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(54) **AIRFOIL TIP GEOMETRY TO REDUCE BLADE WEAR IN GAS TURBINE ENGINES**

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F04D 29/32 (2006.01)

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CPC ***F04D 29/324*** (2013.01); ***F04D 29/164*** (2013.01)

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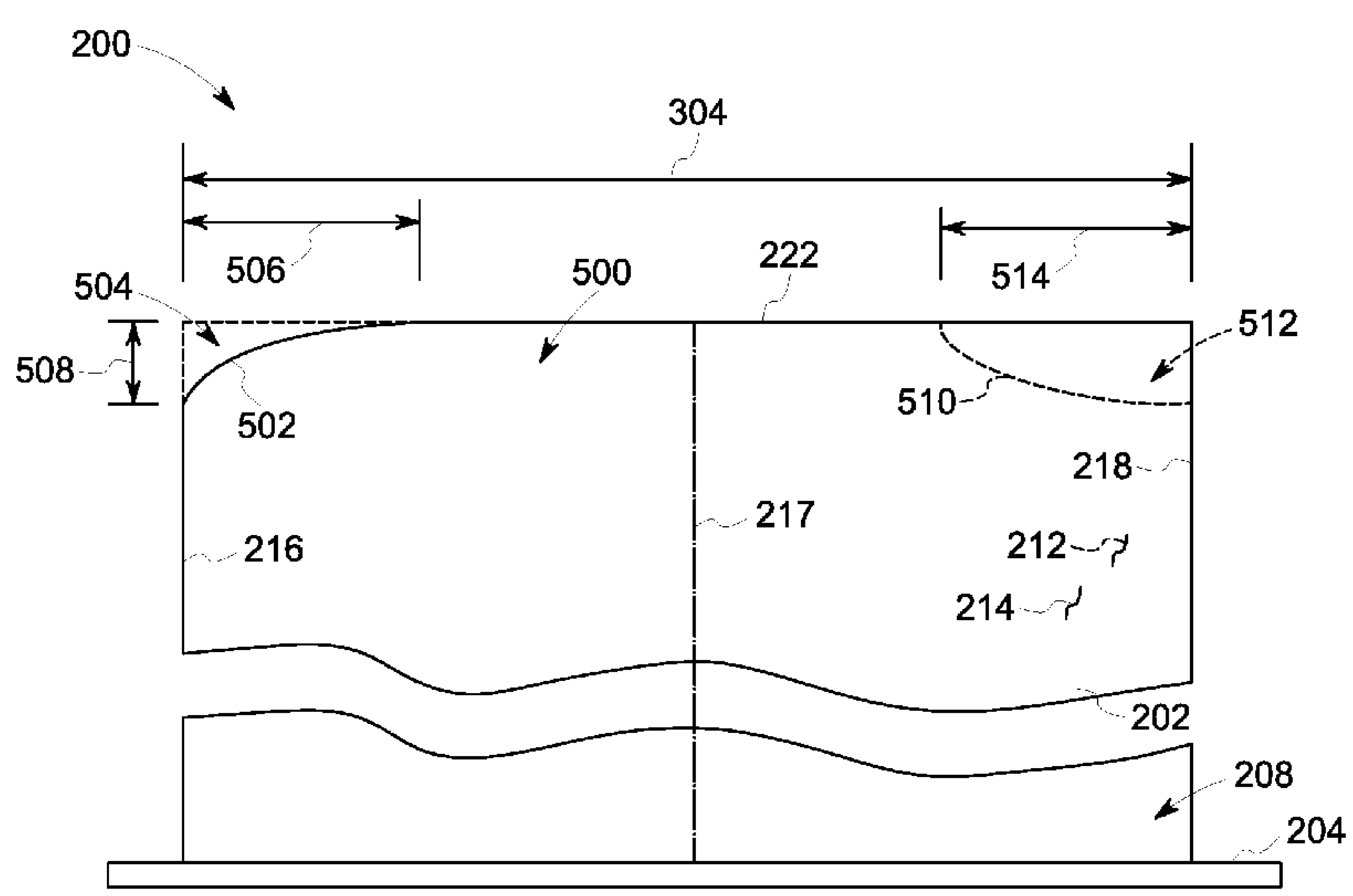
(57) **ABSTRACT**

An airfoil for use in a turbomachine includes a pressure sidewall and a suction sidewall coupled to the pressure sidewall. The suction sidewall and the pressure sidewall define a leading edge and an opposite trailing edge. The leading edge and the trailing edge define a chord distance. The airfoil further includes a root portion, and a tip portion. The tip portion extends between the pressure sidewall and the suction sidewall such that the tip portion is substantially perpendicular to each sidewall. The tip portion includes at least one planar section and at least one oblique section that forms a recess within the tip portion. The at least one oblique section extends from the at least one planar section towards the root portion along the chord distance. The tip portion is configured to reduce airfoil wear during contact with a surrounding casing.

19 Claims, 5 Drawing Sheets



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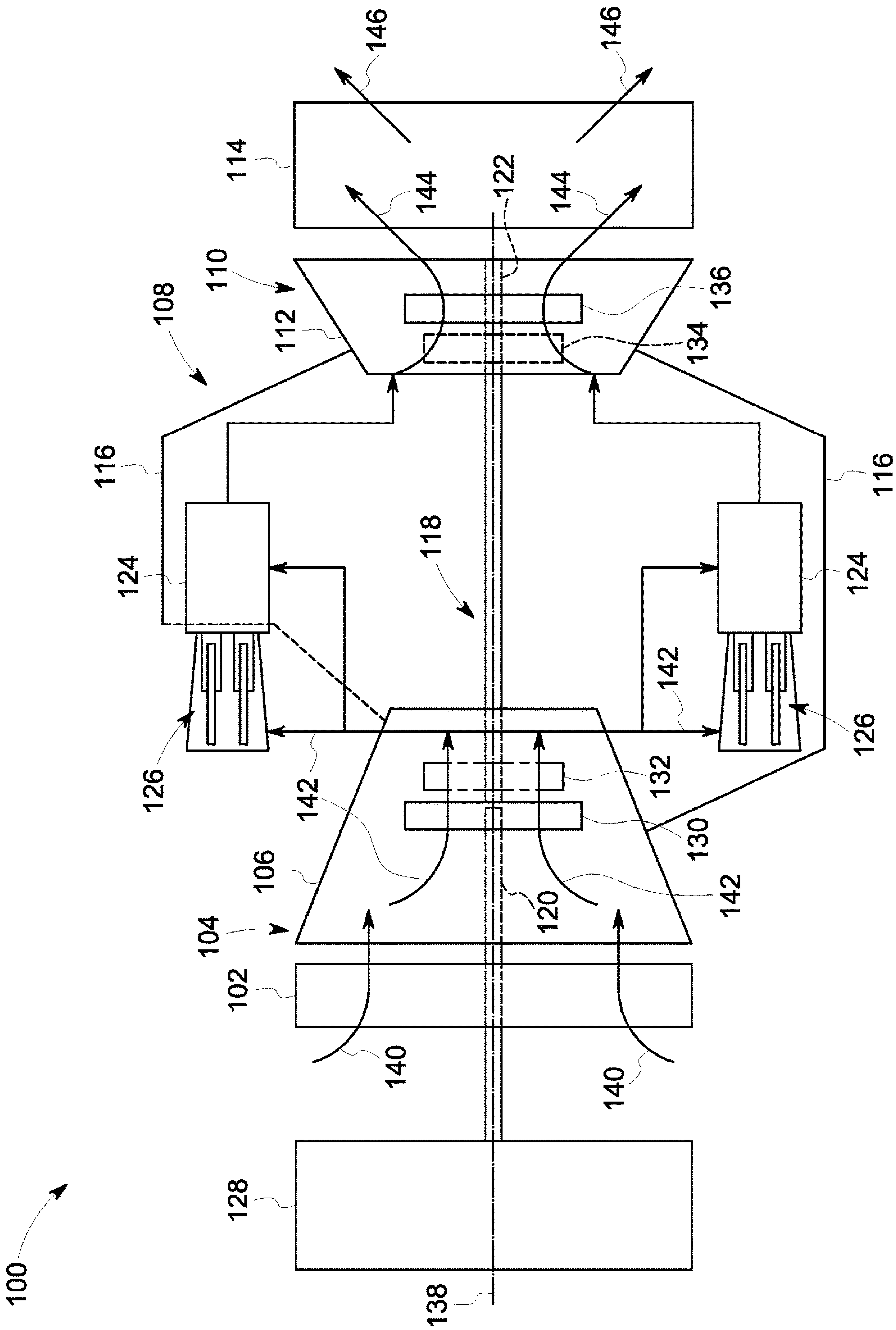
100
102
104
106
108
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118
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122
124
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136
138
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146
146

