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METHOD FOR RAPID SPINNING OF A POLYBENZAZOLE FIBER

The present invention relates to improved processes for spinning fibers that contain polybenzoxazole ("PBO") or polybenzothiazole ("PBT") polymer.

5 Lyotropic liquid-crystalline polybenzoxazole and polybenzothiazole are not thermoplastic. They are typically made into fibers by dry-jet, wet-spinning techniques, in which a dope that contains the polybenzazole polymer and an acid solvent is spun through a spinneret, drawn across an air gap, and coagulated by contact with a fluid that dilutes the solvent and is a non-solvent for the polymer. The individual filaments formed by this process
10 can be combined to form one or more fibers of varying diameter.

It is desirable to spin a large number of filaments in a short time and at a high rate of speed. It is also desirable to minimize the cross-sectional area of the individual filaments within a fiber, producing a continuous fiber with many low denier filaments rather than a few high denier filaments. However, thinner filaments have a greater tendency to break during
15 spinning, especially at high speed and when the spinneret contains orifices for a large number of filaments. It is desirable to minimize the number of filament breaks.

The first aspect of the present invention is a process to spin a fiber made-up of more than one filament from a liquid-crystalline dope that contains a solvent and a polybenzazole polymer which is polybenzoxazole, polybenzothiazole or a copolymer thereof,
20 said process comprising the steps of:

- (A) spinning the dope at a temperature greater than 100°C through a spinneret that contains a plurality of orifices, wherein the density of orifices in the spinneret is at least 2.0 per cm², whereby a plurality of dope filaments is formed;
- (B) drawing the dope filaments across an air gap that contains a gas at a temperature
25 of at least 50°C and at most 100°C, wherein the gas flows through the air gap at a rate sufficient to uniformly reduce the temperature of the dope filaments; and
- (C) contacting the drawn dope filaments with a washing fluid such that the solvent is removed from the filaments.

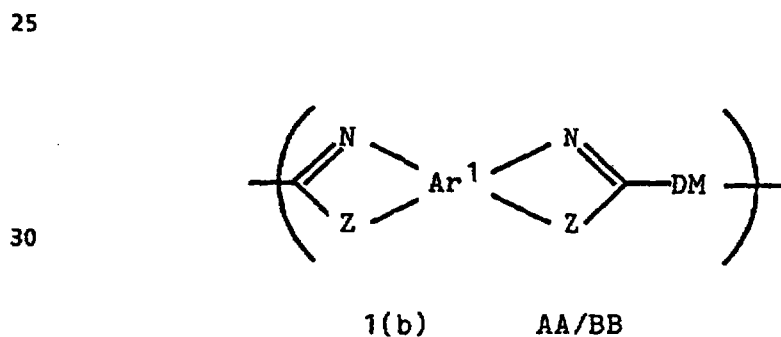
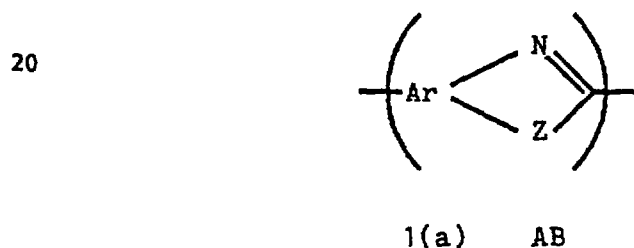
A second aspect of this invention is a polybenzazole fiber with an average fiber
30 diameter of no more than about 18 μm obtained through the process of the first aspect of the present invention.

It is theorized, without being intended to be bound thereby, that when a large number of polybenzazole filaments are spun close together at a high temperature, the outer filaments cool faster than the inner filaments. The different filament temperatures mean that
35 spinning conditions that are optimal for the outer filaments are not best for the inner filaments, and vice-versa. The gas flow in the air gap ensures that all of the filaments experience a similar surrounding temperature. A controlled surrounding temperature acts to

minimize filament breaks. It provides the additional advantages of making the filaments more uniform.

