US011286792B2

(12) United States Patent
Razzell et al.

(10) Patent No.: US 11,286,792 B2
(45) Date of Patent: Mar. 29, 2022

(54) **CERAMIC MATRIX COMPOSITE VANE WITH COOLING HOLES AND METHODS OF MAKING THE SAME**

(71) Applicant: **Rolls-Royce plc**, London (GB)

(72) Inventors: **Anthony Razzell**, London (GB); **Michael J. Whittle**, London (GB); **Ian M. Edmonds**, London (GB)

(73) Assignee: **Rolls-Royce plc**

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 276 days.

(21) Appl. No.: **16/526,274**

(22) Filed: **Jul. 30, 2019**

(65) **Prior Publication Data**

US 2021/0032995 A1 Feb. 4, 2021

(51) **Int. Cl.**

F01D 5/18 (2006.01)
C04B 35/80 (2006.01)
F01D 5/28 (2006.01)

(52) **U.S. Cl.**

CPC ***F01D 5/187*** (2013.01); ***C04B 35/80*** (2013.01); ***F01D 5/284*** (2013.01); *F05D 2220/32* (2013.01); *F05D 2230/20* (2013.01); *F05D 2300/6033* (2013.01)

(58) **Field of Classification Search**

CPC F01D 5/183; F01D 5/186–189; F01D 5/20; F01D 5/284; F01D 5/288; B23B 2603/00; F05D 2230/90; B05D 1/32; B05B 12/26

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

5,916,510 A 6/1999 Jessen
6,113,722 A * 9/2000 Hoffman B81C 99/0085 156/155
6,197,424 B1 * 3/2001 Morrison F01D 11/12 428/402
6,273,678 B1 * 8/2001 Darolia F01D 5/286 415/200
6,408,610 B1 * 6/2002 Caldwell C23C 14/046 29/889.2
6,441,341 B1 * 8/2002 Steibel B23K 26/40 219/121.71
7,247,003 B2 * 7/2007 Burke .... F01D 5/147 416/229 R
7,658,590 B1 * 2/2010 Spanks B82Y 30/00 415/115
7,754,126 B2 7/2010 Subramanian et al.
7,887,300 B2 * 2/2011 Mazzola .... F01D 5/147 416/241 B

(Continued)

FOREIGN PATENT DOCUMENTS

EP 1507957 B1 * 8/2005 .... F01D 5/188
JP 2008121561 A * 5/2008 .... F01D 5/186

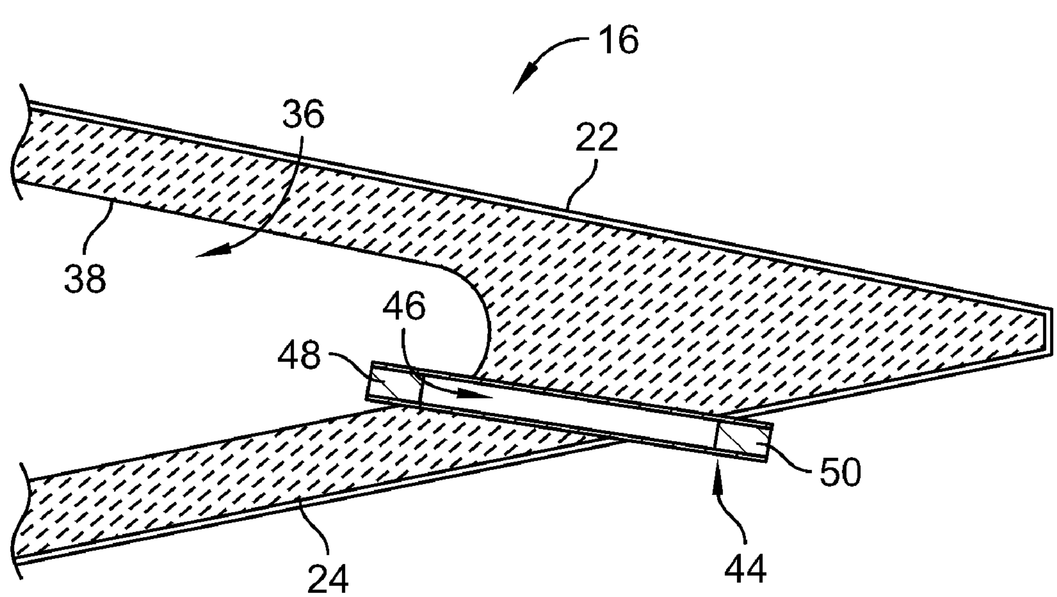
Primary Examiner — Topaz L. Elliott

(74) *Attorney, Agent, or Firm* — Barnes & Thornburg LLP

(57) **ABSTRACT**

An airfoil for a gas turbine engine is made from ceramic matrix composite materials. The airfoil has an inner surface that defines a cooling cavity in the body and an outer surface that defines a leading edge, a trailing edge, a pressure side, and a suction side of the body. The airfoil is formed with a hollow tube that extends through the body to define a cooling passage that extends from the cooling cavity through the airfoil to provide fluid communication between the cooling cavity and a gas path environment surrounding the airfoil.

7 Claims, 6 Drawing Sheets



(56) **References Cited**

U.S. PATENT DOCUMENTS

9,797,263	B2 *	10/2017	Varney	B23K 26/389
10,017,425	B2	7/2018	Tuertscher et al.	
10,024,175	B2	7/2018	Varney	
10,472,972	B2 *	11/2019	Bunker	C23C 28/345
10,539,026	B2 *	1/2020	Xu	F01D 5/186
10,578,115	B2 *	3/2020	Lander	F01D 5/282
10,717,101	B2 *	7/2020	Henson	B05D 1/32
10,731,469	B2 *	8/2020	Xu	F01D 5/147
2002/0076541	A1 *	6/2002	Jarmon	F01D 5/186 428/312.6
2008/0203236	A1 *	8/2008	Mazzola	F01D 5/18 244/35 R
2014/0271131	A1 *	9/2014	Moody	F01D 5/186 415/116
2016/0089692	A1	3/2016	Reid et al.	
2016/0348511	A1 *	12/2016	Varney	C04B 38/065
2016/0348515	A1 *	12/2016	Varney	C04B 35/16
2017/0152749	A1 *	6/2017	Bunker	F01D 9/065
2017/0159488	A1 *	6/2017	Kottilingam	F01D 5/288
2017/0335856	A1 *	11/2017	Lander	F04D 29/388
2017/0368647	A1 *	12/2017	Bunker	B23P 6/045
2018/0281006	A1 *	10/2018	Coskun	B25J 15/0019
2019/0255550	A1 *	8/2019	Henson	F01D 5/288
2020/0080425	A1 *	3/2020	Weaver	B28B 23/0006

