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(54) **CLADDING AND FREEFORM DEPOSITION  
FOR COOLANT CHANNEL CLOSEOUT**

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(56) **References Cited**

U.S. PATENT DOCUMENTS

2,841,545 A \* 7/1958 Zinn ..... G21C 1/02  
376/171  
3,088,893 A \* 5/1963 Spalaris ..... G21C 1/08  
228/131  
4,359,310 A \* 11/1982 Endres ..... F01D 5/187  
415/115  
4,707,225 A \* 11/1987 Schuler ..... C25D 1/02  
205/73  
4,840,025 A \* 6/1989 Coffinberry ..... F02K 9/64  
102/289  
4,850,524 A \* 7/1989 Schick ..... B23K 9/0209  
228/102  
5,249,357 A \* 10/1993 Holmes ..... B23P 15/008  
29/890.01  
5,352,312 A \* 10/1994 Guillot ..... C08K 7/02  
156/172

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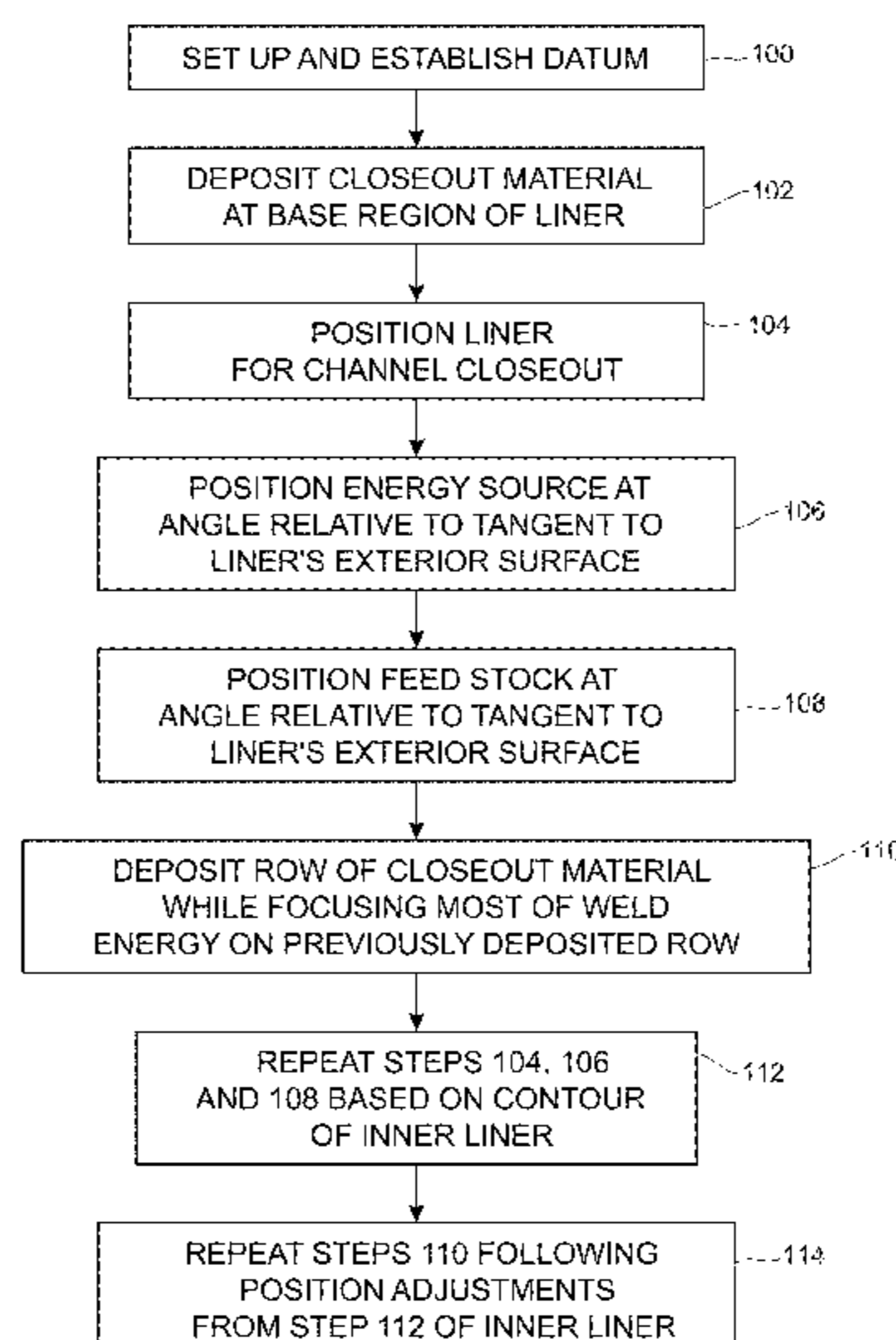
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(57) **ABSTRACT**

A base structure is clad and coolant channels are formed through the cladding and into the base structure. A line of tangency relative to the outer clad surface is defined for each point thereon. Linear rows of a metal feedstock are directed towards and deposited on the outer clad surface as a beam of weld energy is directed to the metal feedstock so-deposited. The metal feedstock is the same material as the cladding or one that is weld compatible therewith. A first angle between the metal feedstock so-directed and the line of tangency is maintained in a range of 20-90°. The beam is directed towards a portion of the linear rows such that less than 30% of the cross-sectional area of the beam impinges on a currently-deposited one of the linear rows. A second angle between the beam and the line of tangency is maintained in a range of 5-65°.

**18 Claims, 13 Drawing Sheets**



(56)

## References Cited

## U.S. PATENT DOCUMENTS

5,380,475	A *	1/1995	Goedtke .....	C04B 35/573 264/162
5,640,434	A *	6/1997	Rottenberg .....	G21C 1/10 376/366
5,837,960	A *	11/1998	Lewis .....	B23K 26/34 219/121.63
5,857,255	A *	1/1999	Wichmann .....	B23K 31/02 228/148
5,899,060	A *	5/1999	Schmidt .....	F02K 9/64 165/155
6,088,420	A *	7/2000	Yokoyama .....	G21C 1/00 376/434
6,122,564	A *	9/2000	Koch .....	B22F 3/1055 700/123
6,151,887	A *	11/2000	Haidn .....	F02K 9/64 60/257
6,182,442	B1 *	2/2001	Schmidt .....	F02K 1/822 239/127.3
6,389,801	B1 *	5/2002	Papenburg .....	F02K 9/97 239/127.1
6,410,105	B1 *	6/2002	Mazumder .....	B23K 26/032 427/554
6,470,671	B1 *	10/2002	Kretschmer .....	B23P 15/008 239/127.1
6,543,135	B2 *	4/2003	Kretschmer .....	B23P 15/008 29/890.01
6,817,184	B2 *	11/2004	Groeber .....	F02K 9/976 239/265.11
7,037,602	B2 *	5/2006	Benitsch .....	B29C 70/088 428/213
7,323,143	B2 *	1/2008	Anderson .....	B01D 61/18 422/502
8,070,473	B2 *	12/2011	Kozlak .....	B29C 70/70 425/375
8,448,335	B2 *	5/2013	Lundgren .....	B23C 3/34 29/890.01
9,636,790	B2 *	5/2017	Suh .....	B22F 3/008
2002/0148590	A1 *	10/2002	Gellert .....	B22D 11/0405 164/95
2005/0013328	A1 *	1/2005	Jurgensen .....	B23K 26/0604 372/6
2005/0112230	A1 *	5/2005	Herzog .....	B22F 3/1055 425/547
2006/0062345	A1 *	3/2006	Farawila .....	G21C 15/02 376/377
2006/0249491	A1 *	11/2006	Jurgensen .....	B23K 26/0643 219/121.69
2007/0003416	A1 *	1/2007	Bewlay .....	B22F 5/009 416/241 B
2009/0100678	A1 *	4/2009	Fint .....	F02K 9/97 29/890.01
2009/0291197	A1 *	11/2009	Bartels .....	B23K 26/02 427/8
2010/0242843	A1 *	9/2010	Peretti .....	B22F 5/04 118/723 E
2011/0064842	A1 *	3/2011	Chen .....	B29C 45/7312 425/552
2011/0143042	A1 *	6/2011	Peretti .....	B23K 9/04 427/455
2013/0056347	A1 *	3/2013	West .....	C23C 14/3407 204/192.12
2013/0101761	A1 *	4/2013	Bunker .....	F01D 5/288 428/34.1
2014/0044982	A1 *	2/2014	Suh .....	B22F 3/008 428/544
2015/0209906	A1 *	7/2015	Denney .....	B23K 26/1423 219/76.14
2015/0209907	A1 *	7/2015	Narayanan .....	B23K 26/1423 219/76.14
2015/0209908	A1 *	7/2015	Peters .....	B23K 26/1423 219/76.14
2015/0209910	A1 *	7/2015	Denney .....	B23K 26/1423 219/76.1
2015/0209913	A1 *	7/2015	Denney .....	B23K 35/0272 219/76.14
2015/0298235	A1 *	10/2015	Hanioka .....	G21C 21/00 219/76.1
2016/0114506	A1 *	4/2016	Tabassi .....	B29C 45/2735
2016/0375527	A1 *	12/2016	Henderson .....	B23P 6/002 29/889.1
2017/0067642	A1 *	3/2017	Szarvasy .....	F23R 3/002
2017/0182590	A1 *	6/2017	Goya .....	B23K 26/0884
2017/0225375	A1 *	8/2017	Suh .....	B22F 3/008

