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(54) COUNTER-VORTEX PAIRED FILM COOLING HOLE DESIGN

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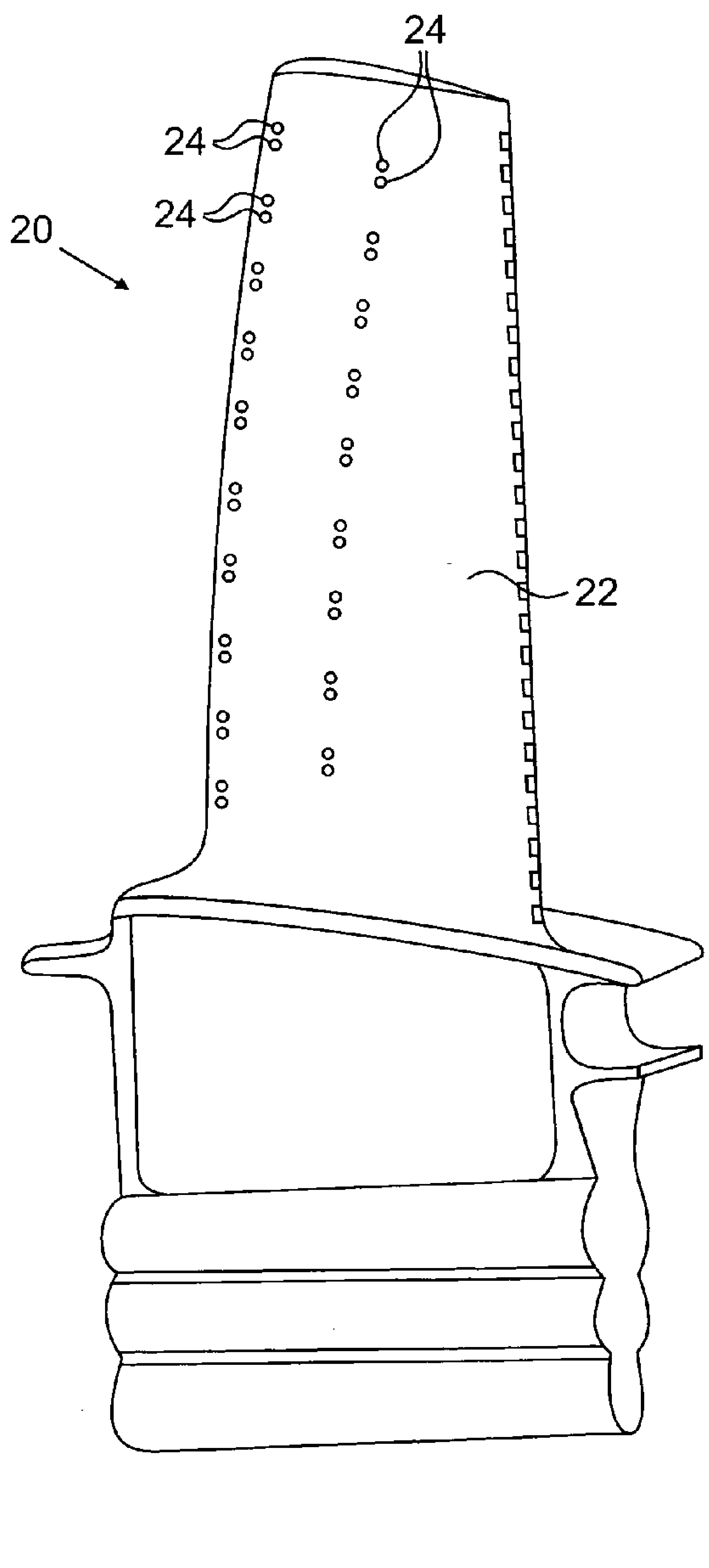
(57) ABSTRACT

An apparatus for use in a gas turbine engine includes a wall defining an exterior face, a first film cooling passage extending through the wall for providing film cooling to the exterior face of the wall, and a second film cooling passage extending through the wall adjacent to the first film cooling passage for providing film cooling to the exterior face of the wall. The first film passage includes a first vortex-generating structure for inducing a vortex in a first rotational direction in a cooling fluid passing therethrough, and the second film passage includes a second vortex-generating structure for inducing a vortex in a second rotational direction in a cooling fluid passing therethrough. The first and second rotational directions are substantially opposite one another.