* cited by examiner

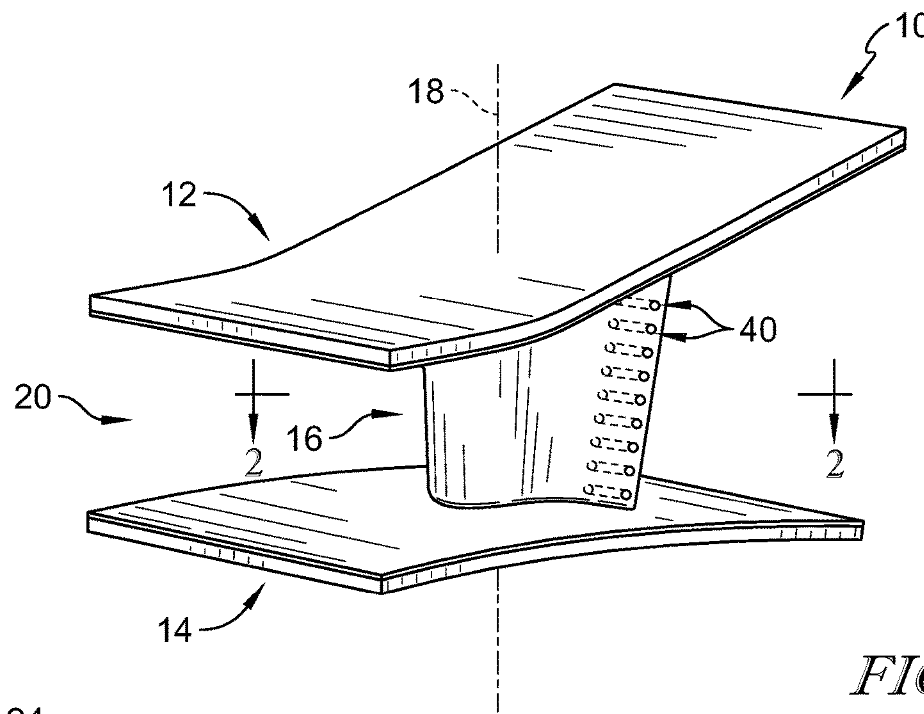


FIG. 1

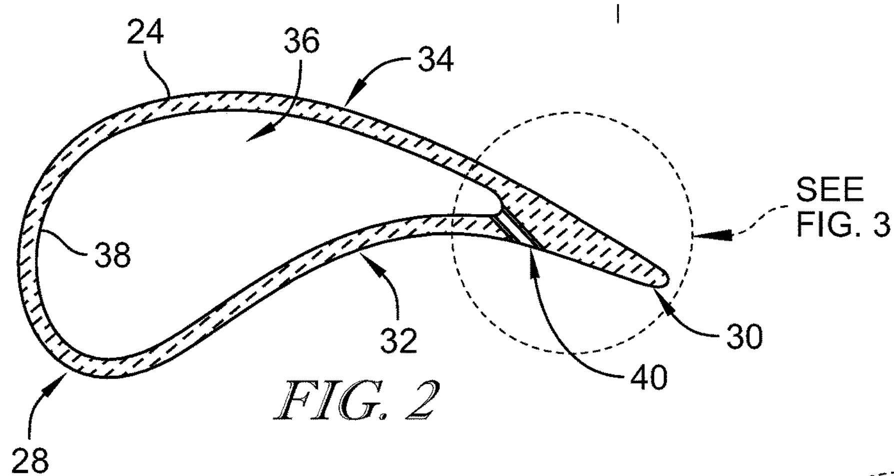


FIG. 2

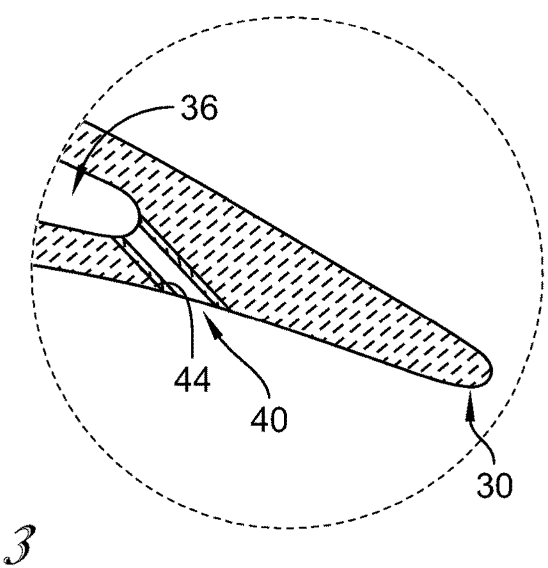


FIG. 3

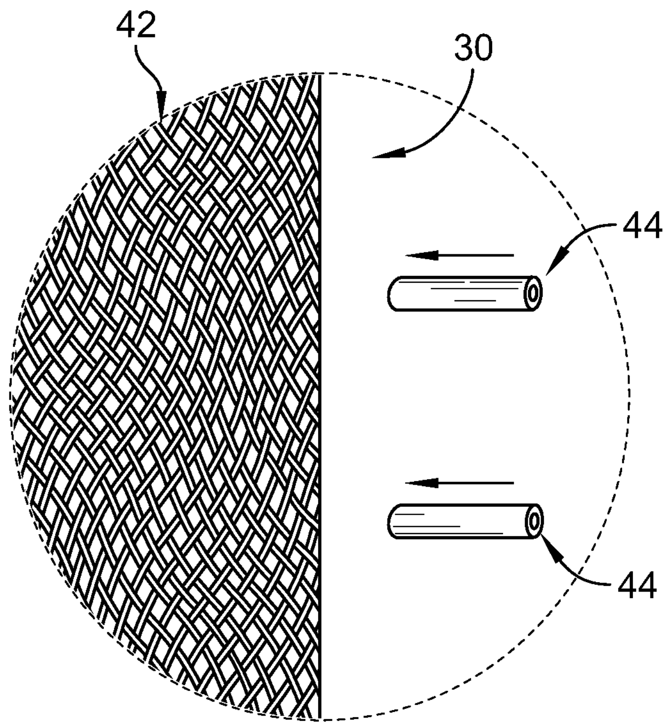


FIG. 4

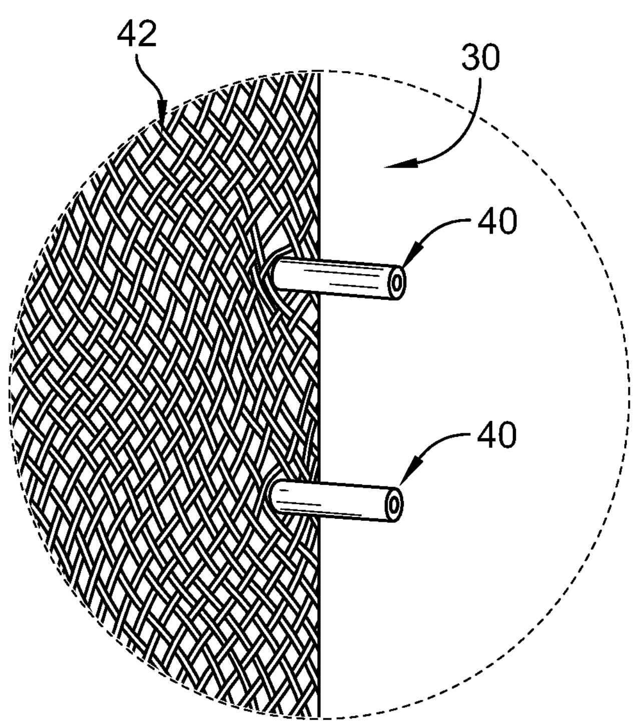


FIG. 5

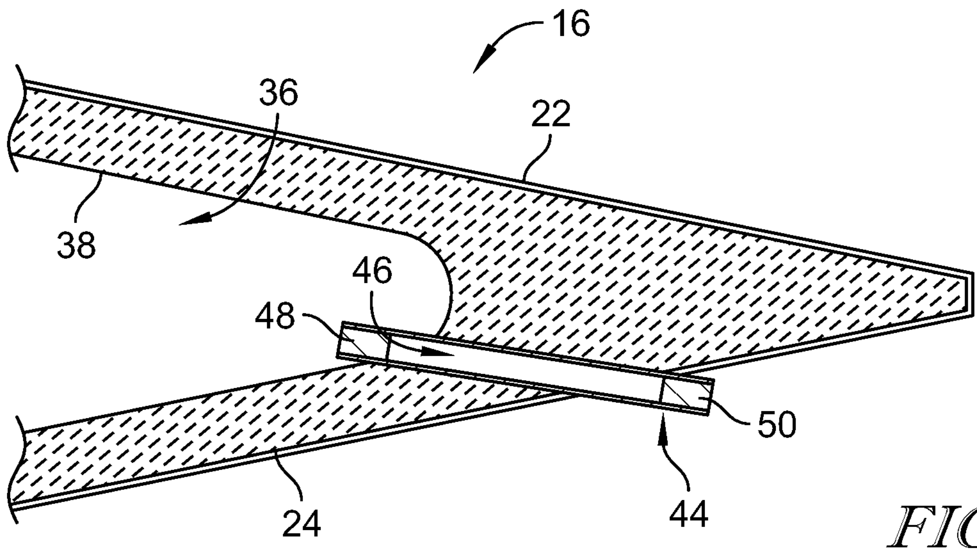


FIG. 6

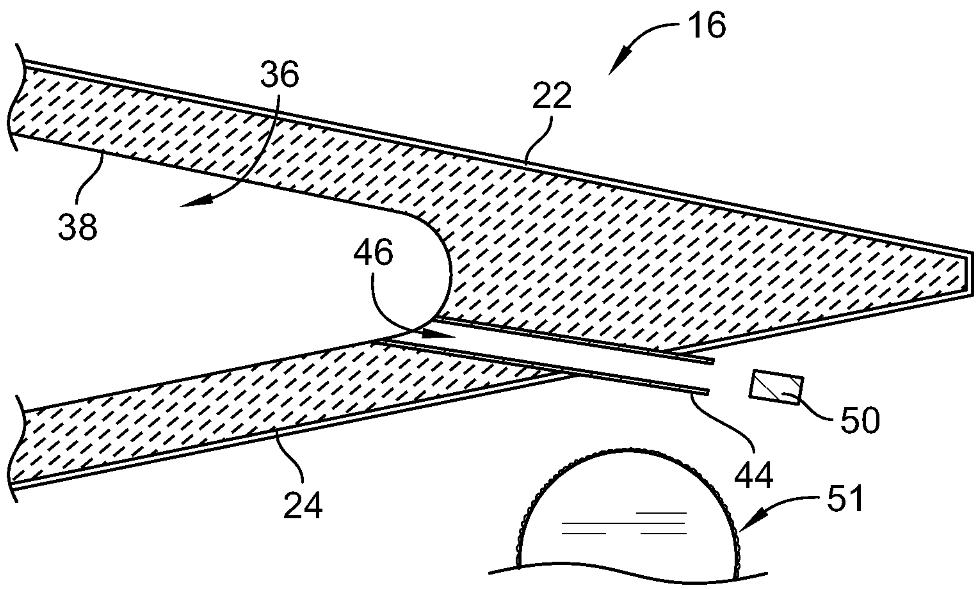


FIG. 7

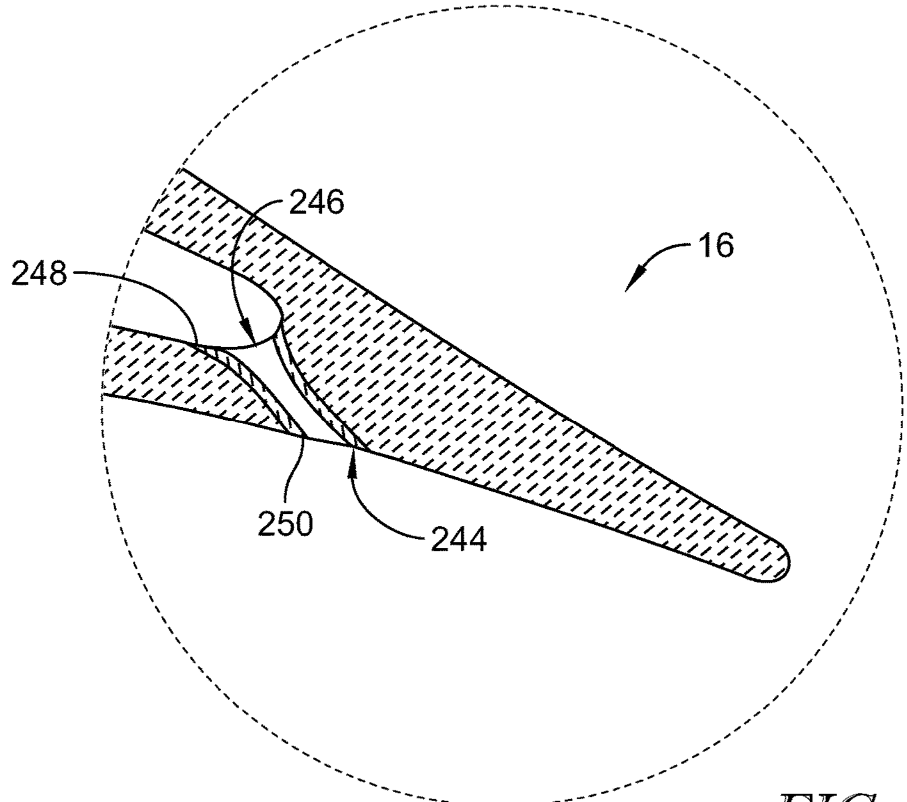


FIG. 8

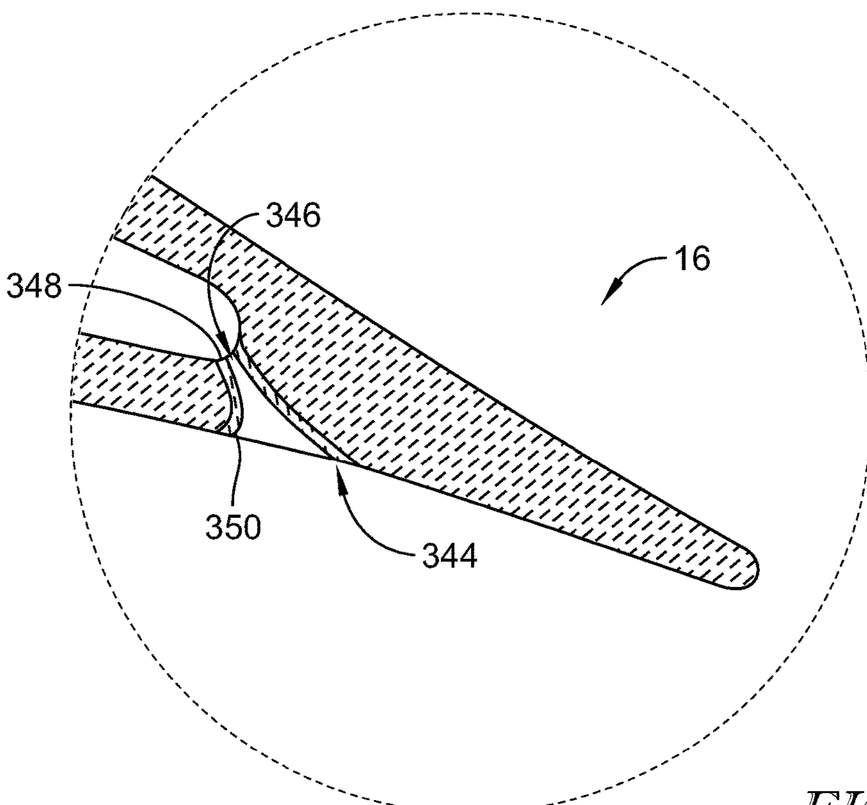


FIG. 9

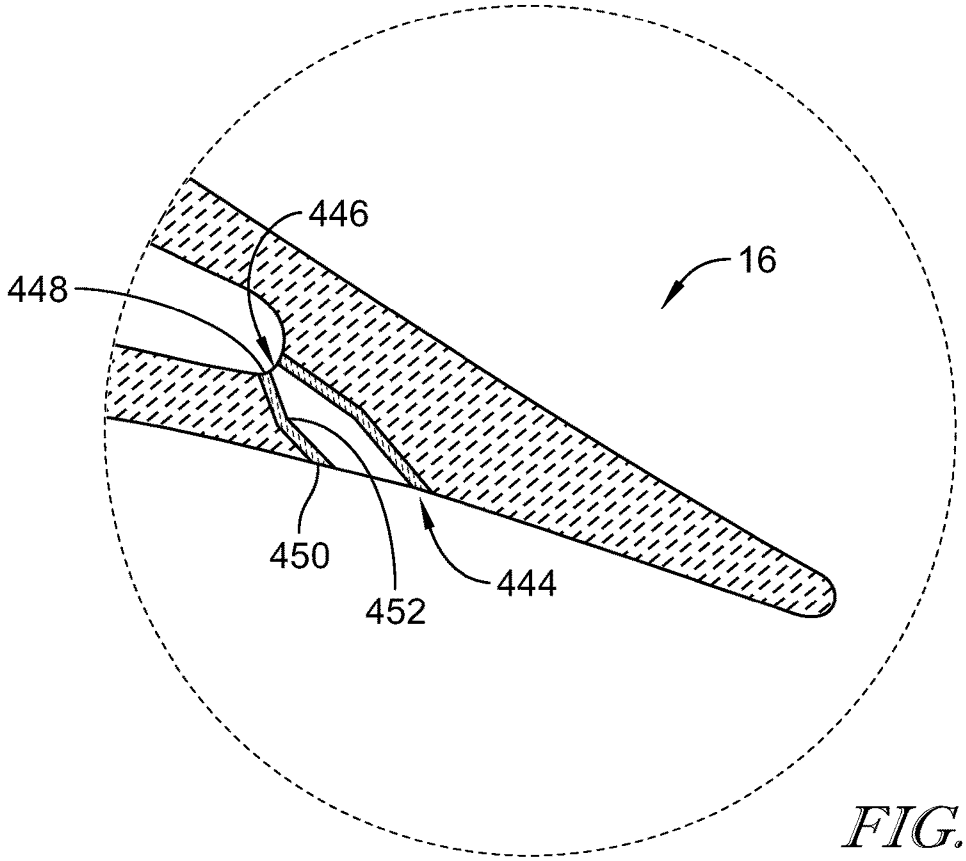


FIG. 10

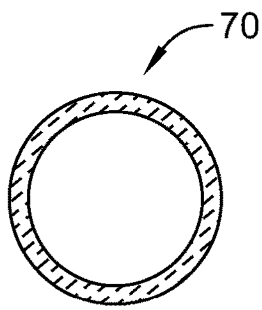


FIG. 11A

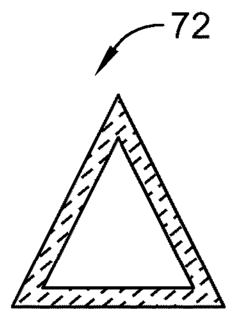


FIG. 11B

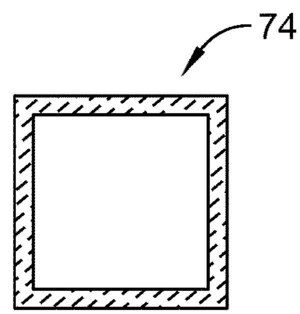


FIG. 11C

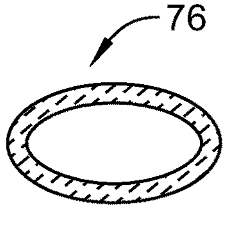


FIG. 11D

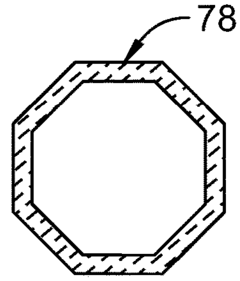


FIG. 11E

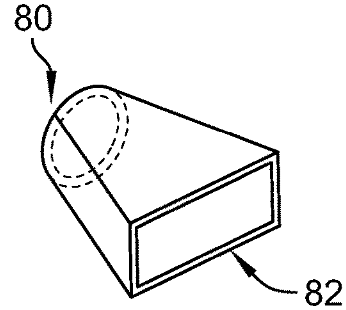


FIG. 11F

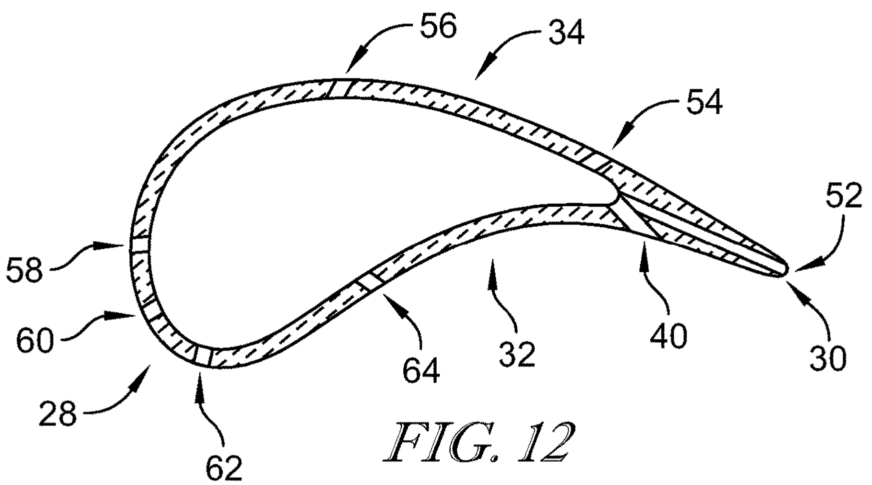

56
34
54
52
58
60
28
62
64
32
40
30

FIG. 12

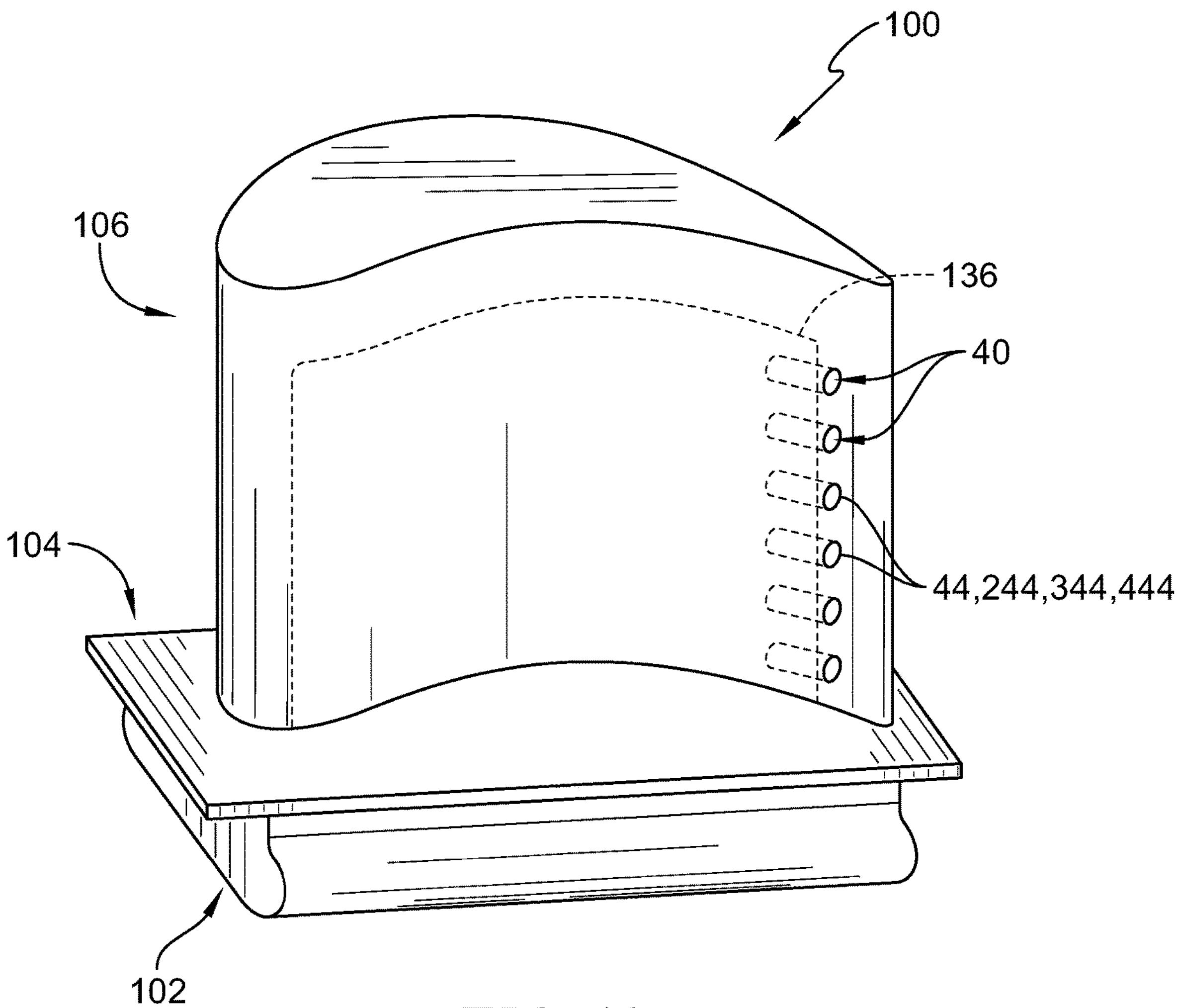

100
106
136
40
44,244,344,444
104
102

FIG. 13

CERAMIC MATRIX COMPOSITE VANE WITH COOLING HOLES AND METHODS OF MAKING THE SAME

FIELD OF THE DISCLOSURE

The present disclosure relates generally to airfoils used in gas turbine engines, and more specifically to airfoils used in gas turbine engines that contain composite materials.

BACKGROUND

Gas turbine engines are used to power aircraft, watercraft, power generators, and the like. Gas turbine engines typically include a compressor, a combustor, and a turbine. The compressor compresses air drawn into the engine and delivers high pressure air to the combustor. In the combustor, fuel is mixed with the high pressure air and is ignited. Products of the combustion reaction in the combustor are directed into the turbine where work is extracted to drive the compressor and, sometimes, an output shaft. Left-over products of the combustion are exhausted out of the turbine and may provide thrust in some applications.