\* cited by examiner

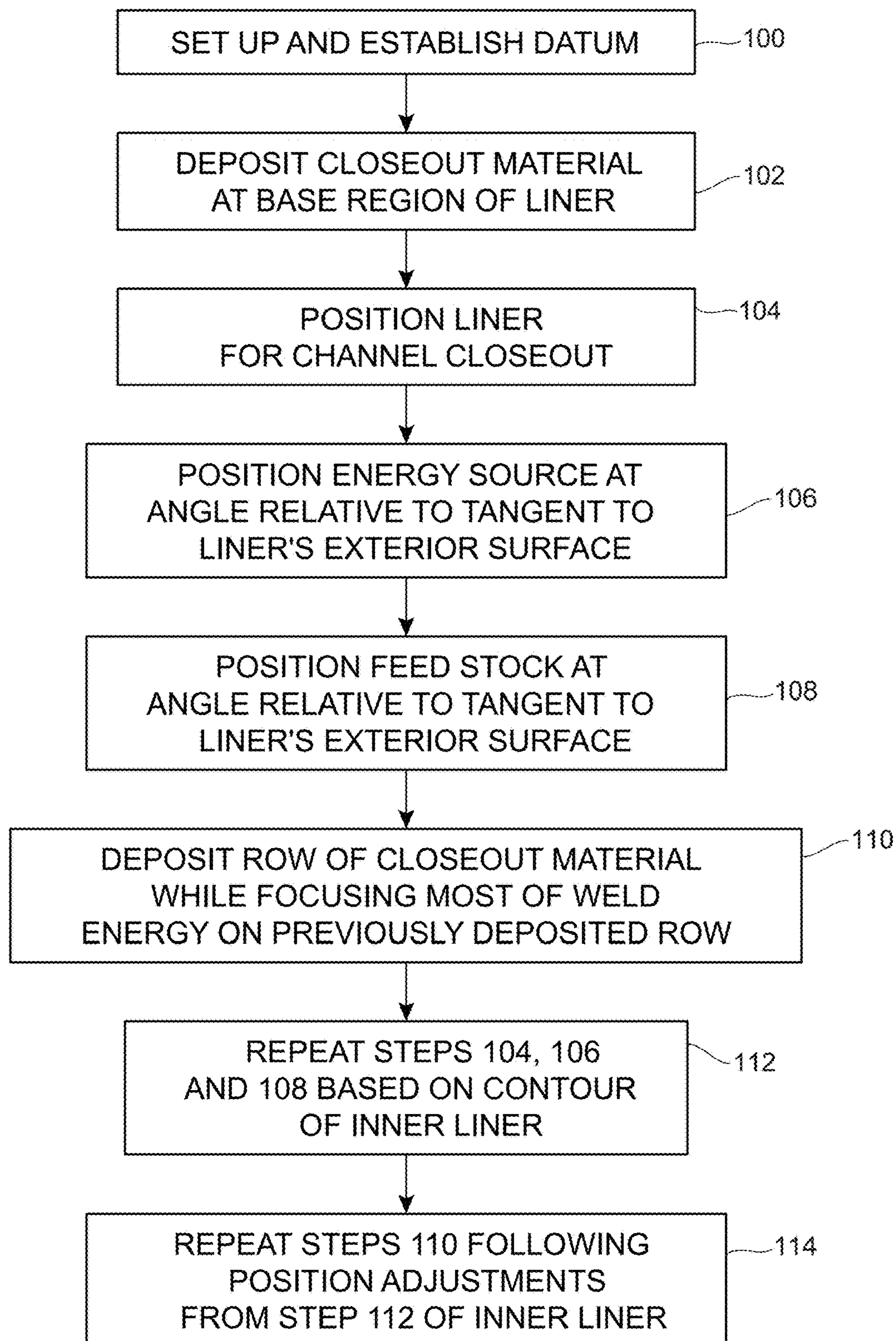


FIG. 1

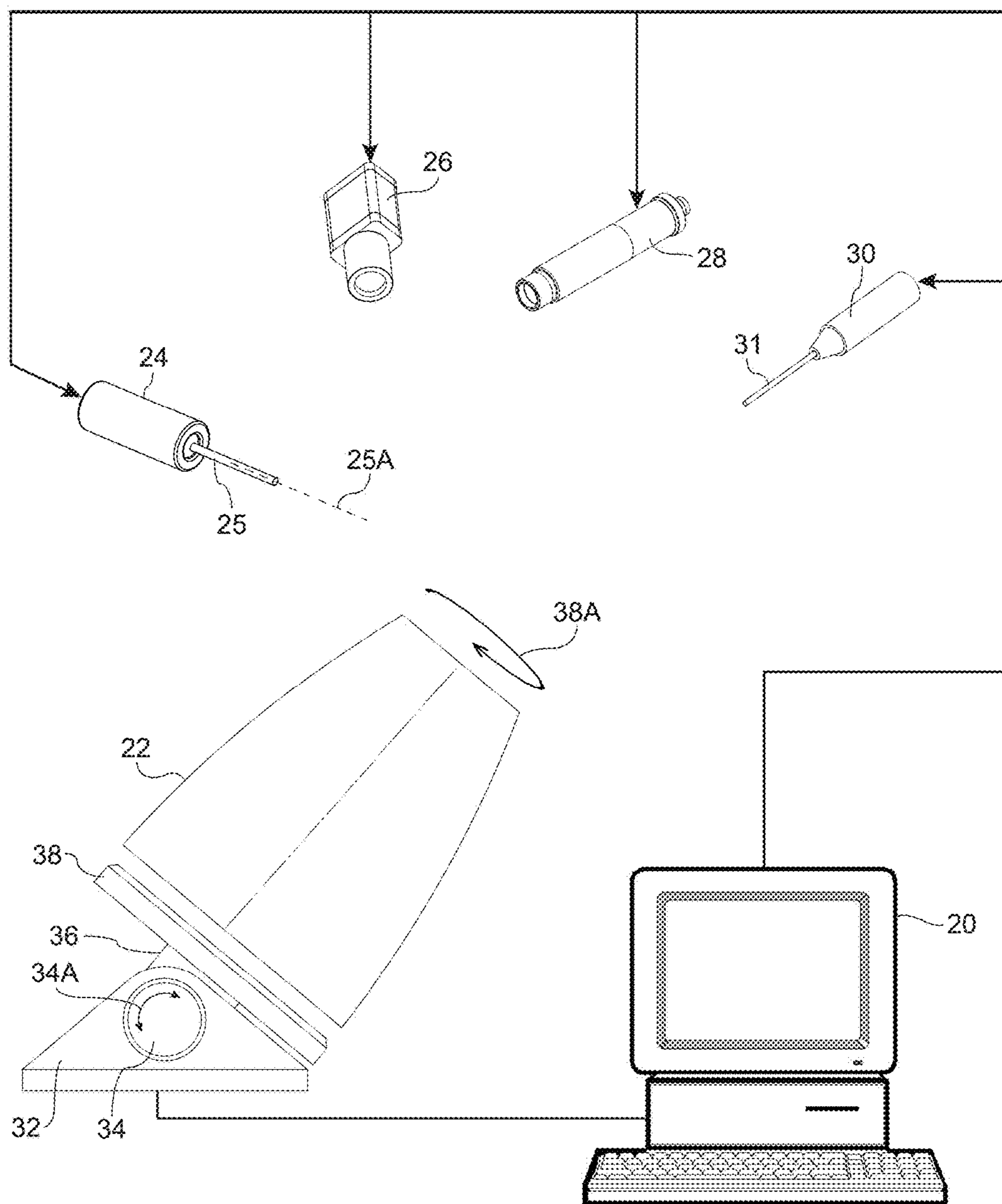


FIG. 2

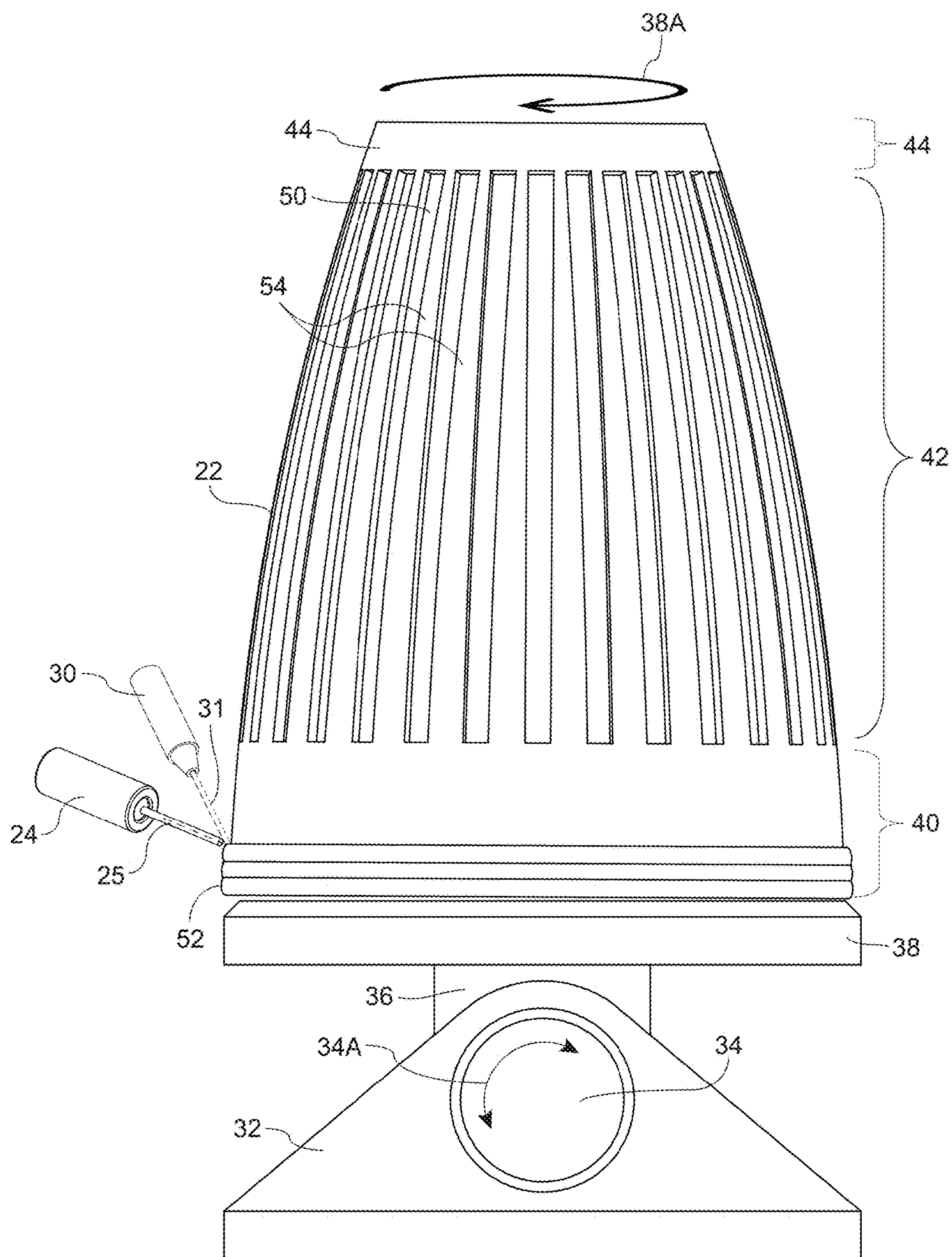


FIG. 3

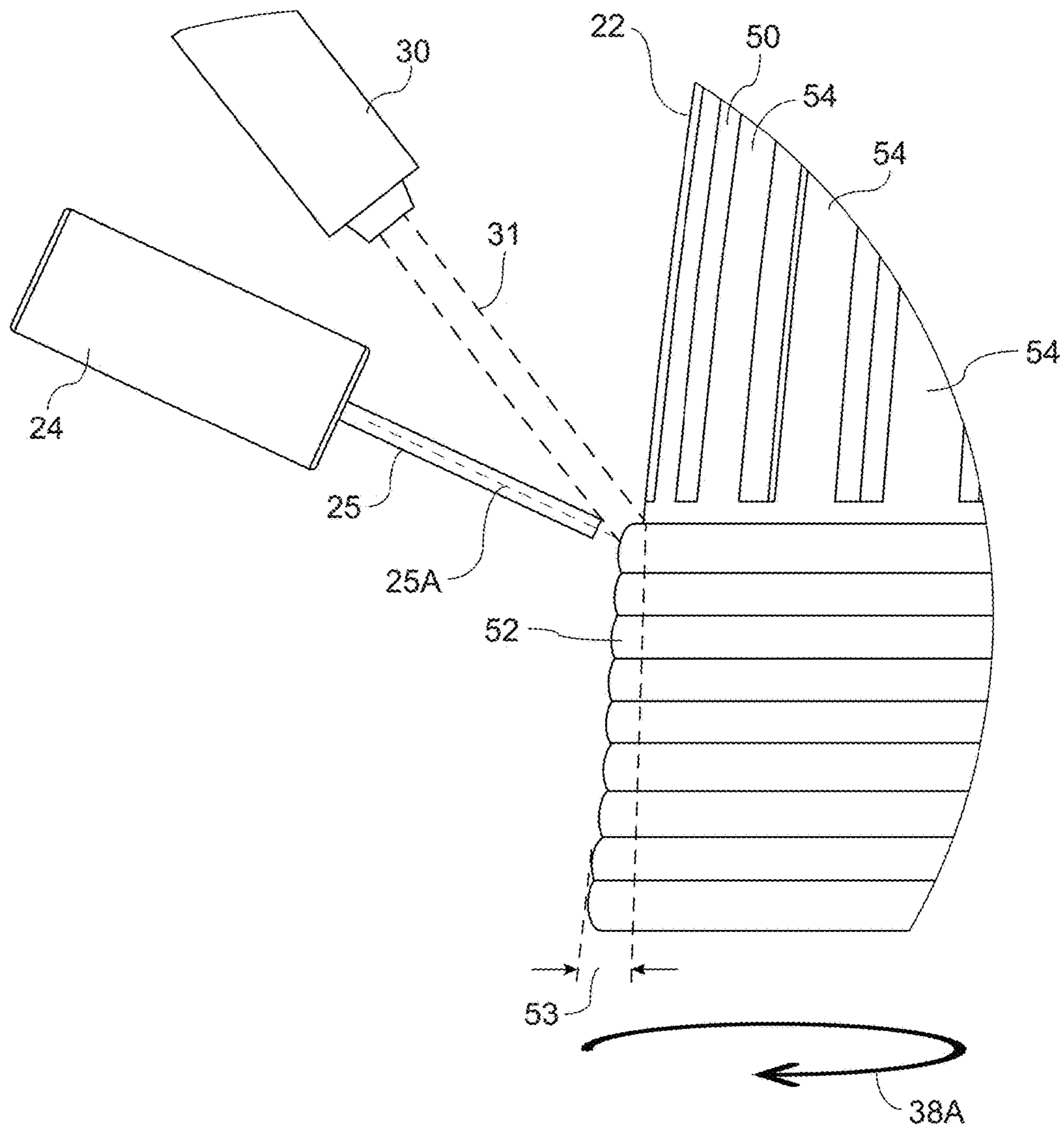


FIG. 4

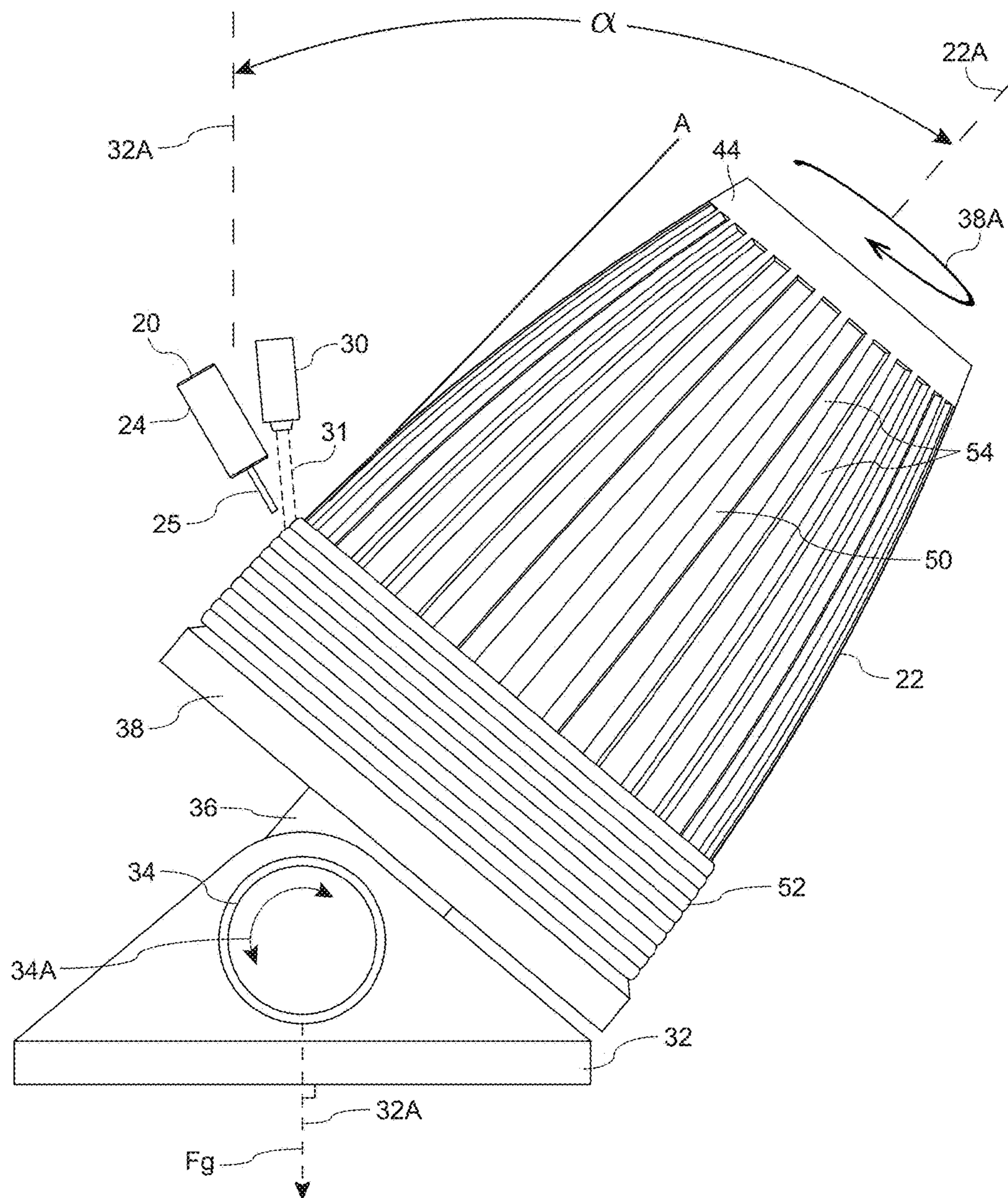


FIG. 5

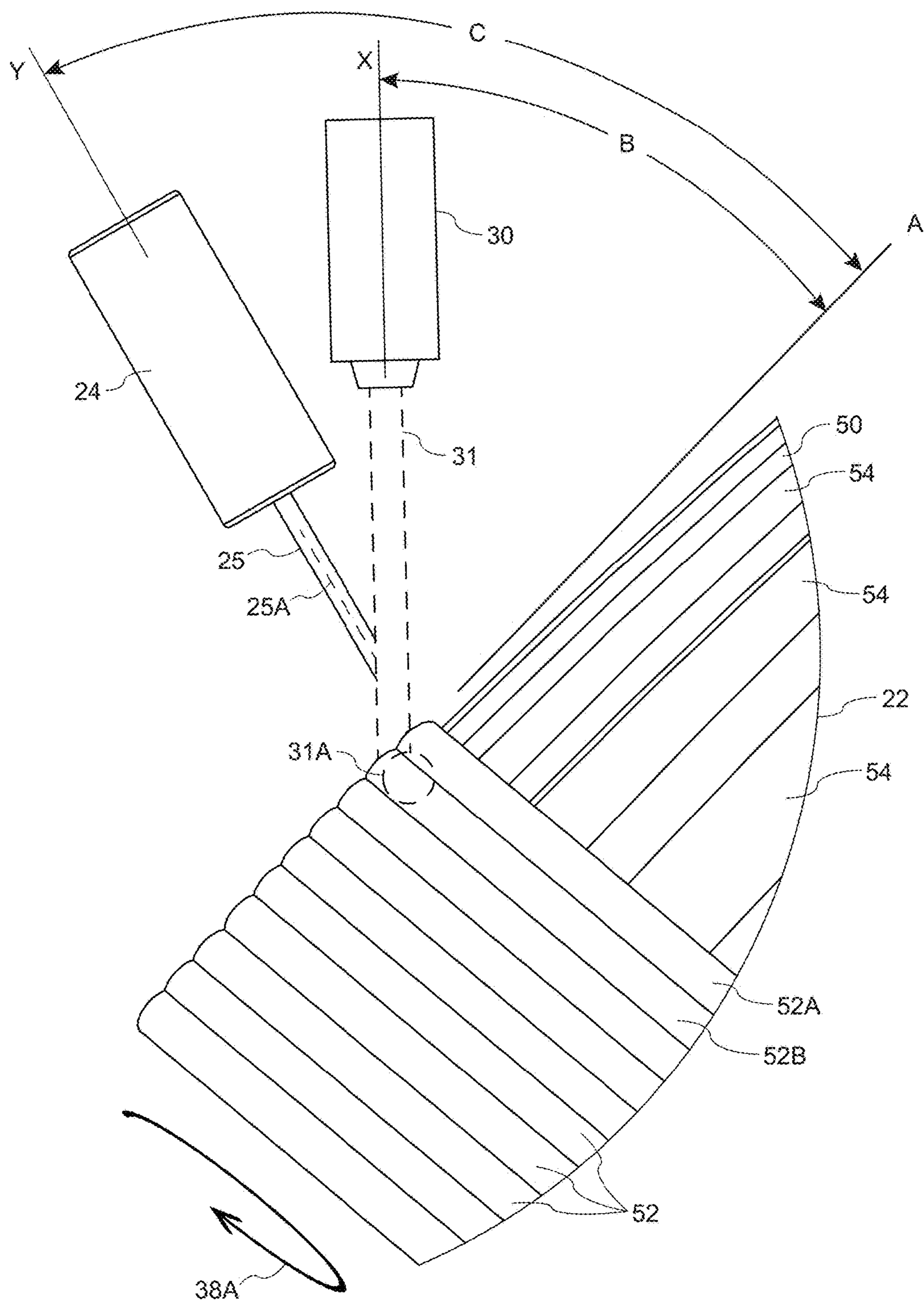


FIG. 6

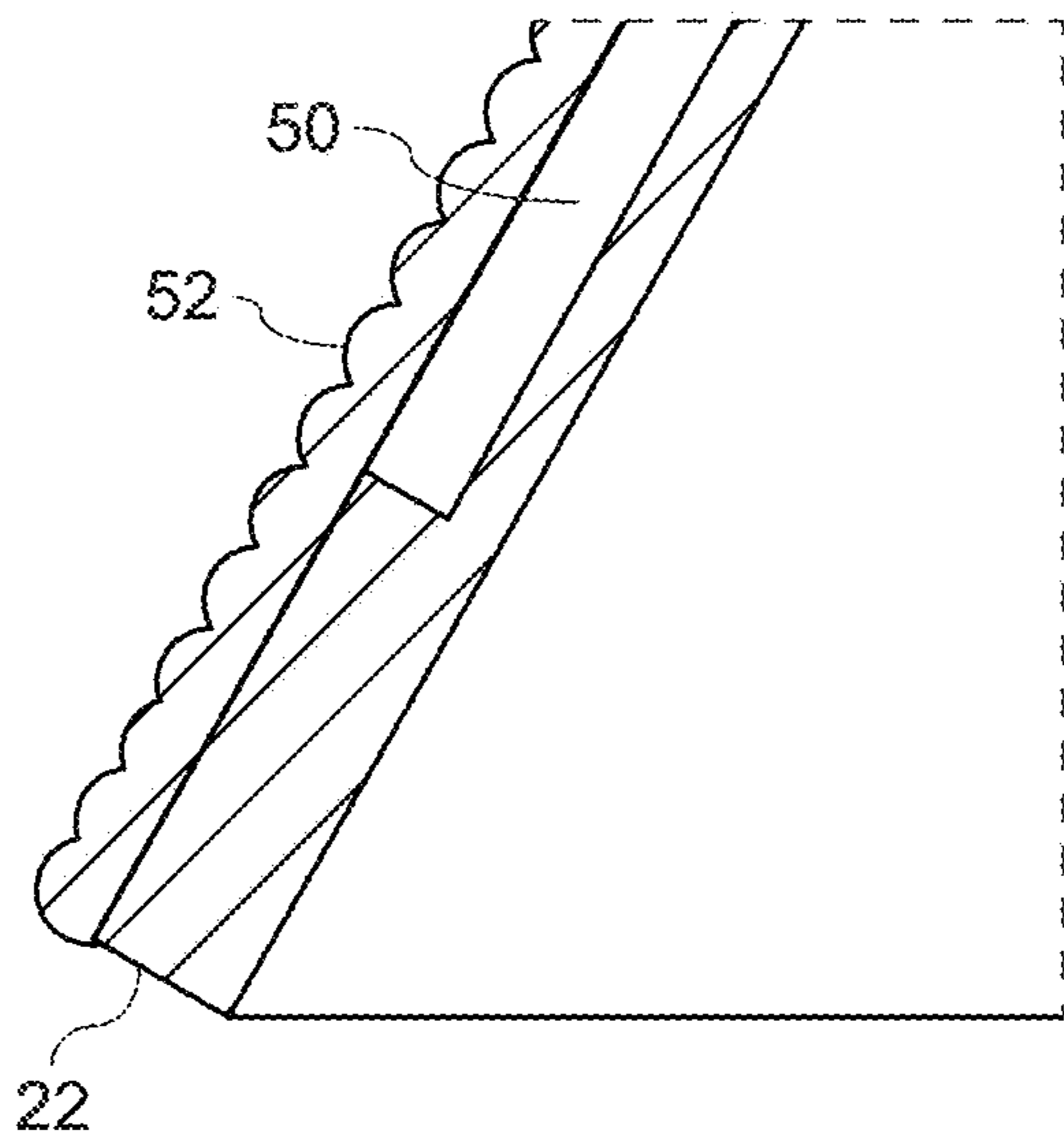


FIG. 7

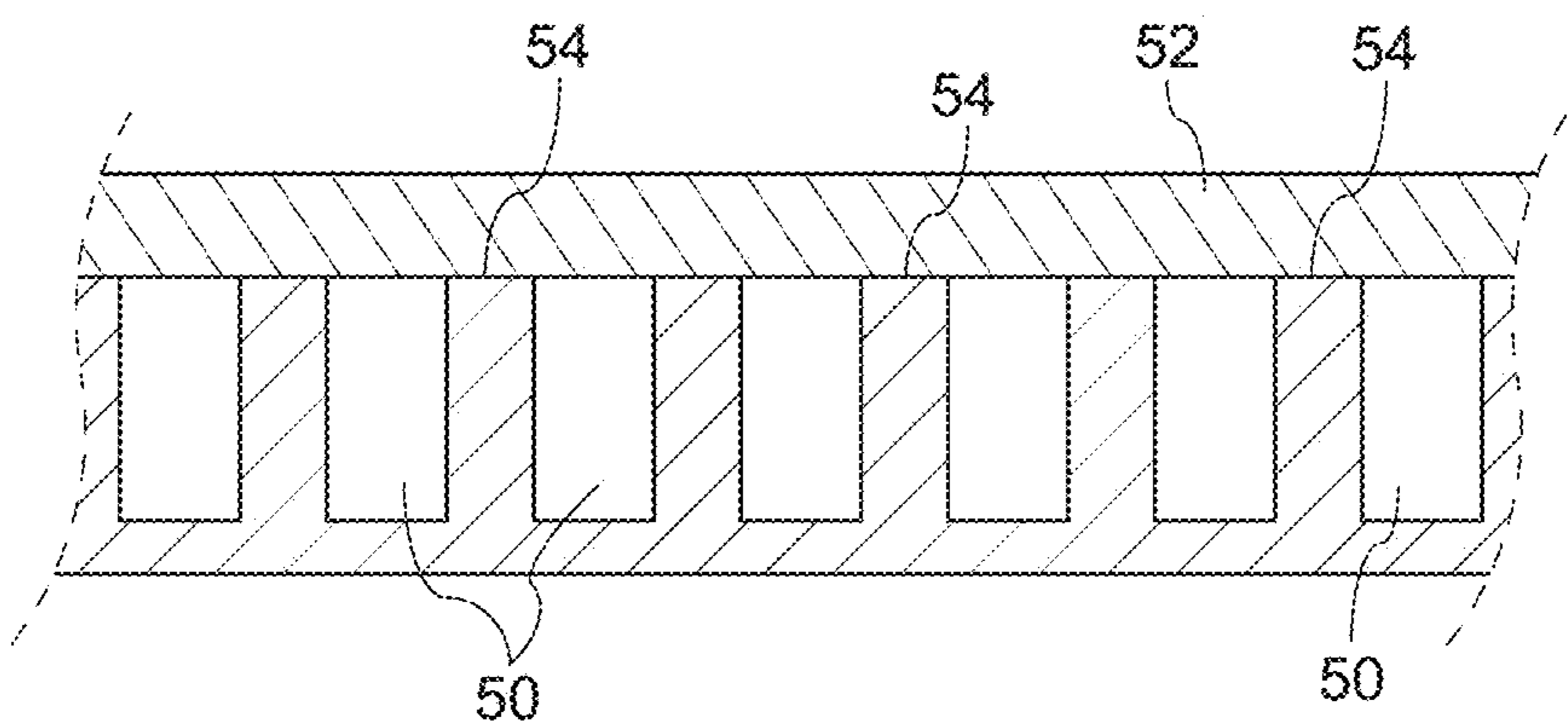


FIG. 8

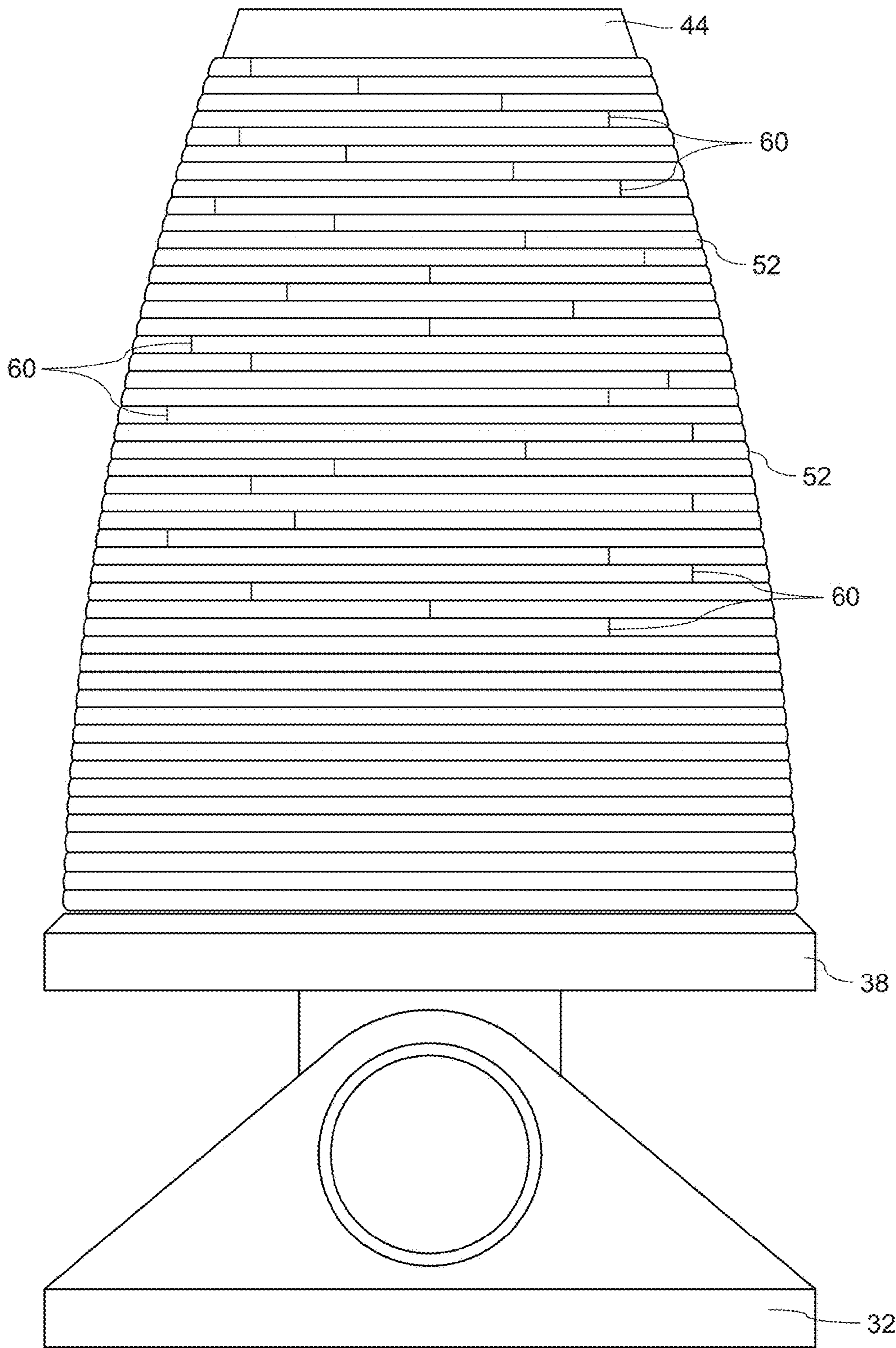


FIG. 9

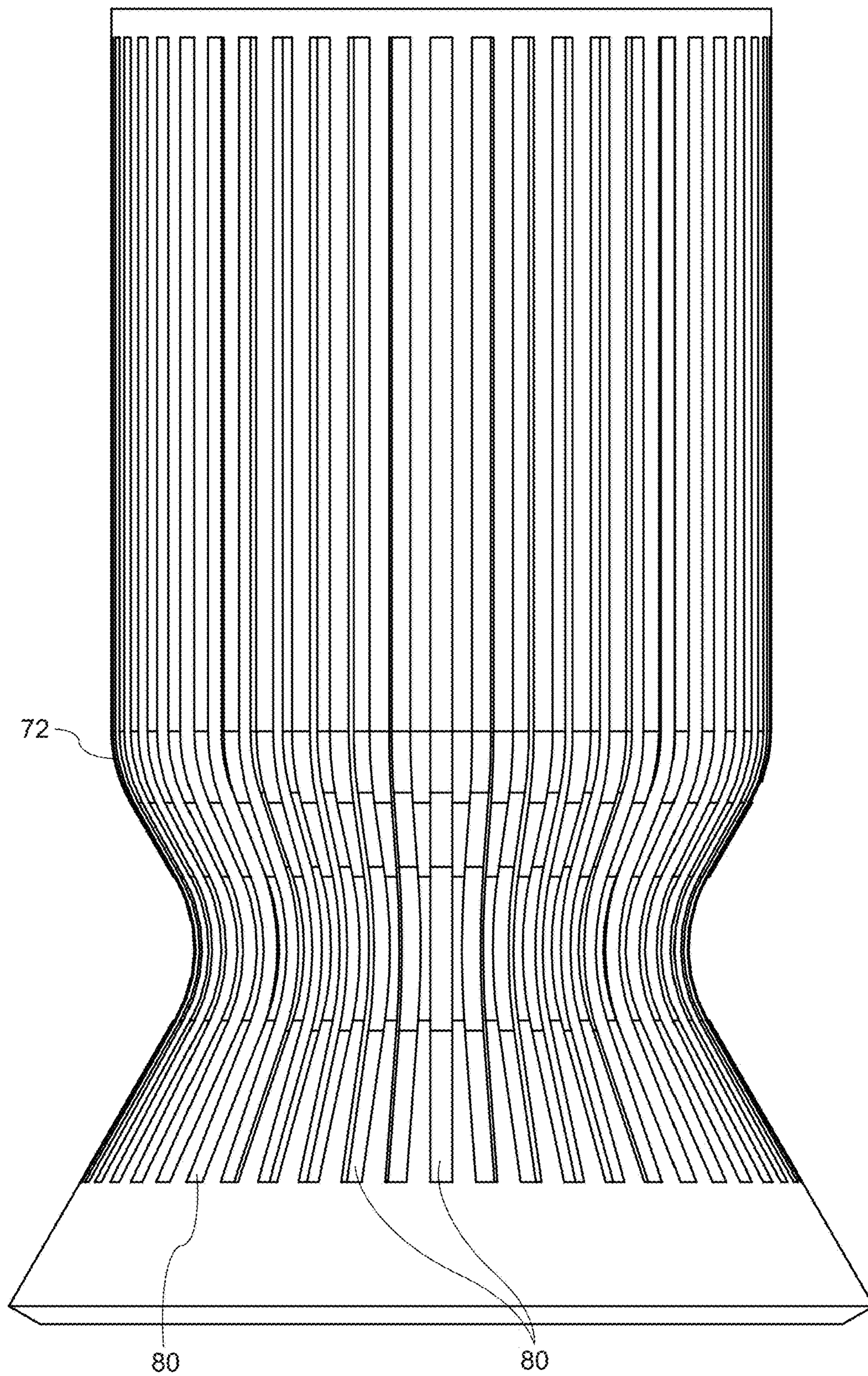


FIG. 10

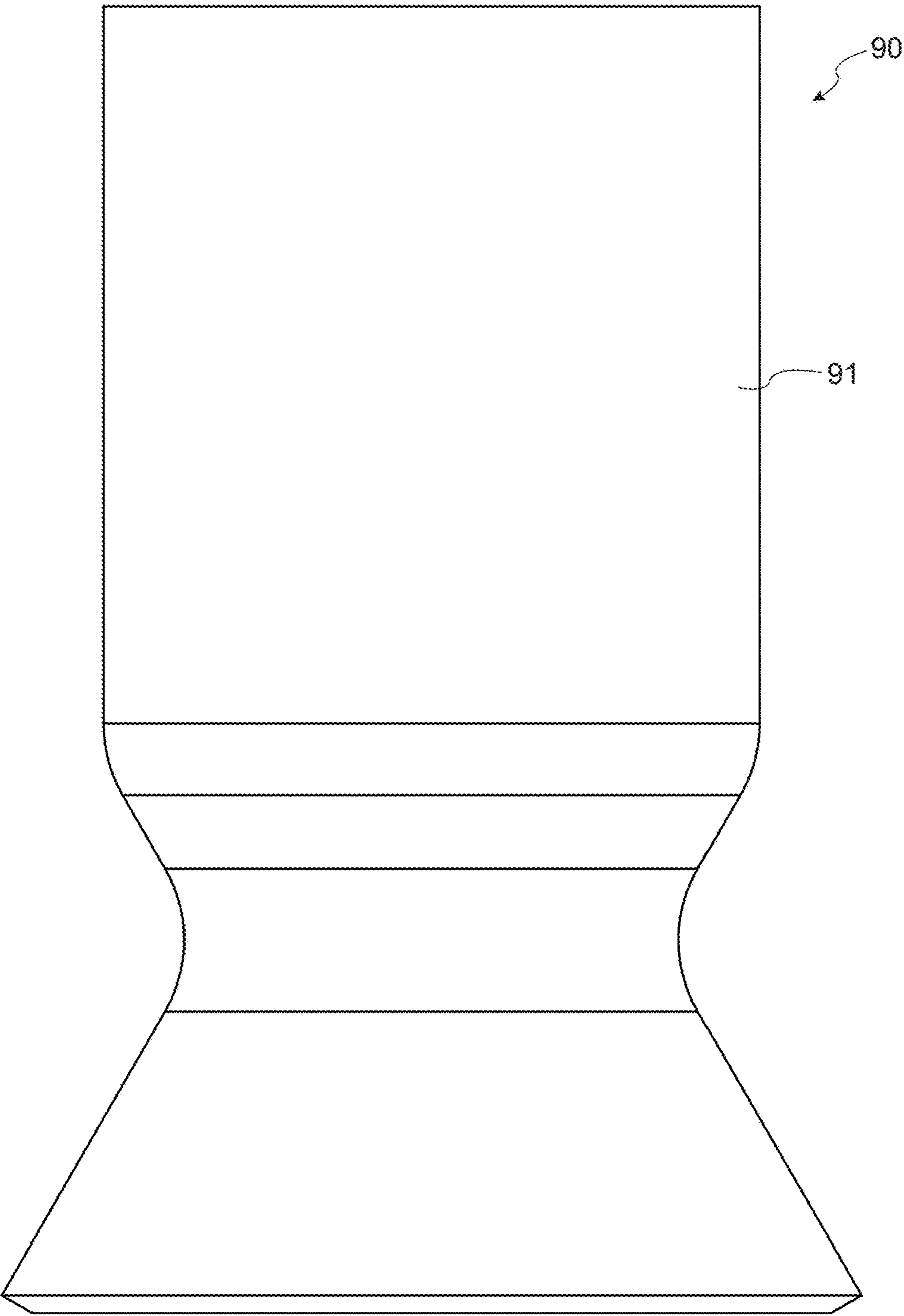


FIG. 11

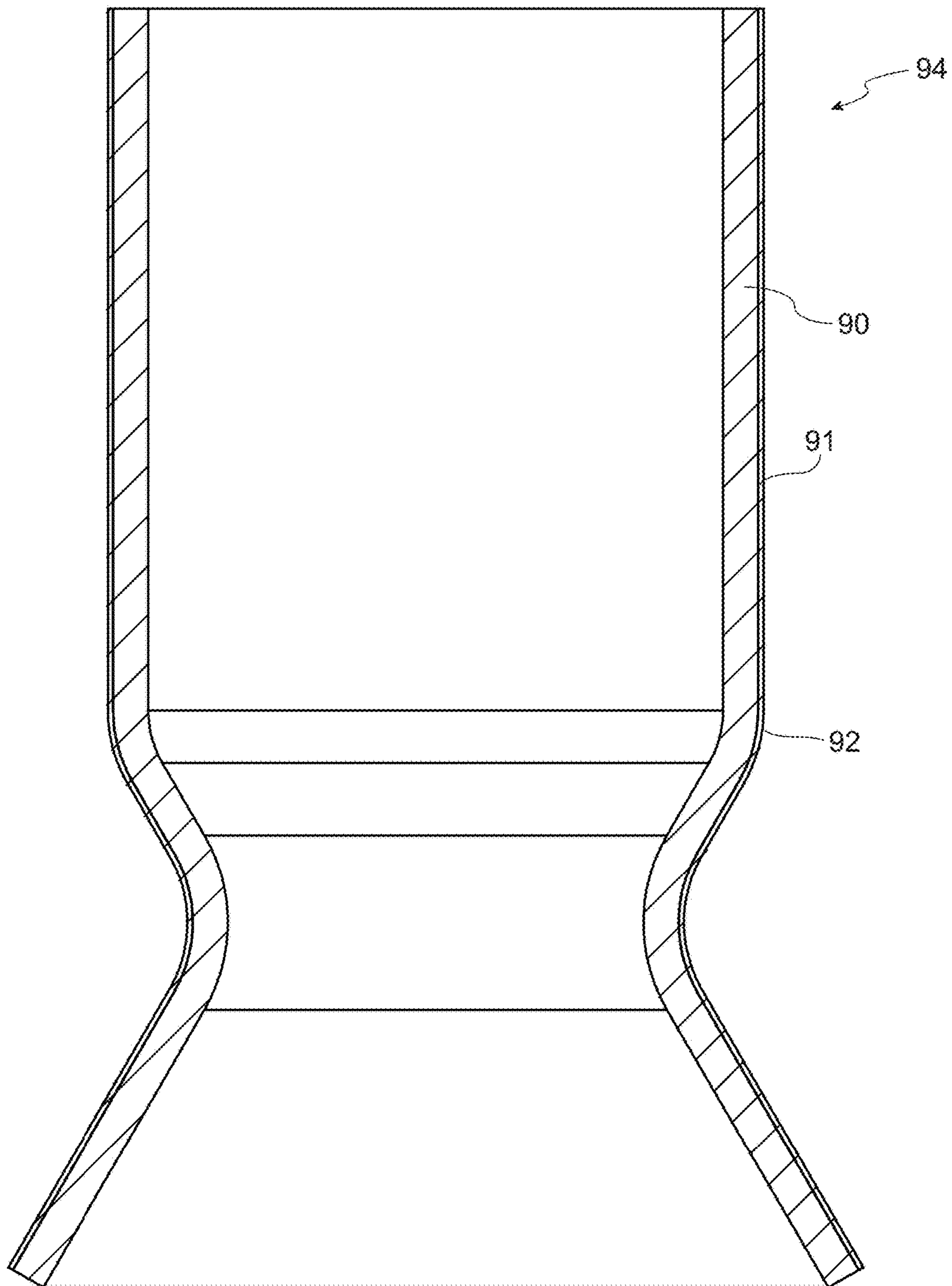


FIG. 12

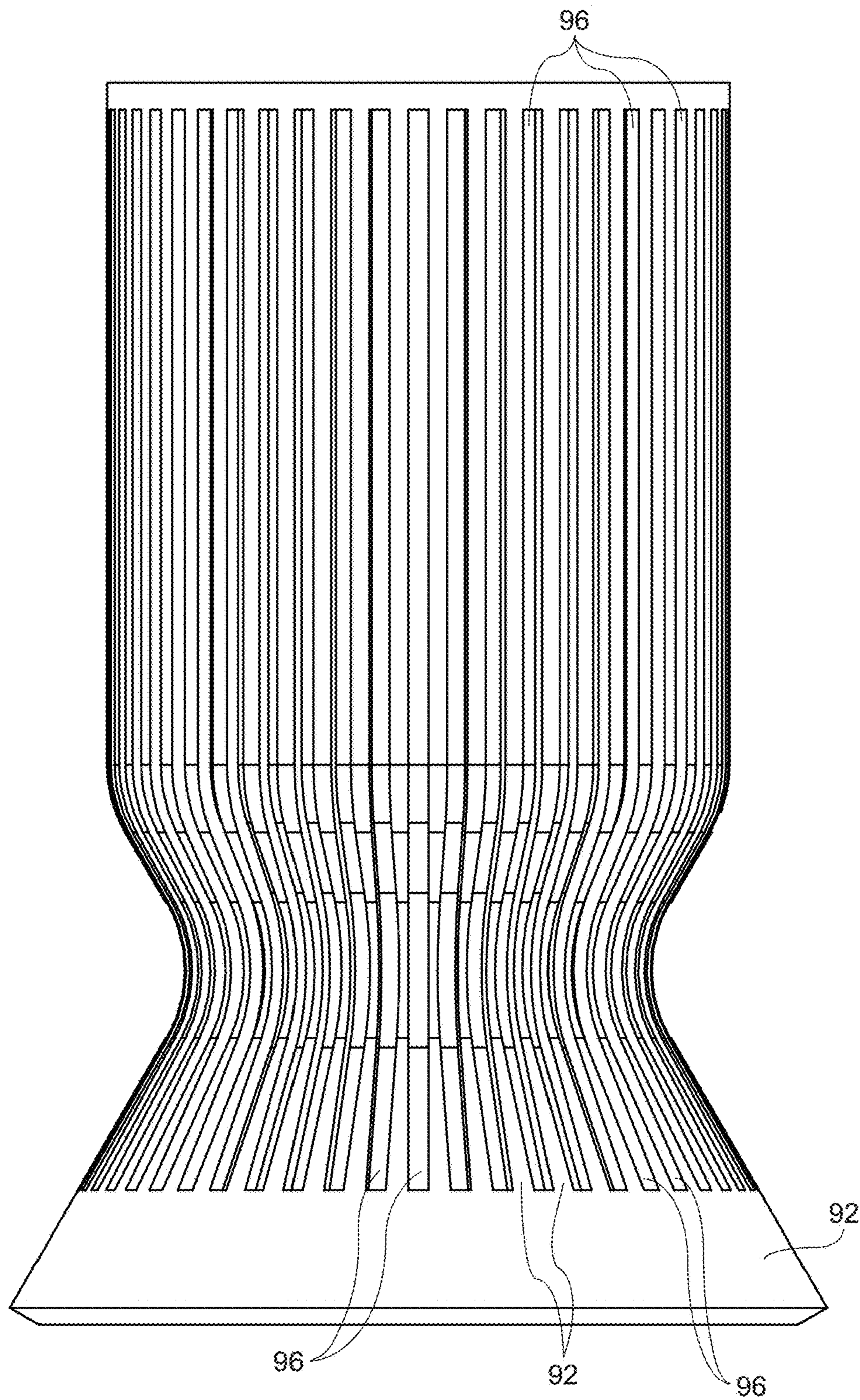


FIG. 13

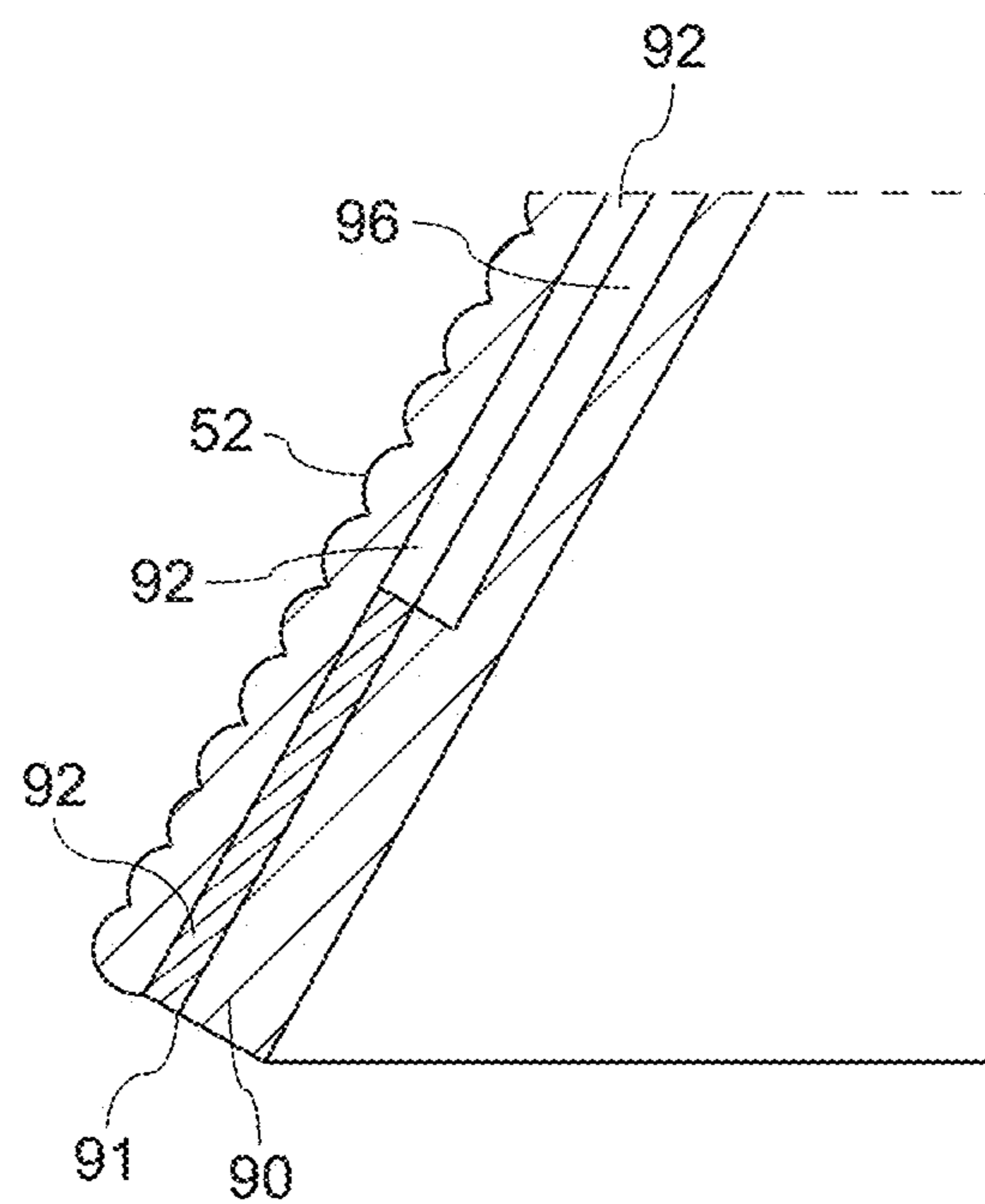


FIG. 14

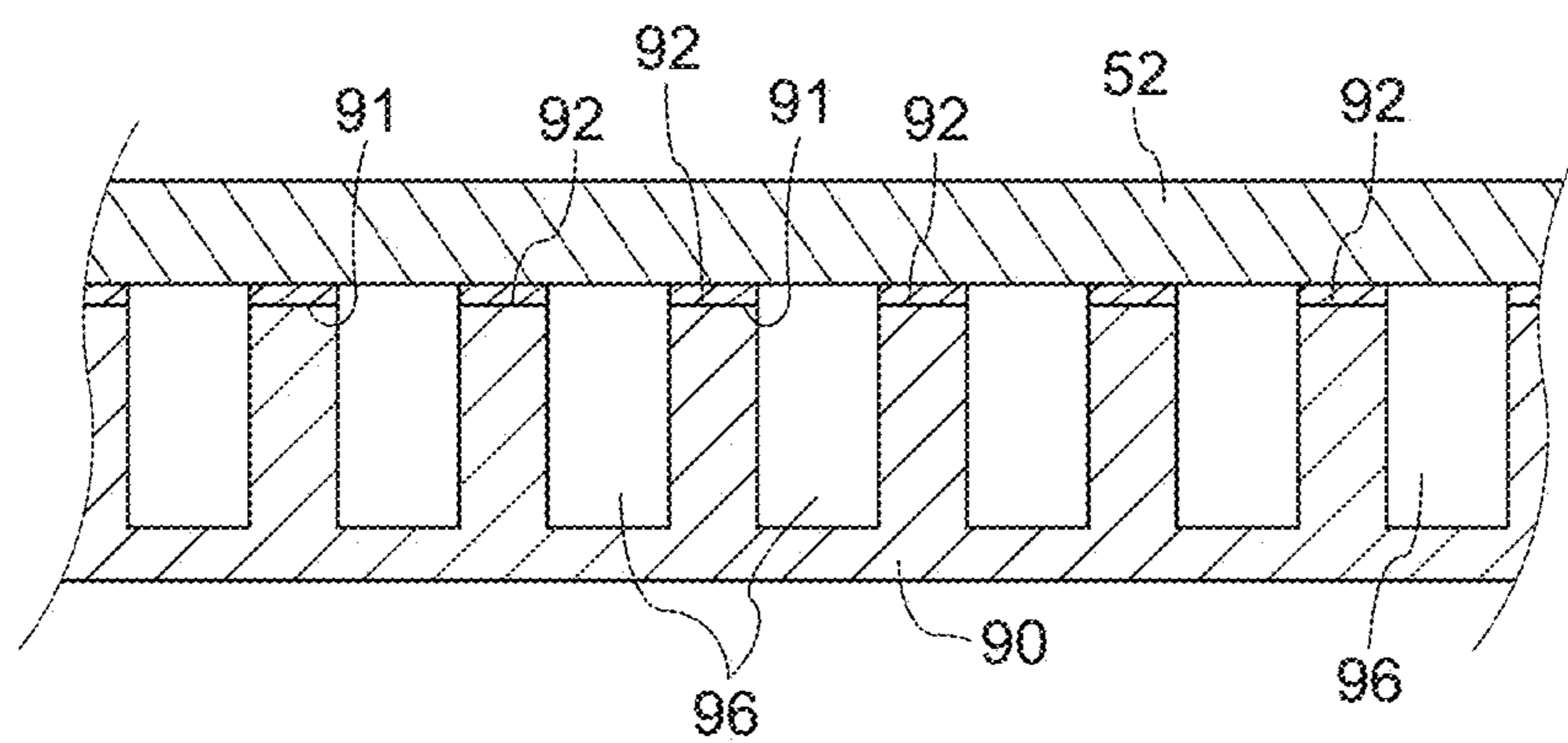


FIG. 15

## CLADDING AND FREEFORM DEPOSITION FOR COOLANT CHANNEL CLOSEOUT

### ORIGIN OF THE INVENTION

The invention described herein was made in part by employees of the United States Government and may be manufactured and used by and for the Government of the United States for governmental purposes without the payment of any royalties thereon or therefor.

### CROSS-REFERENCE TO RELATED PATENT APPLICATIONS

This patent application is co-pending with one related patent application entitled "FREEFORM DEPOSITION METHOD FOR COOLANT CHANNEL CLOSEOUT", application Ser. No. 15/615,539, filed Jun. 6, 2017, and owned by the same assignee as this patent application.

### BACKGROUND OF THE INVENTION

#### 1. Field of the Invention

This invention relates to the fabrication of nozzles or combustion chambers. More specifically, the invention is a method for the closeout of coolant channels in the liners of nozzles and combustion chambers found in rockets and nuclear reactors.

#### 2. Description of the Related Art

Rocket nozzles and combustion chambers used in rocket engines and nuclear reactors operate in extreme environments and require unique features to ensure the hardware operates safely and meets performance requirements. Combustion chambers and nozzles are exposed to high temperature gases generated from combustion byproducts. These high temperatures require unique structural features that are used to dissipate heat and properly cool walls of combustion chambers and nozzles. Combustion chambers and nozzles are contoured to allow these gases to expand and provide the necessary thrust and performance characteristics for the engine. The "hot wall" of a nozzle or combustion chamber is the wall exposed to the gaseous byproducts of combustion. A regenerative cooling scheme is typically incorporated into the wall design of combustion chambers and nozzles to maintain safe operating temperatures of the walls and increase the temperature of the fluid used for downstream processes. Regenerative cooling is a configuration in which some or all of the rocket propellant is passed through coolant channels, or tubes, or in a jacket around the combustion chamber or rocket nozzle to cool the walls of the combustion device's components.

