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(54) **LASER NET SHAPE MANUFACTURING AND REPAIR USING A MEDIAL AXIS TOOLPATH DEPOSITION METHOD**

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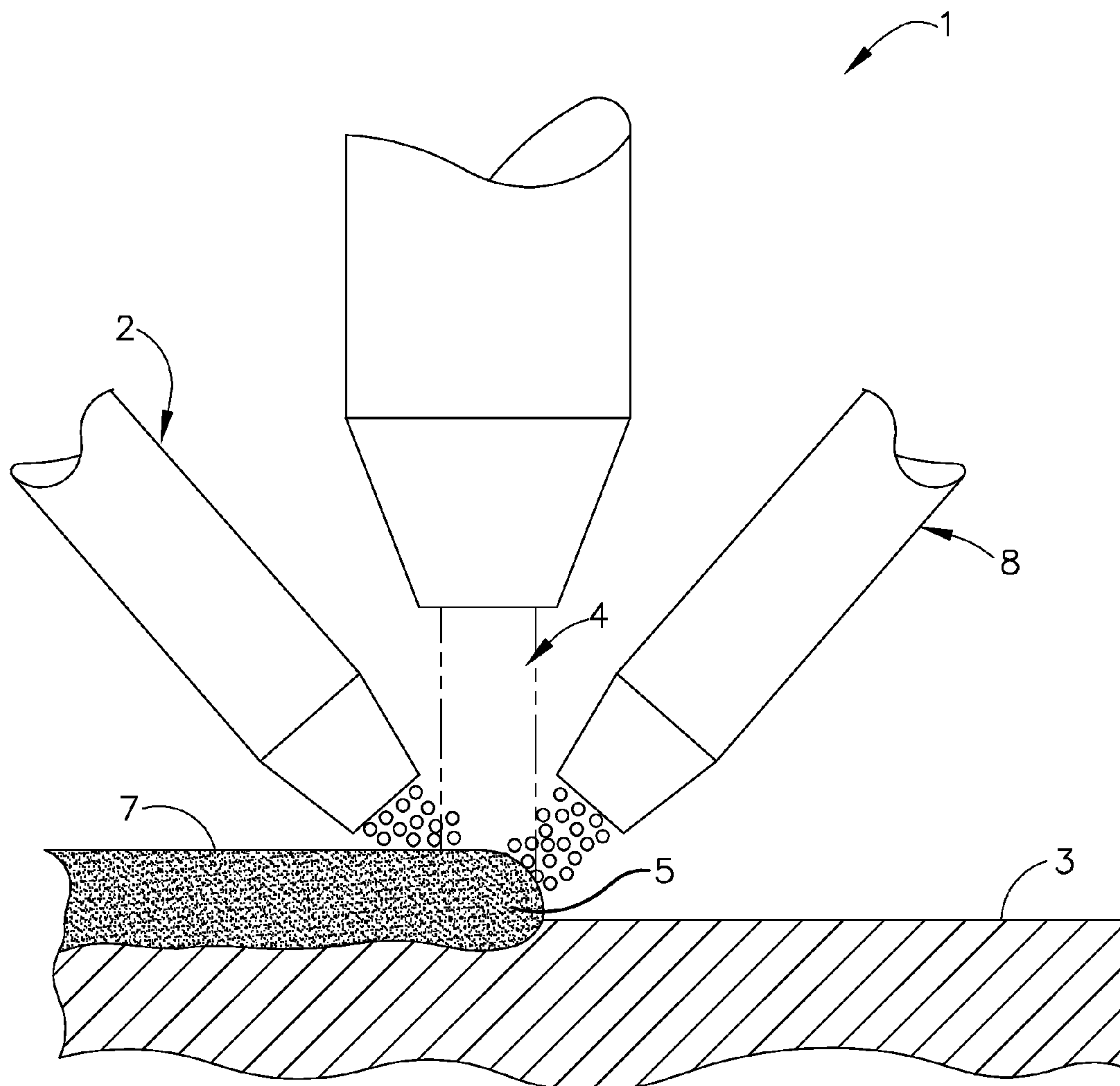
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(57) **ABSTRACT**

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A method is disclosed for laser net shape manufacturing a part or repairing an area of a part comprising providing a CAD model of the part to be manufactured or repaired, digitally slicing the CAD model into a plurality of deposition layers, determining a medial axis for each of the deposition layers of the part or repair area; and depositing a bead of a material in a pattern centered upon the medial axis of each of the deposition layers so as to build-up the material by each of the deposition layer until the part is manufactured or repaired.