Products of the combustion reaction directed into the turbine flow over airfoils included in stationary vanes and rotating blades of the turbine. The interaction of combustion products with the airfoils heats the airfoils and supporting structures to temperatures that require the airfoils and supporting structures to be made from high-temperature resistant materials and/or to be actively cooled by supplying relatively cool air to the vanes and blades. To this end, some composite materials adapted to withstand very high temperatures are being incorporated into vane and blade design. Design and manufacture of vanes and blades including composite components presents challenges.

SUMMARY

The present disclosure may comprise one or more of the following features and combinations thereof.

According to a first aspect of the present disclosure, an airfoil for use in a gas turbine engine includes an airfoil shaped ceramic matrix composite body, and a hollow tube embedded in the body. The airfoil shaped ceramic matrix composite body has an inner surface that defines a cooling cavity in the body and an outer surface that defines a leading edge, a trailing edge, a pressure side, and a suction side of the body. The hollow tube is made from an environmental barrier material and extends through the body between the inner surface and the outer surface to provide fluid communication between the cooling cavity and a gas path environment surrounding the outside surface.

In some embodiments, the body includes a plurality of fibers and matrix material infiltrated with the fibers and the tube is embedded in the plurality of fibers such that the plurality of fibers are parted around the tube to avoid fracturing the plurality of fibers.

In some embodiments, the body extends along an axis, the airfoil further includes a plurality of tubes made from the environmental barrier material, the plurality of tubes includes the first tube, and the plurality of tubes are spaced apart from one another axially relative to the axis. In some embodiments, the environmental barrier material is different than a material of the ceramic reinforcement fiber preform and the ceramic matrix material.

