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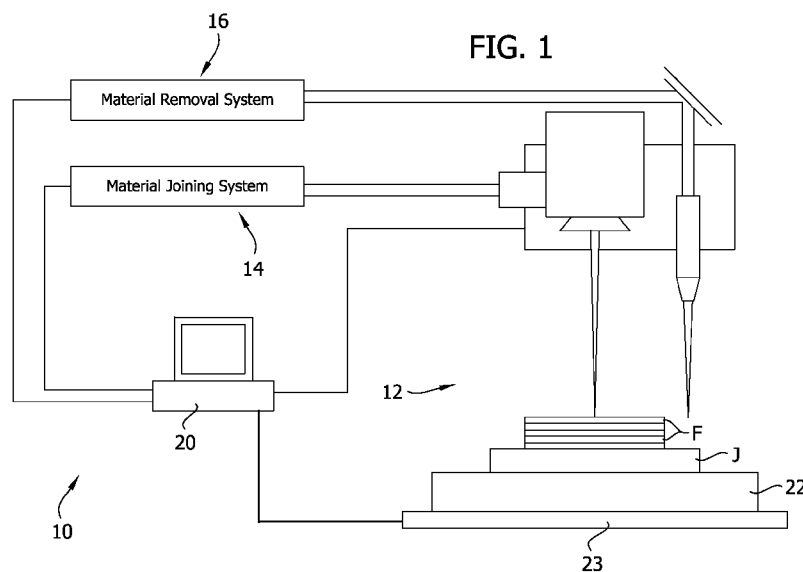
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(S7) Abstract: An additive manufacturing system, method of manufacturing, and fabricated part. The system uses a material joining laser system to join together foil sheets to form a metal part. The material joining laser system can be configured to join adjacent foil sheets together in a substantially uniform manner. The manufacturing system also includes a material removal system that removes material from selected locations of the foil sheets to shape the foil sheets to correspond with selective slices of the part. The material removal system can be a laser system, such as a laser system configured to remove material from a foil sheet without removing material from an underlying layer. The method implements various aspects of the system to form a part.

FOIL-BASED ADDITIVE MANUFACTURING SYSTEM AND METHOD

FIELD

[0001] The present invention generally relates to a system and method for additive manufacturing and more specifically to manufacturing of metal parts from foil sheets.

BACKGROUND

[0002] Additive manufacturing technologies, such as three-dimensional printing, are widely used in various industries and are regularly being adopted by new industries and for new applications. Various additive manufacturing technologies include stereo-lithography, fused deposition modeling, laminated object manufacturing, selective laser sintering, selective laser melting, laser engineered net shaping, direct metal deposition, electron beam melting, etc. These technologies can be used to manufacture articles from various materials such as resin, wax, polymer, plastic, ABS, polycarbonate material, metal powder, etc. Metal parts have proven more difficult to manufacture using additive manufacturing techniques than parts made from other materials. It is particularly difficult to manufacture a metal part using additive manufacturing in a way that yields material properties consonant with parts made using traditional metal machining techniques.

[0003] Most metal additive manufacturing processes are powder based. In selective laser sintering, metal powders are deposited in layers that correspond in shape with slices of the resulting part and are sintered or fused together. Layer by layer, the laser fuses the powder to form the three-dimensional part. Although a wide range of materials can be used in selective laser sintering, the manufacturing tolerance of the resulting part is limited by the size of the powdered metal particles. Moreover, the mechanical strength of as-fabricated parts is far below that of the raw material. Furthermore, powder-based processes face environmental, safety, and handling challenges associated with handling fine powders.

[0004] In laser engineered net shaping and direct metal deposition, a metal part is formed by depositing metal powders in a specific location and then melting the powder. These processes are compatible with many materials, such as stainless steel, nickel alloy, tool steel, copper alloys, and combinations thereof. The laser engineered net shaping process can also be used to repair damaged metal parts. But in these

powder melting techniques, uneven heating and cooling processes introduce residual stresses into the manufactured part. Typically, the finished parts have a poor surface quality that requires an additional finishing process.