Rocket nozzle or combustion chamber walls are formed using a series of thin-walled coolant tubes or integrally-machined coolant channels. These coolant channels run along the length of the component and are connected by an inlet and outlet manifold to distribute the fluid. Typically, a combustion chamber or nozzle incorporates an inner liner that has integral coolant channels for cooling the hot wall of the chamber or nozzle. These coolant channels must be covered to contain coolant fluid where such covering is known as channel "closeout". Since the coolant fluids are generally under high pressure, coolant channel closeouts must be reliable as they experience high strains and cycling under extreme pressures and temperatures.

Prior channel wall designs include the fabrication of an inner liner with machined coolant channels. These coolant channels are typically filled with wax and electrodeposited/plated with copper (e.g., see U.S. Pat. No. 5,249,357 to Holmes et al.) or nickel to form the closeout of the coolant channels and then further plasma sprayed to provide structure. The wax is melted out of the channels and a structural jacket is welded to the electrodeposited closeout. Nozzles manufactured via the Holmes et al. method can only be operated under limited temperatures due to the bond strength of the electrodeposited interface. Further, the Holmes et al. process of closeout exhibits significant limitations to include the introduction of impurities into the metal causing downstream issues during the welding step, and the extensive fabrication time required to fabricate a single chamber or nozzle thereby increasing the cost of production. Because Holmes et al. requires metal to be deposited at high temperatures in a vacuum chamber, the coefficients of thermal expansion of the two metals employed must be closely matched during the process to prevent cracking of the metal when the rocket nozzle or chamber cools. The use of a vacuum in the Holmes et al. process also limits the size of the ultimate nozzle or combustion chamber that can be fabricated.

In another prior art approach, Fint et al. (U.S. Pat. Nos. 7,596,940 and 8,127,443) discloses a method of fabricating a rocket engine nozzle comprising brazing of a slotted or channeled inner liner into a rocket engine nozzle jacket under controlled conditions. The process of manufacturing this assembly can be complex. The nozzle liner is often spun formed or machined from forgings prior to final machining and slotting to produce a component for brazing. Further, a