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Spangler et al.

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(54) **SHELL AND SPAR AIRFOIL**

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(71) Applicant: **United Technologies Corporation**,
Farmington, CT (US)

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(72) Inventors: **Brandon W. Spangler**, Vernon, CT
(US); **Adam P. Generale**, Dobbs Ferry,
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(73) Assignee: **RAYTHEON TECHNOLOGIES**
CORPORATION, Farmington, CT
(US)

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Primary Examiner — Igor Kershteyn

(74) *Attorney, Agent, or Firm* — Cantor Colburn LLP

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(57) **ABSTRACT**

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F01D 5/14 (2006.01)

F01D 5/28 (2006.01)

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

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(2013.01); **F01D 5/141** (2013.01); **F01D 5/282**
(2013.01); **F01D 5/284** (2013.01)

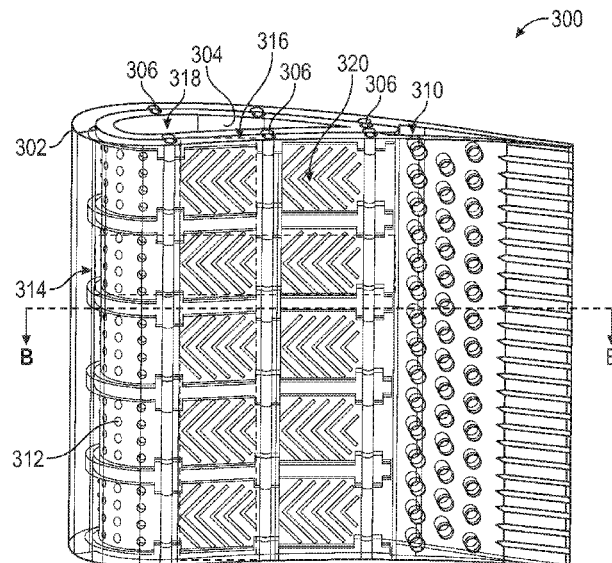
(58) **Field of Classification Search**

CPC F01D 5/141; F01D 5/147; F01D 5/188;
F01D 5/189; F01D 5/282; F01D 5/284;
F05D 2220/32; F05D 2230/64; F05D
2230/642; F05D 2300/177; F05D
2300/20; Y02T 50/676

See application file for complete search history.

Airfoils, shells, and spars are provided. The airfoils include a shell having a first channel and a first engagement element arranged along the first channel and a spar having a second channel and a second engagement element arranged along the second channel and the spar defines an inner cavity. A connector is configured to be installed between and connect the shell and the spar to allow for thermal growth of the shell relative to the spar. The connector has first and second engageable portions connected by a link. The first engageable portion is configured to engage with the shell and the second engageable portion is configured to engage with the spar. When assembled, an outer cavity is formed between the spar and the shell, and the first and second engagement elements and the first and second engageable portions are configured to define an axial flow path through the outer cavity.

20 Claims, 12 Drawing Sheets



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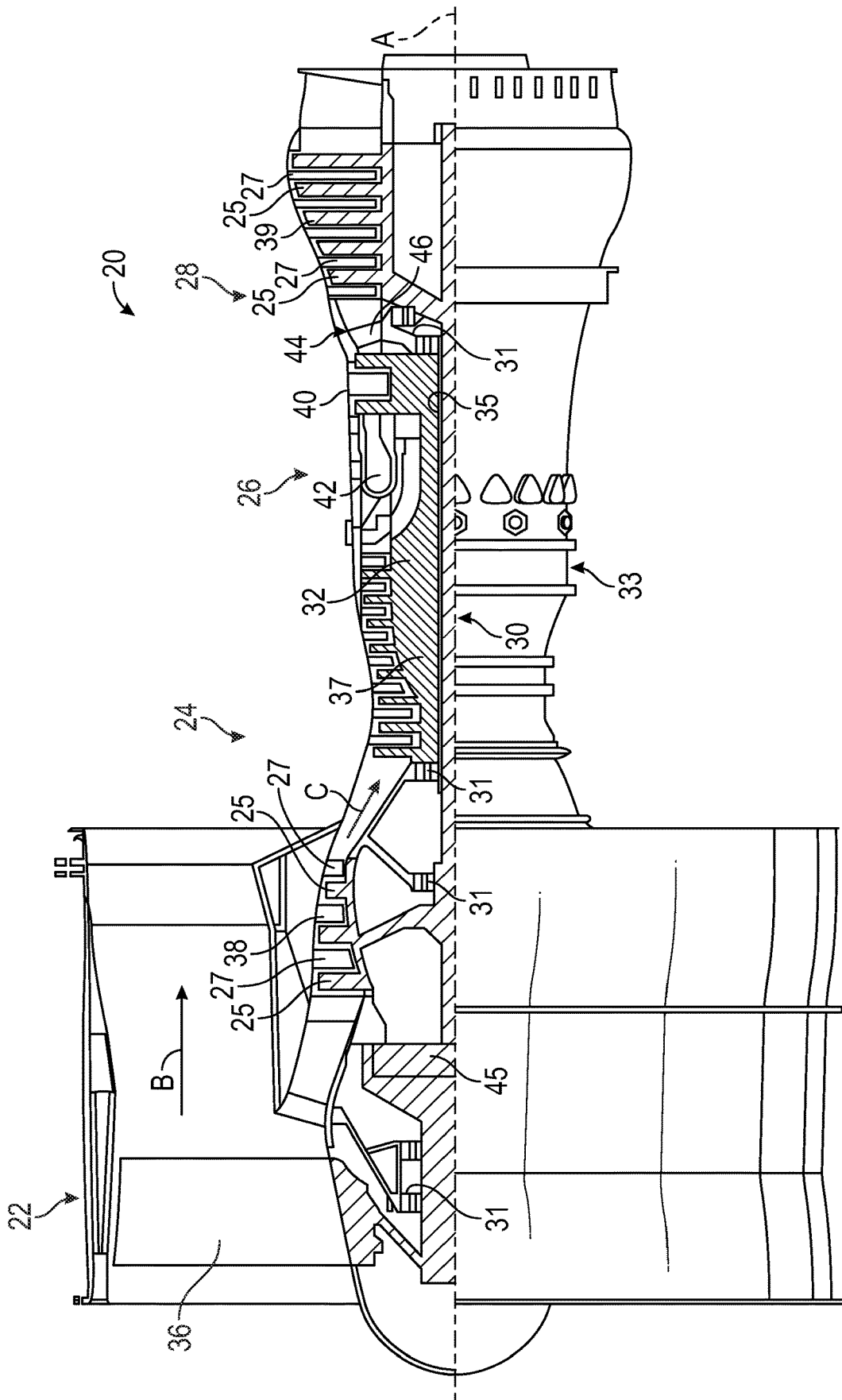