[0005] Laminated object manufacturing is a foil-based process that combines additive and subtractive techniques to build a part, layer upon layer. Initially, laminated object manufacturing processes formed parts from paper bonded together by binders under pressure and heat. The technology was later extended to metal foils, using high powered ultrasonic waves to fuse the foil sheets together. After the foil sheets are fused together, a milling tool is used to cut or trim the foil to the desired shape. The advantages of laminated object manufacturing include low cost per part, low material deformation, and scalability. But the material removal processes are known to produce a large amount of waste, and the mechanical strength of the fabricated parts is typically directional in nature, usually being concentrated along a vertical axis (in the direction perpendicular to the foil surface) so that the part is relatively weak along horizontal axes.

SUMMARY

[0006] In one aspect, a system for manufacturing a three-dimensional metal part comprising n slices from n foil sheets including a first foil sheet, an n th foil sheet, and plurality of intermediate foil sheets comprises a base configured to support a substrate layer and the n foil sheets as each of the n foil sheets is sequentially stacked as another layer upon the substrate layer such that each of the n foil sheets engages a respective underlying layer comprising one of the substrate layer and another of the n foil sheets. A material joining laser system is configured to generate a material joining laser configured for joining any of the n foil sheets to the respective underlying layer. A material removal laser system is configured to generate a material removal laser configured to remove material from any of the n foil sheets substantially without removing material from the respective underlying layer. A controller is configured to receive shape data indicative of a shape of each of the n slices of the three-dimensional metal part. The controller is further configured to perform the following steps after each of the n foil sheets is stacked upon the respective underlying layer: control the material joining laser system to join the respective foil sheet to the respective underlying layer using the material joining laser; and use the shape data to control the material removal

laser system to remove material from the respective foil sheet to shape the respective foil sheet to correspond in shape with a respective slice of the metal part using the material removal laser.

[0007] A system for manufacturing a three-dimensional metal part comprising n slices from n foil sheets including a first foil sheet, an n th foil sheet, and plurality of intermediate foil sheets comprises a base configured to support a substrate layer and the n foil sheets as each of the n foil sheets is sequentially stacked as another layer upon the substrate layer such that each of the n foil sheets engages a respective underlying layer comprising one of the substrate layer and another of the n foil sheets. A material removal system is configured to remove material from any one or more of the n foil sheets. A material joining laser system is configured to generate a material joining laser configured for joining any of the n foil sheets to an underlying layer. A material joining movement system is configured to selectively move at least one of the base and the material joining laser relative to the other of the base and the material joining laser along at least an x axis and a y axis. A controller is configured to receive shape data indicative of a shape of each of the n slices of the three-dimensional metal part. The controller is configured to control the material removal system to remove material from one or more of the n foil sheets to shape each of the n foil sheets to correspond in shape with a respective one of the n slices of the metal part. The controller is further configured to, after each one of the n foil sheets is stacked upon an underlying layer, control the material joining movement system to move said at least one of the base and the material joining laser relative to said other of the base and the material joining laser to cause the material joining laser to travel along a welding path along the respective foil sheet to join the respective foil sheet to the respective underlying layer in a substantially uniform manner across the respective foil sheet.

[0008] In still another aspect, a metal part comprises n slices including a first slice, an n th slice and a plurality of intermediate slices. Each of the n slices is formed from a foil sheet having material removed therefrom to shape the respective foil sheet to correspond in shape with a respective one of the n slices. The n foil sheets are stacked atop one another along a z axis. The metal part further includes a substrate layer underlying the n foil layers. Each of the n foil sheets is joined to a respective underlying layer comprising one of the substrate layer and another of the n foil sheets by a respective laser weld. Each weld extends along a weld path comprising a plurality

of path segments. Each of the path segments of each weld extend along an x axis and the path segments are spaced apart from one another along a y axis.