match-machined mating closeout jacket must be precisely machined to provide minimal gaps for the subsequent brazing operation. Prior to the jointure of the inner liner and the outer jacket, plating is completed and a brazing foil applied. Next, the nozzle is brazed using a pressure-assisted braze furnace with high temperature, high-pressure and vacuum required to be applied within the coolant channels. This method requires significant handling, extensive tooling, and there is only one opportunity for an acceptable braze bond of the outer jacket to the inner liner. This process often requires specialized furnaces limiting the size of any components that can be produced. Upon completion of the brazing process, there is not a reliable inspection method to determine which areas were adequately brazed. The challenges in this process increase significantly with increases in the size of the ultimate combustion chamber or nozzle.

Laser welding closeout techniques are disclosed in U.S. Pat. No. 6,945,032 to Lundgren and U.S. Pat. No. 7,188,417 to Weeks. Briefly, these techniques include welding a metal sheet over an inner liner having coolant channels machined therein. There is no direct means of inspecting the resulting welds even though the welds must be precisely tracked due to the very thin channel lands on the inner liner.

### SUMMARY OF THE INVENTION

Accordingly, it is an object of the present invention to provide a method of closing out coolant channels on rocket nozzles and combustion chambers.

Another object of the present invention is to provide a coolant channel closeout method for rocket nozzles and combustion chambers that is not constrained by the size of the ultimate nozzle or combustion chamber.

Still another object of the present invention is to provide a coolant channel closeout method for rocket nozzles and

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combustion chambers in which the closeout material is securely bonded to the nozzle or combustion chamber.

Other objects and advantages of the present invention will become more obvious hereinafter in the specification and drawings.

In accordance with the present invention, a method is provided for the fabrication of a coolant channel closeout jacket. A base structure having an outer surface is clad with a first material such that a clad structure is fabricated with the clad structure having an outer clad surface. Coolant channels are machined in the clad structure such that each coolant channel extends through the first material and into the base structure. A line of tangency relative to the outer clad surface is defined for each point on the outer clad surface. A feedstock supply is provided for depositing linear rows of a metal feedstock onto the outer clad surface of the