US 20230295842A1

(19) **United States**

(12) **Patent Application Publication**

Weisenberger et al.

(10) **Pub. No.: US 2023/0295842 A1**

(43) **Pub. Date: Sep. 21, 2023**

(54) **METHOD OF MAKING POLYACRYLONITRILE BASED CARBON FIBERS AND POLYACRYLONITRILE BASED CARBON FIBER FABRIC**

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(21) Appl. No.: **18/073,432**

(22) Filed: **Dec. 1, 2022**

Related U.S. Application Data

(63) Continuation-in-part of application No. 16/806,326, filed on Mar. 2, 2020, now abandoned.

(60) Provisional application No. 62/813,359, filed on Mar. 4, 2019.

Publication Classification

(51) **Int. Cl.**
D01F 9/22 (2006.01)

(52) **U.S. Cl.**
CPC ***D01F 9/225*** (2013.01); *D10B 2101/12* (2013.01); *D10B 2401/04* (2013.01); *D10B 2401/06* (2013.01); *D10B 2403/03* (2013.01)

(57) **ABSTRACT**

Methods to produce a polyacrylonitrile-based carbon fiber and polyacrylonitrile-based carbon fiber fabric with physical characteristic closely resembling rayon-based carbon fibers are disclosed. A polyacrylonitrile-based carbon fiber and polyacrylonitrile-based carbon fiber fabric with a unique combination of physical properties are also disclosed.