FIG. 1

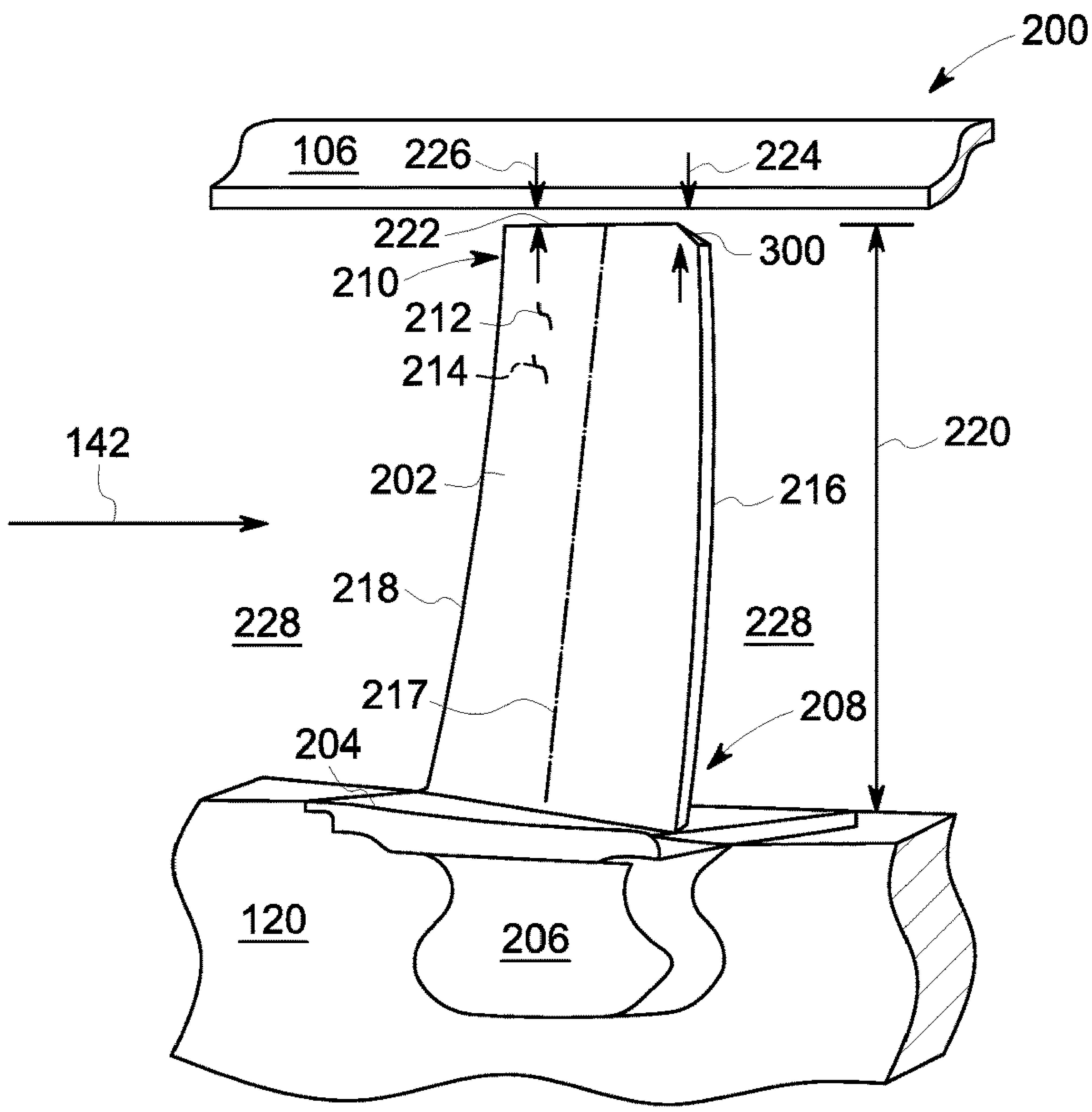

200
106
226
224
222
300
210
212
214
142
202
220
216
218
228
228
217
208
204
120
206

FIG. 2

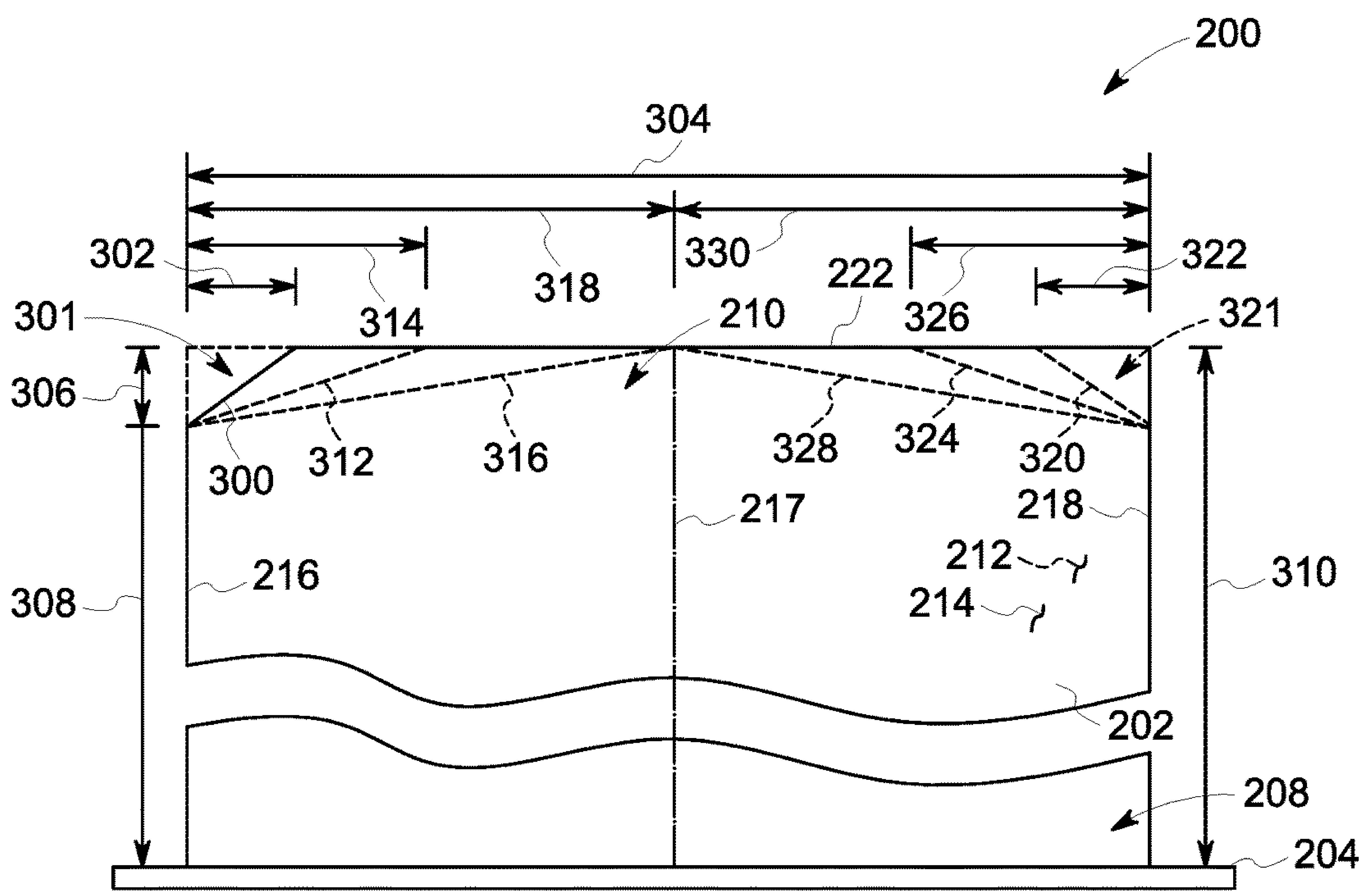
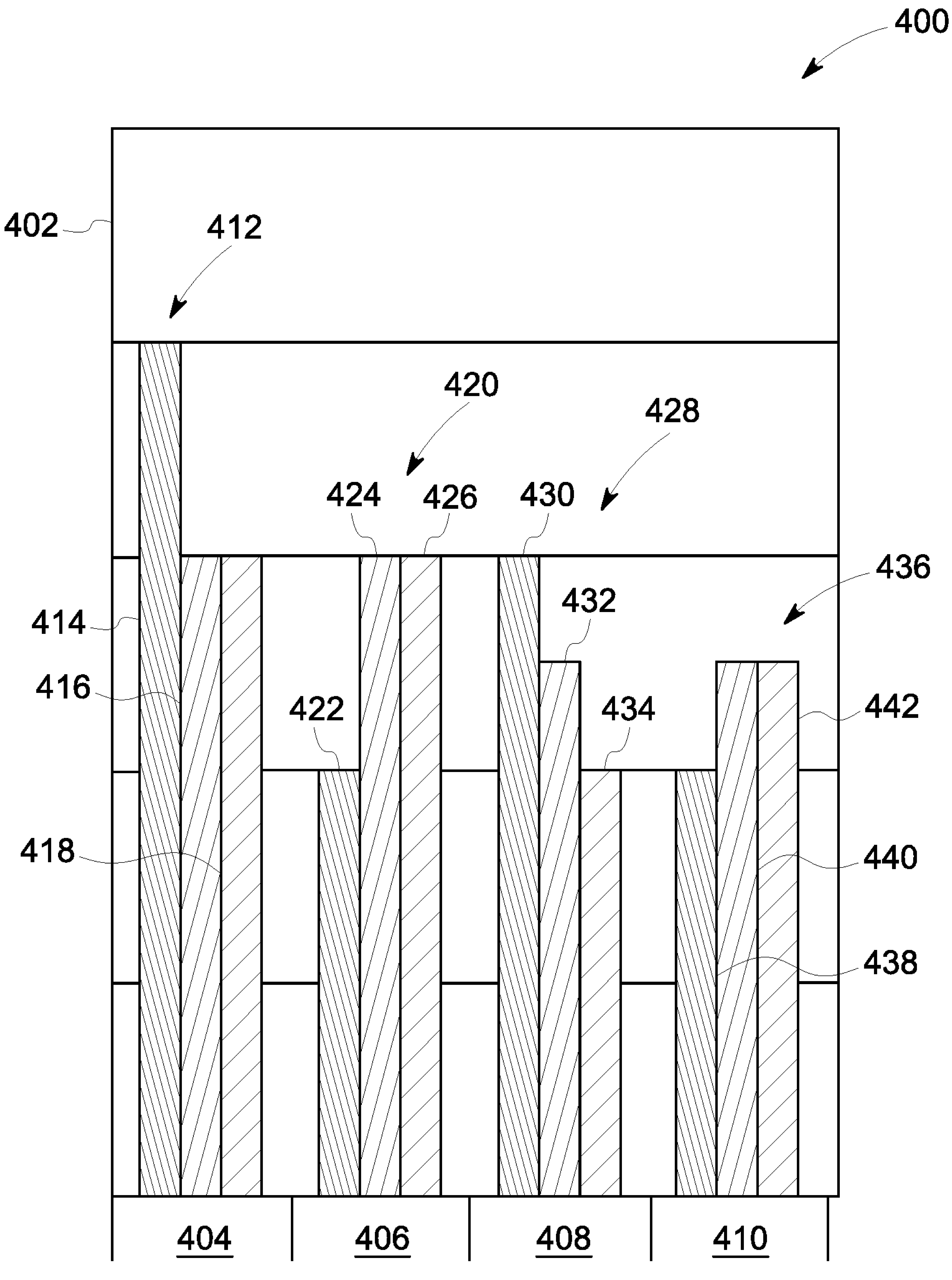

