for the small differences in the strength values for PISO₂ reported in references 7 and 9, although they are still comparable to those of the present study. Note the good strengths retained for those thermally aged up to 5000 hrs at 204°C in reference 7, i.e. 20.5 MPa for RT and 204°C tests.

Figure 4 and Table II present the results of thermal exposure in air at 204°C for LARC-F-SO₂ and PISO₂ (present study). Results are expressed in graphical form for those interested in obtaining a quick pictorial summary of the results and in tabular form for those interested in more detail and additional information not included in the graphs such as T_g, failure mode, and the number of specimens tested. No change in LSS at RT, 177°C and 204°C was observed for LARC-F-SO₂ thermally aged for up to 1000 hrs. A slight increase in strength with test temperature was indicated although the range of strengths tend to overlap in most cases. Failures were primarily cohesive except for the RT tests for the 500 hrs and 1000 hrs exposure which were primarily adhesive failure. The darkening of the adhesive in the fractured area (almost black) is typical of systems which use the amide solvents. A significant increase in T_g, 16°C, was determined after the 1000 hr exposure. This increase is not unusual for polyimides and has been noticed in past studies. T_g, measured by the TBA technique, of LARC-F-SO₂ pretreated for 1 hr each at 100°C, 200°C and 300°C was 282°C compared to the T_g determined by TMA (penetration technique) in the fractured area, 255°C.

A slight decrease in LSS was found for PISO₂ specimens exposed for 500 hrs and 1000 hrs at 204°C. Those exposed for 1000 hrs were 90% of the control's value at RT, 80% at 177°C, 87% at 204°C and 86% at 232°C. Joint failures were primarily cohesive for all tests except for the RT control test which was cohesive/adhesive. The color of the adhesive in the failed bond area was almost black. A slight general increase in T_g with increasing time of thermal exposure was observed, increasing from an average 256°C for the controls to 268°C for those exposed for 1000 hrs. As with LARC-F-SO₂, this phenomenon is typical of polyimides. The T_g determined by TBA for PISO₂ pretreated for 1 hr each at 100°C, 200°C and 300°C was 272°C.

Results of thermal exposure in air at 204°C for LARC-TPI and LARC-STPI are given in Figure 5 and Table III. Data are shown for LSS tests conducted at RT, 177°C and 204°C after thermal exposures of 500 hrs and 1000 hrs.

LARC-TPI provides excellent strength for all three test temperatures with no change in strength due to the thermal exposure. Previous work reported has shown the polymer to have excellent thermooxidative resistance.⁵ There is a general decrease in strength with increasing test temperature; however, the decrease is small: less than 24% for the worst case, i.e. 33.0 MPa to 25.2 MPa. All failures were 100% cohesive. T_gs ranged from 225°C to 246°C. The T_g of a film treated for 1 hr each at 100°C, 200°C and 300°C determined by DSC, was 260°C.¹⁰

The copolymer, LARC-STPI, which has the meta-linked phenylenediamine structure in common with LARC-F-SO₂, showed a slight decrease in strength with thermal exposure. The strengths of those exposed for 500 hrs and

1000 hrs, approximately 23 MPa, are the same, but slightly lower than the control's strengths, approximately 26 MPa. The primary failure mode was cohesive except for the 500 and 1000 hr exposure specimens tested at RT which were cohesive/adhesive and adhesive, respectively. The Tgs determined for LARC-STPI fractured specimens were between 260°C and 267°C. A Tg of 283°C, determined by TBA, was reported earlier for LARC-STPI pretreated for 1 hr each at 100°C, 200°C and 300°C.

An overall comparison of the four adhesive systems shows LARC-TPI to provide the highest LSSs, approximately 33 MPa at RT, 30 MPa at 177°C and 26 MPa at 204°C. LARC-F-SO₂, LARC-TPI and LARC-STPI all retain their strengths after thermal exposure up to 1000 hrs at 204°C and PISO₂ retains greater than 80% of the control's strength at each test temperature after exposure. LARC-TPI had the lowest range of Tgs, 228°C to 246°C, of the four adhesives. All the others ranged from 251°C to 273°C. The predominant failure mode was cohesive.

72-Hour water boil

The resistance of the four adhesive systems to water (humidity) was determined by immersing lap shear specimens in distilled boiling water for a 72-hr period and subsequently testing their LSS at RT, 177°C and 204°C. Results of the present study for LARC-F-SO₂ and PISO₂ are given along with results reported for LARC-TPI and LARC-STPI¹⁰ in Figure 6 and Table IV.

LARC-F-SO₂ which has the lowest control strengths of the four adhesive systems for all three test temperatures shows a slight increase

in strengths at RT and 177°C (112% and 102% of the controls' values, respectively). However, at 204°C the strength was 80% of the control's strength. This percentage retention was excellent when compared to other polyimide systems including those reported here. The primary failure mode after water boil was cohesive whereas the control's failures were a combination of cohesive/adhesive at RT and 177°C. There was essentially no change in T_g due to the water boil.

A decrease in LSS with increasing test temperature was determined for the PISO₂ system. The LSS values after water boil were 79% of the control's RT strength, 68% for the 177°C test, and 61% for the 204°C test. The control strengths for PISO₂ were significantly higher than those for LARC-F-SO₂; therefore, even though the percent of strength retention was lower for PISO₂, the absolute LSS values after water boil were still about the same as those for LARC-F-SO₂. Specimens examined after the water boil tests were found to be primarily cohesive failures as were those of the controls. No significant change in T_g was noted after the water boil tests.

LARC-TPI initially provided the highest control LSSs at RT and 177°C of the four adhesive systems and about the same strength at 204°C as PISO₂ and LARC-STPI (24 to 25 MPa). After water boil, LARC-TPI retained 84% of the control's RT strength, 67% of the control's 177°C strength, and only 40% of the control's 204°C strength, the poorest percent retention and the lowest strength value, 10.1 MPa, of the four adhesives tested. Failures were all primarily cohesive before and after water boil. No significant changes in T_g were found.