The present invention uses dopes that contain a polybenzazole polymer, which is polybenzoxazole, polybenzothiazole or a copolymer of those polymers. PBO, PBT and random, sequential and block copolymers of PBO and PBT are described in references such as Wolfe et al., Liquid Crystalline Polymer Compositions, Process and Products, U.S. Patent 4,703,103 (October 27, 1987); Wolfe et al., Liquid Crystalline Polymer Compositions, Process and Products, U.S. Patent 4,533,692 (August 6, 1985); Wolfe et al., Liquid Crystalline Poly(2,6-Benzo-thiazole) Compositions, Process and Products, U.S. Patent 4,533,724 (August 6, 1985); Wolfe, Liquid Crystalline Polymer Compositions, Process and Products, U.S. Patent 4,533,693 (August 6, 1985); Evers, Thermooxidatively Stable Articulated p-Benzobisoxazole and p-Benzobisthiazole Polymers, U.S. Patent 4,359,567 (November 16, 1982); Tsai et al., Method for Making Heterocyclic Block Copolymer, U.S. Patent 4,578,432 (March 25, 1986); 11 Ency. Poly. Sci. & Eng., Polybenzothiazoles and Polybenzoxazoles, 601 (J. Wiley & Sons 1988) and W. W. Adams et al., The Materials Science and Engineering of Rigid-Rod Polymers (Materials Research Society 1989).

The polymer may contain AB-mer units, as represented in Formula 1(a), and/or AA/BB-mer units, as represented in Formula 1(b)



wherein:

Each Ar represents an aromatic group selected such that the polybenzazole polymer is a lyotropic liquid-crystalline polymer (that is, it forms liquid-crystalline domains when its concentration in solution exceeds a "critical concentration point"). The aromatic group may be heterocyclic, such as a pyridinylene group, but it is preferably carbocyclic. The aromatic group may be a fused or unfused polycyclic system, but is preferably a single six-membered ring. Size is not critical, but the aromatic group preferably contains no more than about 18 carbon atoms, more preferably no more than about 12 carbon atoms and most preferably no more than about 6 carbon atoms. Ar¹ in AA/BB-mer units is preferably a 1,2,4,5-phenylene moiety or an analog thereof. Ar in AB-mer units is preferably a 1,3,4-phenylene moiety or an analog thereof.

Each Z is independently an oxygen or a sulfur atom.

Each DM is independently a bond or a divalent organic moiety selected such that the polybenzazole polymer is a lyotropic liquid crystalline polymer. The divalent organic moiety is preferably an aromatic group (Ar) as previously described. It is most preferably a 1,4-phenylene moiety or an analog thereof.

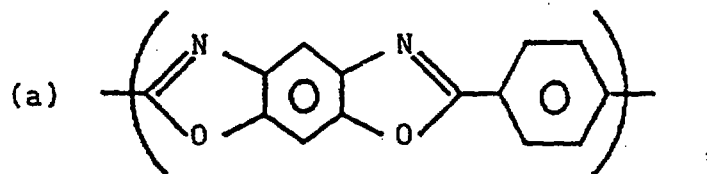
The nitrogen atom and the Z moiety in each azole ring are bonded to adjacent carbon atoms in the aromatic group, such that a five-membered azole ring fused with the aromatic group is formed.

The azole rings in AA/BB-mer units may be in cis- or trans-position with respect to each other, as illustrated in 11 Ency. Poly. Sci. & Eng., *supra* at 602.

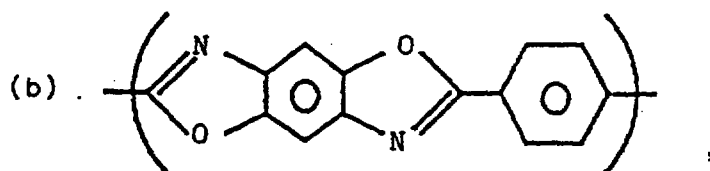
The polymer preferably consists essentially of either AB-PBZ mer units or AA/BB-PBZ mer units, and more preferably consists essentially of AA/BB-PBZ mer units. Azole rings within the polymer are preferably oxazole rings (Z = O).

Preferred mer units are illustrated in Formulae 2(a)-(h). The polymer more preferably consists essentially of mer units selected from those illustrated in 2(a)-(h), and most preferably consists essentially of a number of identical units selected from those illustrated in 2(a)-(d).