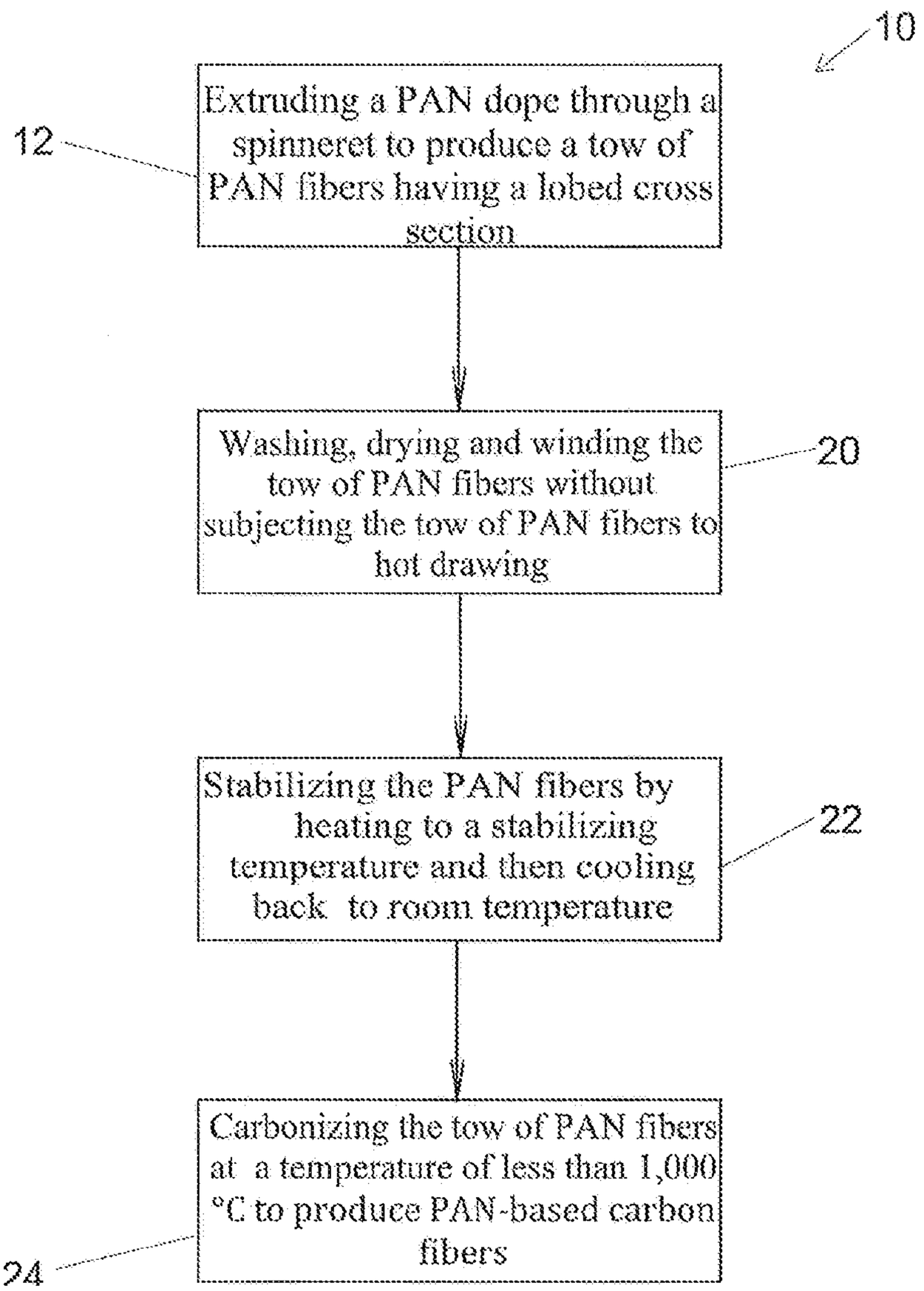


FIG.1

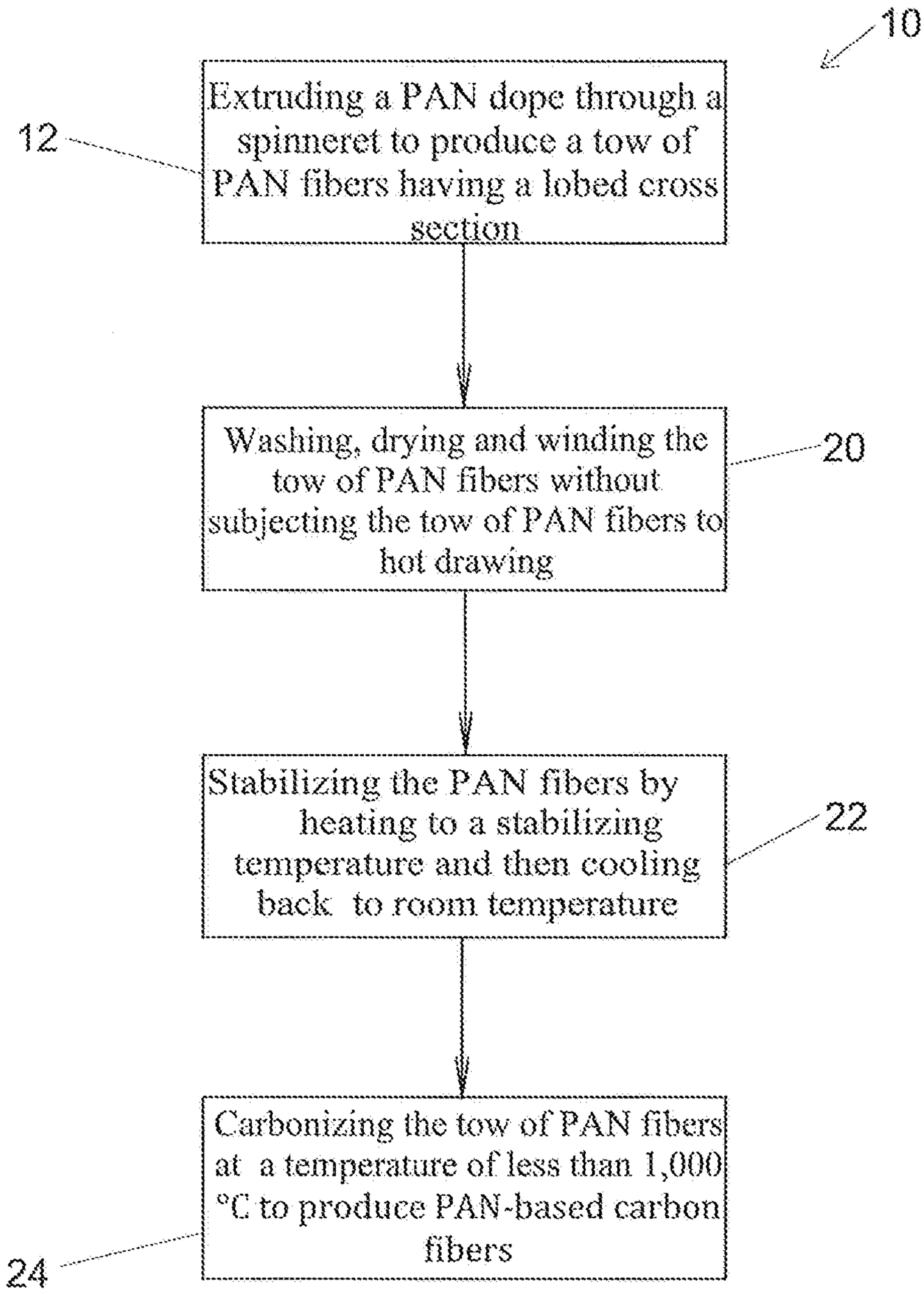

10
Extruding a PAN dope through a spinneret to produce a tow of PAN fibers having a lobed cross section
12
Washing, drying and winding the tow of PAN fibers without subjecting the tow of PAN fibers to hot drawing
20
Stabilizing the PAN fibers by heating to a stabilizing temperature and then cooling back to room temperature
22
Carbonizing the tow of PAN fibers at a temperature of less than 1,000 °C to produce PAN-based carbon fibers
24