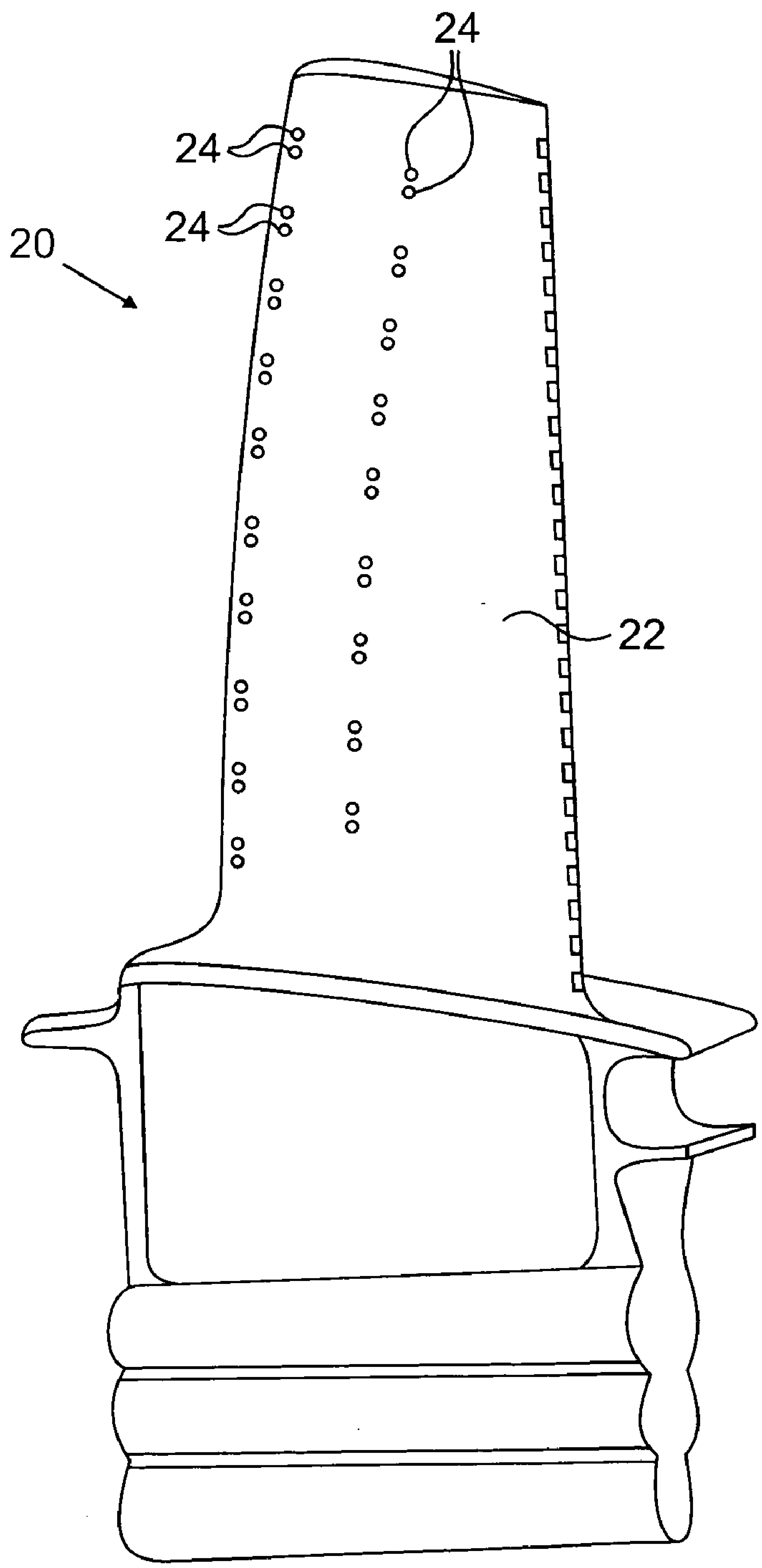


FIG. 1

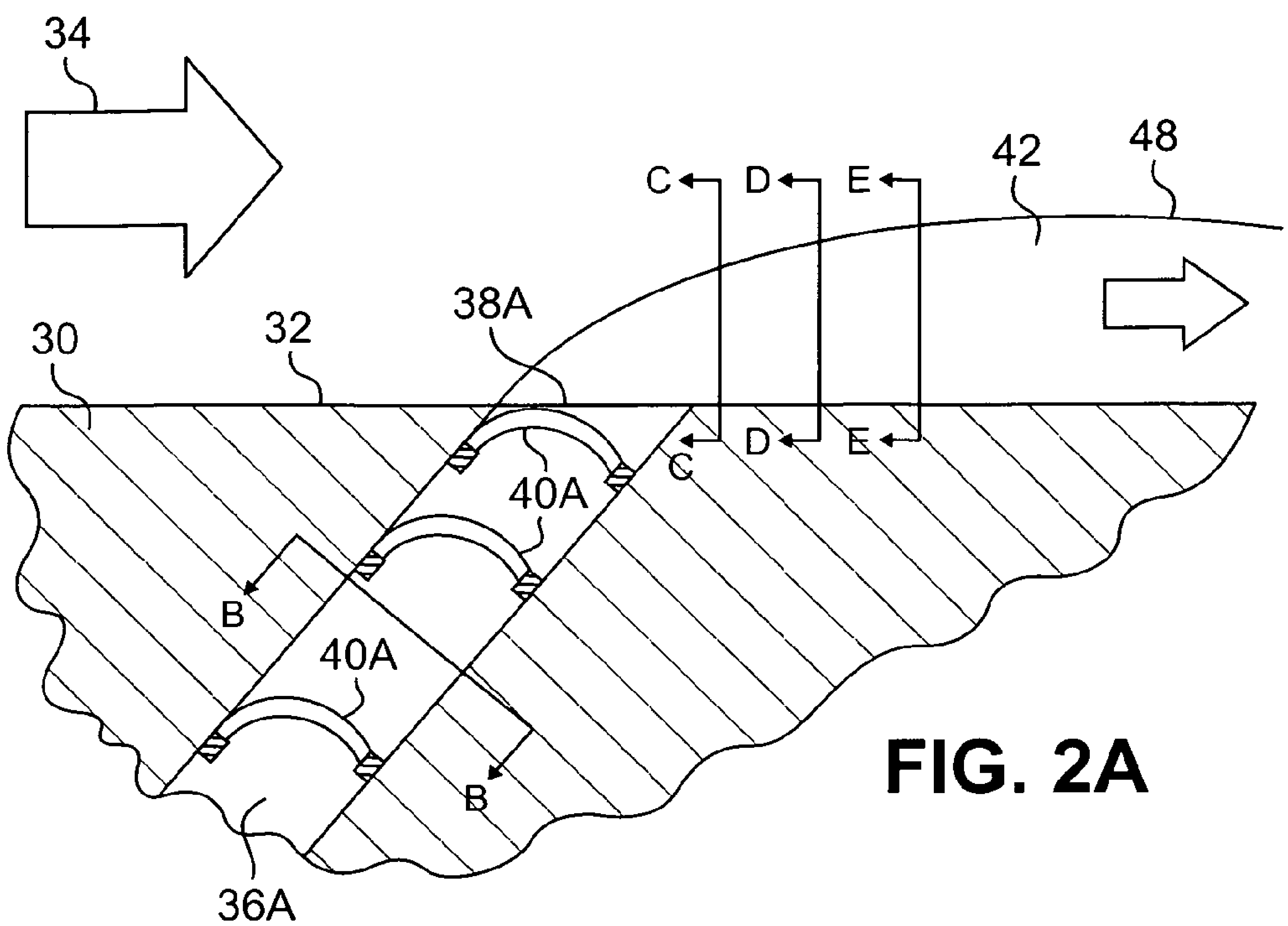

34
C
D
E
42
48
38A
30
32
C
D
E
40A
B
40A
B
36A

FIG. 2A

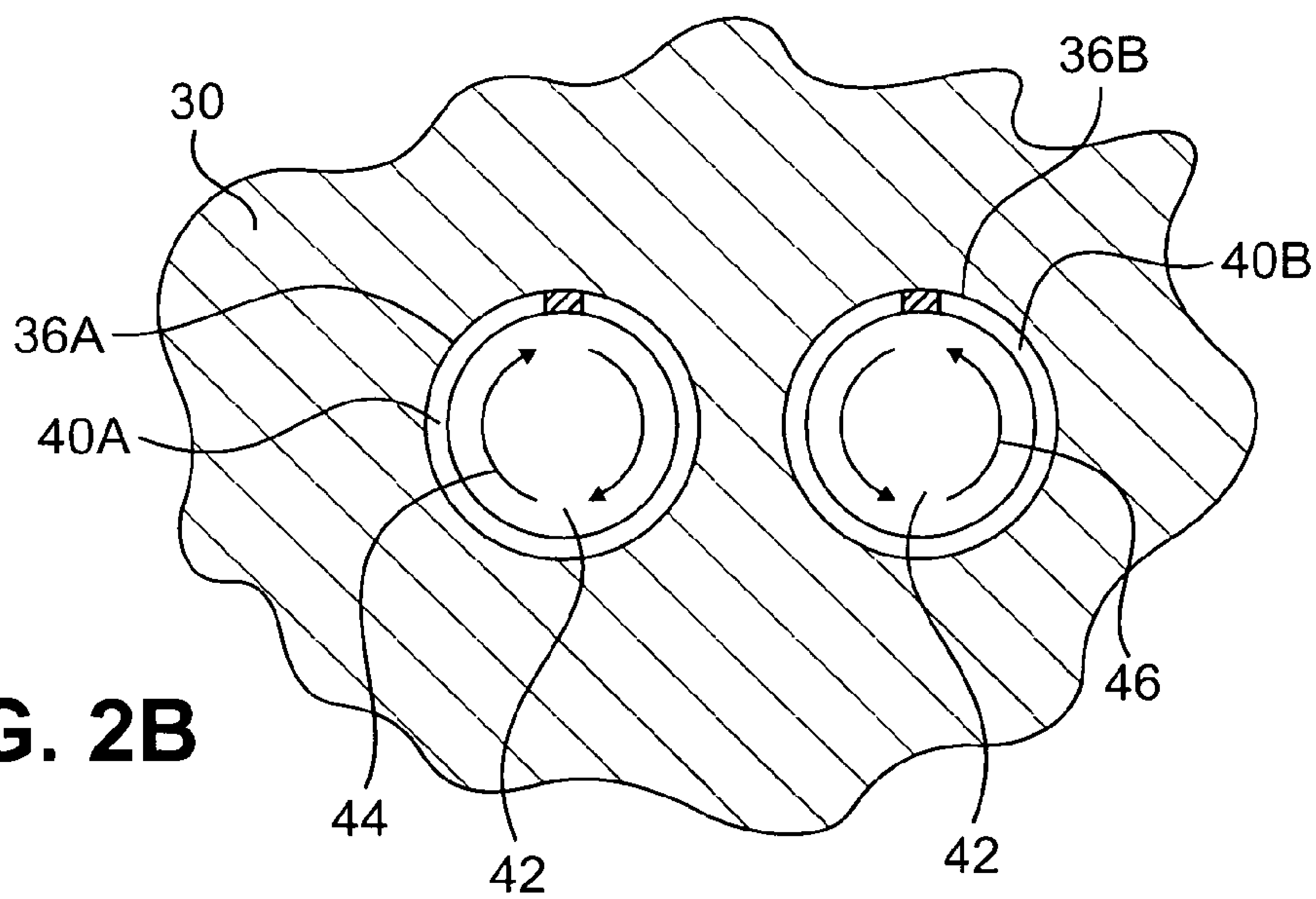

36B
30
40B
36A
40A
46
44
42
42

FIG. 2B

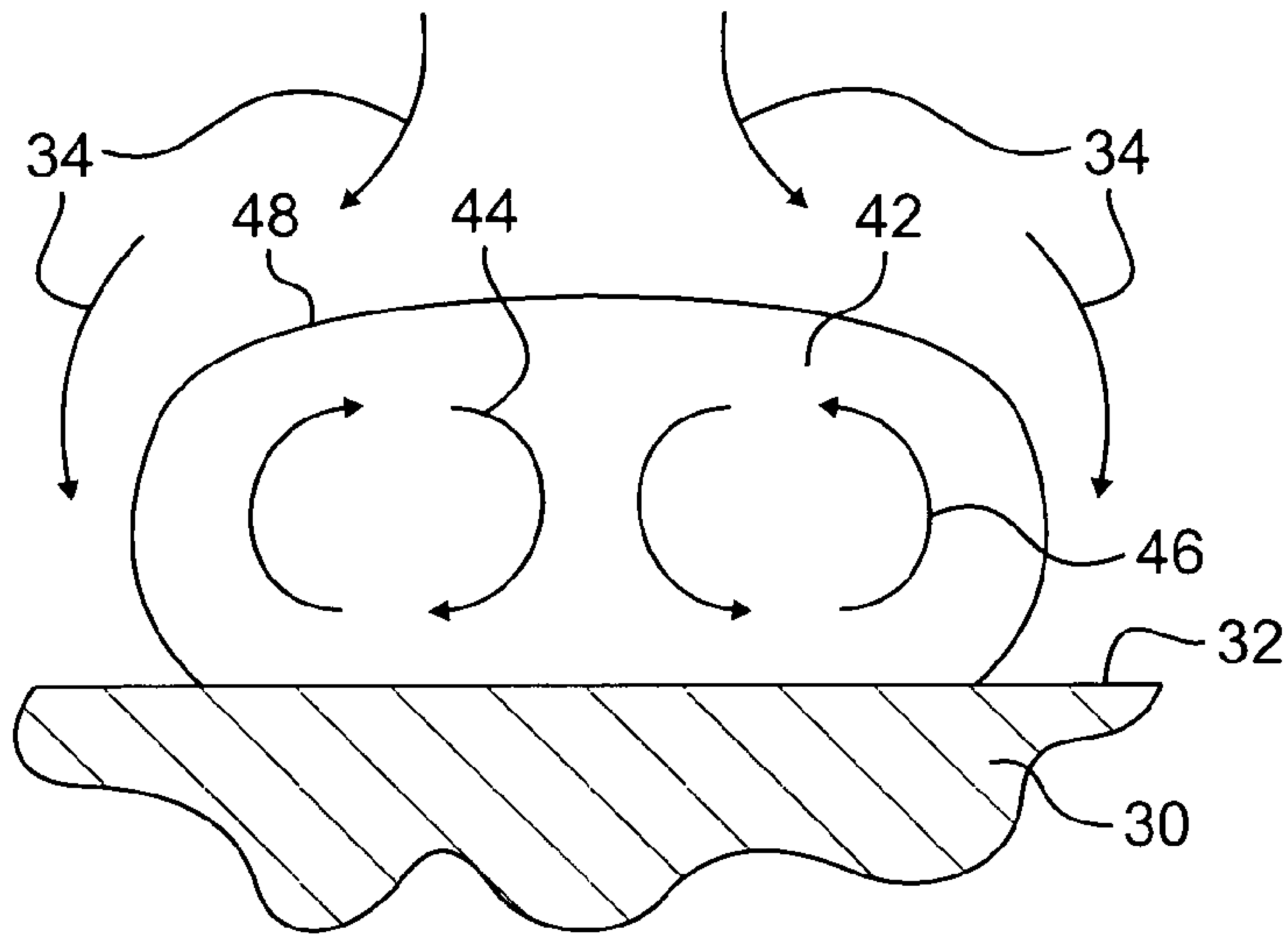


FIG. 2C

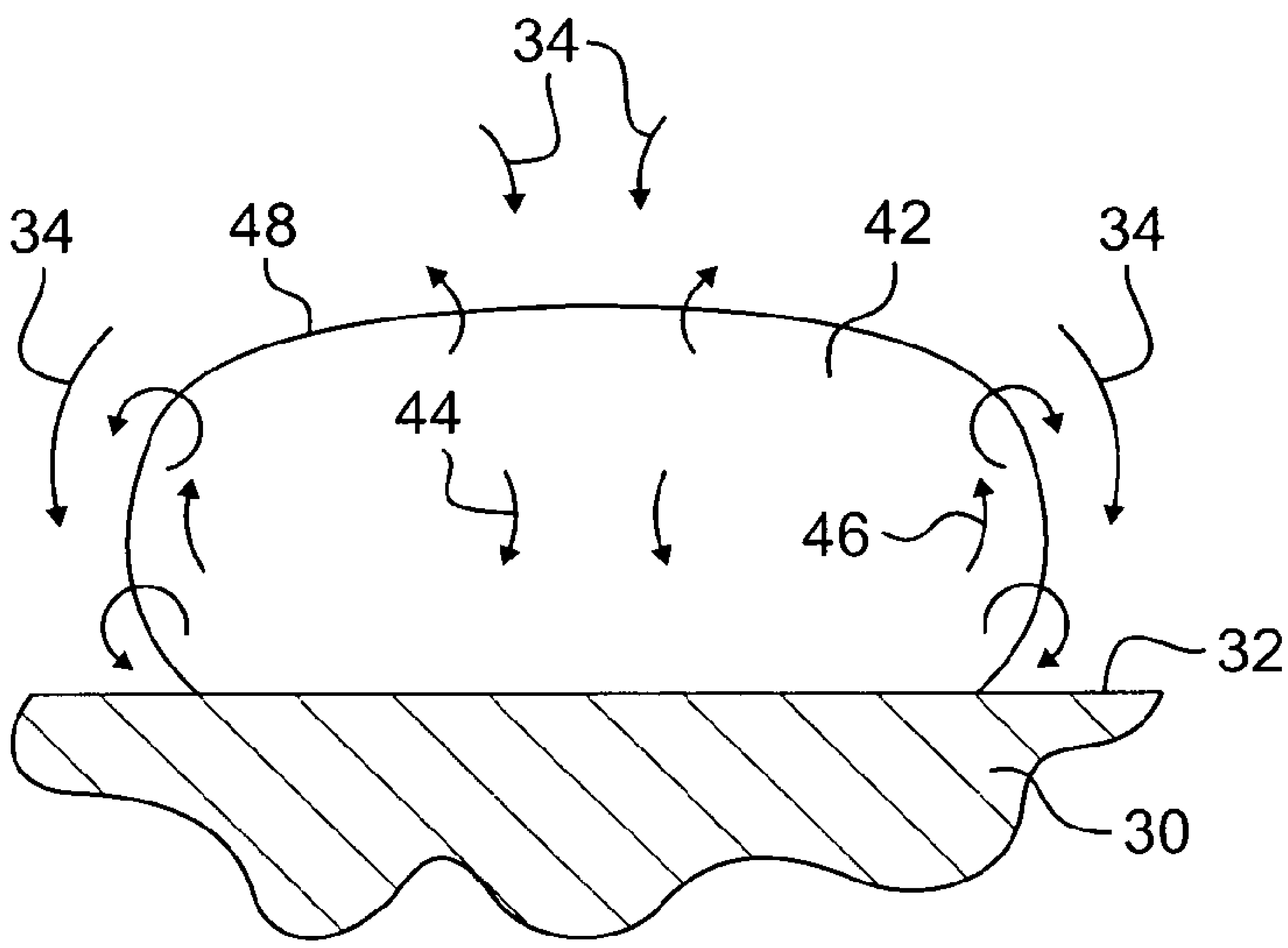


FIG. 2D

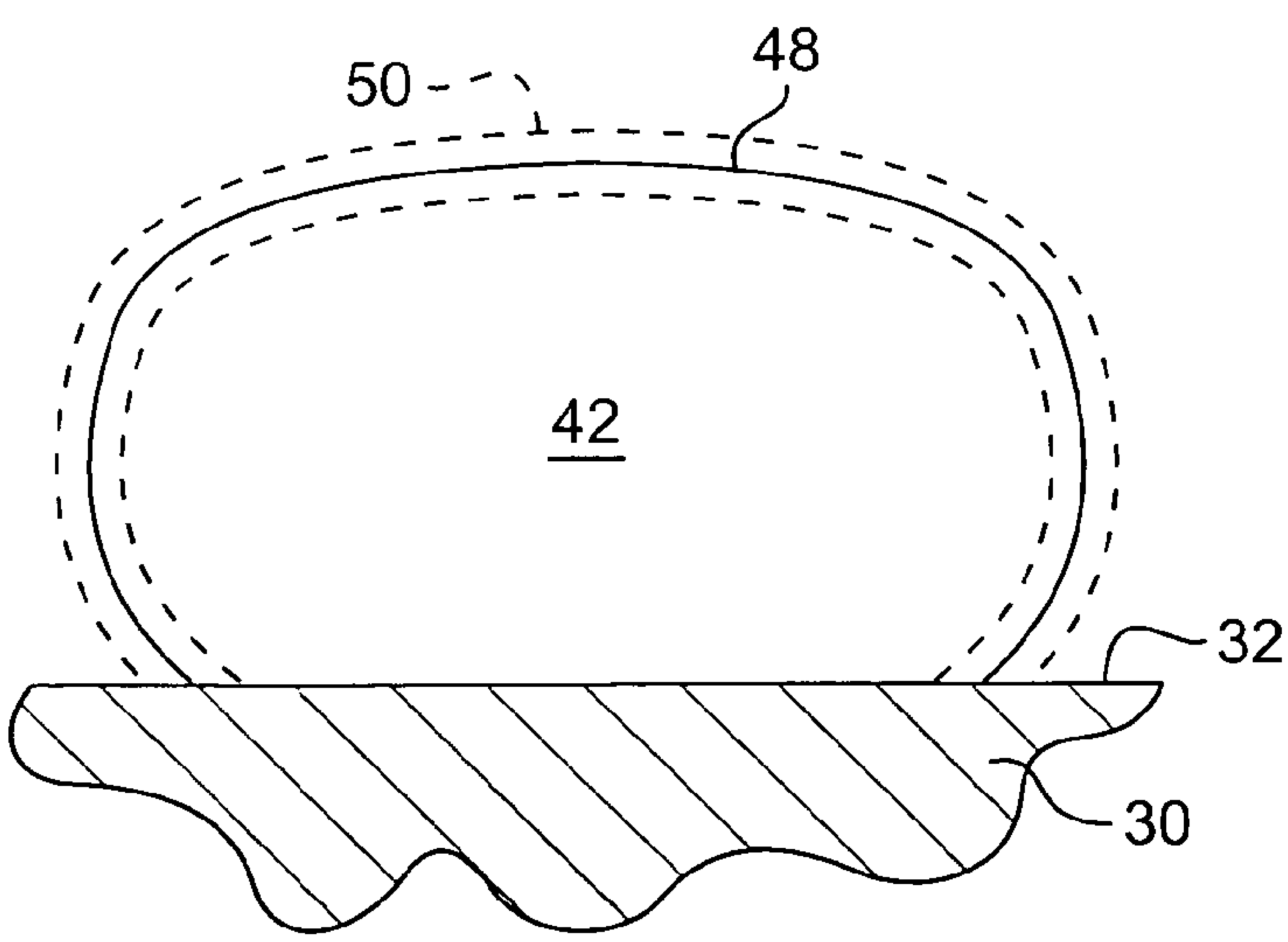


FIG. 2E

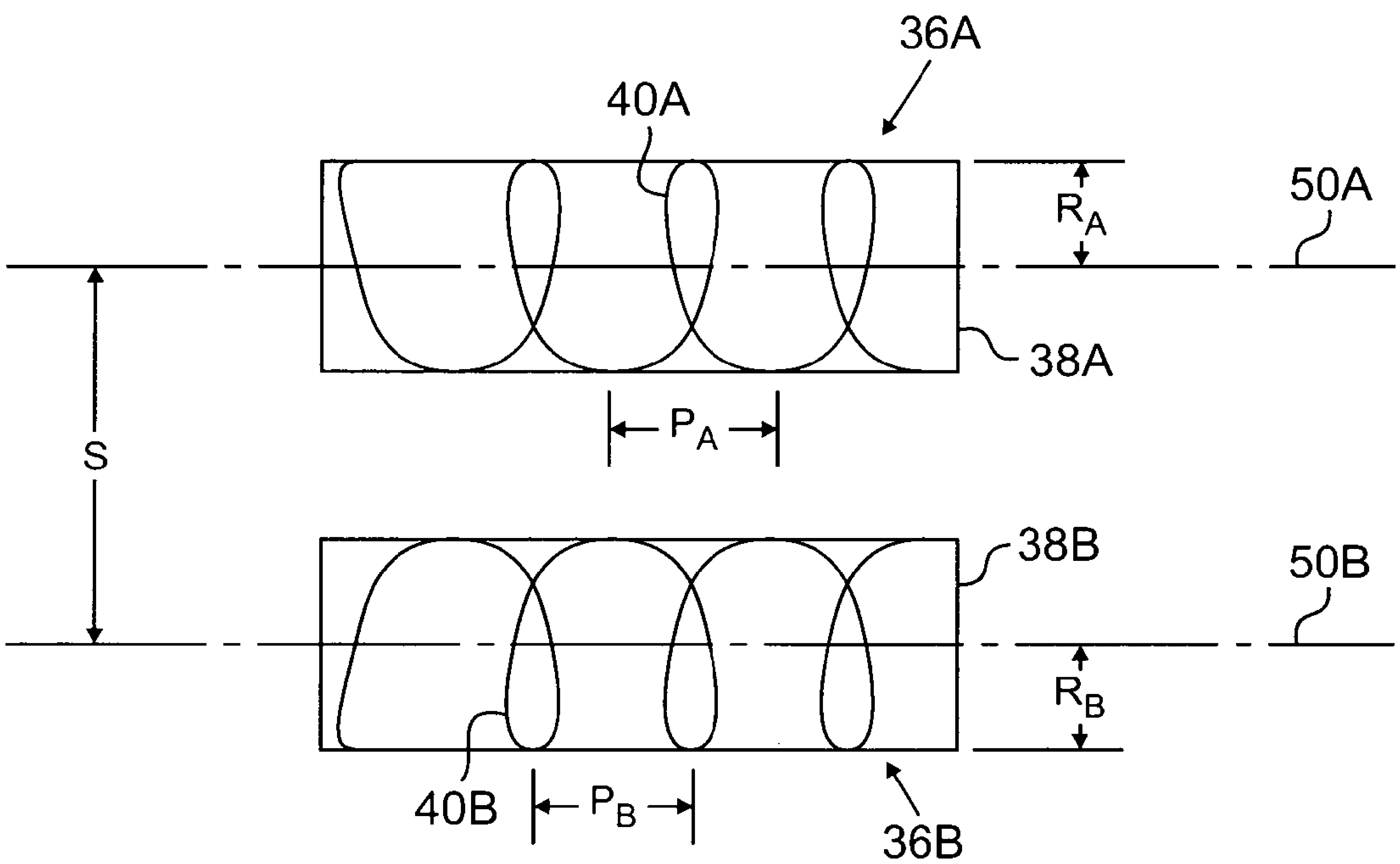


FIG. 3

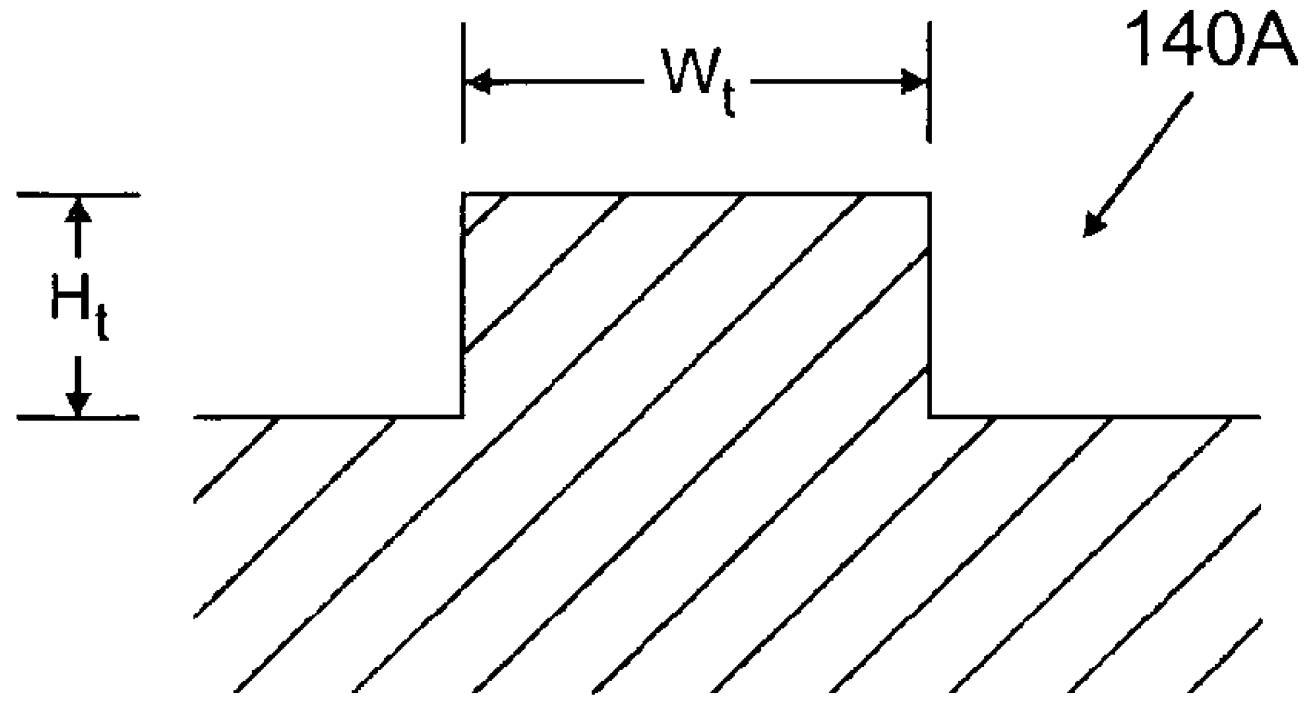


FIG. 4A

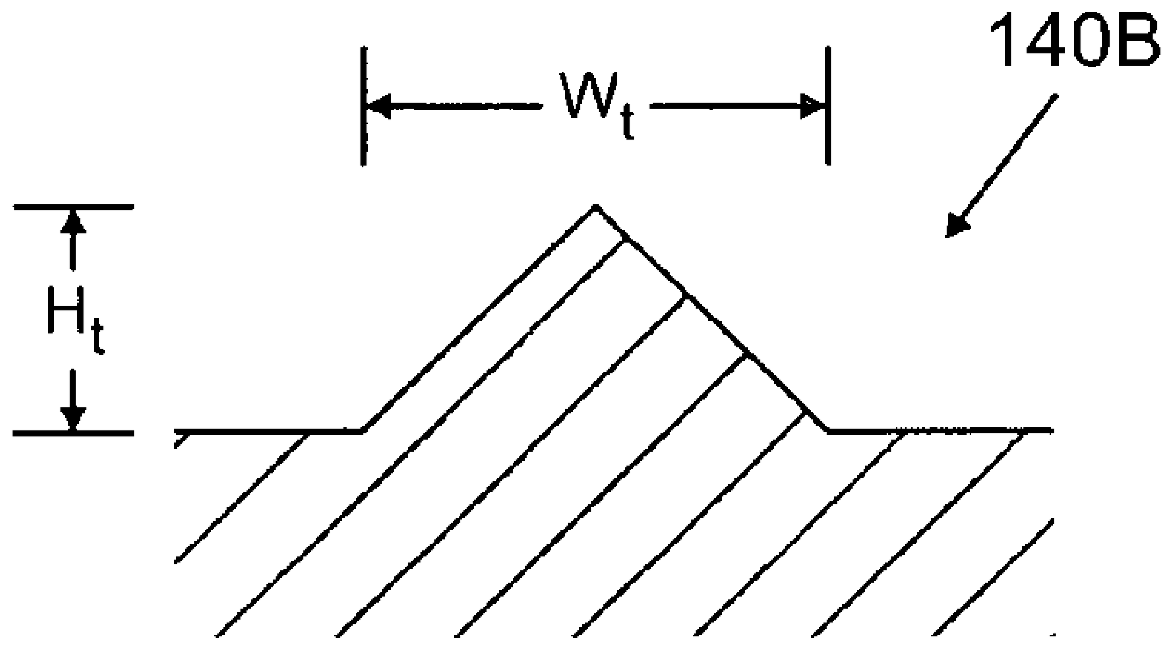


FIG. 4B

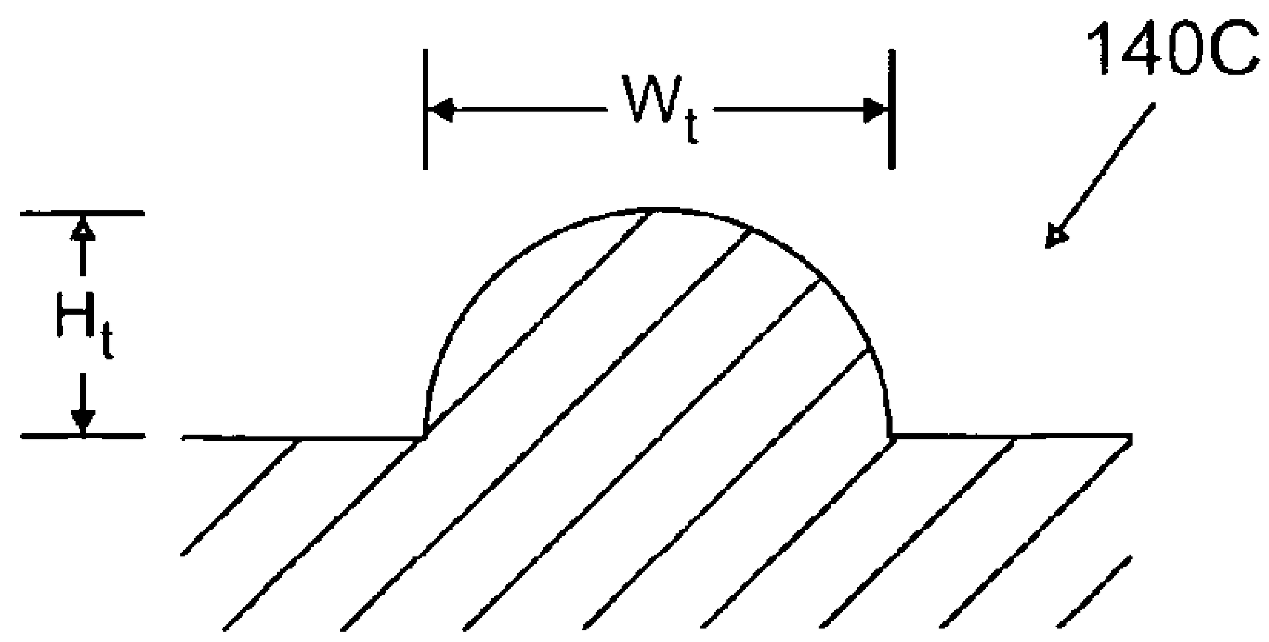


FIG. 4C

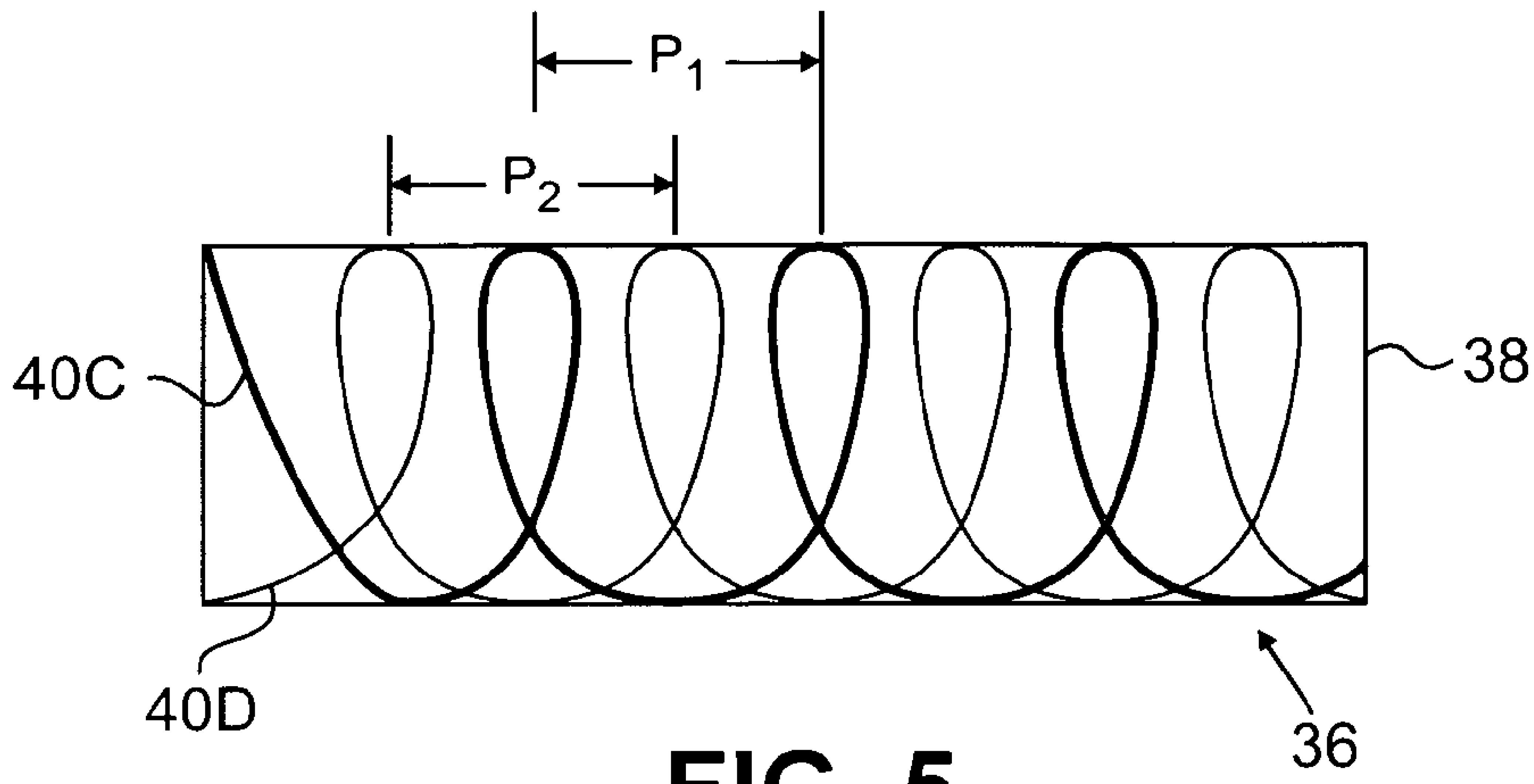


FIG. 5

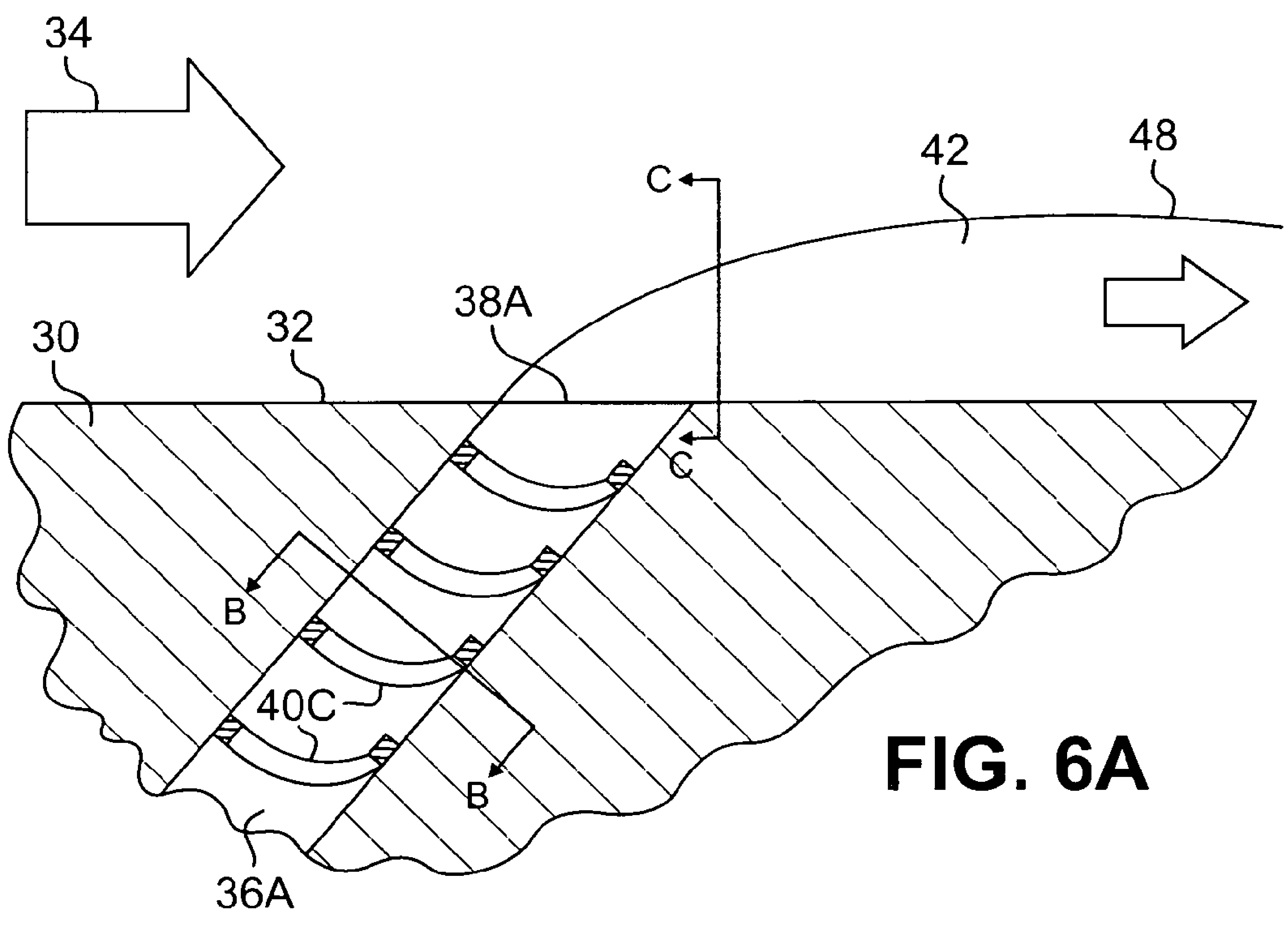


FIG. 6A

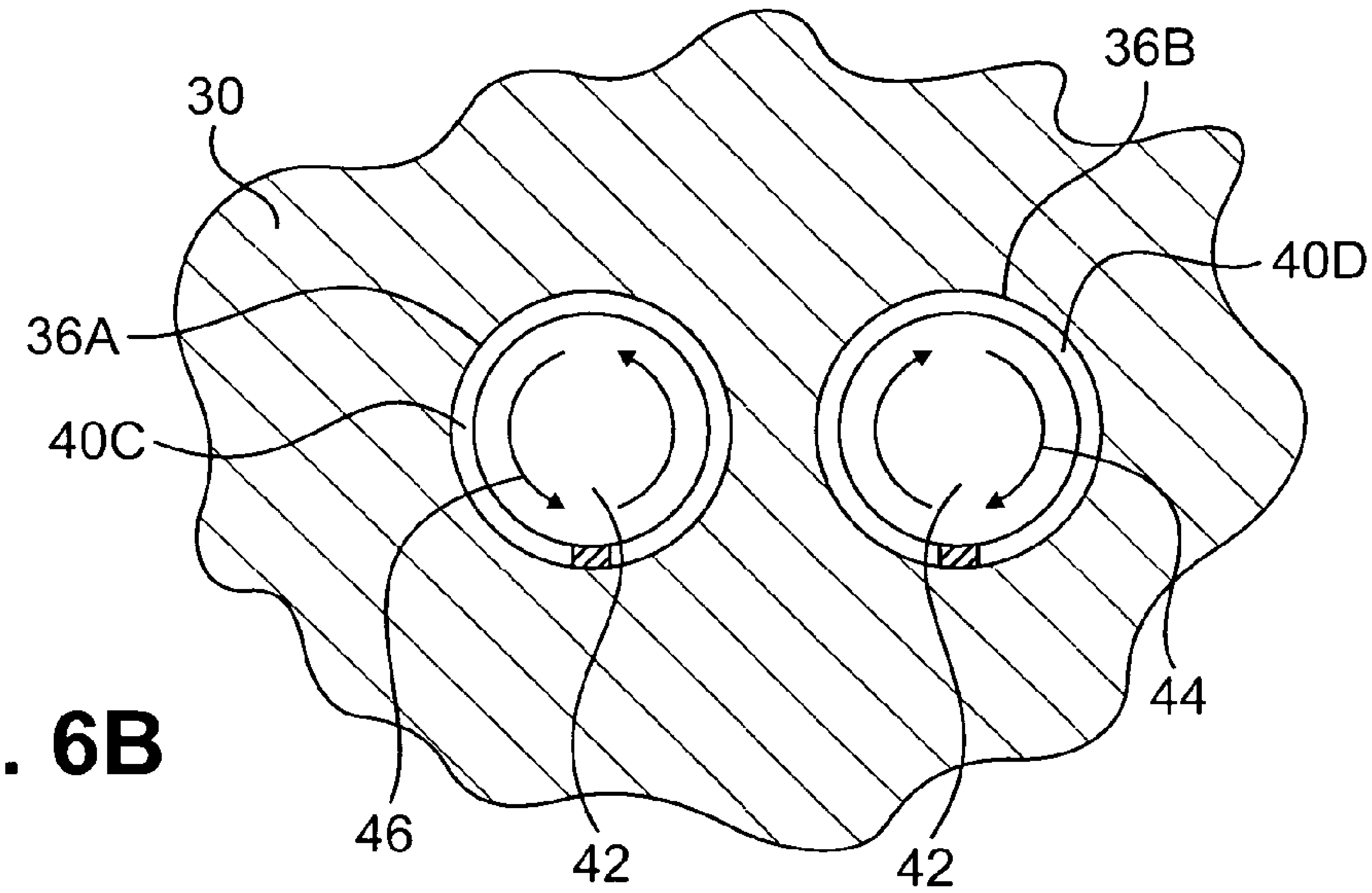


FIG. 6B

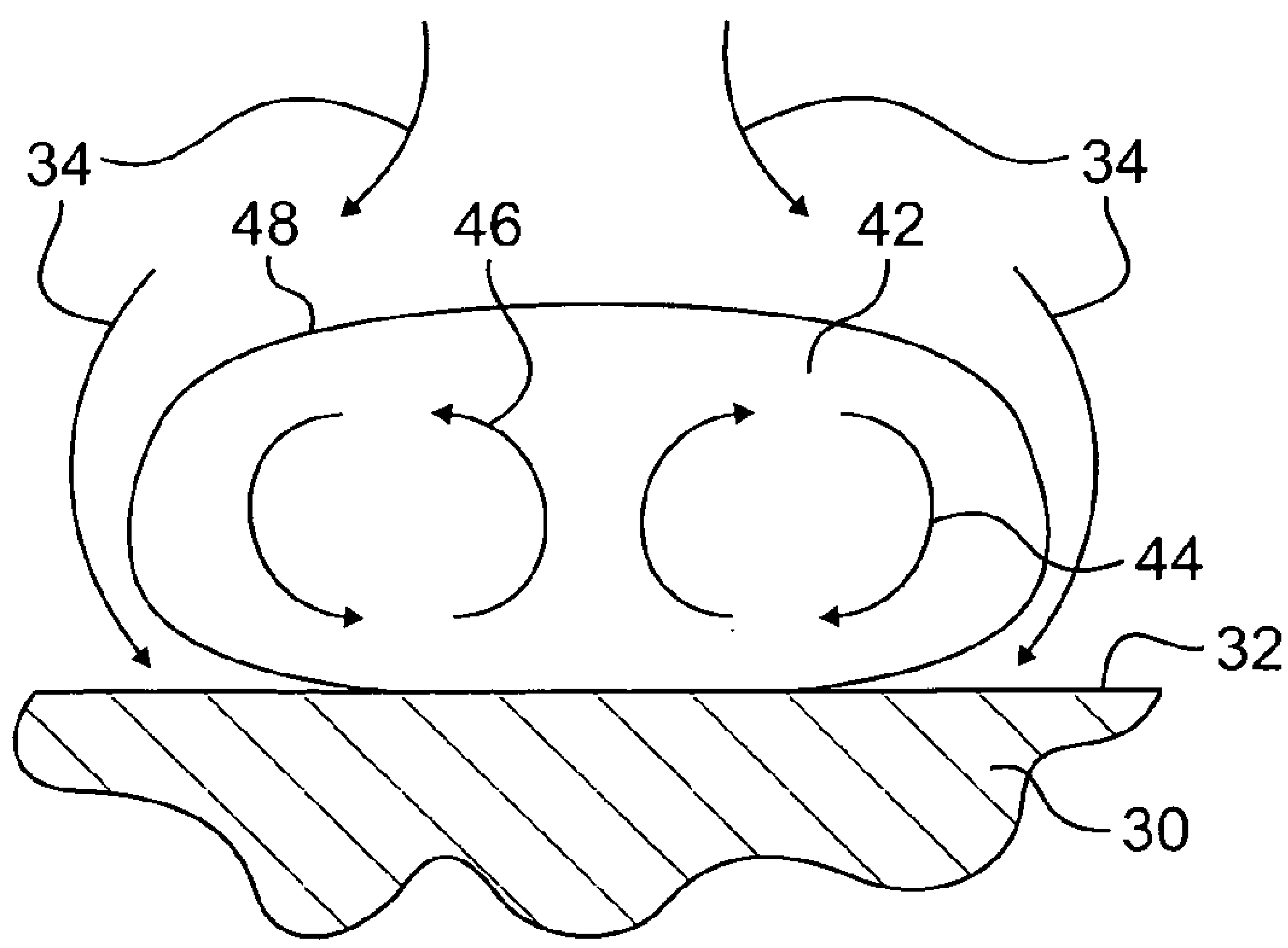


FIG. 6C

COUNTER-VORTEX PAIRED FILM COOLING HOLE DESIGN

BACKGROUND