FIG. 1A

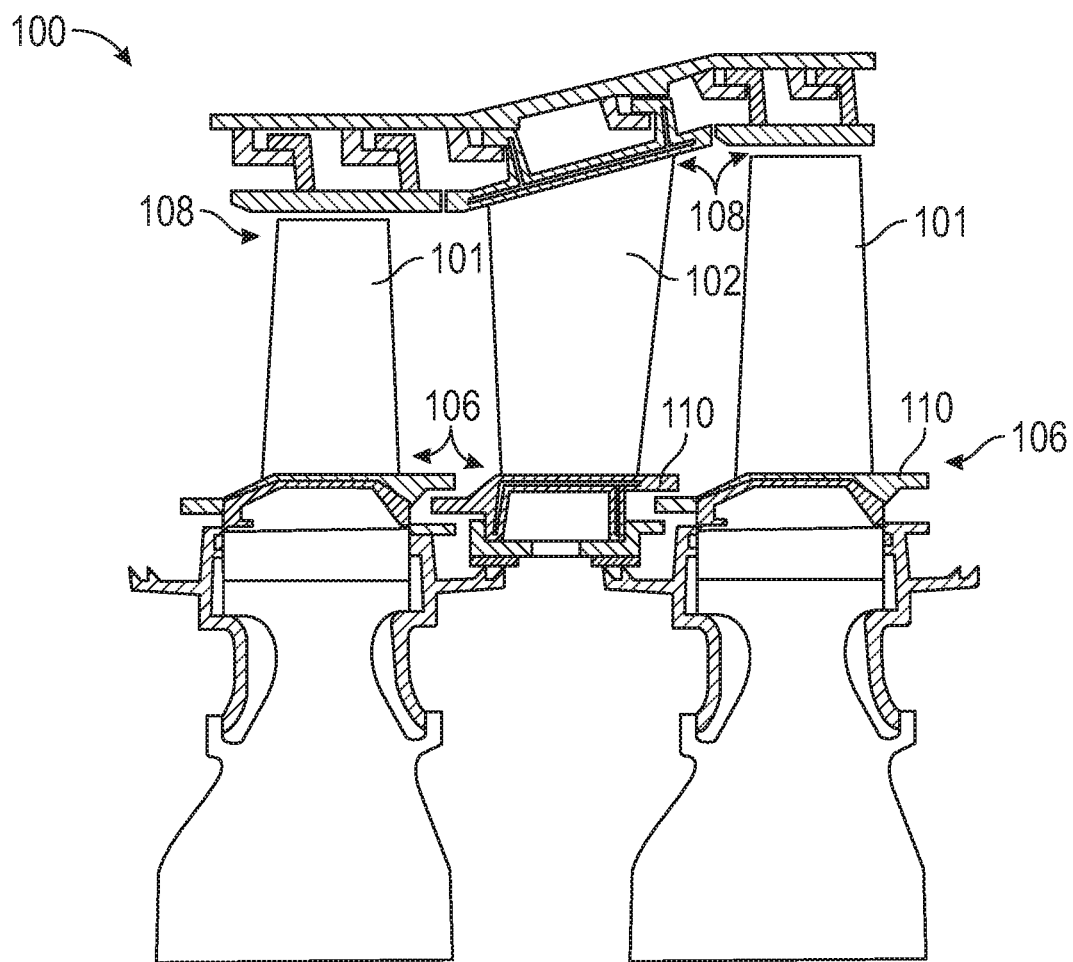


FIG. 1B

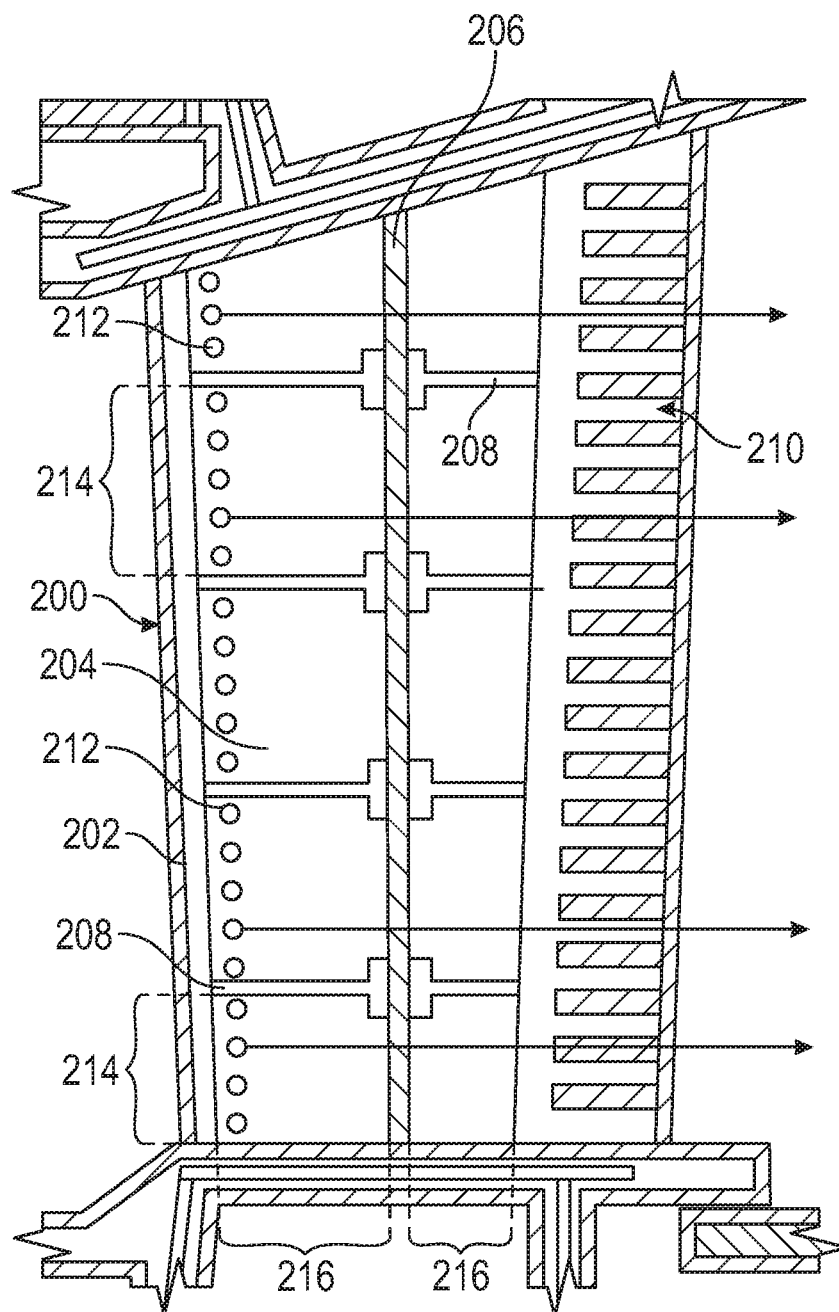


FIG. 2

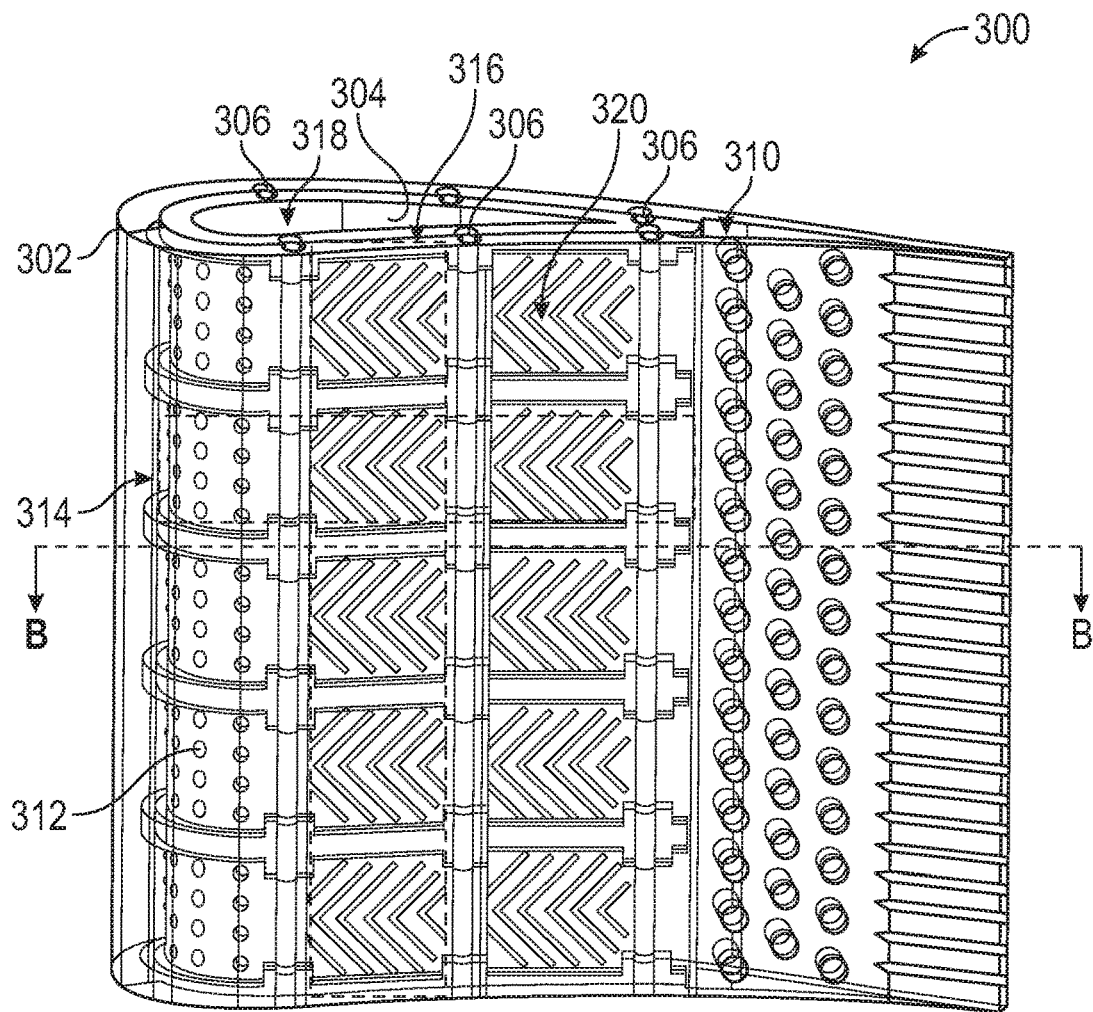


FIG. 3A

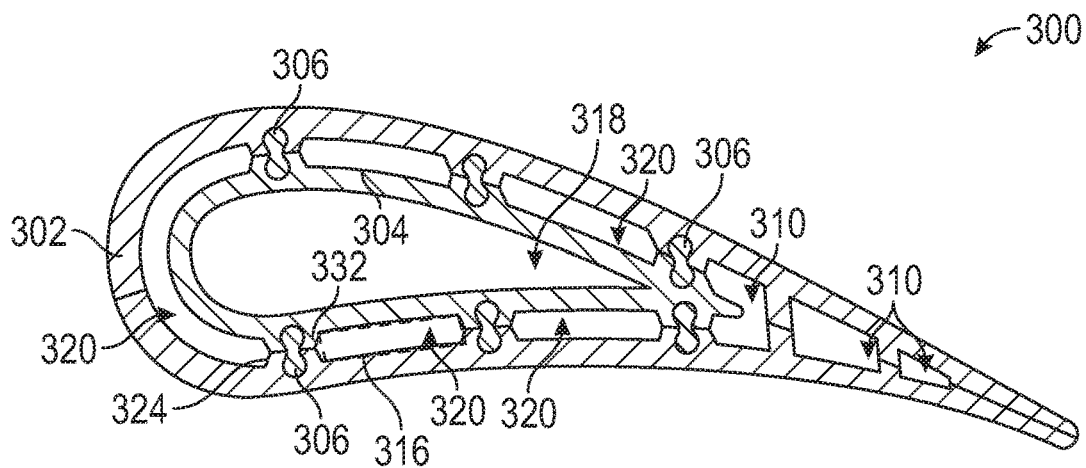


FIG. 3B

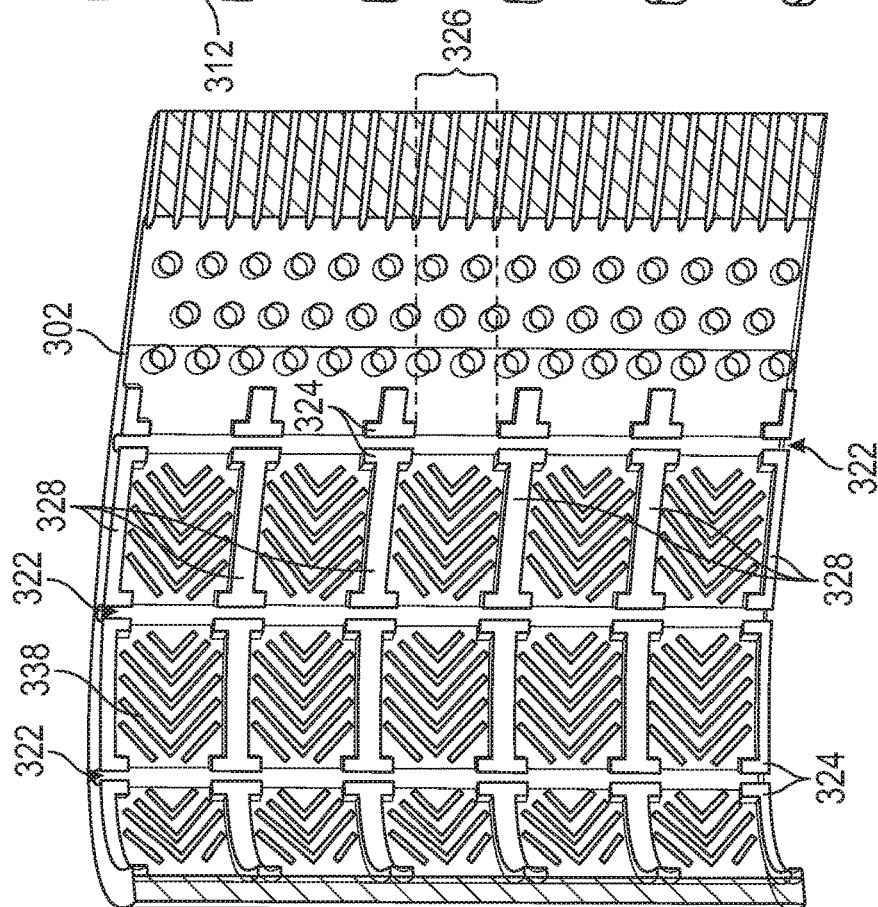
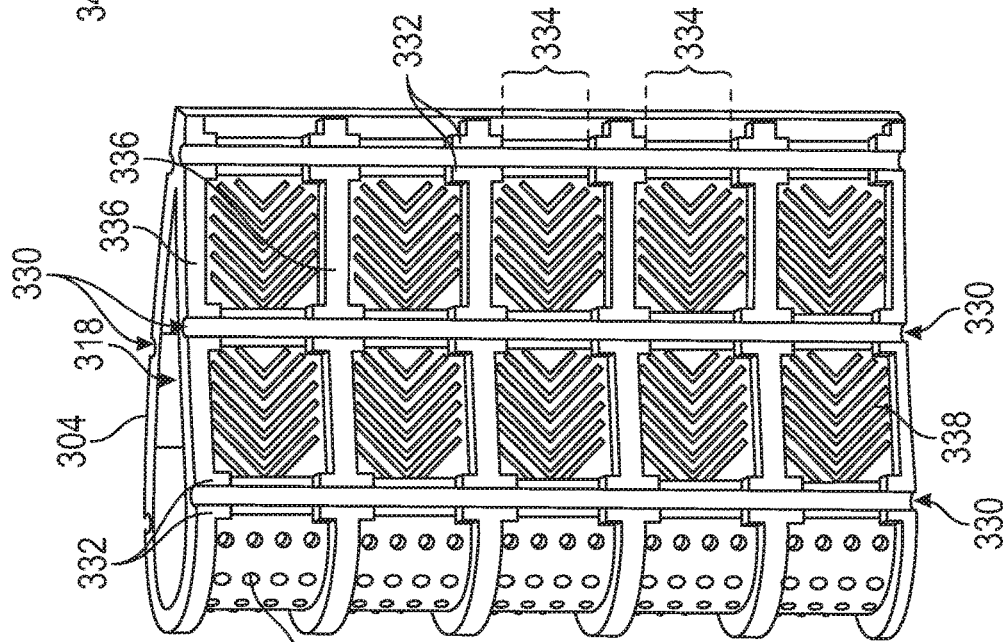
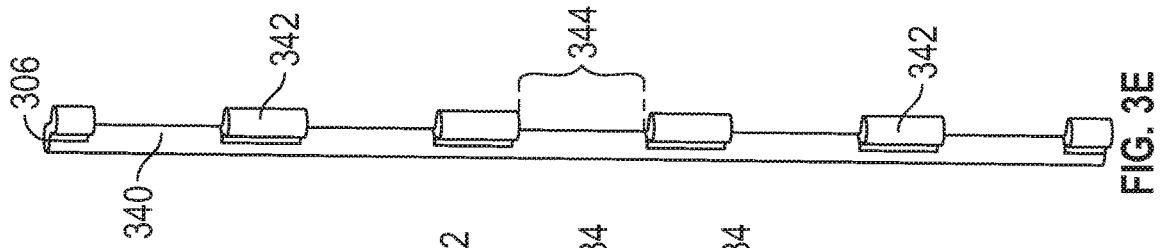