In some embodiments, the tube defines a cooling passageway and has a length that extends between a first end of the tube and a second end of the tube and a cross-sectional area of the passageway varies along the length of the tube. In some embodiments, the tube defines a cooling passageway and has a length that extends between a first end of the tube and a second end of the tube and a cross-sectional area of the passageway is constant along the length of the tube.

In some embodiments, the tube is conical such that the cross-sectional area of the passageway narrows from the first end to the second end. The cross-sectional area of the passageway may vary constantly along the length of the tube. The cross-sectional area of the passageway may vary exponentially along the length of the tube. In some embodiments, the tube has a non-circular cross section when viewed along an axis that extends between the first end and the second end.

In some embodiments, the cooling passage extends between the cooling cavity and the pressure side of the airfoil near the trailing edge. The tube may be made entirely of environmental barrier material. The tube may be self-supporting such that it is embedded into the fibers on its own.

According to another aspect of the present disclosure, a method of forming an airfoil includes: providing an airfoil shaped ceramic reinforcement fiber preform and a tube, the ceramic reinforcement fiber preform having a first side formed to define a cooling cavity in the ceramic reinforcement fiber preform and a second side opposite the first side, the tube being made from an environmental barrier material and having a first end and a second end. The method further includes inserting the tube through the ceramic reinforcement fiber preform so that the first end of the tube extends into the cooling cavity and the second end of the tube extends beyond the second side of the ceramic reinforcement fiber preform.

In some embodiments, the method further includes infiltrating the ceramic reinforcement fiber preform with ceramic matrix material to densify the ceramic reinforcement fiber preform and form a ceramic matrix composite airfoil having the tube fixed therein, the ceramic matrix composite airfoil having an inner surface that defines the cooling cavity and an outer surface