[0001] The present invention relates to film cooling, and more particularly to structures and methods for providing vortex film cooling flows along gas turbine engine components.

[0002] Gas turbine engines utilize hot fluid flows in order to generate thrust or other usable power. Modern gas turbine engines have increased working fluid temperatures in order to increase engine operating efficiency. However, such high temperature fluids pose a risk of damage to engine components, such as turbine blades and vanes. High melting point superalloys and specialized coatings (e.g., thermal barrier coatings) have been used to help avoid thermally induced damage to engine components, but operating temperatures in modern gas turbine engines can still exceed superalloy melting points and coatings can become damaged or otherwise fail over time.

[0003] Cooling fluids have also been used to protect engine components, often in conjunction with the use of high temperature alloys and specialized coatings. One method of using cooling fluids is called impingement cooling, which involves directing a relatively cool fluid (e.g., compressor bleed air) against a surface of a component exposed to high temperatures in order to absorb thermal energy into the cooling fluid that is then carried away from the component to cool it. Impingement cooling is typically implemented with internal cooling passages. However, impingement cooling alone may not be sufficient to maintain suitable component temperatures in operation. An alternative method of using cooling fluids is called film cooling, which involves providing a flow of relatively cool fluid from film cooling holes in order to create a thermally insulative barrier between a surface of a component and a relatively hot fluid flow. Problems with film cooling include flow separation or "liftoff", where the film cooling flow lifts off the surface of the component desired to be cooled, undesirably allowing hot fluids to reach the surface