FIG. 2

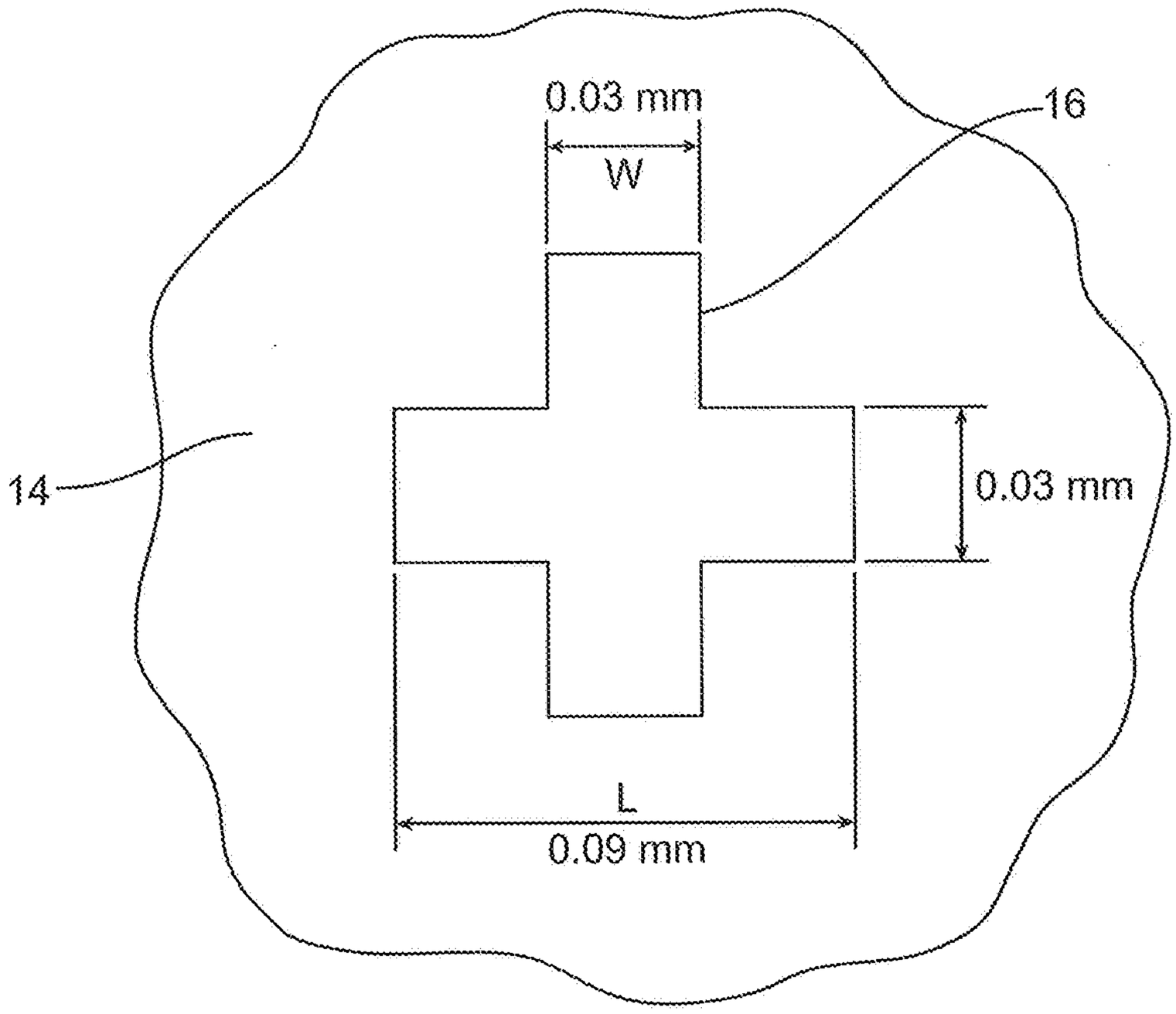


FIG. 3

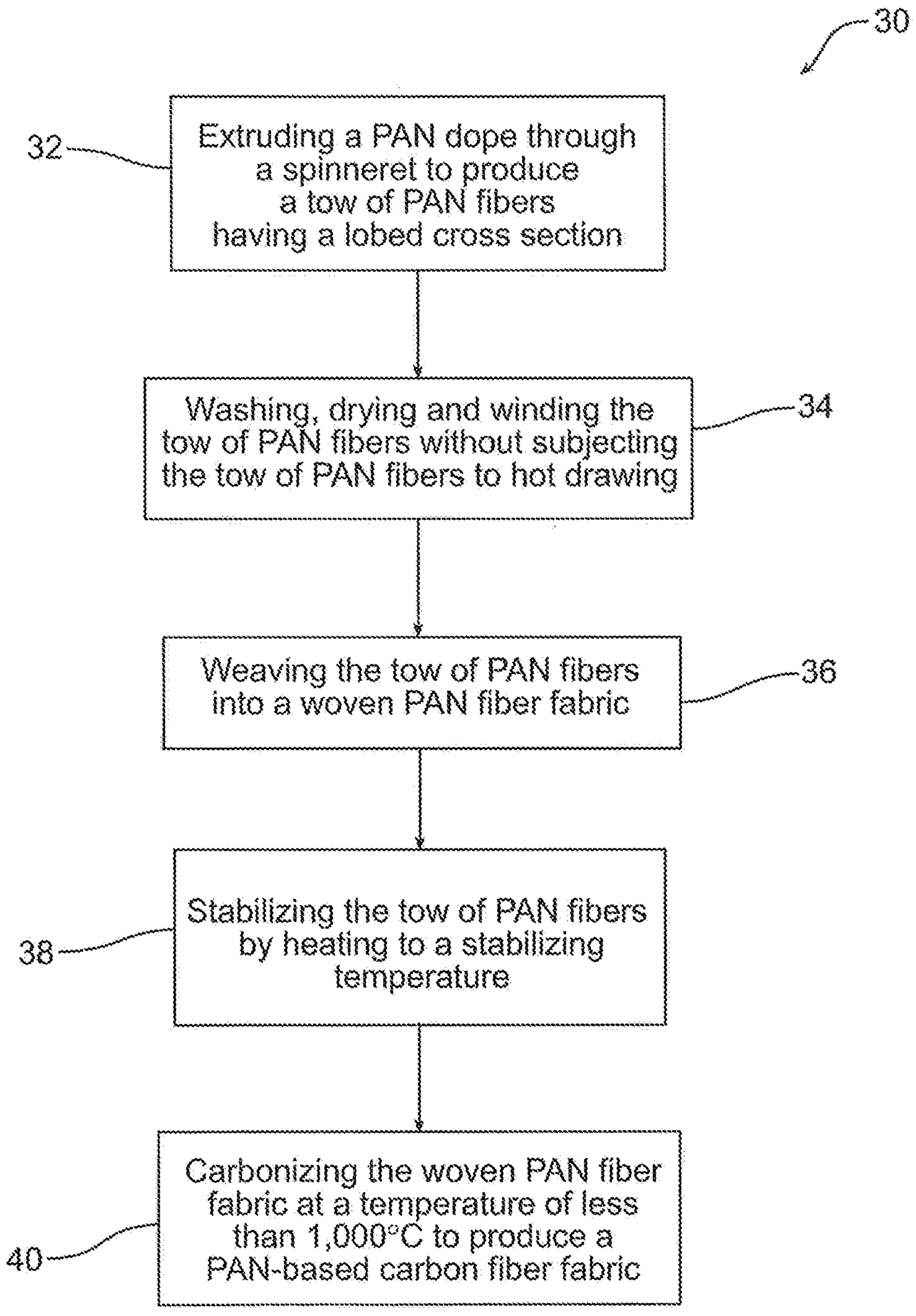

30
32
Extruding a PAN dope through a spinneret to produce a tow of PAN fibers having a lobed cross section
Washing, drying and winding the tow of PAN fibers without subjecting the tow of PAN fibers to hot drawing
34
Weaving the tow of PAN fibers into a woven PAN fiber fabric
36
Stabilizing the tow of PAN fibers by heating to a stabilizing temperature
38
Carbonizing the woven PAN fiber fabric at a temperature of less than 1,000°C to produce a PAN-based carbon fiber fabric
40