200
304
318
330
302
314
222
326
322
301
210
321
306
300
312
316
328
324
320
217
218
216
212
214
310
308
202
208
204

FIG. 3


400
402
412
420
428
424
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410

FIG. 4

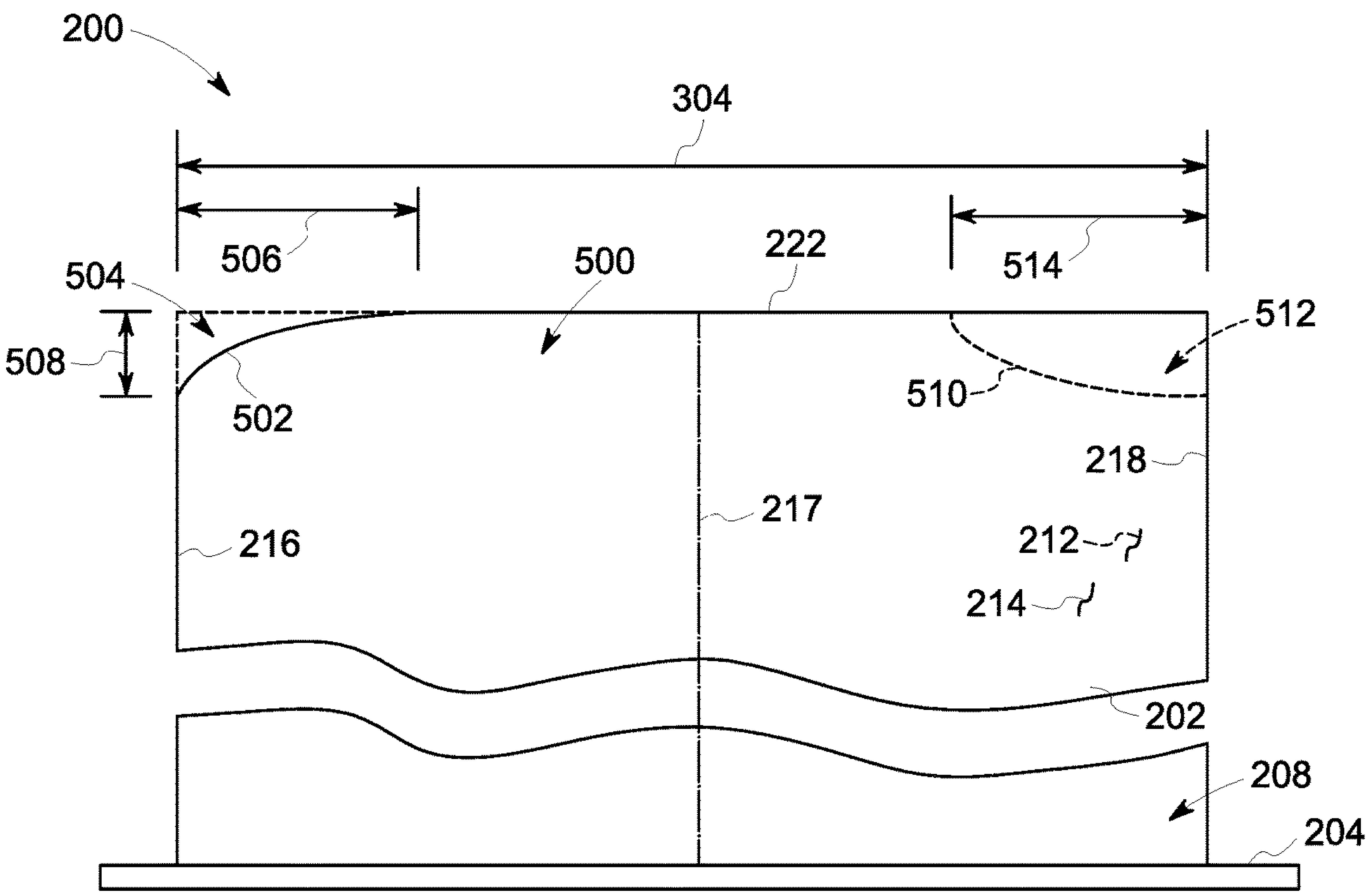
200
304
506
514
504
500
222
512
508
502
510
218
217
216
212
214
202
208
204

FIG. 5

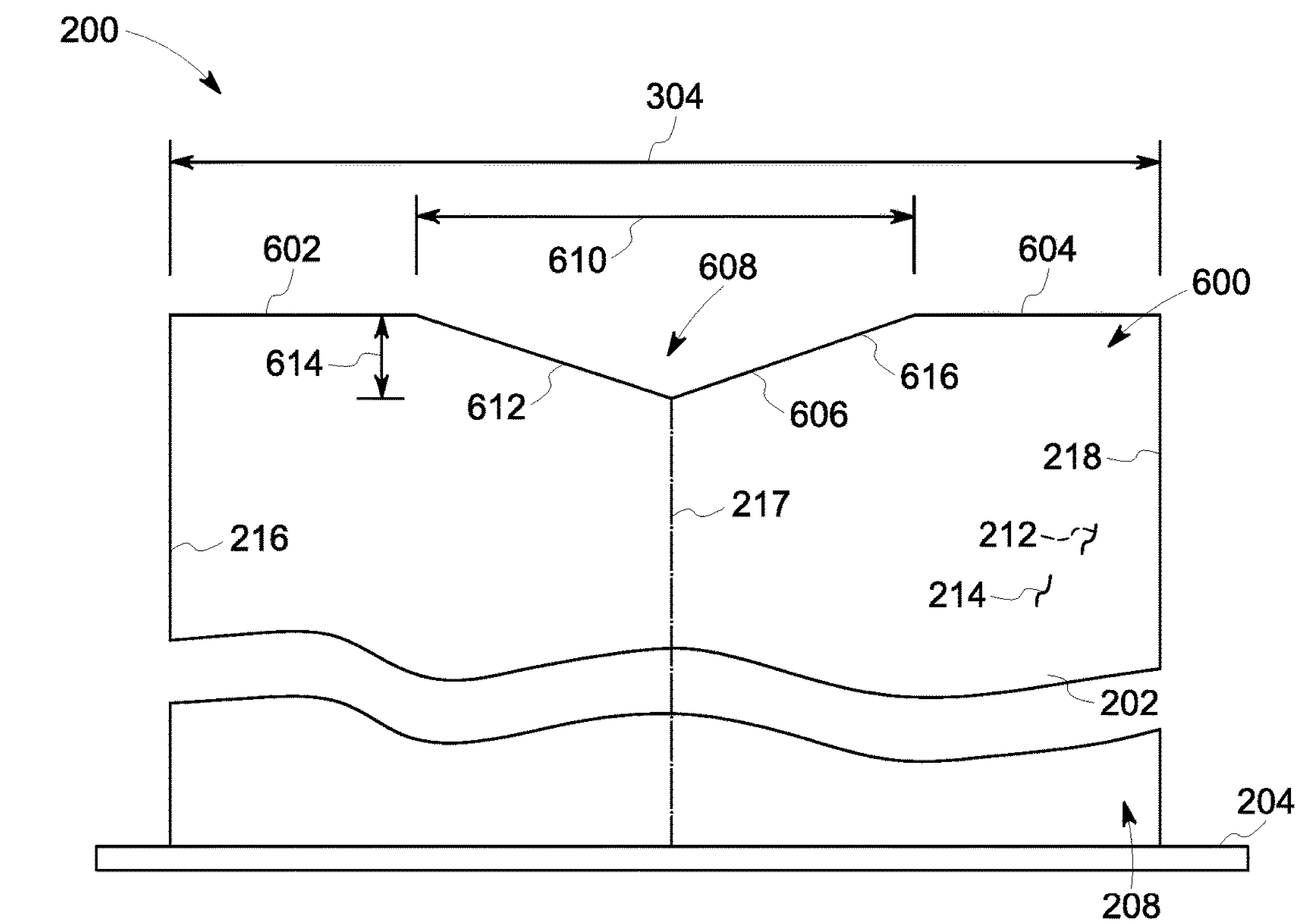
200
304
610
602
608
604
600
614
612
606
616
218
217
216
212
214
202
204
208