Water boil also produced reduced strengths for LARC-STPI. The LSSs of LARC-STPI specimens tested after water boil were 88% of the control's RT strength, 62% of the control's 177°C strength and 68% of the control's 204°C strength. LARC-STPI had the highest strength at 204°C of the four adhesive systems, an average of 17.0 MPa; slightly higher than LARC-F-SO₂, 15.7 MPa and PISO₂, 14.7 MPa and significantly higher than LARC-TPI, 10.1 MPa. The failure mode for the tested LARC-STPI was primarily cohesive. No change in T_g was determined after water boil.

SUMMARY

Research continues at Langley Research Center on synthesis and development of new inexpensive flexible aromatic polyimides as adhesives which contain bridged aromatic diamines with meta catenation. The present work resulted in a material identified as LARC-F-SO₂ with similarities to polyimidesulfone, PISO₂, and other flexible backbone polyimides recently reported by Progar and St. Clair. Also prepared in our laboratory and evaluated was a phthalic anhydride endcapped version of PISO₂. These two polymers were synthesized and evaluated as adhesives and compared with LARC-TPI and LARC-STPI, polyimides researched in our laboratory and reported in literature.

The adhesive evaluation, primarily based on lap shear strength (LSS) tests, involved preparing adhesive tapes, conducting bonding studies, and exposing lap shear specimens to a thermal exposure in air at 204°C for up to 1000 hrs and a 72-hr water boil exposure. LSS tests at RT, 177°C and 204°C were performed before (controls) and after these exposures. The

type of adhesive failure as well as the glass transition temperature, T_g , was determined for the fractured specimens.

When comparing all four adhesive systems, the results indicate that LARC-TPI provides the highest LSSs, 33 MPa at RT, 30 MPa at 177°C and 26 MPa at 204°C. LARC-F-SO₂, LARC-TPI and LARC-STPI all retain their strengths after thermal exposure at 204°C in air for up to 1000 hrs, the maximum time considered in this study and PISO₂ retains greater than 80% of its control strengths. The predominant failure mode was cohesive.

After a 72-hr water boil exposure, most of the four adhesive systems showed reduced strengths for all elevated test temperatures. All adhesive systems exhibited a high percentage of strength retention for the three test temperatures (> 60%) except for LARC-TPI tested at 204°C which had a 40% retention. LARC-STPI retained the highest strength at 204°C, approximately 17.0 MPa; slightly higher than LARC-F-SO₂, 15.7 MPa and PISO₂, 14.7 MPa; and significantly higher than LARC-TPI, 10.1 MPa. Failure modes were primarily cohesive for all adhesive systems. No significant changes in T_g s were found.

Although the LARC-F-SO₂ could not be prepared in diglyme alone as the solvent, the properties of the resulting adhesive were notable. The darkening of the adhesive during bonding was typical of systems which utilize amide solvents.

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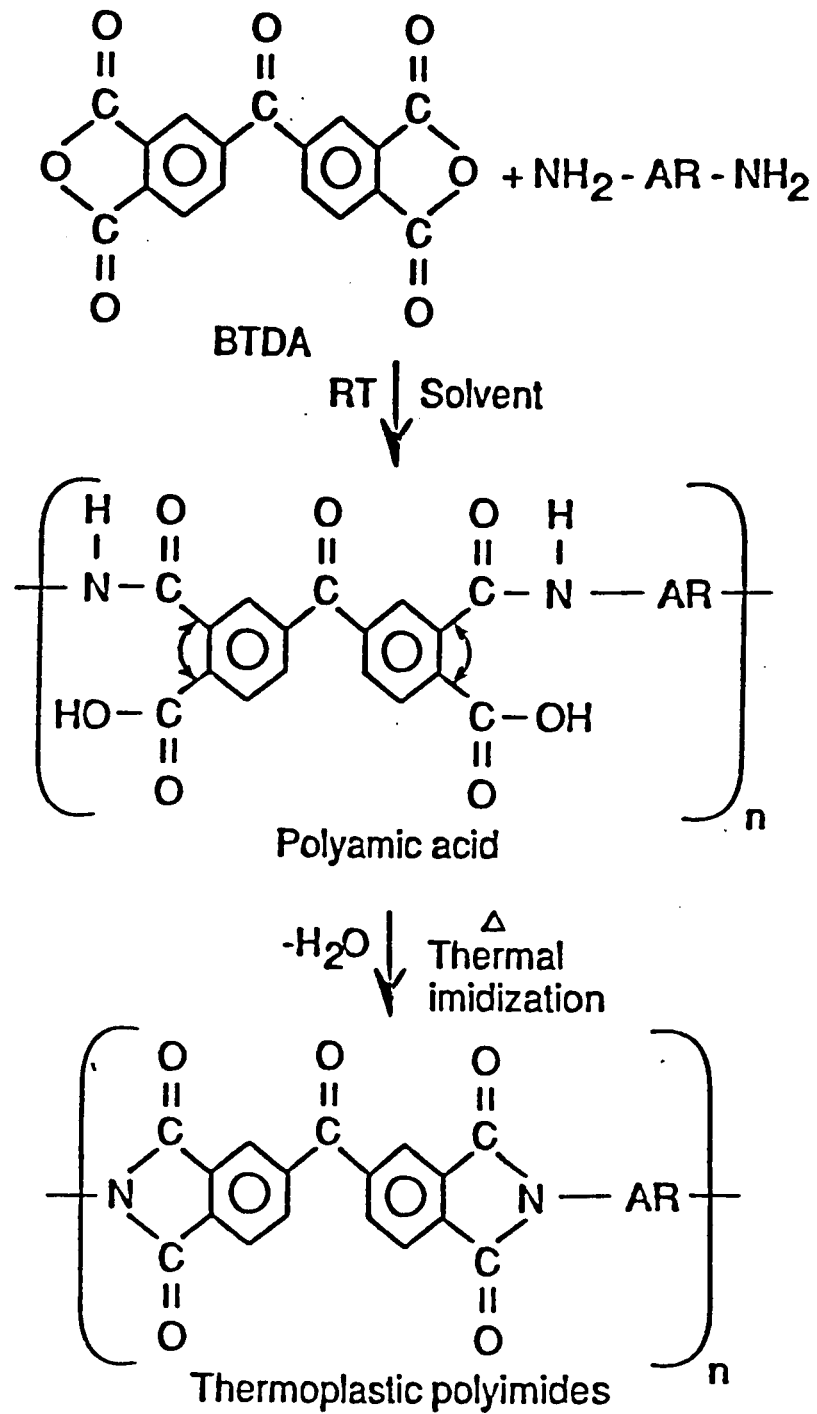