clad structure having the coolant channels. The metal feedstock is selected from the group consisting of the first material and a second material where the second material is one that is weldable to the first material. A line of tangency relative to the outer clad surface is defined for each point on the outer clad surface. An energy source is provided for generating a beam of weld energy. The feedstock supply is positioned to deposit the linear rows of metal feedstock onto a portion of the clad structure's outer clad surface where the coolant channels are formed. A first angle between the metal feedstock discharged from the feedstock supply and the line of tangency is maintained in a range of 20-90°. The energy source is positioned to direct the beam of weld energy towards a portion of the linear rows deposited on the coolant channel portion of the clad structure's outer clad surface such that less than 30% of the cross-sectional area of the beam of weld energy impinges on a currently-deposited one of the linear rows. A second angle between the beam of weld energy and the line of tangency is maintained in a range of 5-65°.

## BRIEF DESCRIPTION OF THE DRAWING(S)

Other objects, features and advantages of the present invention will become apparent upon reference to the following description of the preferred embodiments and to the drawings, wherein corresponding reference characters indicate corresponding parts throughout the several views of the drawings and wherein:

FIG. 1 is a top-level flow diagram of a freeform deposition method for the closeout of coolant channels in accordance with an embodiment of the present invention;

FIG. 2 is a top-level schematic view of a system for implementing the freeform deposition method in accordance with an embodiment of the present invention;

FIG. 3 is an isolated side view of a rocket nozzle's inner liner with coolant channels positioned on a turntable and showing the start of the freeform deposition method;

FIG. 4 is an enlarged view of the closeout material deposition region shown in FIG. 3;

FIG. 5 is an isolated side view of the rocket nozzle's inner liner positioned on the turntable and showing the early stages of coolant channel closeout in accordance with an embodiment of the present invention;

FIG. 6 is an enlarged view of the closeout material deposition region shown in FIG. 5 illustrating specified angular relationships and the distribution of weld energy in accordance with the present invention;

FIG. 7 is a portion of an axial cross-sectional view of the rocket nozzle's inner liner illustrating the closeout material covering a coolant channel;

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FIG. 8 is a portion of a radial cross-sectional view of the rocket nozzle's inner liner illustrating a single row of the closeout material covering a portion of the coolant channels;

