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(54) **FRICTION STIR ADDITIVE MANUFACTURING FORMED PARTS AND STRUCTURES WITH INTEGRATED PASSAGES**

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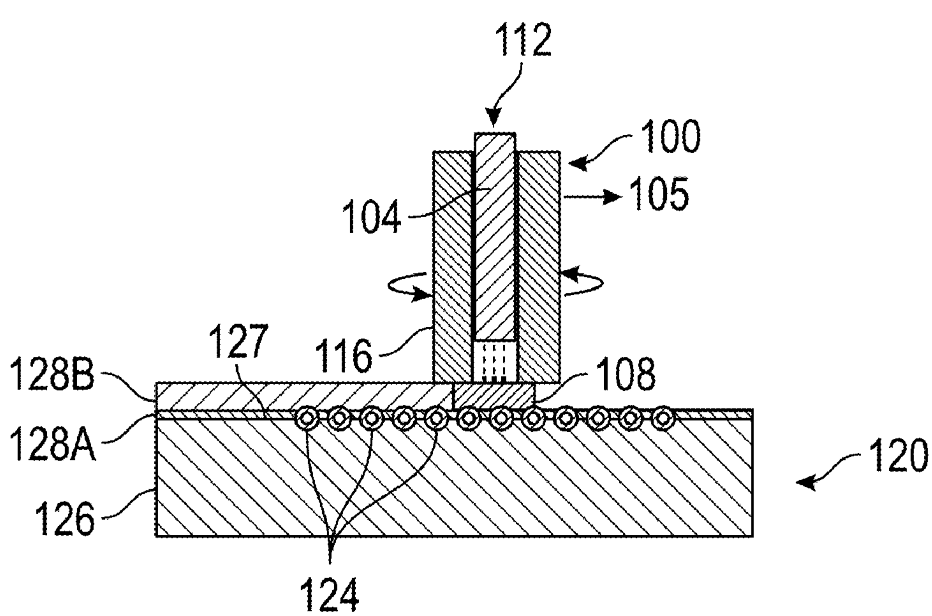
(57) **ABSTRACT**

A method of additive manufacturing a part having integrated passages is provided. In one aspect, the method includes forming a part having a near net shape by moving a friction stir tool to deposit a filler material in a predetermined formation. The tool can include a rotating spindle having a channel configured to hold the filler material. The method can include machining the near net shape part to form a plurality of grooves extending into a surface of the part, the plurality of grooves sized and shaped to each receive a tube. The method can include placing a tube into each of the plurality of grooves and moving the tool across the surface of the part and depositing additional material configured to secure the tubes within the plurality of grooves. The method can include machining the additional material deposited over the tubes to a predetermined shape.

21 Claims, 6 Drawing Sheets



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See application file for complete search history.

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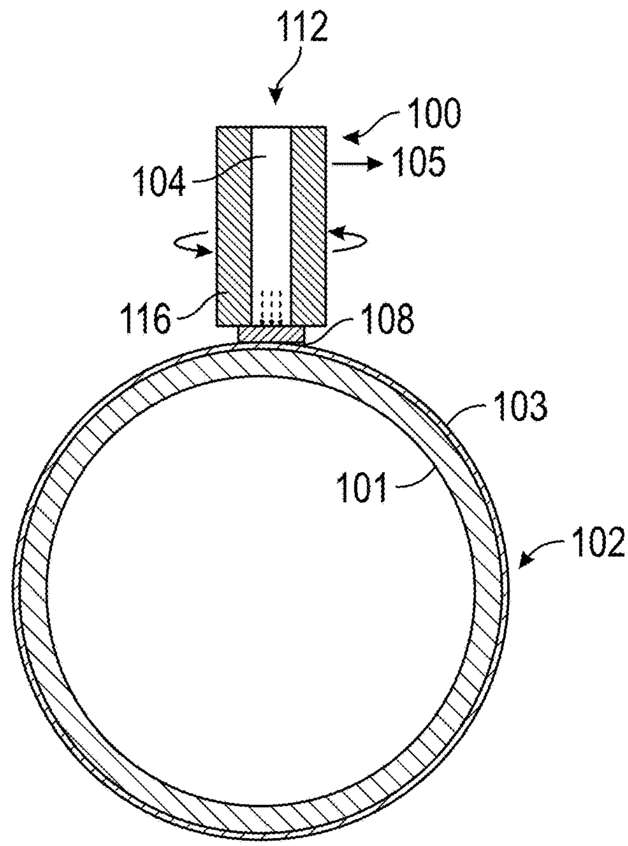
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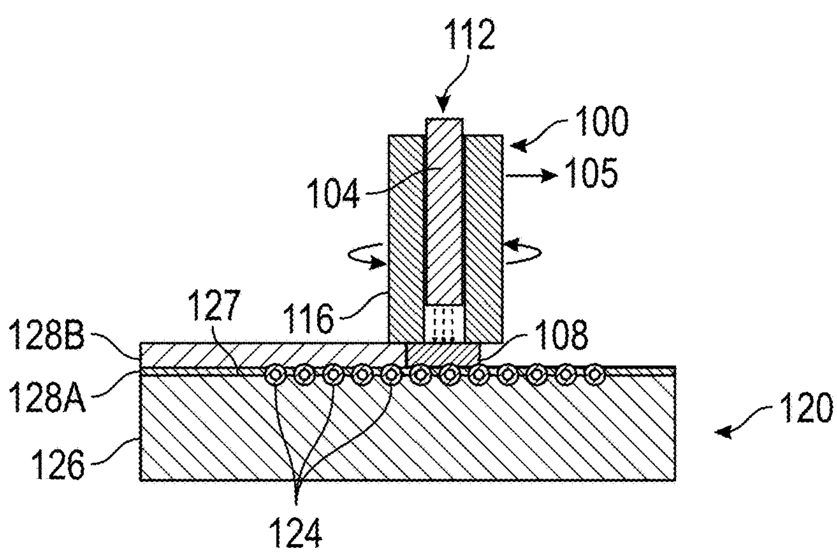
100
105
104
116
108
103
101
102

FIG. 1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100
105
104
127
116
108
128B
128A
120
126
124