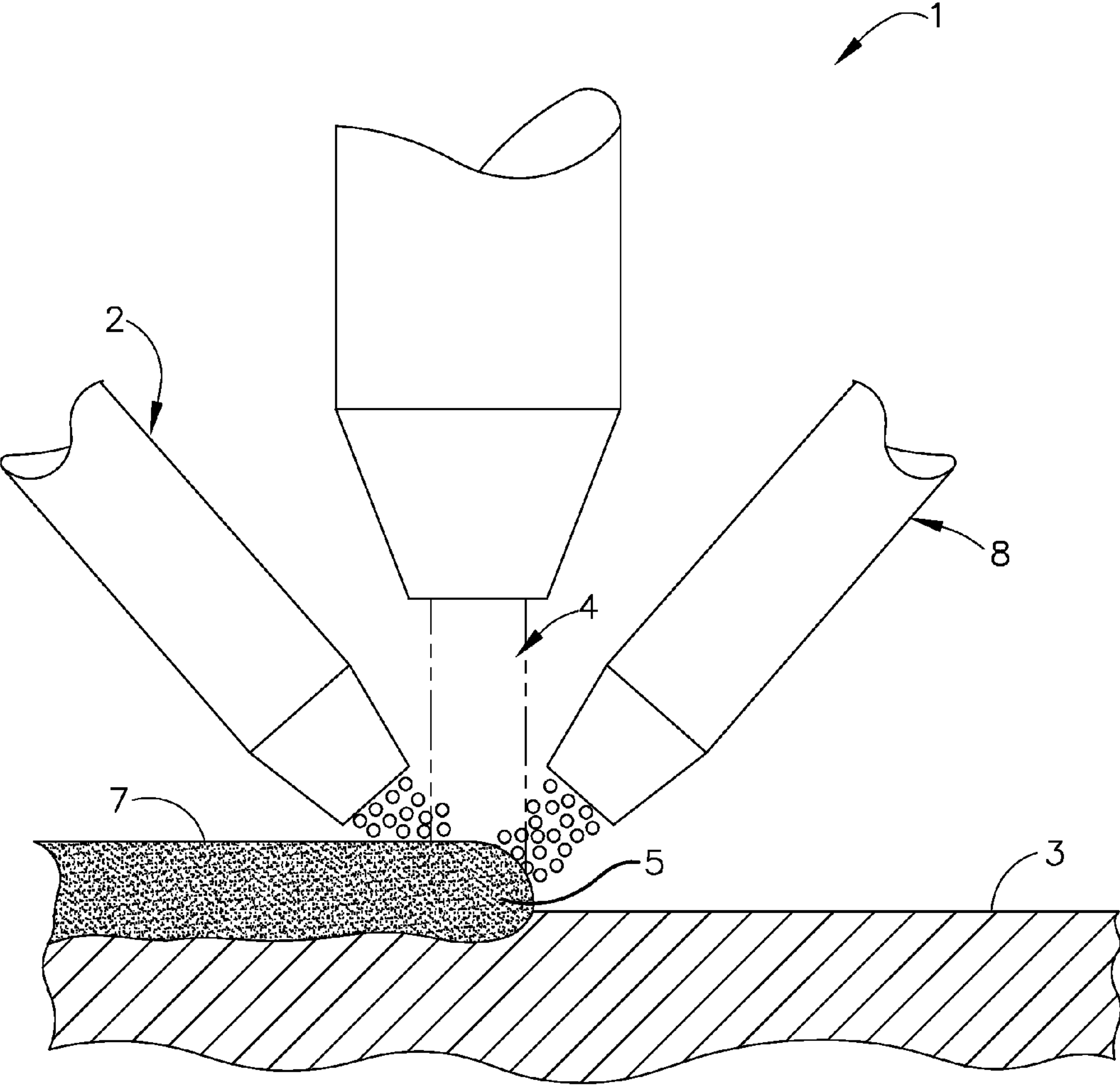


FIG. 1

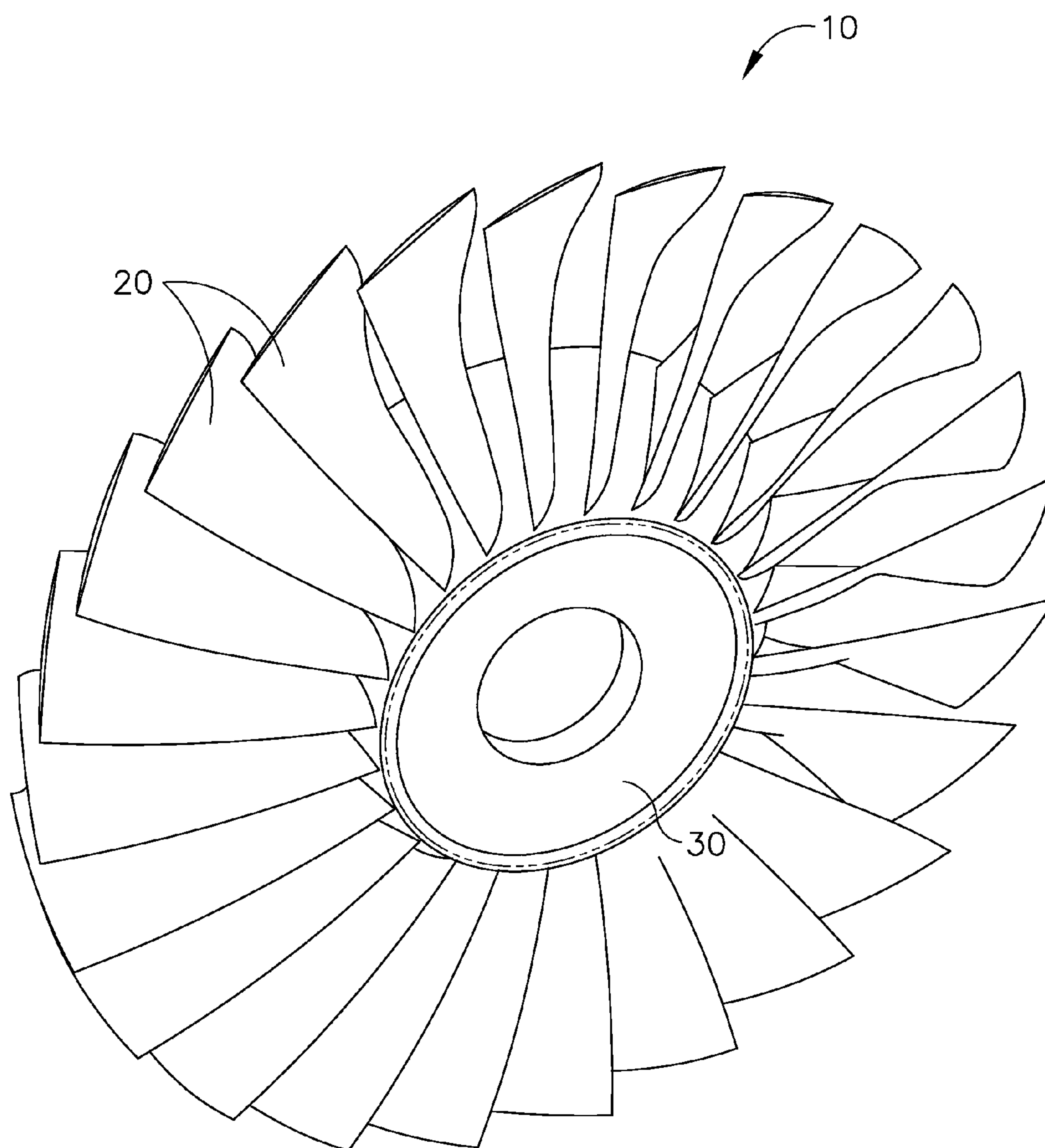


FIG. 2

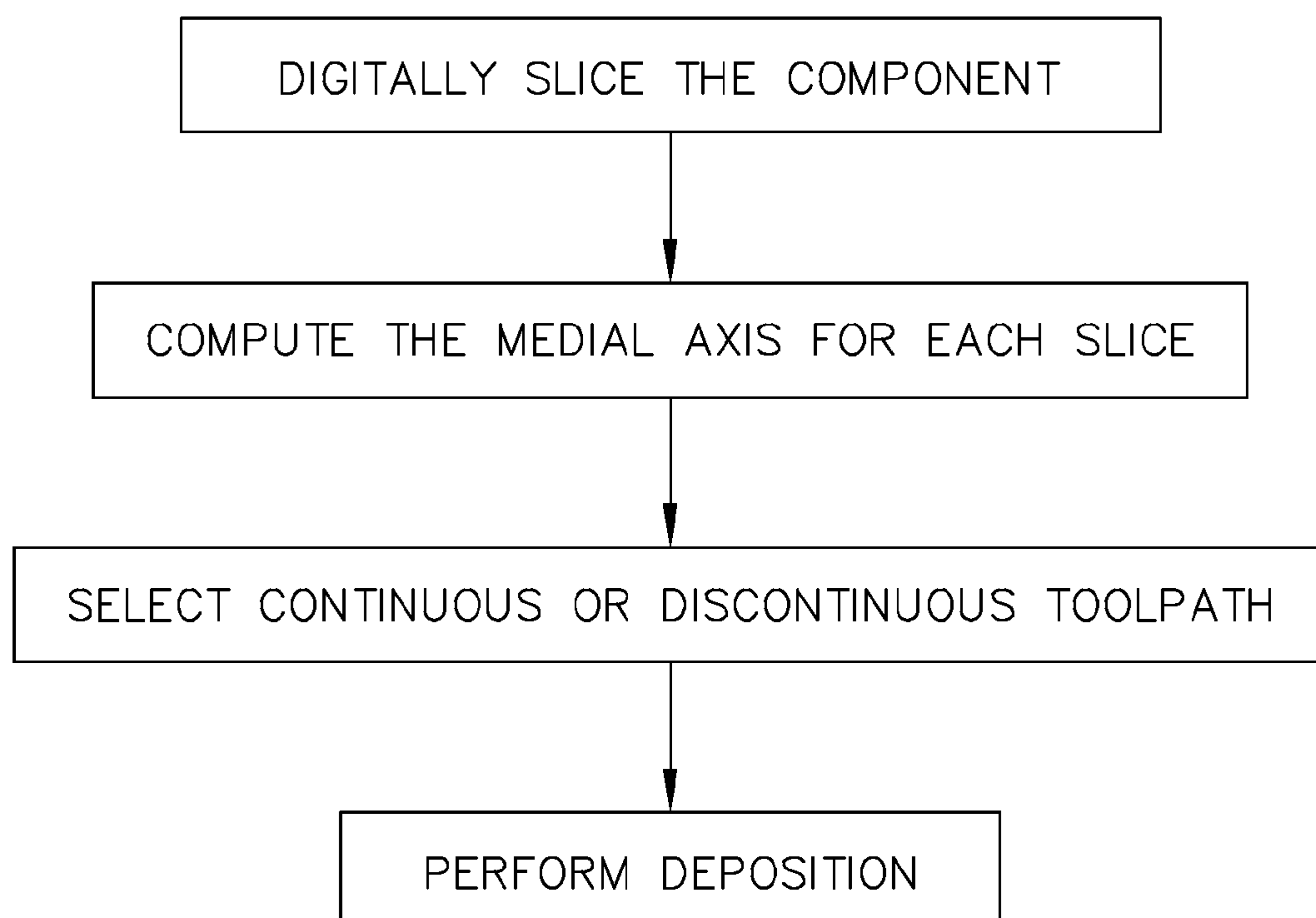


FIG. 3

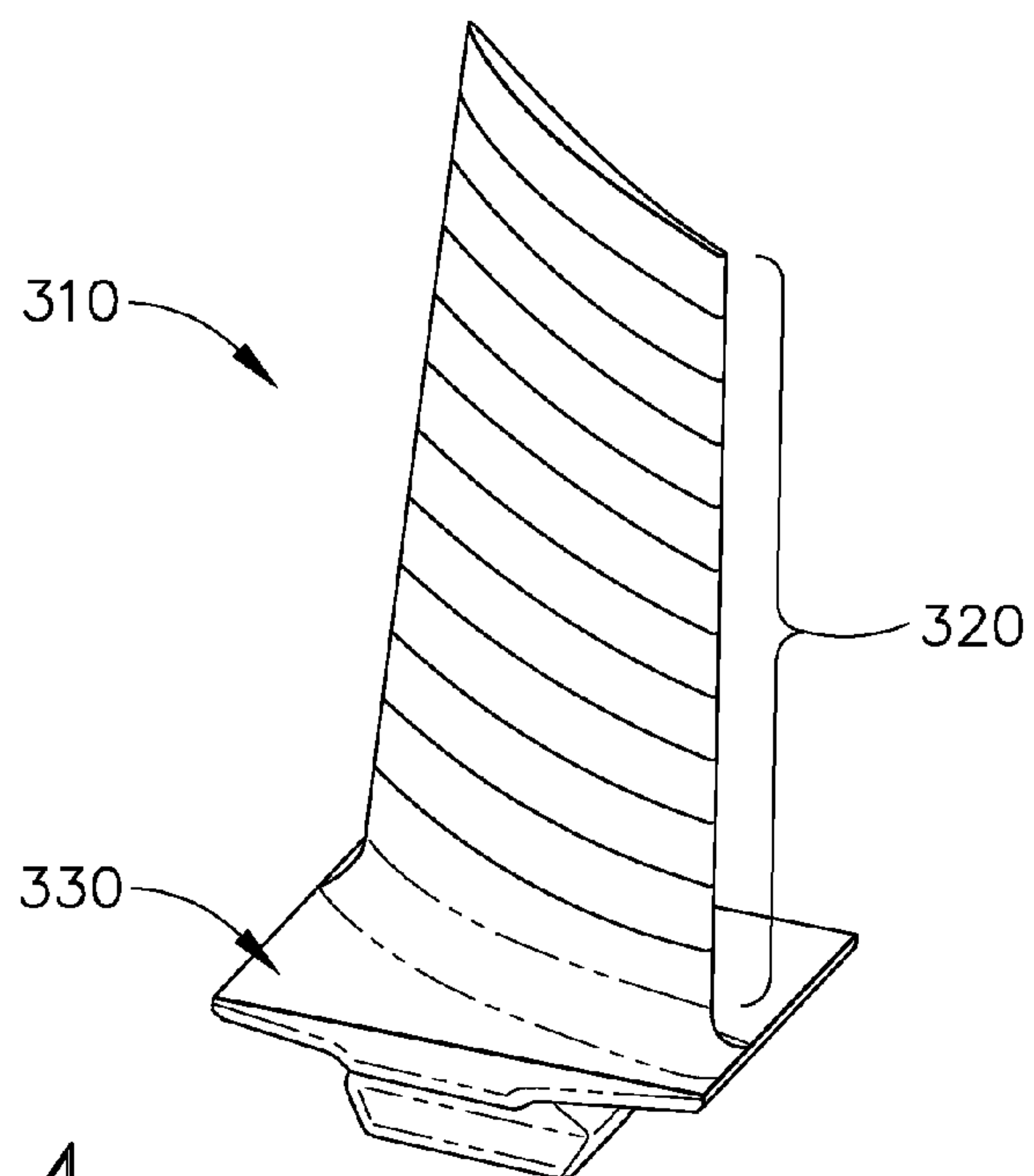


FIG. 4

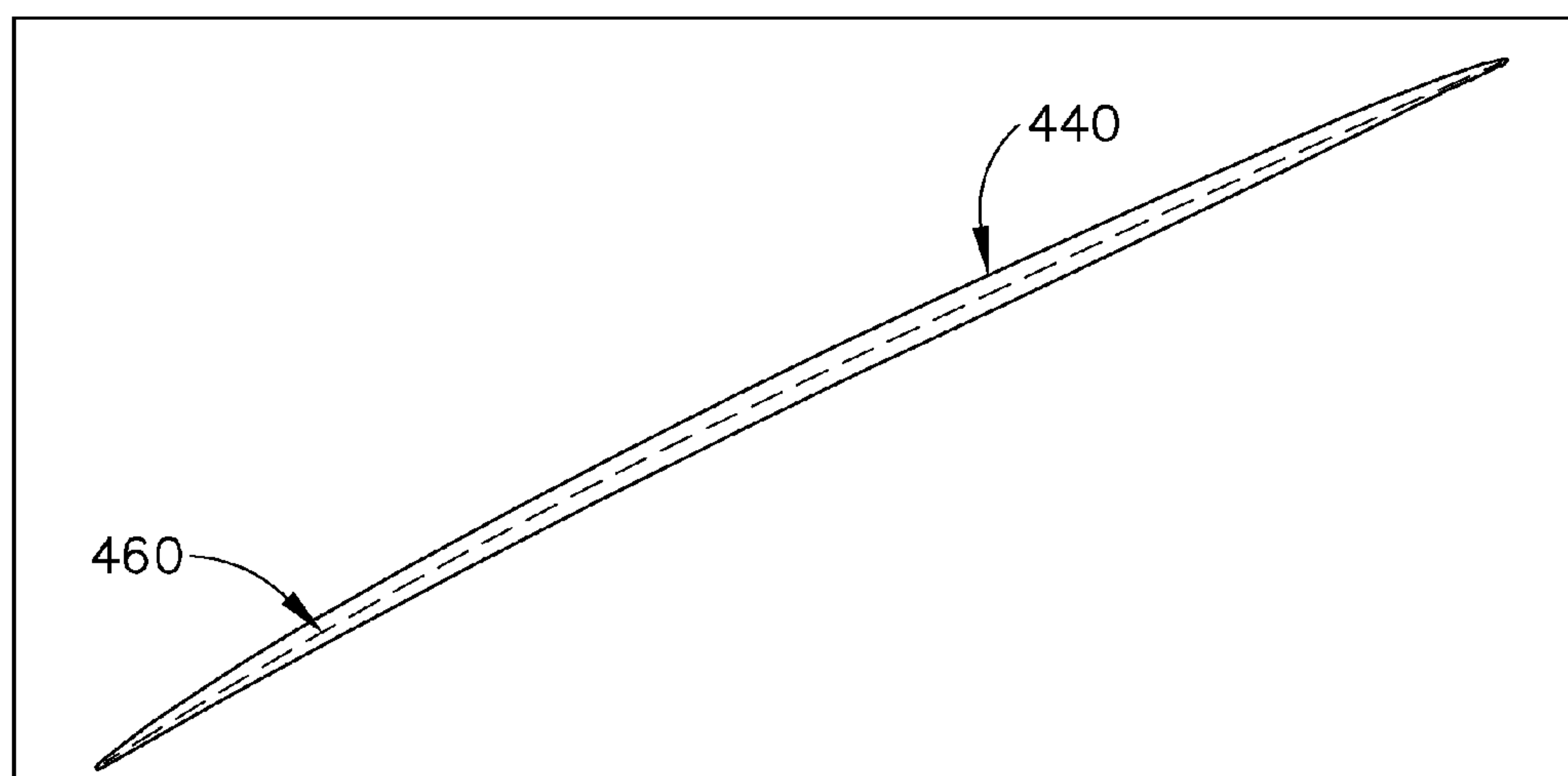


FIG. 5

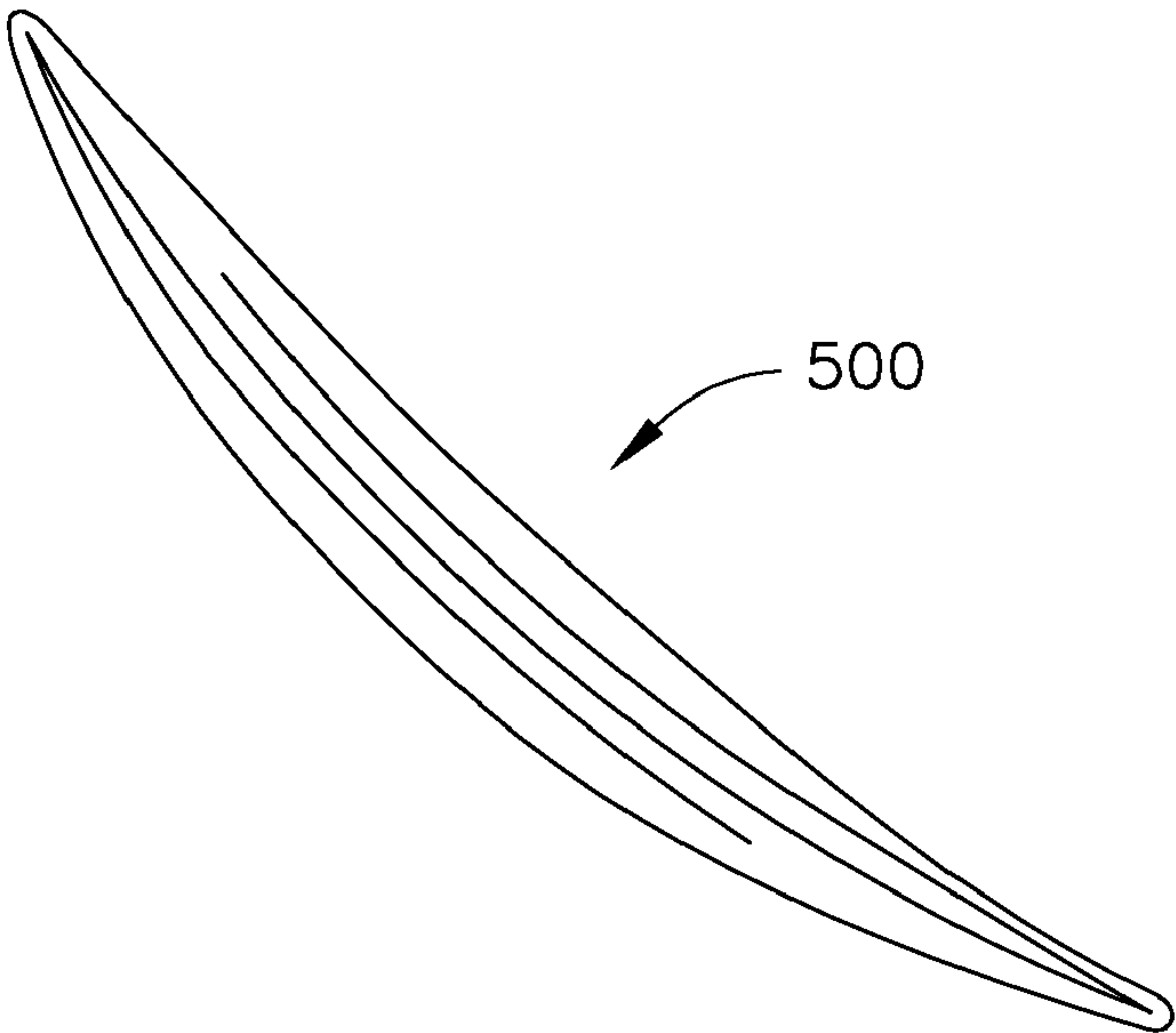