FIG. 6

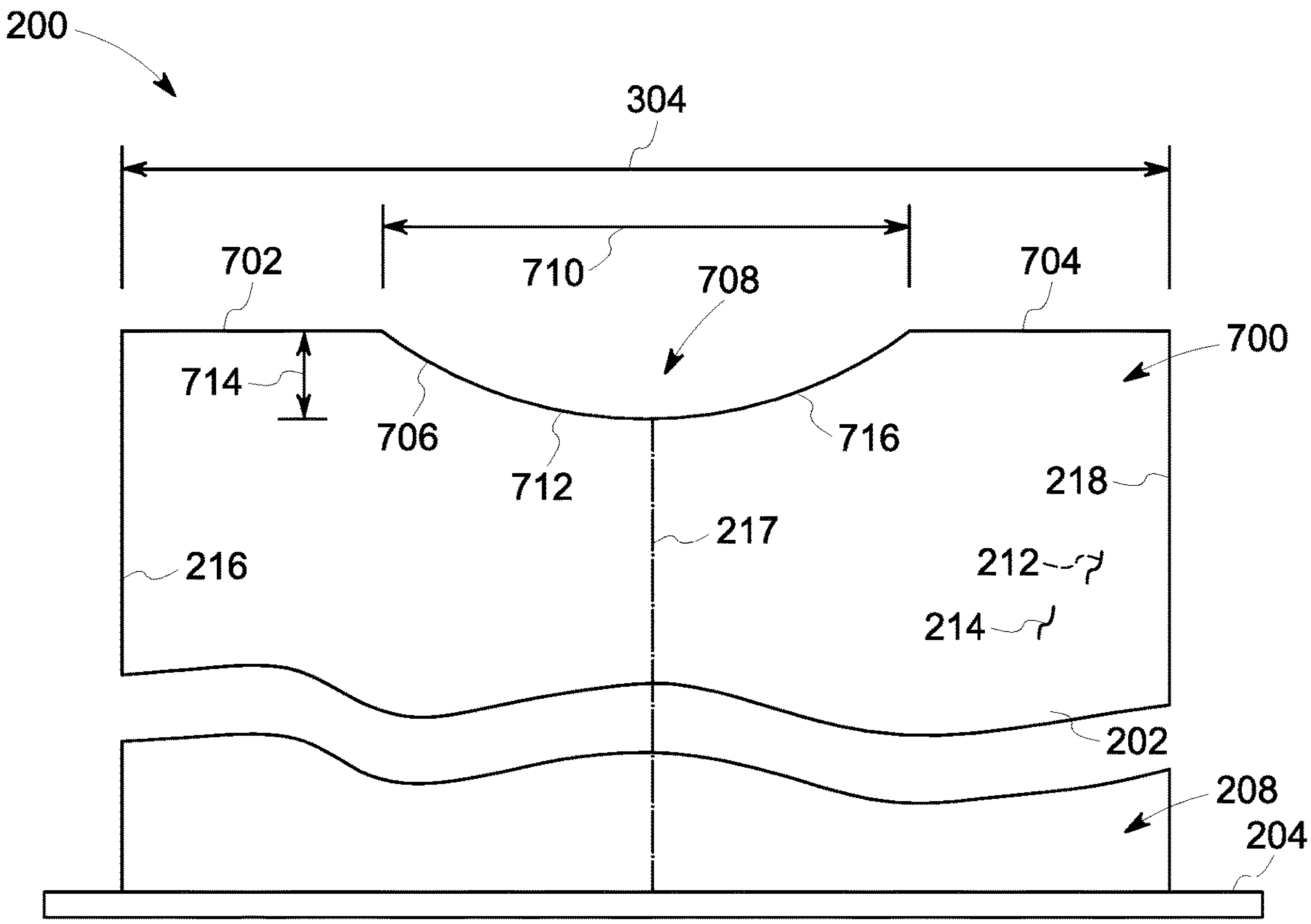
200
304
702
710
708
704
700
714
706
712
716
218
217
216
212
214
202
208
204

FIG. 7

AIRFOIL TIP GEOMETRY TO REDUCE BLADE WEAR IN GAS TURBINE ENGINES

BACKGROUND

The field of the disclosure relates generally to gas turbine engines and, more particularly, to airfoil tip geometry to reduce blade wear in gas turbine engines.

At least some known turbomachines, i.e., gas turbine engines, include a compressor that compresses air through a plurality of rotatable compressor blades enclosed within a compressor casing, and a combustor that ignites a fuel-air mixture to generate combustion gases. The combustion gases are channeled through rotatable turbine blades in a turbine through a hot gas path. Such known turbomachines convert thermal energy of the combustion gas stream to mechanical energy used to generate thrust and/or rotate a turbine shaft to power an aircraft. Output from the turbomachine may also be used to power a machine, such as, an electric generator, a compressor, or a pump.

Under some known operating conditions, rub events occur within the turbomachine, wherein a rotor blade tip contacts or rubs against the surrounding stationary casing inducing radial and tangential loads into a rotor blade airfoil. Generally during rub events, these loads cause the rotor blade to vibrate and deflect causing wear thereto. Excessive tip rub events cause wear to the rotor blade including, but not limited to, loss of blade material, which decreases turbomachine performance.

During tip rub events, the rotor blade is known to lose more material from the tip than the penetration distance into the casing. For example, if the blade tip penetrates the casing 1 mil (25.4 micrometers (μm)) then the blade tip is known to lose as much as 10 mils (254 μm) of material. The thickness of material lost in the blade tip divided by the penetration distance into the casing is known as a rub ratio. In the above example, the rub ratio would be 10:1, or known to have a rub ratio value of 10. Turbomachines with a high rub ratio are known to have decreased performance and decreased service life resulting in higher maintenance costs.

BRIEF DESCRIPTION

In one aspect, an airfoil for use in a turbomachine is provided. The airfoil includes a pressure sidewall and a suction sidewall coupled to the pressure sidewall, the suction sidewall and the pressure sidewall define a leading edge and an opposite trailing edge. The leading edge and the trailing edge define a chord distance. The airfoil further includes a root portion, and a tip portion. The tip portion extends between the pressure sidewall and the suction sidewall such that the tip portion is substantially perpendicular to each sidewall. The tip portion includes at least one planar section and at least one oblique section that forms a recess within the tip portion. The at least one oblique section extends from the at least one planar section towards the root portion to along the chord distance. The tip portion is configured to reduce airfoil wear during contact with a surrounding casing.

In a further aspect, a turbomachine is provided. The turbomachine includes a casing, and a rotor assembly, the casing at least partially extending about the rotor assembly. The rotor assembly includes a rotor shaft, and a plurality of rotor blades coupled to the rotor shaft. Each rotor blade of the plurality of rotor blades includes an airfoil including a pressure sidewall and a suction sidewall coupled to the pressure sidewall. The suction sidewall and the pressure

sidewall define a leading edge and an opposite trailing edge. The leading edge and the trailing edge define a chord distance. The airfoil further includes a root portion, and a tip portion. The tip portion extends between the pressure sidewall and the suction sidewall such that the tip portion is substantially perpendicular to each sidewall. The tip portion includes at least one planar section and at least one oblique section that forms a recess within said tip portion. The at least one oblique section slopes from the at least one planar section towards the root portion along the chord distance. The tip portion is configured to reduce rotor blade wear during contact with the casing.

In another aspect, a method for reducing blade wear during turbomachine operation is provided. The turbomachine includes a casing, a rotor shaft, and a plurality of rotor blades. Each rotor blade of the plurality of rotor blades includes an airfoil including a pressure sidewall and a suction sidewall coupled to the pressure sidewall. The suction sidewall and the pressure sidewall define a leading edge and an opposite trailing edge. The leading edge and the trailing edge define a chord distance. The airfoil further includes a root portion, and a tip portion. The tip portion extends between the pressure sidewall and the suction sidewall such that the tip portion is substantially perpendicular to each sidewall. The method includes removing blade material from the tip portion including forming a recess from at least one oblique section adjacent to at least one planar section on the tip portion. The at least one oblique section extends from the at least one planar section towards the root portion along the chord distance. The method further includes coupling the rotor blade to the rotor shaft such that during turbomachine operation, when the tip portion contacts the casing, wear of the rotor blade is reduced.

