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(54) **Title:** CASTING CORE FOR TWISTED GAS TURBINE ENGINE AIRFOIL HAVING A TWISTED RIB

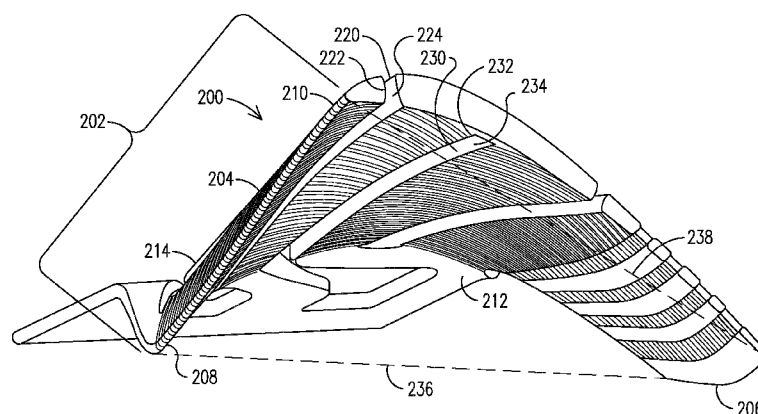


FIG. 9

(57) **Abstract:** A casting core (200) for a twisted gas turbine engine blade, including: an airfoil portion (202) having: an airfoil base end (208), an airfoil tip end (210), a concave side exterior surface (212), a convex side exterior surface (214), a leading edge (204), and a trailing edge (206). The airfoil portion is twisted in a radial direction from the airfoil base end to the airfoil tip end. The airfoil portion includes a first void (220) between the concave side exterior surface and the convex side exterior surface and extending radially to define the shape of a rib of an airfoil to be cast around the core. A first leading edge surface and a first trailing edge surface of the void are twisted from the airfoil base end to the airfoil tip end.

CASTING CORE FOR TWISTED GAS TURBINE ENGINE AIRFOIL HAVING A TWISTED RIB

FIELD OF THE INVENTION

5 The present invention relates to a casting core for gas turbine engine blades having a twisted airfoil. In particular, the invention relates to a casting core having a twisted rib-void therein.

BACKGROUND OF THE INVENTION

10 Gas turbine engine blades have airfoils that may be hollow and may include reinforcing ribs. These ribs may structurally reinforce the blade from several forces, including aerodynamic forces that tend to bend the blade about a base of the blade in a cantilever fashion, forces that tend to balloon a skin of the airfoil caused by higher static pressure present inside the hollow airfoil, and centrifugal force due to rotation of the
15 blade. In addition to adding structural strength, in certain designs these ribs help define cooling channels present in the hollow airfoil.

 Airfoils for gas turbine engine blades may be manufactured in various ways. One common way used is a casting process, due to its relatively low cost. In this process a casting core is first made using a rigid master die set. In this process a first
20 half and a second half of the die are assembled together and form a hollow interior void. A casting core material is put into the hollow interior void and solidifies. Once solidified, the first and second die halves are separated by pulling them apart from each other along a straight separation line. The die halves are rigid, and the casting core is rigid. Consequently, there can be no interference between the casting core and the die
25 halves as they are separated. This has resulted in casting core designs where any features in the casting core must be designed to permit the separation. For example, voids in the casting core, used subsequently to form the reinforcing ribs in the airfoil, are formed such that they are parallel to the direction along which the die halves are pulled apart. This necessarily results in the subsequently formed ribs being parallel to each
30 other.

 Certain airfoil designs include a twist in the airfoil from a base of the airfoil radially outward toward a tip of the airfoil. For any given radial cross section of the

airfoil, a chord line connecting a leading edge of the airfoil to the trailing edge forms a chord line. A radially inward projection of the chord line forms an angle with a longitudinal axis of a rotor shaft of the gas turbine engine. When the angle formed changes from one radial cross section to the next in an airfoil, the blade may be considered twisted. While a casting process is able to accommodate a twist of the outer surfaces of the airfoil, the ribs must remain parallel to each other and to the separation line. As a result, in different radial cross sections the ribs will remain parallel to each other and the separation line, but since the airfoil is twisting, the ribs will change their orientation with respect to a skin of the airfoil. In certain circumstances it is preferred that the rib remain in the same (or similar) orientation to the skin in each cross section, such as for optimum strength, or optimum cooling when the rib defines part of a cooling channel. In certain circumstances it is preferred that the ribs not be parallel. Hence, other manufacturing techniques have been explored.

FIG. 1 shows a prior art airfoil disclosed in U.S. patent number 4,512,069 to Hagemeister. In this twisted airfoil the a first rib 12 and a second rib 14 change orientation from a base cross section 16 to a tip cross section 18. This is accomplished by forging a worked conduit (drawn, swaged etc) into an untwisted airfoil shape and then twisting it. This working, forging, and twisting process is significantly different than casting, and may be more expensive.

A technique for forming ribs that are not parallel includes using two die halves and fugitive inserts. The fugitive inserts are positioned inside the hollow interior void, the casting material is placed in the hollow interior void, and the once the casting core is solidified the fugitive material is removed to form rib voids that are not parallel, and hence the subsequently formed ribs are not parallel.

However, these techniques may be costlier than simple casting, and hence there remains room in the art for improvement.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is explained in the following description in view of the drawings that show:

FIG. 1 shows a prior art blade having a twisted web made via a forging process.

FIG. 2 shows a blade having a cast, monolithic, twisted airfoil.

FIGS. 3-5 show cross sections of a prior art twisted airfoil having planar (not twisted) webs.

FIGS. 6-8 show cross sections of the twisted airfoil of FIG. 2.

5 FIG. 9 is a perspective view of a casting core for casting twisted webs in a twisted airfoil.

FIG. 10 is a side view of the casting core of FIG. 9.

FIGS. 11-12 show cross sections of the casting core of FIG. 10.

10 DETAILED DESCRIPTION OF THE INVENTION

The present inventor has developed an innovative casting core that includes at least one twisted rib-void ("void") therein. Such a configuration allows for an orientation of a subsequently formed rib that is optimized for strength and/or efficient heat exchange.

15 FIG. 2 shows gas turbine engine blade 20 including a platform 22 and an airfoil 24. The airfoil 24 has a leading edge 26, a trailing edge 28, a base end 30, a tip end 32, a pressure side exterior surface 34, and a suction side exterior surface 36. Combustion gases 40 flowing from an upstream side 42 of the a gas turbine engine flow toward a downstream side 44 of the gas turbine engine while encountering the blade
20 20, and an interaction of the combustion gases 40 and the blade 20 causes the blade 20 to rotate about a longitudinal axis 46 of a rotor shaft (not shown) of the gas turbine engine. Discussion herein focuses on turbine blades, but the same concepts can be applied to compressor blades, turbine vanes, and compressor vanes.

FIGS. 3-5 show radial cross sections of a blade similar to that of FIG. 2. FIG. 3
25 shows a cross section at approximately 10% of the span from the base end 30 to the tip end 32. FIG. 4 shows a cross section at approximately 50% of the span. FIG. 5 shows a cross section at approximately 90% of the span. In each of these figures the airfoil 24 has a first rib 60 having a first longitudinal axis 62, and a second rib 64 having a second longitudinal axis 66. The first longitudinal axis 62 and the second longitudinal axis 66
30 both span from the pressure side exterior surface 34 to the suction side exterior surface 36, and are an elongated extend of the respective rib. In general, the longitudinal axes

will bisect the ribs. A radially inward projection of the first longitudinal axis 62 will intersect the longitudinal axis 46 of a rotor shaft, or as shown in FIGS. 3-5, the first longitudinal axis 62 will intersect the longitudinal axis 46 of a rotor shaft to form a first angle 68 in each cross section. Similarly, a radially inward projection of the second longitudinal axis 66 will intersect the longitudinal axis 46 of a rotor shaft, or as shown in FIGS. 3-5, the second longitudinal axis 66 will intersect the longitudinal axis 46 of the rotor shaft to form a second angle 70 in each cross section. As shown in FIGS. 3-5, the first angle 68 remains the same in each figure. Similarly, the second angle 70 remains the same in FIGS. 3-5. In addition, the first longitudinal axis 62 and the second longitudinal axis 66 are parallel to each other.