FIG. 2

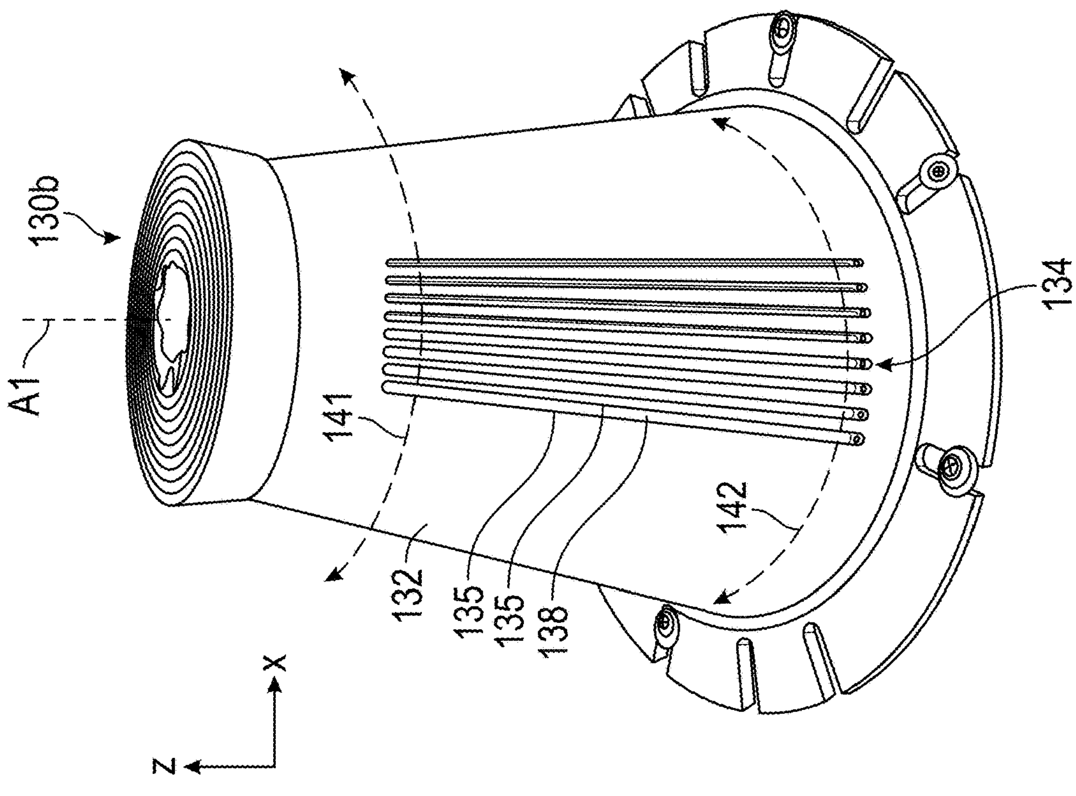

FIG. 4

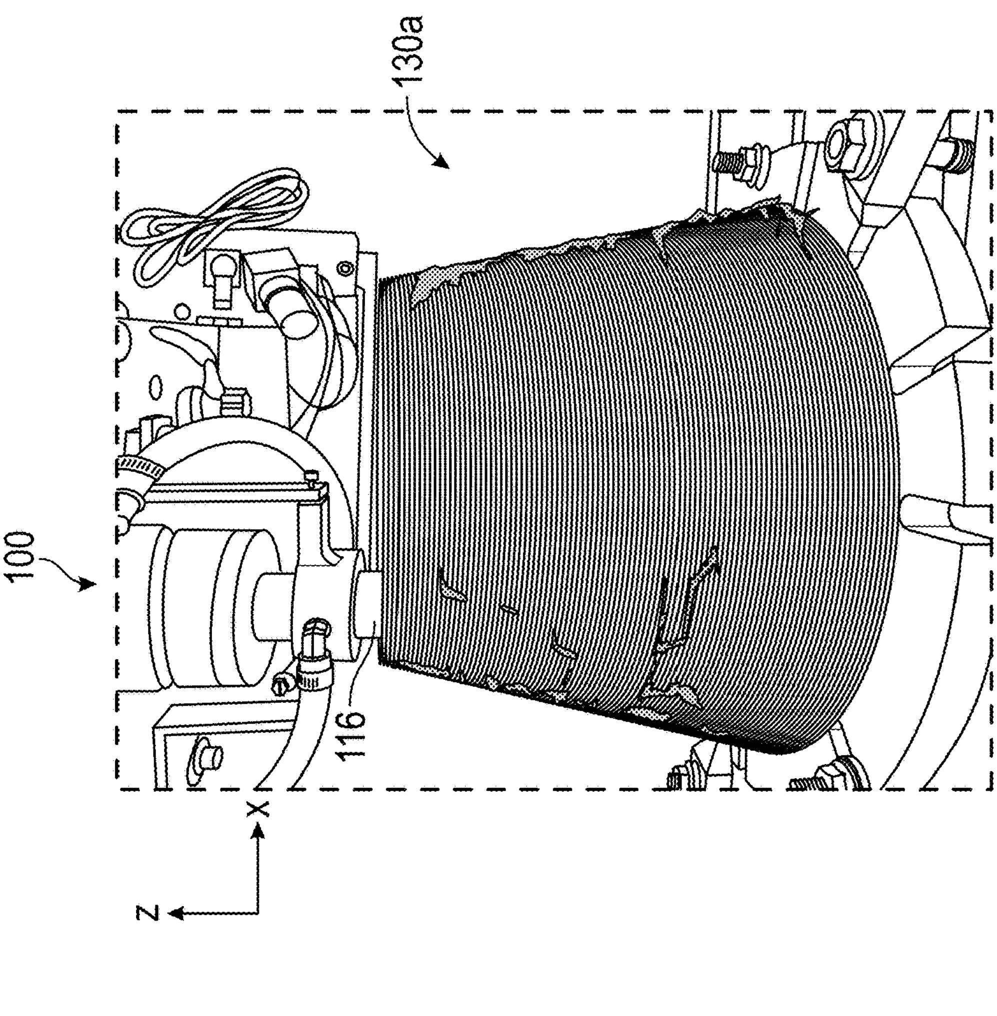

FIG. 3

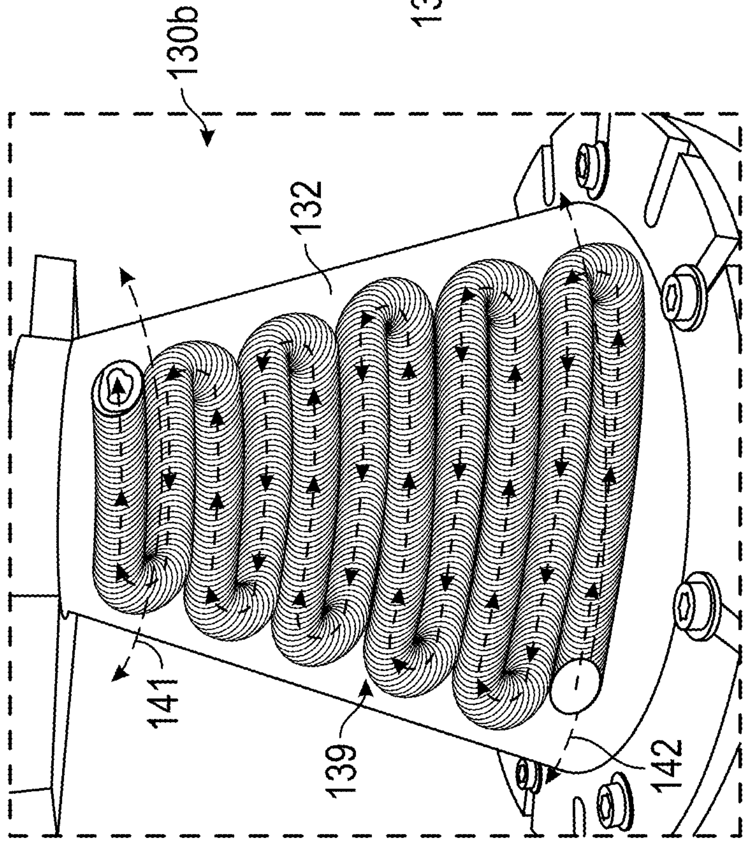

FIG. 5

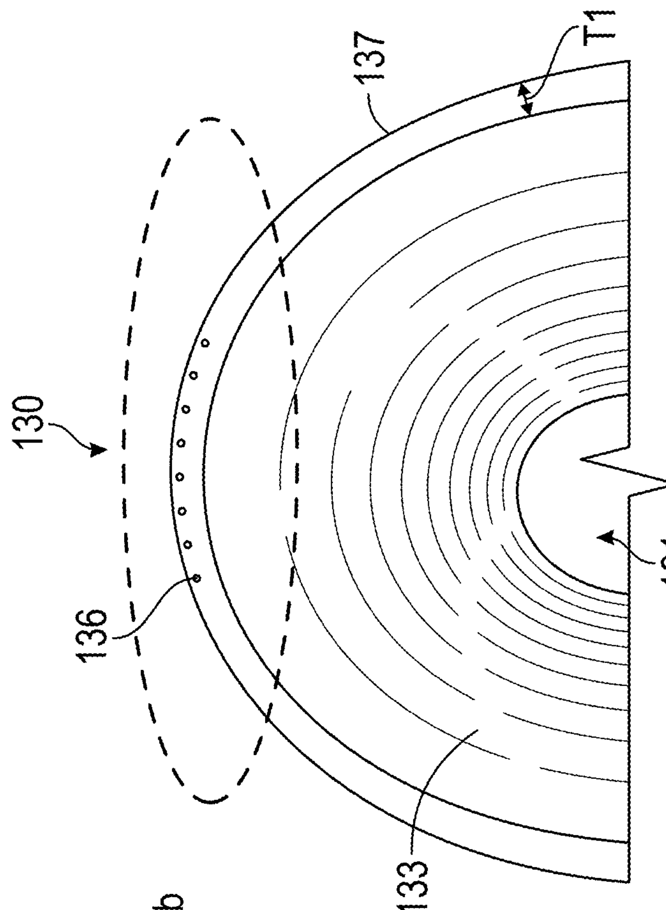

FIG. 6

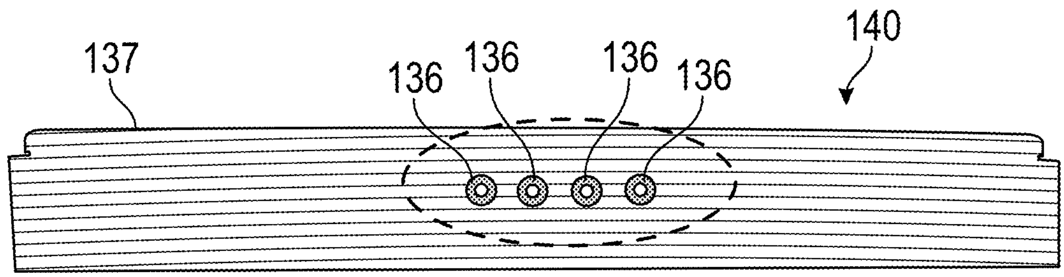
137
136
136
136
136
140

FIG. 7

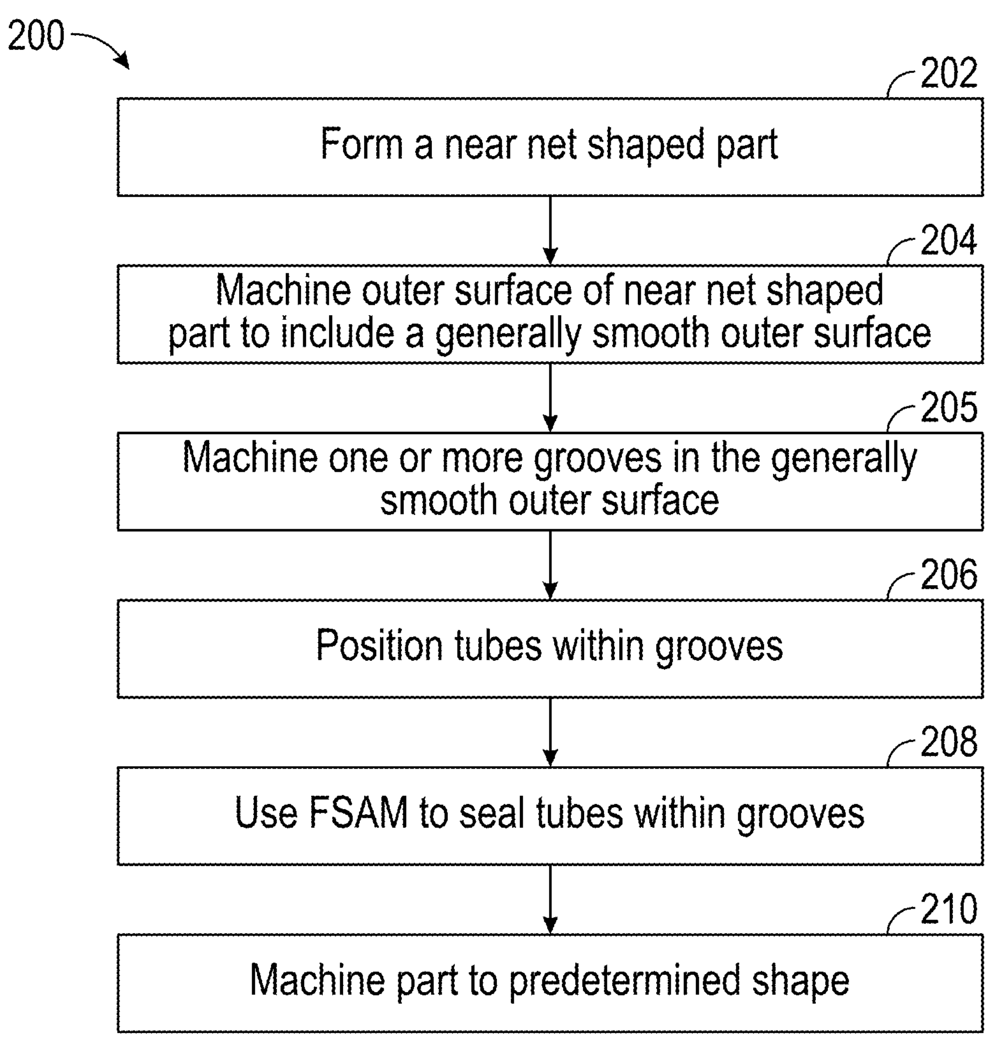
200
202
Form a near net shaped part
204
Machine outer surface of near net shaped part to include a generally smooth outer surface
205