Figure 1. General reaction scheme.

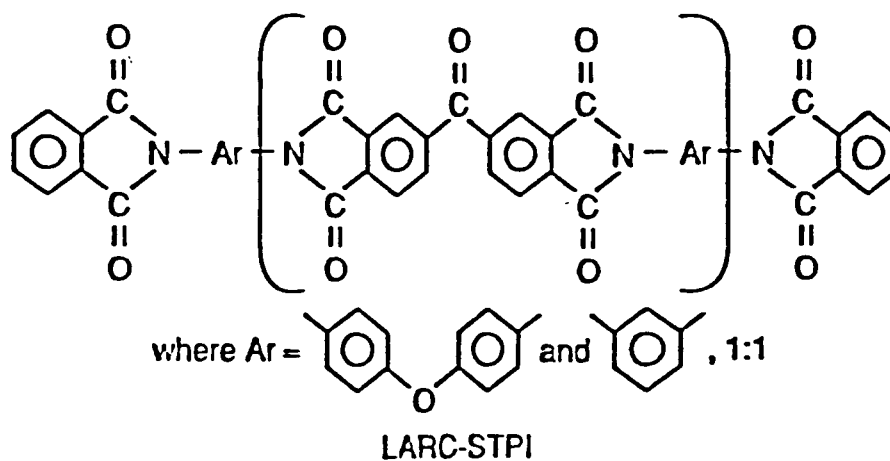
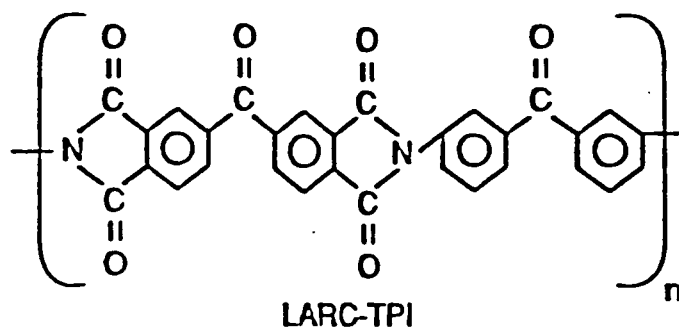
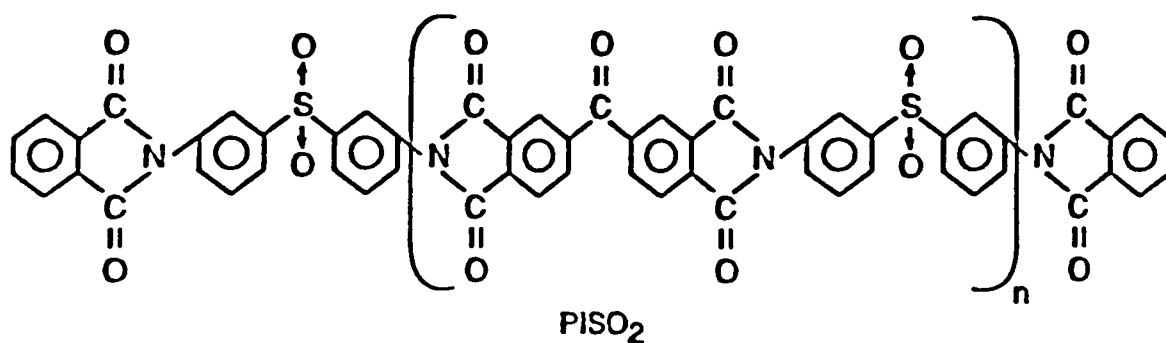
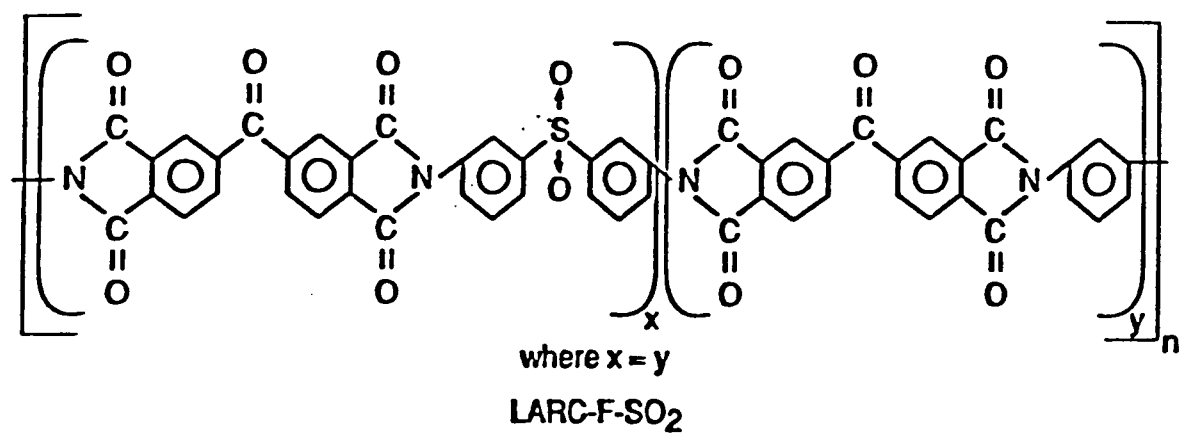


Figure 2. Thermoplastic polyimide structures.