opposite the inner surface and adapted to interface with hot gases. The method further includes removing material from the first end and the second end of the tube such that the first end is about flush with the inner surface and the second end is about flush with the outer surface to form a cooling passage with the tube that extends through the ceramic matrix composite airfoil to provide fluid communication between the cooling cavity and environment surrounding the outer surface outside of the ceramic matrix composite airfoil.

In some embodiments, the tube has a hollow section and the tube includes removable filler material present in the hollow section during the step of infiltrating to block ingress of ceramic matrix material into the hollow section.

In some embodiments, the removable filler material includes a first plug located in the first end of the tube during the infiltrating step, a second plug located in the second end of the tube during the infiltrating step, and the step of removing material from the first end and the second end includes removing the first plug and the second plug.

In some embodiments, the tube has a hollow section and wherein the first end is made of solid material to block access into the hollow section and the second end is made of solid material to block access into the hollow section during the infiltrating step.

In some embodiments, the step of removing material from the first end and the second end includes cutting the first end

from the tube to form a first opening into the hollow section and cutting the second end from the tube to form a second opening into the hollow section.

In some embodiments, the tube includes an inner surface that directly defines the cooling passage and an outer surface that directly engages the ceramic matrix composite airfoil and the environmental barrier material extends between the inner surface and the outer surface of the tube.

In some embodiments, the step of inserting the tube through the ceramic reinforcement fiber preform includes parting fibers included in the ceramic reinforcement fiber preform around the tube to avoid fracturing the fibers.