FIG. 4

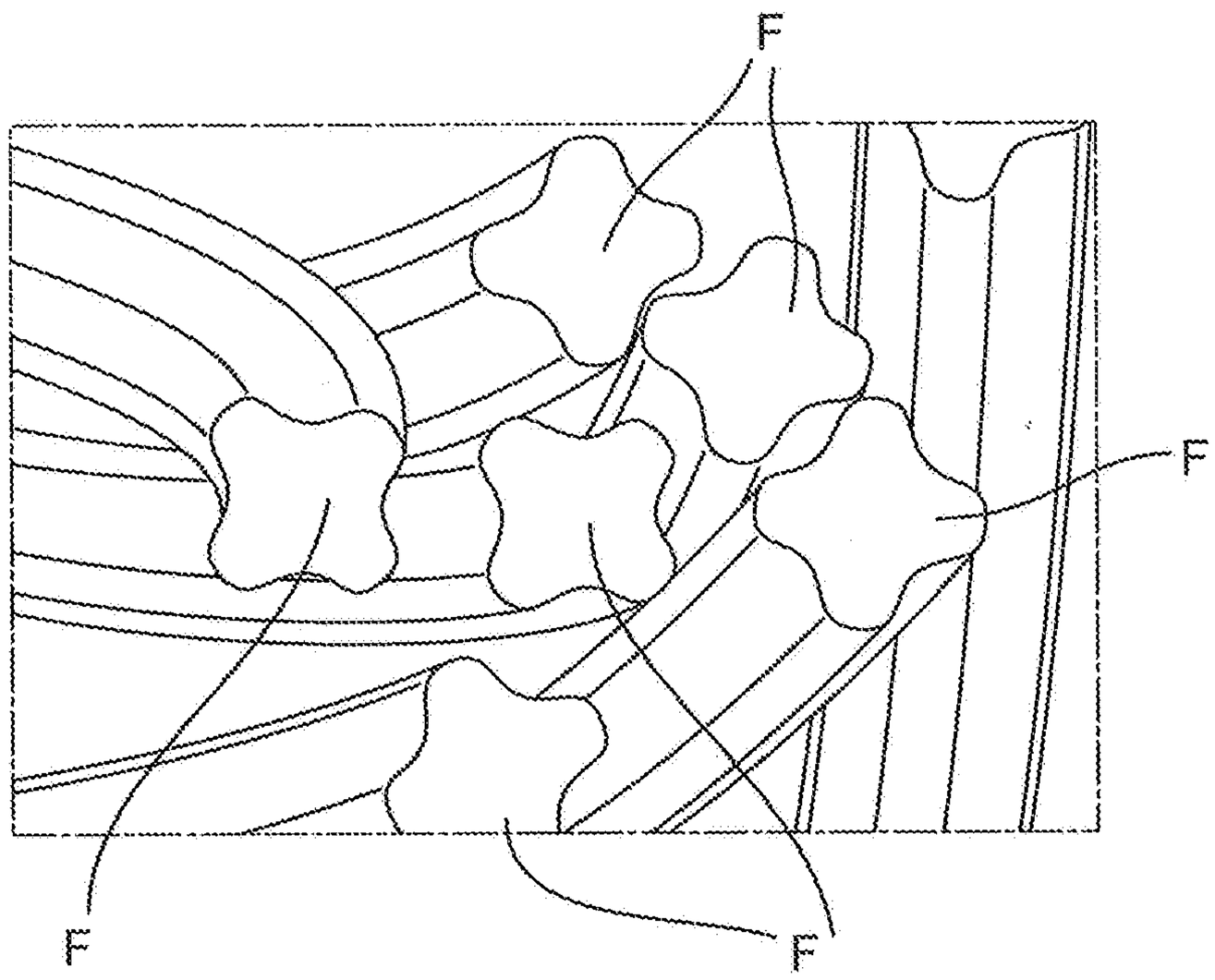
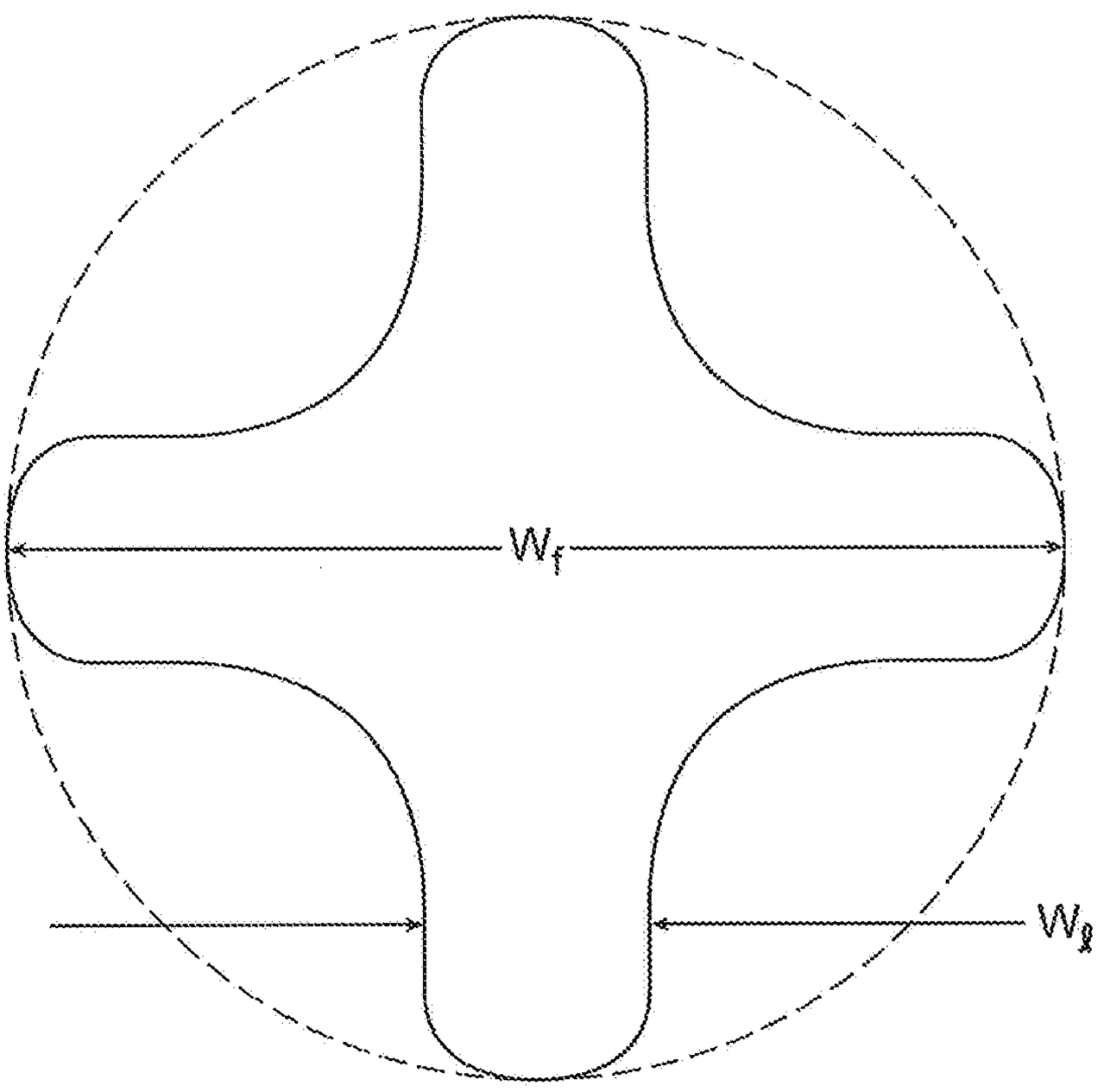


