United States Patent [19]

Olcott

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[54] **TURBINE BLADE**

[75] Inventor: **Eugene L. Olcott,** Falls Church, Va.

[73] Assignee: **The Susquehanna Corporation,** Alexandria, Va.

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[52] **U.S. Cl.** **416/230,** 416/241

[51] **Int. Cl.** **F01d 5/14**

[58] **Field of Search** 416/230, 241, 229

[56] **References Cited**

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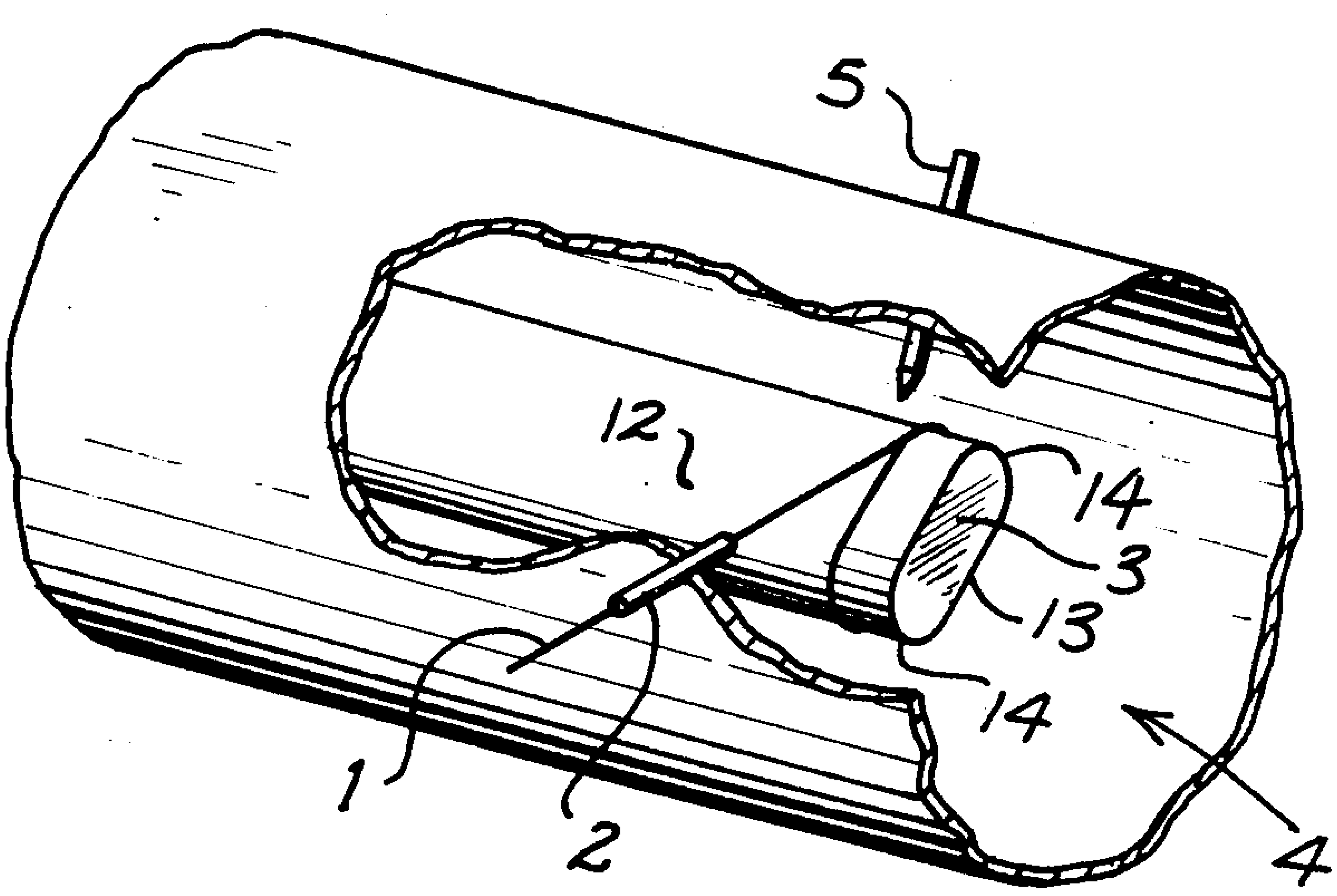
Primary Examiner—Everette A. Powell, Jr.
Attorney—Martha L. Ross

[57] **ABSTRACT**

A turbine blade or vane shaped from an article comprising a pyrolytic graphite matrix containing embedded therein at least one reinforcing refractory strand layer, the refractory being carbon or a refractory metal, carbide, boride, nitride, or oxide. The refractory strand layer comprises a plurality of unidirectional and substantially parallel, laterally spaced, individual, continuous refractory strands. The matrix comprises crystallite layers of pyrolytic graphite nucleated from each of the individual refractory strands and interconnected to form a continuous phase surrounding and interconnecting the individual strands comprising the embedded strand layer. The finished blade or vane has the strength and durability to withstand gas turbine temperatures of 2,000° to 5,000°F.