Machine one or more grooves in the generally smooth outer surface
206
Position tubes within grooves
208
Use FSAM to seal tubes within grooves
210
Machine part to predetermined shape

FIG. 8

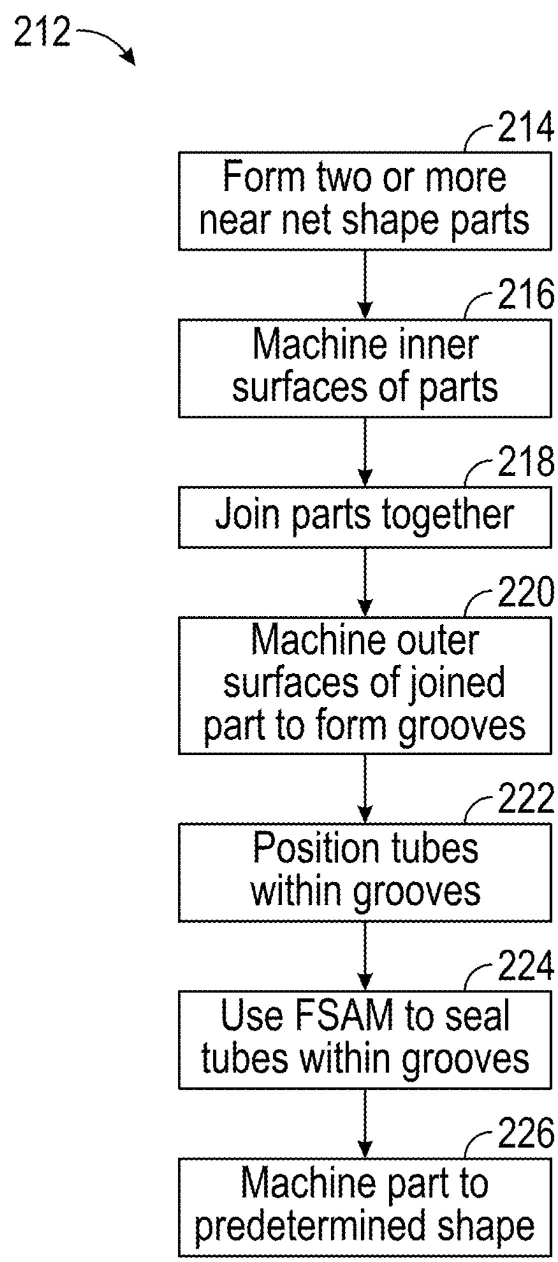
212
214
Form two or more near net shape parts
216
Machine inner surfaces of parts
218
Join parts together
220
Machine outer surfaces of joined part to form grooves
222
Position tubes within grooves
224
Use FSAM to seal tubes within grooves
226
Machine part to predetermined shape