of the component. Film cooling fluid liftoff can necessitate additional, more closely-spaced film cooling holes to achieve a given level of cooling. Cooling flows of any type can present efficiency loss for an engine. The more fluid that is redirected within an engine for cooling purposes, the less efficient the engine tends to be in producing thrust or another usable power output. Therefore, fewer and smaller cooling holes with less dense cooling hole patterns are desirable.

[0004] The present invention provides an alternative method and apparatus for film cooling gas turbine engine components.

SUMMARY

[0005] An apparatus for use in a gas turbine engine includes a wall defining an exterior face, a first film cooling passage extending through the wall for providing film cooling to the exterior face of the wall, and a second film cooling passage extending through the wall adjacent to the first film cooling passage for providing film cooling to the exterior face of the wall. The first film passage includes a first vortex-generating structure for inducing a vortex in a first rotational direction in a cooling fluid passing therethrough, and the second film passage includes a second vortex-generating structure for inducing a vortex in a second rotational direction in a cooling fluid passing therethrough. The first and second rotational directions are substantially opposite one another.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. **1** is a perspective view of an exemplary film cooled turbine blade.

[0007] FIG. **2**A is a cross-sectional view of a portion of a film cooled gas turbine engine component.

[0008] FIGS. **2**B-**2**E are cross-sectional views of portions of the film cooled gas turbine engine component taken along lines B-B, C-C, D-D and E-E, respectively, of FIG. **2**A.

[0009] FIG. **3** is a schematic view of a pair of film cooling passages.