19 Claims, 7 Drawing Figures



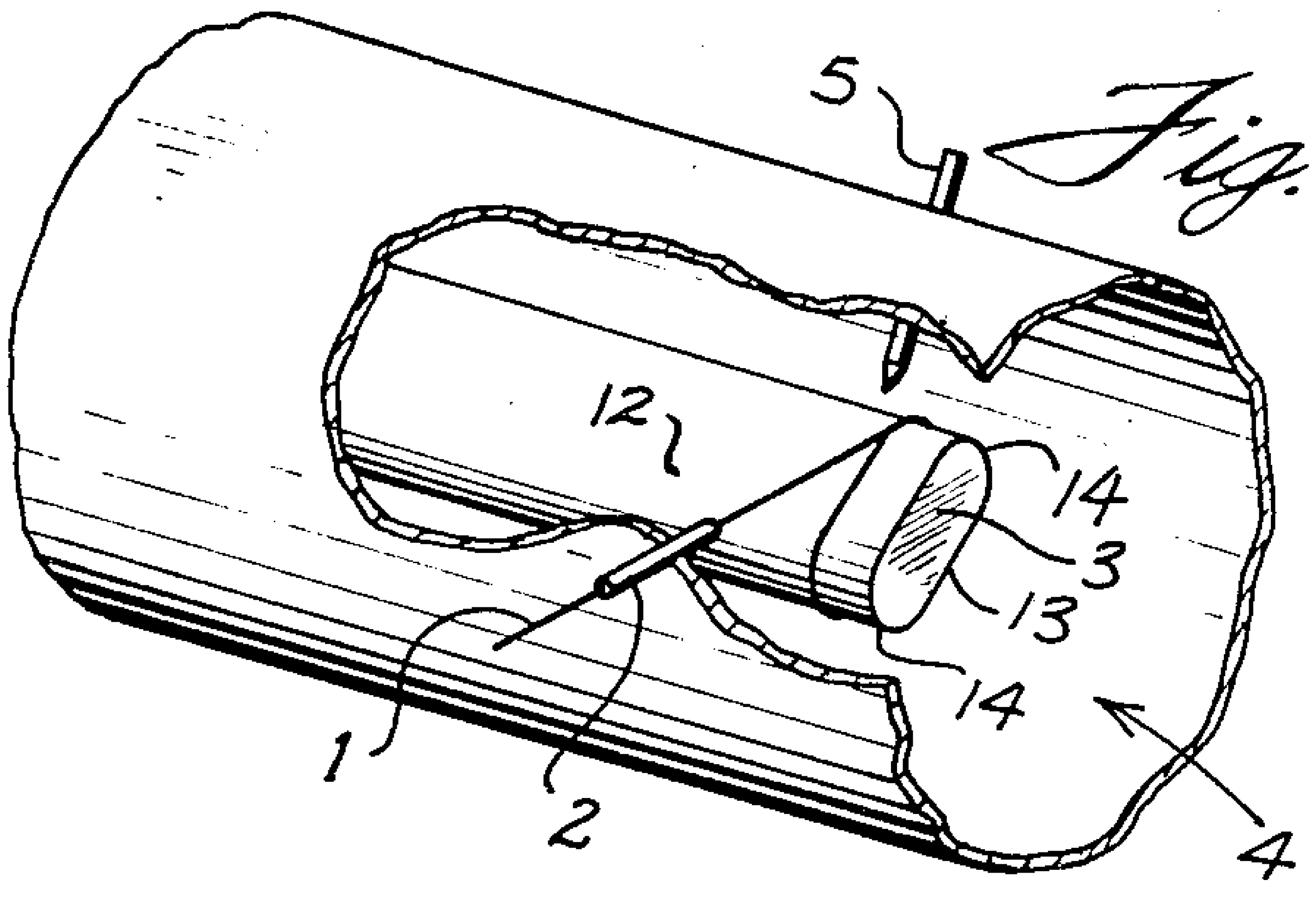
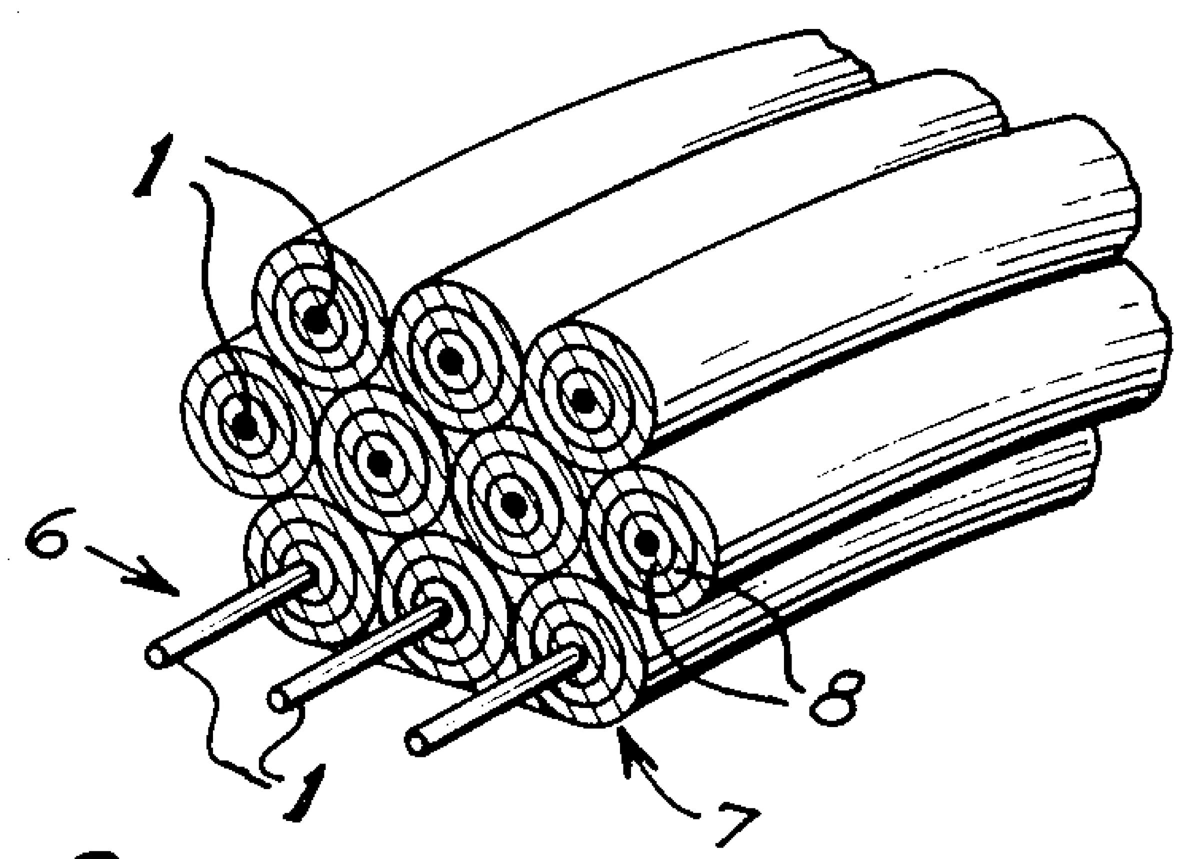