FIG. 5



$$\frac{W_l}{W_f} \geq 0.1$$

METHOD OF MAKING POLYACRYLONITRILE BASED CARBON FIBERS AND POLYACRYLONITRILE BASED CARBON FIBER FABRIC

RELATED APPLICATION

[0001] This application is a continuation-in-part (CIP) of U.S. patent application Ser. No. 16/806,326, filed on Mar. 2, 2020, which claims priority to U.S. Provisional Patent Application Ser. No. 62/813,359 filed on Mar. 4, 2019, both of which are hereby incorporated by reference in their entirety.

GOVERNMENT SUPPORT

[0002] This invention was made with government support under Grant No. W31P4Q-17-C-0009 awarded by the US Army AMRDEC and Materials Sciences Corporation. The government has certain rights in the invention.

TECHNICAL FIELD

[0003] This document relates generally to the field of carbon fibers and, more particularly to a new and improved method for making polyacrylonitrile-based carbon fibers with low thermal conductivity and a lobed profile for ablative composite and other applications.

BACKGROUND

[0004] Rayon-based carbon fibers have long been used for ablative composite applications such as for heat shields and the like required for space vehicles and other technologically advanced vehicles and applications. Environmental concerns related to the production of rayon have led to the cessation of the domestic production of rayon. As a result, the United States has had to rely on old stock and foreign production for the rayon used to produce carbon fibers having the desired characteristics for ablative composite applications. This is a strategic concern for which, to date, there has been no clear solution.

[0005] This document relates to the production of polyacrylonitrile or PAN-based carbon fibers having a unique combination of properties for PAN-based carbon fibers that approach those characteristic of rayon-based carbon fibers. More particularly, the PAN-based carbon fibers of the present method are characterized by (a) a lobed cross section that provides for enhanced mechanical interlocking between fibers, (b) a relatively low thermal conductivity characteristic of rayon-based carbon fibers, and (c) tensile properties similar to rayon-based carbon fibers.

SUMMARY

[0006] In accordance with the purposes and benefits described herein, a new and improved method is provided for the production of PAN-based carbon fibers. That method comprises the steps of: (a) extruding a PAN dope through a spinneret to produce a tow of PAN fibers having a lobed cross section, (b) washing, drying and winding the tow of PAN fibers without subjecting the PAN fibers to hot drawing and (c) carbonizing the tow of PAN fibers at a temperature of less than 1,000° C. to produce PAN-based carbon fibers. For the purposes of this document, "hot drawing" means the drawing of fibers at temperatures at or above 100° C.

[0007] The method may include using a spinneret with a +-shaped opening to produce PAN fiber filaments having a cross section with a lobed shape.

[0008] The method may further include the step of stabilizing the tow of PAN fibers prior to carbonization. That stabilizing may include heating the PAN fibers to 240°–280° C.

[0009] In some embodiments, during carbonizing, the highest fiber temperature reached may be between 850° C. and 950° C. In some embodiments, during carbonizing, the highest fiber temperature reached may be between 885° C. and 915° C.

[0010] PAN-based carbon fibers made by this method are also claimed. Those PAN-based carbon fibers may be characterized by the lobes of the PAN fiber filaments having a characteristic width greater than 10% of a width of the PAN fiber filaments at the largest dimension of the PAN fiber filaments.

[0011] In accordance with an additional aspect, a method is provided for producing a polyacrylonotrile-based/(PAN)-based carbon fiber fabric, comprising: (a) extruding a PAN dope through a spinneret to produce a tow of PAN fibers having a lobed cross section, (b) washing, drying and winding the tow of PAN fibers without subjecting the PAN fibers to hot drawing, (c) weaving the tow of carbon fibers into a woven PAN fiber fabric and (d) carbonizing the woven PAN fiber fabric at a temperature of less than 1,000° C. to produce a woven PAN-based carbon fiber fabric.

[0012] The method may include using a spinneret with a +-shaped opening to produce PAN fiber filaments having a cross section with a lobed shape.

[0013] The method may further include the step of stabilizing the tow of PAN fibers prior to carbonizing. That stabilizing may include heating the PAN fibers to 240°–280° C.

[0014] In some embodiments, during carbonizing, the highest fiber temperature reached may be between 850° C. and 950° C. In some embodiments, during carbonizing, the highest fiber temperature reached may be between 885° C. and 915° C.

[0015] PAN-based carbon fiber fabrics made by this method are also claimed. Those PAN-based carbon fiber fabrics may be characterized by the lobes of the PAN fiber filaments having a characteristic width greater than 10% of a width of the PAN fiber filaments at the largest dimension of the PAN fiber filaments.

[0016] In the following description, there are shown and described several embodiments of the methods as well as the PAN-based carbon fiber and PAN-based carbon fiber fabric products made from the methods. As it should be realized, the methods and the products of those methods are capable of other, different embodiments and their several details are capable of modification in various, obvious aspects all without departing from the methods and products as set forth and described in the following claims. Accordingly, the drawings and descriptions should be regarded as illustrative in nature and not as restrictive.

BRIEF DESCRIPTION OF THE DRAWING FIGURES

[0017] The accompanying drawing figures incorporated herein and forming a part of the specification illustrates

several aspects of the methods and products of those methods and together with the description serves to explain certain principles thereof.

[0018] FIG. **1** is a schematic representation of the carbon fiber production process.

[0019] FIG. **2** illustrates the geometry of a +-shaped spinneret opening of the type that may be utilized to produce the lobed PAN fibers used in the production of the PAN-based carbon fibers.

[0020] FIG. **3** is a schematic representation of the carbon fiber fabric production method.

[0021] FIG. **4** is a cross section illustrating multiple fibers produced as a result of the lobed shaped cross section of those fibers.

[0022] FIG. **5** illustrates the lobe characteristics of the PAN-based carbon fibers.