[0010] FIGS. **4**A-**4**C are cross-sectional views of exemplary embodiments of vortex-generating structures.

[0011] FIG. **5** is a schematic view of another embodiment of a film cooling passage.

[0012] FIG. **6**A is a cross-sectional view of a portion of another embodiment of a film cooled gas turbine engine component.

[0013] FIGS. **6**B and **6**C are cross-sectional views of a portion of the film cooled gas turbine engine component, taken along lines B-B and C-C, respectively, of FIG. **6**A.

DETAILED DESCRIPTION

[0014] The present invention, in general, relates to structures and methods for generating a counter-rotating vortex film cooling flow along a surface of a component for a gas turbine engine exposed to hot gases, such as a turbine blade, vane, shroud, duct wall, etc. Such a film cooling flow can provide a thermally insulative barrier between the gas turbine engine component and the hot gases. According to the present invention, a pair of film cooling passages have closely-spaced outlets at an exterior surface (or face) of the component that is exposed to the hot gases. A vortex-generating structure is positioned within each film cooling passage of the pair to generate a vortex flow. The vortex flow generated within a first of the pair of film cooling passages rotates in a first rotational direction therein, prior to reaching an outlet, and the vortex flow generated within a second of the pair of film cooling passages rotates in a substantially opposite direction (i.e., counter-rotates with respect to the first rotational direction). In one embodiment of the present invention, the vortex-generating structures can comprise helical ribs (or rifling), with the helical ribs of the first and second film cooling passages winding in opposite directions. Additional features and benefits of the present invention will be recognized in light of the description that follows.

[0015] FIG. **1** is a perspective view of an exemplary film cooled turbine blade **20** having an airfoil portion **22**. Pairs of film cooling hole outlets **24** are positioned along exterior sidewall surfaces of the airfoil portion **22** (only one side of the airfoil portion **22** is visible in FIG. **1**). The hole outlets **24** of each pair are located at substantially the same streamwise location along the airfoil portion **22**. During operation, the pairs of film cooling hole outlets **24** eject a film cooling fluid (e.g., compressor bleed air) to provide a thermally insulative barrier along portions of the turbine blade **20** exposed to hot gases. The particular arrangement of the pairs of film cooling hole outlets **24** shown in FIG. **1** is merely exemplary, and nearly any desired arrangement of the pairs of film cooling hole outlets **24** is possible in alternative embodiments. It should also be noted that the turbine blade **20** is shown merely as one example of a gas turbine engine component that can be film cooled according to the present invention. The present invention is equally applicable to other types of gas turbine engine components, such as vanes, shrouds, duct walls, etc.

[0016] FIG. **2**A is a cross-sectional view of a portion of a wall **30** of a film cooled gas turbine engine component. The wall **30** has an exterior surface **32** that is exposed to a hot gas flow **34**. As shown in FIG. **2**A, a substantially cylindrically shaped first film cooling passage **36**A extends through the wall **30** to a first outlet **38**A located at the exterior surface **32** of the wall **30**, the first film cooling passage **36**A angled slightly toward a free stream direction of the hot gas flow **34**. The first outlet **38**A can be shaped similarly to a cross-sectional profile of an interior portion of the first film cooling passage **36**A. A substantially helically-shaped vortex generating rib **40**A is positioned along an interior surface of the first film cooling passage **36**A, and can be formed using electro-discharge machining (EDM), stem drilling, casting, or other suitable processes. A film cooling fluid **42** passes through the first film cooling passage **36**A and is ejected from the first outlet **38**A, and then forms a thermally insulative barrier along the exterior surface **32** of the wall **30** that extends downstream from the first outlet **38**A. Although only the first film cooling passage **36**A is visible in FIG. **2**A, a second film cooling passage **36**B can be positioned adjacent to the first film cooling passage **36**A and have a similar configuration. The first and second film cooling passages **36**A and **36**B respectively can be arranged substantially parallel to one another, angled toward one another (i.e., in a non-parallel arrangement), or have other configurations. Furthermore, the first and second film cooling passages **36**A and **36**B respectively can be connected to a common fluid supply manifold (not shown), or otherwise branched together opposite the first and second outlets **38**A and **38**B respectively.

[0017] FIG. **2**B is a cross-sectional view of a portion of the wall **30** of the film cooled gas turbine engine component, taken along line B-B of FIG. **2**A. The pair of first and second film cooling passages **36**A and **36**B respectively have a first and second substantially helically-shaped vortex-generating ribs **40**A and **40**B, respectively. The first vortex-generating rib **40**A generates a vortex flow within the first film cooling passage **36**A in generally a first rotational direction **44** (e.g., clockwise). The second vortex-generating rib **40**B generates a vortex flow within the second film cooling passage **36**B in generally a second rotational direction **46** (e.g., counter-clockwise). It should be noted that the cross-section of FIG. **2**B is taken at a location within the wall **30**, upstream from the first and second outlets **38**A and **38**B respectively of the film cooling passages **36**A and **36**B (see FIG. **2**A), and vortex flows are present within the film cooling passages **36**A and **36**B upstream from the first and second outlets **38**A and **38**B respectively.

[0018] FIG. **2**C is a cross-sectional view of a portion of the wall **30** of the film cooled gas turbine engine component, taken along line C-C of FIG. **2**A just downstream from the first and second outlets **38**A and **38**B respectively (not shown in FIG. **2**C) along the exterior surface **32** of the wall **30** (relative to the hot gas flow **34**). As shown in FIG. **2**C, cooling fluid **42** from both the first and second film cooling passages **36**A and **36**B respectively (not shown in FIG. **2**C) have mixed together to form a contiguous jet of the film cooling fluid **42** upon leaving the first and second outlets **38**A and **38**B, respectively (not shown in FIG. **2**C). A boundary **48** is defined between the jet of the film cooling fluid **42** and the hot gas flow **34**. The cooling fluid **42** passes along the exterior surface **32** of the wall **30**, attached thereto, that is, the film cooling fluid **42** remains substantially in contact with the exterior surface **32** to form a barrier between the exterior surface **32** and the hot gas flow **34**. The film cooling fluid **42** includes counter-rotating vortices defined by fluid rotating in the substantially opposite first and second rotational directions **44** and **46** respectively. The first and second rotational directions **44** and **46** respectively can be arranged to generally oppose a tendency of the hot gas flow **34** to move toward the exterior surface **32** of the wall **30**, thereby reducing "liftoff" or "flow separation" that occur when a portion of the hot gas flow **34** extends between the film cooling fluid **42** and the exterior surface **32** of the wall **30**. In the illustrated embodiment, the first and second rotational directions **44** and **46** respectively are arranged to flow generally toward the exterior surface **32** at a location where the vortexes adjoin each other, and generally away from the exterior surface **32** at lateral boundaries of the jet of the film cooling fluid **42**.

[0019] FIG. **2**D is a cross-sectional view of a portion of the wall **30** of the film cooled gas turbine engine component, taken along line D-D of FIG. **2**A downstream from the cross-sectional view shown in FIG. **2**C (relative to the hot gas flow **34**). As shown in FIG. **2**D, the counter-rotating vortices defined by the film cooling fluid **42** rotating in the substantially opposite first and second rotational directions **44** and **46** respectively causes mixing with the hot gas flow **34** at or near the boundary **48**, which can reduce momentum of the counter-rotating vortices of the film cooling fluid **42** and also reduce or disrupt momentum of the hot gas flow **34** in a direction toward the wall **30**. This mixing can help reduce "liftoff" of the film cooling fluid **42**, such that the film cooling fluid **42** remains substantially attached to the exterior surface **32** of the wall.

[0020] FIG. **2**E is a cross-sectional view of a portion of the wall **30** of the film cooled gas turbine engine component, taken along line E-E of FIG. **2**A downstream from the cross-sectional view of FIG. **2**D. As shown in FIG. **2**E, mixing of the film cooling fluid **42** with the hot gas flow **34** (not labeled in FIG. **2**E) has formed a mixed fluid zone **48** around the original location of the boundary **48**, which is no longer a distinct transition. The film cooling fluid **42** has lost essentially all rotational kinetic energy, meaning the counter-rotating vortices have substantially ceased to rotate. The film cooling fluid **42** still moves downstream along wall **30** substantially attached to the exterior surface **32**. The film cooling fluid **42** will inevitably degrade as it continues downstream along the exterior surface **32** of the wall **30**. However, the present invention can allow the film cooling fluid **42** to provide a relatively effective thermal barrier that is substantially attached to the exterior surface **32** for a relatively long distance along the wall **32** downstream from the first and second outlets **38**A and **38**B respectively.

[0021] FIG. **3** is a schematic view of the pair of first and second film cooling passages **36**A and **36**B respectively. The first and second film cooling passages **36**A and **36**B respectively define first and second central axes **50**A and **50**B, respectively. The first and second central axes **50**A and **50**B respectively are arranged substantially parallel to one another, and are closely spaced apart by a distance S. As used herein, the term "closely spaced" means spaced from each other on the order of a few diameters. The first film cooling passage **36**A has a radius R_A, and the second film cooling passage has a radius R_B. In one embodiment, the radii R_A and

R_B can be substantially equal. The first vortex-generating structure **40**A has a pitch P_A, and the second vortex-generating structure **40**B has a pitch P_B. The pitches P_A and P_B can be substantially constant (as shown in FIG. **3**) or variable along lengths of the first and second film cooling passages **36**A and **36**B, respectively.