Fig. 1

Fig. 2a



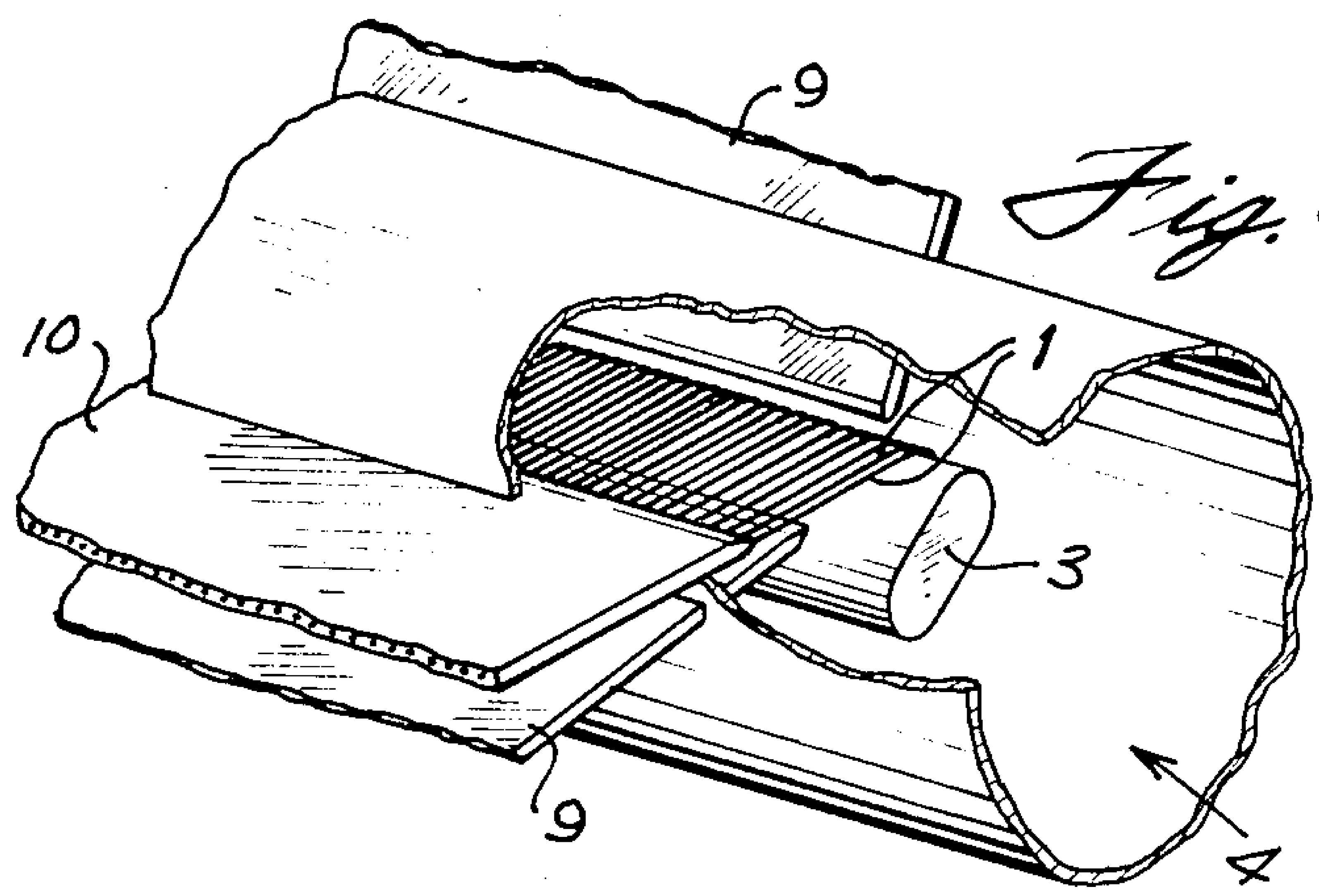
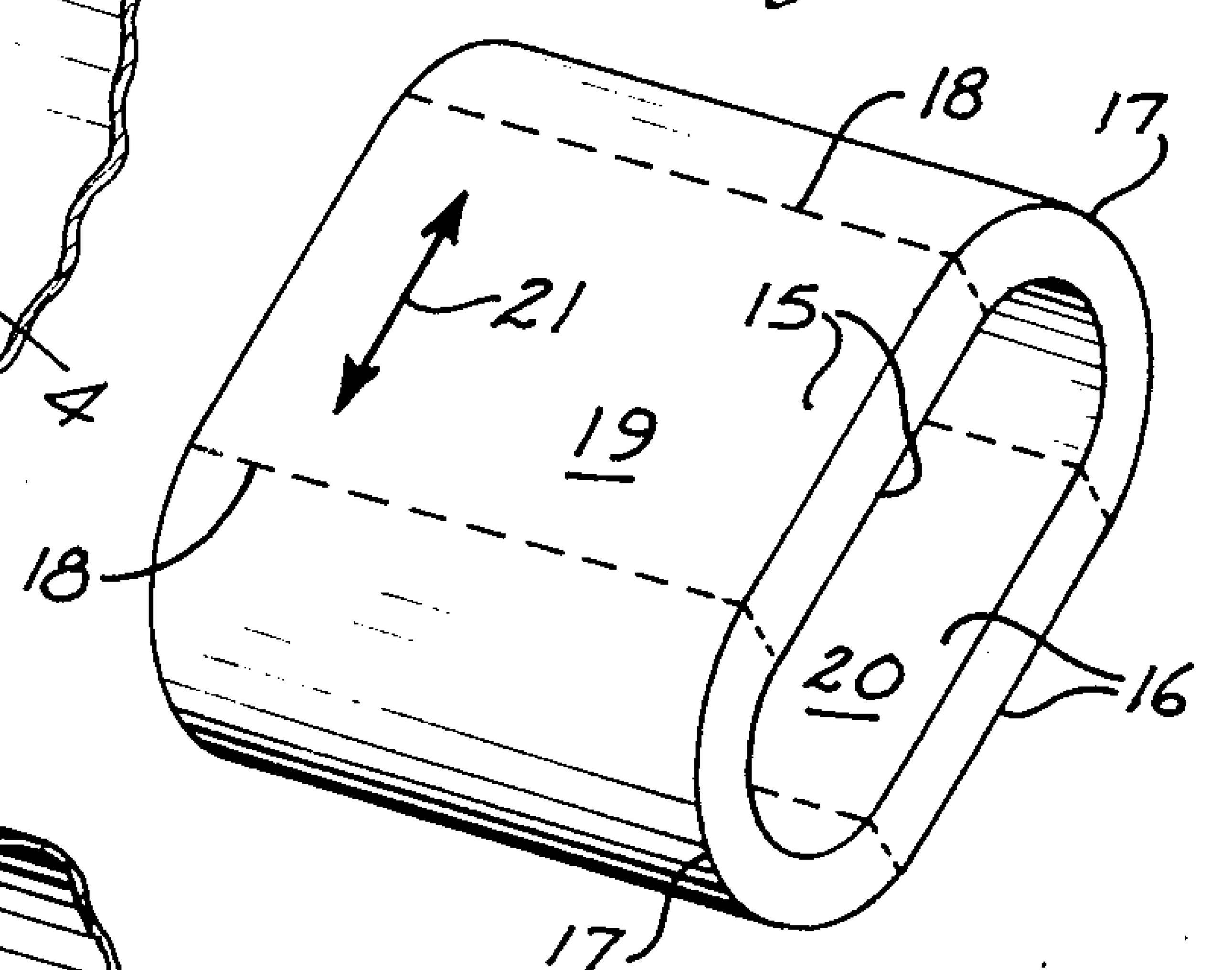