FIG. 9 is a side view of a rocket nozzle's inner liner with the coolant channel closeout being completed in accordance with an embodiment of the present invention;

FIG. 10 is a side view of the rocket engine thrust chamber's inner liner with coolant channels formed therein;

FIG. 11 is a side view of a rocket engine thrust chamber inner liner having no coolant channels;

FIG. 12 is a cross-sectional view of the thrust chamber inner liner clad with a metal material in accordance with a process step of the present invention;

FIG. 13 is a side view of the clad structure shown in FIG. 12 after coolant channels have been machined therein in accordance with a process step of the present invention;

FIG. 14 is a portion of an axial cross-sectional view of the clad structure having coolant channels illustrating the closeout material covering a coolant channel in accordance with the present invention; and

FIG. 15 is a portion of a radial cross-sectional view of the clad structure having coolant channels illustrating a single row of the closeout material covering a portion of the coolant channels in accordance with the present invention.

## DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

The present invention is directed to a new method and system for use in the fabrication of rocket engine nozzles, rocket thrust or combustion chambers, and other regenerative cooling systems, such as cooling systems used in nuclear reactors. While this invention is susceptible of embodiment in many different forms, there are shown in the drawings and will herein be described in detail, several embodiments with the understanding that the present disclosure should be considered as an exemplification of the principles of the invention and is not intended to limit the invention to the embodiments so illustrated. For purpose of illustration, the present invention will be described herein for coolant channel closeout in a rocket nozzle. Accordingly, to the extent that any numerical values or other specifics of materials, etc., are provided herein, they are to be construed as exemplifications of the inventions herein, and the inventions are not to be considered as limited thereto.

The following description and drawings are illustrative and are not to be construed as limiting. Numerous specific details are described to provide a thorough understanding of the disclosure. However, in certain instances, well-known or conventional details are not described in order to avoid obscuring the description. References to one, or an, embodiment in the present disclosure can be, but are not necessarily, references to the same embodiment; and, such references mean at least one of the embodiments.