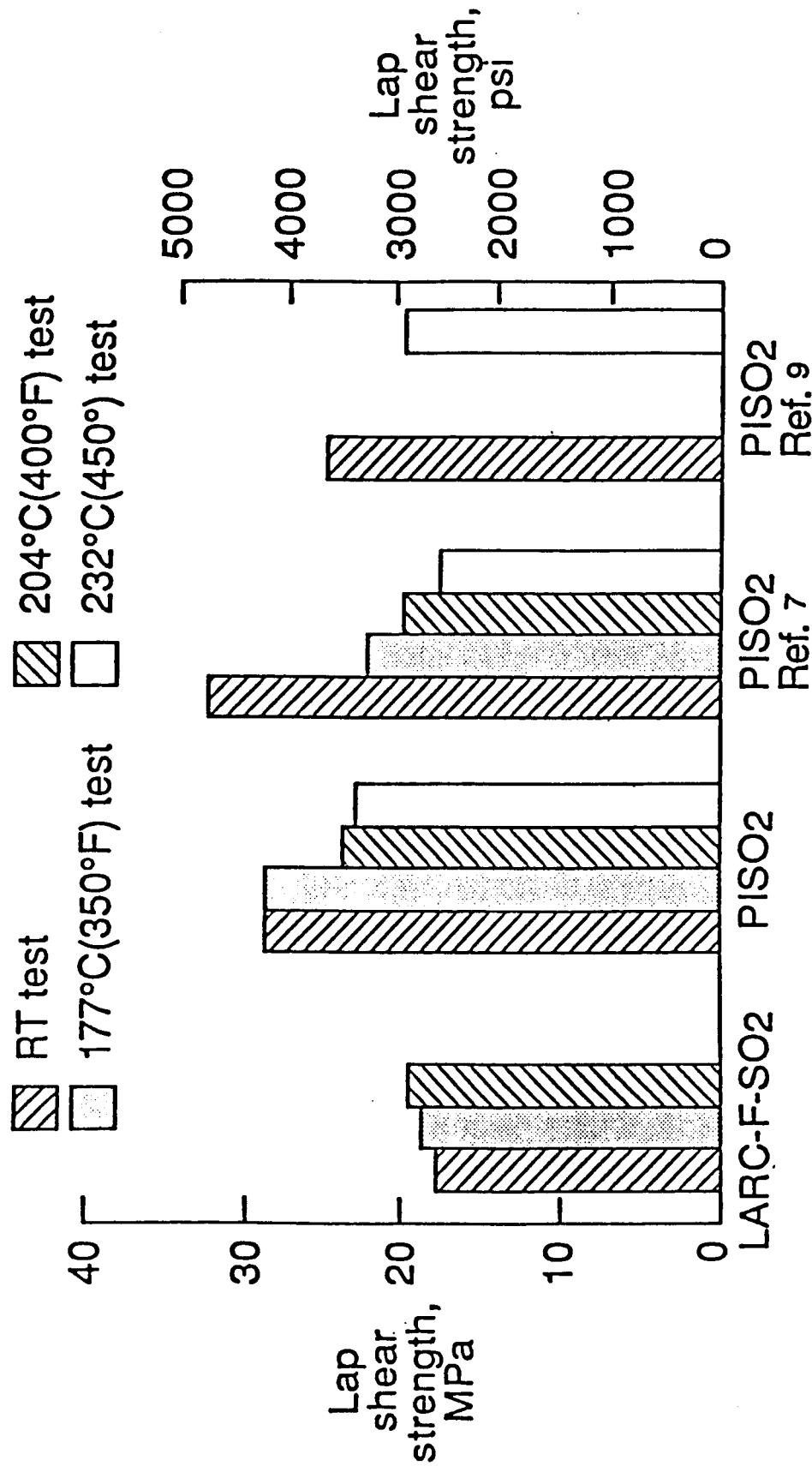


Figure 3. Comparative LSS data for LARC-F-SO₂ and PISO₂.