Fig. 3

Fig. 2b



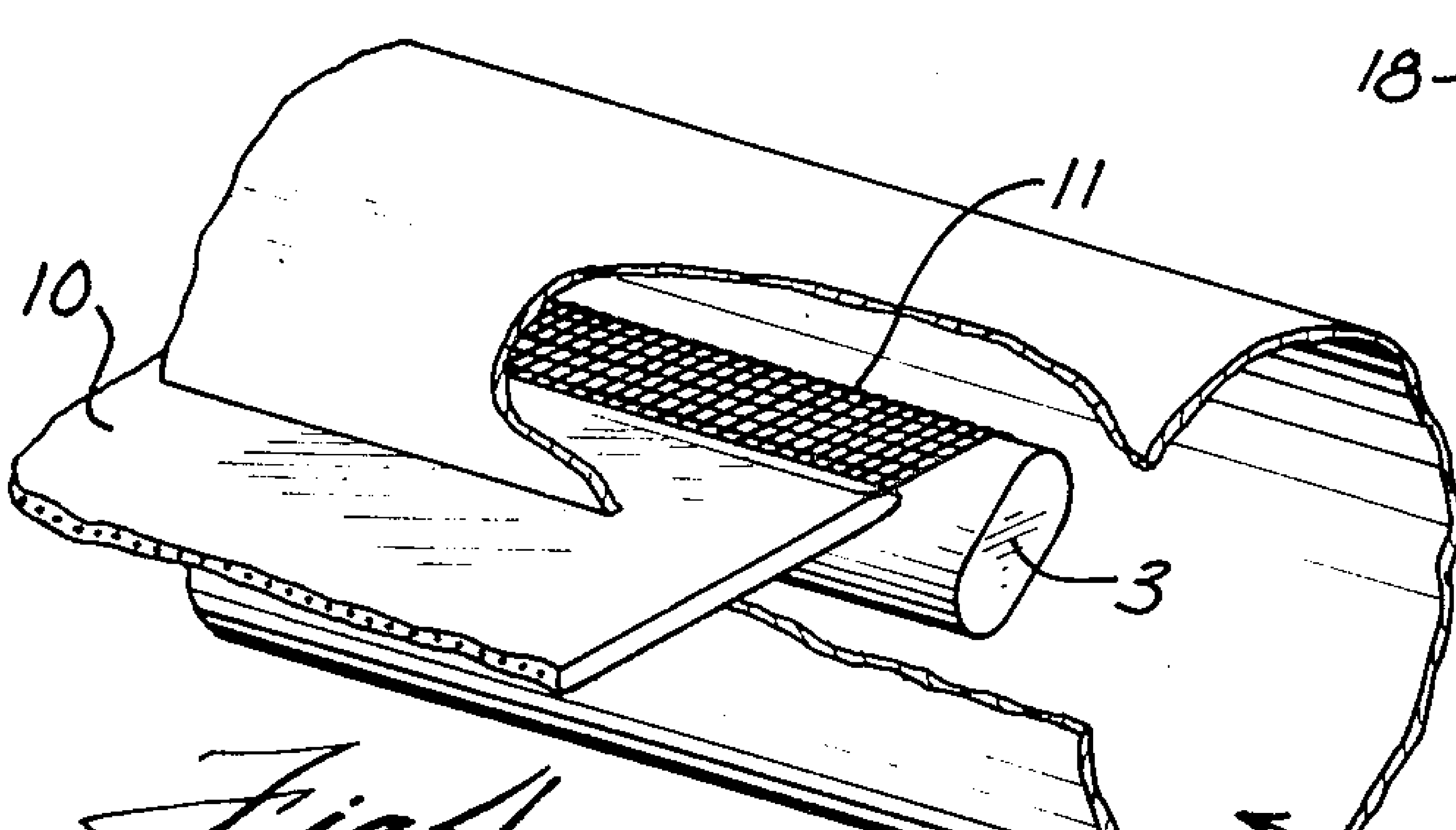


Fig. 4

Fig. 2c

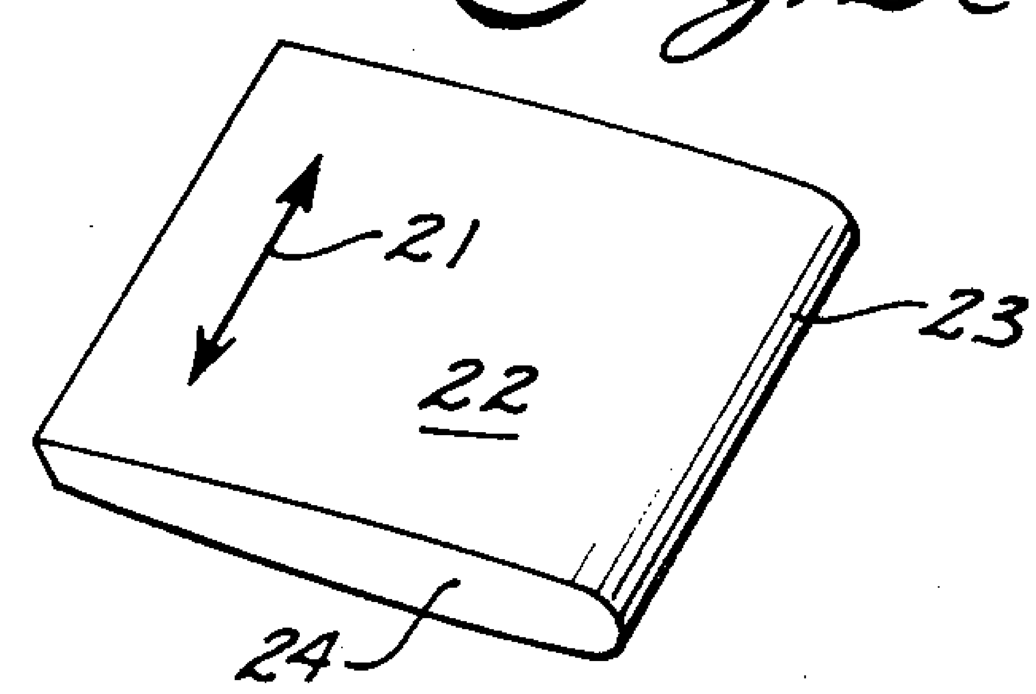
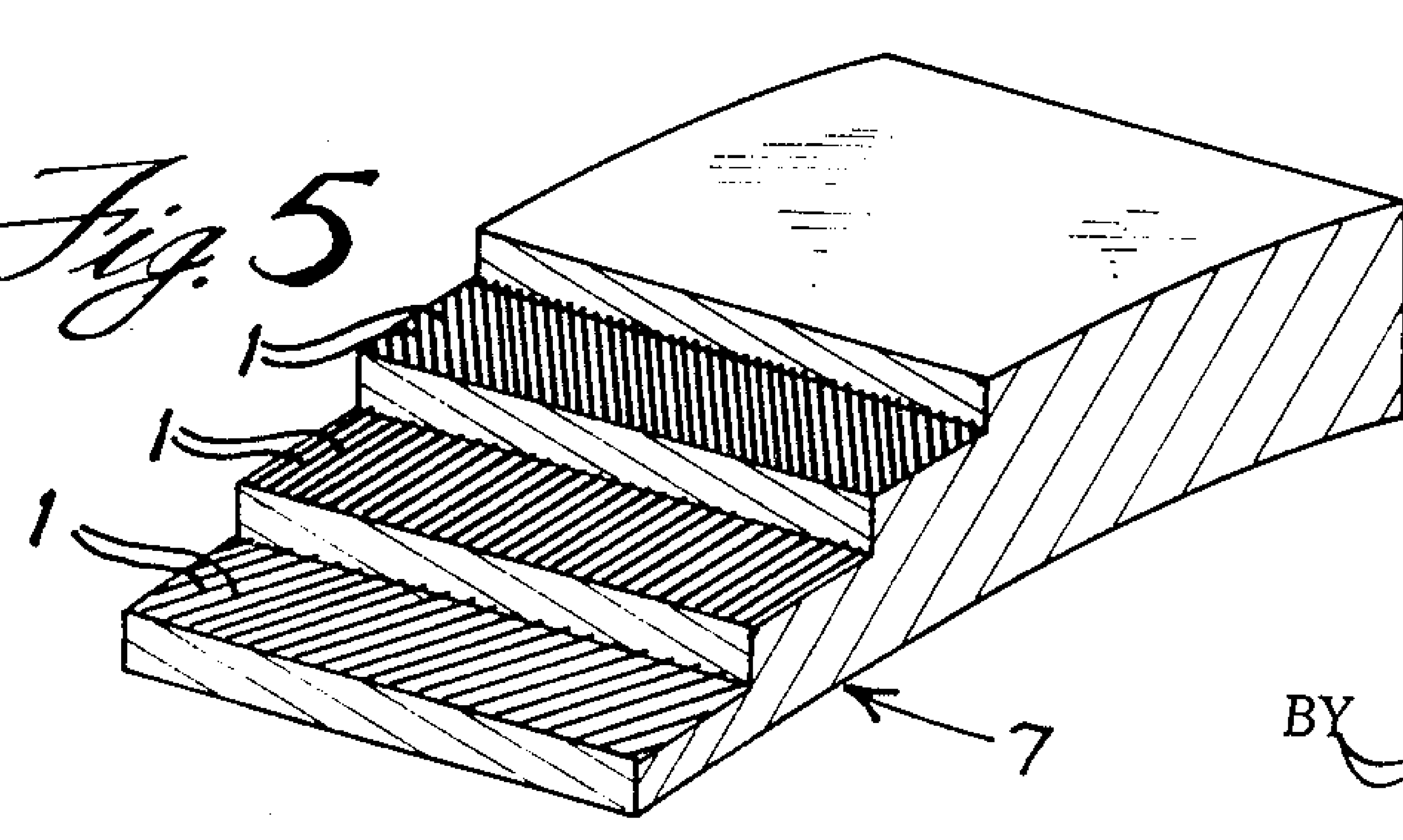


Fig. 5



INVENTOR
EUGENE L. OLCOTT

BY Tipton D. Jennings
ATTORNEY

TURBINE BLADE

BACKGROUND OF THE INVENTION

The present invention relates to gas turbine blades and specifically to turbine blades having a strength and durability to withstand operating temperatures of 2,000°F and above.

At present, in gas turbines used in jet engines and the like, stator vanes and rotor blades are, from a practical standpoint, limited to maximum operational temperatures of about 1,800°F. The blade and vane materials most commonly used are refractory metals such as tungsten, molybdenum and alloys of cobalt and nickel bases which have been found to have sufficient strength and erosion- and oxidation-resistance to perform satisfactorily at this temperature, and a density in the range of 0.28 pounds per cubic inch which can be tolerated under the size and weight constraints imposed in the design of jet engines. If higher operating temperatures are attempted, these blades and vanes will become deformed or will weaken and fracture.

There are, of course, other materials which are capable of withstanding temperatures greater than 1,800°F, but at those temperatures these materials have been found to be unsatisfactory for one or more of the following factors: lack of strength, unacceptable size or weight, and a tendency to erode or become oxidized in the flow of hot gases. As a result of being temperature-limited by the blade and vane materials, gas turbines are restricted to operating at power output levels much lower than what could be attained merely by increasing the temperature of the gas flow. The state-of-the-art of fuels is such that combustion gases can be readily generated in the range of 2,000° to 3,500°F and higher. If a satisfactory blade and vane material was discovered that would operate at these higher temperature levels, gas turbines could increase their output power by 150 to 200 percent.

The present invention proposes the use of novel pyrolytic graphite materials as the blades and vanes for such gas turbines. Hereinafter for convenience, reference will be made only to turbine blades; but such term is to be considered to encompass turbine vanes within its scope as well.