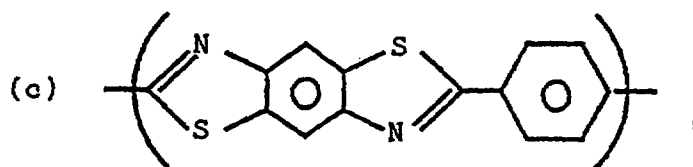
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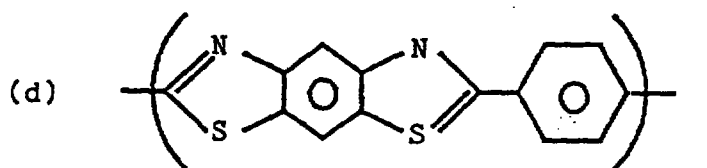
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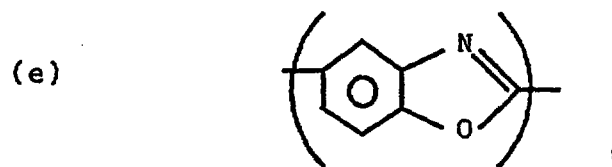
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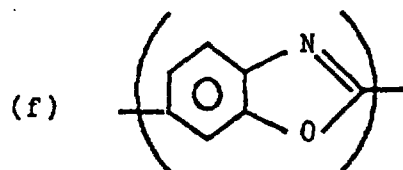
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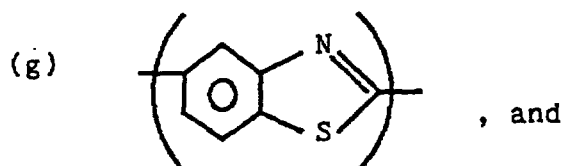
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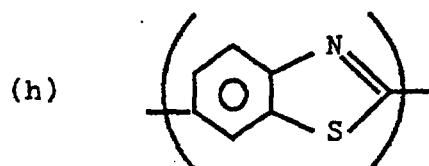
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Each polymer preferably contains on average at least about 25 repeating units, more preferably at least about 50 repeating units and most preferably at least about 100 repeating units. The intrinsic viscosity of rigid AA/BB-PBZ polymers in methanesulfonic acid at 25°C is preferably at least about 10 dL/g, more preferably at least about 15 dL/g and most preferably at least about 20 dL/g. For some purposes, an intrinsic viscosity of higher than 25 dL/g or 30 dL/g may be best. Intrinsic viscosities of 60 dL/g are possible. The intrinsic viscosity of semi-rigid AB-PBZ polymers is preferably at least about 5 dL/g, more preferably at least about 10 dL/g and most preferably at least about 15 dL/g.

The polymer or copolymer is dissolved in a solvent to form a solution or dope. Some polybenzoxazole and polybenzothiazole polymers are soluble in cresol, but the solvent is preferably an acid capable of dissolving the polymer. The acid is preferably non-oxidizing. Examples of suitable acids include polyphosphoric acid, methanesulfonic acid and sulfuric acid and mixtures of those acids. The acid is preferably polyphosphoric acid and/or methanesulfonic acid, and is more preferably polyphosphoric acid.

The dope should contain a high enough concentration of polymer for the dope to contain liquid crystalline domains. The concentration of the polymer is preferably at least

about 7 weight percent, more preferably at least about 10 weight percent and most preferably at least about 14 weight percent. The maximum concentration is limited primarily by practical factors, such as polymer solubility and dope viscosity. The concentration of polymer is seldom more than 30 weight percent, and usually no more than about 20 weight percent.

- 5 Suitable polymers or copolymers and dopes can be synthesized by known procedures, such as those described in Wolfe et al., U.S. Patent 4,533,693 (August 6, 1985); Sybert et al., U.S. Patent 4,772,678 (September 20, 1988); Harris, U.S. Patent 4,847,350 (July 11, 1989); Gregory, U.S. Patent 5,089,591 (February 18, 1992); and Ledbetter et al., "An Integrated Laboratory Process for Preparing Rigid Rod Fibers from the Monomers," The Materials Science
10 and Engineering of Rigid-Rod Polymers at pp. 253-64 (Materials Res. Soc. 1989). In summary, suitable monomers (AA-monomers and BB-monomers or AB-monomers) are reacted in a solution of nonoxidizing and dehydrating acid under nonoxidizing atmosphere with vigorous mixing and high shear at a temperature that is increased in step-wise or ramped fashion from no more than about 120°C to at least about 190°C. Examples of suitable
15 AA-monomers include terephthalic acid and analogs thereof. Examples of suitable BB-monomers include 4,6-diaminoresorcinol, 2,5-diaminohydroquinone, 2,5-diamino-1,4-dithiobenzene and analogs thereof, typically stored as acid salts. Examples of suitable AB-monomers include 3-amino-4-hydroxybenzoic acid, 3-hydroxy-4-aminobenzoic acid, 3-amino-4-thiobenzoic acid, 3-thio-4-aminobenzoic acid and analogs thereof, typically stored
20 as acid salts.