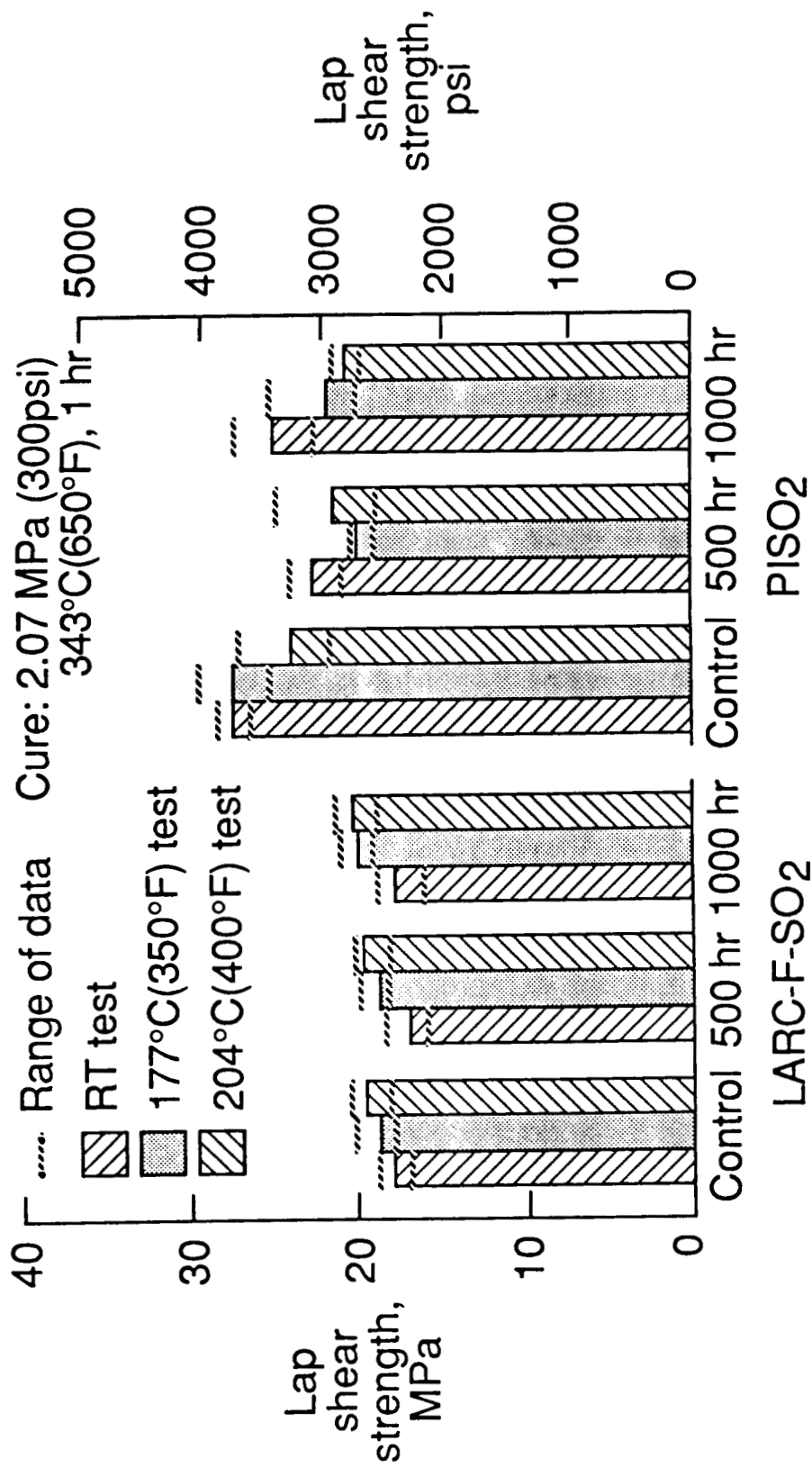


Figure 4. Effects of thermal exposure at 204°C (400°F) on LSS for LARC-F-SO2 and PISO2 bonded Ti-6Al-4V.