Pyrolytic graphite is known to have superior high temperature and erosion-resistant properties. Pyrolytic graphite, however, does have certain disadvantageous properties stemming from its particular crystalline structure and from its tendency to oxidize, particularly at high temperatures in an oxidizing atmosphere.

Pyrolytic graphite is normally produced by the pyrolysis of a carbonaceous gas, such as methane or propane, onto a heated substrate. Flat, hexagonal crystallites oriented parallel to the substrate surface are deposited in layers which build up into an essentially laminar structure. As a result, pyrolytic graphite is highly anisotropic in many of its properties, including strength, heat conductivity and thermal expansion, with attendant difficulties in practical use. As an example, the material has an exceedingly high coefficient of thermal expansion in the thickness or *c*-axis direction and a relatively low coefficient in the *a—b* plane or direction. Because of its weakness in the *c*-direction, due to its flat, plate-like and, thereby, laminar microstructure, pyrolytic graphite tends to delaminate under high stresses. As a result of all these undesirable properties, such pyrolytic graphite has heretofore not been considered a suitable candidate for gas turbine blades.

In copending United States applications Ser. No. 592,846 filed Nov. 8, 1966, now U.S. Pat. No. 3,629,049 and Ser. No. 870,948 filed Aug. 28, 1969, there are disclosed novel pyrolytic graphite articles comprising a matrix of pyrolytic graphite containing embedded therein at least one reinforcing layer consisting of a plurality of unidirectional and substantially parallel, laterally spaced, individual, continuous carbon strands. The matrix comprises crystallite layers of pyrolytic graphite nucleated from each of the individual carbon strands and interconnected to form a continuous phase surrounding and interconnecting the individual strands comprising the embedded strand layers. By conforming the crystallite pyrolytic graphite layers to embedded strand surfaces instead of to the surface of a conventional base substrate, anisotropy of the pyrolytic graphite and its attendant disadvantages are substantially reduced.