FIG. 6

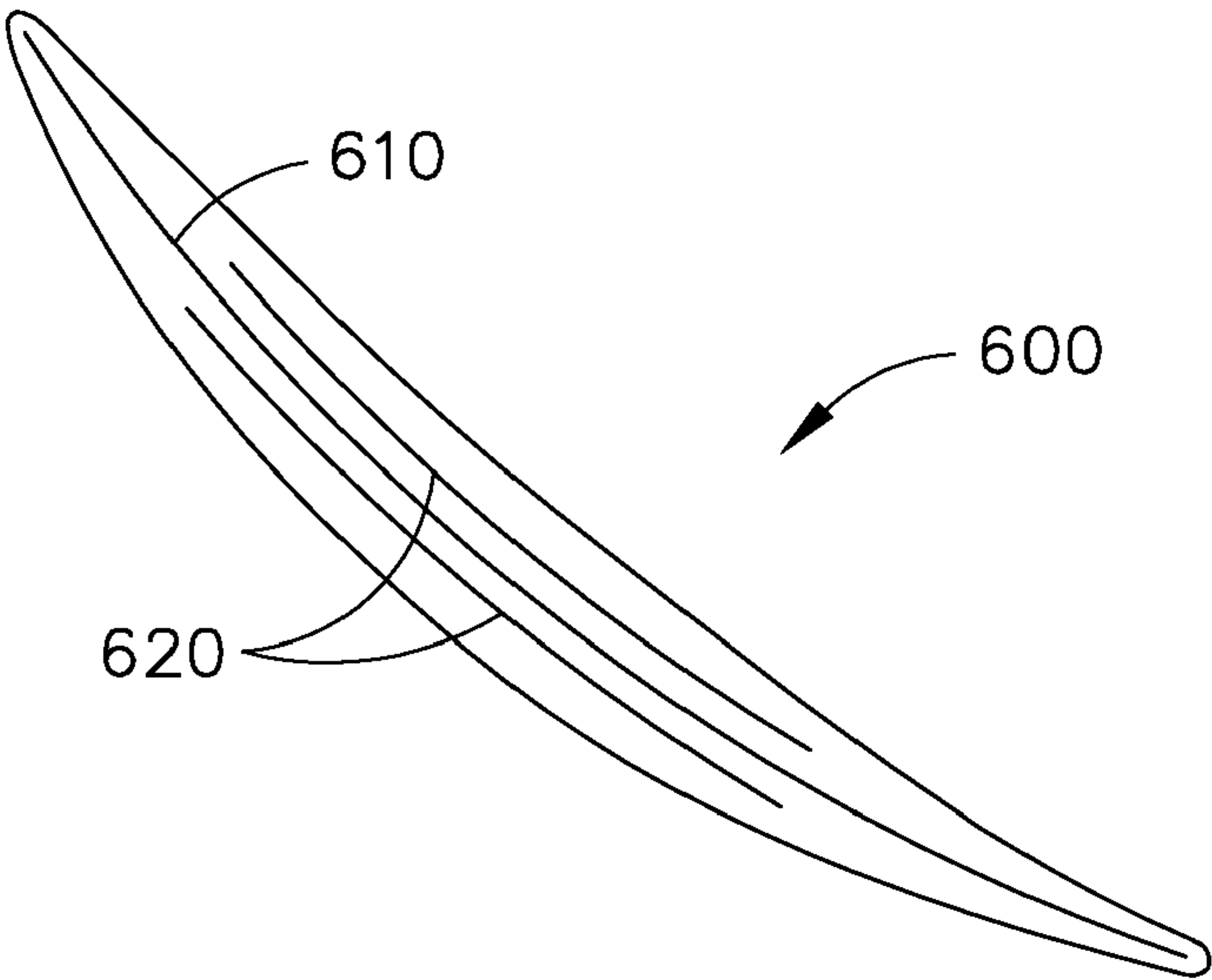


FIG. 7

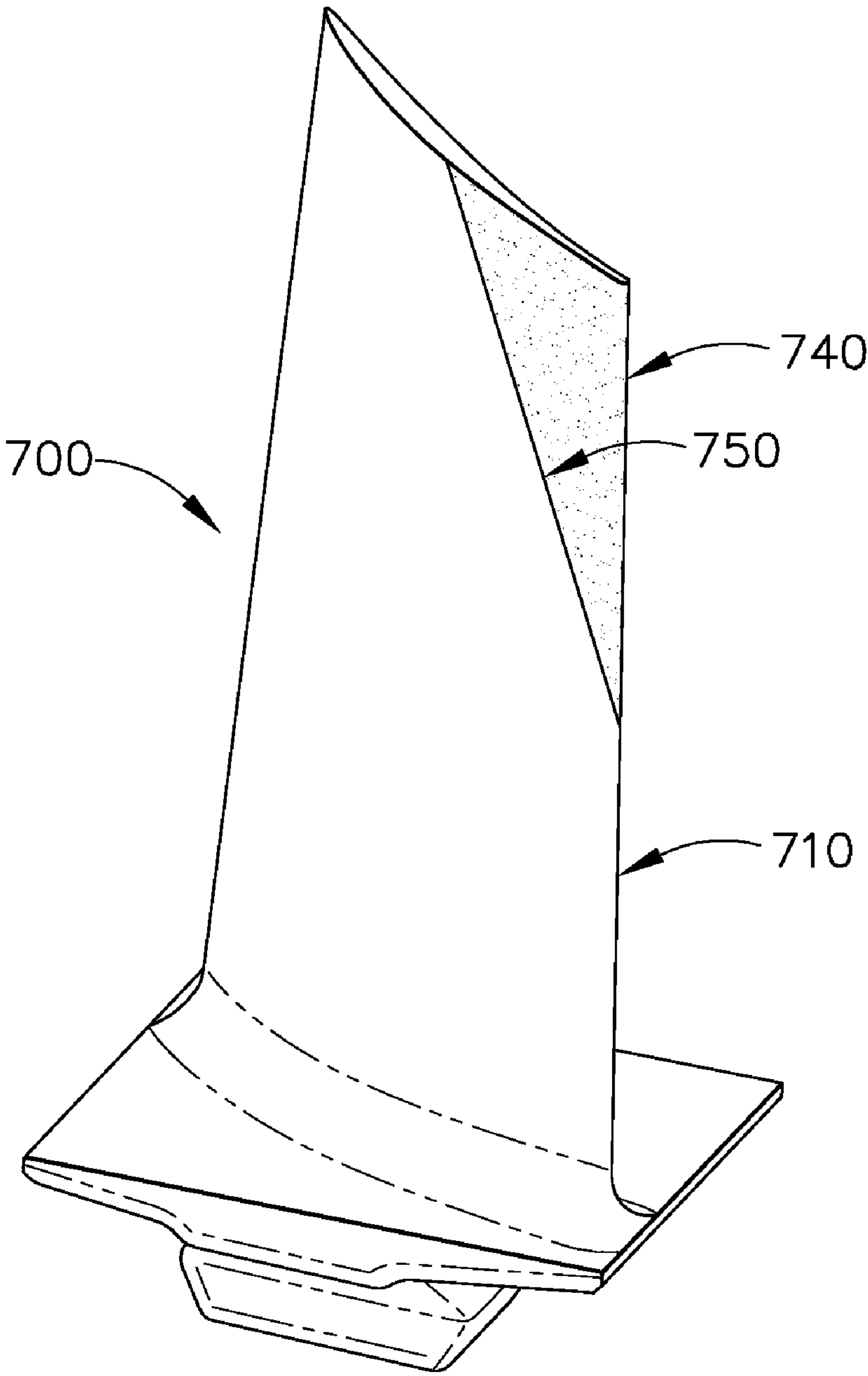


FIG. 8

LASER NET SHAPE MANUFACTURING AND REPAIR USING A MEDIAL AXIS TOOLPATH DEPOSITION METHOD

FIELD OF THE INVENTION

[0001] This invention relates to laser cladding method for fabricating or repairing a part, such as a BLISK, compressor blade or compressor component.

BACKGROUND OF THE INVENTION

[0002] An aircraft gas turbine engine or jet engine draws in and compresses air with an axial flow compressor, mixes the compressed air with fuel, burns the mixture and expels the combustion gases through an axial flow turbine that powers the compressor. The compressor includes a disk with blades projecting from its periphery. The disk turns rapidly on a shaft, and the curved blades draw in and compress air.