Reference in this specification to "one embodiment" or "an embodiment" means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment of the disclosure. The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments mutually exclusive of other embodiments. Moreover, various features are described which may be exhibited by some embodiments and not by others. Similarly, various requirements are described which may be requirements for some embodiments, but not other embodiments.

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The terms used in this specification generally have their ordinary meanings in the art, within the context of the disclosure, and in the specific context where each term is used. Certain terms that are used to describe the disclosure are discussed below, or elsewhere in the specification, to provide additional guidance to the practitioner regarding the description of the disclosure. For convenience, certain terms may be highlighted, for example using italics and/or quotation marks. The use of highlighting has no influence on the scope and meaning of a term; the scope and meaning of a term is the same, in the same context, whether or not it is highlighted. It will be appreciated that the same thing can be said in more than one way.

Consequently, alternative language and synonyms may be used for any one or more of the terms discussed herein, or is any special significance to be placed upon whether or not a term is elaborated or discussed herein. Synonyms for certain terms are provided. A recital of one or more synonyms does not exclude the use of other synonyms. The use of examples anywhere in this specification, including examples of any terms discussed herein, is illustrative only, and in no way limits the scope and meaning of the disclosure or of any exemplified embodiment. Likewise, the disclosure is not limited to various embodiments given in this specification.

Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure pertains. In the case of conflict, the present document, including definitions will control.

FIG. 1 sets forth the steps of the freeform deposition closeout method used to fabricate coolant channel closeout of an inner liner of a rocket nozzle, rocket thrust or combustion chamber, or any structure having coolant channels that must be closed out. This method fabricates an external metal jacket onto a pre-fabricated metal inner liner having integrated coolant channels. Such metal inner liners are typically made from copper (e.g., for combustion chambers) or stainless/Inconel (e.g., for nozzles), while the external closeout material is typically a high-strength stainless steel alloy or superalloy having the strength needed to contain high operational pressures that will exist in coolant channels. The freeform deposition closeout method described herein speeds up the production of both a rocket nozzle or rocket thrust chamber enabling their manufacture within a significantly reduced timeframe. The process steps will be described briefly below, and then in greater detail with reference to additional figures.

Step **100** involves the set up and establishment of datum/parameters for the operation of the method as would be understood in the art of robotic welding operations. In general, the present invention provides for the deposition of rows of closeout material on a pre-fabricated inner liner as relative rotation is introduced between the inner liner and the source of closeout material being deposited. Accordingly, in step **102**, an inner liner previously fabricated with coolant channels is placed in either a vertical or horizontal position, and coolant channel closeout material is deposited in rows along the outer circumference of the inner liner at a base region thereof where there are no coolant channels. Step **102** is repeated until the region of the inner liner having coolant channels is reached. Next, at step **104**, the inner liner is positioned in accordance with angular specifications (to be described further below) prior to starting channel closeout procedures. At step **106**, the energy source is positioned at an angle relative to a line projected tangentially along the exterior surface of the inner liner. At step **108**, the metal

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feedstock used to create the external jacket is positioned at an angle relative to the line projected tangential to the exterior surface of the inner liner. Next, at step **110**, a row of closeout material is deposited from the feedstock onto the area containing the coolant channel lands. The energy source's energy beam is applied to the metal feedstock being deposited so that a greater amount of the weld energy is focused on the previously-deposited row of closeout material than on the currently-deposited row of closeout material. This process allows adequate bonding to each row of closeout material to the channel lands without deforming either feature. Each row of closeout material is deposited while the inner liner is being rotated/repositioned relative to the metal feedstock source. Since the outer contour of a rocket nozzle or thrust chamber is curvilinear, it is necessary to adjust the position(s) of the inner liner and/or the closeout material's deposition and welding sources to maintain appropriate angles relative to the above-referenced tangent line. Accordingly, step **112** involves repeating steps **104**, **106**, and **108** based on the contour of the outer surface of the inner liner so that appropriate angles are maintained relative to the line projected tangential to the outer surface of the inner liner. Next, at step **114**, deposition step **110** is repeated following the position adjustments of step **112**. As will be explained further below, each row of closeout material deposition begins at a point different from the starting point of the immediately-previous row.

The necessary components to practice the present invention's "freeform closeout method" are depicted in FIG. 2. Computer **20** is programmed to run the method of FIG. 1. Computer **20** may be a personal computer, a personal logic controller, or other processing system. The freeform closeout method may be pre-programmed into computer **20**, guided by machine vision, or a combination of the two. Computer **20** monitors and controls (as indicated by the solid lines of connectivity) all of the components used in the present invention. Such components can include, but are not limited to: wire feed unit **24**, camera **26**, pyrometer **28**, energy source and purge unit **30**, and turntable **38** mounted on a base **32**. Other components may be added. For example, an additional purge nozzle may be added to help prevent oxidation of the welds created during coolant channel closeout.

The geometry of the inner liner having coolant channels along its length can vary and is generally derived or programmed into computer **20** directly from a CAD model. Because this is an automated process controlled by computer **20**, a closed loop feedback mechanism may be incorporated to adjust the process to ensure the quality of the weld. The welding method herein allows full visual access for a variety of sensors including digital videography or photography using camera **26** and infrared measurements using pyrometer **28** or infrared thermography. This provides valuable process information in real-time to monitor and regulate heat input, and to detect defects/anomalies in real-time so that the freeform deposition closeout method can be stopped or adjusted as necessary. Since the external metal jacket closing out the coolant channels is being built onto the inner liner in rows, a localized defect can be repaired using machining, grinding, or alternate techniques, and the building process continued. This is a significant advantage over the current methods that do not allow any opportunity for repair during the closeout process.

In general, the present invention uses a robotic laser beam welding system wherein a wire-based fusion welding system is used to create a freeform deposition shell or external jacket onto the outside of a rocket nozzle inner liner or a

rocket thrust chamber inner liner. Alternate embodiments of this method may include a robotic pulsed-arc/pulsed MIG, hotwire welding (combined MIG preheat and laser beam), an electron beam, or other methods to weld a metal feedstock. The metal feedstock may be deposited-wire or deposited-powder melted within the energy source. As is known in the art, wire feed unit **24** can include a control switch, a contact tip, a power cable, a gas nozzle, an electrode conduit and liner, and a gas hose. The control switch, or trigger, when initiated by the processor, initiates the wire feed, electric power, and the inert shielding gas flow, causing an electric arc to be struck when using a pulsed-arc method. When used with a laser beam, wire feed unit **24** only requires the metal feed stock and inert shielding gas to be initiated. Most wire feed units **24** provide wire through a nozzle **25** at a constant feed rate, but more advanced machines can vary the feed rate in response to variable energy of the directed energy source.

The present invention can be implemented using one or more camera(s) **26** to enable the real-time observation of each individual weld and, thus, permit real-time correction of any welding errors thereby reducing the overall time for fabrication of a regenerative cooling system. Camera(s) **26** can be one or more laser triangulation cameras **26** for online monitoring of the weld bead geometry right after the welding point. Pyrometer **28** may comprise both an optical system and thermal detection device. An optical high-speed pyrometer **28** mounted coaxially or off-axis on the laser welding head may be connected through an optical fiber to provide temperature measurements of the focal spot area at a frequency up to 40 kHz. A back-reflection sensor can be mounted coaxially or off-axis on the optical head of pyrometer **28**. Thermal radiation and back-reflection sensing spots may be centered on the energy or laser focal spot. Pyrometer **28** uses changes in temperature, including temperature drops, to detect welding defects that may need correction.

Energy source and purge unit **30** can include both an energy source (e.g., a laser generating a beam **31** of weld energy) to melt/fuse (i.e., weld) the feedstock supplied via wire feed unit **24**, and a gas purge used to shield both sides of the weld while forming the external jacket. The purge function of energy source and purge unit **30** prevents oxidation of the deposited or welded closeout material. Although not required, an additional purge nozzle may be added to further enhance the quality of the metal jacket fabricated onto the inner liner. A rocket nozzle inner liner **22** (with integrated coolant channels being omitted from this illustration thereof) is positioned onto turntable **38**. Turntable **38** can be repositioned by a pivoting support **34** coupled to a base **32** and a support arm **36** so that inner liner **22** is positioned at certain angles that can vary during fabrication in order to facilitate the formation of an external jacket onto inner liner **22**. Pivoting movement of pivoting support is indicated by two-headed arrow **34A**. As would be well understood in the art, pivoting support **34** and turntable **38** are responsive to the commands of computer **20**. Other components can be coupled to computer **20** to assist in the implementation of the method herein.

Referring additionally now to FIG. 3, the setup is illustrated for step **102**. Specifically, inner liner **22** with integral coolant channels **50** is shown positioned on turntable **38**. Inner liner **22** includes the following three areas: inner liner bottom stock region **40** that has a flat surface lacking coolant channels **50**, coolant channel region **42** that includes coolant channels **50** that run the length of region **42**, and inner liner top stock region **44** that includes a flat surface free of coolant channels **50**. Arrow **38A** indicates that turntable **38** can be

rotated or repositioned during the freeform deposition closeout method. Turntable **38** can be rotated in a clockwise direction shown by arrow **38A** or in a counter-clockwise direction without departing from the scope of the present invention. In response to instructions from computer **20** (not shown in FIG. 3), arm **36** is rotated by pivoting support **34** thereby changing the angle of turntable **38** with inner liner **22** thereon as indicated by arrow **34A**.

Step **102** of the freeform deposition closeout method starts at bottom stock region **40** as wire fed from wire feed unit **24** is heated by energy source **30** to thereby weld a first linear row **52** of closeout material onto the bottom circumference of inner liner **22**. For clarity of illustration, the wire feedstock material discharged from nozzle **25** of unit **24** has been omitted from the figures. Wire feed unit **24** can be held at any angle relative to the surface of inner liner **22** at its bottom stock region **40**. The closeout material is deposited onto inner liner **22** in linear rows **52** so that each row **52** is welded to the previous row **52** and to portions of inner liner **22** to thereby start the formation of an external jacket. Energy source and purge unit **30** can be used to purge the backside of the weld to reduce defects. For clarity of illustration, wire feed unit **24** and energy source and purge unit **30** are shown as independent elements. However, it is to be understood that the functions of these two elements could be combined such that the wire feedstock and laser (or other energy beam) are collinear with one another without departing from the scope of the present invention. Furthermore, while FIG. 3 depicts inner liner **22** in an upright vertical position during step **102**, it is to be understood that inner liner **22** could be tilted relative to vertical for step **102** without departing from the scope of the present invention.

FIG. 4 illustrates an enlarged view of the weld region in step **102**. Each row **52** of closeout material has a width **53** measured from the external surface of inner liner **22** to the furthest external surface of row **52**. Laser beam **31** emitted from energy source and purge unit **30** has an energy level associated therewith sufficient to weld the metal (discharged from nozzle **25** of wire feed unit **24**) to inner liner **22** and to an immediately adjacent row. Step **102** terminates prior to commencement of the closeout of coolant channels **50**. In the illustrated embodiment, inner liner **22** is rotated, while wire feed unit **24** and energy source and purge unit **30** are held stationary. However, it is to be understood that inner liner **22** could remain stationary, while units **24** and **30** are rotated about inner liner **22** without departing from the scope of the present invention.

Referring now to FIGS. 5 and 6, the closeout of coolant channels **50** in accordance with the present invention will be described. FIGS. 5 and 6 illustrate the above-described method steps **104-112**. In step **104**, turntable **38**, in response to instructions from computer **20** (not shown), is repositioned so that inner liner **22** is positioned at an angle  $\alpha$  of 5-70° defined between the longitudinal axis **22A** of inner nozzle **22** and a line **32A** that is perpendicular to the support portion of base **32**, i.e., aligned with the local force of gravity  $F_g$ . That is, line **32A** would be aligned with longitudinal axis **22A** when inner liner **22** is in a vertical orientation. Turntable **38** is rotated relative to base **32**, while wire feed unit **24** and energy source and purge unit **30** are stationary. The angles of wire feed unit **24** and energy source and purge unit **30** are set so that the closeout material is deposited in rows **52** onto coolant lands **54** without entering coolant channels **50**. Coolant channel lands **54** are the portions of the exterior surface of inner liner **22** remaining after the inner liner is slotted with coolant channels **50**.

Typically, rows **52** are deposited such that they are perpendicular to coolant channels **50** and lands **54**.