FIG. 3D

FIG. 3C

FIG. 3E

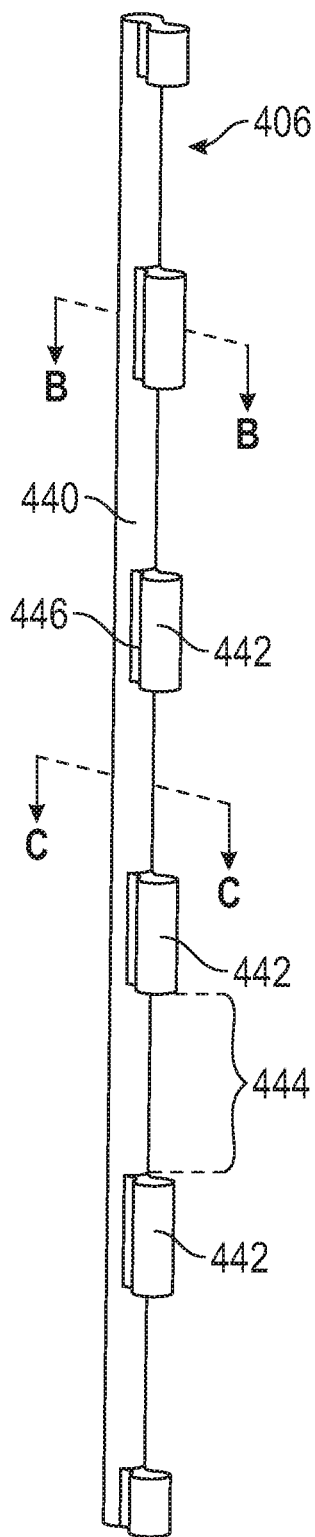


FIG. 4A

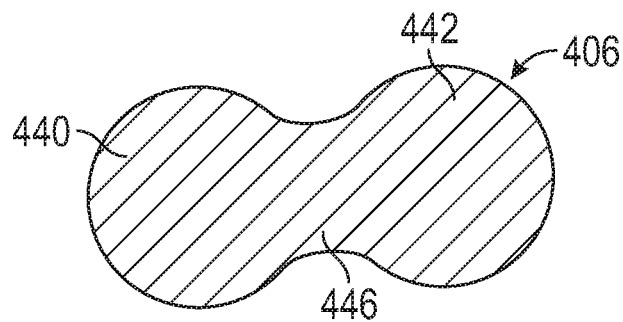


FIG. 4B

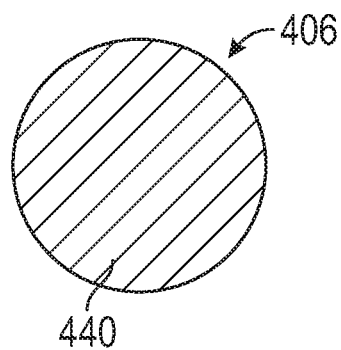


FIG. 4C

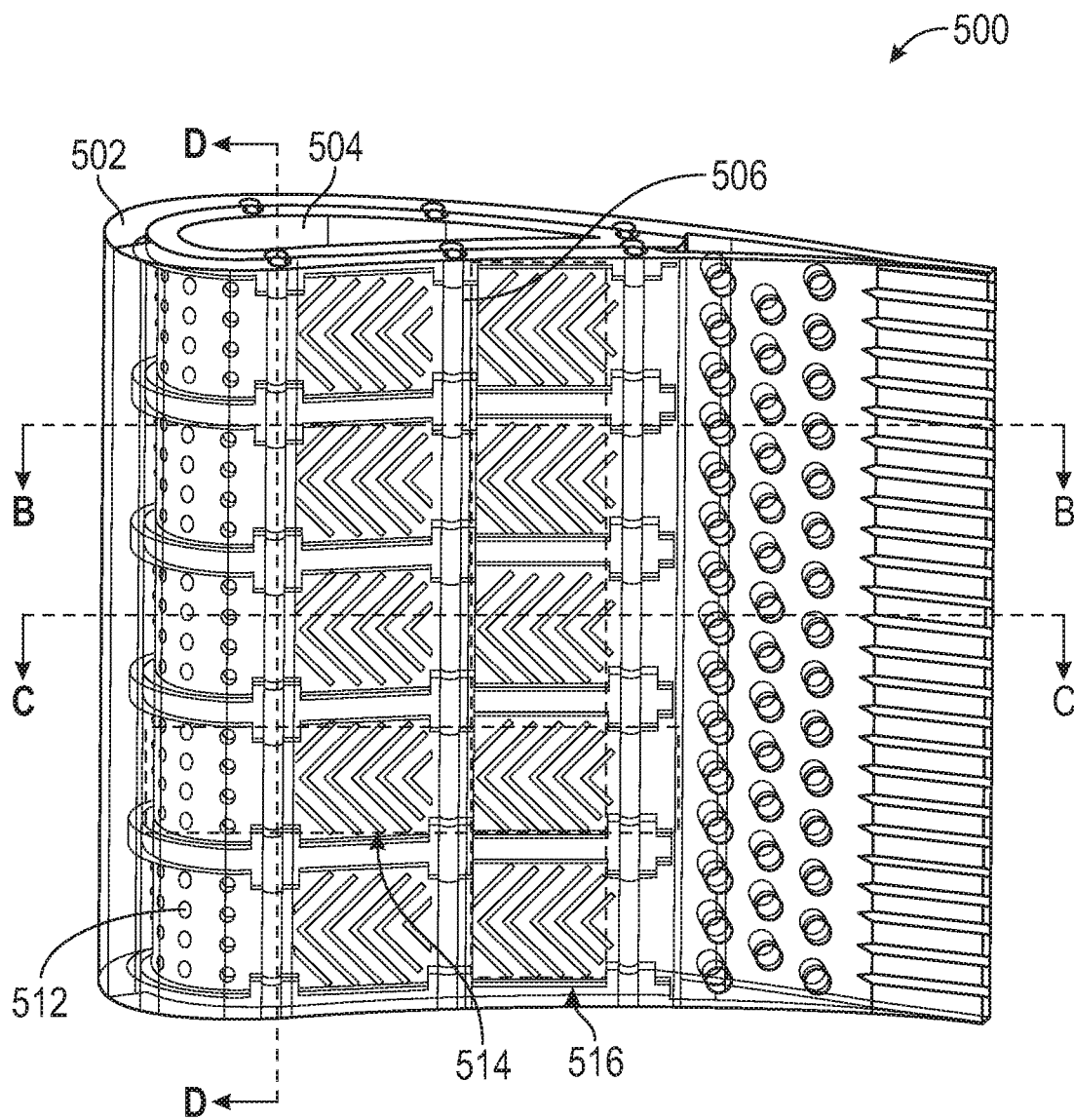


FIG. 5A

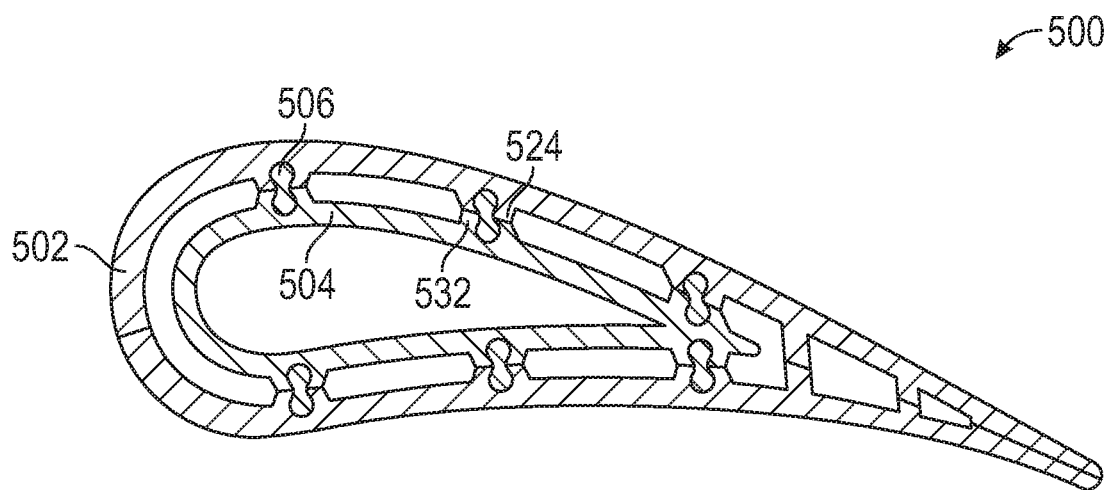


FIG. 5B

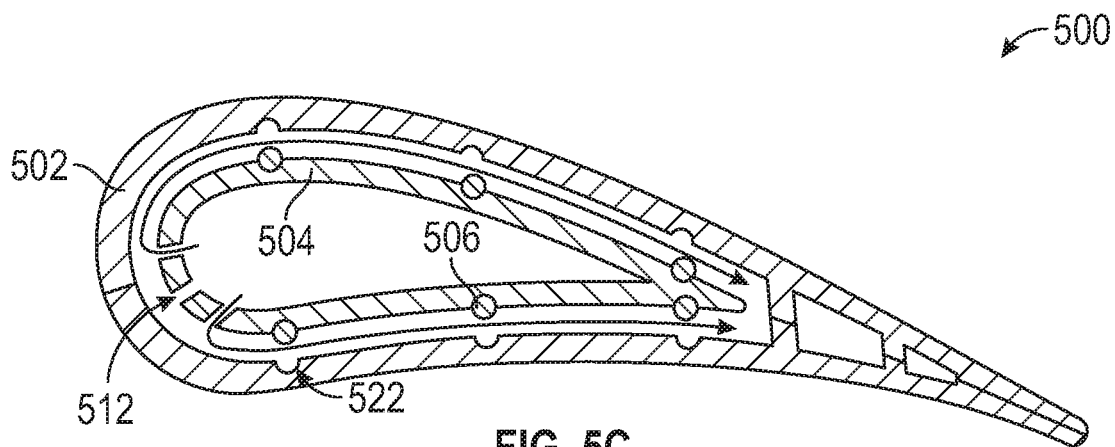


FIG. 5C

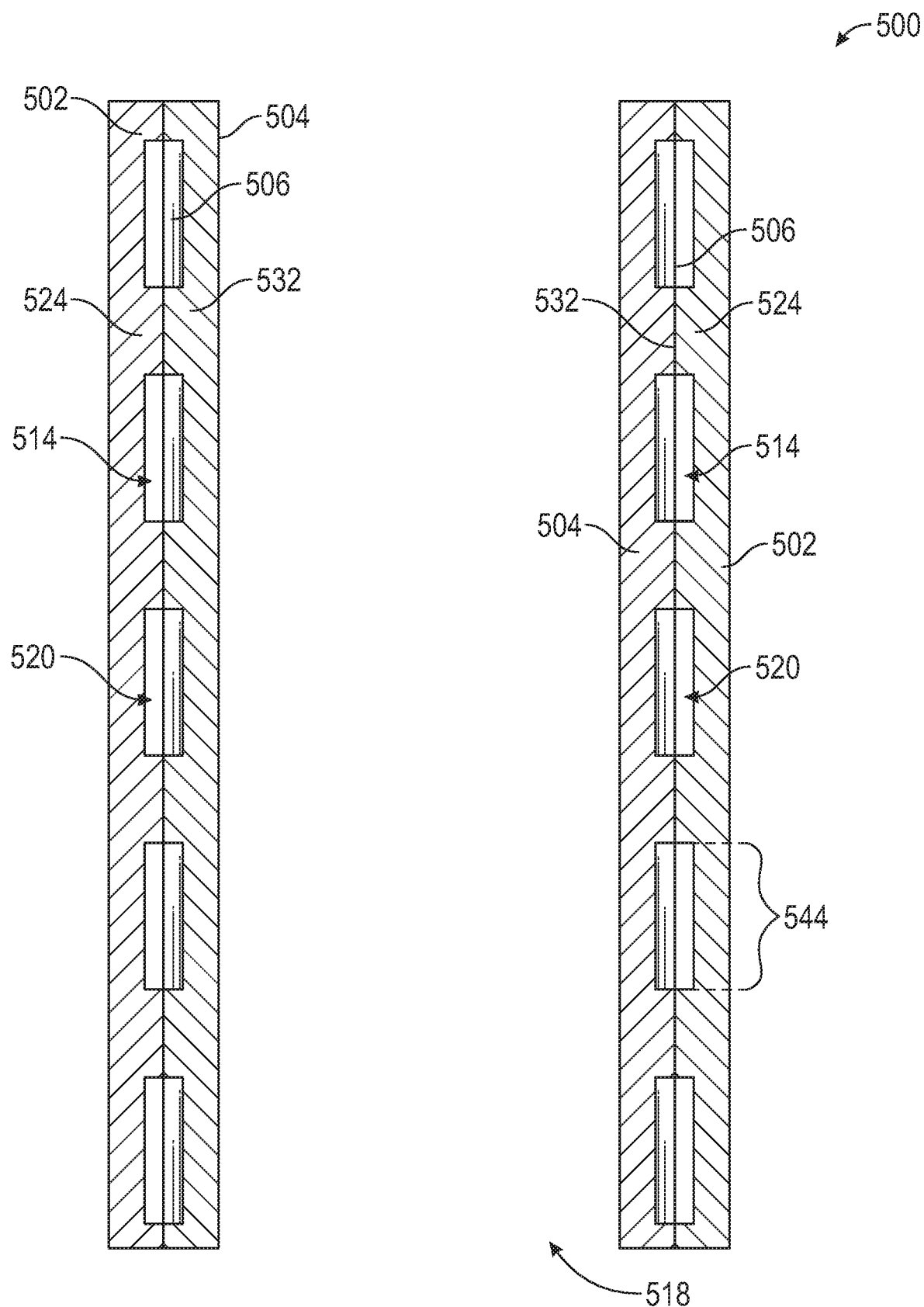


FIG. 5D

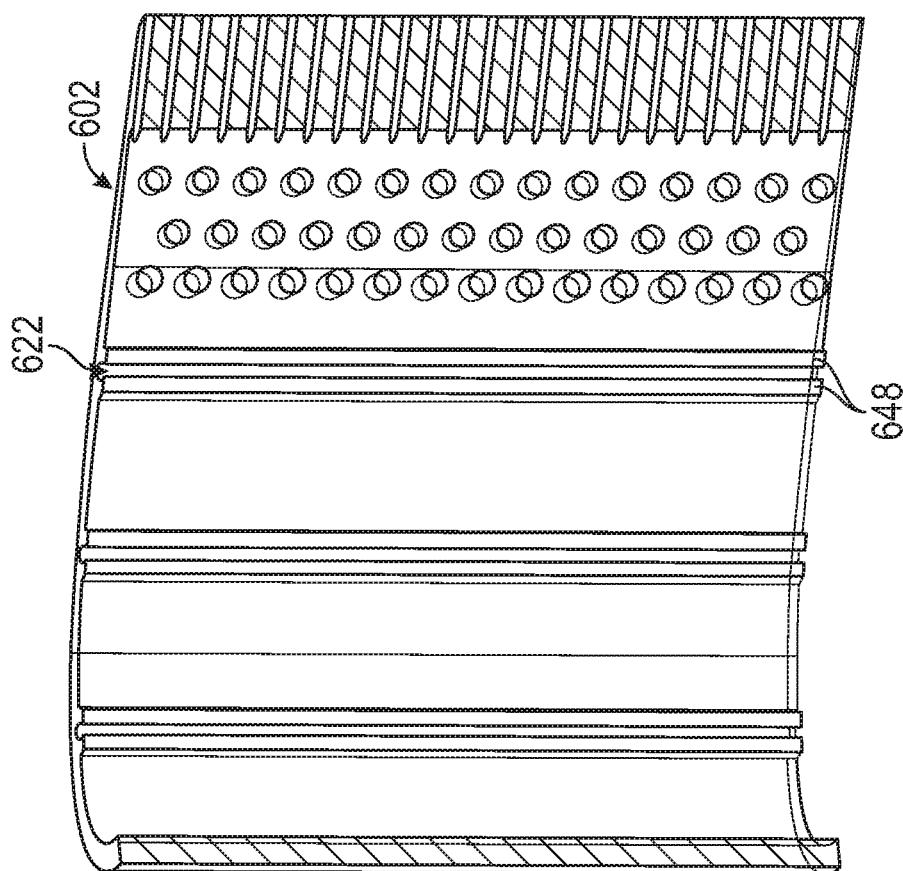


FIG. 6B

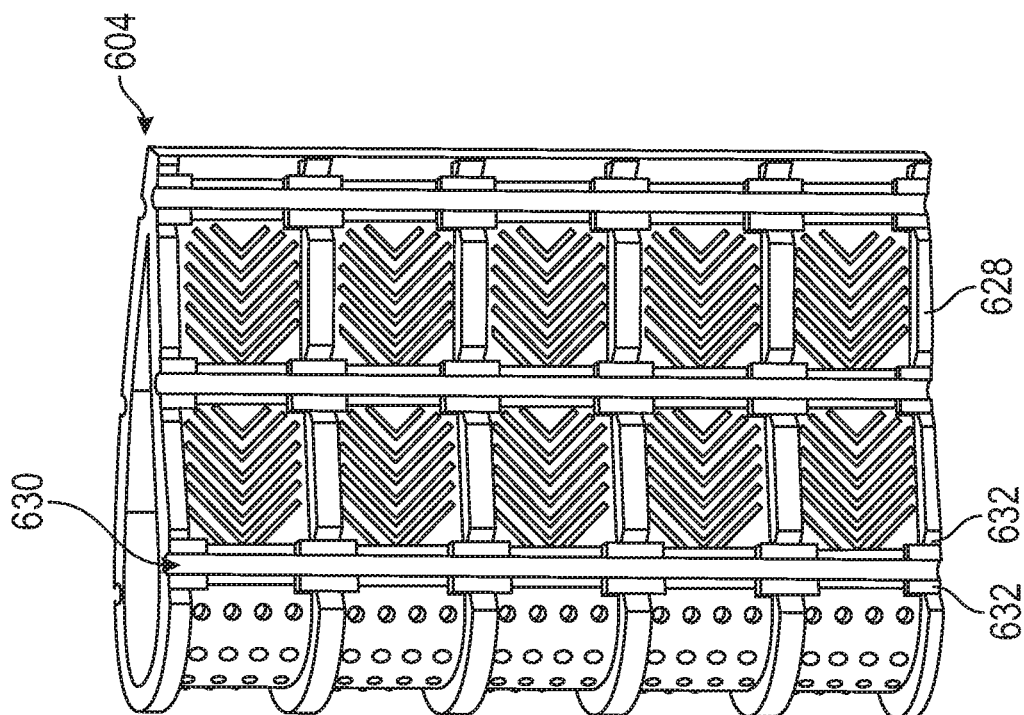


FIG. 6A

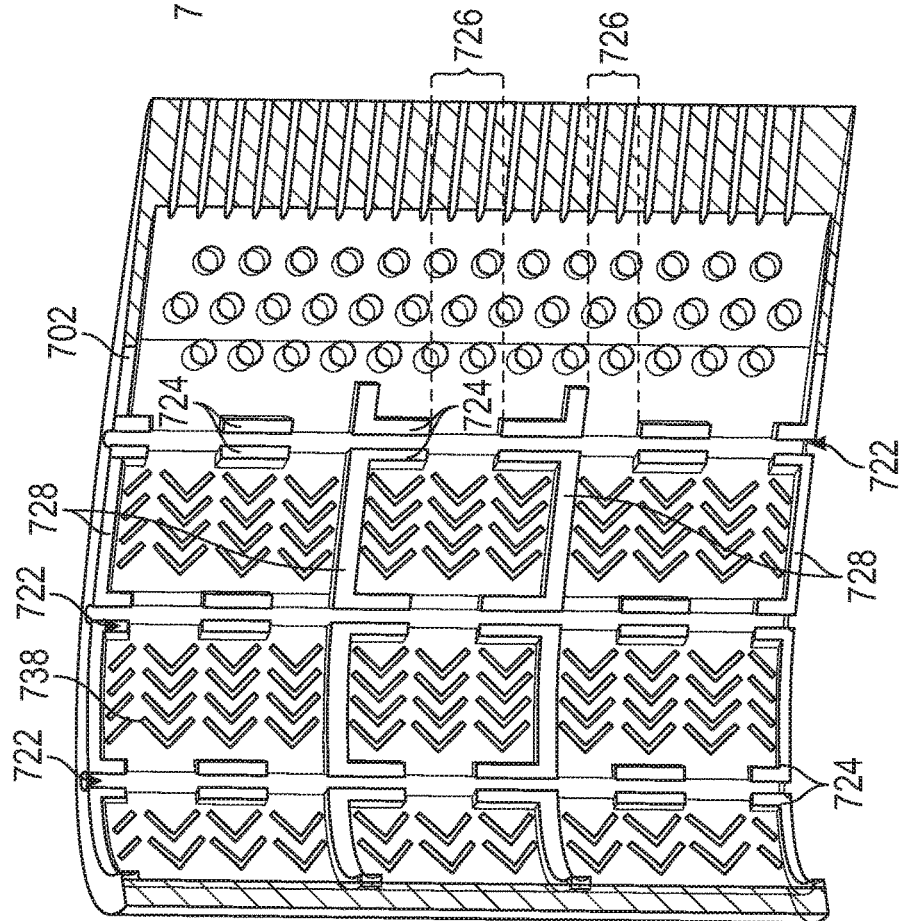


FIG. 7A

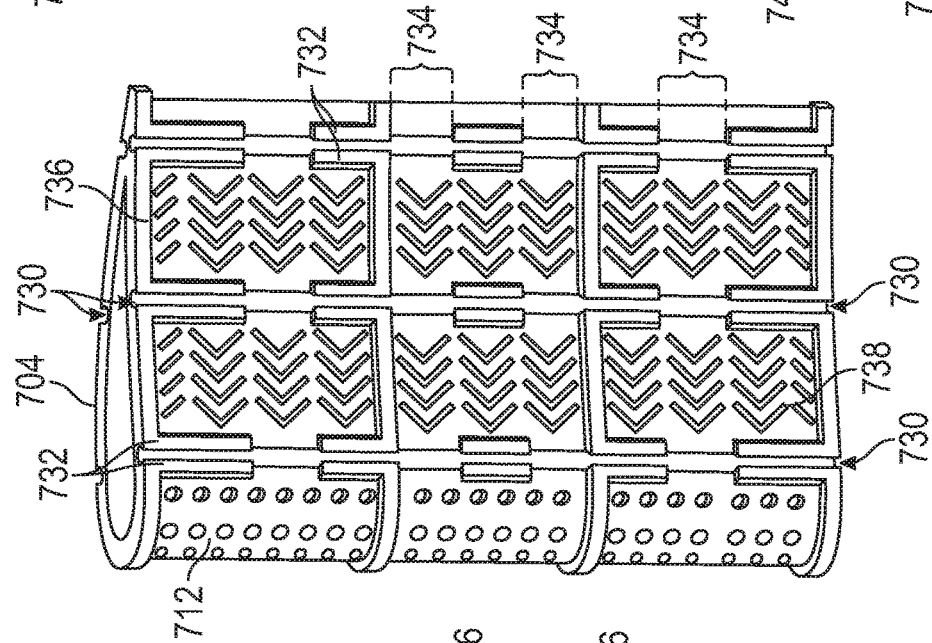


FIG. 7B

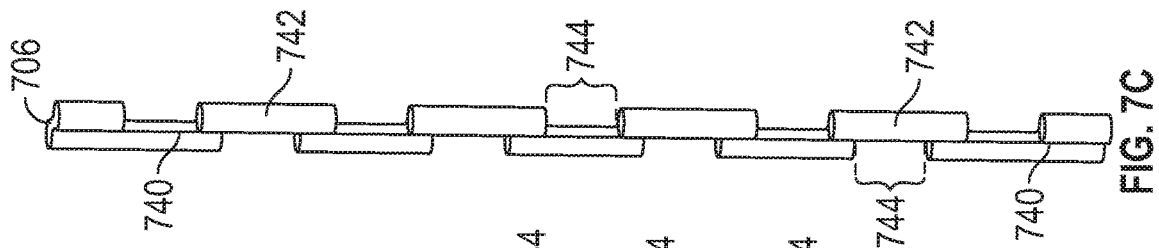


FIG. 7C

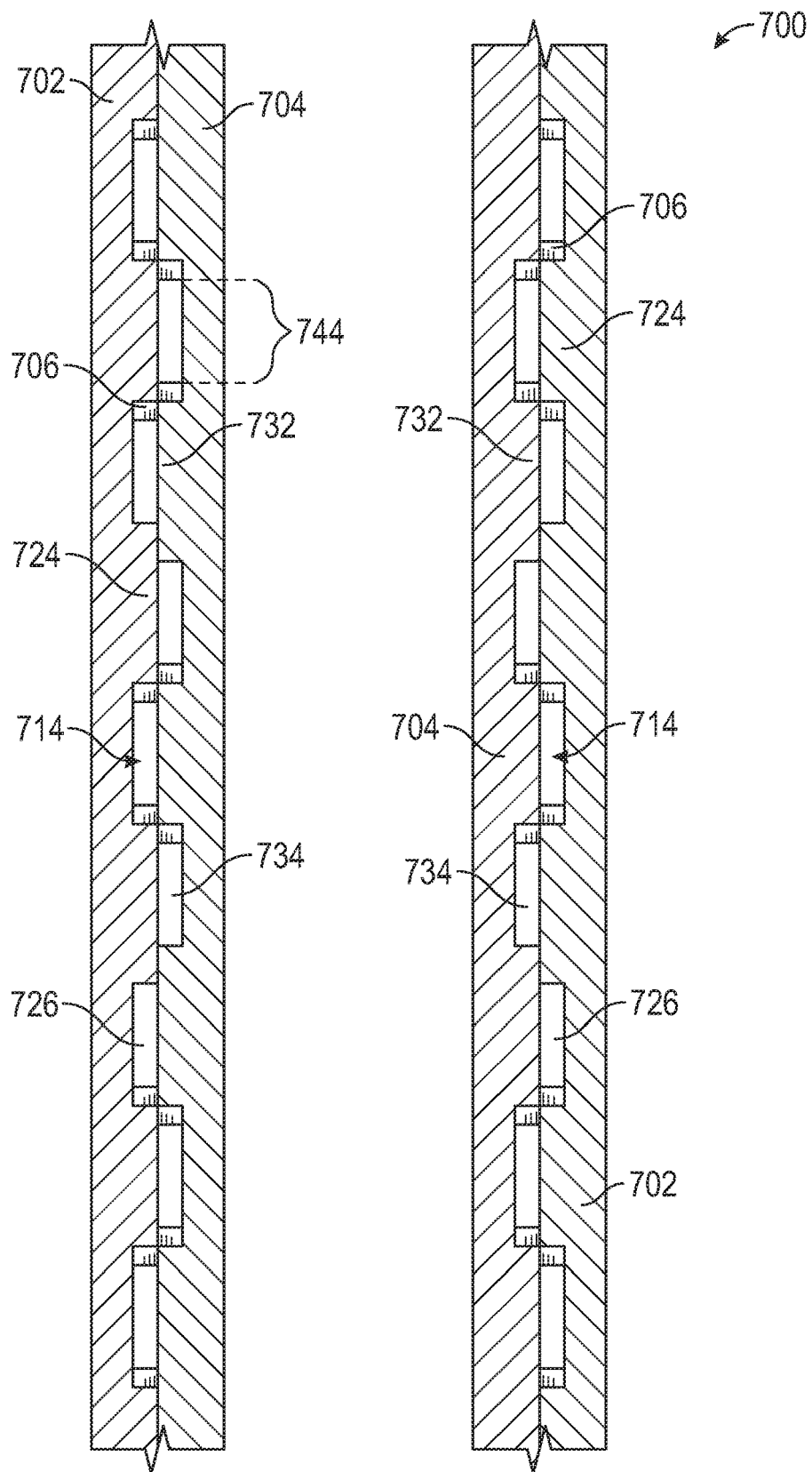


FIG. 7D

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SHELL AND SPAR AIRFOIL**BACKGROUND**

The subject matter disclosed herein generally relates to airflow in components of gas turbine engines and, more particularly, to shell and spar airfoils for gas turbine engines.

Airfoils, and particularly airfoils of gas turbine engines, may include internal flow passages to enable cooling of the airfoils. The supply of the cooling air through cavities of the airfoils may be carefully designed so as to provide an efficient cooling configuration. However, various structures and/or features of the airfoils may impact cooling schemes, thus reducing the efficiency and/or effectiveness of a cooling scheme.

One type of airfoil construction is a spar-and-shell configuration, with the spar providing a structural frame with the shell installed external thereto. As such, the shell defines an external surface, such as a flow surface, and may be exposed to high temperatures within a gas turbine engine.

Spar-and-shell airfoils may be subject to the shell and the spar having high thermal stress loads formed due to large temperature differences (e.g., high temperature at shell, relatively low temperature at the spar). The shell is exposed to the high temperature gas flow while the spar is cooled with cooling air so that the temperature is much lower than the shell. If the shell is rigidly secured to the spar (e.g., at ribs), the temperature difference will produce high thermal stress loads on the ribs that connect the shell to the spar. A number of ribs are required to hold the thin shell wall to the spar when a high cooling air pressure is formed between the shell and the spar that tends to push the shell wall away from the spar. Thus, the ribs are used to hold the thin shell wall to the spar so that high pressure cooling air can be used between these two surfaces. If the ribs are rigidly fixed to the spar and the shell, then the high thermal stress loads may produce cracks in the ribs. Accordingly, improved spar-and-shell airfoil configurations may be desirable.

SUMMARY

According to some embodiments, airfoils of gas turbine engines are provided. The airfoils include a shell having a first receiving channel and a first engagement element arranged along the first receiving channel, the first receiving channel extending in a radial direction along the shell between a first end and a second end of the shell in the radial direction, a spar having a second receiving channel and a second engagement element arranged along the second receiving channel, the second receiving channel extending in a radial direction along the shell between a first end and a second end of the spar in the radial direction, wherein the spar defines an inner cavity, and a connector configured to be installed between the shell and the spar to connect the shell to the spar to allow for thermal growth of the shell relative to the spar, wherein the connector comprises a first engageable portion and a second engageable portion connected by a link, wherein the first engageable portion is configured to engage with the first engagement element of the shell and the second engageable portion is configured to engage with the second engagement element of the spar. When assembled, an outer cavity is formed between the spar and the shell, and the first engagement element, second engagement element, the first engageable portion, and the second engageable portion are configured to define an axial flow path through the outer cavity.