[0003] In current manufacturing practice, the compressor is made by forging the compressor disk as a single piece with slots at the periphery. The compressor blades are individually forged or cast to shape with a root section termed a dovetail that fits into slots formed in the disk. Assembly is completed by sliding the dovetail sections of the blades into the slots in the disk. If a blade does not fit properly, fails, or is damaged during service, it may be readily replaced by reversing the assembly procedure to remove the blade, and providing a new blade.

[0004] Blades may also be formed integrally with the disk, in a combination termed a BLISK. BLISKS may also be referred to as integrally bladed rotors. The BLISK approach to manufacturing offers the potential for increased performance through reduced weight. Such an article can be forged or cast as a large disk with an excess of metal at the periphery. The blades are then machined from the excess metal, integrally attached to the disk. The final product is expensive to produce, as it requires extensive high-precision machining operations. An error in machining even one of the blades may result in rejection and scrapping of the entire BLISK or it may require an expensive and time consuming repair to render the part useable.

[0005] In the past, a common repair method has included the mechanical removal of the damaged material and essentially leaving the BLISK as-is. While this repair method is suitable for minor airfoil edge damage, it is not acceptable for more significantly damaged areas due to imbalance problems and potential mechanical property degradation.

[0006] Replacement or repair of a damaged blade portion of the BLISK presents a difficult problem with this cast and machine approach. If all or a portion of a blade breaks off from impact of a foreign body during operation, for example, the BLISK becomes unbalanced. Damaged BLISKS are often repaired by welding excess metal into the damaged area and machining the metal to form the appropriate shape, or by cutting out the damaged area and replacing the cut out material by diffusion bonding a new piece of material into the damaged area. However, such an approach is both expensive and results in reduced performance.

[0007] A different approach to manufacture and repair BLISKS has been disclosed in U.S. Pat. No. 5,038,014, incorporated herein by reference. This approach utilizes a laser cladding or welding technique that melts powders in a feed

and deposits the molten material onto a surface. Melted powder layers are built upon one another to form new parts and to repair damaged parts.

[0008] Past laser cladding techniques have resulted in imperfections and inclusions in the formed or repaired part resulting from incomplete fusion of the melted layers to the underlying substrate or previously welded material. These imperfections and inclusions are often associated with complex geometry of the formed or repaired part. Therefore, a need exists to provide a layered fabrication technique that solves the problems associated with the past manufacture and repair techniques.

[0009] Laser Net Shape Manufacturing (LNSM) provides an economical and highly flexible method to fabricate and restore BLISKS, turbine blades and turbine components. The LNSM technique is based on laser cladding, wherein a laser is used to create a 3D geometry by precisely cladding thin layers of metal powder on a base material.

[0010] LNSM has been used in the fabrication of new parts and the repair of damaged parts. A Computer Aided Design (CAD) model of a part to be fabricated is uniformly sliced along the desired direction of material buildup. Powder is applied and fused along a toolpath to create a bead of the deposited material. Deposited material beads are formed adjacent to and overlapping one another to form a layer of the deposited material, then, a plurality of layers are built upon one another until the part is fabricated or repaired. Alternatively, a layer of material can be formed utilizing a single bead of material, then, a plurality of layers are built upon one another until the part is fabricated or repaired.

[0011] Various toolpaths have been used in depositing beads of the material, depending on whether the material is forming an internal area or a surface area of the part. However, prior LNSM methods have resulted in inclusions or fusion imperfections in newly fabricated or repaired part, requiring that the part either be scrapped or further processed to repair the imperfections. In addition, past laser deposition methods for repair have not focused on producing accurate shapes and geometries.

[0012] Therefore, a need exists to develop a LNSM method that reduces fusion imperfections to allow a part, such as a turbine blade, bladed disk, BLISK or compressor airfoil to be manufactured or repaired.

SUMMARY OF THE INVENTION

[0013] In accordance with a first embodiment of the invention, a method for laser net shape manufacturing a part is disclosed, which comprises providing a CAD model of the part, digitally slicing the CAD model into a plurality of deposition layers, determining a spine (hereinafter referred to as the medial axis) for each of the deposition layers, and depositing a bead of a material in a pattern centered upon the medial axis of each of the deposition layers so as to build-up the material in layers until the part is manufactured.

[0014] In accordance with a second embodiment of the invention, a method for laser net shape repair of a part is disclosed comprising the steps of providing a part with a damaged area; shaping the damaged area to provide a substrate deposition surface that may be smooth and continuous; comparing the damaged part to a non-damaged part to determine a material deposition area; digitally slicing the determined material deposition area into deposition layers; determining a medial axis for each layer; and depositing material

in a pattern centered upon the medial axis of each layer so as to build-up the material layer by layer until the part is repaired.

[0015] In accordance with a third embodiment of the invention, a method for laser net shape repairing a part is disclosed comprising providing a part with an area to be repaired, shaping the area by removing the area to be repaired to provide a smooth and continuous surface, comparing the removed area to be repaired to a baseline shape to determine a material deposition area, digitally slicing the determined material deposition area into a plurality of deposition layers, determining a medial axis for each of the deposition layers, and depositing a material in a pattern centered upon the medial axis of each of the deposition layers so as to build-up the material by each of the deposition layers until the part is repaired.

[0016] The disclosed invention presents many advantages over the prior art method of layered deposition. By depositing a bead width along the medial axis tool path and its offsets, the number of lack of fusion imperfections in the solid deposit can be reduced or eliminated.

[0017] Other features and advantages of the present invention will be apparent from the following more detailed description of the preferred embodiment, taken in conjunction with the accompanying drawings which illustrate, by way of example, the principles of the invention. The scope of the invention is not, however, limited to this preferred embodiment.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] FIG. 1 is an illustration of a general LNSM deposition system.

[0019] FIG. 2 is an illustration of a BLISK.

[0020] FIG. 3 is a block diagram of an embodiment of the medial axis toolpath method.

[0021] FIG. 4 is a sectional view of an exemplary BLISK blade showing exemplary fabrication slices.

[0022] FIG. 5 is a cross-section layer showing an exemplary medial axis toolpath within a slice.

[0023] FIG. 6 is an illustration of an exemplary zigzag pattern within a fabrication slice.

[0024] FIG. 7 is an illustration of an exemplary zig pattern within a fabrication slice.

[0025] FIG. 8 is an illustration of an exemplary damaged BLISK blade.

DETAILED DESCRIPTION OF THE INVENTION

[0026] In Laser Net Shape Manufacturing (LNSM), the dimensions and overall geometry of the repair are rendered in accordance with a computer-aided design (CAD) description. The geometry of the repair must be described mathematically. Modeling of the shapes is achieved through the use of a CAD system, and from these representations, tool paths are generated to drive the LNSM process.