- In order for the most efficient spinning, the dope should preferably be very homogeneous and free of gas bubbles and solid particulates. This can be accomplished, but by no means is limited to, by implementation of shear-filtration media (extensive known shear-filtration media includes the use of silica sand, metal filings and particulates, glass beads,
25 sintered ceramics, sintered porous metal plates and shaped structures and metal screens). Additional known homogenizing equipments includes single- and multiple-screw extruders, static mixers and other mixing devices.

- The dope is spun from a spinneret that contains a plurality of orifices. The density of orifices in the spinneret should be at least about 1.0 per cm² preferably at least about 2.0 per
30 cm², and more preferably at least about 3.0 per cm². Each orifice may be of any size desired, but the average diameter at the point where the dope leaves the spinneret is preferably no more than about 0.5 mm, more preferably no more than about 0.4 mm, and most preferably no more than about .35 mm. The orifices may be in any desired arrangement, but it is convenient to use a circular or lattice shaped arrangement.

The dope is spun through the spinneret at a temperature greater than 100°C. The temperature is preferably at least about 120°C and more preferably at least about 140°C. The maximum temperature is limited by the stability of the dope. It is preferably no more than about 220°C and more preferably no more than about 200°C. The optimum rate at which dope passes through the spinneret varies depending upon the spinneret, the dope and the conditions in which they are used.

Dope filaments exiting the spinneret enter a gap between the spinneret and the coagulation zone where the dope can be drawn. The gap is typically called an "air gap" although it need not contain air. The gap may contain any gas that does not induce coagulation or react adversely with the dope, such as air, nitrogen, argon, helium or carbon dioxide. The spin-draw ratio is the ratio of the take-up velocity of the fiber divided by the extrusion velocity of the dope. In the air gap, the dope filaments are drawn to a spin-draw ratio that is at least about 10, preferably at least about 20, highly preferably at least about 40, more highly preferably at least about 50 and most highly preferably at least about 63. The length of the air gap is usually at least about 5 cm and at most about 100 cm, although longer and shorter air gaps may be used.

The gas in the air gap is at a temperature of at least 50°C and at most 100°C. The temperature is more preferably between about 60°C and about 90°C. The gas serves to cool the filaments before they are contacted with a washing fluid. If the temperature is less than 50°C, the filaments cool too fast. When the filaments cool too fast it has been observed that the spinning stress increases rapidly and spinning becomes unstable. This is believed to be the result of the high activation energy of extensional (elongational) flow. If the temperature is more than 100°C, resonance-like spinning instability is believed to occur.

The cooling gas in the air gap flows at a rate sufficient to uniformly reduce the temperature of the dope filaments, so that the filaments all experience about the same cooling profile. The rate of gas flow is between about 0.02 m/sec. and 0.1 m/sec., more preferably between .05 m/sec. and 0.08 m/sec. and most preferably between .075 m/sec. and 0.08 m/sec. The gas flow is preferably perpendicular to the direction in which the filaments move through the air gap.

After the dope filament has been drawn, it is contacted with a fluid that dilutes the solvent and is a non-solvent for the polybenzazole polymer. The process of separating the solvent from the polymer is usually referred to as coagulation in the beginning and later, as most of the solvent is removed, as washing. The fluid may be a gas, such as steam, but it is preferably a liquid and more preferably an aqueous liquid. The fiber may be contacted with fluid in a bath or spray form. The bath may be in many different forms, such as the baths

described in Japan Laid Open Patent No. 63-12710; Japan Laid Open Patent No. 51-35716; or Japan Published Patent No. 44-22204. The fiber is preferably washed until the residual solvent is reduced to less than about 2.0 percent, more preferably less than 0.5 percent and most preferably less than about 0.1 percent.