In each cross section there is a chord line 80 and a radially inward projection of the chord line 80 will intersect the longitudinal axis 46 of a rotor shaft, or as shown in FIGS. 3-5, the chord line 80 will intersect the longitudinal axis 46 of a rotor shaft to form a chord line angle 82. In each of the three cross sections the chord line 80 twists, and as a result the chord line angle 82 changes. Consequently, in these figures it is apparent that while the airfoil 24 is twisted, the first rib 60 and the second rib 64 do not twist. This lack of twist may not be optimal in terms of structural strength and cooling.

In the prior art the first longitudinal axis 62 may form a first-axis-to-pressure-side-normal angle 84 with a line 86 normal to the pressure side exterior surface 34 and emanating from an intersection point 87 of the first longitudinal axis 62 and the pressure side exterior surface 34. It may also form a first-axis-to-suction-side-normal angle 88 with a line 90 normal to the suction side exterior surface 36 and emanating from an intersection point 89 of the first longitudinal axis 62 and suction side exterior surface 36.

The greater the angles 84, 88, the less effective the first rib 60 is at resisting aerodynamic forces that work to deflect the airfoil 24 in a cantilever manner about the platform 22, and ballooning forces that tend to deflect the suction side exterior surface 36 outward. Also, as the angles 84, 88 increase, a length 92 of the first rib 60 increases. This increased length adds weight, and this added weight increases centrifugal forces in the rotating blade 20. Further, in an exemplary embodiment where the first rib 60 helps to define a cooling channel 100, these angles 84, 88 create a skewing of a corner 102 of the cooling channel 100. Skewed corners are not optimum

for cooling in that they create stagnant areas that interferes with cooling in other areas of the cooling channel 100.

Similar to the first longitudinal axis 62, the second longitudinal axis 66 may form a second-axis-to-pressure-side-normal angle 120 with a line 122 normal to the pressure side exterior surface 34 and emanating from an intersection point 123 of the second longitudinal axis 66 and the pressure side exterior surface 34. (Line 122 is shown as not exactly normal in the figure for sake of clarity of the drawing itself.) It may also form a second-axis-to-suction-side-normal angle 124 with a line 126 normal to the suction side exterior surface 36 and emanating from an intersection point 127 of the second longitudinal axis 66 and the suction side exterior surface 36. The greater the angles 120, 124 the greater the same problems are that are encountered with the angles 84, 88.

FIGS. 6-8 show radial cross sections of a blade similar to that of FIG. 2, but with the twisted ribs disclosed herein. FIG. 6 shows a cross section at approximately 10% of the span from the base end 30 to the tip end 32. FIG. 7 shows a cross section at approximately 50% of the span. FIG. 8 shows a cross section at approximately 90% of the span. In each cross section there is the chord line 80 and the chord line angle 82, and it can be seen that the chord line angle 82 changes in each cross section, meaning that the airfoil 24 is twisted. However, the twist may occur in fewer than every cross section. For example, the twist may only occur for a portion of a span of the airfoil 24, or may occur as a transition from a first untwisted portion of the span to a second untwisted portion of the span. Stated another way, the twist can be present in some or all of the span from the base end 30 to the tip end 32.

In each of these figures the airfoil 24 has a first rib 130 having a first longitudinal axis 132, and a second rib 134 having a second longitudinal axis 136. Similar to the prior art, a radially inward projection of the first longitudinal axis 132 will intersect the longitudinal axis 46 of the rotor shaft, or as shown in FIGS. 6-8, the first longitudinal axis 132 will intersect the longitudinal axis 46 of the rotor shaft to form a first angle 138 in each cross section. Similarly, a radially inward projection of the second longitudinal axis 136 will intersect the longitudinal axis 46 of the rotor shaft, or as shown in FIGS. 6-8, the second longitudinal axis 136 will intersect the longitudinal axis 46 of the rotor

shaft to form a second angle 140 in each cross section. Unlike the prior art, as shown in FIGS. 6-8, the first angle 138 does not remain the same in each figure. Stated another way, the first longitudinal axis 132 in FIG. 6, which can be considered a first reference axis taken at a base end 30 of the airfoil 24, is not parallel to the first longitudinal axis 132 in FIG. 7 or in FIG. 8. Similarly, the second longitudinal axis 136 FIG. 6, which can be considered a second reference axis taken at a base end 30 of the airfoil 24, is not parallel to the second longitudinal axis 136 in FIG. 7 or in FIG. 8, the second angle 140 does not remain the same in FIGS. 6-8, and likewise, the second longitudinal axis 136 of FIG. 6 is not parallel to the second longitudinal axis 136 of FIGS. 7 or 8. In addition, the first longitudinal axis 132 and the second longitudinal axis 136 are not necessarily parallel to each other. Thus, in this twisted airfoil 24, the first rib 130 and the second rib 134 are twisted as well. The twist may be smooth and continuous, or may be abrupt and discontinuous.

With the twisted ribs 130, 134 disclosed herein, the first longitudinal axis 132 may form a first-axis-to-pressure-side-normal angle 150 with a line 152 normal to the pressure side exterior surface 34 and emanating from an intersection point 153 of the first longitudinal axis 132 and the pressure side exterior surface 34. As shown, the first longitudinal axis 132 and the line 152 normal to the pressure side exterior surface 34 are parallel, and thus in the exemplary embodiment shown the first-axis-to-pressure-side-normal angle 150 is zero degrees. Stated another way, the first longitudinal axis 132 is normal/perpendicular to the pressure side exterior surface 34. Similarly, the first longitudinal axis 132 may form a first-axis-to-suction-side-normal angle 154 with a line 156 normal to the pressure side exterior surface 34 and emanating from an intersection point 157 of the first longitudinal axis 132 and the suction side exterior surface 36. A smaller angle 150, 154 means a length 158 of the first rib 130 is shorter. This reduces weight and centrifugal forces while providing increased strength.

As shown, the first longitudinal axis 132 and the line 156 normal to the pressure side exterior surface 34 are parallel, and thus in the exemplary embodiment shown the first-axis-to-suction-side-normal angle 154 is zero degrees. This may occur if the pressure side exterior surface 34 and the suction side exterior surface 36 are parallel to each other at those points. However, it is also possible that the pressure side exterior

surface 34 and the suction side exterior surface 36 are not parallel to each other when they intersect the first longitudinal axis 132. In that case the first-axis-to-pressure-side-normal angle 150 and the first-axis-to-suction-side-normal angle 154 may not be the same. In any case, the angles 150, 154 are to be close to zero, plus or minus 10
5 degrees. When the angles 150, 154 are closer to perpendicular to the pressure side exterior surface 34 and suction side exterior surface 36 respectively this results in a greater resistance to aerodynamic forces that work to cantilever the airfoil 24 about the platform 22, and a greater resistance to ballooning forces that tend to balloon the suction side exterior surface 36 outward. In addition, in an exemplary embodiment
10 where the first rib 130 helps to define a cooling channel 160, when the first longitudinal axis 132 is nearly normal to the pressure side exterior surface 34 and suction side exterior surface 36 there is less skew in the corners 162 of the cooling channel 160. This allows for more efficient cooling. Still further, the ability to control the angles 150, 154 allows designers to ensure robust support exist at locations where subsequent
15 manufacturing steps require it. For example, in some instances snubbers may be joined to the airfoil 24 in a process whereby substantial force is imparted to the airfoil 24, such as by a friction welding process. The closer angles 150, 154 are to perpendicular, the greater the support they provide during the joining process.