[0027] A CAD model of a part to be fabricated or repaired is generated by numerically characterizing the shape of the article such as a blade from drawings or a part prepared by more conventional methods such as machining. Once the shape of the part is numerically characterized, the computer generates a series of uniform slices along the desired direction of material buildup, and the computer determines a medial axis or spine (hereinafter referred to as a medial axis) for each slice. Based on a predetermined width of a bead of

deposited material, it may be necessary to apply more than one pass of material in a slice to form a desired part width. In that case, offset toolpaths are determined based on the bead width, to complete the slice. Alternatively, a series of non-uniform slices along the desired direction of the material build-up could be made, with the computer determining a medial axis or spine for each slice.

[0028] The medial axis and its offsets can be connected leading to two distinct cases. In the first case, the offsets may be connected to the medial axis in such a way that the toolpath becomes a continuous zigzag toolpath. Alternately, the offsets may be discontinuous from the medial axis, in which case the toolpaths consist of a series of beads which include a medial axis bead and offsets to that bead. This is referred to as a medial discontinuous zig toolpath. The zigzag pattern is preferred as it is continuous and may lead to a more stable deposition. The zig pattern is most often used in fabricating narrow layers. The deposition may include depositing material only upon the medial axis, for example in a narrow tip section of a part. Adjacent beads of deposited material overlap to a determined extent to form a uniform layer. Adjacent beads may overlap between about 10% to about 90%. Medial axis toolpath deposition reduces the number of changes in the direction of laser motion during material deposition, thereby stabilizing material deposition and improving fabrication quality.

[0029] The movement of the deposition head, or equivalently, the part, is then programmed using available numerical control computer programs to create a pattern of instructions, to deposit material along the determined medial axis path within a uniform or adaptive thickness slice. Multiple offset medial slices may be deposited within a slice as determined by the bead width of the deposited material. The actual laser deposition parameters that are used to deposit material will have been determined through prior experimentation. The developed instructions maintain a desired bead width and overlap of a deposited material in accordance with the invention. The resulting article reproduces the shape of the numerical characterization very accurately, to net shape or near-net shape specifications, including complex curves of a BLISK, turbine blade, compressor blade or turbine component.

[0030] Process parameters such as laser power and toolpath speed are varied along the length of the toolpath depending on the thickness of the slice cross-section. Stable build-up is achieved using medial axis toolpaths because of the few changes in direction of deposition within the slice cross-section and the variation of laser process parameters along the medial axis. The bead width can be varied by increasing the laser power and reducing the deposition speed. Typically, laser power is increased where the layer cross section is thicker, for example at the center of a blade, and the laser power is reduced when approaching the thinner sections of the layer, for example at leading and trailing edges of a blade.

[0031] For the repair of articles, including BLISKS, turbine blades and turbine components, material is deposited to repair the damaged area or section. If a compressor blade breaks near the midpoint, it may be necessary to grind a smooth and continuous surface onto the blade corresponding to the closest remaining undamaged area or section, and then to deposit material upon the surface until the part is repaired. If an area or section of a part is damaged, it may be necessary to remove material to form a notch upon which material may be deposited. The repaired blade is virtually indistinguishable from the

original fabricated blade, as it is accomplished by the same apparatus and with the same shape-controlling pattern.

[0032] Often, damage to a part is in the form of uneven and irregular shaped damage. In order to prepare the part for repair, the damaged area may be prepared by machining away material in the area approximate to the damage in order to form a smooth and continuous surface. Machining away the damage is preferably conducted automatically in a multi-axis numerically controlled milling machine that is programmed to form a predetermined smooth surface or notch proximate to the damaged area. The repair region is then cleaned, as needed, by aqueous cleaners and/or solvents, and dried, followed by the computer controlled deposition of material to form a repaired part. The repaired portion of the part has no macroscopically detectable bond line after finishing or discontinuity to the base portion of the part. The damaged part may be a turbine blade, bladed disk, BLISK or compressor airfoil, but is not limited to these parts.

[0033] In fabricating or repairing a part by the present approach, the composition of the powder feed may be maintained constant throughout the entire part. Alternatively, the composition of the powder feed may be intentionally varied within any bead or as between successive beads, to produce controllable composition variations throughout the article. For example, in a compressor blade, a strong, tough alloy composition may be used near the base, and a hard, wear resistant or abrasive alloy near the tip.

[0034] A wide variety of materials may be deposited using the approach of the invention. For example, metals and metal alloys including titanium and titanium alloys, nickel and nickel alloys, cobalt and cobalt alloys, and iron and iron alloys, superalloys including Ni-based, Co-based, and Fe based superalloys, ceramics, cermets and plastics may be deposited. The deposited material may be a single material or a mixture of different materials. Also, the deposited material may be varied or changed during the deposition such that the bead of material is formed of different materials or more than one material. The toolpath file is generated from commercial computer-aided manufacturing (CAM) software containing commands that are understandable to the computer numerically controlled (CNC) operating system. The commands are loaded into memory and executed. Typical commands are move commands, which tell the CNC to move to a new point at a given speed, turn on/off the laser, designate laser power and powder flow. These commands are all embedded directly within the part program when it is created, and are triggered at specific points in the program. Some parameters that control the process must be changed dynamically during the processing of a part, including but not limited to laser power, tool velocity, powder feed rate, and overlap ratio. Although specific embodiments discussed below are directed to BLISKS, the invention is equally applicable to the LNSM of other parts, including a variety of turbine parts including but not limited to turbine blades.

[0035] A Laser Net Shape Manufacturing (LNSM) system is illustrated in FIG. 1. As shown in FIG. 1, a powder supply (not shown) feeds a powder nozzle 2 for deposition upon a substrate 3. A laser 4 melts the powder as it is fed upon the substrate surface and also melts the substrate surface to create a melt pool 5 in the vicinity where the laser 4 is directed on the powder and the surface of the substrate 3. The system 1 and substrate 3 are moved relatively to form a layer of a solidified deposited material 7 as the melt pool 5 cools.

[0036] The path the laser 4 takes along the substrate 3 is referred to as a toolpath. The deposited material 7 is referred to as a bead of material. The width of deposited material 7 along the toolpath is referred to as a bead width. The formed melt pool 5 cools and solidifies as the laser 4 moves along the substrate 3. More than one powder feed may be used to form the deposited material 7, and in this illustration, a second powder nozzle 8 is shown contributing to the solidified deposited material 7. The laser 4, by melting both the powder feed and the surface of the substrate 3, forms a strongly bonded deposited material 7.

[0037] Upon completion of a first bead of the deposited material 7, the nozzle 2 and laser 4 are positioned and moved relative to the substrate 3 so that an adjacent second bead of deposited material 7 may be deposited along side of the first bead, the width of the second bead overlapping the width of the first bead. The process is repeated until a layer of the deposited material 7 is formed.

[0038] In accordance with a specific embodiment of the invention, a BLISK 10 as shown in FIG. 2 was fabricated. The BLISK 10 shown in FIG. 2 is illustrative, and the invention is not limited to a specific BLISK design but rather finds application in the fabrication and repair of a variety of components including compressor blades and airfoils, turbine blades and BLISKS. The BLISK 10 is formed of BLISK blades 20 formed upon a BLISK compressor disk 30. The BLISK 10 was fabricated according to the process flowchart of FIG. 3 and the detailed inventive process as provided herein.