These and other features of the present disclosure will become more apparent from the following description of the illustrative embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is perspective view of a nozzle guide vane adapted for use in a gas turbine engine, the nozzle guide vane including an outer endwall, an inner endwall, and an airfoil extending generally along an axis between the outer endwall and the inner endwall, the airfoil made from ceramic matrix composite materials and formed with a plurality of cooling passageways that extend through a trailing edge of the airfoil to cool the trailing edge;

FIG. **2** is a cross section of the airfoil taken along line **2-2** in FIG. **1** showing that the airfoil is made from ceramic matrix composite materials and includes an outer surface shaped to interact with gases flowing through a gas path of the gas turbine engine and an inner surface defining a cooling cavity within the airfoil and showing one of the cooling passageways extending from the inner surface to the outer surface to direct cooling fluid from cooling cavity to the gas path of the gas turbine engine to cool the trailing edge of the airfoil;

FIG. **3** is an enlarged view of the airfoil shown in FIG. **2** showing that the cooling passageway is defined by a tube that is made from an environmental barrier material that is embedded into the ceramic matrix composite airfoil during manufacture of the nozzle guide vane;

FIG. **4** is an enlarged perspective view of the airfoil during a preforming stage of manufacturing the nozzle guide vane showing that the ceramic matrix composite material forming the airfoil include a plurality of woven or braided reinforcement fibers and showing a pair of rigid environmental barrier tubes preparing to be embedded in the plurality of reinforcement fibers;

FIG. **5** is an enlarged perspective view similar to FIG. **4** showing the environmental barrier tubes being embedded into the plurality of reinforcement fibers forming the airfoil and the plurality of reinforcement fibers moving away from the tubes so that fiber fractures are avoided during formation of the airfoil with the cooling holes;

FIG. **6** is an enlarged cross-section view of the trailing edge of the airfoil after the tubes have been embedded in the plurality of reinforcement fibers and the reinforcement fibers have been infiltrated with ceramic matrix material to form a ceramic matrix composite airfoil showing that the tube is closed at each end to block ceramic matrix material from entering a passageway defined by the tube during infiltration of the airfoil;

FIG. **7** is an enlarged cross-section view similar to FIG. **6** showing the tube with one of its ends removed to open the passageway after the airfoil has been full processed and a diamond wheel grinder preparing to machine the other end of the tube so that the tube is flush with the inner and outer surfaces of the airfoil and the cooling passageway is formed;

FIG. **8** is an enlarged cross-section view of an airfoil with another embodiment of a tube embedded in the airfoil to provide a cooling passageway with a varying cross-sectional area that decreases along a length of the tube from a first end to a second end;

FIG. **9** is an enlarged cross-section view of an airfoil with a third embodiment of a tube embedded in the airfoil to provide a cooling passageway with a varying cross-sectional area that increases along a length of the tube from a first end to a second end;

FIG. **10** is an enlarged cross-section view of an airfoil with a fourth embodiment of a tube embedded in the airfoil to provide a cooling passageway with a varying cross-sectional area that increases from a first end of the tube to a point between the first end and a second end and decreases from the point to the second end;

FIGS. **11A-11E** show various cross-sections of tubes that may be used to provide cooling passageways in an airfoil;

FIG. **11**A is a cross section of a tube with a circular shape;

FIG. **11**B is a cross section of a tube with a triangular shape;

FIG. **11**C is a cross section of a tube with a square shape;

FIG. **11**D is a cross section of a tube with an oval shape; and

FIG. **11**E is a cross section of a tube with a polygonal shape.

FIG. **11**F is a perspective view of a tube with a circular shape at a first end that transitions to a rectangular shape at a second end;

FIG. **12** is a cross-section of an airfoil illustrating various locations in the airfoil where the cooling passageways may be formed; and

FIG. **13** is a perspective view of a blade for use in a gas turbine engine, the blade including a root, a platform, and an airfoil with cooling passageways formed in the airfoil using the tubes made from the environmental barrier material.

DETAILED DESCRIPTION OF THE DRAWINGS

For the purposes of promoting an understanding of the principles of the disclosure, reference will now be made to a number of illustrative embodiments illustrated in the drawings and specific language will be used to describe the same.

An illustrative nozzle guide vane **10** for use in a gas turbine engine is shown in FIG. **1**. The nozzle guide vane **10** includes an outer endwall **12**, an inner endwall **14** spaced apart from the outer endwall **12**, and an airfoil **16** extending between the outer endwall **12** and the inner endwall generally along an axis **18** as shown in FIGS. **1** and **2**. The outer endwall **12** and the inner endwall **14** are spaced apart axially from one another relative to the axis to define a gas flow path **20** therebetween. The airfoil **16** has an outer surface **24** shaped to interact with gases flowing through the gas flow path **20** and direct the gases toward rotating blades (not shown) to increase efficiencies of the gas turbine engine.

The airfoil **16** has a leading edge **28**, a trailing edge **30**, a pressure side **32**, and a suction side **34** and is formed to include an airfoil shaped cooling cavity **36** defined by an inner surface **38** of the airfoil **16** as shown in FIG. **2**. The airfoil **16** is also formed to include a plurality of cooling passages **40** that extend aft from the cooling cavity **36** generally through the trailing edge **30** to conduct a cooling fluid from the cooling cavity **36** through the airfoil **16** to the gas flow path **20**. The cooling fluid exits the cooling passages **40** into the gas flow path **20** to provide a film of cooling fluid along the outer surface **24** of the airfoil **16** to cool the vane **10**.

The vane **10** may be subjected to very high temperatures by virtue of being downstream of a combustor included in the gas turbine engine. In the illustrative embodiment, the vane **10** is made from ceramic matrix composite materials to guard against the high temperatures and increase durability and useful life of the vane **10**. The ceramic matrix composite (CMC) materials forming the vane **10** may include a silicon carbide fiber preform embedded in silicon carbide matrix material. In other embodiments, another suitable CMC may be used. The ceramic fiber preform may include a plurality of reinforcement fibers **42** that are two-dimensionally or three-dimensionally woven or braided together as shown in FIGS. **4** and **5**.

Prior to being infiltrated with ceramic matrix material, the plurality of reinforcement fibers **42** are movable relative to one another as suggested in FIGS. **4** and **5**. The cooling passages **40** in the illustrative embodiment are formed prior to the ceramic fiber preform being processed with ceramic matrix material by inserting hollow tubes **44** into the ceramic fiber preform. The tubes **44** are already sintered to full density at this point in time such that they are rigid tubes. The fibers **42** are moved out of the way as the tubes **44** are embedded in the ceramic fiber preform to avoid fracturing any of the fibers **42**. Fracturing or breaking fibers **42** may compromise the airfoil's **16** structural integrity. In other embodiments, passages may be machined in the airfoil **16** during a preforming stage and the tubes **44** may be inserted into the machined passages. Once the tubes **44** are embedded in the ceramic preform, the airfoil **16** may be infiltrated with the ceramic matrix material to densify the fiber preform and form the CMC airfoil **16**. In illustrative embodiments, the tubes **44** are not densified by the ceramic matrix material. Some suitable densification processes include polymer infiltration, pyrolysis, chemical vapor infiltration, slurry infiltration, and/or melt infiltration.

In use, some CMC components are vulnerable to recession caused by reaction of silica, which may be formed upon exposure to high temperatures, with water vapor, which may be present in the hot gases as a result of fuel combustion in the combustor. An environmental barrier coating (EBC) **22** may be applied to an outer surface **24** of the airfoil to block this reaction and, hence, the recession of the vane **10** from occurring as shown in FIGS. **6** and **7**. The EBC coating **22** may be applied using an air plasma spray technique, Electrophoretic deposition (EPD), slurry cast, or oxide reaction bonding.

The cooling passages **40** in the illustrative embodiment have a relatively small diameter and a relatively high aspect ratio (i.e. the tube's length compared to the tube's diameter). In the illustrative embodiment, each cooling passage **40** has a width equal to about 1 mm and an aspect ratio that is greater than or equal to about 20. Cooling passages **40** of this diameter may be too small to receive the EBC coating **22**, leaving the surfaces of the airfoil **16** defining the passages **40** devoid of EBC material and vulnerable to recession. As such, the tubes **44** in the illustrative embodiment are also made from an environmental barrier material and line the surfaces defining the cooling passages **40** to block recession of those areas.

The environmental barrier material forming the tubes **44** is a different material than the ceramic materials forming the airfoil **16** and is at least partially solidified and/or densified to form the hollow tubes **44**. Illustratively, the tubes **44** are fully solidified and/or densified by sintering, for example. In this way, the tubes **44** are rigid and self-supporting and can be inserted in to the fibers **42** during the preforming stage of the airfoil **16** as shown in FIGS. **4** and **5**. The tubes **44** may be formed by extrusion prior to being solidified. In one embodiment, the tubes **44** are strengthened with a fugitive polymer for handling purposes. In another embodiment, the tubes **44** may be strengthened with a removable filler such as, for example, a closed-cell carbonaceous material which is resistant to ceramic matrix infiltration in subsequent manufacturing processes. Since the tubes **44** are fully dense, they have a higher thermal conductivity than an EBC material that is applied by air plasma spray.