The present invention discloses that gas turbine blades manufactured from these novel pyrolytic graphite composites are especially suited to high-temperature operation in the range of 2,000° to 5,000°F without experiencing the disadvantages which would be encountered with prior art pyrolytic graphite materials and with refractory metals. Additionally, such blades are relatively light in weight, since pyrolytic graphite has a density of about 0.07 pounds per cubic inch, enjoy adequate useful strength in this elevated temperature range, and are substantially improved in their resistance to erosion and oxidation in the high temperature gas flow.

SUMMARY OF THE INVENTION

Broadly, the invention is directed to a turbine blade for gas turbines designed to operate in the temperature range of approximately 2,000° to 5,000°F and preferably above 3,000°F, said turbine blade being composed of a composite material comprising a pyrolytic graphite matrix and at least one reinforcing refractory strand layer disposed in said matrix, said strand layer comprising a plurality of laterally spaced, individual, continuous refractory strands, all of said strands in each layer being substantially unidirectionally oriented, and said matrix being nucleated from and laterally connecting said strands.

It is an object of the present invention to provide an improved turbine blade having the strength and durability to withstand operating temperatures of 2,000°F and above.

It is another object of the present invention to provide an improved turbine blade composed of a reinforced pyrolytic graphite composite having improved strength in the thickness dimension and greater resistance to delamination and oxidation.

It is a further object of the present invention to provide an improved turbine blade which is lightweight and has superior high temperature and erosion-resistant properties.

Other objects and advantages will become apparent from a reading of the following specification in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic illustration of apparatus used in the preferred manufacturing process for the article of this invention;

FIG. 2*a* is an enlarged schematic illustration of the internal construction of a reinforced pyrolytic graphite composite from which the article of this invention is formed;

FIG. 2*b* depicts the configuration of the reinforced pyrolytic graphite composite from which the article of this invention is formed;

FIG. 2*c* is an illustration of the article of the present invention;

FIGS. 3 and 4 are schematic representations of modified apparatus used in the manufacturing process for the article of this invention;

FIG. 5 schematically illustrates an alternative arrangement of reinforcing strands in the composite from which the article of this invention is formed.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The turbine blades of the present invention are formed from rigid articles comprising pyrolytic graphite containing embedded therein at least one reinforcing layer of a plurality of unidirectional and substantially parallel, laterally-spaced, individual, continuous refractory filaments or strands. The pyrolytic graphite is nucleated from each of the individual refractory elements or strands and is interconnected to form a continuous matrix phase surrounding and interconnecting the individual filaments or strands comprising the embedded filament or strand layer. The refractory filament or strand can be an individual fiber or can comprise a multiplicity of fibers which have been spun or otherwise incorporated to form the continuous strand.

The refractory filament or strand, which for convenience will hereinafter be referred to as the refractory strand, can comprise any suitable refractory material such as carbon in any suitable form including, for example, pyrolyzed rayon, polyacrylonitrile, and pitch. The method of making a novel pyrolytic graphite composite by depositing pyrolytic graphite on spaced carbon strands is fully disclosed in the aforementioned copending applications Ser. No. 592,846 now U.S. Pat. No. 3,629,049 and Ser. No. 870,948, which applications and their disclosures are hereby specifically incorporated herein by reference.

Other examples of refractory material suitable for use as refractory strands are those selected from the group consisting of refractory metals, such as boron, tungsten, and molybdenum and alloys thereof; refractory carbide, such as silicon, boron, tantalum, zirconium, hafnium, titanium, and niobium carbide and mixtures thereof; refractory borides, such as zirconium, hafnium, titanium, and tantalum boride and mixtures thereof; refractory nitrides, such as silicon and boron nitride and mixtures thereof; refractory oxides, such as aluminum, silicon, zirconium, and hafnium oxides and mixtures thereof. Silicon carbide, boron, and aluminum oxide are preferred. Such refractory strands possess certain advantages for some applications as compared with carbon because of their generally higher resistance to oxidation so that that they are particularly useful in highly oxidative environments. The method of making a novel pyrolytic graphite composite by depositing pyrolytic graphite on refractory strands made of the above-listed refractory materials is fully disclosed in copending United States application Ser. No. 157,138, filed June 28, 1971, which application and its disclosure is hereby specifically incorporated herein by reference.

By reference now to the schematic representation of FIG. 1, the first step in the preferred manufacturing process for the article of the present invention can be understood. As shown therein, a continuous, individual refractory strand **1**, is fed through a guide tube **2**, and connected to a mandrel **3**, disposed in a chamber **4**. In order to prevent oxidation of carbonaceous gas, atmospheric oxygen is removed and continuously excluded from the chamber by evacuation and/or purging with inert gases such as helium or nitrogen. The strand is heated to and maintained at a temperature sufficient to pyrolyze carbonaceous gases by induction, radiant, or resistance heating means, not shown. This temperature should be in the range of 2,800° to 4,000°F, preferably about 3,200°to 3,800°F. The mandrel is rotated and moved longitudinally relative to the strand guide tube **2**, by means not shown. In this manner, spaced turns of strand are progressively positioned on the mandrel. As the strand is wound, carbonaceous gas is fed through tube **5**, to impinge upon the strand at about the point of winding contact. Pyrolysis of the gas occurs and a pyrolytic graphite matrix is nucleated from the heated strand substrate. As winding continues, pyrolytic graphite is simultaneously deposited on the strand being wound and on the matrix deposited on previously wound strands. Thus, the strands are not only individually enveloped in a pyrolytic graphite matrix but are interconnected and bonded to each other by the matrix. The winding is continued to produce a composite article whose internal construction is as schematically illustrated in FIG. 2a in an enlarged manner. As shown, the article comprises one or more spaced, reinforcing refractory strand layers **6**, each of which comprises a plurality of spaced refractory strands **1**, disposed in and interconnected by a pyrolytic graphite matrix **7**, composed of graphite crystallite layers **8**.

It is seen that the crystallite layers of the matrix in the composite are oriented in conformity to surfaces of the strands and are, therefore, aligned around the strands and in the direction of strand orientation. Crystallite alignment in the direction of strand orientation provides the maximum strength of pyrolytic graphite in that direction. Furthermore, the embedded strands significantly reinforce the composite in the direction of strand orientation.