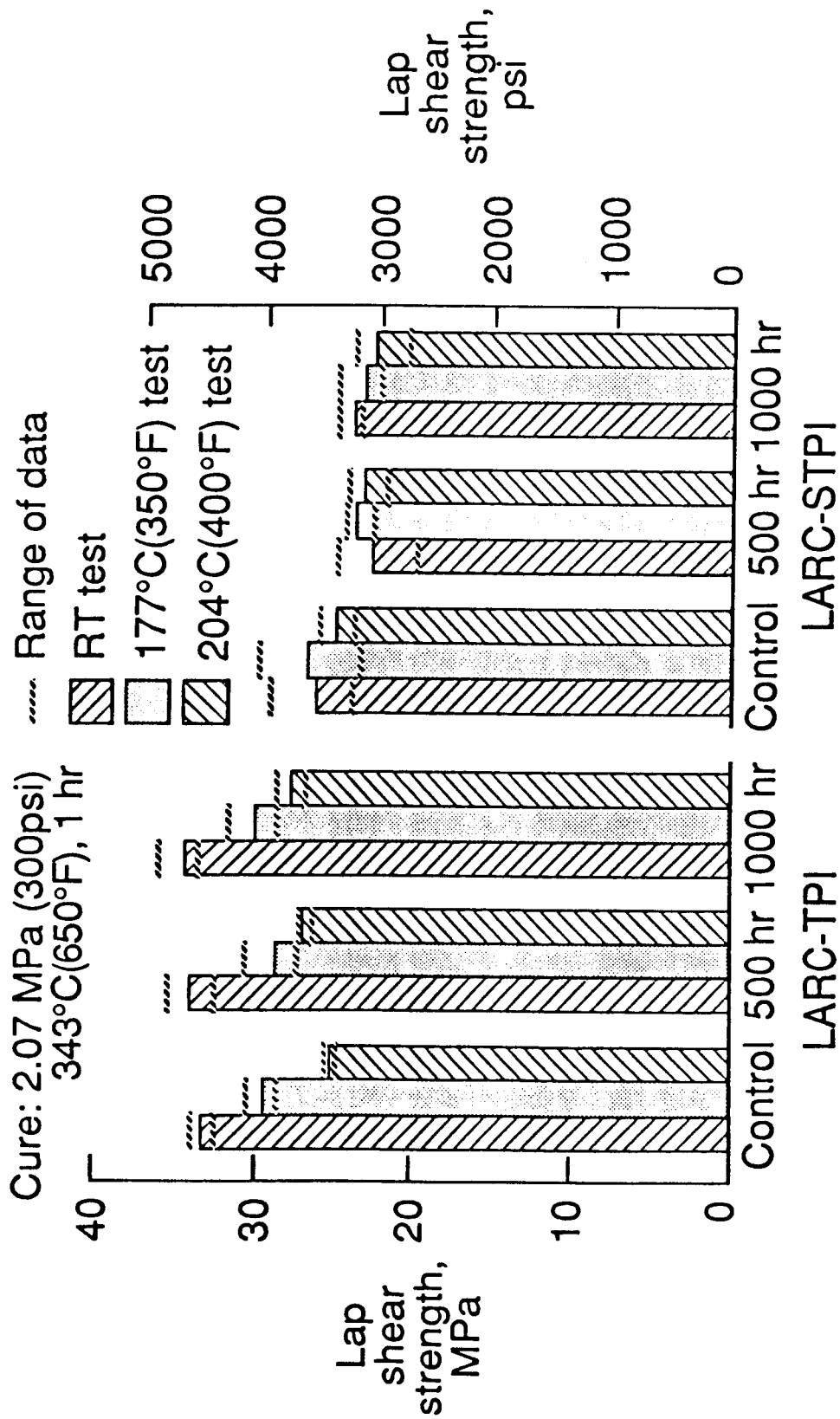


Figure 5. Effects of thermal exposure in air at 204°C (400°F) on LSS for LARC-TPI and LARC-STPI bonded Ti-6Al-4V.

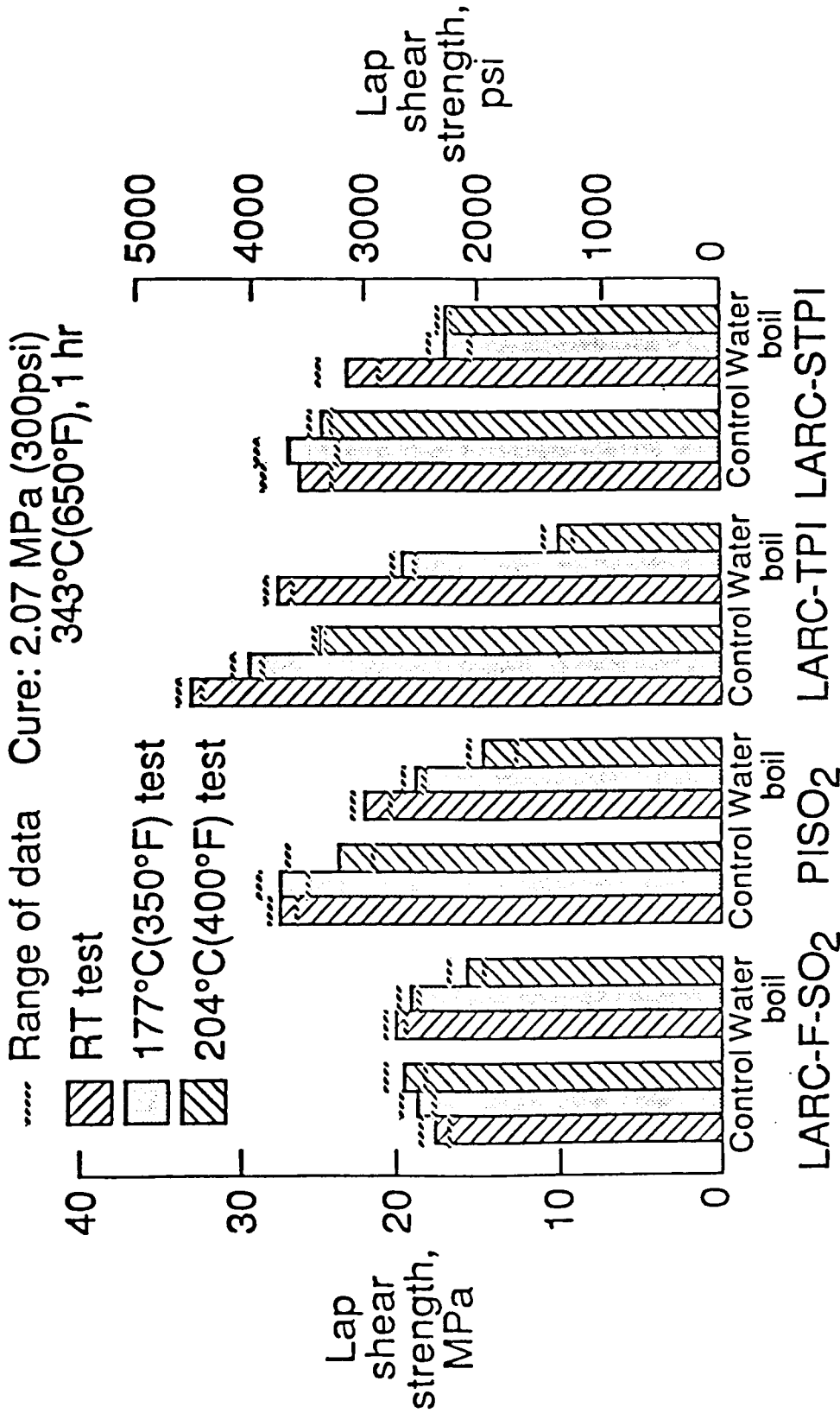


Figure 6. Effects of a 72-hour water boil on LSS for bonded Ti-6Al-4V.