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In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include at least one axial rib on at least one of the shell and the spar, wherein the at least one axial rib defines, in part, the axial flow path in the outer cavity.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that the spar further comprises at least one impingement hole on a leading edge thereof.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that, when assembled, impinging air is configured to flow from the inner cavity to the outer cavity at an inner surface leading edge of the shell and flow axially aftward through the axial flow path of the outer cavity.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include at least one heat transfer augmentation feature formed on at least one of an inner surface of the shell and an outer surface of the spar such that the at least one heat transfer augmentation feature is located within the outer cavity when the shell is attached to the spar by the connector.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that the at least one heat transfer augmentation feature comprises at least one of trip strips, pedestals, and dimples.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that both the inner surface of the shell and the outer surface of the spar comprise at least one heat transfer augmentation feature.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that the connector has a lemniscate geometry in cross-section.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that the shell is formed from at least one of nickel and ceramic matrix composite.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that at least one of the first engageable portion and the second engageable portion of the connector comprise a segmented structure.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that the segmented structure of the at least one of the first engageable portion and the second engageable portion defines connector gaps separating segments thereof.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that both the first engageable portion and the second engageable portion of the connector comprise segmented structures.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that the first engageable portion is a continuous element that, when installed, extends a full radial extent of the airfoil and the second engageable portion of the connector comprises a segmented structure.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that the first engagement element extends a continuous full radial extent in a radial direction along the shell between the first end and the second end of the shell about the first receiving channel.

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In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that the shell further comprises a trailing edge cavity that is fluidly connected to the outer cavity when the shell is assembled to the spar.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that the shell, the spar, and the connector form a vane of a gas turbine engine.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that the shell, the spar, and the connector form a blade of a gas turbine engine.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that the spar is formed from at least one of nickel and ceramic matrix composite.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include a plurality of additional first receiving channels formed on the shell, wherein each additional first receiving channel includes at least one first engagement element arranged along a radial length thereof, a plurality of additional second receiving channels formed on the spar, wherein each additional second receiving channel includes at least one second engagement element arranged along a radial length thereof, and a plurality of additional connectors configured to be installed between the shell and the spar in the plurality of additional first and second receiving channels.

In addition to one or more of the features described above, or as an alternative, further embodiments of the airfoils may include that the outer cavity comprises one or more radial flow paths.

According to some embodiments, spars for airfoils of gas turbine engines are provided. The spars include a spar body having a receiving channel and an engagement element arranged along the receiving channel, the receiving channel extending in a radial direction along the spar body between a first end and a second end of the spar body in the radial direction, wherein the spar body defines an inner cavity and wherein the receiving channel and the engagement element are arranged on an exterior surface of the spar body opposite the inner cavity. The engagement element comprises one or more radial gaps that define axial flow paths relative to the receiving channel and the receiving channel and the engagement element are configured to receive a connector to attach a shell to the spar.