5 The filaments produced by this process are typically combined into one or more fibers of varying thickness. This combination step usually takes place during the process of making the filament at the stage before, during or after the coagulation/washing of the filament. Fibers made-up of one filament are referred to as monofilament fibers and fibers made-up of more than one filament are referred to as multi-filament fibers. A fiber tow is "a
10 large strand of continuous manufactured fiber filaments without definite twist, collected in loose, rope-like form, usually held together by crimp. "(Dictionary of Fiber & Textile Technology, copyright 1990 by Hoechst Celanese.)

 The coagulated and washed fiber may be collected and dried by known methods. It may be heat treated to increase tensile modulus if desired. A finish may also be applied if
15 desired.

 Fibers may be produced by the process at high speed. The speed (measured after the coagulation/ washing step) at which fiber is produced is preferably at least about 75 m/min., more preferably at least about 100 m/min., and most preferably at least about 200 m/min. Line speeds of 400 m/min., 600 m/min. or more are possible under optimal
20 conditions.

 The resulting fiber preferably has an average diameter of no more than about 21 μm (.83 mils), more preferably no more than about 19 μm (.75 mils) and most preferably no more than about 15 μm (.59 mils). Its denier ("denier" is the weight in grams of 9000 meters of any fiber) is preferably no more than about 5 dpf ("denier-per-filament") and more preferably
25 no more than about 4 dpf. The minimum filament diameter and denier are limited by practical considerations. Each individual filament usually has an average diameter of about 8 μm (.32 mils) and an average denier of at least about .70 dpf. The average tensile strength of the fiber is preferably at least about 200 ksi (1.38 GPa), more preferably at least about 400 ksi (2.76 GPa), more highly preferably at least about 600 ksi (4.14 GPa), and most preferably at
30 least about 800 ksi (5.48 GPa). The tensile modulus of the heat-treated fiber is preferably at least 35 msi (241 GPa) and more preferably at least 42 msi (290 GPa). The tensile modulus of non-heat-treated fiber is usually less than (about half of) the tensile modulus of heat-treated fiber.

 The present invention improves the stability in the simultaneously spinning of a
35 large number of closely space filaments. It makes it possible to effectively spin while minimizing line breaks. It has the additional benefits of reducing denier variation between different filaments.

Examples

The following examples are for illustrative purposes only. They should not be taken as limiting the scope of either the specification or the claims. Unless stated otherwise, all parts and percentages are by weight.

5 Example 1 - Spinning of PBO Dope

A polymer solution which consisted of 14 weight percent of cis-polybenzoxazole (30 I.V.) and polyphosphoric acid was extruded from the spinneret at 160°C under the conditions shown in Table 1. The extruded filaments were coagulated in deionized water at about room temperature. The resulting fiber was washed as it traveled around five rollers. The
10 surface water was removed using an air knife, and the fiber passed over a series of heated roller pairs at sequentially increasing temperatures to dry. Table 1 describes the observations of spinning and the physical properties for each fiber. The table shows that filament breaks occurred more frequently when spinning at high speeds outside of the claimed conditions. Table 1 refers to tenacity (tensile strength) in terms of grams/denier. For polybenzoxazole, one
15 gram/denier was approximately equivalent to 20 ksi (the direct equivalency was $\text{ksi} = 12.83 \text{ gram/denier times density of fiber}$ which for PBO yields an equivalency of 20.481 ksi).

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Table 1

Experimental #		A	B	C	D	E	F	G	H	I	J	K
SPINNING SPECIFICATIONS/PROPERTIES	unit	example	reference	reference	reference	reference	reference	example	reference	example	example	reference
Through-put per spinneret	g/min	79.9	79.9	79.9	47.9	79.9	79.9	79.9	79.9	40	152	151
No. of orifices		334	334	334	334	334	334	334	334	167	167	100
Diameter of orifice	mm	0.22	0.22	0.22	0.17	0.22	0.22	0.22	0.22	0.25	0.32	0.4
Through-put per orifice	ml/min	0.12	0.12	0.12	0.07	0.12	0.12	0.12	0.12	0.12	0.46	0.77
Shear rate	/sec	1946	1946	1946	2529	1946	1946	1946	1946	1328	2407	2045
Orifice density	/cm ²	5.00	5.00	5.57	5.00	5.00	5.00	5.00	5.00	4.00	4.00	2.39
Surface area of Spinneret	cm ²	66.8	66.8	60	66.8	66.8	66.8	66.8	66.8	41.8	41.8	41.8
Distance between Spinneret and quench chamber	cm	2	-	-	-	2	2	2	2	2	3	3
Length of Quench Chamber	cm	20	-	-	-	20	20	20	20	35	50	-
Quench air velocity	m/sec	0.2	-	-	-	0.2	0.2	0.6	0.01	0.2	0.2	-
Quench air temperature	°C	70	-	-	-	110	40	70	22	60	60	-
Distance between spinneret and coagulation bath	cm	35	35	35	35	35	35	35	35	35	50	50