[0009] In yet another aspect, a method of manufacturing a metal part comprising n slices from n foil sheets including a first foil sheet, an nth foil sheet, and a plurality of intermediate foil sheets comprises sequentially stacking each of the n foil sheets on a substrate layer such that each of the n foil sheets engages a respective underlying layer comprising one of the substrate layer and another of the n foil sheets. Each of the n foil sheets are joined to the respective underlying layer using a material joining laser after each respective sheet is stacked on the respective underlying layer. Material is removed from one or more of the n foil sheets to shape said one or more of the n foil sheets to correspond in shape with one or more respective slices of the metal part. Said steps of joining each of the n foil sheets to the respective underlying layer and removing material from said one or more of the n foil sheets are controlled based on shape data indicative of a shape of each of the n slices of the metal part.

[0010] Other objects and features will be in part apparent and in part pointed out hereinafter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. 1 is a schematic block diagram of an additive manufacturing system;

[0012] FIG. 2 is a perspective comparing a stack of foil sheets to a part manufactured from the foil sheets using the additive manufacturing system;

[0013] FIG. 3 is a more detailed schematic block diagram of the additive manufacturing system;

[0014] FIG. 4 is photograph illustrating a cross section of a weld formed by the additive manufacturing system that joins a foil sheet to a substrate;

[0015] FIG. 5 is a photograph illustrating a top surface of a foil sheet after being welded to an underlying layer by the additive manufacturing system;

[0016] FIG. 6 is a photograph of a cross section of a first foil sheet after being joined to a second foil sheet by the additive manufacturing system;

[0017] FIG. 7 is photograph of an edge of a foil sheet after having been cut by the additive manufacturing system;

[0018] FIG. 8 is a flow chart illustrating the steps and decision block of a method of manufacturing a metal part using the additive manufacturing system;

[0019] FIG. 9 is a photograph of a metal part formed using the additive manufacturing system;

[0020] FIG. 10 is a table showing the results of microhardness testing performed on a cubic part formed by the additive manufacturing system and the raw foil from which the part was formed with a photograph of a cross section of the cubic part superimposed on the table;

[0021] FIG. 11 is a photograph of another metal part formed using the additive manufacturing system;

[0022] FIG. 12 is a photograph of another metal part formed using the additive manufacturing system; and

[0023] FIG. 13 is a photograph of another metal part formed using the additive manufacturing system.

[0024] Corresponding reference characters indicate corresponding parts throughout the drawings.

DETAILED DESCRIPTION

[0025] Referring to Figs. 1 and 2, an additive manufacturing system for manufacturing a three-dimensional metal part P is generally indicated at reference numeral 10. As will be explained in further detail below, the manufacturing system 10 forms the part P by stacking, shaping, and joining together a plurality of foil sheets F. The manufacturing system 10 includes a foil sheet positioning system, generally indicated at 12, material joining system, generally indicated at 14, and material removal system, generally indicated at 16, that operate together to form the part P from the foil sheets F. A controller 20 is operatively connected to the foil sheet positioning system 12, material joining system 14, and material removal system 16 to control the system 10 to manufacture the part P based on a three-dimensional model of the part.

[0026] Referring to Fig. 2, the three-dimensional part P can be characterized as n slices S of material that form the part. Each slice S has a thickness extending along a z-axis a shape extending in a horizontal plane defined by x and y axes oriented orthogonal to the z axis. As will be explained in further detail below, the manufacturing system 10 is configured to manufacture the part P from n foil sheets F that are joined together and shaped to correspond in shape with respective slices S of the metal part. Each of the foil sheets F has the same thickness as one of the slices S of the part P.

The foil sheets F are shown as a stack of rectangular sheets in Fig. 2 to represent how the foil is layered in use. But typically the foil sheets F will be removed from one or more rolls of foil. Although the illustrated sheets F have the same dimensions, sheets of different dimensions can also be used without departing from the scope of the invention. For example, one or more of the n foil sheets may have a different thickness than others of the n foil sheets. In addition, one or more of the n foil sheets may be made from a different material than others of the n foil sheets. Where slices S of the part P comprise different materials at different locations, foil sheets of different materials may be used to form an individual slice.