FIG. 9

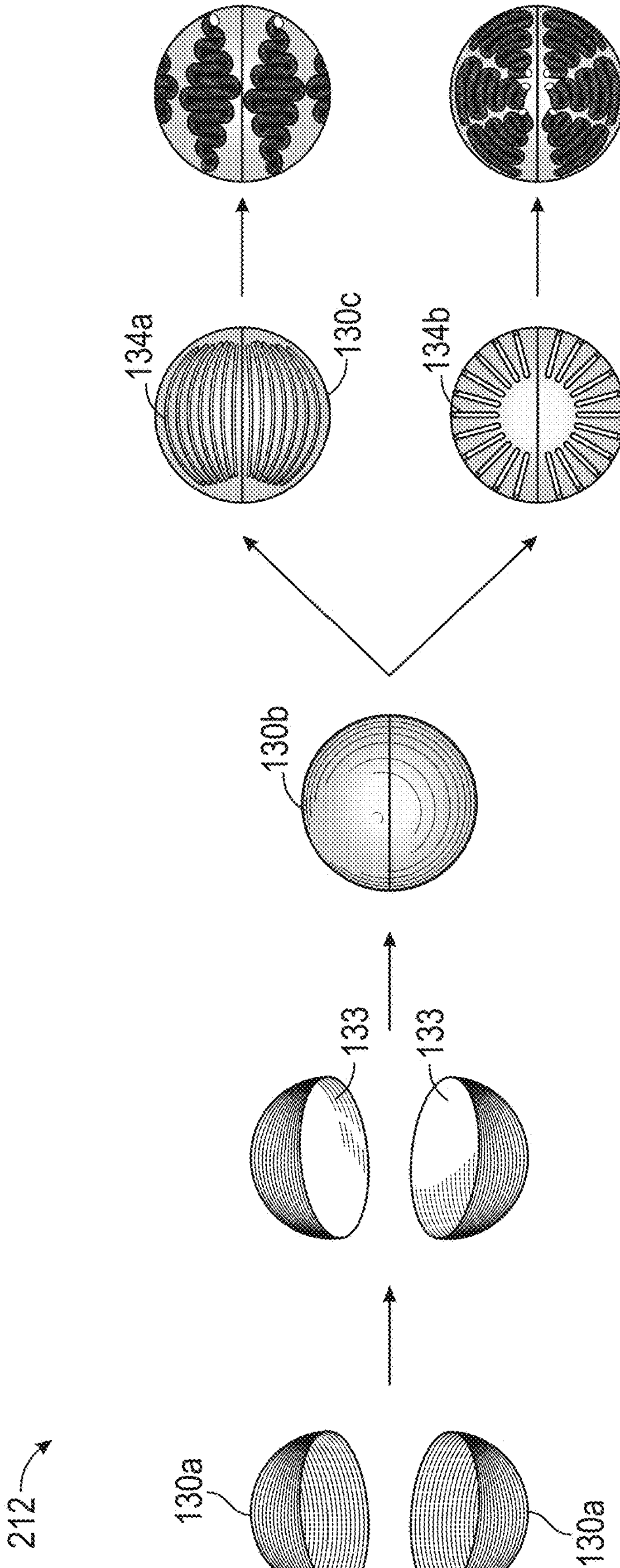

FIG. 10

FRICTION STIR ADDITIVE MANUFACTURING FORMED PARTS AND STRUCTURES WITH INTEGRATED PASSAGES

BACKGROUND

Field

The technology relates generally to the use of friction stir additive manufacturing to form parts and structures having integrated passages.

Description of the Related Art

The formation of parts and structures having integrated passages can be very costly, labor intensive, and prone to quality issues. The large number of manufacturing steps needed can lead to these and other issues. Typically, it is easier to attach passages to the exterior of a part or structure after the part or structure is formed, rather than form integral passages as the part or structure is being formed. It is therefore desirable to have an efficient manufacturing process with limited steps to form parts with integrated passages.

SUMMARY

The embodiments disclosed herein each have several aspects no single one of which is solely responsible for the disclosure's desirable attributes. Without limiting the scope of this disclosure, its more prominent features will now be briefly discussed. After considering this discussion, and particularly after reading the section entitled "Detailed Description" one will understand how the features of the embodiments described herein provide advantages over existing approaches over existing methods of forming parts and/or structures having integrated passages using friction stir additive manufacturing.

In one aspect, a method of additive manufacturing a part is provided. The method includes forming a part having a near net shape by moving a friction stir tool configured to deposit a filler material in a predetermined formation. The method also includes machining the near net shape part to form a generally smooth outer surface. The method also includes machining the generally smooth outer surface to form a plurality of grooves extending into the outer surface of the near net shape part. The plurality of grooves are sized and shaped to each receive a tube. The method also includes placing a tube into each of the plurality of grooves. The method also includes moving the friction stir tool across the surface of the part and depositing additional filler material configured to secure the tubes within the plurality of grooves. The method also includes machining the additional filler material deposited over the tubes to a predetermined shape.

In some embodiments, the part is a nozzle for a rocket engine. In some embodiments, the filler material is copper. In some embodiments, the tubes are configured to transport a liquid. In some embodiments, the filler material is a first material and the tubes are formed of a second material different than the first material. In some embodiments, the filler material is a first material and the tubes are formed of a second material that is the same as or substantially the same as the first material. In some embodiments, the friction stir tool comprises a spindle having a channel extending along a central axis of the spindle and configured to hold the filler material. The forming of a part having a near net shape includes rotating the spindle of the friction stir tool to deposit the filler material held in the channel in the predetermined formation.

In another aspect, a method of additive manufacturing a part is provided. The method includes forming a part having a near net shape by depositing layers of material using a friction stir tool. A new layer is added to a surface of a previously deposited layer. The method also includes machining a plurality of grooves extending into a surface of the part. The plurality of grooves are sized to each receive a wire. The method also includes positioning a wire into each of the plurality of grooves. The method also includes securing the wires within the plurality of grooves with additional material deposited over the wires. The method also includes machining the additional material to a predetermined shape.

In some embodiments, the part having a near net shape is formed using friction stir additive manufacturing. In some embodiments, the part is a nozzle for a rocket engine. In some embodiments, the material is copper. In some embodiments, the wires comprise hollow wires. In some embodiments, wherein the hollow wires are configured to transport a liquid. In some embodiments, the wires comprise solid wires. In some embodiments, the wires comprise solid aluminum wires. In some embodiments, the method includes removing the solid wires from the predetermined shape using a chemical or thermal process. In some embodiments, the material is a first material and the wires are formed of a second material different than the first material. In some embodiments, the material is a first material and the wires are formed of a second material that is the same as or substantially the same as the first material.

In another aspect, a structure comprising integrated passages produced by an additive manufacturing process is provided. The process includes forming a first initial part having a near net shape by moving a friction stir tool to deposit layers of material in a predetermined formation. The process also includes machining a plurality of grooves into an external surface of the first initial part. The process also includes positioning a tube into each of the plurality of grooves. The process also includes moving the friction stir tool across the surface of the first initial part and depositing an additional layer of material to secure the tubes within the plurality of grooves. The process also includes machining the additional layer of material or at least one layer deposited over the additional layer of material to a predetermined shape to form the structure.

In some embodiments, the friction stir tool comprises a spindle having a channel extending along a central axis of the spindle and configured to hold the material. The forming a first initial part having a near net shape includes rotating the spindle of the friction stir tool to deposit the material held in the channel in layers. In some embodiments, the structure comprises a nozzle for a rocket engine. In some embodiments, the material is copper. In some embodiments, the tubes are configured to transport a liquid. In some embodiments, the material is a first material and the tubes are formed of a second material different than the first material. In some embodiments, the material is a first material and the tubes are formed of a second material that is the same as or substantially the same as the first material.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other features of the present disclosure will become more fully apparent from the following description and appended claims, taken in conjunction with the accompanying drawings. Understanding that these drawings depict only several embodiments in accordance with the disclosure and are not to be considered limiting of its scope, the disclosure will be described with additional specificity and detail through use of the accompanying drawings. In the following detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be utilized, and other changes may be made, without departing from the spirit or scope of the subject matter presented here. In some drawings, various structures according to embodiments of the present disclosure are schematically shown. However, the drawings are not necessarily drawn to scale, and some features may be enlarged while some features may be omitted for the sake of clarity. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the figures, can be arranged, substituted, combined, and designed in a wide variety of different configurations, all of which are explicitly contemplated and make part of this disclosure.

FIG. **1** is a schematic view of an additive manufacturing tool being used to form a part according to an embodiment of the present disclosure.

FIG. **2** is a cross-sectional view of an additive manufacturing tool being used to form a part having integrated passages according to an embodiment of the present disclosure.

FIG. **3** illustrates a near net shaped part formed using additive manufacturing according to an embodiment of the present disclosure.