According to some embodiments, shells for airfoils of gas turbine engines are provided. The shells include a shell body having a receiving channel and an engagement element arranged along the receiving channel, the receiving channel extending in a radial direction along the shell between a first end and a second end of the shell in the radial direction, the shell having an interior surface and an exterior surface, wherein the exterior surface defines a flow surface of the airfoil. The engagement element comprises one or more radial gaps that define axial flow paths relative to the receiving channel and wherein the receiving channel and the engagement element are configured to receive a connector to attach the shell to a spar.

The foregoing features and elements may be executed or utilized in various combinations without exclusivity, unless expressly indicated otherwise. These features and elements as well as the operation thereof will become more apparent in light of the following description and the accompanying drawings. It should be understood, however, that the fol-

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lowing description and drawings are intended to be illustrative and explanatory in nature and non-limiting.

BRIEF DESCRIPTION OF THE DRAWINGS

The subject matter is particularly pointed out and distinctly claimed at the conclusion of the specification. The foregoing and other features, and advantages of the present disclosure are apparent from the following detailed description taken in conjunction with the accompanying drawings in which:

FIG. 1A is a schematic cross-sectional illustration of a gas turbine engine that may employ various embodiments disclosed herein;

FIG. 1B is a schematic illustration of a turbine that may employ various embodiments disclosed herein;

FIG. 2 is a schematic illustration of an airfoil in accordance with an embodiment of the present disclosure;

FIG. 3A is a schematic illustration of an airfoil as assembled in accordance with an embodiment of the present disclosure;

FIG. 3B is a plan cross-sectional view illustration of the airfoil of FIG. 3A as viewed along the line B-B;

FIG. 3C is a schematic illustration of a portion of a shell of the airfoil of FIG. 3A;

FIG. 3D is a schematic illustration of a spar of the airfoil of FIG. 3A;

FIG. 3E is a schematic illustration of a connector that connects the shell to the spar to form the airfoil of FIG. 3A;

FIG. 4A is an isometric illustration of a connector in accordance with an embodiment of the present disclosure;

FIG. 4B is a cross-sectional illustration of the connector of FIG. 4A as viewed along the line B-B;

FIG. 4C is a cross-sectional illustration of the connector of FIG. 4A as viewed along the line C-C;

FIG. 5A is an isometric illustration of an airfoil in accordance with an embodiment of the present disclosure;

FIG. 5B is a cross-sectional illustration of the airfoil of FIG. 5A as viewed along the line B-B;

FIG. 5C is a cross-sectional illustration of the airfoil of FIG. 5A as viewed along the line C-C;

FIG. 5D is a cross-sectional illustration of the airfoil of FIG. 5A as viewed along the line D-D;

FIG. 6A is schematic illustration of a spar in accordance with an embodiment of the present disclosure;

FIG. 6B is a schematic illustration of a portion of a shell in accordance with an embodiment of the present disclosure that is attachable to the spar of FIG. 6A;

FIG. 7A is a schematic illustration of a portion of a shell of an airfoil in accordance with an embodiment of the present disclosure;

FIG. 7B is a schematic illustration of a spar that is connectable to the shell of FIG. 7A;

FIG. 7C is a schematic illustration of a connector that connects the shell of FIG. 7A to the spar of FIG. 7B to form an airfoil in accordance with an embodiment of the present disclosure; and

FIG. 7D is a schematic illustration of a portion of a formed airfoil using the spar, shell, and connector of FIGS. 7A-7C.

DETAILED DESCRIPTION

FIG. 1A schematically illustrates a gas turbine engine 20. The exemplary gas turbine engine 20 is a two-spool turboprop engine that generally incorporates a fan section 22, a compressor section 24, a combustor section 26, and a turbine

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section 28. The fan section 22 drives air along a bypass flow path B, while the compressor section 24 drives air along a core flow path C for compression and communication into the combustor section 26. Hot combustion gases generated in the combustor section 26 are expanded through the turbine section 28. Although depicted as a turbofan gas turbine engine in the disclosed non-limiting embodiment, it should be understood that the concepts described herein are not limited to turbofan engines and these teachings could extend to other types of engines.