[0027] Throughout this disclosure, the variable 'n' is used to refer to a number of slices S that form at least a portion of the part P, which portion is manufactured by layering, shaping, and joining together 'n' foil sheets F. In some embodiments, the 'n' foil sheets may be joined together to form the entire part P. In other embodiments, the 'n' foil sheets are joined together to form only a portion of the part P and are further joined to another piece (e.g., a foil sheet not included in the n foil sheets, a substrate, etc.) to form the entire part. In general, the manufacturing system 10 will manufacture the part P from four or more sheets of foil F (i.e., $n \geq 4$, e.g., from 4 to about 25, 4 to about 40, 4 to about 50, 4 to about 75, 4 to about 100, 4 to about 150, 4 to about 200, 4 to about 500, 4 to about 1000, 4 to about 5000, 4 to about 10,000, 4 to about 25,000, or more), including a first foil sheet, an nth foil sheet, and a plurality of intermediate foil sheets layered between the first and nth foil sheets. But particularly thin parts can be manufactured from fewer than four sheets without departing from the scope of the invention.

[0028] The foil sheets F can comprise any suitable metal material. In certain embodiments, the foil sheets F comprise a steel, such as 1010 steel. An exemplary steel foil is 1010 steel, UPC No. 16850, available from Precision Brand Products, Inc. of Downers Grove, IL. In one or more preferred embodiments, the foil sheets F have a thickness of from about 50 μm to about 750 μm (e.g., about 150 μm). Foil sheets of other thickness can also be used without departing from the scope of the invention.

[0029] Referring again to Fig. 1, the foil positioning system 12 includes a base 22 configured to support the foil sheets F that form the part P. In a preferred embodiment, the base 22 comprises a platform operatively connected to a movement stage 23 for moving the platform along the x and y axes. In other embodiments, the platform may

be static or may move along any one, two, or three of the x, y, and z axes without departing from the scope of the invention.

[0030] In certain embodiments, a joining substrate J is positioned on the base 22 before the n foil sheets F are layered on the base. The first foil sheet F is stacked onto the substrate J so that the first foil sheet forms one layer and the substrate forms an underlying layer. Preferably, the substrate J is suitable for being joined to the first foil sheet F by welding. The substrate J can be thicker than each of the foil sheets F. For example, in one or more embodiments, the substrate J has a thickness of from about 2 mm to about 25 mm (e.g., about 3 mm). The substrate J can also be thicker or thinner without departing from the scope of the invention. If the substrate J is to be joined to the foil sheets F, it is preferably either shaped to correspond with a portion of the metal part P or removed from the part after fabrication. In some embodiments, the manufacturing system 10 can shape the substrate J after it is positioned on the platform 22. In other embodiments, the substrate J is shaped before being positioned on the platform 22.

[0031] In the illustrated embodiment, the foil sheets F are manually loaded onto the substrate J. For example, sheets of foil F taken from a roll are positioned, one at a time, atop the substrate J. As will be explained in further detail below, after each sheet F is loaded onto the platform 22, the material joining system 14 and the material removal system 16 are used to join the sheet to the underlying layer and to shape the sheet to correspond in shape with a slice S of the part P. It will be understood that an automated sheet loading system (not shown) could be used to place the foil sheets F onto the base without departing from the scope of the invention.

[0032] Referring to Fig. 3, in the illustrated embodiment, the joining system 14 is a material joining laser system configured to generate a material joining laser 26. In other embodiments, other types of material joining systems (e.g., ultrasonic joining systems, etc.) may be used without departing from the scope of the invention. The material joining laser system is configured to generate a material joining laser 26 that is configured to join each of the n foil sheets F to an underlying layer. For each of the foil sheets F, an "underlying layer" can comprise a substrate or an underlying foil sheet that engages and directly underlies the respective foil sheet. As will be explained in further detail below, the material joining laser system 14 is preferably controlled by the controller 20 to join each of the n foil sheets to its respective underlying layer in a

substantially uniform manner. This produces strong bonding among the slices of the part P, for a high strength metal part whose strength is not directionally dependent.