Similar to the first longitudinal axis 132, the second longitudinal axis 136 may
20 form a second-axis-to-pressure-side-normal angle 170 with a line 172 normal to the pressure side exterior surface 34 and emanating from an intersection point 173 of the second longitudinal axis 136 and the pressure side exterior surface 34. It may also form a second-axis-to-suction-side-normal angle 174 with a line 176 normal to the suction side exterior surface 36 and emanating from an intersection point 177 of the
25 second longitudinal axis 136 and the suction side exterior surface 36. As with angles 150, 154, the smaller the angles 170, 174 the greater the resistance to aerodynamic forces that work to cantilever the airfoil 24 about the platform 24, the greater the resistance to the ballooning forces, the more efficient the cooling, and the greater design freedom for strength that may be needed during subsequent manufacturing etc.
30 The twist of the first longitudinal axis 132 and the second longitudinal axis 136 may or may not follow the twist of the airfoil 24. For example, a rate of twist, which may be

defined as a change in the chord line angle 82 for a given change in radial distance, from the base end 30 to the tip end 32, may be constant for the airfoil 24. If a rate of twist from the base end 30 to the tip end 32 of the rib is constant, then the twist of the rib may be considered to follow the twist of the airfoil 24. Alternately, the rate of twist of the airfoil may be greater than or less than the rate of twist of the rib. The rates may vary radially as well, such that the rate of twist of the airfoil 24 may, in one radial range, be greater than the rate of twist of the rib, and at another radial range the rate of twist of the airfoil 24 may be less than the rate of twist of the rib. Any combination of the above may be possible.

A further difference from the prior art is that the first rib 130 and the second rib 134 within any cross section may not be parallel to each other. This may be influenced by a profile of the airfoil 24, and not limitations of the core casting process. As a result, there may be cross sections where the first rib 130 and the second rib 134 are not parallel, and one or more cross sections where the first rib 130 and the second rib 134 are parallel to each other.

FIG. 7 shows an exemplary embodiment of the airfoil 24 where a first leading edge side 180 of the first rib 130 and a first trailing edge side 182 of the first rib 130 are not parallel to each other. Similarly, a second leading edge side 184 of the second rib 134 and a second trailing edge side 186 of the second rib 134 may not be parallel to each other. The sides may be symmetrically tapered as shown, in either direction, or may be asymmetric. The same manufacturing procedure that enables the formation of the twisted ribs enables the formation of ribs that would not be possible when the core is manufactured using the rigid die set. A longitudinal axis of a rib is that axis along which the rib offers the most structural rigidity. Consequently, when the rib is symmetric the axis typically bisects the cross section of the rib. When a rib is asymmetric, the longitudinal axis may have to be determined, but will still be the axis along which the rib offers the most resistance to the cantilevering and ballooning forces disclosed herein.

The monolithic airfoil 24 having the twisted ribs may be formed using a flexible silicone mold, such as in a technique developed by Mikro Systems, Inc. of Charlottesville, VA, and described in U.S. Patent number 8,062,023 issued November 22, 2011 to Appleby et al., which is incorporated herein by reference. The core used

may be thermally reshaped during its manufacture to reach its desired shape, as disclosed in U.S. patent application publication number 2011/0132562 to Merrill et al., published June 19, 2011 and incorporated herein by reference. In this process, prior to full curing the core can be heated to beyond the epoxy reversion temperature, bent into a new shape, such as by pressing it into a fixture, and either cooled to below the reversion temperature, or heated until it reaches a cured state. Alternately, the monolithic airfoil 24 may be cast using a fugitive core die, where the fugitive material itself has a twist to it, which in turn leaves a twisted void for the rib in the casting core. The monolithic airfoil 24 may further be manufactured using a core that becomes an integral core once multiple core components have been assembled together. Any feature disclosed herein regarding the twisted ribs may be formed by creating an associated feature in the casting core disclosed herein.

An exemplary embodiment of a casting core 200 that may be used to create the twisted first rib 130 and second rib 134 is shown in FIG. 9. The casting core 200 has an airfoil portion 202 that includes a leading edge 204, a trailing edge 206, an airfoil base end 208, an airfoil tip end 210, a pressure side exterior surface 212, and a suction side exterior surface 214. Within the casting core 200 is a first void 220 defined by a first leading edge surface 222 and a first trailing edge surface 224. Also present is a second void 230 defined by a second leading edge surface 232 and a second trailing edge surface 234. There may be one void, or several voids, depending on the design. It can be seen that a base end chord line 236 and a tip end chord line 238 are not parallel and thus the airfoil portion 202 twists from the airfoil base end 208 to the airfoil tip end 210. The twist of the casting core 200 is associated with a twist of the airfoil, but the two may or may not be the same, depending on the interior design of the airfoil 24.

FIG. 10 is a side view of the casting core 200 of FIG. 9 showing the first void 220 (pointing to the wrong place) defined by the first leading edge surface 222 (wrong location) and the first trailing edge surface 224 (wrong location), and the second void 230 (wrong location) defined by the second leading edge surface 232 (wrong location) and the second trailing edge surface 234 (wrong location). FIG. 11 is a cross section taken along line A-A of FIG. 10, looking radially inward, again showing first void 220, the first leading edge surface 222, the first trailing edge surface 224, the second void 230,

the second leading edge surface 232, and the second trailing edge surface 234. The first void 220 defines a first longitudinal axis 240 that spans the airfoil portion 202 from the pressure side exterior surface 212 to the suction side exterior surface 214, and is an elongated extent of the first void 220 that will generally bisect the first void 220. The
5 second void 230 defines a second longitudinal axis 242 that spans the airfoil portion 202 from the pressure side exterior surface 212 to the suction side exterior surface 214, and is an elongated extent of the second void 230 that will generally bisect the second void 230.

The pressure side exterior surface surfaces 244 of the casting core 200 define a
10 pressure side exterior surface curvature 246, which is a curve that follows a contour defined by the pressure side exterior surface surfaces 244, and which spans the first void 220 and the second void 230 as though they didn't exist, thereby forming a continuous pressure side exterior surface curvature 246. Likewise, suction side exterior surface surfaces 248 define a suction side exterior surface curvature 250, which is a
15 curve that follows a contour defined by the suction side exterior surface surfaces 248, and which spans the first void 220 and the second void 230 as though they didn't exist, thereby forming a continuous suction side exterior surface curvature 250.

The first longitudinal axis 240 intersects the pressure side exterior surface curvature 246 at a first pressure side intersection point 252. The first longitudinal axis
20 240 intersects a tangent line 253 of the pressure side curvature line 246, taken at the first pressure side intersection point 252, at right angles, or within 10 degrees of being at right angles. The first longitudinal axis 240 intersects the suction side exterior surfaces 248 at a first suction side intersection point 254. The first longitudinal axis 240 intersects a tangent line 255 of the suction side exterior surface surfaces 248, taken at
25 the first suction side intersection point 254, at right angles, or within 10 degrees of being at right angles.

Similarly, the second longitudinal axis 242 intersects the pressure side exterior surface curvature 246 at a second pressure side intersection point 256. The second longitudinal axis 242 intersects a tangent line 257 of the pressure side curvature line
30 246, taken at the second pressure side intersection point 256, at right angles, or within 10 degrees of being at right angles. The second longitudinal axis 242 intersects the

suction side exterior surfaces 248 at a second suction side intersection point 258. The second longitudinal axis 242 intersects a tangent line 259 of the suction side exterior surface surfaces 248, taken at the second suction side intersection point 258, at right angles, or within 10 degrees of being at right angles.

5 Base end chord line 236 forms a chord line angle 260 with a reference line 262, which is a line that retains its absolute orientation in both FIG. 11 and FIG. 12. In FIG. 12 it is apparent that the chord line angle 260 formed between the tip end chord line 238 and the reference line 262 is different than in FIG. 11 and thus the airfoil portion 202 twists from the airfoil base end 208 to the airfoil tip end 210. The first longitudinal
10 axis 240 forms a first angle 270 with the reference line 262. The first angle 270 in FIG. 11 is different than the first angle 270 in FIG. 12, and thus the first void twists from the airfoil base end 208 to the airfoil tip end 210. This can also be seen simply by the fact that the first longitudinal axis 240 in FIG. 11 is not parallel to the first longitudinal axis 240 in FIG. 12. Stated another way, the first longitudinal axis 240 in FIG. 11, which can
15 be considered a first reference axis taken at the airfoil base end 208 of the airfoil portion 202, is not parallel to the first longitudinal axis 240 in FIG. 12.