DETAILED DESCRIPTION

[0023] Reference is now made to FIG. **1** which schematically illustrates the new and improved method **10** for producing polyacrylonitrile-based carbon fibers/PAN-based carbon fibers. For purposes of this document, the terminology "PAN-based carbon fibers" includes carbon fibers made from polymer precursor fibers with a chemical composition consisting greater than 80% of the acrylonitrile monomer repeat units. The glass transition temperature for such fibers is about 110° C. as determined by dynamic mechanical analysis (DMA) by the temperature of the peak of the tan(delta).

[0024] That method includes the step **12** of extruding a PAN dope of a type known in the art through a spinneret to produce a tow of PAN fibers wherein the filaments thereof have a lobed cross section. The spinneret **14** may include a plurality of openings **16** through which the PAN dope is extruded into a water coagulation bath of a type known in the art to be useful in the spinning of PAN fibers. More particularly, as illustrated in FIG. **2**, each spinneret opening or hole **16** may have a +-shape adapted to produce fibers having the appearance of crenulated fibers. For example, each leg **18** may have a width W of 0.03 mm with the opposed legs having a total length L of 0.09 mm.

[0025] Following extruding, the method includes the washing, drying and winding **20** of the tow of PAN fibers without subjecting the PAN fibers to hot drawing: that is, without drawing of the fibers at temperatures above 100° C.: that is, without drawing the fibers at a temperature above the glass transition temperature (T_g) of the final PAN fibers as measured by DMA. The absence of hot drawing is an important factor in producing PAN-based carbon fibers having the desired physical characteristics for use in ablative composite applications.

[0026] Hot drawing of the PAN fibers collapses residual microporosity interior the filaments, densifying the fibers. It also increases the relative degree of molecular orientation along the fiber axes. Here, preserving some residual microporosity in the PAN filaments is desirable for low thermal conductivity in the final carbon fiber. Moreover, a relatively lower tensile modulus of the carbon fiber is desired to improve drape-ability of the fabric and more-closely mimic rayon-based carbon fiber.

[0027] Following winding, the method includes stabilizing **22** the tow of PAN fibers by heating to a stabilizing temperature of, for example, 240°–280° C. in air and then cooling back to room temperature. In one particularly useful embodiment, the tow of PAN fibers is heated to 265° C.

[0028] Following stabilizing, the tow of PAN fibers is subjected to carbonizing **24** in an inert atmosphere at a temperature of less than 1,000° C. to produce PAN-based carbon fibers from the PAN fiber tow. In one possible embodiment of the method, the highest fiber temperature reached during carbonization is between 850° C. and 950° C. In another possible embodiment of the method, the carbonization temperature is between 885° C. and 915° C. In still another, the carbonization temperature is 900° C. In one possible embodiment, the fibers are maintained at peak carbonization temperature for between one and ten minutes.

[0029] Reference is now made to FIG. **3** which illustrates the new and improved method **30** of producing a polyacrylonitrile-based carbon fiber fabric/PAN-based carbon fiber fabric. That method includes the step **32** of extruding a PAN dope of a type known in the art through a spinneret to produce a tow of PAN fibers having a lobed cross section.

[0030] As noted above, the spinneret **14** may include a plurality of openings **16** through which the PAN dope is extruded into a water coagulation bath of a type known in the art to be useful in the spinning of PAN fibers. More particularly, as illustrated in FIG. **2**, each spinneret opening or hole **16** may have a +-shape adapted to produce fibers having the appearance of crenulated fibers. For example, each leg **18** may have a width W of 0.03 mm with the opposed legs having a total length L of 0.09 mm.

[0031] Following extruding, the method includes the washing, drying and winding **34** of the tow of PAN fibers without subjecting the PAN fibers to hot drawing: that is, without drawing of the fibers at temperatures above 100° C. As noted in more detail above, the absence of hot drawing is an important factor in producing PAN-based carbon fibers having the desired physical characteristics for use in ablative composite applications.

[0032] Following winding, the method includes the step **36** of weaving the tow of PAN fibers into a woven PAN fiber fabric. Durable weave patterns are those with more drape, such as 8 harness satin.

[0033] Following weaving, the method includes stabilizing **38** the PAN fibers of the woven fabric by heating in air to a desired stabilizing temperature of, for example, 240-280° C. In one particularly useful embodiment, the tow of PAN fibers is heated to 265° C.

[0034] Next, the woven PAN fiber fabric is subjected to carbonizing **40** in an inert atmosphere at a temperature of less than 1,000° C. to produce a PAN-based carbon fiber fabric from the PAN woven PAN fiber fabric. In one possible embodiment of the method, the highest fiber temperature reached during carbonization is between 850° C. and 950° C. In another possible embodiment of the method, the carbonization temperature is between 885° C. and 915° C. In still another, the carbonization temperature is 900° C.

[0035] As should be appreciated, the crenulated or lobed cross section of the PAN fiber filaments allows the fibers F to better mechanically interlock into the matrix material of the final composite.

[0036] The PAN-based carbon fiber filaments produced by the method disclosed herein include lobes or legs having a characteristic width W_1 greater than 10% of a width W_f of the fiber filaments at the largest dimension of the fiber filaments: that is $W_1/W_f >= 0.1$ (see FIG. **5**).

[0037] The PAN-based carbon fibers are characterized by a unique combination of physical characteristics that make them particularly useful for ablative composite applications. The PAN-based carbon fibers have a thermal diffusivity of less than 2 mm^2/sec along the fiber axis. More specifically, with the low-fire carbonization temperature of 900° C. an axial thermal diffusivity of as low as 1.503 mm^2/sec has been achieved. The incumbent rayon based carbon fiber has an axial thermal diffusivity of 1.944 mm^2/sec.

[0038] The PAN-based carbon fibers have a modulus of less than 100 GPa along the fiber axis in tension. More specifically, under the no draw conditions, a modulus of as low as 60.06 GPa has been achieved. The rayon based carbon fiber is approximately 39.7 GPa.

[0039] The PAN-based carbon fibers have a break stress of less than 1 GPa along the fiber axis in tension. More specifically, under the no draw conditions, a break stress of 0.506 GPa has been achieved. The rayon based carbon fiber is approximately 0.454 GPa.

[0040] Finally, the PAN-based carbon fibers have a lobe width W_1/max fiber diameter W_f of greater than 0.1. More specifically, under the indicated processing conditions, a W_1 of 6 microns and a W_f of 12 microns for a W_1/W_f of 0.5 has been achieved.