[0033] Any suitable joining laser system (e.g., a gas laser system, a solid state laser system, etc.) may be used for the material joining laser system 14. The choice of joining laser system type can depend on such factors as cost, desired welding quality, and foil type, etc. The illustrated material joining laser system 14 includes a laser generator 30, an optical fiber 32, laser coupler 33, and beam expander 34. The laser generator 30 is preferably configured to generate a continuous wavelength laser 26. In some embodiments, the laser generator is configured to generate a material joining laser 26 having a wavelength (e.g., a continuous wavelength) of from about 355 nm to about 10,600 nm (e.g., about 1070 nm). In certain preferred embodiments, the material joining laser generator 30 is a fiber laser generator. The laser generator 30 can, in one or more embodiments, be configured to generate a material joining laser 26 with a maximum power of from about 200 W to about 2000 W (e.g., about 1000 W). One suitable laser generator 30 is an IPG YLR-1000 CW fiber laser generator, available from IPG Photonics Corporation of Oxford, MA.

[0034] In the illustrated embodiment, the optical fiber 32 is optically coupled between the laser generator 30 and the laser coupler 33 to transmit the material joining laser 26 from the laser generator to the laser coupler. An initial segment 26a of the material joining laser 26 extends generally along the y axis from the laser coupler 33 to the beam expander 34, which increases the beam size of a second segment 26b of the laser 26. The second segment 26b extends further along the y axis toward a scanner 40. As will be discussed in further detail below, the scanner 40 is configured to orient a third, welding segment 26c of the material joining laser 26 to extend generally along the z axis and to move the welding segment along the x and y axes. The welding segment 26c passes through a focusing lens 42 which focuses the material joining laser 26 at a beam spot.

[0035] The focusing lens 42 is configured to focus the material joining laser 26 for welding each of the foil sheets F to its respective underlying layer. The focusing lens 42 has a focal length which focuses the welding segment 26c on a beam spot spaced apart from the focusing lens 42 along the z axis. In certain embodiments, the focal length is from about 10 cm to about 580 cm (e.g., about 33 cm). The beam spot of the material joining laser 26 has a spot diameter. Preferably, the spot diameter is

less than or equal to the thickness of each of the foil sheets F. For example in one or more embodiments, the ratio of the foil sheet thickness to the spot diameter is from about 0.1 to about 10.

[0036] In the illustrated embodiment, the focusing lens 42 and scanner 40 are mounted on a z-movement stage 44 configured to move the focusing lens 42 and scanner 40 relative to the platform 22 along the z axis. Preferably, the controller is operatively connected to the z-movement stage 44 to automatically operatively align the beam spot with each successive foil sheet as it is stacked upon the platform 22. Thus, the z-movement stage 44 preferably moves the focusing lens 42 and scanner 40 upward along the z axis each time a new foil sheet F is stacked upon the platform 22. The z-movement stage is broadly understood to be part of a material joining movement system configured to selectively move the platform 22 and material joining laser 26 relative to one another along the x, y, and z axes (the x and y movement components of the material joining movement system are discussed in further detail below). Other ways of moving the base and material joining laser relative to one another along the z axis to operatively align the beam spot of the material joining laser with each successive foil sheet as it is added to the base may also be used without departing from the scope of the invention.

[0037] The material joining laser 26 is preferably configured to penetrate each of the n foil sheets F in a keyhole penetration mode (i.e., the material joining laser 26 has a laser intensity of greater than about $1 \times 10^4 \text{ W/cm}^2$, e.g., $1.1 \times 10^6 \text{ W/cm}^2$). In the illustrated embodiment, the material joining laser system 14 includes a shielding gas dispenser 43 that dispenses shielding gas toward the beam spot to enhance material joining. Shielding gas (e.g., argon, helium, etc.) is dispensed during welding to prevent oxidation. It will be understood that the illustrated material joining laser system 14 is but one exemplary embodiment of a system that is suitable for joining successive foil sheets F to one another in a substantially uniform manner. Other suitable material joining systems such as other types of laser welding systems, etc., may also be used without departing from the scope of the invention.