DRAWINGS

These and other features, aspects, and advantages of the present disclosure will become better understood when the following detailed description is read with reference to the accompanying drawings in which like characters represent like parts throughout the drawings, wherein:

FIG. **1** is a schematic diagram of an exemplary turbomachine, i.e., a turbofan;

FIG. **2** is a perspective view of an exemplary rotor blade that may be used within the turbomachine shown in FIG. **1**;

FIG. **3** is a schematic view of an exemplary tip portion of the rotor blade shown in FIG. **2**;

FIG. **4** is a graphical view of operational features of the tip portion shown in FIG. **3**;

FIG. **5** is a schematic view of an alternative tip portion that may be used with the rotor blade shown in FIG. **2**;

FIG. **6** is a schematic view of another alternative tip portion that may be used with the rotor blade shown in FIG. **2**; and

FIG. **7** is a schematic view of a further alternative tip portion that may be used with the rotor blade shown in FIG. **2**.

Unless otherwise indicated, the drawings provided herein are meant to illustrate features of embodiments of this disclosure. These features are believed to be applicable in a wide variety of systems comprising one or more embodiments of this disclosure. As such, the drawings are not meant to include all conventional features known by those of ordinary skill in the art to be required for the practice of the embodiments disclosed herein.

DETAILED DESCRIPTION

In the following specification and claims, reference will be made to a number of terms, which shall be defined to have the following meanings.

The singular forms “a”, “an”, and “the” include plural references unless the context clearly dictates otherwise.

“Optional” or “optionally” means that the subsequently described event or circumstance may or may not occur, and that the description includes instances where the event occurs and instances where it does not.

Approximating language, as used herein throughout the specification and claims, may be applied to modify any quantitative representation that could permissibly vary without resulting in a change in the basic function to which it is related. Accordingly, a value modified by a term or terms, such as “about”, “approximately”, and “substantially”, are not to be limited to the precise value specified. In at least some instances, the approximating language may correspond to the precision of an instrument for measuring the value. Here and throughout the specification and claims, range limitations may be combined and/or interchanged, such ranges are identified and include all the sub-ranges contained therein unless context or language indicates otherwise.

Rotor blade tip geometries as described herein provide a method for reducing blade wear in a turbomachine. Specifically, a rotor blade includes an airfoil having a suction sidewall coupled to a pressure sidewall at a leading edge and a trailing edge. A tip portion extends between the suction sidewall and the pressure sidewall and includes a planar section and an oblique section. In some embodiments, the tip portion includes a first oblique section and a second oblique section. Modifying the rotor blade tip geometry by grinding the tip portion and forming the oblique section reduces the rub ratio of the rotor blade, and thereby, the wear of the rotor blade. Specifically, the oblique section is sized such that a contact area between the rotor blade and a surrounding casing is reduced, thereby decreasing the radial and tangential loads induced into the rotor blade during a rub event. Reducing the loads resulting from a rub event decreases vibration and deflection of the rotor blade and reduces material loss at the tip portion. Furthermore, modifying the rotor blade tip geometry changes the vibratory modes of the rotor blade such that radial elongation is decreased further reducing material loss at the tip portion. Additionally, a reduction in radial deflection allows the rotor blade to be positioned closer to the surrounding casing. Accordingly, decreasing the rub ratio of the rotor blade decreases wear and material loss during a rub event, increases turbomachine performance, and reduces maintenance costs.

As used herein, the terms “axial”, and “axially”, refer to directions and orientations which extend substantially parallel to a centerline **138**, as shown in FIG. **1**, of a turbine engine. Moreover, the terms “radial”, and “radially”, refer to directions and orientations which extend substantially perpendicular to centerline **138** of the turbine engine. In addition, as used herein, the terms “circumferential”, and “circumferentially”, refer to directions and orientations which extend arcuately about centerline **138** of the turbine engine. The term “fluid”, as used herein, includes any medium or material that flows, including, but not limited to, air.

FIG. **1** is a schematic view of a turbomachine **100**, i.e., a gas turbine engine, and more specifically, an aircraft engine or turbofan. In the exemplary embodiment, turbomachine **100** includes an air intake section **102**, and a compressor section **104** that is coupled downstream from, and in flow communication with, intake section **102**. Compressor section **104** is enclosed within a compressor casing **106**. A combustor section **108** is coupled downstream from, and in flow communication with, compressor section **104**, and a turbine section **110** is coupled downstream from, and in flow communication with, combustor section **108**. Turbine section **110** is enclosed within a turbine casing **112** and includes an exhaust section **114** that is downstream from turbine section **110**. A combustor housing **116** extends about combustor section **108** and is coupled to compressor casing **106** and turbine casing **112**. Moreover, in the exemplary embodiment, turbine section **110** is coupled to compressor section **104** through a rotor assembly **118** that includes, without limitation, a compressor rotor, or drive shaft **120** and a turbine rotor, or drive shaft **122**.

In the exemplary embodiment, combustor section **108** includes a plurality of combustor assemblies, i.e., combustors **124** that are each coupled in flow communication with compressor section **104**. Combustor section **108** also includes at least one fuel nozzle assembly **126**. Each combustor **108** is in flow communication with at least one fuel nozzle assembly **126**. Moreover, in the exemplary embodiment, turbine section **110** and compressor section **104** are rotatably coupled to a fan assembly **128** through drive shaft **120**. Alternatively, turbomachine **100** may be a gas turbine engine and for example, and without limitation, be rotatably coupled to an electrical generator and/or a mechanical drive application, e.g., a pump. In the exemplary embodiment, compressor section **104** includes at least one compressor stage that includes a compressor blade assembly **130** and an adjacent stationary stator vane assembly **132**. Each compressor blade assembly **130** includes a plurality of circumferentially spaced blades (not shown) and is coupled to rotor assembly **118**, or, more specifically, compressor drive shaft **120**. Each stator vane assembly **132** includes a plurality of circumferentially spaced stator vanes (not shown) and is coupled to compressor casing **106**. Also, in the exemplary embodiment, turbine section **110** includes at least one turbine blade assembly **134** and at least one adjacent stationary nozzle assembly **136**. Each turbine blade assembly **134** is coupled to rotor assembly **118**, or, more specifically, turbine drive shaft **122** along a centerline **138**.

In operation, air intake section **102** channels air **140** towards compressor section **104**. Compressor section **104** compresses air **140** to higher pressures and temperatures prior to discharging compressed air **142** towards combustor section **108**. Compressed air **142** is channeled to fuel nozzle assembly **126**, mixed with fuel (not shown), and burned within each combustor **124** to generate combustion gases **144** that are channeled downstream towards turbine section **110**. After impinging turbine blade assembly **134**, thermal energy is converted to mechanical rotational energy that is used to drive rotor assembly **118**. Turbine section **110** drives compressor section **104** and/or fan assembly **128** through drive shafts **120** and **122**, and exhaust gases **146** are discharged through exhaust section **114** to the ambient atmosphere.

FIG. **2** is a perspective view of an exemplary rotor blade **200**, and more specifically, a compressor blade, that may be found within turbomachine **100** (shown in FIG. **1**). In the exemplary embodiment, rotor blade **200** includes an airfoil **202**, a platform **204**, and a dovetail **206** that is used for mounting rotor blade **200** to compressor drive shaft **120** (shown in FIG. **1**). Airfoil **202** includes a root portion **208**, adjacent platform **204**, and an opposite tip portion **210**. Further, airfoil **202** includes a pressure sidewall **212** and an opposite suction sidewall **214**. In the exemplary embodiment, pressure sidewall **212** is substantially concave and suction sidewall **214** is substantially convex. Pressure sidewall **212** is coupled to suction sidewall **214** at a leading edge **216** and at an axially spaced trailing edge **218**. Trailing edge **218** is spaced chord-wise and downstream from leading edge **216**. Pressure sidewall **212** and suction sidewall **214** each extend longitudinally or radially outward in a length **220** from root portion **208** to blade tip portion **210**. Along a chord of blade **200**, a mid-chord line **217** is defined at the mid-point of the chord. Tip portion **210** is defined between sidewalls **212** and **214** and includes a planar section **222** that is defined as the radially outer surface of blade **200** and substantially perpendicular to each sidewall **212** and **214**. Tip portion **210** also includes an oblique section **300** adjacent to planar section **222** and described further below in reference to FIG. **3**. In an alternative embodiment, rotor blade **200** may have any other configuration that enables turbomachine to function as described herein.

In the exemplary embodiment, compressor casing **106** circumferentially extends around rotor blade **200**, and tip portion **210**. Specifically, tip portion **210** at leading edge **216** and oblique section **300** has a gap distance **224** that is substantially not equal to a gap distance **226** of tip portion **210** at trailing edge **218** and planar section **222**. Furthermore, a flow path **228** for compressed air **142** (shown in FIG. **1**) is defined between compressor casing **106** and shaft **120**.