Table 1 ...continued

Experimental #		A	B	C	D	E	F	G	H	I	J	K
Spinning speed	m/min	200	200	200	120	200	200	200	200	200	380	380
Spin Draw Ratio		63	63	63	37	63	63	63	63	80	64	62
Spinnability		Excellent	Impossible	Poor	Good	Impossible	Impossible	Poor	Impossible	Excellent	Good	Good
Fiber breaks	T/hrs	0.02	>20	2.8	1.3	>20	>20	3.3	>20	0.015	0.5	0.62
Washing/Drying		IN-LINE			IN-LINE			IN-LINE		IN-LINE	OFF-LINE	OFF-LINE
Dry Fiber properties												
DENIER		501			499			503		250	501	499
Filament Denier	dpt	1.5			1.5			1.5		1.5	3	5
Tenacity	g/d	40			38			39		40	39	41
Elongation at break	%	3.9			3.8			3.8		3.8	8.7	3.9
Tensile Modulus	g/d	1119			1056			1187		1211	1128	998
Weathering Test	%	89			88			86		89	82	78
Moisture Content	%	0.7			0.8			0.7		0.7	0.8	0.8

Table 1continued

Experimental #		A	B	C	D	E	F	G	H	I	J	K
Void Generation		None			None			None		None	None	None
Kink Band		None			None			None		None	Some	Some
Heat Treatment		OFF-LINE			OFF-LINE			OFF-LINE		OFF-LINE	OFF-LINE	OFF-LINE
Temperature of Heat Treatment	°C	550			550			550		550	550	550
Residence time	sec	10			10			10		10	10	10
Stress of heat treatment	g/d	4.5			4.5			4.5		4.5	4.5	4.5
Heat treated fiber properties												
Tenacity	g/d	34			35			35		39	38	38
Elongation at Break	%	2.0			2.0			2.0		2.1	2.0	2.1
Tensile Modulus	g/d	2230			2201			2175		2231	2047	1984
Weathering test	%	90			89			91		90	88	85
Void Generation		None			None			None		None	None	None
Kink Band		Few			Few			Few		Few	Some	Some

Claims:

1. A process for making a fiber made-up of more than one filament from a liquid-crystalline dope that contains a solvent and a polybenzazole polymer which is polybenzoxazole, polybenzothiazole or a copolymer thereof, said process having the steps of:
 - (A) spinning the dope at a temperature greater than 100°C through a spinneret that contains a plurality of orifices, wherein the density of orifices in the spinneret is at least 2.0 per cm², whereby a plurality of dope filaments is formed;
 - (B) drawing the dope filaments across an air gap that contains a gas at a temperature of at least 50°C and at most 100°C, wherein the gas flows through the air gap at a rate sufficient to uniformly reduce the temperature of the dope filaments; and
 - (C) contacting the drawn dope filaments with a fluid such that the solvent is removed from the filaments.
2. The process of Claim 1 in which the filaments are combined into one or more fibers before, during or after the time said filaments are contacted with said washing fluid.
3. The process of Claim 1 in which the flow rate of the gas in the air gap is at least .02 meters/second.
4. The process of Claim 1 in which the flow rate of the gas in the air gap is at least .05 meters/second.
5. The process of Claim 1 in which the flow rate of the gas in the air gap is at least 0.1 meters/second.
6. A polybenzazole filament made by the process of Claim 1.
7. A polybenzazole filament with an average filament diameter of no more than about 21 μm obtained through the process of Claim 1.
8. A polybenzazole filament with an average filament diameter of no more than about 18 μm obtained through the process of Claim 1.
9. The polybenzazole filament of Claim 6 in which the polybenzazole is polybenzoxazole.
10. The polybenzazole filament of Claim 7 in which the polybenzazole is polybenzoxazole.