The gas turbine engine 20 generally includes a low speed spool 30 and a high speed spool 32 mounted for rotation about an engine centerline longitudinal axis A. The low speed spool 30 and the high speed spool 32 may be mounted relative to an engine static structure 33 via several bearing systems 31. It should be understood that other bearing systems 31 may alternatively or additionally be provided.

The low speed spool 30 generally includes an inner shaft 34 that interconnects a fan 36, a low pressure compressor 38 and a low pressure turbine 39. The inner shaft 34 can be connected to the fan 36 through a geared architecture 45 to drive the fan 36 at a lower speed than the low speed spool 30. The high speed spool 32 includes an outer shaft 35 that interconnects a high pressure compressor 37 and a high pressure turbine 40. In this embodiment, the inner shaft 34 and the outer shaft 35 are supported at various axial locations by bearing systems 31 positioned within the engine static structure 33.

A combustor 42 is arranged between the high pressure compressor 37 and the high pressure turbine 40. A mid-turbine frame 44 may be arranged generally between the high pressure turbine 40 and the low pressure turbine 39. The mid-turbine frame 44 can support one or more bearing systems 31 of the turbine section 28. The mid-turbine frame 44 may include one or more airfoils 46 that extend within the core flow path C.

The inner shaft 34 and the outer shaft 35 are concentric and rotate via the bearing systems 31 about the engine centerline longitudinal axis A, which is co-linear with their longitudinal axes. The core airflow is compressed by the low pressure compressor 38 and the high pressure compressor 37, is mixed with fuel and burned in the combustor 42, and is then expanded over the high pressure turbine 40 and the low pressure turbine 39. The high pressure turbine 40 and the low pressure turbine 39 rotationally drive the respective high speed spool 32 and the low speed spool 30 in response to the expansion.

The pressure ratio of the low pressure turbine 39 can be pressure measured prior to the inlet of the low pressure turbine 39 as related to the pressure at the outlet of the low pressure turbine 39 and prior to an exhaust nozzle of the gas turbine engine 20. In one non-limiting embodiment, the bypass ratio of the gas turbine engine 20 is greater than about ten (10:1), the fan diameter is significantly larger than that of the low pressure compressor 38, and the low pressure turbine 39 has a pressure ratio that is greater than about five (5:1). It should be understood, however, that the above parameters are only examples of one embodiment of a geared architecture engine and that the present disclosure is applicable to other gas turbine engines, including direct drive turbofans.

In this embodiment of the example gas turbine engine 20, a significant amount of thrust is provided by the bypass flow path B due to the high bypass ratio. The fan section 22 of the gas turbine engine 20 is designed for a particular flight condition—typically cruise at about 0.8 Mach and about 35,000 feet. This flight condition, with the gas turbine

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engine 20 at its best fuel consumption, is also known as bucket cruise Thrust Specific Fuel Consumption (TSFC). TSFC is an industry standard parameter of fuel consumption per unit of thrust.

Fan Pressure Ratio is the pressure ratio across a blade of the fan section 22 without the use of a Fan Exit Guide Vane system. The low Fan Pressure Ratio according to one non-limiting embodiment of the example gas turbine engine 20 is less than 1.45. Low Corrected Fan Tip Speed is the actual fan tip speed divided by an industry standard temperature correction of $[(T_{\text{amb}} - 518.7) / 518.7]^{0.5}$, where T represents the ambient temperature in degrees Rankine. The Low Corrected Fan Tip Speed according to one non-limiting embodiment of the example gas turbine engine 20 is less than about 1150 fps (351 m/s).

Each of the compressor section 24 and the turbine section 28 may include alternating rows of rotor assemblies and vane assemblies (shown schematically) that carry airfoils that extend into the core flow path C. For example, the rotor assemblies can carry a plurality of rotating blades 25, while each vane assembly can carry a plurality of vanes 27 that extend into the core flow path C. The blades 25 of the rotor assemblies create or extract energy (in the form of pressure) from the core airflow that is communicated through the gas turbine engine 20 along the core flow path C. The vanes 27 of the vane assemblies direct the core airflow to the blades 25 to either add or extract energy.

Various components of a gas turbine engine 20, including but not limited to the airfoils of the blades 25 and the vanes 27 of the compressor section 24 and the turbine section 28, may be subjected to repetitive thermal cycling under widely ranging temperatures and pressures. The hardware of the turbine section 28 is particularly subjected to relatively extreme operating conditions. Therefore, some components may require internal cooling circuits for cooling the parts during engine operation. Example cooling circuits that include features such as airflow bleed ports are discussed below.

FIG. 1B is a schematic view of a turbine section that may employ various embodiments disclosed herein. Turbine 100 includes a plurality of airfoils, including, for example, one or more blades 101 and vanes 102. The airfoils 101, 102 may be hollow bodies with internal cavities defining a number of channels or cavities, hereinafter airfoil cavities, formed therein and extending from an inner diameter 106 to an outer diameter 108, or vice-versa. The airfoil cavities may be separated by partitions within the airfoils 101, 102 that may extend either from the inner diameter 106 or the outer diameter 108 of the airfoil 101, 102. The partitions may extend for a portion of the length of the airfoil 101, 102, but may stop or end prior to forming a complete wall within the airfoil 101, 102. Thus, each of the airfoil cavities may be fluidly connected and form a fluid path within the respective airfoil 101, 102. The blades 101 and the vanes 102 may include platforms 110 located proximal to the inner diameter thereof. Located below the platforms 110 may be airflow ports and/or bleed orifices that enable air to bleed from the internal cavities of the airfoils 101, 102. A root of the airfoil may be connected to or be part of the platform 110.

Although an aero or aircraft engine application is shown and described above, those of skill in the art will appreciate that airfoil configurations as described herein may be applied to industrial applications and/or industrial gas turbine engines, land based or otherwise.

Dual-wall cooling configurations are extremely efficient at cooling a component. For example, a vane or blade, such as airfoils 101, 102, may be formed with a dual-wall

construction. Such dual-wall configuration may be a spar-and-shell arrangement, with a spar defining a structural body and a shell installed about the spar to provide a flow or exterior surface. Advantageously, such airfoil constructions can employ different materials for the spar and the shell, with the shell typically being made from high temperature alloys or material.

However, the internal wall typically runs a lot cooler than the external wall, creating a thermal conflict between the internal (spar) and external (shell) walls. The induced stresses from this thermal conflict may be extremely high and can be a challenge designing nickel components to handle such stresses. Furthermore, the thermal stresses are too high for the capability of often brittle, high-temperature materials, such as ceramic matrix composites (CMCs), making the conventional dual wall configurations impossible using high-temperature materials.

There are configurations that address the thermal conflict issue between the inner and outer walls. For example, the inner and outer walls may be arranged as a spar-and-shell design with connectors (e.g., pins, ribs, bars, etc.) that tie the shell to the spar. The connectors will physically connect the spar to the shell, but allow for thermal conflict. Such designs are arranged with radial cooling flow that provides for dedicated cooling in each separate radially extending passage (e.g., from the inner diameter to the outer diameter). Further improvements may be desirable.

One such further improvement upon the spar-and-shell configuration may relate to additional cooling schemes. A significant amount of the cooling flow exits the trailing edge of a component, such as at the trailing edge of a vane. Embodiments of the present disclosure are directed to creating an axial flow dual-wall cooling scheme that utilizes the trailing edge flow and minimizes the thermal conflict between the inner and outer walls. Moreover, in accordance with some embodiments described herein, an amount of flow required to cool a component may be minimized or reduced.

Embodiments of the present disclosure employ a connector configuration to join a spar and a shell, with the connectors being connected to both the spar and the shell. The connection by the connectors allows for axial thermal expansion or growth of the shell. Specifically, the connectors may move or rotate to allow for relative movement of the shell relative to the spar. The connectors, in some arrangements, may be configured half in the spar and half in the shell, and have a dog-bone, figure eight, infinity symbol geometry (i.e., lemniscate geometry in cross-section). In other embodiments, the connectors may have a cross-sectional geometry with a first engageable portion engageable with an exterior surface of the spar and a second engageable portion engageable with an interior surface of the shell, and a link connecting the first and second engageable portions. The connections by the engageable portions are not fixed connections, such that the engageable portions are rotatable within the connection to the respective spar or shell surface. The engageable portions may be connected to the respective spar and shell within grooves formed on the respective outer and inner surfaces thereof.

The connector is configured to prevent the shell from bulging away, circumferentially, from the spar, while allowing the hotter outer shell to grow axially more than the colder inner spar. As the hotter outer shell grows axially more than the colder inner spar, the connector pivots within respective grooves of the spar and the shell, minimizing the stresses on the spar and the shell. Embodiments provided herein are directed to a modification of the connector and/or

connector engagements (e.g., a groove in the spar and the shell) by creating cutouts in the spar, shell, and/or connector to allow flow to communicate between the two adjacent cavities relative to the connector. Such a configuration allows for the trailing edge flow to be utilized in the dual-wall portion of the component before exiting the trailing edge, thus minimizing the amount of dedicated cooling in the dual-wall portion.

Turning now to FIG. 2, a schematic illustration of an airfoil **200** in accordance with an embodiment of the present disclosure is shown. The airfoil **200**, in this illustrative embodiment, is arranged as a vane for a gas turbine engine. The airfoil **200** includes a shell **202** and a spar **204**, with the spar **204** disposed inside the shell **202**. The shell **202** defines an exterior surface of the airfoil **200** which may be exposed to a gaspath of a gas turbine engine. The spar **204** provides structural support and defines cooling cavities within the airfoil **200**. Also shown in FIG. 2 is a connector **206** that attaches the shell **202** to the spar **204**. The connector **206** extends radially through the airfoil **200**, between the shell **202** and the spar **204**. Additionally, one or both of the shell **202** and the spar **204** may include axial ribs **208** to define flow paths within the airfoil **200**.

The airfoil **200** further includes a trailing edge cavity **210** through which cooling flow may exit the airfoil **200**. Cooling air may be sourced from within the spar **204** and may impinge upon a leading edge of the airfoil **200**, and upon an interior leading edge surface of the shell **202** through impingement holes **212**. The cooling air may then flow axially aftward toward the trailing edge, through one or more axial flow paths **214**. The axial flow paths **214** are defined between the shell **202** and the spar **204** and between radially adjacent axial ribs **208**. The axial flow paths **214** may extend from the location of the impingement holes **212** (e.g., at the leading edge) axially aftward to the trailing edge cavity **210**. Furthermore, radial flow paths **216** are defined, in part, by the radially extending connector **206**. The radial flow paths **216** may receive cooling air from the inner diameter or the outer diameter of the airfoil **200** (e.g., through a platform) as will be appreciated by those of skill in the art.

Turning now to FIGS. 3A-3E, schematic illustrations of an airfoil **300**, and parts thereof, in accordance with an embodiment of the present disclosure are shown. FIG. 3A is a schematic illustration of the airfoil **300** as assembled. FIG. 3B is a plan cross-sectional view illustration of the airfoil **300** as viewed along the line B-B of FIG. 3A. FIG. 3C is a schematic illustration of a portion of a shell **302** of the airfoil **300**. FIG. 3D is a schematic illustration of a spar **304** of the airfoil **300**. FIG. 3E is a schematic illustration of a connector **306** that connects the shell **302** to the spar **304** to form the airfoil **300**.

As shown in FIGS. 3A-3B the spar **304** defines an inner cavity **318** and a plurality of outer cavities **320** are defined between the spar **304** and the shell **302**. The outer cavities **320** are fluidly connected to define the flow paths of cooling air along an inner surface of the shell **302**. The outer cavities **320** define axial flow paths **314** and radial flow paths **316**. In some embodiments, cooling air may be supplied into the airfoil **300** in the inner cavity **318**. The cooling air will cool the spar **304** and will then exit the inner cavity **318** through one or more impingement holes **312** and enter the outer cavities **320** at the leading edge of the airfoil **300**. The cooling air will then flow axially aftward toward the trailing edge and flow into the trailing edge cavity **310** (i.e., along the axial flow paths **314**). The cooling air will then exit the airfoil **300** out from the trailing edge cavity **310**. In some

embodiments, additional cooling air may be directly fed into the outer cavities **320** in a radial direction (i.e., along the radial flow paths **316**), which may mix with the cooling air from the inner cavity **318** that is flowing along the axial flow paths **314**.