During operation, rotor blade **200** rotates within casing **106** about centerline **138** (shown in FIG. **1**). In some operating conditions, such as an imbalanced load, rotor blade **200**, specifically tip portion **210**, contacts or rubs against casing **106**, which is also known as a rub event. Specifically, tip portion **210** is jammed into casing **106**, such that radial and tangential loads are induced into rotor blade **200**. Generally during rub events, these loads cause rotor blade **200** to vibrate and deflect causing wear thereto. The deflection of rotor blade **200**, at least in part, depends on the vibratory modes of the blade that are excited during the rub event. Some vibratory modes are known to increase radial elongation of rotor blade **200** resulting in an increased amount of wear to tip portion **210**.

At least some of the wear rotor blade **200** incurs during the rub event includes material loss from tip portion **210**. Specifically, when tip portion **210** contacts casing **106**, rotor blade **200** loses material at tip portion **210** such that overall length **220** is reduced. A rub ratio is a value that may be used to quantify the amount of wear rotor blade **200** experiences during the rub event. A rub ratio is defined as a thickness of material lost from tip portion **210** during a rub event divided by an amount of penetration by tip portion **210** into casing **106**. For example, if tip portion **210** penetrates into the casing 1 mil (25 μm) and 10 mils (101 μm) of blade material is lost from tip portion **210**, the rub ratio is 10.

FIG. **3** is a schematic view of an exemplary tip portion **210** for use with rotor blade **200**. In the exemplary embodiment, tip portion **210** includes planar section **222** that extends from pressure sidewall **212** to suction sidewall **214** and substantially perpendicular thereto. Additionally, tip portion **210** includes an oblique section **300** that slopes from planar section **222** inwards towards root portion **208** to leading edge **216** forming a recess **301**. Oblique section **300** also extends from pressure sidewall **212** to suction sidewall **214** and is substantially perpendicular thereto. In the exemplary embodiment, oblique section **300** extends a distance **302** along tip portion **210**. Specifically, oblique section **300** extends along tip portion **210** from leading edge **216** within a range from approximately 5% to approximately 50% of a chord distance **304** of airfoil **202**. For example, oblique section **300** extends along tip portion **210** from leading edge **216** within a range from approximately 5% to approximately 15% of a chord distance **304** of airfoil **202**. More specifically, in the illustrated embodiment, oblique section **300** extends along tip portion **210** from leading edge **216** approximately 15% of chord distance **304**. Oblique section **300** also has a depth **306** from planar section **222** such that a length **308** of leading edge **216** that extends from tip portion **210** to root portion **208** is shorter than a length **310** of trailing edge **218** from tip portion **210** to root portion **208**. Said another way, distance **224** (shown in FIG. **2**) between casing **106** (shown in FIG. **2**) and leading edge **216** is greater than distance **226** (shown in FIG. **2**) between casing **106** and trailing edge **218**. In the exemplary embodiment, depth **306** is within a range including approximately 2 mils (51 μm) to approximately 5 mils (127 μm). In alternative embodiments, depth **306** may have any other distance that enables tip portion **210** to function as described herein.

In some embodiments, for example, oblique section **300** is formed at line **312** that extends a distance **314** along tip portion **210** from leading edge **216** within a range from approximately 15% to approximately 30% of chord distance **304** forming recess **301**. Specifically, in the illustrated embodiment, oblique section line **312** extends approximately 30% of chord distance **304** from leading edge **216**. Extending recess **301** further from leading edge **216**, such as with oblique section line **312**, reduces the area of planar section **222** that contacts with casing **106** during a rub event thereby lowering the contact force between rotor blade **200** and casing **106**. In other embodiments, for example, oblique section **300** is formed at line **316** that extends a distance **318** along tip portion **210** from leading edge **216** within a range from approximately 30% to approximately 50% of chord distance **304** forming recess **301**. Specifically, in the illustrated embodiment, oblique section line **316** extends approximately 50% of chord distance **304** from leading edge **216**. Extending recess **301** further from leading edge **216**, such as with oblique section line **316**, further reduces the area of planar section **222** that contacts with casing **106** during a rub event thereby lowering the contact force between rotor blade **200** and casing **106**. In further embodiments, oblique section **300** may extend any other distance along tip portion **210** from leading edge **216** that enables tip portion **210** to function as described herein.

Additionally, in some embodiments, an oblique section **320** is defined from trailing edge **218** such that a length of trailing edge **218** from tip portion **210** to root portion **208** is shorter than a length of leading edge from tip portion **210** to root portion **208**. Said another way, distance **226** between casing **106** and trailing edge **218** is greater than distance **224** between casing **106** and leading edge **216**. In the exemplary embodiment, oblique section **320** extends along tip portion **210** from trailing edge **218** within a range from approximately 5% to approximately 50% of chord distance **304** of airfoil **202**. For example, oblique section **320** extends a distance **322** from trailing edge **218** within a range from approximately 5% to approximately 15% of chord distance **304** forming a recess **321**. Specifically, in the illustrated embodiment, oblique section **320** extends approximately 15% of chord distance **304** from trailing edge **218**. In other embodiments, for example, oblique section **320** is formed at line **324** that extends a distance **326** from trailing edge **218** within a range from approximately 15% to approximately 30% of chord distance **304** forming recess **321**. Specifically, in the illustrated embodiment, oblique section line **324** extends approximately 30% of chord distance **304** from trailing edge **218**. Extending recess **321** further from trailing edge **216**, such as with oblique section line **324**, reduces the area of planar section **222** that contacts with casing **106** during a rub event thereby lowering the contact force between rotor blade **200** and casing **106**. In yet other embodiments, for example, oblique section **320** is formed at line **328** that extends a distance **330** from trailing edge **218** within a range from approximately 30% to approximately 50% of chord distance **304** forming recess **321**. Specifically, in the illustrated embodiment, oblique section line **328** extends approximately 50% of chord distance **304** from trailing edge **218**. Extending recess **321** further from trailing edge **218**, such as with oblique section line **328**, reduces the area of planar section **222** that contacts with casing **106** during a rub event thereby lowering the contact force between rotor blade **200** and casing **106**. In alternative embodiments, oblique section **320** extends any other distance along tip portion **210** from trailing edge **218** that enables tip portion **210** to function as described herein.

Furthermore, in some embodiments, tip portion **210** includes oblique sections on both leading edge **216** and trailing edge **218**. For example, tip portion **210** includes oblique section **300** and oblique section **320** such that a length of leading edge **216** from tip portion **210** to root portion **208** is substantially equal to a length of trailing edge **218** from tip portion **210** to root portion **208**. Said another way, distance **224** between casing **106** and leading edge **216** is substantially equal to distance **226** between casing **106** and trailing edge **218**.

In the exemplary embodiment, oblique section **300** is formed by grinding tip portion **210** and removing rotor blade **200** material in a machine shop using known machining techniques. Alternatively, oblique section **300** can be formed by any other method that enables rotor blade **200** to function as described herein.

FIG. **4** is a graphical view, i.e., chart **400**, of operational features of tip portion **210** shown in FIGS. **2-3**. Specifically, chart **400** illustrates a rub ratio value for four different tip geometries of tip portion **210** (shown in FIG. **3**). The rub ratio is defined as a thickness of material lost from tip portion **210** during a rub event divided by an amount of penetration by tip portion **210** into casing **106** as described in reference to FIG. **2**. Chart **400** includes a y-axis **402** defining the rub ratio value on a linear scale. Along the x-axis, four different tip geometries are shown: a baseline geometry **404**, which includes planar section **222** (shown in FIG. **3**) that extends the full length of tip portion **210** from leading edge **216** (shown in FIG. **3**) to trailing edge **218** (shown in FIG. **3**); a first geometry **406**, which includes oblique section **300** (shown in FIG. **3**) adjacent to leading edge **216**; a second geometry **408**, which includes oblique section **320** (shown in FIG. **3**) adjacent to trailing edge **218**; and a third geometry **410**, which includes both oblique sections **300** and **320**.

In the exemplary chart **400**, each tip geometry **404**, **406**, **408**, and **410** is subjected to a rub event with casing **106** (shown in FIG. **1**) and a thickness of material loss at each of leading edge **216**, mid-chord line **217** (shown in FIG. **3**), and trailing edge **218** are recorded. Then the rub ratio at each leading edge **216**, mid-chord line **217**, and trailing edge **218** are determined. Chart **400** includes a first group of bars **412** that represents the rub ratio for tip portion **210** with baseline geometry **404**. A leftmost bar **414** represents the rub ratio at leading edge **216** of baseline geometry **404**, a middle bar **416** represents the rub ratio at mid-chord line **217**, and a rightmost bar **418** represents the rub ratio at trailing edge **218**.

Further, in the exemplary chart **400**, a second group of bars **420** represents the rub ratio for tip portion **210** with first tip geometry **406**. A leftmost bar **422** represents the rub ratio at leading edge **216** which is less than the rub ratio of baseline geometry **404** thereby reducing wear to tip portion **210** during a rub event. A middle bar **424** represents the rub ratio at mid-chord line **217**, and a rightmost bar **426** represents the rub ratio at trailing edge **218**.

A third group of bars **428** represents the rub ratio for tip portion **210** with second tip geometry **408**. A leftmost bar **430** represents the rub ratio at leading edge **216**, a middle bar **432** represents the rub ratio at mid-chord line **217**, and a rightmost bar **434** represents the rub ratio at trailing edge **218**. At each location, leading edge **216**, mid-chord line **217**, and trailing edge **218**, the rub ratio is less than baseline geometry **404** thereby reducing wear of tip portion **210** during a rub event.