[0038] Referring to Fig. 4, an exemplary weld W1 formed by the material joining laser system 14 joins a foil sheet F1 to a substrate layer J1. The weld W1 has a depth d1 that is larger than a thickness t of the foil sheet F1. It will be understood that the size and shape of the weld W1 is determined by various factors such as the materials

being joined, laser power, laser wavelength, scanning speed, beam spot size, shielding gas type, etc. In one or more preferred embodiments, the depth d_1 of the weld W1 is at least about 130% of the thickness t of the foil sheet F1. In the illustrated example, the weld W1 is about 130% of the thickness t of the foil sheet F1. The weld W1 has a width w_i at the top surface of the foil sheet F1. In one or more embodiments the width w_i is from about 80% to about 200% of the thickness t of the foil sheet F1. In the illustrated example, the width w_i is about 175% of the thickness t . The weld W1 also has a width w_{ii} at the interface between the foil sheet F1 and the underlying layer J1. In one or more embodiments the width w_{ii} is from about 80% to about 150% of the thickness t of the foil sheet F1. In the illustrated example, the width w_{ii} is about 115% of the thickness t . In other embodiments, the material joining system is configured to form welds having other shapes and dimensions without departing from the scope of the invention.

[0039] In the illustrated embodiment, the scanner 40 controls the x and y axes movement between the material joining laser 26 and the base 22. Thus, in the illustrated embodiment, the scanner 40 and the z-movement stage 44 function together as a material joining movement system configured to selectively move the platform 22 and material joining laser 26 relative to one another along the x, y, and z axes to control the position of the material joining laser with respect to the sheets of foil F positioned on the platform. Although a laser scanner is used to control x and y axis movement in the illustrated embodiments, other embodiments can include material joining movement systems with other types of x and y axis control, such as by using the x-y movement stage, etc., without departing from the scope of the invention. In a preferred embodiment, the material joining movement system moves one of the base 22 and material joining laser 26 relative to the other at a rate of from about 350 mm/min to about 700 mm/min.

[0040] Before joining each foil sheet F to the underlying layer in a substantially uniform manner, the additive manufacturing system 10 is configured to temporarily fix the foil sheet to the underlying layer. In one or more embodiments, each time a foil sheet F is loaded onto the platform 22, the controller 20 is configured to control the laser generator 30 and scanner 40 to spot weld the new foil sheet to the underlying layer. The scanner 40 moves the material joining laser 26 along the x and y axes and the laser generator 30 delivers the material joining laser 26 to form spot welds at spaced apart locations along the respective foil sheet F. The spot welds provide

temporary attachment between the foil sheet F and its underlying layer. Other ways of temporarily attaching the foil sheet to its underlying layer (e.g., clamping, mechanically fastening, screwing, etc.) can also be used without departing from the scope of the invention.

[0041] After temporarily fixing the foil sheet F to the underlying layer, the material joining laser system 14 is configured to join the foil sheet to the underlying layer in a substantially uniform manner. As shown in Fig. 5, the controller 20 is operatively connected to the scanner 40 to control the scanner to move the welding segment 26c of the material joining laser 26 relative to the foil sheet F2 along a welding path Q. The welding path Q is preferably configured so that, by causing the material joining laser 26 to travel along the welding path at a suitable scanning rate in operative alignment the foil sheet F along the z axis, the material joining laser forms a weld across the foil sheet that joins the foil sheet to the underlying layer in a substantially uniform manner.

[0042] In the illustrated embodiment, the weld path Q includes a plurality of parallel segments. Each segment extends along the x axis, and the segments are spaced apart from an adjacent segment along the y axis. Beginning outboard of one end of a foil sheet F2, the scanner 40 moves the material joining laser 26 along the x axis in a first direction x_i at a scanning rate until the laser 26 passes over the opposite end of the foil sheet. The scanner 40 then moves the material joining laser 26 along the y axis a distance d_2 , before scanning along the x axis in an opposite second direction x_{ii} . The scanner 40 moves the material joining laser 26 in the second direction x_{ii} until it passes over the first end of the foil sheet F2 and then again moves the laser along the y axis a distance d_2 . The scanner 40 repeats these steps until the weld path Q spans the entire distance of the foil sheet F2 along the y axis.