FIG. **4** illustrates the part of FIG. **3** after being machined to have a plurality of grooves according to an embodiment of the present disclosure.

FIG. **5** illustrates the part of FIG. **4** after a layer of material has been deposited over the plurality of grooves according to an embodiment of the present disclosure.

FIG. **6** illustrates a bottom view of the part of FIGS. **3-5** after the exterior surface of the part has been machined according to an embodiment of the present disclosure.

FIG. **7** is a cross-sectional view of a plurality of integrated passages in a part according to an embodiment of the present disclosure.

FIGS. **8** and **9** are flow charts representing example methods of forming a part including integrated passages according to an embodiment of the present disclosure.

FIG. **10** illustrates an example method of forming a structure including integrated passages by joining two initial parts according to an embodiment of the present disclosure.

DETAILED DESCRIPTION

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

Various embodiments will now be described with reference to the accompanying figures, wherein like numerals refer to like elements throughout. The terminology used in the description presented herein is not intended to be interpreted in any limited or restrictive manner, simply because it is being utilized in conjunction with a detailed description of certain specific embodiments of the present disclosure. Furthermore, embodiments of the present disclosure may include several novel features, no single one of which is solely responsible for its desirable attributes or which is essential to practicing the present disclosure.

Embodiments of the present disclosure relate generally to the use of friction stir additive manufacturing (FSAM) to form parts or structures with integrated passages or other hollow internal structures. It can be understood that two or more parts can be joined to form a structure and that a single part can be a structure. Friction stir additive manufacturing devices and methods can use a tool with a high speed rotation sleeve or spindle that generates heat to soften a filler material or feed stick material. For example, the sleeve or spindle can rotate at a speed between 200 rpm and 600 rpm. Under a high pressure applied by the rotating spindle, the softened material will flow out from the spindle and can be deposited on a part or a component, for example a substrate or workpiece. The tool can be moved repeatedly over the same area to apply additional layers of materials. Alternatively, the part that the material is applied to can be moved relative to the tool. This can be used to form a part with integrated passages or other hollow internal structures.

The use of FSAM to form parts and/or structures provides various advantages. For example, FSAM uses a low process temperature. The materials used to form the parts and structures are not melted, and can be molded and joined while the material is in a softened state. FSAM also allows for better material properties. Since the materials are not melted, the materials do not experience significant precipitation reactions or phase changes. The properties of the incoming material are close to the properties of the final part. FSAM can be multifunctional. For example, FSAM can be used to build a part using different materials, such as aluminum and copper, together in a component, such as a heat exchanger. The component can benefit from advantages associated with the different materials. For example, while copper can be more effective in conducting heat than aluminum, aluminum can have better structural efficiency, such that thermal and structural benefits can be integrated into the same component. In addition, FSAM is a solid-state process uniquely suited to embed objects, for example channels, passages, and sensors, into solid parts by depositing a softened filler material over the objects.

The parts, structures, systems, and methods described herein can use FSAM to build near net shape structures and parts having integrated or embedded passages or other hollow internal structures. For example, embodiments of the present disclosure can integrate or embed passages, such as cooling channels, in various structures, including but not limited to nozzles for rocket engines, heat exchanges, actively-cooled structures, and propellant tanks, as these structures are being formed. In a first FSAM process, FSAM can be used to form a near net shape part or structure. The near net shape structure or part can be a base structure. In a first machining process, a first surface or initial outer surface of the base structure can be machined to include a plurality of grooves or channels. Tubes, conduits, or other hollow structures can be inserted into the grooves or channels. In a second FSAM process, FSAM can then be used to seal the tubes within the base structure. The sealing of the tubes, conduits, or hollow structures within the base structure can provide protection to the tubes, conduits, or hollow structures. This can prevent structural and/or heat-related damage to the tubes, conduits, or hollow structures. In a second machining process, a second surface, for example, a new outer surface of the base structure formed by the material that overlies the tubes, conduits, or hollow structures, can be machined to form a smooth outer surface. Embodiments of FSAM processes according to the present disclosure can reduce manufacturing costs, reduce manufacturing steps and time, simplify quality control, and enhance structural reliability and integrity of structures formed with integrated passages.

Various example embodiments of the present disclosure will now be described with respect to the figures. FIG. **1** is a schematic view of an additive manufacturing tool **100** configured to form a part **102** according to an embodiment of the present disclosure. The additive manufacturing tool **100** can be used to deposit a filler material **104** to a deposition zone **108**. Example filler materials include but are not limited to copper, titanium, steels, and nickel alloys. The filler material **104** can be a single type of material or a mixture of materials. The filler material **104** can flow through a channel **112** of a spindle **116**. The spindle **116** can be configured to rotate about a central axis extending through the center of the spindle **116**. The rotation of the spindle **116** can generate heat to soften the filler material **104**, which can allow the filler material **104** to flow through the channel **112** and to the deposition zone **108**.

The spindle **116** can be configured to move transversely across a substrate **101** to form an initial layer **103** of the part **102**. The spindle **116** can then continue to move transversely across the surface of the part **102** to form additional layers, one on top of the next. For example, the spindle **116** can be moved in the direction of arrow **105** while the part **102** remains stationary. Alternatively, the part **102** can be moved and the spindle **116** can remain stationary. In still another embodiment, the part **102** and the spindle **116** can both move as layers of material are deposited. While the spindle **116** is moved across the current outer surface of the part **102**, for example, the surface of the initial layer **103** as shown in FIG. **1**, the filler material currently being deposited can continue to exit the spindle **116** and be deposited to the deposition zone **108**. The deposition zone **108** can include the area where the filler material exits the additive manufacturing device **100** and/or the area where the filler material contacts the part **102** or uppermost layer of material that was previously deposited. As the spindle **116** moves across the surface of the part **102**, the deposition zone **108** can move to correspond to where the filler material is currently being deposited. The filler material that has exited the spindle **116** can remain at the location where it was deposited. The spindle **116** can be moved along the surface of the part **102** a predetermined number of times to deposit a predetermined number of layers of filler material **104**.

While FIG. **1** depicts one initial layer **103** deposited on the substate **101**, any number of layers can be deposited to form the part **102**, for example, one layer, two layers, three layers, four layers, or more. The number of layers deposited can be predetermined based on the desired characteristics of the final part. The substrate **101** can be preformed or additive manufactured. The substate **101** can include the same or different material as the filler material being deposited. The substate **101** can be removed from the part **102** after the final part is formed or the substrate **101** can remain a portion of the final part.

The additive manufacturing tool **100** can be used to deposit filler material on a curved surface of a part **102**, as illustrated in the example embodiment of FIG. **1**. In another non-limiting example, the additive manufacturing tool **100** can be used to deposit filler material on a generally planar surface of a part, as will be described below with reference to the example embodiment of FIG. **2**.

FIG. **2** is a cross-sectional view of the additive manufacturing tool **100** being used to form a part **120** having integrated passages **124** according to an embodiment of the present disclosure. The base structure or base layer **126** can be formed using the additive manufacturing tool **100**. Alternatively, the base structure or base layer **126** can be formed using any suitable manufacturing method. The base **126** can include one or more layers. The number of layers forming the base **126** can be dependent on the desired characteristics of the final part. For example, the number of layers can be adjusted to achieve a desired shape of the final part, a desired thickness of the final part, and a desired location of the passages **124**.

The part **120** can have one or more passages **124**. The passages **124** can be disposed over a top surface **127** of base **126**, in contact with the top surface **127** of the base **126**, and/or at least partially within the base **126**. This is discussed in more detail below with reference to FIG. **4**. The passages **124** can be disposed adjacent to each other, in a uniform pattern and/or in a non-uniform pattern. For example, the passages **124** can be positioned at different depths within the part **120**. For another example, each passage **124** can be spaced a uniform or a non-uniform distance from adjacent passages **124**. Many different configurations can be suitably implemented. In one non-limiting embodiment, a first passage **124** or set of passages **124** can be positioned after a first predetermined number of layers of material. A second passage **124** or set of passages **124** can be positioned after a second predetermined number of layers of material, the second predetermined number of layers being different than the first. The passages **124** can be formed using tubing, conduits, or the like. Once positioned over and/or in contact with the surface of the base **126**, the passages **124** can be sealed in place by using the additive manufacturing tool **100** to deposit one or more layers on top of and/or around the passages **124**, for example, layers **128**A and **128**B. The layers **128**A, **128**B can vary in thickness or have the same thickness. As shown in FIG. **2**, the layer **128**A has a smaller thickness than the layer **128**B which is shown as in the process of being deposited on top of layer **128**A. The layers **128**A, **128**B will transition from a softened state to a hardened state over and/or around the passages **124**, securing the passages **124** within the final part **120**. Non-limiting embodiments of these processes are described in more detail below.