Table I.- Comparative LSS data for PISO₂ and LARC-F-SO₂

Adhesive	Bonding conditions	Test temperature, °C(°F)	Exposure time at 204°C, hr	LSS, MPa(psi)
LARC-F-SO ₂ (present study)	8°C/min, 2.07 MPa (300psi), RT to 343°C (650°F), hold 1 hr	RT (RT)	0	17.9 (2600)
		177 (350)	0	18.8 (2720)
		204 (400)	0	19.6 (2840)
		RT (RT)	500	17.0 (2460)
		177 (350)	500	19.3 (2800)
		204 (400)	500	19.8 (2870)
		RT (RT)	1000	18.0 (2620)
		177 (350)	1000	20.1 (2920)
		204(400)	1000	20.4 (2950)
PISO ₂ (present study)		RT (RT)	0	27.5 (4000)
		177 (350)	0	27.5 (4000)
		204 (400)	0	24.0 (3490)
		232 (450)	0	23.1 (3340)
		RT (RT)	500	22.8 (3310)
		177 (350)	500	20.2 (2930)
		204 (400)	500	21.7 (3140)
		232 (450)	500	20.2 (2940)
		RT (RT)	1000	24.8 (3590)
		177 (350)	1000	22.0 (3190)
		204 (400)	1000	20.8 (3020)
		232 (450)	1000	19.8 (2870)
PISO ₂ Ref. 7	7°C/min, RT to 325°C (617°F), apply 1.38 MPa (200psi) at 280°C (536°F), hold 325°C for 15 min	RT (RT)	0	32.0 (4650)
		177 (350)	0	22.1(3210)
		204 (400)	0	20.1(2920)
		232 (450)	0	18.1(2620)
		RT (RT)	5000	20.5 (2980)
		204 (400)	2500	21.9 (3180)
204 (400)	5000	20.5 (2980)		
PISO ₂ Ref. 9	Vacuum, contact pressure, 4°C/min, RT to 343°C (650°F), apply 0.34 MPa (50psi) at 250°C (482°F), after 5 min at 343°F, apply 1.38(200psi), hold 343°C for 5 min	RT (RT)	0	25.2 (3650)
		232 (450)	0	19.8 (2870)

Table II.- LSS test results of thermal exposure in air at 204°C for bonded Ti-6Al-4V

Thermal exposure, hr	Number of specimens	Test temperature, °C(°F)	Average LSS, MPa(psi)	Range of LSS, MPa(psi)	Primary failure mode ^a	Glass transition temperature, T _g °C(°F)
LARC-F-SO ₂						
0 (controls)	4	RT (RT)	17.9 (2600)	16.9 - 18.6 (2450 - 2700)	Co/Ad	255 (491)
	4	-177(350)	18.8 (2720)	17.8 - 19.8 (2580 - 2880)	Co/Ad	-
	4	204 (400)	19.6 (2840)	18.2 - 20.7 (2640 - 3000)	Co	-
500	3	RT (RT)	17.0 (2460)	15.8 - 18.6 (2300 - 2700)	Ad	257 (495)
	3	177(350)	19.3 (2800)	18.6 - 19.9 (2700 - 2890)	Co	-
	4	204 (400)	19.8 (2870)	19.1 - 20.6 (2780 - 2990)	Co	-
1000	4	RT (RT)	1.80 (2620)	16.7 - 19.1 (2420 - 2760)	Ad	273 (523)
	4	177(350)	20.1 (2920)	19.4 - 20.8 (2820 - 3010)	Co	-
	3	204 (400)	20.4 (2950)	19.3 - 21.0 (2800 - 3040)	Co	-
PISO ₂						
0 (controls)	4	RT (RT)	27.5 (4000)	26.2 - 28.3 (3800 - 4100)	Co/Ad	251 (484)
	4	177(350)	27.5 (4000)	25.1 - 29.3 (3640 - 4250)	Co	258 (496)
	4	204 (400)	24.0 (3490)	21.5 - 27.2 (3120 - 3950)	Co	258 (496)
500	4	RT (RT)	22.8 (3310)	21.0 - 24.1 (3040 - 3500)	Co	262 (504)
	4	177(350)	20.2 (2930)	19.6 - 20.6 (2850 - 2990)	Co	263 (505)
	4	204 (400)	21.7 (3140)	19.4 - 25.1 (2820 - 3640)	Co	262 (504)
1000	4	RT (RT)	24.8 (3590)	23.0 - 27.3 (3330 - 3960)	Co	271 (520)
	4	177(350)	22.0 (3190)	20.4 - 25.2 (2960 - 3650)	Co	265 (509)
	4	204 (400)	20.8 (3020)	20.3 - 21.5 (2950 - 3120)	Co	266 (511)

Bonding conditions: 2.07 MPa(300psi) pressure, heating rate of 8°C/min(14°F/min), RT to 343°C(650°F), held 1 hr

a Cohesive - Co, adhesive - Ad

b Single measurement

Table III.- LSS test results of thermal exposure in air at 204°C for bonded Ti-6Al-4V

Thermal exposure, hr	Number of specimens	Test temperature, °C(°F)	Average LSS, MPa(psi)	Range of LSS, MPa(psi)	Primary failure mode ^a	Glass transition temperature, T _g °C(°F)
LARC-TPI						
0 (controls)	4	RT (RT)	33.0 (4790)	32.3 - 33.5 (4680 - 4860)	Co	228 (442)
	4	177(350)	29.5 (4280)	28.8 - 30.7 (4180 - 4450)	Co	225 (437)
	4	204 (400)	25.2 (3660)	25.0 - 25.4 (3620 - 3690)	Co	236 (457)
500	4	RT (RT)	34.1 (4940)	32.7 - 35.3 (4740 - 5120)	Co	242 (468)
	4	177(350)	29.0 (4200)	27.5 - 30.5 (3980 - 4420)	Co	242 (468)
	4	204 (400)	26.9 (3900)	26.6 - 27.1 (3860 - 3940)	Co	237 (459)
1000	4	RT (RT)	32.9 (4780)	32.3 - 34.4 (4690 - 4980)	Co	242 (468)
	4	177(350)	29.9 (4340)	28.5 - 31.0 (4140 - 4490)	Co	246 (475)
	4	204 (400)	27.8 (4020)	27.2 - 28.6 (3940 - 4160)	Co	238 (460)
LARC-STPI						
0 (controls)	4	RT (RT)	26.6 (3860)	24.2 - 29.6 (3500 - 4300)	Co	267 (513)
	4	177(350)	27.0 (3920)	23.6 - 30.0 (3420 - 4360)	Co	-
	4	204 (400)	25.0 (3630)	24.1 - 26.0 (3490 - 3780)	Co	-
500	4	RT (RT)	23.2 (3370)	20.0 - 25.0 (2900 - 3620)	Co/Ad	265 (509)
	4	177(350)	23.9 (3460)	23.2 - 24.6 (3360 - 3570)	Co	-
	4	204 (400)	23.4 (3390)	22.4 - 24.5 (3240 - 3550)	Co	-
1000	4	RT (RT)	24.1 (3500)	23.6 - 25.1 (3420 - 3640)	Ad	260 (500)
	4	177(350)	23.2 (3370)	22.1 - 25.0 (3200 - 3640)	Co	-
	4	204 (400)	22.7 (3290)	20.7 - 24.1 (3000 - 3490)	Co	-