Experimental Section:

[0041] Dope Preparation:

[0042] 14 wt % of polyacrylonitrile (PAN) polymer powder (relative to the solvent, dimethylsulfoxide, DMSO plus the PAN masses) was mixed and prepared into a spinning solution or dope. For example, 196 g of PAN was mixed with 1204 g of DMSO. It is recommended that the PAN powder be dried under vacuum for 1 hour at 50° C. to remove moisture. After hand mixing to break up any large polymer powder agglomerates, the dope was poured into a purpose-built dope mixer and heated to 55° C. for overnight mixing. The dope was then extracted from the mixer with a 15 psi overpressure of nitrogen, directly into the spinning pump system. Next, the dope in the pump system was placed under vacuum to remove any entrained air bubbles in the dope. This degassing step is important for good fiber spinning.

[0043] Spin Preparation:

[0044] First the spinneret was inspected for cleanliness by optical microscopy, to ensure that no capillaries were clogged. Inspection of individual capillaries is best done under the microscope. If any are clogged, the spinneret is placed into a container of clean dimethylacetamide (DMAc) and sonicated using a wand sonicator at an intensity of 20% for 15 minutes. Similarly, after a spin run, this cleaning process was repeated and the spinneret was allowed to sonicate for one hour.

[0045] A new 3 micron filter element was placed in the filter housing. Then the spinning pump system, the filter housing, and the spinneret die head were heated to 50° C. On back to back spin runs, the same filter element is typically used. Down the line, the heated godet dryer rollers were heated to 90° C. The pump and heated godet were given an hour to fully heat up. The adapter hardware for the wet spinning spinneret was also placed in an oven at 50° C.

[0046] A 0.65 wt % silicone oil based emulsion spin finish was prepared by mixing 3.25 g of a proprietary spin finish concentrate, with 196.75 g of deionized water (1.625 wt %). As well a 0.5 wt % polyvinyl alcohol (PVA) spin/warp finish was prepared by mixing 11 g of a warp sizing, with 189 g of deionized water (5.5 wt %).

[0047] Spinning Procedure:

[0048] The spinning pump was connected to the filter manifold and die head by flexible pressure hoses. 40-50 ml of dope was purged through all components to eliminate contaminates and air bubbles. On back to back spin runs only 20 ml of dope was purged through the system. The spinneret was attached to the preheated adapter hardware and then attached to the die head. At an initial flow rate of 3.0 ml/min the spinneret (500 holes) was submerged into a 78 wt % DMSO/DI water coagulation bath and the nascent 500 filament tow is formed. The spinneret used was a special shaped hole spinneret as to generate fibers with cross sectional shapes that emulated crenulated fiber—(as observed in lobed fibers).

[0049] Out of coagulation the tow was pulled on to the Y0 (initial) godet set to 0.9 m/min. Upon stable spinning, the flow rate was incrementally stepped down from approximately 4 ml/min (for start-up) to 1.38 ml/min. After coagulation, the fiber tow was then stretched 2.1× through a 50 wt % DMSO/DI water bath (at room temperature) and pulled onto the Y1 (second) godet at 1.9 m/min. The fiber tow then travelled down the line through six deionized water wash baths at 1.9 m/min speeding up slightly to 2-2.2 m/min to keep the tow taught (line speeds would be much higher in commercial practice). Significantly, no hot drawing was applied to the tow (typically precursor PAN fiber is significantly drawn in steam or glycerol at temperatures of about 160° C.).

[0050] The fiber tow was then passed through the silicone emulsion spin finish and onto the heated godet (90° C.) for drying. After drying on the first four rollers, the fiber tow passed through the PVA spin finish bath at the fifth roller. The fiber was then dried on the remaining three rollers of the heated godet and taken onto cardboard cores at 2 m/min. The tow was traverse wound on the cardboard cores and accumulated for subsequent weaving processing. Significantly, prior to weaving and/or thermal conversion, the fibers were stretched slightly in a heated water bath (at approximately 90° C.) but were not exposed to temperatures at or above 100° C. in order to generate the desired combination of physical properties in the final carbon fiber product.

[0051] Weaving:

[0052] The spun tow, in continuous form, was woven into a satin-harness fabric. An approximately 6 inch wide by 10s of feet long fabric was woven from 180 warp ends of the low k PAN precursor fiber.

[0053] Thermal Conversion:

[0054] Thermal conversion can be done on the spun PAN fiber, or on the woven fabric. For the purposes of ablative carbon composites, the woven is preferred.

[0055] Stabilization:

[0056] The woven fabric was placed in an air convection oven, unconstrained, and heated at a rate of 10 C/min to 175° C., then 0.5° C./min to 265° C. The fabric was not stacked or folded directly, instead a breathable carbon fiber paper was placed between each layer of fabric. Then it was allowed to cool to room temperature.

[0057] Carbonization:

[0058] The stabilized fabric was carbonized under an inert atmosphere by ramping to 900° C. at 5° C./min. We consider this a 'low-fired' carbonization temperature. Higher carbonization temperatures increased the resulting carbon fiber

thermal diffusivity (and thermal conductivity) beyond values of interest, see Table 1. The highest heat treatment (HTT) needs to be <1000 C.

[0059] The primary goal was to demonstrate a PAN-based carbon fiber with as similar as possible thermal, and mechanical properties to the incumbent rayon-derived carbon fiber—shown in Table 1 as Rayon derived carbon fiber. First, the data suggested that a highest heat treatment temperature (HTT) during carbonization of 900 C resulted in the PAN-based carbon fiber with thermal diffusivity most similar to the Rayon derived carbon fiber. Second, the 900 C HTT resulted in the modulus of the PAN-based carbon fiber most similar to the Rayon derived carbon fiber. Third, the no-hot-draw condition of the PAN precursor, coupled with the low fire HTT of 900 C resulted in the PAN-based carbon fiber most similar to the Rayon derived carbon fiber. Lastly, the lobed (or crenulated) shape of the PAN precursor fiber, rendered a PAN-based carbon fiber similar to the Rayon carbon fiber. The absence of hot drawing of the precursor PAN fiber contributed to the lower modulus and lower thermal diffusivity measured in the final carbon fiber for reasons described above.