FIGS. **3**-**6** illustrate various example stages of a part **130** being formed with integrated/embedded passages using systems and methods according to the present disclosure. FIG. **8** is a corresponding flow chart representing an example method **200** of forming the part **130** according to an embodiment of the present disclosure. With reference to FIG. **3**, an initial part **130**a can be formed during a first FSAM process using the additive manufacturing tool **100** according to an embodiment of the present disclosure. As described herein, the additive manufacturing tool **100** can have a rotating spindle **116** having a channel **112**. The channel **112** can be configured to hold the filler material **104**, and the filler material **104** can be deposited as layers of material to form the initial part **130***a*. The layers of filler material **104** can transition from a softened state to a hardened state to form the base structure of the initial part **130***a*. Layers of material can be deposited one on top of each other and/or one next to each other. The number of layers deposited can be dependent on various factors, including the part thickness, the part geometry, and the intended location of embedded objects (for example, passages).

The motion of the rotating spindle **116** and the shape of the layers being deposited can be determined by the intended shape of the initial part **130***a*. According to an embodiment of the present disclosure, the initial part **130***a* can have a general cone or nozzle shaped base structure. The rotating spindle **116** can move in the z-axis direction while simultaneously moving in circles of decreasing diameter as it deposits filler material in layers. The deposited material can be arranged in ring-shaped layers surrounding an internal cavity (for example, internal cavity **131** shown in FIG. **6**). The internal cavity **131** can form a cavity of a nozzle or combustion chamber. While a cone or nozzle-shaped initial part **130***a* is depicted, a structure of any predetermined shape can be formed by adjusting the motion of the rotating spindle **116**.

The initial part **130***a* can be formed to have a near net shape. For example, the initial part **130***a* can be formed to closely resemble the intended final part. The motion of the rotating spindle **116** can move in a predetermined formation that is predetermined to deposit the layers of filler material in a way to closely resemble the intended final part. The formation of the initial part **130***a* having a near net shape can eliminate unnecessary manufacturing steps. This formation of the initial part **130***a* is represented by block **202** in FIG. **8**.

Moving to FIG. **4** and block **204** of FIG. **8**, an outer surface of the initial part **130***a* can be machined during a first machining process to form a machined part **130***b* according to an embodiment of the present disclosure. The machined part **130***b* can generally resemble the initial part **130***a* in size and shape. The outer surface(s) of the machined part **130***b* can be machined to have a generally smooth outer surface **132**. The inner surface(s) (for example, inner surface **133** shown in FIG. **6**) of the machined part **130***b* can be machined to have a generally smooth inner surface.

Moving to block **205**, the generally smooth outer surface **132** of the machined part **130***b* can be machined during a second machining process to form one or more grooves or channels **134** in the generally smooth outer surface **132**. The generally smooth outer surface **132** can be curved. The one or more grooves **134** can extend into the generally smooth outer surface **132** of the machined part **130***b*. Alternatively, in some instances the one or more grooves **134** can be machined prior to the outer surface of the initial part **130***a* being machined.

The number of grooves **134** can be dependent on the intended number of integrated passages in the final part. While 8 grooves **134** are depicted, there could be more than 8 grooves **134**, less than 8 grooves **134**, or 8 grooves **134**. The one or more grooves **134** can be arranged in a predetermined section of the generally smooth surface **132**. The one or more grooves **134** can be arranged around the entire circumference of the machined part **130***b*. The one or more grooves **134** can extend an entire length or width of the generally smooth surface **132**, or the one or more grooves **132** can have a predetermined length or width that is less than the corresponding length or width of the generally smooth surface **132**. The predetermined length or width of each of a plurality of the grooves **134** can be the same or different. The one or more grooves **134** can be formed in a curved surface, a planar surface, or a surface having a combination of curved and planar features. The one or more grooves **134** can be formed in a surface that slants inward toward a central axis **A1** of the machined part **130***b* as the surface extends from a bottom to a top of the machined part in the z-axis direction. The distance between adjacent grooves **134** can change along the z-axis direction. The distance between adjacent grooves **134** can remain generally constant along the z-axis direction. The grooves **134** can all extend in the same general direction. The grooves **134** can be positioned generally parallel to each adjacent groove **134**. The grooves **134** can extend varying directions. Each groove **134** can have a constant depth along the groove **134** or a depth that varies along the groove **134**. Each of a plurality of the grooves **134** can have the same depth but other configurations can be implanted. The grooves **134** can extend in a generally linear path but other configurations can be implanted, for example, the grooves **134** can have portions that are non-linear or turn in different directions. For example, in one non-limiting example, the groove **134** can follow a curved path. Each groove **134** can have sidewalls **135** extending the length of the groove **134** that are substantially parallel. The grooves **134** can be oriented such that no two grooves **134** intersect but other configurations can be implemented.

The one or more grooves **134** can be configured to receive corresponding tubes **136** (not shown in FIG. **4**, but an example is shown in FIG. **7** discussed below). The tubes **136** can be positioned into the grooves **134**, as represented by block **206** of FIG. **8**. The tubes **136** can be positioned one at a time, or a plurality of tubes **136** can be positioned simultaneously. The tubes **136** can be positioned manually or in an automated manner. The tubes **136** can be hollow to define a passage, channel, or other enclosed/hollow structure **136**. The passages or channels formed by the tubes or other hollow structures **136** can be configured to transport a liquid, such as but not limited to a coolant, such as but not limited to a fuel. Tubes **136** can have any suitable cross-sectional shape. For example, a tube **136** can have a rectangular cross-section. In one non-limiting embodiment of a rectangular tube **136**, the tube has inner dimensions of about 0.08 inches by 0.2 inches and an inner cross-sectional area of about 0.016 in^2. In another example, a tube **136** has a circular cross-section. In one non-limiting embodiment of a circular tube **136**, the tube has an inner radius of about 0.07 inches and a cross-sectional area of about 0.015 in^2. Cross-sectional shapes and dimensions of grooves **134** can be selected such that the grooves **134** are configured to receive tubes **136** having particular cross-sectional shapes and dimensions.

The tubes **136** can be formed of any suitable material, such as but not limited to a metal. The tubes **136** can be formed of and/or include the same material of the initial part **130***a*, or the tubes **136** can be formed of and/or include a material that is different than the material of the initial part **130***a*.

Embodiments of the present disclosure are not limited to receiving hollow structures in the grooves **134**. In some non-limiting examples, non-hollow structures are received in the grooves **134**. For instance, solid structures, such as solid wires, can be received in the grooves **134**. The wires can be formed of aluminum or any other suitable material. The wires can be placed in grooves **134** and secured in the grooves **134** using FSAM in accordance with embodiments of the present disclosure. In some cases, after the wires are secured in the grooves **134** using FSAM, the wires are removed from the final part. For example, the wires may be removed from the grooves **134** using chemical and/or thermal processes after a layer or layers of FSAM material is placed over the wires. In instances where the wires are removed, removal of the wires can form passages, channels, or voids within the final part. The passages, channels, or voids can have cross-sectional shapes and dimensions corresponding to the cross-sectional shapes and dimensions of the wires before the wires were removed.

The passages formed by the tubes **136**, as shown in FIG. **6**, are integrated into a curved final part. The grooves **134** can be sized and shaped depending on the size and shape of the tubes **136** that form the passages in the final part. The grooves **134** can extend a predetermined depth into the machined part **130***b*. The depth that each groove **134** extends into the outer surface **132** can be the same or different. For example, the intended positioning of the tubes **136** can vary depending on the purpose and design parameters of the final part. In one non-limiting embodiment, one or more tubes **136** can be positioned in a first set of grooves **134** extending into the outer surface **132** at a first depth, and one or more tubes **136** can be positioned in a second set of grooves **134** extending into the outer surface **132** at a second depth different than the first depth. In some instances, all tubes of a plurality of tubes **136** can be positioned in grooves **134** that extend into the outer surface **132** at the same depth.