 Since the first longitudinal axis 240 is dependent on a shape and orientation of the first void 220, and the first void 220 is defined by the first leading edge surface 222 and the first trailing edge surface 224, it necessarily follows that the first leading edge
20 surface 222 and the first trailing edge surface 224 also twist from the airfoil base end 208 to the airfoil tip end 210. This is the case regardless of a cross sectional shape the first leading edge surface 222 and the first trailing edge surface 224 take, from straight, to rounded etc. Similar to the twist of the ribs, the twist of the voids may occur in fewer than every cross section. Hence, the twist may occur in some, or all, of the span from
25 the airfoil base end 208 to the airfoil tip end 210.

 Similar to the first void 220, in the second void 230, the second longitudinal axis 242 forms a second angle 272 with the reference line 262. The second angle 272 in FIG. 11 is different than the second angle 272 in FIG. 12, and thus the second void 230 twists from the airfoil base end 208 to the airfoil tip end 210. This can also be seen
30 simply by the fact that the second longitudinal axis 242 in FIG. 11 is not parallel to the second longitudinal axis 242 in FIG. 12. Stated another way, the second longitudinal

axis 242 of FIG. 11, which can be considered a second reference axis taken at the airfoil base end 208 of the airfoil portion 202, is not parallel to the second longitudinal axis 242 in FIG. 12. It necessarily follows that the second leading edge surface 232 and the second trailing edge surface 234 twist from the airfoil base end 208 to the airfoil tip end 210, regardless of their particular cross sectional shape.

Accordingly, it has been shown that the inventor has devised an innovative gas turbine engine airfoil design that incorporates structural ribs that twist in a radial direction. This twist enables the blade to better withstand forces encountered during operation, while incorporating ribs that are shorter, and therefore lighter and less expensive, using proven manufacturing techniques that are known to be cost effective and reliable. The monolithic structure eliminates any welds or other joints that might not be as robust as the cast monolith. Consequently, the disclosure herein represents an improvement in the art.

While various embodiments of the present invention have been shown and described herein, it will be obvious that such embodiments are provided by way of example only. Numerous variations, changes and substitutions may be made without departing from the invention herein. Accordingly, it is intended that the invention be limited only by the spirit and scope of the appended claims.

CLAIMS

The invention claimed is:

- 5 1. A casting core comprising:
 an airfoil portion having: an airfoil base end, an airfoil tip end, a concave side
 exterior surface, a convex side exterior surface, a leading edge, and a trailing edge,
 wherein the airfoil portion is twisted in a radial direction from the airfoil base end
 to the airfoil tip end,
- 10 wherein the airfoil portion comprises a first void between the concave side
 exterior surface and the convex side exterior surface and extending radially, the first
 void defined by a first leading edge surface of the airfoil portion extending between the
 concave side exterior surface and the convex side exterior surface and extending
 radially, and a first trailing edge surface of the airfoil portion extending between the
- 15 concave side exterior surface and the convex side exterior surface and extending
 radially, and
 wherein the first leading edge surface and the first trailing edge surface are
 twisted from the airfoil base end to the airfoil tip end of the first void.
- 20 2. The casting core of claim 1, further comprising a second void between the
 concave side exterior surface and the convex side exterior surface and extending
 radially, the second void defined by a second leading edge surface of the airfoil portion
 between the concave side exterior surface and the convex side exterior surface and
 extending radially, and a second trailing edge surface of the airfoil portion between the
- 25 concave side exterior surface and the convex side exterior surface and extending
 radially, and
 wherein the second leading edge surface and the second trailing edge surface
 are twisted from the airfoil base end to the airfoil tip end of the second void.

3. The casting core of claim 2, wherein for at least one radial cross section of the airfoil portion, longitudinal axes of the first void and of the second void are not parallel.

5 4. The casting core of claim 1, wherein in at least one radial cross section of the airfoil portion a longitudinal axis of the first void is within 10 degrees of being perpendicular to at least one of a curvature of the concave side exterior surface and a curvature of the convex side exterior surface at respective points of intersection.

10 5. The casting core of claim 1, wherein for each radial cross section of the airfoil portion a longitudinal axis of the first void is within 10 degrees of being perpendicular to at least one of a curvature of the concave side exterior surface and a curvature of the convex side exterior surface at respective points of intersection.

15 6. The casting core of claim 1, wherein for each radial cross section of the airfoil portion a longitudinal axis of the first void is within 10 degrees of being perpendicular to a curvature of the concave side exterior surface and a curvature of the convex side exterior surface at respective points of intersection.

20 7. The casting core of claim 1, wherein in at least one radial cross section of the airfoil portion the first leading edge surface and the first trailing edge surface are not parallel.

8. A casting core comprising:

an airfoil portion having: an airfoil base end, an airfoil tip end, a concave side exterior surface, a convex side exterior surface, a leading edge, and a trailing edge,

wherein the airfoil portion is twisted in a radial direction from the airfoil base end to the airfoil tip end,

wherein the airfoil portion comprises a first void between the concave side exterior surface and the convex side exterior surface and extending radially, the first void defined by a first leading edge surface of the airfoil portion extending between the concave side exterior surface and the convex side exterior surface and extending radially, and a first trailing edge surface of the airfoil portion extending between the concave side exterior surface and the convex side exterior surface and extending radially, and

wherein in each radial cross section of the airfoil portion the first void defines a first longitudinal axis that defines a first reference axis, and

wherein in another radial cross section of the airfoil portion a respective first longitudinal axis is not parallel to the first reference axis, thereby forming a first angle of intersection with the first reference axis.

9. The casting core of claim 8, wherein the first angle varies continuously from the airfoil base end to the airfoil tip end.

10. The casting core of claim 8, wherein the first angle varies to follow a twist of the airfoil portion.

11. The casting core of claim 8, wherein in at least one radial cross section of the airfoil portion the first longitudinal axis is within 10 degrees of being perpendicular to at least one of a curvature of the concave side exterior surface and a curvature of the convex side exterior surface at respective points of intersection.

12. The casting core of claim 8, wherein in at least one radial cross section of the airfoil portion the first leading edge surface and the first trailing edge surface are not parallel.

5 13. The casting core of claim 8, further comprising a second void between the concave side exterior surface and the convex side exterior surface and extending radially, the second void defined by a second leading edge surface of the airfoil portion extending between the concave side exterior surface and the convex side exterior surface and extending radially, and a second trailing edge surface of the airfoil portion
10 extending between the concave side exterior surface and the convex side exterior surface and extending radially, and

wherein in each radial cross section of the airfoil portion the second void defines a second longitudinal axis that defines a second reference axis, and

15 wherein in another radial cross section of the airfoil portion a respective second longitudinal axis is not parallel to the second reference axis, thereby forming a second angle of intersection with the second reference axis.

14. The casting core of claim 13, wherein the second angle varies to follow a twist of the airfoil portion.

20 15. The casting core of claim 13, wherein for at least one radial cross section of the airfoil portion the first longitudinal axis and the second longitudinal axis are not parallel.

25 16. The casting core of claim 13, wherein in at least one radial cross section of the airfoil portion the second longitudinal axis is within 10 degrees of being perpendicular to at least one of a curvature of the concave side exterior surface and a curvature of the convex side exterior surface at respective points of intersection.

17. The casting core of claim 13, wherein in at least one radial cross section of the airfoil portion the second leading edge surface and the second trailing edge surface are not parallel.