Bonding conditions: 2.07 MPa(300psi) pressure, heating rate of 8°C/min(14°F/min), RT to 343°C(650°F), held 1 hr

a Cohesive - Co, adhesive - Ad

b Single measurement

Table IV.- LSS test results of a 72-hour water boil

	Number of specimens	Test temperature, °C(°F)	Average LSS, MPa(psi)	Range of LSS, MPa(psi)	Primary failure mode ^a	Glass transition temperature, T _g °C(°F)
LARC-F-SO ₂						
Controls	4	RT (RT)	17.9 (2600)	16.9 - 18.6 (2450 - 2700)	Co/Ad	255 (491)
	4	177(350)	18.8 (2720)	17.8 - 19.8 (2580 - 2880)	Co/Ad	-
	4	204 (400)	19.6 (2840)	18.2 - 20.7 (2640 - 3000)	Co	-
72-hr water boil	3	RT (RT)	20.0 (2900)	19.2 - 20.7 (2790 - 3000)	Co	264 (507)
	3	177(350)	19.1 (2770)	18.6 - 19.9 (2710 - 2880)	Co	261 (502)
	3	204 (400)	15.7 (2280)	14.4 - 17.2 (2090 - 2500)	Co	250 (482)
PISO ₂						
Controls	4	RT (RT)	27.5 (4000)	26.2 - 28.3 (3800 - 4100)	Co/Ad	251 (484)
	4	177(350)	27.5 (4000)	25.1 - 29.3 (3640 - 4250)	Co	258 (496)
	4	204 (400)	24.0 (3490)	21.5 - 27.2 (3120 - 3950)	Co	258 (496)
72-hr water boil	4	RT (RT)	21.8 (3170)	19.9 - 22.9 (2890 - 3320)	Co	259 (498)
	4	177(350)	18.8 (2730)	18.3 - 19.3 (2660 - 2800)	Co	257 (495)
	4	204 (400)	14.7 (2140)	12.1 - 15.8 (1750 - 2300)	Co	253 (487)
LARC-TPI						
Controls	4	RT (RT)	33.0 (4790)	32.3 - 33.5 (4680 - 4860)	Co	228 (442)
	4	177(350)	29.5 (4280)	28.8 - 30.7 (4180 - 4450)	Co	225 (437)
	4	204 (400)	25.2 (3660)	25.0 - 25.4 (3620 - 3690)	Co	236 (457)
72-hr water boil	4	RT (RT)	27.8 (4030)	26.7 - 28.8 (3870 - 4180)	Co	239 (462)
	4	177(350)	19.7 (2860)	19.1 - 20.3 (2760 - 2950)	Co	230 (446)
	4	204 (400)	10.1 (1470)	9.4 - 11.0 (1360 - 1600)	Co	225 (437)
LARC-STPI						
Controls	4	RT (RT)	26.6 (3860)	24.2 - 29.6 (3500 - 4300)	Co	267 (513)
	4	177(350)	27.0 (3920)	23.6 - 30.0 (3420 - 4360)	Co	-
	4	204 (400)	25.0 (3630)	24.1 - 26.0 (3490 - 3780)	Co	-
72-hr water boil	4	RT (RT)	23.3 (3380)	20.8 - 25.2 (3020 - 3660)	Co	265 (509)
	4	177(350)	16.9 (2450)	14.8 - 18.1 (2160 - 2620)	Co	264 (507)
	4	204 (400)	17.0 (2460)	16.7 - 17.5 (2420 - 2440)	Co	257 (495)

Bonding conditions: 2.07 MPa(300psi) pressure, heating rate of 8°C/min(14°F/min), RT to 343°C(650°F), held 1 hr

a Cohesive - Co, adhesive - Ad

b Single measurement



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16. Abstract <p>Continuing research at Langley Research Center on the synthesis and development of new inexpensive flexible aromatic polyimides as adhesives has resulted in a material identified as LARC-F-SO₂ with similarities to polyimidesulfone, PISO₂, and other flexible backbone polyimides recently reported by Progar and St. Clair. Also prepared and evaluated was an endcapped version of PISO₂. These two polymers were compared with LARC-TPI and LARC-STPI, polyimides researched in our laboratory and reported in the literature.</p> <p>The adhesive evaluation, primarily based on lap shear strength (LSS) tests at RT, 177°C and 204°C, involved preparing adhesive tapes, conducting bonding studies and exposing lap shear specimens to 204°C air for up to 1000 hrs and to a 72-hour water boil. The type of adhesive failure as well as the T_g was determined for the fractured specimens.</p> <p>The results indicate that LARC-TPI provides the highest LSSs. LARC-F-SO₂, LARC-TPI and LARC-STPI all retain their strengths after thermal exposure for 1000 hrs and PISO₂ retains greater than 80% of its control strengths.</p> <p>After a 72-hr water boil exposure, most of the four adhesive systems showed reduced strengths for all test temperatures although still retaining a high percentage of their original strength (> 60%) except for one case.</p> <p>The predominant failure type was cohesive with no significant change in the T_gs.</p>					
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