To keep closeout material out of coolant channels **50** while also eliminating the use of filler materials in channels **50** that could contaminate the weld, specific angular relationships must be maintained between a tangent line "A" and the angles that the wire feed stock and the welding laser beam make with tangent line A. Tangent line A is a line of tangency of the exterior surface of inner liner **22** at lands **54** at the point of deposition for a particular row **52** of closeout material. Since inner liner **22** is contoured, tangent line A changes with positions along the length of inner liner **22**. Steps **106** and **108** are implemented to achieve the following angular relationships. As shown in the enlarged view of FIG. **6**, the angle that laser beam **31** (originating from unit **30**) makes with tangent line A is referenced by angle "B", and the angle that the wire feedstock (not shown for reasons of clarity) makes with tangent line A is referenced by angle "C". As is known in the art, the end of nozzle **25** is generally positioned very close to inner liner **22**. Accordingly, the longitudinal axis **25A** of nozzle **25** will be aligned with the wire feedstock discharged from nozzle **25** such that angle B between tangent line A and the wire feedstock can be considered to be measured between tangent line A and the longitudinal axis **25A** of nozzle **25**. Throughout the closeout of coolant channels **50**, angle B should be maintained in the range of 5-65° relative to tangent line A, and angle C should be maintained in the range of 20-90° relative to tangent line A.

In addition to maintaining the above-described angular relationships, the method of the present invention controls the amount of energy supplied by laser beam **31** to a currently-deposited row **52** by controlling the placement of the cross-sectional area of laser beam **31** impinging on the deposited rows **52**. Accordingly, the present invention controls the position of unit **30** to distribute the energy of laser beam **31** as noted in step **110**. More specifically, laser beam **31** is directed at the region of closeout material deposition such that less than 30 percent of the beam's energy is focused on the currently-deposited row **52A**, while greater than 70 percent of the beam's energy is focused on the immediately adjacent and previously-deposited row **52B**. The division of beam energy in this fashion prevents material from current row **52A** from melting into a coolant channel **50**, while welding current row **52A** to lands **54** and to its adjacent and previously-deposited row **52B**. The division of beam energy can be based on the cross-sectional area (indicated by dashed line circle **31A**) of laser beam **31** as would be understood in the art.

The above-described processing steps are repeated in step **112** for each subsequent row **52** of the coolant channel closeout process. Step **112** includes the step of adjusting the above-described angular relationships of inner liner **22**, the feedstock emitted from nozzle **25**, and laser beam **31** emitted from energy source and purge unit **30**. When coolant channel closeout is complete, the welded-together rows **52** cover coolant channels **50** (FIG. **7**) with each row **52** circumscribing inner liner **22** and welded to lands **54** (FIG. **8**).

After a deposited row **52** circumscribes inner liner **22**, the various components described herein are adjusted as described above prior to deposition of a next row. As shown in FIG. **9**, start/stop points **60** for deposited rows **52** can be staggered where such staggering can be random or regular without departing from the scope of the present invention. The present invention could also be practiced by spiraling the closeout material thereby eliminating intermediate start/stop points **60**.

As mentioned above, the present invention can be used to perform coolant channel closeout on a variety of rocket components and nuclear reactor components. Such components can include outer surfaces having complex curves such as those used on a rocket engine thrust chamber. For example and as illustrated in FIG. **10**, a rocket engine thrust chamber inner liner **72** is shown having coolant channels **80**. The above-described system and method would be implemented identically as described herein to closeout coolant channels **80**.

As also mentioned above, inner liners for thrust or combustion chambers are typically made from copper, while the closeout material is typically a high-strength stainless steel alloy or super alloy (e.g., Inconel). The mismatch between the inner liner material and the closeout material can have an effect on the strength of the bond between the two materials generated during the above-described freeform deposition process. In addition, using the freeform closeout technique when there is a mismatch between the liner material and closeout material requires significant changes in energy between the channel and rib structures due to the high thermal conductivity material typically used for a liner. However, changes in energy necessitate complex programming and can even render the entire process impractical since poor bonding results can be caused by rapid changes in energy. To alleviate these problems, the following additional steps can be implemented as will be explained with reference to FIGS. **11-15**.

In FIG. **11**, a thrust chamber's inner liner **90** is illustrated in a side view thereof. For purpose of description, it will be assumed that inner liner **90** is fabricated from copper. The inside surfaces (not shown) of inner liner **90** would be machined to a final finish, although the outside surface **91** of inner liner **90** need only be machined to a rough finish.

In accordance with the present invention, outer surface **91** of inner liner **90** is clad with a thin layer of a cladding material **92** as illustrated in the cross-sectional view presented in FIG. **12**. As is generally known in the art, an interim cladding preparation can be used to limit or prevent oxidation of copper inner liner. The resulting clad inner liner is referenced generally by numeral **94**. In general, cladding material **92** is one that will be weld-compatible or weldable with the closeout material deposited thereon in accordance with the above-described deposition process. For example, cladding material **92** could be the same material used for the closeout material, e.g., the same high-strength stainless steel alloy or super alloy (e.g., Inconel) used for the linear rows **52** described above. Similar families of materials can be used to help compensate for coefficient of thermal expansion (CTE) mismatches and provide a gradient of material as the CTE changes (e.g., copper liner to Monel cladding to Inconel closeout). Processes for applying cladding material **92** to inner liner **90** are well-known in the art and will, therefore, not be described further herein.

The above-described clad inner liner **94** is next machined, or slotted as defined in the art, to define coolant channels **96** therein as shown in FIG. **13**. Each coolant channel **96** extends through cladding material **92** and into inner liner **90**. Accordingly, each of the above-described tangent lines (e.g., one tangent line A is illustrated in FIG. **13**) is now referenced to the outer surface of cladding material **92** for any point on the inner liner structure that has cladding material **92** and coolant channels **96**. The machining of the coolant channels can be completed following final machining of the outer surface after cladding or machined in the as-clad surface condition without departing from the scope of the present invention.

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The inner liner with its cladding material **92** and coolant channels **96** is next subjected to the same freeform deposition closeout process steps **102-114** (FIG. 1) described above. When the coolant channel closeout is complete, the welded-together rows **52** cover coolant channels **96** (FIG. 14) with each row **52** circumscribing the inner liner structure and being welded to cladding material **92** that is adjacent to each coolant channel **96** (FIG. 15). Since the material used for rows **52** is the same or weldable relative to cladding material **92**, the resulting bond strength between the two materials is assured.

The advantages of the present invention are numerous. The freeform deposition method fabricates an exterior jacket onto an inner liner's channel lands so that the coolant channels can withstand the high pressures and extreme temperatures produced during use of the liner. The method utilizes directed energy/fusion deposition of closeout material along the coolant channel lands of the inner liner eliminating the need to pre-fill the channels with a filler medium. The described method allows for real-time row-by-row inspection of the coolant channel closeout thereby permitting correction of any defects in the closeout welds during the fabrication process. The cladding of a structure followed by coolant channel machining allows the present invention to be adapted to accommodate a mismatch between the closeout material and the liner material without sacrificing bond strength. The method will significantly reduce the overall time for fabrication of a rocket nozzle or rocket thrust chamber, while also providing for strength-to-weight optimized structures requiring the use of two or more alloys for the liner and jacket wall.

Although the invention has been described relative to a specific embodiment thereof, there are numerous variations and modifications that will be readily apparent to those skilled in the art in light of the above teachings. It is therefore to be understood that, within the scope of the appended claims, the invention may be practiced other than as specifically described.

The invention claimed is:

1. A method of fabricating a coolant channel closeout jacket, comprising the steps of:
  - providing a base structure having an outer surface;
  - cladding said outer surface with a first material wherein a clad structure is fabricated, said clad structure having an outer clad surface;
  - machining coolant channels in said clad structure wherein each of said coolant channels extends through said first material and into said base structure, wherein a line of tangency relative to said outer clad surface is defined for each point on said outer clad surface;
  - providing a feedstock supply for depositing linear rows of a metal feedstock onto said outer clad surface of said clad structure having said coolant channels, said metal feedstock being selected from the group consisting of said first material and a second material wherein said second material is weldable to said first material;
  - providing an energy source for generating a beam of weld energy having a cross-sectional area;
  - positioning said feedstock supply to deposit said linear rows of said metal feedstock onto a portion of said outer clad surface having said coolant channels, wherein a first angle between said metal feedstock discharged from said feedstock supply and said line of tangency is maintained in a range of 20-90°; and
  - positioning said energy source to direct said beam of weld energy towards a portion of said linear rows deposited on said portion of said outer clad surface, wherein less

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than 30% of said cross-sectional area of said beam of weld energy impinges on a currently-deposited one of said linear rows, and wherein a second angle between said beam of weld energy and said line of tangency is maintained in a range of 5-65°.

2. A method according to claim 1, further comprising the step of introducing relative rotation between said clad structure and a combination of said feedstock supply and said energy source, wherein each of said linear rows circumscribes said clad structure.

3. A method according to claim 1, wherein each of said linear rows is perpendicular to said coolant channels.

4. A method according to claim 1, wherein greater than 70% of said cross-sectional area of said beam of weld energy impinges on another one of said linear rows immediately adjacent to said currently-deposited one of said linear rows.

5. A method according to claim 1, wherein said clad structure has a longitudinal axis, and wherein said method further comprises the step of positioning said clad structure wherein an angle between said longitudinal axis of said clad structure and a local force of gravity is maintained in a range of 5-70°.

6. A method according to claim 1, further comprising the step of depositing additional linear rows of said metal feedstock on said outer clad surface where none of said coolant channels are formed.

7. A method of fabricating a coolant channel closeout jacket, comprising the steps of:

- providing a base structure having an outer surface;
- cladding said outer surface with a first material wherein a clad structure is fabricated, said clad structure having an outer clad surface;

- machining coolant channels in said clad structure wherein each of said coolant channels extends through said first material and into said base structure, wherein a line of tangency relative to said outer clad surface is defined for each point on said outer clad surface;

- directing a metal feedstock towards a portion of said outer clad surface of said clad structure where said coolant channels are formed therein, said metal feedstock being selected from the group consisting of said first material and a second material wherein said second material is weldable to said first material, said metal feedstock being directed along a first angle between said metal feedstock and said line of tangency, said first angle being maintained in a range of 20-90°, wherein said metal feedstock is deposited in a linear row on said portion of said outer clad surface;

- generating a beam of weld energy having a cross-sectional area; and

- directing said beam of weld energy towards said linear row wherein less than 30% of said cross-sectional area of said beam of weld energy impinges on said linear row, and wherein a second angle between said beam of weld energy and said line of tangency is maintained in a range of 5-65°.

8. A method according to claim 7, further comprising the step of rotating said clad structure about a longitudinal axis thereof during said steps of directing, wherein said linear row circumscribes said clad structure.

9. A method according to claim 7, wherein said linear row is perpendicular to said coolant channels.

10. A method according to claim 7, wherein another linear row of said metal feedstock lies immediately adjacent to said linear row, and wherein greater than 70% of said cross-sectional area of said beam of weld energy impinges on said another linear row.

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11. A method according to claim 7, wherein said clad structure has a longitudinal axis, and wherein said method further comprises the step of positioning said clad structure wherein an angle between said longitudinal axis of said clad structure and a local force of gravity is maintained in a range of 5-70°.

12. A method according to claim 7, further comprising the step of depositing additional linear rows of said metal feedstock on said outer clad surface where none of said coolant channels are formed.

13. A method of fabricating a coolant channel closeout jacket, comprising the steps of:

providing a base structure having an outer surface;

cladding said outer surface with a first material wherein a clad structure is fabricated, said clad structure having an outer clad surface;

machining coolant channels in said clad structure wherein each of said coolant channels extends through said first material and into said base structure, wherein a line of tangency relative to said outer clad surface is defined for each point on said outer clad surface;

directing a metal feedstock towards a portion of said outer clad surface of said clad structure where said coolant channels are formed therein, said metal feedstock being selected from the group consisting of said first material and a second material wherein said second material is weldable to said first material, said metal feedstock being directed along a first angle between said metal feedstock and said line of tangency, said first angle being maintained in a range of 20-90°, wherein said metal feedstock is deposited in a linear row on said portion of said outer clad surface;

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generating a beam of weld energy having a cross-sectional area;

directing said beam of weld energy towards said linear row wherein less than 30% of said cross-sectional area of said beam of weld energy impinges on said linear row, and wherein a second angle between said beam of weld energy and said line of tangency is maintained in a range of 5-65°; and

repeating said steps of directing until said coolant channels are covered by a plurality of said linear row.

14. A method according to claim 13, further comprising the step of rotating said clad structure about a longitudinal axis thereof during said steps of directing, wherein each said linear row circumscribes said clad structure.

15. A method according to claim 13, wherein each said linear row is perpendicular to said coolant channels.

16. A method according to claim 13, wherein another linear row of said metal feedstock lies immediately adjacent to said linear row, and wherein greater than 70% of said cross-sectional area of said beam of weld energy impinges on said another linear row.

17. A method according to claim 13, wherein said clad structure has a longitudinal axis, and wherein said method further comprises the step of positioning said clad structure wherein an angle between said longitudinal axis of said clad structure and a local force of gravity is maintained in a range of 5-70°.

18. A method according to claim 13, further comprising the step of depositing additional linear rows of said metal feedstock on said outer clad surface where none of said coolant channels are formed.

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