Further, as shown in FIG. 3B, the shell **302** is joined or connected to the spar **304** by one or more connectors **306**. The connectors **306** extend radially through the airfoil **300**, between the shell **302** and the spar **304**. In some embodiments, the connectors **306** may extend a full length from a root-to-tip or inner diameter-to-outer diameter (e.g., as shown). In other embodiments, the connectors may be partial-extent connectors that extend less than the full length between ends (e.g., top and bottom in the radial direction) of the airfoil. In some other embodiments, as shown and described below, the connectors **306** may have a cross-sectional geometry with a first engageable portion engageable with an exterior surface of the spar **304** and a second engageable portion engageable with an interior surface of the shell **302**, and a link connecting the first and second engageable portions.

FIG. 3C illustrates a partial internal illustration of the shell **302**. As shown, the shell **302** includes a plurality of first receiving channels **322**. The first receiving channels **322** are grooves or recesses formed in the interior surface of the shell **302** to enable receiving and engagement with the connector **306**. The first receiving channels **322** extend radially along the interior surface of the shell **302**. In some embodiments, the first receiving channels **322** extend radially between a first end of the shell **302** to a second end of the shell **302** (e.g., between inner and outer diameters, between root and tip, etc.). Arranged along the first receiving channels **322** are first engagement elements **324**. The first engagement elements **324** may be tabs or other types of protrusions that are located adjacent the first receiving channels **322**. The first engagement elements **324** are configured to receive and engage with the connectors **306**. The first engagement elements **324** are discrete elements that do not extend the full radial length of the shell **302**. That is, the first engagement elements **324** are located at specific positions, and there are first radial gaps **326** between the first engagement elements **324** arranged along a given first receiving channel **322**. The first radial gaps **326** define, in part, the axial flow paths **314** shown in FIG. 3A. That is, the positioning and spacing of the first engagement elements **324** allows for a portion of cooling air to flow in the axial direction along the interior surface of the shell **302**. The shell **302** further includes optional first axial ribs **328** which extend in the axial direction and further define the axial flow paths **314**. The first axial ribs **328** extend between and/or connect axially adjacent first engagement elements **324**, as illustratively shown. The first axial ribs **328** may align with the first engagement elements **324** (i.e., connect) to minimize blockage of axial flow.

FIG. 3D illustrates the spar **304**. As shown, the spar **304** includes a plurality of second receiving channels **330**. The second receiving channels **330** are grooves or recesses formed in the exterior surface of the spar **304** to enable receiving and engagement with the connector **306**. The second receiving channels **330** extend radially along the exterior surface of the spar **304**. In some embodiments, the second receiving channels **330** extend radially between a first end of the spar **304** to a second end of the spar **304** (e.g., between inner and outer diameters, between root and tip, etc.). Arranged along the second receiving channels **330** are second engagement elements **332**. The second engagement elements **332** may be tabs or other types of protrusions that

are located adjacent the second receiving channels **330**. The second engagement elements **332** are configured to receive and engage with the connectors **306**. The second engagement elements **332** are discrete elements that do not extend the full radial length of the spar **304**. That is, the second engagement elements **332** are located at specific positions, and there are second radial gaps **334** between the second engagement elements **332** arranged along a given second receiving channel **330**. The second radial gaps **334** define, in part, the axial flow paths **314** shown in FIG. 3A. That is, the positioning and spacing of the second engagement elements **332** allows for a portion of cooling air to flow in the axial direction along the exterior surface of the spar **304**. The spar **304** further includes optional second axial ribs **336** which extend in the axial direction and further define the axial flow paths **314**. The second axial ribs **336** extend between and/or connect axially adjacent second engagement elements **332**, as illustratively shown. The second axial ribs **336** may align with the second engagement elements **332** (i.e., connect) to minimize blockage of axial flow. Also shown in FIG. 3D, the spar **304** includes impingement holes **312** along the leading edge of the spar **304** to fluidly connect the inner cavity **318** with the outer cavities defined between the spar **304** and the shell **302**, when assembled.

Further, as shown in FIGS. 3C-3D, one or both of the interior surface of the shell **302** or the exterior surface of the spar **304** may include optional heat transfer augmentation features **338**. The heat transfer augmentation features **338** may be formed as trip strips, pedestals, dimples, etc. and may be arranged along the surfaces of the shell **302** and/or the spar **304** that define the axial flow paths **314**.

Turning to FIG. 3E, a schematic illustration of one connector **306** in accordance with an embodiment of the present disclosure is shown. The connector **306** is configured to fit within the first receiving channel **322** and the second receiving channel **330** when the shell **302** is positioned around the spar **304**. When assembling the shell **302** to the spar **304**, the first receiving channels **322** and the second receiving channels **330** align and can receive a connector **306**. When the connector **306** is installed within the first receiving channel **322** and the second receiving channel **330** (i.e., between the spar **304** and the shell **302**), the connector **306** will be engaged by the first engagement elements **324** and the second engagement elements **332**. The first engagement elements **324** and the second engagement elements **332** can provide secure and semi-fixed engagement with the connector **306** such that the connector **306** can retain or hold the shell **302** to the spar **304**, but also allow for movement of the shell **302** relative to the spar **304**, such as due to thermal expansion or thermal growth.

FIG. 3E illustrates one connector **306**. The connector **306** has a dog-bone, figure eight, infinity symbol geometry (i.e., lemniscate geometry in cross-section). In other embodiments, the connectors may have a cross-sectional geometry with a first engageable portion engageable with an exterior surface of the spar and a second engageable portion engageable with an interior surface of the shell, and a link connecting the first and second engageable portions. As shown in FIG. 3E, the connector **306** includes a first engageable portion **340** and a second engageable portion **342**. The first engageable portion **340**, in this embodiment, is a continuous element that, when installed to the spar **304** and the shell **302**, extends a full radial extent of the airfoil **300**. The second engageable portion **342** is a discontinuous or segmented element having connector gaps **344** separating sections or segments of the second engageable portion **342**. The connector gaps **344** are configured to align with the first and

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second radial gaps **326**, **344** of the shell **302** and the spar **304** to form and define the axial flow paths **314**. The connector **306** shown in FIGS. **3A-3E** may be installed such that the first engageable portion **340** and the second engageable portion **342** are interchangeable, such that one or the other may be engaged with one or the other of the first receiving channels **322** or the second receiving channels **330**. That is, the specific installation and orientation for which of the first engageable portion **340** and the second engageable portion **342** engage with the first and second engagement elements **324**, **332** of the shell **302** and the spar **304** is arbitrary and either orientation is possible without departing from the scope of the present disclosure.

Turning now to FIGS. **4A-4C**, schematic illustrations of a connector **406** in accordance with an embodiment of the present disclosure. The connector **406** may be used to attach and connect a shell to a spar, as shown and described above. FIG. **4A** is an isometric illustration of the connector **406**; FIG. **4B** is a cross-sectional illustration of the connector **406** as viewed along the line B-B of FIG. **4A**; and FIG. **4C** is a cross-sectional illustration of the connector **406** as viewed along the line C-C of FIG. **4A**.

As shown, the connector **406** includes a first engageable portion **440**, a second engageable portion **442**, and a link **446** connecting the first engageable portion **440** to the second engageable portion **442**. The first engageable portion **440** is a continuous element or structure and the second engageable portion **442** is a discontinuous or segmented element or structure. The elements of the second engageable portion **442** are separated by connector gaps **444**. The connector gaps **444** are configured to define, in part, axial flow paths through a cavity or to connect cavities of an airfoil, i.e., between a shell and spar, as shown and described above. FIGS. **4B** and **4C** illustrate cross-sectional illustrations of the connector **406**, with FIG. **4B** illustrating the link **446** connecting the first engageable portion **440** to the second engageable portion **442**. The geometric shape of the cross-section of the first engageable portion **440** to the second engageable portion **442** is such that the connector **406** can be installed within an airfoil to connect a shell to a spar, as shown and described above.

Turning now to FIGS. **5A-5D**, schematic illustrations of an airfoil **500** in accordance with an embodiment of the present disclosure is shown. FIG. **5A** is an isometric illustration of the airfoil **500**, FIG. **5B** is a cross-sectional illustration of the airfoil **500** as viewed along the line B-B of FIG. **5A**, FIG. **5C** is a cross-sectional illustration of the airfoil **500** as viewed along the line C-C of FIG. **5A**, and FIG. **5D** is a cross-sectional illustration of the airfoil **500** as viewed along the line D-D of FIG. **5A**. The airfoil **500** may be similar to that shown and described above, having a shell **502** attached to a spar **504** by one or more connectors **506**. The shell **502**, spar **504**, and connectors **506** define an outer cavity (or cavities) that include axial flow paths **514** and radial flow paths **516**, as shown and described above.

The connectors **506** connect the shell **502** to the spar **504** at engagement elements **524**, **532**, as shown and described above. Further, the connectors **506** fit within respective receiving channels of the shell **502** and the spar **504**. In this configuration, first receiving channels **522** are shown in FIG. **5C**, where connector gaps are located and thus the connector **506** does not include an engageable portion at such locations. The gaps allow for axial flow of cooling air, as illustratively shown. As can be seen in FIG. **5B** as well as FIG. **5D**, the engagement tabs **524**, **532** of the shell **502** and the spar **504** do not span all the way across the outer cavity between the shell **502** and the spar **504**. Rather, the engage-

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ment tabs **524**, **532** only span partway across to meet up with the corresponding engagement tab on the other part. In FIG. **5B**, the connections of the connectors **506** to both the shell **502** and the spar **504** (at the engagement elements **524**, **532**) forms a blockage where air cannot flow axially. As illustratively shown, the cooling air is sourced from impingement holes **512** located at the leading edge or axially forward section of the spar **504**.

FIG. **5D** illustrates an inner cavity **518** formed within the spar **504** and an outer cavity **520** formed between the spar **504** and the shell **502**. As shown, axial flow paths **514** form part of the outer cavity **520** and are defined by the spar **504**, the shell **502**, the engagement elements **524**, **532**, and connector gaps **544**.

Although shown and described so far with the connector having a full extent or continuous engageable portion engaging with the spar, and a segmented or non-continuous engageable portion engaging with the shell, the opposite may be true. That is, the full extend or continuous engageable portion may engaged with the shell, and the segmented or non-continuous engageable portion may engage with the spar.

Further, in some embodiments, one of the engagement elements of the spar or shell may be continuous in radial extent. That is, the engagement elements that are formed along the receiving channels are not required to be discrete or discontinuous elements in the radial direction. For example, turning to FIGS. **6A-6B**, schematic illustrations of a spar **604** and a part of a shell **602** are shown. In FIG. **6A**, the spar includes engagement elements **632** similar to that shown and described above, that are discrete and arranged along second receiving channels **630**. Further, the spar **604** includes axial ribs **628**. In this embodiment, however, the shell **602** includes continuous engagement elements **648** that extend a full radial length of the inner surface of the shell **602**. In this embodiment, because the engagement elements **648** are full-length, the shell **602** does not include axial ribs. Further, the engagement elements **648** define and extend along first receiving channels **622**. It will be appreciated by those of skill in the art that the opposite of that shown in FIGS. **6A-6B** may be employed, where the spar includes full-length engagement elements and the shell includes segmented or discrete engagement elements. In these embodiments, the connector that joins the spar and the shell may be substantially similar to that shown and described above.

Turning now to FIGS. **7A-7D**, schematic illustrations of a portion of a shell **702** (FIG. **7A**), a spar **704** (FIG. **7B**), and a connector **706** (FIG. **7C**) used to form an airfoil **700** (shown in cross-section as assembled in FIG. **7D**) in accordance with an embodiment of the present disclosure are shown.

FIG. **7A** illustrates a partial internal illustration of the shell **702**. As shown, the shell **702** includes a plurality of first receiving channels **722**. The first receiving channels **722** are grooves or recesses formed in the interior surface of the shell **702** to enable receiving and engagement with the connector **706**. The first receiving channels **722** extend radially along the interior surface of the shell **702**. Arranged along the first receiving channels **722** are first engagement elements **724**. The first engagement elements **724** may be tabs or other types of protrusions that are located adjacent the first receiving channels **722**. The first engagement elements **724** are configured to receive and engage with the connectors **706**. The first engagement elements **724** are discrete elements that do not extend the full radial length of the shell **702**. That is, the first engagement elements **724** are located at specific

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positions, and there are first radial gaps **726** between the first engagement elements **724** arranged along a given first receiving channel **722**. The first radial gaps **726** define, in part, the axial flow paths, as described above. That is, the positioning and spacing of the first engagement elements **724** allows for a portion of cooling air to flow in the axial direction along the interior surface of the shell **702**. The shell **702** further includes optional first axial ribs **728** which extend in the axial direction and further define the axial flow paths. The first axial ribs **728** extend between and/or connect axially adjacent first engagement elements **724**, as illustratively shown (but not all). The first axial ribs **728** may align with the first engagement elements **724** (i.e., connect) to minimize blockage of axial flow.