[0060] Together these three issues; low fire carbonization temperature, no precursor if draw, and lobed fiber shape, result in a unique low k PAN-based carbon fiber, similar thermally, mechanically, and in cross sectional shape, to the Rayon based carbon fiber.

TABLE 1

Thermal and mechanical properties of low-k PAN derived carbon fibers as a function of highest heat treatment temperature, compared to Rayon derived carbon fiber.

	HTT	Thermal Diffusivity (mm^2/s)	Stress at Break (MPa)	Modulus (GPa)	Strain at Break (%)	H/C Ratio	Corrected Heat Capacity at 25 C (J/gC)
Rayon derived carbon fiber	N/A	1.944 (0.052)	454 (144)	39.7 (2)	1.14 (0.35)	0.01645	0.8740
Baseline	900	1.549 (0.079)	981 (381)	135.3 (15)	0.71 (0.24)	0.02337	1.0589
Low-k	1000	3.805 (0.242)	1786 (404)	204 (13)	0.87 (0.19)	0.00862	0.6802
PAN (367)	1200	5.83 (0.127)	1889 (411)	206 (14)	0.92 (0.19)	0.00643	0.6302
	1400	9.713 (0.573)	1774 (693)	231 (13)	0.76 (0.28)	0.00435	0.6647
	1600	13.879 (1.744)	2010 (570)	248 (23)	0.81 (0.23)	0.01383	0.6343
Unstretched	900	1.503 (0.108)	1167 (469)	92 (14)	1.27 (0.50)	0.02432	0.8310
Low k	1000	3.662 (0.285)	1678 (443)	175 (9)	0.95 (0.23)	0.00605	0.6222
PAN (368):	1200	5.868 (0.199)	1863 (441)	191 (12)	0.98 (0.22)	0.00865	0.7299
	1400*	7.964 (0.226)	2025 (511)	210 (17)	0.96 (0.20)	0.00402	0.8092
	1600	13.706 (0.465)	1134 (387)	228 (29)	0.49 (0.15)	0.00581	0.6167
No Draw (374)	900		506.31 (168.8)	60.06 (3.43)	0.833 (0.237)		

Standard derivations are shown in parenthesis.

[0061] Typically the fibers were stretched in the spinning process in 2 stages, which involved a heated water stretch (stage 1) followed by a hot glycerol stretch (stage 2). Here "Unstretched"=stretched in hot water, but not stretched in hot glycerol, or no 2nd stage stretch. "No Draw"=not stretched in hot water or hot glycerol (no stage 1 or stage 2). However, in all cases, the fibers were drawn approximately 2× just after their initial coagulation in the first step of the washing process.

[0062] The foregoing has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the embodiments to the precise form disclosed. Obvious modifications and variations are possible in light of the above teachings. All such modifications and variations are within the scope of the appended claims when interpreted in accordance with the breadth to which they are fairly, legally and equitably entitled.

What is claimed:

1. A method of producing polyacrylonitrile (PAN)-based carbon fibers, comprising:

extruding a PAN dope through a spinneret to produce a tow of PAN fibers having a lobed cross section and a glass transition temperature above 100° C.;

washing, drying and winding the tow of PAN fibers without subjecting the PAN fibers to hot drawing at a temperature at or above 100° C.; and

stabilizing and carbonizing the tow of PAN fibers at a temperature of less than 1,000° C. to produce PAN-based carbon fibers.

2. The method of claim **1**, including using a spinneret with a +-shaped opening to produce PAN fiber filaments having a cross section with a lobed shape.

3. The method of claim **2**, wherein the stabilizing includes heating the tow of PAN fibers to 240°–280° C.

4. The method of claim **2**, wherein a highest fiber temperature reached during carbonization is between 850° C. and 950° C.

5. The method of claim **2**, wherein a highest fiber temperature reached during carbonization is between 885° C. and 915° C.

6. A method of producing a polyacrylonitrile (PAN)-based carbon fiber fabric, comprising:

extruding a PAN dope through a spinneret to produce a tow of PAN fibers having a lobed cross section and a glass transition temperature above 100° C.;

washing, drying and winding the tow of PAN fibers without subjecting the PAN fibers to hot drawing at a temperature at or above 100° C.;

weaving the tow of PAN fibers into a woven PAN fiber fabric; and

stabilizing and carbonizing the woven PAN fiber fabric at a temperature of less than 1,000° C. to produce PAN-based woven carbon fiber fabric.

7. The method of claim **6**, including using a spinneret with a +-shaped opening to produce PAN fiber filaments having a cross section with a lobed shape.

8. The method of claim **7**, wherein the stabilizing includes heating the woven PAN fiber fabric to 265° C.

9. The method of claim **6**, wherein a highest fiber temperature reached during carbonization is between 850° C. and 950° C.

10. The method of claim **6**, wherein a highest fiber temperature reached during carbonization is between 885° C. and 915° C.

11. The method of claim **6**, including using a spinneret with a +-shaped opening to produce PAN fibers having a cross section with a lobed shape.

12. The PAN-based carbon fibers made by the method of claim **1**.

13. The PAN-based carbon fibers of claim **12**, wherein lobes of PAN fiber filaments have a characteristic width greater than 10% of a width of said PAN fiber filaments at a largest dimension of said PAN fiber filaments.

14. The PAN-based carbon fiber fabric made by the method of claim **7**.

15. The PAN-based carbon fiber fabric of claim **14**, wherein lobes of said PAN fiber filaments have a characteristic width greater than 10% of a width of said PAN fiber filaments at a largest dimension of said fiber.

16. A PAN-based carbon fiber, comprising a thermal diffusivity of less than 2 mm^2/sec along a longitudinal axis of the PAN-based carbon fiber, a modulus of less than 100 GPa along the longitudinal axis in tension, and a lobe width W_1/max fiber diameter W_f greater than 0.1.

17. The PAN-based carbon fiber of claim **16**, wherein the thermal diffusivity is less than 1.6 mm^2/sec along the longitudinal axis of the PAN-based carbon fiber.

18. The PAN-based carbon fiber of claim **17**, wherein the modulus is less than 65 GPa along the longitudinal axis in tension.

19. The PAN-based carbon fiber of claim **16**, wherein the PAN-based carbon fiber has a break stress of less than 1 GPa along the longitudinal axis in tension.

* * * * *