[0039] In accordance with the specific embodiment, a BLISK 10 was fabricated according to the invention. As shown in FIG. 4, a CAD model 310 was digitally sliced into individual deposition layers 320. A medial axis was determined for each layer. FIG. 5 shows an exemplary layer 440 with a medial axis 460. Material was deposited in a pattern centered upon the medial axis 460 of each layer in accordance with the teaching of the invention. The first layer of material was deposited upon the BLISK compressor platform surface 330, so as to build-up the material by each layer until the BLISK 10 was manufactured.

[0040] The material was deposited by varying the control deposition parameters including, but not limited to laser power, laser scanning velocity, and powder feed rate so as to maintain a constant bead overlap of approximately 50 percent while varying the deposited bead width in a given layer. The bead width varied in a given layer from between about 0.035 inches and about 0.056 inches. In this specific embodiment, the deposited material was a nickel-based superalloy Inconel 718, also known as IN718. However, the material may be selected from any of the known structural materials in the field of the invention.

[0041] The material deposition pattern was the continuous zigzag pattern 500 as shown in FIG. 6. In this BLISK fabrication, a discontinuous zig pattern 600, formed of a medial axis 610 and two exterior offsets 620 as shown in FIG. 7, was not used, but may have been used, especially in the narrow tip section of the BLISK.

[0042] Process parameters such as laser power and toolpath speed were varied along the length of the medial axis depending on the thickness of the slice cross-section. Stable build-up was achieved using the medial axis toolpaths because of the few changes in direction of deposition within the slice cross-section and the variation of laser process parameters along the medial axis. Laser power was increased toward the center of

the medial axis, and decreased as moving away to the ends of the medial axis and approaching trailing edges.

[0043] In this manner, a BLISK blade **10** was fabricated that was substantially free of imperfections, including gap imperfections. The resulting article reproduced the shape of the CAD model very accurately, to net shape or near-net shape specifications, including complex curves of the airfoil.

[0044] In accordance with a second specific embodiment of the invention, a BLISK was repaired in accordance with the invention. A damaged BLISK **700**, shown as a cut away BLISK blade, was provided as shown in FIG. **8**. The damaged BLISK **700** had an area to be repaired **740** and an area not needing repair **710**. The area to be repaired **740** was removed to surface **750** by machining away the area to be repaired. The machining was conducted automatically in a multi-axis numerically controlled milling machine that was programmed to form a predetermined notch approximate to the area to be repaired. The notch was then cleaned, as needed, by aqueous cleaners and/or solvents, and dried. The invention, while directed to a BLISK repair in this embodiment, is not limited to BLISK repair, but may be applied to repairing and fabricating components including compressor blades.

[0045] A measurement was made of the remaining undamaged portion **710** and was compared to a CAD model containing a baseline shape of the area of a desired BLISK shape. From the comparison, a material deposition volume corresponding to the damaged area was determined by the CNC, and sliced into deposition layers.

[0046] A medial axis was determined for each layer. Material was deposited in a pattern centered upon the medial axis of each layer in accordance with the teaching of the invention, starting with a first layer upon the surface **750**, so as to build-up the material by each layer until the BLISK **10** was repaired.

[0047] The material was deposited by varying the control deposition parameters including, but not limited to laser power, laser velocity, and powder feed rate so as to maintain a constant bead overlap of approximately 50 percent while varying the deposited bead width in a given layer. The bead width varied in a given layer from between about 0.035 inches and about 0.056 inches. In this specific embodiment, the deposited material was a nickel-based superalloy Inconel 718, also known as IN718, and the compressor disk was formed also of IN718.

[0048] The material deposition pattern was the continuous zigzag pattern **500** as shown in FIG. **6**. In this BLISK repair, a discontinuous zig pattern was not used, but may have been used, especially in the narrow blade section of the BLISK.

[0049] Process parameters such as laser power and toolpath speed were varied along the length of the medial axis depending on the thickness of the slice cross-section. Stable build-up was achieved using the medial axis toolpaths because of the few changes in direction of deposition within the slice cross-section and the variation of laser process parameters along the medial axis. Laser power was increased in the center of the layer cross-section and decreased upon approaching the leading and trailing edges.

[0050] In this manner, a damaged BLISK blade **700** was repaired that was substantially free of imperfections, including gap imperfections. The resulting repaired article reproduced the shape of the CAD model very accurately, to net shape or near-net shape specifications, including complex curves of the airfoil. The performance of the BLISK was not reduced as a result of the repair according to the invention.

[0051] The performance of the BLISK is not reduced as a result of a repair according to the invention. This approach allows the blades of the BLISK to be repaired multiple times, without loss of the functionality of the BLISK due to an excessive reduction in its dimensions in the non-repaired regions to below the minimum specified values.

[0052] The disclosed invention presents many advantages over the prior art method of layered deposition. By depositing a bead width along a medial axis tool path and its offsets, the number of lack of fusion imperfections in the solid deposit can be reduced or effectively eliminated.

[0053] While the invention has been described with reference to a preferred embodiment, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims.

1. A method for laser net shape manufacturing a part, comprising:

providing a CAD model of the part;

digitally slicing the CAD model into a plurality of deposition layers;

determining a medial axis for each of the deposition layers; and

depositing a bead of a material in a pattern centered upon the medial axis of each of the deposition layers so as to build-up the material by each of the deposition layer until the part is manufactured.

2. The method of claim **1**, wherein the pattern comprises a zigzag pattern or a zig pattern about the medial axis.

3. The method of claim **1**, wherein the pattern comprises a single bead centered upon the medial axis.

4. The method of claim **1**, wherein the bead of material is a mixture of different materials.

5. The method of claim **1**, wherein the bead of material is formed of a single material.

6. The method of claim **1**, wherein the bead of material is formed of different materials.

7. The method of claim **1**, wherein a first layer of the deposited material is deposited upon a substrate.

8. The method of claim **1**, wherein the deposited material is selected from a group comprising metals, metal alloys, ceramics, and plastics.

9. The part formed by the method of claim **1**.

10. The method of claim **1**, wherein the part is a BLISK, turbine blade, compressor blade or turbine component.

11. A method for laser net shape repairing a part comprising:

providing a part with an area to be repaired;

shaping the area by removing the area to be repaired to provide a smooth and continuous surface;

comparing the removed area to be repaired to a baseline shape to determine a material deposition area;

digitally slicing the determined material deposition area into a plurality of deposition layers;

determining a medial axis for each of the deposition layers; and

depositing a material in a pattern centered upon the medial axis of each of the deposition layers so as to build-up the material by each of the deposition layers until the part is repaired.

12. The method of claim **11**, wherein the pattern comprises a zigzag pattern about the medial axis.

13. The method of claim **11**, wherein the pattern comprises a zig pattern about the medial axis.

14. The method of claim **11**, wherein the pattern comprises a single bead centered upon the medial axis.

15. The method of claim **11**, wherein the deposited material is selected from a group comprising metals, metal alloys, ceramics, and plastics.

16. The method of claim **11**, wherein the deposited material comprises more than one material.

17. The method of claim **11**, wherein the part is a BLISK, turbine blade, compressor blade or turbine component.

18. The method of claim **11**, wherein a first layer of the deposited material is deposited upon a BLISK compressor disk.

19. A BLISK, turbine blade, compressor blade or turbine component fabricated by the method of claim **1**.

20. A BLISK, turbine blade, compressor blade or turbine component repaired by the method of claim **11**.

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