A fourth group of bars **436** represents the rub ratio for tip portion **210** with third tip geometry **410**. A leftmost bar **438** represents the rub ratio at leading edge **216**, a middle bar **440** represents the rub ratio at mid-chord line **217**, and a rightmost bar **442** represents the rub ratio at trailing edge **218**. At each location, leading edge **216**, mid-chord line **217**, and trailing edge **218**, the rub ratio is lower than baseline geometry **404** thereby reducing wear of tip portion **210** during a rub event.

As shown in chart **400**, modifying the geometry of tip portion **210** and grinding an oblique section, such as oblique section **300** and/or **320** into tip portion **210**, reduces the wear of rotor blade **200** (shown in FIG. **3**) when compared to baseline geometry **404** without the oblique section. Specifically, modifying tip portion **210** geometry reduces the rub ratio of blade **200**. For example, oblique section **300** within tip portion **210** alters the way in which blade **200** contacts casing **106** during a rub event. Oblique section **300** lowers the contact force between rotor blade **200** and casing **106** thereby reducing vibration and deflection. By reducing the radial and tangential loads induced into rotor blade **200**, vibration is reduced, thereby reducing radial elongation of rotor blade **200**. Additionally, modifying the geometry of tip portion **210** also modifies the vibratory modes that contribute to radial elongation within blade **200**. Reducing radial elongation within rotor blade **200** decreases the amount of material loss due to rubbing against casing **106** and thus wear of rotor blade **200**. In alternative embodiments, modifying the geometry of tip portion **210** results in different rub ratio values of blade **200** then illustrated in chart **400**.

In the embodiments described above and referencing FIGS. **1-3**, rotor blade **200** is shown and described as a compressor blade. Within compressor section **104**, each compressor stage may incorporate rotor blades **200** that include different oblique sections, such as oblique sections **300** and **320**. For example, a first compressor stage includes a plurality of rotor blades **200** with tip portion **210** having oblique section **300**, while a second compressor stage includes a plurality of rotor blades **200** with tip portion **210** having oblique section **320**. Moreover, in alternative embodiments, tip portion **210** having an oblique section, such as oblique section **300**, is in any other blade within turbomachine **100**, such as, turbine section **112**.

FIG. **5** is a schematic view of an alternative tip portion **500** for use with rotor blade **200** (shown in FIG. **2**). In this alternative embodiment, rotor blade **200** includes pressure sidewall **212** and an opposing suction sidewall **214** which extend from root portion **208** to tip portion **500**. Additionally, tip portion **500** includes planar section **222** that extends from pressure sidewall **212** to suction sidewall **214** and substantially perpendicular thereto. Further, tip portion **500** includes an oblique section **502** that convexly curves from planar section **222** inward towards root portion **208** to leading edge **216** forming a recess **504**. Specifically, convex oblique section **502** extends a distance **506** along tip portion **500** from leading edge **216** approximately 30% of chord distance **304** of airfoil **202**. Additionally, convex oblique section **502** extends a depth **508** from planar section **222**. In alternative embodiments, convex oblique section **502** extends for any other distance **506** and/or depth **508** that enables rotor blade **200** to function as described herein.

Additionally, or alternatively, in this alternative embodiment, tip portion **500** includes oblique section **510** that concavely curves from planar section **222** inward towards root portion **208** to trailing edge **218** forming a recess **512**. Specifically, concave oblique section **510** extends a distance **514** along tip portion **500** from trailing edge **218** approximately 30% of chord distance **304** of airfoil **202**. Additionally, concave oblique section **510** extends for depth **508** from planar section **222**. In alternative embodiments, concave oblique section **510** extends for any other distance **514** and/or depth **508** that enables rotor blade **200** to function as described herein. Further, in alternative embodiments, concave oblique section **510** is adjacent to leading edge **216** and/or convex oblique section **502** is adjacent to trailing edge **218**.

Similar to tip portion **210** (shown in FIG. **3**), tip portion **500** reduces the rub ratio of blade **200**. Oblique section **502** and/or **510** lowers the contact force between rotor blade **200** and casing **106** (shown in FIG. **1**) thereby reducing radial elongation. Reducing radial elongation within rotor blade **200** decreases the amount of material loss due to rubbing against casing **106** and thus wear of rotor blade **200**.

FIG. **6** is a schematic view of another alternative tip portion **600** for use with rotor blade **200** (shown in FIG. **2**). In this alternative embodiment, rotor blade **200** includes pressure sidewall **212** and an opposing suction sidewall **214** which extend from root portion **208** to tip portion **600**. Additionally, tip portion **600** includes a first planar section **602** and a second planar section **604** that each extend from pressure sidewall **212** to suction sidewall **214** and substantially perpendicular thereto. Further, tip portion **600** includes an oblique section **606** forming a recess **608** between first and second planar sections **602** and **604**. Specifically, oblique section **606** extends a distance **610** along tip portion **600** from first planar section **602** to second planar section **604** at approximately 40% of chord distance **304** of airfoil **202** centering about mid-chord line **217**. Oblique section **606** has a first section **612** that extends from first planar section **602** to mid-chord line **217** at a depth **614** such that first section **612** slopes from first planar section **602** towards root portion **208** in a direction towards trailing edge **218**. Oblique section **606** has a second section **616** that extends from second planar section **604** to mid-chord line **217** such that second section **616** slopes from second planar section **604** towards root portion **208** in a direction towards leading edge **216**. In this alternative embodiment, oblique section **606** forms a V-shaped recess **608** about mid-chord line **217**. In alternative embodiments, oblique section **606** extends for any other distance **610** and/or depth **614** that enables rotor blade **200** to function as described herein. Additionally, in alternative embodiments, oblique section **606** does not center about mid-chord line **217**.

Similar to tip portion **210** (shown in FIG. **3**), tip portion **600** reduces the rub ratio of blade **200**. Oblique section **606** lowers the contact force between rotor blade **200** and casing **106** (shown in FIG. **1**) thereby reducing radial elongation. Reducing radial elongation within rotor blade **200** decreases the amount of material loss due to rubbing against casing **106** and thus wear of rotor blade **200**.

FIG. **7** is a schematic view of a further alternative tip portion **700** for use with rotor blade **200** (shown in FIG. **2**). In this alternative embodiment, rotor blade **200** includes pressure sidewall **212** and an opposing suction sidewall **214** which extend from root portion **208** to tip portion **700**. Additionally, tip portion **700** includes a first planar section **702** and a second planar section **704** that each extend from pressure sidewall **212** to suction sidewall **214** and substantially perpendicular thereto. Further, tip portion **700** includes an oblique section **706** forming a recess **708** between first and second planar sections **702** and **704**. Specifically, oblique section **706** extends a distance **710** along tip portion **700** from first planar section **702** to second planar section **704** at approximately 40% of chord distance **304** of airfoil **202** centering about mid-chord line **217**. Oblique section **706** has a first section **712** that extends from first planar section **702** to mid-chord line **217** at a depth **714** such that first section **712** concavely slopes from first planar section **602** towards root portion **208** in a direction towards trailing edge **218**. Oblique section **706** has a second section **716** that extends from second planar section **704** to mid-chord line **217** such that second section **716** convexly slopes from second planar section **704** towards root portion **208** in a direction towards leading edge **216**. In this alternative embodiment, oblique section **706** forms a U-shaped recess **708** about mid-chord line **217**. In alternative embodiments, oblique section **706** extends for any other distance **710** and/or depth **714** that enables rotor blade **200** to function as described herein. Additionally, in alternative embodiments, oblique section **706** does not center about mid-chord line **217**.

Similar to tip portion **210** (shown in FIG. **3**), tip portion **700** reduces the rub ratio of blade **200**. Oblique section **706** lowers the contact force between rotor blade **200** and casing **106** (shown in FIG. **1**) thereby reducing radial elongation. Reducing radial elongation within rotor blade **200** decreases the amount of material loss due to rubbing against casing **106** and thus wear of rotor blade **200**.

The above described rotor blade tip geometries reduces wear in a turbomachine. Specifically, a rotor blade includes an airfoil having a suction sidewall coupled to a pressure sidewall at a leading edge and a trailing edge. A tip portion extends between the suction sidewall and the pressure sidewall and includes a planar section and an oblique section. In some embodiments, the tip portion includes a first oblique section and a second oblique section. Modifying the rotor blade tip geometry by grinding the tip portion and forming the oblique section reduces the rub ratio of the rotor blade and, thereby, the wear of the rotor blade. Specifically, the oblique section is sized such that a contact area between the rotor blade and a surrounding casing is reduced, thereby decreasing the radial and tangential loads induced into the rotor blade during a rub event. Reducing the loads resulting from a rub event decreases vibration and deflection of the rotor blade and reduces material loss at the tip portion. Furthermore, modifying the rotor blade tip geometry changes the vibratory modes of the rotor blade such that radial elongation is decreased further reducing material loss at the tip portion. Additionally, a reduction in radial deflection allows the rotor blade to be positioned closer to the surrounding casing. Accordingly, decreasing the rub ratio of the rotor blade decreases wear and material loss during a rub event, increases turbomachine performance, and reduces maintenance costs.