The path of the grooves **134** can depend on a number of factors, for example, the shape of the machined part **130***b* and the intended pathway for the passages formed by the tubes **136**. For example, in the example of FIG. **4** in which grooves are formed on the surface of a conical-shaped part **130***b*, the grooves **134** follow a substantially linear path that slants towards axis **A1** as the groove extends from a bottom of the groove to a top of the groove along the z-axis direction (for example, the grooves **134** follow a substantially linear path in a z-y plane extending into the page of FIG. **4**). In some instances, the grooves follow a non-linear path that curves to follow a curved surface in the part **130***b* (for example, the grooves **134** follow a curved path in an x-y plane through part **130***b* (not shown in FIG. **4**)). In addition, the cross-sectional profile of the grooves **134** can take any suitable form, including but not limited to a semi-circular or square cross-sectional profile. In the non-limiting embodiment illustrated in FIG. **4**, the grooves **134** have a semi-circular profile with a rounded bottom surface **138** and curved sidewalls **135**. The grooves **134** illustrated in FIG. **4** are configured to receive a cylindrical tube **136**. In another non-limiting embodiment, the grooves **134** can have a square cross-sectional profile with a substantially planar bottom surface **138** and substantially planar sidewalls **135**. Such grooves **134** can be configured to receive a tube **136** having a square cross-sectional profile. It will be understood that grooves **134** having any suitable shape, size, and/or cross-sectional profile can be implemented in the embodiments of the present disclosure.

Moving to FIG. **5** and block **208** of FIG. **8**, additional material **139** can be deposited over the tubes **136** using a second FSAM process according to an embodiment of the present disclosure. The additional material **139** can include one or more additional layers of material being deposited over the machined part **130***b* with the tubes **136** positioned in the grooves **134**. The additional material **139** can secure and/or seal the tubes **136** within the grooves **134** when the material hardens. The filler material **104** being applied over the grooves **134** can fill in any portions of the grooves **134** that are not filled by the tubes **136**. The filler material **104** can fill the grooves **134** such that the tubes **136** are secured in place in the grooves **134** and do not move within the grooves **134**. The additional material **139** can be deposited on a portion of a surface of the machined part **130***b* or over the entire surface of the machined part **130***b*. The number of additional layers deposited can be dependent on the intended characteristics of the final part for example, the final part thickness, the final part geometry, and the intended location of embedded objects (for example, passages formed by tubes **136**).

Moving to FIG. **6** and block **210** of FIG. **8**, the part **130***b* can be machined to a predetermined final shape according to an embodiment of the present disclosure. The additional material **139** deposited over the tubes **136** can be machined to a predetermined shape. The additional material **139** deposited as shown in FIG. **5** can be machined to form a generally smooth exterior surface **137**. FIG. **6** illustrates a bottom view of the final part **130** after the exterior surface **137** of the part **130***b* has been machined according to an embodiment of the present disclosure. The final part **130** can have an internal cavity **131** defined by an internal surface **133** of the base structure that is composed of layers deposited in the first FSAM process and was machined to form a smooth internal surface **133** in the first machining process. The thickness T**1** of the final part **130** can be determined in part by how many layers of material were deposited during the FSAM processes, and the extent to which the part **130***a* and the part **130***b* were machined during the first and second machining process, respectively. The thickness T**1** can be constant but other configurations can be implemented.

FIG. **7** illustrates another non-limiting embodiment of passages formed by tubes **136** embedded/integrated into a part or structure according to the present disclosure. FIG. **7** is a partial cross-section of integrated passages formed by tubes **136** of a part **140** after an exterior surface **137** of the part has been machined in a second machining process according to an embodiment of the present disclosure. In contrast to the embodiment of FIGS. **3**-**6** having passages formed by tubes **136** embedded/integrated within curved walls of a conical-shaped base structure, passages formed by tubes **136** are embedded/integrated into a substantially planar base structure in FIG. **7**. In accordance with embodiments of the present disclosure described above, the tubes **136** are sealed in place to form integral/embedded passages formed by tubes **136** within the part **140**. For example, the passages formed by tubes **136** are substantially enclosed between an exterior surface **137** and an internal surface **133** of the part **140**. For another example, the passages formed by tubes **136** are substantially bounded by the exterior surface **137** and the internal surface **133** of the part **130**. The additional material deposited in a second FSAM process (for example, additional material described above with reference to FIG. **5**) can fill and surround grooves **134** machined into the part (for example, as described above with reference to FIG. **4**). When the additional layers of material transition from a softened state to a hardened state, the additional layers of material deposited in the second FSAM process and the initial layers of material deposited in the first FSAM process can become fused or joined to form a single integral part around the passages formed by tubes **136**. For example, as shown in FIG. **7**, there is no break or noticeable discontinuation between the initial layers of material deposited in the first FSAM process and the additional layers of material deposited in the second FSAM process. The tubes **136** can be a material that is different than the material of the part **130**. As such, embodiments of parts **130** with integrated passageways according to the present disclosure can advantageously integrate dissimilar materials into the final part.

After the exterior surface **137** of the final part **130** has been machined to form the generally smooth surface, the part **130** can be further processed to expose an entrance and an exit of the tubes **136** which were embedded/integrated within the final part **130**. In one example further processing step, the part **130** is cut along a plane indicated by lines **141** and **142**, as shown in FIGS. **4** and **5**, thereby forming and/or exposing an entrance and an exit to each tube **136**. Example entrances/exits of the passages formed by tubes **136** are illustrated in FIG. **6**. In some embodiments, the grooves **134** and/or tubes **136** can terminate into a common channel or manifold at one or both ends of the grooves **134** and tubes **136**. The common channel or manifold can function as a single entrance and/or exit. In some embodiments the grooves **134** and/or tubes **136** can be connected to a chamber embedded in the part **130** or welded to the part **130**.

FIG. **9** is a flow chart representing another example method **212** of forming a part having integrated passages according to an embodiment of the present disclosure. FIG. **10** schematically illustrates the method **212** according to a non-limiting embodiment of the present disclosure. It will be understood that the method **212** can be implemented in many other suitable ways, resulting in other intermediate and final parts than those illustrated in the examples illustrated in FIG. **10**. Starting at block **214**, two or more initial parts (for example, initial part **130***a*) are formed. The two or more initial parts can be formed using any suitable manufacturing technique, for example an additive manufacturing technique, for example an FSAM technique. The two or more parts can be formed to have a near net shape using any of the processes described herein. The two or more parts can have any shape or geometry. For example, the parts can have curved surfaces and/or substantially planar surfaces. The number of initial parts being formed can be dependent upon the intended shape of the final part.

Moving to block **216**, inner surfaces (for example, inner surfaces **133**) of the two or more initial parts are machined. The inner surfaces can be machined to have a generally smooth surface. Moving to block **218**, after machining the inner surfaces of the two or more parts, the two or more parts can be joined together forming a joined part or structure **130***b*. Example methods of joining the two or more parts include welding, gluing, melting, and fastening.

Moving to block **220**, once the joined part **130***b* is formed, the outer surface of the joined part **130***b* can be machined, for example, similar to the processes described with reference to FIG. **4** and FIG. **8** above. The joined part or structure **130***b* can be machined to have a generally smooth outer surface. The joined part or structure can be machined to include one or more grooves (for example, grooves **134**) in the outer surface. The one or more grooves can be machined into the generally smooth outer surface, or the one or more grooves can be machined into the outer surface prior to machining the joined part or structure **130***b* to have a generally smooth outer surface. The one or more grooves can be machined in a predetermined orientation. The one or more grooves can be formed in a portion of the joined part or structure or extend over an entire surface of the joined part or structure. For example, as shown in FIG. **10**, a portion of the joined part or structure may have grooves, or substantially the entire surface of the joined part or structure may have grooves. Additionally, the grooves may extend in different directions relative to the orientation of the joined part or structure. For example, as illustrated in FIG. **10**, the grooves **134** can include grooves **134***a* extending as shown in the part **130***c*. In another non-limiting example, the grooves **134** can include grooves **134***b* extending in an alternate way, as shown in the part **130***d*.