5 18. A casting core comprising:

an airfoil portion having: an airfoil base end, an airfoil tip end, a concave side exterior surface, a convex side exterior surface, a leading edge, and a trailing edge,

10 a first void between the concave side exterior surface and the convex side exterior surface and extending radially, the first void defined by a first leading edge surface of the airfoil portion extending between the concave side exterior surface and the convex side exterior surface and extending radially, and a first trailing edge surface of the airfoil portion extending between the concave side exterior surface and the convex side exterior surface and extending radially, wherein the first leading edge surface and the first trailing edge surface are twisted from the airfoil base end to the
15 airfoil tip end of the first void, and

a second void between the concave side exterior surface and the convex side exterior surface and extending radially, the second void defined by a second leading edge surface of the airfoil portion between the concave side exterior surface and the convex side exterior surface and extending radially, and a second trailing edge surface
20 of the airfoil portion between the concave side exterior surface and the convex side exterior surface and extending radially, wherein the second leading edge surface and the second trailing edge surface are twisted from the airfoil base end to the airfoil tip end of the second void,

25 wherein the airfoil portion is twisted in a radial direction from the airfoil base end to the airfoil tip end, and

wherein in at least one radial cross section of the airfoil portion, the first longitudinal axis and the second longitudinal axis are not parallel.

30 19. The casting core of claim 18, wherein in each radial cross section of the airfoil portion the first longitudinal axis and the second longitudinal axis are not parallel.