[0022] The first and second vortex-generating structures **40**A and **40**B respectively can have nearly any desired cross-sectional shape (or profile). FIGS. **4**A, **4**B, and **4**C are cross-sectional views of exemplary embodiments of vortex-generating structures **140**A, **140**B, and **140**C, respectively, each defining a height H_t and a width W_t. The vortex-generating structure **140**A shown in FIG. **4**A has a substantially rectangular cross-sectional shape, the vortex-generating structure **140**B shown in FIG. **4**B has a substantially triangular cross-sectional shape, and the vortex-generating structure **140**C shown in FIG. **4**C has a substantially arcuate cross-sectional shape. It should be understood that further cross-sectional shapes can be utilized in alternative embodiments.

[0023] The following are descriptions of particular dimensions and proportions for exemplary embodiments of the present invention. These embodiments are provided merely by way of example and not limitation. The first and second film cooling passages **36**A and **36**B and the first and second vortex-generating structures **40**A and **40**B can be described as having vortex generating structures with a pitch P that is a multiple of a radius R, where P represents either the pitch P_A or P_B and R represents the corresponding radius R_A or R_B. The pitch P can be in the range of approximately 1 to 10 times the radius R, or alternatively in the range of approximately 1.5 to 3 times the radius R.

[0024] A ratio of the height of vortex-generating structure H_t over the diameter of the associated film cooling passage (i.e., two time the radius R_A or R_B) can be between approximately 0.05 and 0.5, or alternatively between approximately 0.1 and 0.3. A ratio of the width W_t over the height H_t of the vortex-generating structures **40**A and **40**B can be between approximately 0.5 and 4, or alternatively between approximately 0.5 and 1.5. The distance S between the axes **50**A and **50**B can be less than approximately ten times the radius R, or alternatively between approximately two to six times the radius R. Furthermore, a length of the first and second film cooling passages **36**A and **36**B respectively can be at least approximately three to ten times a hydraulic diameter at the respective first and second outlets **38**A and **38**B, or alternatively at least approximately 5 to ten times the hydraulic diameter at the respective first and second outlets **38**A and **38**B (where the hydraulic diameter is four times the area divided by the perimeter).

[0025] FIG. **5** is a schematic view of an alternative embodiment of a film cooling passage **36** of the present invention (applicable to either one of the pair of film cooling passages **36**A or **36**B). As shown in FIG. **5**, the film cooling passage **36** includes two sets of helical vortex-generating ribs **46**C and **46**D that wind in the same direction, adjacent one another (the vortex-generating rib **46**C is represented by a weighted line in FIG. **5**, for illustrative purposes). In the illustrated embodiment, the rib **46**C has a pitch P_1 and the rib **46**D has a pitch P_2. The pitches P_1 and P_2 can be substantially equal. The pitches P_1 and P_2 can be substantially constant (as shown in FIG. **3**) or variable along lengths of the film cooling passage **36**. In further embodiments, still more additional ribs can be provided.

[0026] The present invention provides numerous advantages. For example, while mixing of film cooling fluid jets with hot gas flows represents an efficiency loss, that loss is balanced against improved film cooling effectiveness per film cooling passage. This can permit a given level of film cooling to be provided to a given component with a relatively small number of film cooling passages for a given film cooling fluid flow rate and/or increasing spacing between pairs of cooling hole outlets. Moreover, even with the presence of paired, closely spaced cooling hole outlets, the present invention can provide film cooling to a given surface area with a relatively low density of cooling holes and a relatively low total cooling hole area. Film cooling according to the present invention can help allow gas turbine engine components to operate in higher temperature environments with a relatively low risk of thermal damage.

[0027] FIGS. **6**A, **6**B and **6**C illustrate an alternative embodiment of the present invention, configured to produce a different effect from the previously described embodiments. FIG. **6**A is a cross-sectional view of another embodiment of a portion of a wall **30** of the film cooled gas turbine engine component. FIG. **6**B is a cross sectional view of a portion of the film cooled gas turbine engine component **30**, taken along line B-B of FIG. **6**A. In this embodiment, the first film cooling passage **36**A has a first helical vortex-generating rib **40**C, which winds in an opposite direction with respect to the first vortex-generating rib **40**A of previously-described embodiments, and a second helical vortex-generating rib **40**D, which winds in an opposite direction with respect to the second vortex-generating rib **40**B of previously-described embodiments (vortex-generating ribs **40**A and **40**B are not shown in FIG. **6**B). In this configuration, the film cooling fluid **42** rotates in the second rotational direction **46** (e.g., counter-clockwise) within the first film cooling passage **36**A, and the film cooling fluid **42** rotates in the first rotational direction **44** (e.g., clockwise) within the second film cooling passage **36**B.

[0028] FIG. **6**C is a cross sectional view of a portion of the film cooled gas turbine engine component **30**, taken along line C-C of FIG. **6**A (i.e., downstream from an outlet of the film cooling passage **36**A). In the illustrated embodiment, the first and second rotational directions **44** and **46** are arranged to flow generally away from the exterior surface **32** at a location where the vortexes adjoin each other, and generally toward the exterior surface **32** at lateral boundaries of the jet of the film cooling fluid **42**. This configuration would essentially encourage liftoff of the fluid **42** from the exterior surface **32** (i.e., the entrainment of the hot gas flow **34** between the exterior surface **32** and the cooling fluid **42**), which may be desirable for fluidic injection applications, etc.

[0029] Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention. For instance, the particular angle of film cooling passages relative to a film cooled surface can vary as desired for particular applications. Moreover, a cross-sectional area of film cooling passages of the present invention can vary over their length (e.g., with substantially conical film cooling passages).

1. An apparatus for use in a gas turbine engine, the apparatus comprising:

a wall defining an exterior face;

a first film cooling passage extending through the wall for providing film cooling to the exterior face of the wall, wherein the first film passage includes a first vortex-generating structure for inducing a vortex in a first rotational direction in a cooling fluid passing therethrough; and

a second film cooling passage extending through the wall adjacent to the first film cooling passage for providing film cooling to the exterior face of the wall, wherein the second film passage includes a second vortex-generating structure for inducing a vortex in a second rotational direction in a cooling fluid passing therethrough, and wherein the first and second rotational directions are substantially opposite one another.

2. The apparatus of claim **1**, wherein the first vortex-generating structure comprises a first helical rib disposed along an interior surface of the first film cooling passage.

3. The apparatus of claim **2**, wherein the second vortex-generating structure comprises a second helical rib disposed along an interior surface of the second film cooling passage, and wherein the first and second helical ribs of the first and second vortex-generating structures wind about respective central axes in opposite directions.

4. The apparatus of claim **1**, wherein the first and second vortex-generating structures are configured as mirror images of one another.

5. The apparatus of claim **1**, wherein the first and second film cooling passages have respective first and second outlets closely spaced from each other along the exterior face of the wall.

6. The apparatus of claim **5**, wherein the first and second film cooling passages define respective first and second central axes, wherein the first film cooling passage defines a first diameter, and wherein the first and second central axes are spaced from each other by a distance less than or equal to approximately ten times the first diameter.

7. The apparatus of claim **1**, wherein the first and second film cooling passages are both substantially cylindrically-shaped.

8. The apparatus of claim **1**, wherein the first and second film cooling passages are arranged substantially parallel to each other.

9. The apparatus of claim **1**, wherein the first and second rotational directions are arranged to flow generally toward the exterior face of the wall at a location where the vortexes adjoin each other.

10. An apparatus for use in a gas turbine engine, the apparatus comprising:

a wall defining an exterior face;

a pair of closely spaced film cooling passages extending through the wall for providing film cooling to the exterior face of the wall, the pair comprising:

a first film cooling passage extending to a first outlet on the exterior face of the wall, wherein the first film passage includes a first helically-shaped vortex-generating structure disposed along an interior surface of the first film cooling passage for inducing a vortex in a first rotational direction in a cooling fluid passing therethrough; and

a second film cooling passage extending to a second outlet on the exterior face of the wall, wherein the second film passage includes a second helically-shaped vortex-generating structure disposed along an interior surface of the second film cooling passage for inducing a vortex in a second rotational direction in a cooling fluid passing therethrough.

11. The apparatus of claim **10**, wherein the first and second vortex-generating structures are configured as substantially mirror images of each other.

12. The apparatus of claim **10**, wherein the first and second rotational directions are arranged to flow generally toward the exterior face of the wall at a location where the vortexes adjoin each other.

13. The apparatus of claim **10**, wherein the first and second film cooling passages define respective first and second central axes, wherein the first film cooling passage defines a first diameter, and wherein the first and second central axes are spaced from each other by a distance less than or equal to approximately ten times the first diameter.

14. The apparatus of claim **10**, wherein the first and second film cooling passages are both substantially cylindrically-shaped.

15. The apparatus of claim **10**, wherein the first and second film cooling passages extend substantially parallel to each other through the wall.

16. The apparatus of claim **10**, wherein the first and second rotational directions are substantially opposite one another.

17. A method of film cooling a gas turbine engine component exposed to a hot fluid stream, the method comprising:

directing a cooling fluid into a first film cooling passage of the component;

passing the cooling fluid over at least one first vortex-generating structure to rotate a portion of the cooling fluid within the first film cooling passage in a first rotational direction;

directing a cooling fluid into a second film cooling passage of the component;

passing the cooling fluid over at least one second vortex-generating structure to rotate a portion of the cooling fluid within the second film cooling passage in a second rotational direction that counter-rotates with respect to the first rotational direction;

ejecting the cooling fluid rotating in the first rotational direction out of a first outlet in fluid communication with the first film cooling passage;

ejecting the cooling fluid rotating in the second rotational direction out of a second outlet in fluid communication with the second film cooling passage, wherein the counter-rotating cooling fluid ejected from the first and second outlets forms a contiguous cooling film jet; and

passing the counter-rotating cooling film jet along an exterior surface of the component to provide film cooling therealong.

18. The method of claim **17**, wherein the counter-rotation of the film cooling jet concentrates mixing with the hot fluid stream at a region spaced away from the exterior surface of the component.

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