In the illustrative embodiment, the tubes **44** are capped at both ends to form a hollow tube passageway **46** that is closed off to prevent the tubes from being clogged with ceramic matrix material during densification of the ceramic fiber preform as shown in FIG. **6**. The tubes **44** may include removable plugs **48**, **50** disposed at both ends of the tube **44** to maintain the hollow tube passageway **46** during infiltration of the fibers **42** with ceramic matrix material. In another embodiment, the environmental barrier material forming the tubes **44** may provide and define both ends to close off the hollow tube passageway **46** without the plugs **48**, **50**. In other words, the tubes **44** may be formed fully of environmental barrier material with solid ends and a hollow pocket in the midsection. Once embedded in to the fibers **42**, the preform of the airfoil is processed further with the tubes **44** to form the ceramic matrix composite airfoil **16** with cooling passages **40**. The processing may include machining, cutting, removing the plugs **48**, **50**, burning, or any other suitable material for removing material and/or exposing the hollow midsection of the tube **44**.

The airfoil **16** shown in FIG. **6** has completed all ceramic matrix infiltration steps and the tube **44** of environmental barrier material lines the cooling passage **40** to block recession in this area. The ceramic matrix material also fills any gaps formed between the fibers **42** and the embedded tubes **44**. At this point, the plugs **48**, **50** and/or the ends of the tubes **44** may be removed to open the hollow tube passages **46**. If the ends of the tubes **44** extend past the outer surface **24** and/or the inner surface **38**, the tubes **44** may be machined off so that they are flush with the outer surface **24** and the inner surface **38** as shown in FIG. **7**. A tool **51** may be used to remove (i.e. by grinding) the ends of the tubes **44** off until ends of the tubes **44** are flush with the outer and inner surfaces **24**, **38** of the airfoil **16**. The cutting tool **51** may include a diamond cutting wheel or another suitable cutting and/or material removing tool.

Forming the airfoil **16** with cooling passages **40** using the hollow tubes **44** made from densified environmental barrier material as described above allows the cooling passages **40** to be sized to optimize cooling of the airfoil **16**. For example, airfoils formed without the tubes **44** may have cooling holes machined through the airfoil using a typical spiral drill bit, a diamond core drill or burr, or a laser. Typical spiral drill bits form cylindrical passages with a constant cross-sectional area. Drilling may also cause fracturing and/or forming/exposing terminal ends of the fibers. Even if coated with a barrier coating at a later stage, the formed and exposed terminal ends may not be as desired as intact fibers that are parted around the tubes **44** to form the passages **40**.

The tubes **44** in the illustrative embodiment may be formed to have a passage **46** with a varying cross-sectional area, as shown in FIGS. **8-10**, because they are formed without any drilling or machining through the airfoil **16**. Varying the cross-sectional area of the passage **46** may change the cooling fluids flow profile through the passage **46** to optimize properties of the cooling fluid such as, for example, flow rate, pressure, and/or heat transfer and minimizing interaction losses with the primary flow through the gas flow path **20**.

A second embodiment of a tube **244** made from densified environmental barrier material and embedded in the airfoil **16** during the preforming stage is shown in FIG. **8**. The tube **244** is formed to include a hollow passage **246** that extends from a first end **248** to a second end **250** defining a total length of the tube **244**. The hollow passage **246** has a cross-sectional area that decreases or narrows from the first end **248** to the second end **250**. As such, the hollow passage **246** acts as a nozzle. The cross-sectional area of the hollow passage **246** may decrease constantly from the first end **248** to the second end **250** such that the surfaces defining the passage **246** have a linear or exponentially changing slope.

A third embodiment of a tube **344** made from densified environmental barrier material and embedded in the airfoil **16** during the preforming stage is shown in FIG. **9**. The tube **344** is formed to include a hollow passage **346** that extends from a first end **348** to a second end **350** defining a total length of the tube **344**. The hollow passage **346** has a cross-sectional area that increases or expands from the first end **348** to the second end **350**. As such, the hollow passage **346** acts as a diffuser. The cross-sectional area of the hollow passage **346** may increase constantly from the first end **348** to the second end **350** such that the surfaces defining the passage **346** have a linear or exponentially changing slope.

A fourth embodiment of a tube **444** made from densified environmental barrier material and embedded in the airfoil **16** during the preforming stage is shown in FIG. **10**. The tube **444** is formed to include a hollow passage **446** that extends from a first end **448** to a second end **450** defining a total length of the tube **444**. The hollow passage **446** has a cross-sectional area that increases from the first end to a point **452** between the first end **448** and the second end **450** and decreases from the point **452** to the second end **450**. As such, the hollow passage **446** has a diffuser and then a nozzle like profile. The cross-sectional area of the hollow passage **446** may vary constantly from the first end **448** to the point **452** and from the point **452** to the second end **450** such that the surfaces of the passage **446** have a linear or exponentially changing slope.

Any of the tubes **44**, **244**, **344**, **444** in the illustrative embodiment may have a circular or a non-circular cross-sectional shape as shown in FIGS. **11**A-**11**E. In one embodiment, the tubes **44**, **244**, **344**, **444** may have a circular cross-sectional shape **70** as shown in FIG. **11**A. In another embodiment, the tubes **44**, **244**, **344**, **444** may have a triangular cross-sectional shape **72** as shown in FIG. **11**B. In another embodiment, the tubes **44**, **244**, **344**, **444** may have a square or rectangular cross sectional shape **74** as shown in FIG. **11**C. In another embodiment, the tubes **44**, **244**, **344**, **444** may have an oval cross-sectional shape **76** as shown in FIG. **11**D. In other embodiments, the tubes **44**, **244**, **344**, **444** may have any polygonal cross-sectional shape which is represented by the octagonal cross-sectional shape **78** as shown in FIG. **11**E. In another embodiment, the tubes **44**, **244**, **344**, **444** may have a first cross sectional shape (i.e. a circular shape) at a first end **80** and a second cross sectional shape (i.e. a rectangular shape) different than the first shape at a second end **82** as shown in FIG. **11**F. In another embodiment, the tubes **44**, **244**, **344**, **444** may have an oval cross-sectional shape **76** as shown in FIG. **11**D. Typical spiral drill bits or diamond core drills or burrs used to drill passages in airfoils or other components in the gas turbine engine may not be able to form the non-circular cross-sectional shapes described above and may leave the surfaces of the passages devoid of environmental barrier material.

Although the cooling passages **40** shown in FIGS. **1**-**9** are formed through the trailing edge **30** of the airfoil **16** and open along the pressure side **32** of the airfoil **16**, other cooling passages may be formed in other locations of the airfoil as shown in FIG. **12**. Such passages are formed using the same process and any of the environmental barrier tubes **44**, **244**, **344**, **444** described above. A second cooling passage **52** may be formed to extend through the trailing edge **30** and exit directly at the trailing edge **30**. A third cooling passage **54** may extend aft from the cooling cavity **36** at the trailing edge **30** and exit along the suction side **34**. A fourth cooling passage **56** may be spaced apart from the trailing edge **30** and extend from the cooling cavity **36** and exit along the suction side **34**. A fifth cooling passage **58** may be formed at the leading edge **28** and extend forward from the cooling cavity **36** and exit along the suction side **34**. A sixth cooling passage **60** may be formed at the leading edge **28** and extend forward from the cooling cavity and exit directly at the leading edge **28**. A seventh cooling passage **62** may be formed at the leading edge **28** and extend forward from the cooling cavity **36** and exit along the pressure side **32**. An eighth cooling passage **64** may be spaced apart from the leading edge **28** and the trailing edge **30** and extend from the cooling cavity **36** and exit along the pressure side **32**. Other arrangements and locations of cooling passages in the airfoil **16** may also be used.