1/6

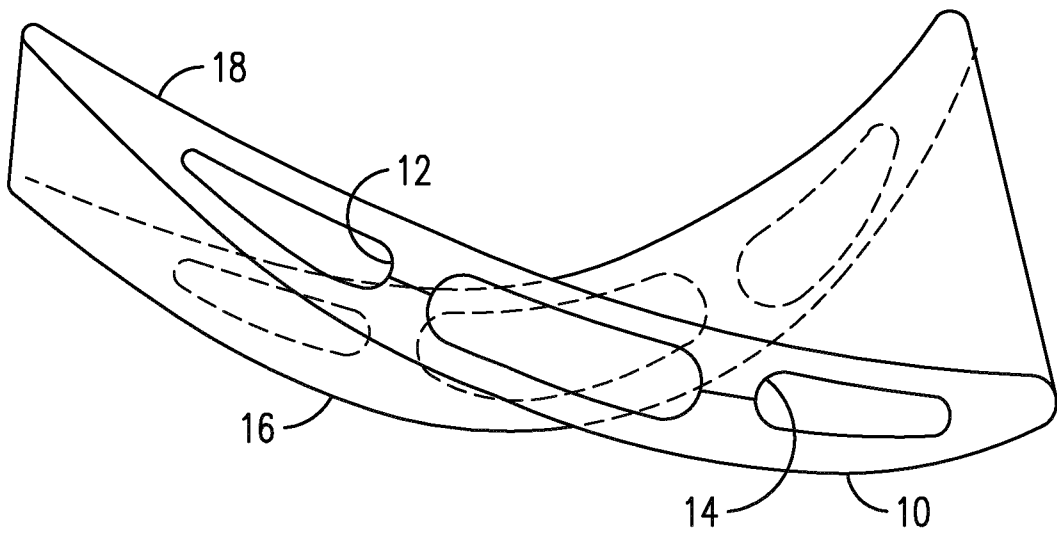


FIG. 1
PRIOR ART

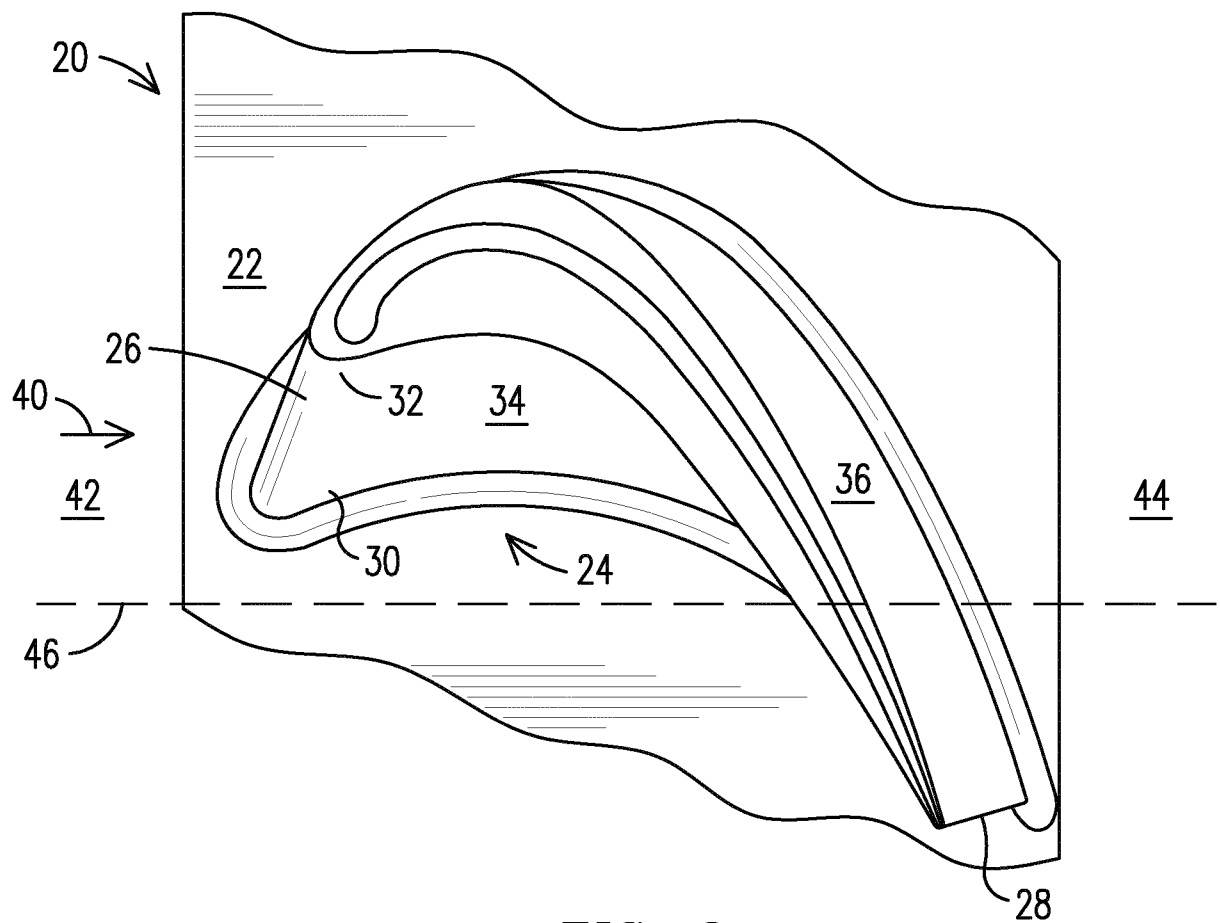


FIG. 2

2/6

FIG. 5
PRIOR ART

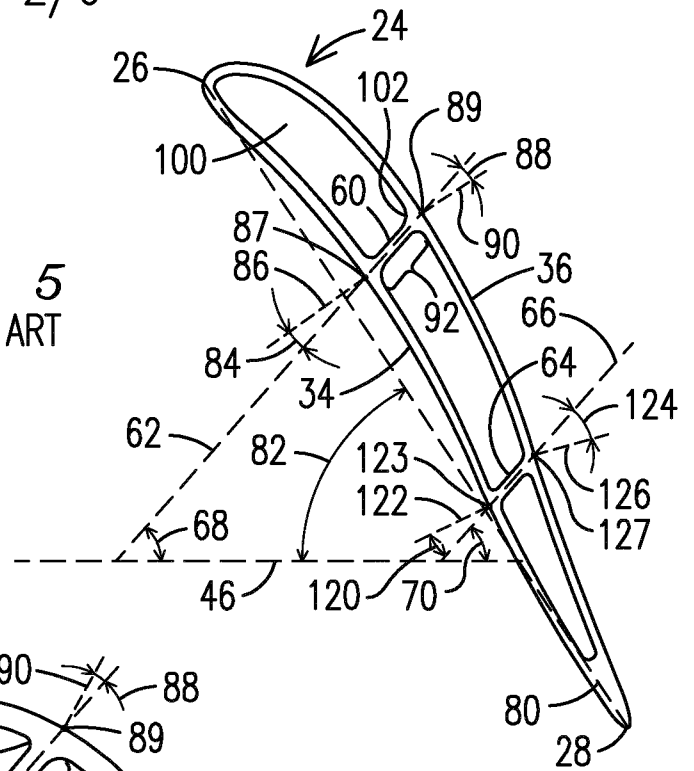


FIG. 4
PRIOR ART