Moving to blocks **222**, **224**, and **226**, tubes (for example, tubes **136**) can be positioned within the grooves (for example, grooves **134***a* in the part **130***c* or grooves **134***b* in the part **130***d*). The tubes can be positioned one at a time, or a plurality of tubes can be positioned simultaneously. The tubes can be positioned manually or in an automated manner. The tubes can then be sealed within the grooves using FSAM in accordance with embodiments of the present disclosure. The part **130***b* can then be machined to a predetermined final shape, as described above in accordance with embodiments of the present disclosure. In one non-limiting embodiment illustrated in FIG. **10**, the final part is a spherical tank with embedded tubes.

The methods and structures according to the present disclosure can provide various advantages and benefits. They can allow for the formation of a final structure having a more complex design, while still integrating internal passages. This can reduce the overall thickness of the final structure as the passages will no longer need to be mounted external to the final structure. The integrated internal passages can reduce the overall weight of the final structure as the thickness of the internal tubing can be thinner because the surrounding structure provides additional protection to the tubes. The integration of the passages can also eliminate or reduce the fragile nature of the tubing by providing the additional protection. Further, the methods and structures can eliminate the potential for the tubing to become delaminated to the surface of a structure (for example, a tank). The functioning of the internal passageways can also result in higher efficiencies as the tubing and the overall shape of the structure can be uniform. Further, the heat transfer efficiencies can have improved predictability as the tubing can be in full contact with the wall of the structure (for example, a tank) instead of only making contact on one side. The lack of a bonding material can also improve the predictability of the heat transfer efficiencies.

While the above detailed description has shown, described, and pointed out novel features of the present disclosure as applied to various embodiments, it will be understood that various omissions, substitutions, and changes in the form and details of the device or process illustrated may be made by those skilled in the art without departing from the spirit of the present disclosure. As will be recognized, the present disclosure may be embodied within a form that does not provide all of the features and benefits set forth herein, as some features may be used or practiced separately from others. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

The term "comprising" as used herein is synonymous with "including," "containing," or "characterized by," and is inclusive or open-ended and does not exclude additional, unrecited elements or method steps. With respect to the use of substantially any plural and/or singular terms herein, those having skill in the art may translate from the plural to the singular and/or from the singular to the plural as is appropriate to the context and/or application. The various singular/plural permutations may be expressly set forth herein for sake of clarity.

It will be understood by those within the art that, in general, terms used herein are generally intended as "open" terms (e.g., the term "including" should be interpreted as "including but not limited to," the term "having" should be interpreted as "having at least," the term "includes" should be interpreted as "includes but is not limited to," etc.). It will be further understood by those within the art that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases "at least one" and "one or more" to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim recitation to embodiments containing only one such recitation, even when the same claim includes the introductory phrases "one or more" or "at least one" and indefinite articles such as "a" or "an" (e.g., "a" and/or "an" should typically be interpreted to mean "at least one" or "one or more"); the same holds true for the use of definite articles used to introduce claim recitations.

In addition, even if a specific number of an introduced claim recitation is explicitly recited, those skilled in the art will recognize that such recitation should typically be interpreted to mean at least the recited number (e.g., the bare recitation of "two recitations," without other modifiers, typically means at least two recitations, or two or more recitations). Furthermore, in those instances where a convention analogous to "at least one of A, B, and C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, and C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). In those instances where a convention analogous to "at least one of A, B, or C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, or C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). It will be further understood by those within the art that virtually any disjunctive word and/or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms. For example, the phrase "A or B" will be understood to include the possibilities of "A" or "B" or "A and B."

All numbers expressing quantities of ingredients, reaction conditions, and so forth used in the specification and claims are to be understood as being modified in all instances by the term "about." Accordingly, unless indicated to the contrary, the numerical parameters set forth in the specification and attached claims are approximations that may vary depending upon the desired properties sought to be obtained by the present invention. At the very least, and not as an attempt to limit the application of the doctrine of equivalents to the scope of the claims, each numerical parameter should be construed in light of the number of significant digits and ordinary rounding approaches. For example, terms such as about, approximately, substantially, and the like may represent a percentage relative deviation, in various embodiments, of +1%, +5%, +10%, or +20%.

The above description discloses several methods and materials of the present disclosure. The present disclosure is susceptible to modifications in the methods and materials, as well as alterations in the fabrication methods and equipment. Such modifications will become apparent to those skilled in the art from a consideration of this disclosure. Consequently, it is not intended that the present disclosure be limited to the specific embodiments disclosed herein, but that it covers all modifications and alternatives coming within the true scope and spirit of the present disclosure.

What is claimed is:

1. A method of additive manufacturing a nozzle for a rocket engine comprising:

forming an initial part by moving a friction stir tool configured to deposit a filler material in a predetermined formation;

machining a curved surface of the initial part;

machining the machined curved surface to form a plurality of grooves extending into the machined curved surface, the plurality of grooves sized and shaped to each receive a tube;

placing a tube into each of the plurality of grooves;

moving the friction stir tool across the machined curved surface and depositing additional filler material configured to secure the tubes within the plurality of grooves; and

machining the additional filler material deposited over the tubes to form the nozzle.

2. The method of claim **1**, wherein the filler material is copper.

3. The method of claim **1**, wherein the tubes are configured to transport a liquid.

4. The method of claim **1**, wherein the filler material is a first material and the tubes are formed of a second material different than the first material.

5. The method of claim **1**, wherein the filler material is a first material and the tubes are formed of a second material that is the same as or substantially the same as the first material.

6. The method of claim **1**, wherein the friction stir tool comprises a spindle having a channel extending along a central axis of the spindle and configured to hold the filler material, and wherein forming the initial part comprises rotating the spindle of the friction stir tool to deposit the filler material held in the channel in the predetermined formation.

7. A method of additive manufacturing a nozzle for a rocket engine comprising:

forming an initial part by depositing layers of material using a friction stir tool, a new layer added to a surface of a previously deposited layer;

machining a plurality of grooves extending into a curved surface of the initial part, the plurality of grooves sized to each receive a wire;

positioning a wire into each of the plurality of grooves;

securing the wires within the plurality of grooves with additional material deposited over the wires;

machining the additional material to form the nozzle; and

removing the wires from the nozzle to form integrated passages.

8. The method of claim **7**, wherein the initial part is formed using friction stir additive manufacturing.

9. The method of claim **7**, wherein the material is copper.

10. The method of claim **7**, wherein the wires comprise hollow wires.

11. The method of claim **7**, wherein the wires comprise solid wires.

12. The method of claim **11**, wherein the wires comprise solid aluminum wires.

13. The method of claim **7**, wherein the wires are removed from the nozzle using a chemical or thermal process.

14. The method of claim 7, wherein the material is a first material and the wires are formed of a second material different than the first material.

15. The method of claim 7, wherein the material is a first material and the wires are formed of a second material that is the same as or substantially the same as the first material.

16. A method of additive manufacturing a nozzle for a rocket engine comprising:

forming an initial part by depositing layers of material using a friction stir tool, a new layer added to a surface of a previously deposited layer;

machining a plurality of grooves extending into a curved surface of the initial part, the plurality of grooves sized to each receive a wire;

positioning a hollow wire into each of the plurality of grooves;

securing the hollow wires within the plurality of grooves with additional material deposited over the hollow wires; and

machining the additional material to form the nozzle.

17. The method of claim 16, wherein the initial part is formed using friction stir additive manufacturing.

18. The method of claim 16, wherein the material is copper.

19. The method of claim 16, wherein the hollow wires are configured to transport a liquid.

20. The method of claim 16, wherein the material is a first material and the hollow wires are formed of a second material different than the first material.

21. The method of claim 16, wherein the material is a first material and the hollow wires are formed of a second material that is the same as or substantially the same as the first material.

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