FIG. 7B is an illustrative illustration of the spar **704**. As shown, the spar **704** includes a plurality of second receiving channels **730**. The second receiving channels **730** are grooves or recesses formed in the exterior surface of the spar **704** to enable receiving and engagement with the connector **706**. The second receiving channels **730** extend radially along the exterior surface of the spar **704**. Arranged along the second receiving channels **730** are second engagement elements **732**. The second engagement elements **732** may be tabs or other types of protrusions that are located adjacent the second receiving channels **730**. The second engagement elements **732** are configured to receive and engage with the connectors **706**. The second engagement elements **732** are discrete elements that do not extend the full radial length of the spar **704**. That is, the second engagement elements **732** are located at specific positions, and there are second radial gaps **734** between the second engagement elements **732** arranged along a given second receiving channel **730**. The second radial gaps **734** define, in part, the axial flow paths. That is, the positioning and spacing of the second engagement elements **732** allows for a portion of cooling air to flow in the axial direction along the exterior surface of the spar **704**. The spar **704** further includes optional second axial ribs **736** which extend in the axial direction and further define the axial flow paths **714**. The second axial ribs **736** extend between and/or connect axially adjacent second engagement elements **732**, as illustratively shown. The second axial ribs **736** may align with the second engagement elements **732** (i.e., connect) to minimize blockage of axial flow. Also shown in FIG. 7B, the spar **704** includes impingement holes **712** along the leading edge of the spar **704** to fluidly connect the inner cavity with the outer cavities defined between the spar **704** and the shell **702**, when assembled.

Further, as shown in FIGS. 7A-7B, one or both of the interior surface of the shell **702** or the exterior surface of the spar **704** may include optional heat transfer augmentation features **738**. The heat transfer augmentation features **738** may be formed as trip strips, pedestals, dimples, etc. and may be arranged along the surfaces of the shell **702** and/or the spar **704** that define the axial flow paths **714**.

Turning to FIG. 7C, a schematic illustration of one connector **706** in accordance with an embodiment of the present disclosure is shown. The connector **706** is configured to fit within the first receiving channel **722** and the second receiving channel **730** when the shell **702** is positioned around the spar **704**. When assembling the shell **702** to the spar **704**, the first receiving channels **722** and the second receiving channels **730** align and can receive a connector **706**. When the connector **706** is installed within the first receiving channel **722** and the second receiving channel **730** (i.e., between the spar **704** and the shell **702**), the connector **706** will be engaged by the first engagement elements **724** and the second engagement elements **732**. The first engage-

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ment elements **724** and the second engagement elements **732** can provide secure and semi-fixed engagement with the connector **706** such that the connector **706** can retain or hold the shell **702** to the spar **704**, but also allow for movement of the shell **702** relative to the spar **704**, such as due to thermal expansion or thermal growth.

FIG. 7C illustrates one connector **706**. The connector **706** has a dog-bone, figure eight, infinity symbol geometry (i.e., lemniscate geometry in cross-section). In other embodiments, the connectors may have a cross-sectional geometry with a first engageable portion engageable with an exterior surface of the spar and a second engageable portion engageable with an interior surface of the shell, and a link connecting the first and second engageable portions. As shown in FIG. 7C, the connector **706** includes a first engageable portion **740** and a second engageable portion **742**, connected by a link, as shown and described above.

In contrast to the prior embodiments, both the first engageable portion **740** and the second engageable portion **742** are discontinuous or segmented elements having connector gaps **744** separating the discrete sections or segments of the respective first and second engageable portions **740**, **742**. The connector gaps **744** are configured to align with the first and second radial gaps **726**, **744** of the shell **702** and the spar **704** to form and define the axial flow paths. The connector **706** shown in FIG. 7C may be installed such that the first engageable portion **740** and the second engageable portion **742** are interchangeable, such that one or the other may be engaged with one or the other of the first receiving channels **722** or the second receiving channels **730**. That is, the specific installation and orientation for which of the first engageable portion **740** and the second engageable portion **742** engage with the first and second engagement elements **724**, **732** of the shell **702** and the spar **704** is arbitrary and either orientation is possible without departing from the scope of the present disclosure.

FIG. 7D illustrates a formed airfoil **700** as assembled from the shell **702**, the spar **704**, and connectors **706** (shown in FIGS. 7A-7C). The assembled airfoil **700** includes axial flow paths **714** that are formed in an alternating configuration due to the geometry of the connector **706** and the placement of the engagement elements **724**, **732**, and connector gaps **744** of the shell **702**, the spar **704**, and the connector **706**. As can be seen in FIG. 7D, the shell engagement tabs **724** only span partway across the outer cavity between the shell **702** and the spar **704** and cooperate with the spar gaps **734** and the connector gaps **744** to form axial flow paths **714**. Similarly, the spar engagement tabs **732** only span partway across the outer cavity between the shell **702** and the spar **704** and cooperate with the shell gaps **726** and the connector gaps **744** to form the axial flow paths **714**.

The above described embodiments are provided to illustrative and explanatory purposes and are not intended to be limiting. For example, the structure of the shell, the spar, and/or the connector may be adjusted to provide a desired cooling scheme for an assembled airfoil. Further, although primarily shown as a vane, embodiments described herein are equally applicable to blades. Moreover, in the illustrations, a partial section of the shell is shown. This partial section may be representative of a piece that is assembled to one or more additional pieces to form the complete shell. However, in some embodiments, the shell may be a single continuous construction.

Advantageously, embodiment described herein provide for airfoils with improved cooling. Specifically, embodiments of the present disclosure provide for improved cool-

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ing and construction of spar-and-shell type airfoils. Embodiments of the present disclosure provide cutouts in the spar, shell, and connectors to allow trailing edge flow to be utilized in the dual-wall portion of the airfoil. Such use of trailing edge flow may simultaneously minimize a required dedicated cooling for the dual-wall portion of the airfoil as well as reducing the stresses in the spar and shell caused by thermal growth mismatch. Advantageously, unlike prior spar-and-shell systems, embodiments provided herein may be utilized in both nickel and CMC applications.

The use of the terms “a,” “an,” “the,” and similar references in the context of description (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or specifically contradicted by context. The modifier “about” and/or “approximately” used in connection with a quantity is inclusive of the stated value and has the meaning dictated by the context (e.g., it includes the degree of error associated with measurement of the particular quantity). All ranges disclosed herein are inclusive of the endpoints, and the endpoints are independently combinable with each other. It should be appreciated that relative positional terms such as “forward,” “aft,” “upper,” “lower,” “above,” “below,” “radial,” “axial,” “circumferential,” and the like are with reference to normal operational attitude and should not be considered otherwise limiting.

While the present disclosure has been described in detail in connection with only a limited number of embodiments, it should be readily understood that the present disclosure is not limited to such disclosed embodiments. Rather, the present disclosure can be modified to incorporate any number of variations, alterations, substitutions, combinations, sub-combinations, or equivalent arrangements not heretofore described, but which are commensurate with the scope of the present disclosure. Additionally, while various embodiments of the present disclosure have been described, it is to be understood that aspects of the present disclosure may include only some of the described embodiments.

Accordingly, the present disclosure is not to be seen as limited by the foregoing description, but is only limited by the scope of the appended claims.

What is claimed is:

1. An airfoil of a gas turbine engine comprising:

a shell having a first receiving channel and a first engagement element arranged along the first receiving channel, the first receiving channel extending in a radial direction along the shell between a first end and a second end of the shell in the radial direction;

a spar having a second receiving channel and a second engagement element arranged along the second receiving channel, the second receiving channel extending in a radial direction along the spar between a first end and a second end of the spar in the radial direction, wherein the spar defines an inner cavity; and

a connector configured to be installed between the shell and the spar to connect the shell to the spar to allow for thermal growth of the shell relative to the spar, wherein the connector comprises a first engageable portion and a second engageable portion connected by a link, wherein the first engageable portion is configured to engage with the first engagement element of the shell and the second engageable portion is configured to engage with the second engagement element of the spar,

wherein when assembled an outer cavity is formed between the spar and the shell, and

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wherein the first engagement element, second engagement element, the first engageable portion, and the second engageable portion are configured to define an axial flow path through the outer cavity.

2. The airfoil of claim 1, further comprising at least one axial rib on at least one of the shell and the spar, wherein the at least one axial rib defines, in part, the axial flow path in the outer cavity.

3. The airfoil of claim 1, wherein the spar further comprises at least one impingement hole on a leading edge thereof.

4. The airfoil of claim 3, wherein, when assembled, impinging air is configured to flow from the inner cavity to the outer cavity at an inner surface leading edge of the shell and flow axially aftward through the axial flow path of the outer cavity.

5. The airfoil of claim 1, further comprising at least one heat transfer augmentation feature formed on at least one of an inner surface of the shell and an outer surface of the spar such that the at least one heat transfer augmentation feature is located within the outer cavity when the shell is attached to the spar by the connector.

6. The airfoil of claim 5, wherein both the inner surface of the shell and the outer surface of the spar comprise at least one heat transfer augmentation feature.

7. The airfoil of claim 1, wherein the connector has a lemniscate geometry in cross-section.

8. The airfoil of claim 1, wherein the shell is formed from at least one of nickel and ceramic matrix composite.

9. The airfoil of claim 1, wherein at least one of the first engageable portion and the second engageable portion of the connector comprise a segmented structure.

10. The airfoil of claim 9, wherein the segmented structure of the at least one of the first engageable portion and the second engageable portion defines connector gaps separating segments thereof.

11. The airfoil of claim 9, wherein both the first engageable portion and the second engageable portion of the connector comprise segmented structures.

12. The airfoil of claim 1, wherein the first engageable portion is a continuous element that, when installed, extends a full radial extent of the airfoil and the second engageable portion of the connector comprises a segmented structure.

13. The airfoil of claim 1, wherein the first engagement element extends a continuous full radial extent in a radial direction along the shell between the first end and the second end of the shell about the first receiving channel.

14. The airfoil of claim 1, wherein the shell further comprises a trailing edge cavity that is fluidly connected to the outer cavity when the shell is assembled to the spar.

15. The airfoil of claim 1, wherein the shell, the spar, and the connector form one of a vane and a blade of a gas turbine engine.

16. The airfoil of claim 1, wherein the spar is formed from at least one of nickel and ceramic matrix composite.

17. The airfoil of claim 1, further comprising:

a plurality of additional first receiving channels formed on the shell, wherein each additional first receiving channel includes at least one first engagement element arranged along a radial length thereof;

a plurality of additional second receiving channels formed on the spar, wherein each additional second receiving channel includes at least one second engagement element arranged along a radial length thereof; and

a plurality of additional connectors configured to be installed between the shell and the spar in the plurality of additional first and second receiving channels.

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18. The airfoil of claim 1, wherein the outer cavity comprises one or more radial flow paths.

19. A spar for an airfoil of a gas turbine engine comprising:

a spar body having a receiving channel and an engagement element arranged along the receiving channel, the receiving channel extending in a radial direction along the spar body between a first end and a second end of the spar body in the radial direction, wherein the spar body defines an inner cavity and wherein the receiving channel and the engagement element are arranged on an exterior surface of the spar body opposite the inner cavity,

wherein the engagement element comprises one or more radial gaps that define axial flow paths relative to the receiving channel, and

wherein the receiving channel and the engagement element are configured to receive a connector to attach a shell to the spar.

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20. A shell for an airfoil of a gas turbine engine comprising:

a shell body having a receiving channel and an engagement element arranged along the receiving channel, the receiving channel extending in a radial direction along the shell between a first end and a second end of the shell in the radial direction, the shell having an interior surface and an exterior surface, wherein the exterior surface defines a flow surface of the airfoil,

wherein the engagement element comprises one or more radial gaps that define axial flow paths relative to the receiving channel, and

wherein the receiving channel and the engagement element are configured to receive a connector to attach the shell to a spar.

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