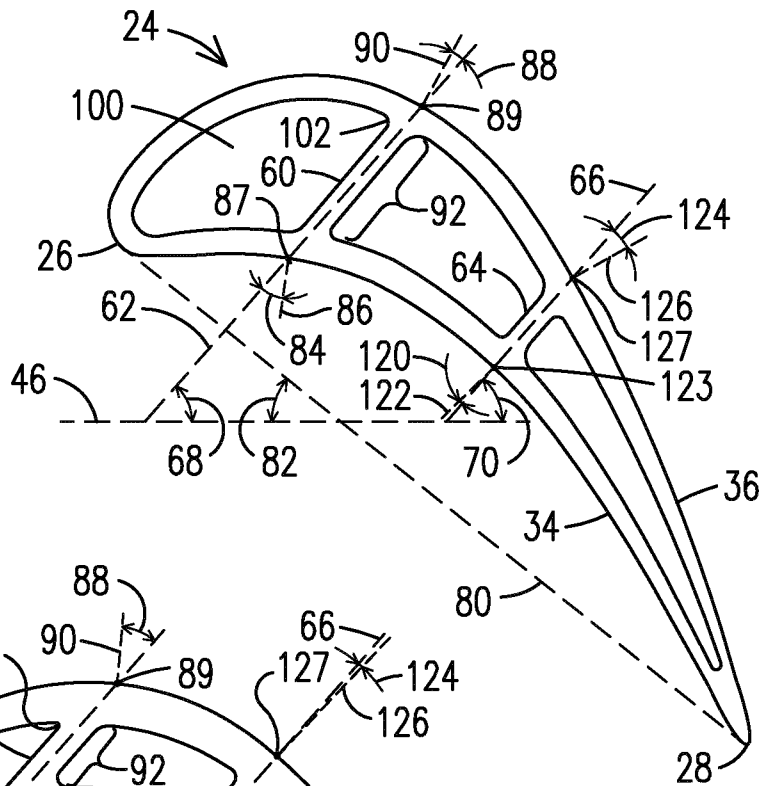
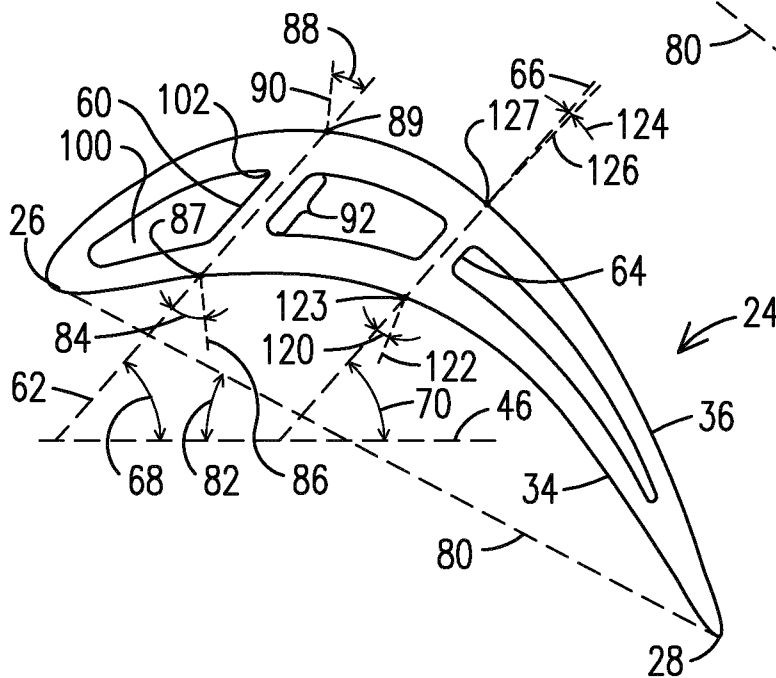


FIG. 3
PRIOR ART



3/6

FIG. 8

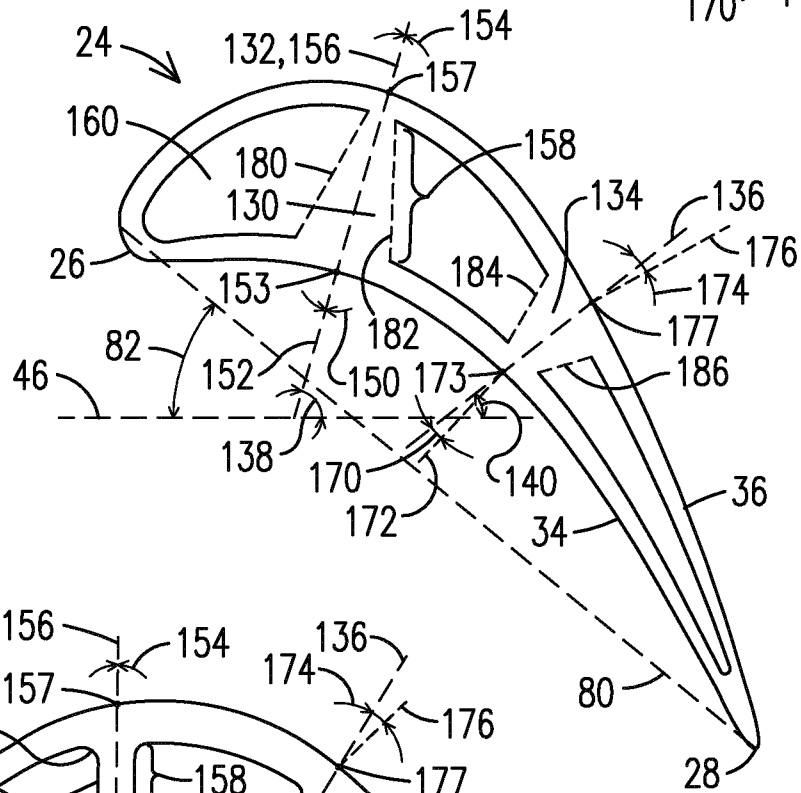
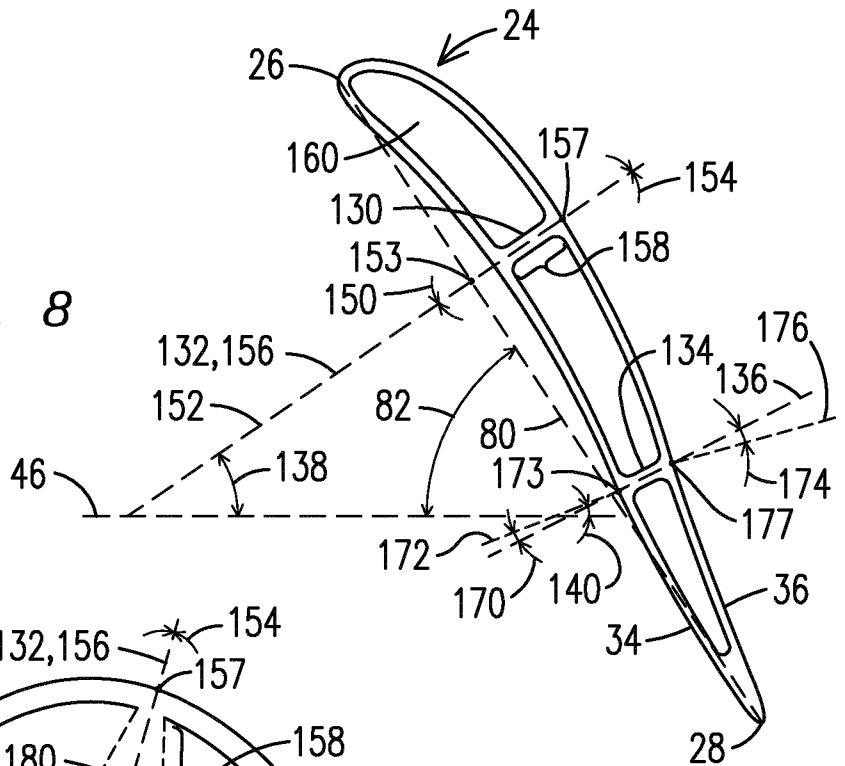