Since the orientation of crystallite layers conforms to the strand surfaces rather than the surface of the composite, the composite does not have the continuous laminar structure characteristic of conventional pyrolytic graphite. The absence of continuous laminae advantageously tends to prevent propagation of cracks and delaminations. Composite strength in the thickness direction is significantly improved by the increased degree of crystallite layer alignment in that direction. In addition, the orientation of crystallite layers in the composite renders the material less anisotropic than conventional pyrolytic graphite. As regards the step of pyrolyzing a carbonaceous gas during the above-described process, it should be understood that other vapors can be copyrolyzed with such gas to create composite matrices including, for example, such crystallites as boron carbide, silicon carbide and zirconium carbide.

The refractory strands also prevent delamination failures by restricting the thickness of laminar matrix growth units nucleated from these strands. It is known that growth units less than 0.05 inches thick are less subject to delamination. Since, in the composition of this invention, the thickness of laminar units is generally about one-half the distance between the strands, preferred unit size is obtained by spacing the strands within about 0.1 inch of each other.

The mandrel 3 shown in FIG. 1 preferably has flat top and bottom surfaces 12 and 13 and rounded sides 14 to facilitate the manufacture of the turbine blades. Once winding on this mandrel 3 has been completed, the mandrel is removed and the configuration of the finished graphite composite article is as depicted in FIG. 2*b*. The article shown has an elongated annular shape with flat top and bottom, inner and outer surfaces 15 and 16 and rounded sides 17. These rounded sides are now removed by cutting or machining away the rounded ends along the imaginary line 18. What remains of the composite is two flat plates which can be visualized in FIG. 2b by reference to the identifying numerals 19 and 20 less the removed portions. The direction of strand orientation is laterally across the flat surfaces of the plates as represented by the double-pointed arrow 21.

Each flat plate can now be formed into a turbine blade by machining, hot deformation, or other suitable forming steps. An example of a finished turbine blade is shown in FIG. 2c. This blade 22 has a rounded leading edge 23 and a gradual rearward taper. The blade is designed to be attached to a turbine wheel (not shown) or the like on its side face 24 and thereby project radially outwardly from the wheel surface. The direction of orientation of the refractory strands in the blade 22 is as again represented by the double-pointed arrow 21.

By selectively forming the blades with such strand orientation, substantially all of the individual strands within the finished blade are continuous throughout the height of the blade from side face 24 to its opposite face which is hidden in this view. By keeping unsevered strands to a minimum, the increase in strength created by the strand reinforcing is maximized.

When the blade 22 is mounted on the aforementioned turbine wheel, this strand orientation is normal to the direction of gas flow past the blade, and radial with respect to the turbine wheel. By manufacturing the turbine blade 22 with such strand orientation, the greatest blade strength is in the direction of greatest stress during turbine operation, namely, that created by the centrifugal force of the turbine wheel.

The process for fabrication of the graphite composite of FIG. 2*b* can be practiced with individual refractory strands as in the embodiment described hereinabove or with multi-strand structures such as a plurality of laterally spaced, unidirectionally oriented individual refractory strands, or with woven cloths or tapes comprising refractory strands oriented in both warp and woof directions. When using multi-strand structures to prepare a composite, it is preferred to simultaneously impinge carbonaceous gas on both sides of the strand structure as it is progressively laid down to ensure that the gas penetrates between the strands to effect the highest degree of lateral bonding. This can be accomplished by apparatus such as schematically illustrated in FIG. 3, wherein gas injector channels 9 feed gas into contact with spaced strands 1, or by apparatus as shown in FIG. 4, wherein woven cloth 11 made from a refractory material such as silicon carbide, boron, or aluminum oxide and gas are both fed through guide channel 10.

When the method for fabrication of graphite composites is practiced with woven fabrics, little matrix bond is obtained between strands where warp and woof intercross since it is difficult for the carbonaceous gas to penetrate between the touching strands. It is, therefore, preferred that all strands in each reinforcing strand layer in the composite of this invention be substantially unidirectionally oriented. Such orientation eliminates weaknesses which result from the absence of a matrix bond at points of strand-to-strand contact. In composites having multiple reinforcing strand layers, the direction of strand orientation can be varied in different reinforcing layers as shown, for example, in FIG. 5. Thus composites having desired directional strength characteristics can readily be prepared. With regard to manufacture of a turbine blade using a varied strand orientation, it is preferred that the variance for each composite on a layer-by-layer basis be concentrated about what will be the radial direction for the finished blade. In such case, the strand orientation from an average or overall standpoint will be radial with respect to the aforementioned turbine wheel or the like.

This method can, of course, be practiced by positioning refractory strands on a variety of shaped forms other than mandrel 3 to produce graphite composite articles having the desired configuration to finish into turbine blades. The strand can be progressively positioned on the shaped form by any desired technique however, winding is preferred for reasons of simplicity. It will be understood from the foregoing discussion that the term "progressively" positioning connotes a gradual laying down of strand to continuously and progressively increase the area of strand contact with the shaped form rather than effecting overall lateral strand contact as by "stacking." This permits matrix formation between strands as they are positioned and eliminates the necessity of forcing carbonaceous gas between prepositioned strands.

It may be preferred or required in some gas turbines applications to have turbine blades manufactured from a pyrolytic graphite composite which has even less anisotropy and/or improved oxidation resistance as compared with composites manufactured as described hereinabove. As described in copending United States application Ser. No. 65,899 filed Aug. 21, 1970, which application and its disclosure is hereby specifically incorporated herein by reference, such improvements can be realized by embedding, within the laminar pyrolytic graphite crystallite structure, aciculae of crystalline SiC which are oriented in the *c*-direction, as compared to the planar orientation of the layers of the pyrolytic graphite in the *a—b* direction.

The manufacturing process of the graphite composite with embedded SiC can also be practiced with the apparatus illustrated in FIGS. 1, 3, and 4. With specific reference to FIG. 1, a continuous, individual refractory strand is fed through a guide tube 2, and connected to a mandrel 3, disposed in chamber 4. To prevent oxidation of the carbonaceous gas, atmospheric oxygen is removed and continuously excluded from the chamber by evacuation and/or purging with inert gases such as helium or nitrogen. The strand is heated to and maintained at a temperature sufficient to pyrolyze the methyl trichlorosilane and hydrocarbon gases by induction, radiant, or resistance heating means, not shown. This temperature should be about 2,800° to 4,000°F, preferably about 3,200° to 3,800°F. The mandrel is rotated and moved longitudinally relative to the strand guide tube 2, by means not shown. In this manner, spaced turns of strand are progressively positioned on the mandrel. As the strand is wound, methyl trichlorosilane, hydrocarbon and carrier gas mixture are fed through tube 5, to impinge upon the strand at about the point of winding contact. Pyrolysis of the methyl trichlorosilane and hydrocarbon gas occurs and a pyrolytic graphite-SiC microcomposite matrix is nucleated from the heated strand substrate. As winding continues, the microcomposite is simultaneously deposited on the strand being wound and on the matrix deposited on previously wound strands. Thus, the strands are not only individually enveloped in a microcomposite matrix but are interconnected and bonded to each other by the matrix. The winding is continued to produce a composite article such as schematically illustrated in FIG. 2a in which the microcomposite matrix 7 is now composed of graphite crystallite layers 8 containing embedded, perpendicularly oriented, codeposited aciculae of SiC. The embedded strands significantly reinforce the microcomposite-strand composite in the direction of strand orientation.