An exemplary technical effect of the methods, systems, and apparatus described herein includes at least one of the following: (a) decreasing material loss of the rotor blade tip during a rub event with a surrounding casing; (b) reducing wear of the rotor blade; (b) decreasing a clearance gap between the rotor blade and the casing; (c) reducing maintenance costs of turbomachines; and (d) increasing turbomachine performance.

Exemplary embodiments of methods, systems, and apparatus for reducing rotor blade tip wear are not limited to the specific embodiments described herein, but rather, components of systems and/or steps of the methods may be utilized independently and separately from other components and/or steps described herein. Further, the methods, systems, and apparatus may also be used in combination with other systems requiring decreasing wear from a rub event, and the associated methods are not limited to practice with only the systems and methods described herein. Rather, the exemplary embodiment can be implemented and utilized in connection with many other applications, equipment, and systems that may benefit from reducing wear on a blade tip.

Although specific features of various embodiments of the disclosure may be shown in some drawings and not in others, this is for convenience only. In accordance with the principles of the disclosure, any feature of a drawing may be referenced and/or claimed in combination with any feature of any other drawing.

This written description uses examples to disclose the embodiments, including the best mode, and also to enable any person skilled in the art to practice the embodiments, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the disclosure is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal language of the claims.

What is claimed is:

1. An airfoil for use in a turbomachine, said airfoil comprising: a pressure sidewall; a suction sidewall coupled to said pressure sidewall, wherein said suction sidewall and said pressure sidewall define a leading edge and an opposite trailing edge, wherein said leading edge and said trailing edge define a chord distance; a root portion; and a tip portion extending between said pressure sidewall and said suction sidewall such that said tip portion is substantially perpendicular to each sidewall, said tip portion comprises at least one planar section and at least one oblique section that forms a recess within said tip portion, said at least one oblique section extends from said at least one planar section towards said root portion along said chord distance, said tip portion is configured to reduce airfoil wear during contact with a surrounding casing, wherein said at least one oblique section comprises a first oblique section and a second oblique section, said first oblique section extends convexly from said leading edge to said at least one planar section and said second oblique section extends concavely from said trailing edge to said at least one planar section.

2. The airfoil in accordance with claim **1**, wherein said at least one oblique section extends from said leading edge within a range from approximately 5% to approximately 15% of said chord distance to said at least one planar section, wherein said leading edge has a first length that extends between said root portion and said at least one oblique section and said trailing edge has a second length that extends between said root portion and said at least one planar section such that said first length is less than said second length, and

wherein the at least one planar section defines a radially outer surface of the airfoil.

3. The airfoil in accordance with claim **1**, wherein said at least one oblique section extends from said leading edge within a range from approximately 15% to approximately 30% of said chord distance to said at least one planar section, wherein said leading edge has a first length that extends between said root portion and said at least one oblique section and said trailing edge has a second length that extends between said root portion and said at least one planar section such that said first length is less than said second length.

4. The airfoil in accordance with claim **1**, wherein said at least one oblique section extends from said leading edge within a range from approximately 30% to approximately 50% of said chord distance to said at least one planar section, wherein said leading edge has a first length that extends between said root portion and said at least one oblique section and said trailing edge has a second length that extends between said root portion and said at least one planar section such that said first length is less than said second length.

5. The airfoil in accordance with claim **1**, wherein said at least one oblique section extends from said trailing edge within a range from approximately 5% to approximately 15% of said chord distance to said at least one planar section, wherein said leading edge has a first length that extends between said root portion and said at least one planar section and said trailing edge has a second length that extends between said root portion and said at least one oblique section such that said first length is greater than said second length.

6. The airfoil in accordance with claim **1**, wherein said at least one oblique section extends from said trailing edge within a range from approximately 15% to approximately 30% of said chord distance to said at least one planar section, wherein said leading edge has a first length that extends between said root portion and said at least one planar section and said trailing edge has a second length that extends between said root portion and said at least one oblique section such that said first length is greater than said second length.

7. The airfoil in accordance with claim **1**, wherein said at least one oblique section extends from said trailing edge within a range from approximately 30% to approximately 50% of said chord distance to said at least one planar section, wherein said leading edge has a first length that extends between said root portion and said at least one planar section and said trailing edge has a second length that extends between said root portion and said at least one oblique section such that said first length is greater than said second length.

8. The airfoil in accordance with claim **2**, wherein said at least one oblique section comprises a first oblique section and a second oblique section, said first oblique section extends from said leading edge approximately 15% of said chord distance to said at least one planar section and said second oblique section extends from said trailing edge approximately 15% of said chord distance to said at least one planar section.

9. The airfoil in accordance with claim 8, the at least one planar section comprising exactly one planar section, the exactly one planar section extending from the first oblique section to the second oblique section,

wherein said leading edge has a first length that extends between said root portion and said first oblique section and said trailing edge has a second length that extends between said root portion and said second oblique section such that said first length is substantially equal to said second length.

10. The airfoil in accordance with claim 1, wherein said at least one oblique section extends from said at least one planer section towards said root portion within a range including approximately 2 mils to less than 5 mils.

11. The airfoil in accordance with claim 1, wherein said at least one planar section comprises a first planar section adjacent said leading edge and a second planar section adjacent trailing edge, said at least one oblique section extends between said first planar section and said second planar section.

12. The airfoil in accordance with claim 9, wherein said at least one oblique section is defined with a convex curve.

13. A turbomachine comprising: a casing; a rotor assembly, said casing at least partially extending about said rotor assembly, said rotor assembly comprising: a rotor shaft; a plurality of rotor blades coupled to said rotor shaft, each rotor blade of said plurality of rotor blades comprises an airfoil comprising a pressure sidewall and a suction sidewall coupled to said pressure sidewall, wherein said suction sidewall and said pressure sidewall define a leading edge and an opposite trailing edge, wherein said leading edge and said trailing edge define a chord distance, said airfoil further comprising a root portion and a tip portion extending between said pressure sidewall and said suction sidewall such that said tip portion is substantially perpendicular to each sidewall, said tip portion comprising at least one planar section and at least one oblique section that forms a recess within said tip portion, said at least one oblique section extends from said at least one planar section towards said root portion along said chord distance, said tip portion is configured to reduce rotor blade wear during contact with said casing, wherein said at least one oblique section comprises a first oblique section and a second oblique section, said first oblique section extends convexly from said leading edge approximately 15% of said chord distance to said at least one planar section and said second oblique section extends concavely from said trailing edge approximately 15% of said chord distance to said at least one planar section.

14. The turbomachine in accordance with claim 13, wherein said at least one oblique section extends from said leading edge to said at least one planar section, wherein a distance measured between said casing and said leading edge is greater than a distance measured between said casing and said trailing edge, and

wherein each rotor blade of the plurality of rotor blades comprises a turbine rotor blade.

15. The turbomachine in accordance with claim 13, wherein said at least one oblique section extends from said trailing edge to said at least one planar section, wherein a distance measured between said casing and said trailing edge is greater than a distance measured between said casing and said leading edge.

16. A method for reducing blade wear during turbomachine operation, the turbomachine including a casing, a rotor shaft, and a plurality of rotor blades, each rotor blade of the plurality of rotor blades including an airfoil including a pressure sidewall and a suction sidewall coupled to the pressure sidewall, wherein the suction sidewall and the pressure sidewall define a leading edge and an opposite trailing edge, wherein the leading edge and the trailing edge define a chord distance, the airfoil further includes a root portion and a tip portion extending between the pressure sidewall and the suction sidewall such that the tip portion is substantially perpendicular to each sidewall, said method comprising: removing blade material from the tip portion comprising forming a recess from at least one oblique section adjacent at least one planar section on the tip portion, the at least one oblique section extends from the at least one planar section towards the root portion along the chord distance; and coupling the rotor blade to the rotor shaft such that during turbomachine operation when the tip portion contacts the casing, wear of the rotor blade is reduced, wherein the at least one oblique section extends from the at least one planar section to at least one of the leading edge and the trailing edge, wherein said at least one oblique section comprises a first oblique section and a second oblique section, said first oblique section extends convexly from said leading edge to said at least one planar section and said second oblique section extends concavely from said trailing edge to said at least one planar section.

17. The method in accordance with claim 16, wherein removing blade material from the tip portion further comprises removing blade material from the tip portion at the leading edge such that the leading edge has a first length that extends between the root portion and the at least one oblique section and the trailing edge has a second length that extends between the root portion and the at least one planar section such that the first length is less than the second length.

18. The method in accordance with claim 16, wherein removing blade material from the tip portion further comprises removing blade material from the tip portion at the trailing edge such that the leading edge has a first length that extends between the root portion and the at least one planar section and the trailing edge has a second length that extends between the root portion and the at least one oblique section such that the first length is greater than the second length, and wherein the recess is not centered about a mid-chord line.

19. The method in accordance with claim 16, wherein removing blade material from the tip portion further comprises:

removing the leading edge tip portion via a grinding process to form a first oblique section; and

removing the trailing edge tip portion via a grinding process to form a second oblique section.

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