FIG. 7

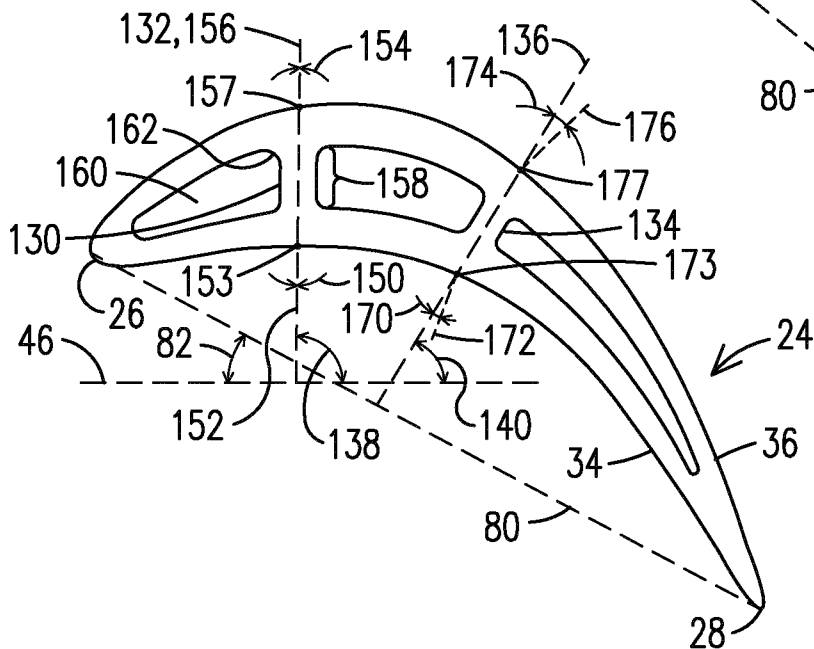


FIG. 6

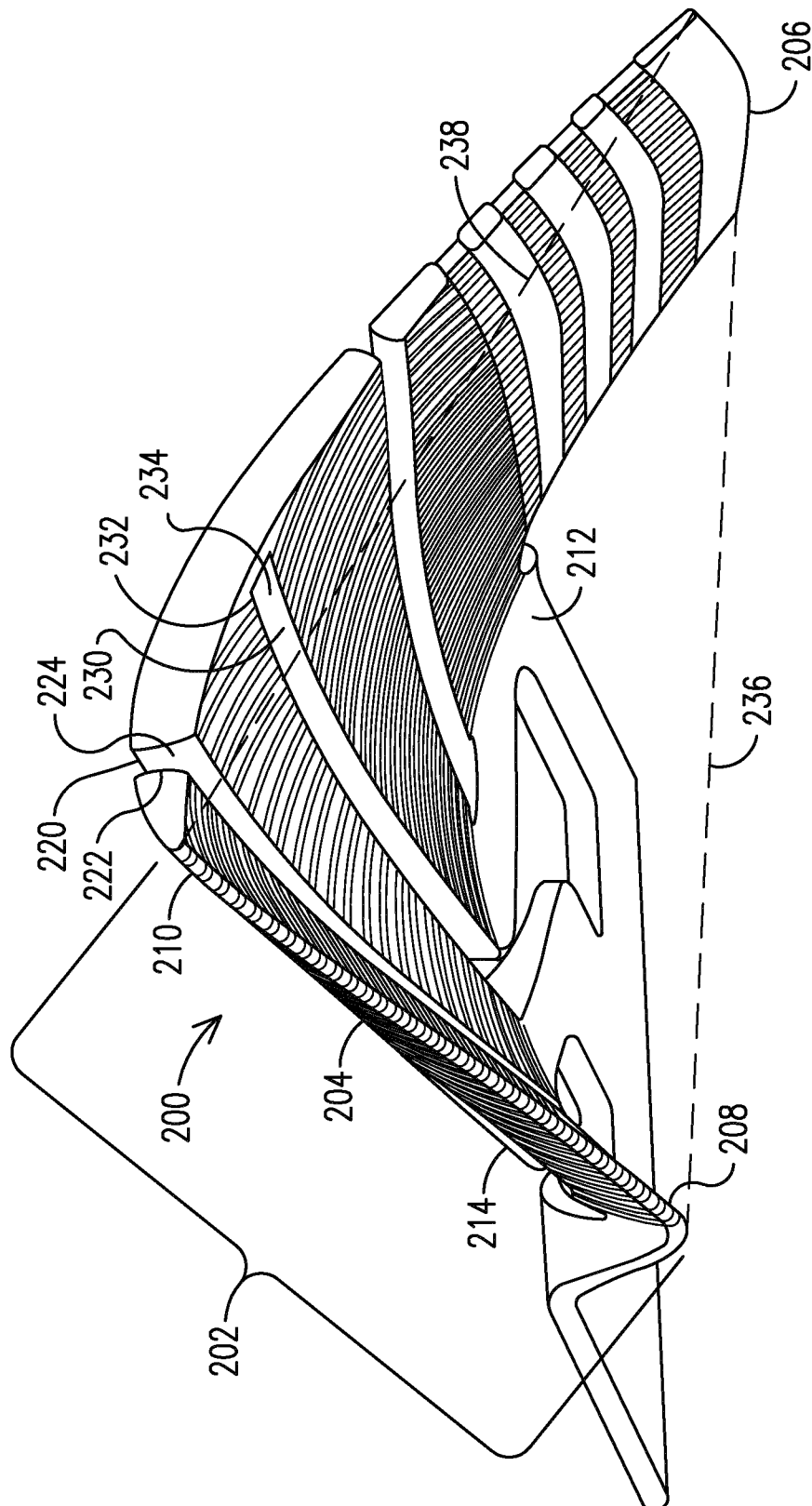


FIG. 9

5/6

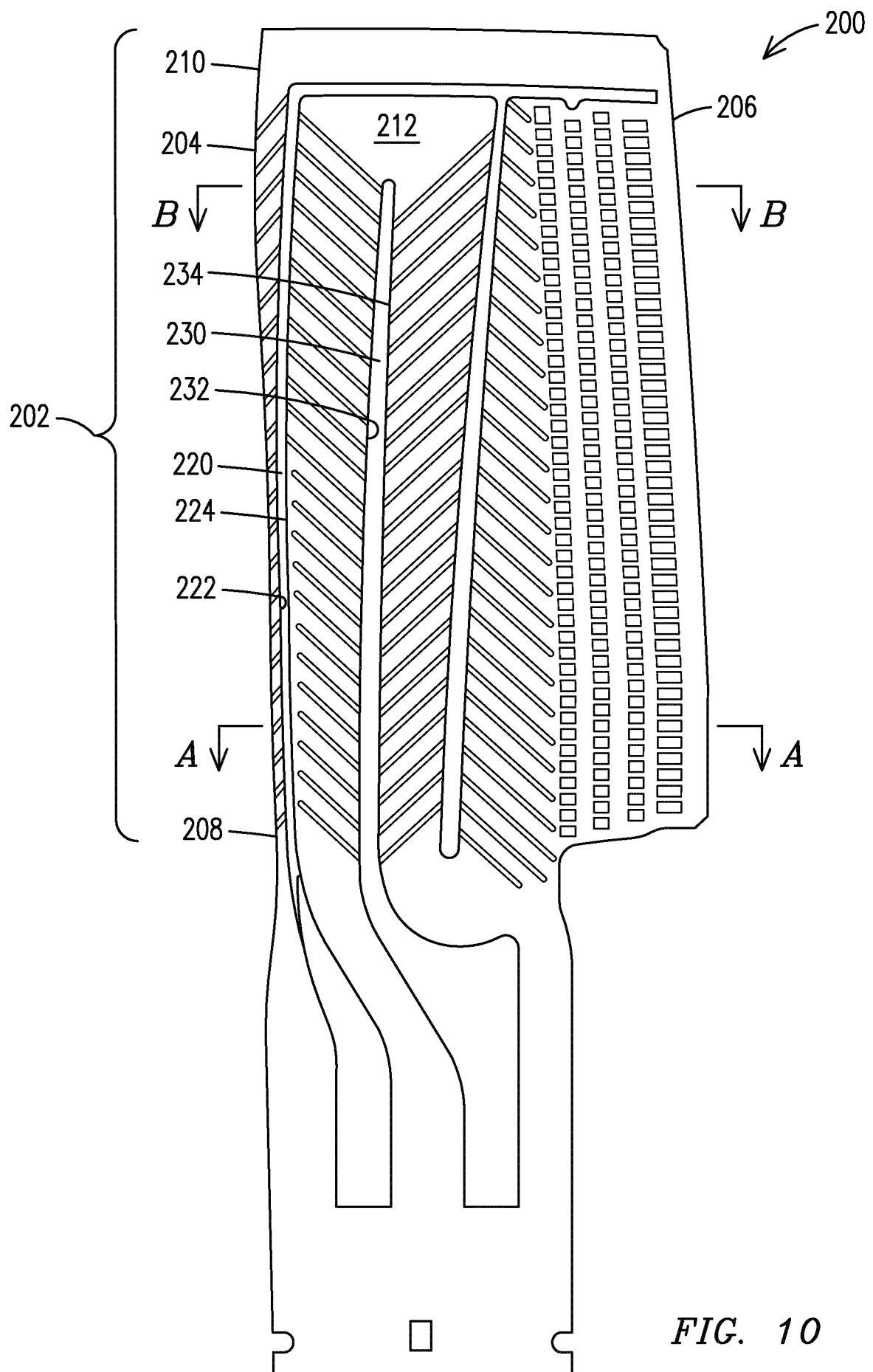
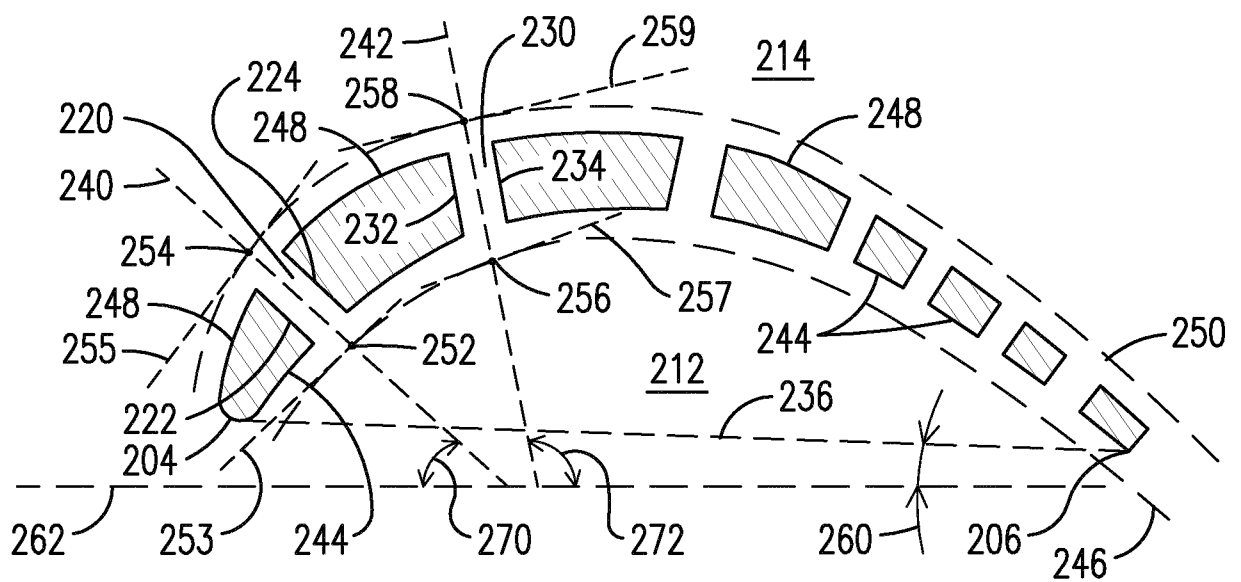
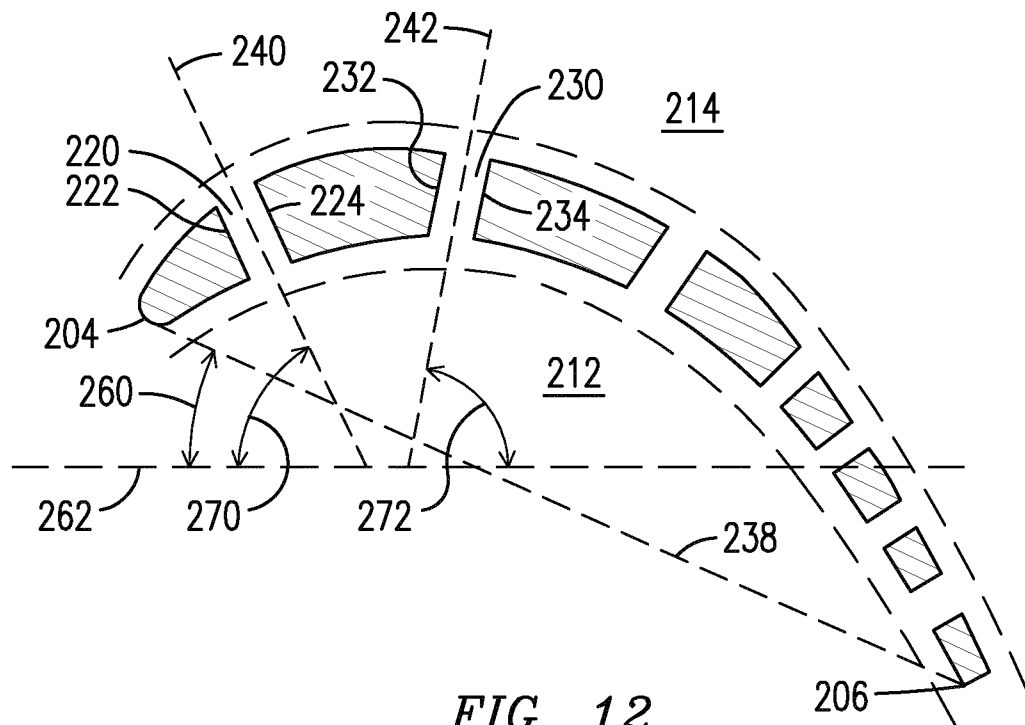


FIG. 10

6/6



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2014/051229

A. CLASSIFICATION OF SUBJECT MATTER
INV. B22C9/10 F01D5/18
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B22C F01D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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X	US 7 270 170 B2 (BEALS JAMES T [US] ET AL) 18 September 2007 (2007-09-18) paragraph [0024]; figures 2,3 -----	1-19
A	GB 2 462 087 A (ROLLS ROYCE PLC [GB]) 27 January 2010 (2010-01-27) figures 4,5 -----	1-19
A	US 6 206 638 B1 (GLYNN CHRISTOPHER C [US] ET AL) 27 March 2001 (2001-03-27) figures 7-10,13,14 -----	1-19



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See patent family annex.

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"&" document member of the same patent family

Date of the actual completion of the international search

15 April 2014

Date of mailing of the international search report

28/04/2014

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Authorized officer

Baumgartner, Robin

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2014/051229

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