Any of the tubes **44**, **244**, **344**, **444** described above may also be used in other CMC components to provide cooling passages **40**. For example, the tubes **44**, **244**, **344**, **444** may be included in a turbine blade **100** as shown in FIG. **13**. The turbine blade **100** illustratively includes a root **102**, a platform **104**, and an airfoil **106**. The root **102** is sized and shaped to attach the blade **100** to a turbine disk (not shown) for rotation about a central axis of a gas turbine engine. The platform **104** provides a radial boundary for a gas flow path. The airfoil **106** extends into the gas flow path and interacts with hot gases which cause the turbine blade, and the disk to rotate about the central axis. The airfoil **106** is similar to airfoil **16** in vane **10** and is formed with cooling passages **40** provided by the tubes **44**, **244**, **344**, **444** as shown in FIG. **13**. The cooling passages **40** extend from a cooling cavity **136** in the airfoil **106** to conduct cooling fluid from the cavity **136** to the gas flow path.

In other airfoils, cooling holes may be made in an airfoil by CVD diamond coated conventional twist drills, ultrasonically assisted diamond drilling, or laser drilling. However, some portions around the cooling holes may be unprotected by EBC on the machined surfaces which may lead to life concerns. Additionally, such machining processes may be challenging due to material heterogeneity. Forming holes or passages in situ with the preform, in accordance with the present disclosure, also avoids drill/spindle breakage. In some embodiments, the trailing edge of a CMC vane may be difficult to cool due to the relatively long distance (perhaps ⅓ of the airfoil chord) between the internal passage or cavity within the vane and the trailing edge. Cooling holes may be an attractive option to create a film of relatively cool air to protect the trailing edge. Silicon carbide CMCs may be vulnerable to recession caused by reaction of the surface silica (that forms on exposure to high temperatures) with water vapour (present in the environment or introduced as a result of combustion). An environmental barrier coating (EBC) may be applied to the surface of the CMC by techniques such as air plasma spray to address this issue but may not work inside cooling holes which have a diameter around 1 mm and a high aspect ratio (>20).

Accordingly, the present disclosure includes inserting a hollow tube made of the environmental barrier material (typically a rare earth (RE) silicate, for example, in the form of RE_2SiO_5 or $RE_2Si_2O_7$ where RE comprises at least one of yttrium, ytterbium, erbium, lutetium, europium, terbium, neodymium, praseodymium, dysprosium, or any other suitable rare earth element) into the CMC at the preforming stage. The tube may stick out of the preform outside and inside the airfoil and remain in place through the subsequent densification process steps which may include boron nitride and/or silicon carbide chemical vapour infiltration (CVI), slurry infiltration, and/or melt infiltration. This may have an additional component cooling benefit in increasing local heat transfer coefficient, i.e. act as a turbulator. To prevent ingress of infiltration materials, end plugs made of suitable refractory material may be employed and removed after final densification process steps are complete. In some embodiments, the plugged ends of the tube may be removed by employing a localized diamond cutting wheel to leave the correct internal and external profile of the airfoil. The ends of the tube may also be removed by oxidation or chemical leaching depending on materials used.

In some embodiments, the EBC tube is first strengthened for handling purposes with fugitive or removable filler which could also act as a plug to prevent infiltration. A closed cell carbonaceous material is one example of such a filler. The tube could be manufactured by extrusion. The EBC tube in the illustrative embodiment may be fully dense and therefore have a higher thermal conductivity than EBC which is typically applied to the external surface of a component by air plasma spray. This may be an advantage for lining a cooling hole.

In some embodiments, the EBC tube may not have a constant cross-section which may offer improve aerodynamic and cooling performance through more accurately matching the free-stream fluid behavior at the hole exit. In some embodiments, the tubes provide environmental protection from cooling flow passing through the CMC structure. In some embodiments, the tubes may be relatively simple to create and apply to the CMC pre-form (i.e. opportunity to mass produce or automate the process). In some embodiments, the tube may provide opportunity for very tight internal tube dimensional tolerances (i.e. very good for cooling flow performance and reducing uncertainty on coolant consumption).

In some embodiments, an exposed SiC surface (especially one which includes sources of boron) may form a silica glass layer at elevated temperatures. This may create blockage or partial blockage in the bore of the cooling hole. A rare earth silicate EBC lining to the cooling hole may reduce or eliminate this effect as it will not tend to form a glassy layer. In some embodiments, a ratio of Rare Earth monosilicates to disilicates can be tailored to optimize the environmental resistance, recession tolerance, and likelihood of de-bonding the EBC tube from the CMC structure. Tailoring the ratio of monosilicate to disilicate may also allow optimization of resistance to CMAS (calcium magnesium aluminosilicate) and coefficient of thermal expansion mismatch.

In some embodiments, the CMC vanes offer cooling flow and consequent fuel burn reductions in gas turbine engines. The cooling holes may be applicable to all gas turbines which utilize high overall pressure ratio (OPR)/high turbine entry temperature (TET) to obtain high thermal efficiency. In some embodiments, the in situ EBC for cooling holes could be applied to other hot end gas turbine components made from SiC/SiC CMCs.

While the disclosure has been illustrated and described in detail in the foregoing drawings and description, the same is to be considered as exemplary and not restrictive in character, it being understood that only illustrative embodiments thereof have been shown and described and that all changes and modifications that come within the spirit of the disclosure are desired to be protected.

What is claimed is:

1. A method comprising

providing an airfoil shaped ceramic reinforcement fiber preform and a tube, the ceramic reinforcement fiber preform having a first side formed to define a cooling cavity in the ceramic reinforcement fiber preform and a second side opposite the first side, the tube being made from an environmental barrier material and having a first end and a second end,

inserting the tube through the ceramic reinforcement fiber preform so that the first end of the tube extends into the cooling cavity and the second end of the tube extends beyond the second side of the ceramic reinforcement fiber preform,

infiltrating the ceramic reinforcement fiber preform with ceramic matrix material to densify the ceramic reinforcement fiber preform and form a ceramic matrix composite airfoil having the tube fixed therein, the ceramic matrix composite airfoil having an inner surface that defines the cooling cavity and an outer surface opposite the inner surface and adapted to interface with hot gases, and

removing material from the first end and the second end of the tube such that the first end is about flush with the inner surface and the second end is about flush with the outer surface to form a cooling passage with the tube that extends through the ceramic matrix composite airfoil to provide fluid communication between the cooling cavity and environment surrounding the outer surface outside of the ceramic matrix composite airfoil,

wherein the tube includes a central hollow section,

wherein the first end is made of solid material and the second end is made of solid material to block ingress of ceramic matrix composite material into the hollow section during the infiltrating step, and

wherein the solid material is environmental barrier material.

2. The method of claim **1**, wherein the step of removing material from the first end and the second end includes cutting the first end from the tube to form a first opening into the hollow section and cutting the second end from the tube to form a second opening into the hollow section.

3. The method of claim **1**, wherein the tube includes an inner surface that directly defines the cooling passage and an outer surface that directly engages the ceramic matrix composite airfoil and the environmental barrier material extends between the inner surface and the outer surface of the tube.

4. The method of claim **1**, wherein the step of inserting the tube through the ceramic reinforcement fiber preform includes parting fibers included in the ceramic reinforcement fiber preform around the tube to avoid fracturing the fibers.

5. The method of claim **1**, further comprising:

sintering the tube to full density before inserting the tube through the ceramic reinforcement fiber preform such that the tube is a rigid tube.

6. The method of claim 1, further comprising:

machining a passage in the ceramic reinforcement fiber preform before the step of inserting the tube through the ceramic reinforcement fiber preform,

wherein the step of inserting the tube through the ceramic reinforcement fiber preform includes inserting the tube through the passage.

7. The method of claim 5, further comprising:

forming the tube by extrusion prior to sintering.

* * * * *