Since the orientation of the pyrolytic graphite crystallite layers conforms to the strand surfaces rather than the base or mandrel substrate surface of the composite, the pyrolytic graphite component of the microcomposite does not have the continuous laminar structure characteristic of conventional pyrolytic graphite. This, together with the embedded codeposited SiC aciculae, further tends to prevent propagation of cracks and delaminations. Composite strength in the thickness direction is also further significantly improved by the increased degree of crystallite layer alignment in that direction. In addition, the marked disparity in thermal expansion in the *a—b* and *c* directions characteristic of conventional pyrolytic graphite is further reduced.

Once winding on mandrel 3 has been completed, the mandrel is removed. As described with regard to the earlier embodiment, flat plates are now produced from the graphite composite article of FIG. 2*b* and these plates are then formed into turbine blades of FIG. 2*c* by suitable forming steps. The preferred direction of strand orientation is again radial with respect to the turbine wheel, as more fully discussed hereinabove.

In the manufacture of the graphite composite of the last embodiment, the amount of SiC should be at least about 5 percent, preferably at least about 10 percent, by volume of the microcomposite. Depending upon the desired properties for a particular application, the percent of SiC can be as high as 90 or even 95. In general, the preferred range is about 10 to 50 volume percent, with the pyrolytic graphite making up the remainder of the matrix phase. Samples of the composite containing 25 percent SiC have been subjected to direct impingement of a 4,500°F oxy-acetylene flame for periods of up to 5 minutes with no weight loss.

The relative flow rates of the methyl trichlorosilane and hydrocarbon gas vary generally with the desired microcomposite composition. In general, the silane may be introduced at a weight percent flow rate of about 5 to 75 percent, preferably about 15 to 50 percent and the hydrocarbon gas at a weight percent flow rate of about 25 to 95 percent, preferably about 15 to 50 percent.

The hydrocarbon gas can be any of those generally employed in producing pyrolytic graphite by vapor phase deposition, such as the lower alkanes, e.g., methane, ethane, and propane; ethylene; acetylene; and mixtures thereof. Methane is preferred.

Although this invention has been described with reference to illustrative embodiments thereof, it will be apparent to those skilled in the art that the principles of this invention can be embodied in other forms but within the scope of the claims.

What is claimed is:

1. A turbine blade for gas turbines, said blade being designed to operate within the temperature range of approximately 2,000°to 5,000°F and being composed of a composite material comprising a pyrolytic graphite matrix containing embedded therein at least one reinforcing refractory strand layer, said strand layer comprising a plurality of unidirectional and substantially parallel, laterally spaced, individual, continuous refractory strands, said matrix comprising crystallite layers of pyrolytic graphite nucleated from each of said individual strands and interconnected to form a continuous phase surrounding and interconnecting each of said individual strands comprising said embedded at least one strand layer.

2. The turbine blade of claim 1 wherein said at least one reinforcing refractory strand layer comprises a plurality of layer.

3. The turbine blade of claim 2 wherein the unidirectional, substantially parallel strands comprising at least one refractory strand layer are oriented in a direction different from the unidirectional, substantially parallel strands comprising at least one other refractory strand layer.

4. The turbine blade of claim 1 wherein said individual continuous refractory strands have a lateral spacing between adjacent strands of substantially no grater than about 0.1 inch.

5. The turbine blade of claim 1 wherein said refractory is carbon.

6. The turbine blade of claim 2 wherein said refractory is carbon.

7. The turbine blade of claim 3 wherein said refractory is carbon.

8. The turbine blade of claim 4 wherein said refractory is carbon.

9. The turbine blade of claim 1 wherein said refractory is selected from the group consisting of metals and alloys thereof, carbides, borides, nitrides, and oxides.

10. The turbine blade of claim 9 wherein said metal and alloys thereof are boron, tungsten or molybdenum or alloys thereof, said carbides are silicon, boron, tantalum, zirconium, hafnium, titanium, or niobium carbides or mixtures thereof, said borides are zirconium, hafnium, titanium, or tantalum borides or mixtures thereof, said nitrides are boron nitride or silicon nitride or mixtures thereof, and said oxides are aluminum oxide, silicon oxide, zirconium oxide or hafnium oxide or mixtures thereof.

11. The shaped pyrolytic graphite article of claim 10 wherein said refractory is silicon carbide, boron, or aluminum oxide.

12. The turbine blade of claim 2 wherein said refractory is selected from the group consisting of metals and alloys thereof, carbides, borides, nitrides, and oxides.

13. The turbine blade of claim 12 wherein said metal and alloys thereof are boron, tungsten or molybdenum or alloys thereof, said carbides are silicon, boron, tantalum, zirconium, hafnium, titanium, or niobium carbides or mixtures thereof, said borides are zirconium, hafnium, titanium, or tantalum borides or mixtures thereof, said nitrides are boron nitride or silicon nitride or mixtures thereof, and said oxides are aluminum oxide, silicon oxide, zirconium oxide or hafnium oxide or mixtures thereof.

14. The shaped pyrolytic graphite article of claim 13 wherein said refractory is silicon carbide, boron, or aluminum oxide.

15. The turbine blade of claim 1 wherein said crystallite layers include codeposited silicon carbide comprising aciculae of silicon carbide, said aciculae being oriented in the c-direction relative to the *a—b* plane of the pyrolytic graphite crystallite at the point of embedment.

16. The turbine blade of claim 12 wherein said crystallite layers include codeposited silicon carbide comprising aciculae of silicon carbide, said aciculae being oriented in the c-direction relative to the *a—b* plane of the pyrolytic graphite crystallite at the point of embedment.

17. The turbine blade of claim 1 wherein the direction of strand orientation in the blade is substantially radial with respect to the use of the blade in the aforesaid gas turbine.

18. The turbine blade of claim 6 wherein the direction of strand orientation in the blade is substantially radial with respect to the use of the blade in the aforesaid gas turbine.

19. The turbine blade of claim 16 wherein the direction of strand orientation in the blade is substantially radial with respect to the use of the blade in the aforesaid gas turbine.

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