[0043] For clarity, the illustrated weld path Q is shown as sequentially traversing adjacent path segments. However, in certain preferred embodiments, the weld path will travel along a first path segment and subsequently travel along a second path segment spaced apart from the first path segment by one or more intervening segments, repeating this pattern the material joining laser 26 scans along paths segments spanning the entire foil sheet F. For example, to minimize thermal stresses and distortion in the part P, each weld path Q can alternate between scanning along segments adjacent opposite ends of the foil sheet F.

[0044] In other embodiments, it is contemplated that, instead of welding the foil sheet F to the underlying layer by scanning the material joining laser 26 along a weld path comprising parallel weld segments, the foil sheet can be joined to the underlying layer in a substantially uniform manner by spot welding a matrix of spot welds along the surface of the foil sheet that overlap one another along their widths.

[0045] Referring to Figs. 4 and 5, the weld dimensions and distance d_2 between adjacent path segments are preferably such that at least about 40% (e.g., about 50%) of the width w_i of the weld at the top surface of the foil sheet F in each weld path segment overlaps the width of the weld at the top surface of the foil sheet in an adjacent weld path segment. Likewise, the weld dimensions and distance between adjacent path segments are preferably such that the weld extends substantially continuously across the bottom surface of the respective foil sheet F. For example, there is at least a marginal amount overlap between the width w_{ii} of the weld in each path segment and an adjacent segment. The resulting weld joins each foil sheet F to the respective underlying layer in a substantially uniform manner that provides good strength along the x, y, and z axes of the manufactured part P.

[0046] The photograph of Fig. 5 shows a solidification pattern at the top surface of the foil sheet F2 after being welded to an underlying layer. Although the weld pattern is visible, the top surface remains quite smooth after welding. The surface roughness was measured at a level of about 10 μm . Thus, in one or more embodiments, the material joining laser system 14 is configured to form a part P with a welded surface having an unfinished surface roughness of less than about 20 μm .

[0047] Referring to Fig. 6, the exemplary material joining conditions and system described above were used to join a first foil sheet F3 to a second foil sheet F4. Figure 6 shows a photograph of a cross section of the foil sheets F3 and F4 after being fused together. As is evident from the photograph, the first foil sheet was fused to the second foil sheet F4 in a substantially uniform manner. No porosity or microcracking is evident, and the two foil sheets F3, F4 are scarcely distinguishable. An apparent absence of microcracking and porosity and total fusion between a foil sheet and an underlying layer are not, however, narrowly critical to a foil sheet being joined to the underlying layer in a substantially uniform manner.

[0048] Referring again to Fig. 3, the material removal system 14 is configured to remove material from any one or more of the n foil sheets F to shape the foil sheets as

the part P. More specifically, the controller 20 is operatively connected to the material removal system 14 to use shape data indicative of a shape of each of the n slices S of the part P to remove material from the sheets F to shape each of the sheets to correspond in shape with a respective one of the slices. In the illustrated embodiment, the material removal system 14 is a material removal laser system configured to generate a material removal laser 46. But in other embodiments, other types of material removal systems (e.g., machining systems such as multi-axis mills, etc.) may also be used without departing from the scope of the invention.

[0049] Any suitable material removal laser system may be used for the material removal laser system 14. In the illustrated embodiment, the material removal laser system 14 includes a Q-switched laser generator 50, half wave plate 52, and beam expander 54. Other laser generators besides Q-switched laser generators may also be used, but a Q-switched laser generator may be preferable to produce a laser 46 of high instantaneous power for clean cutting of the foil sheets F. In one or more embodiments, the laser generator 50 is configured to generate a pulsed material removal laser 46. For example, the material removal laser can have a pulse having a pulse duration of from about 10 ns to about 600 ns (e.g., about 30 ns). Shorter pulse durations are thought to improve the quality of cuts formed in the foil sheets F by reducing the thermal effects of the laser 46 on the foil. In certain embodiments, the laser generator 50 is configured to generate a material removal laser 46 having an ultraviolet wavelength. In some embodiments, the material removal laser generator 50 is configured to generate a material removal laser 46 having a wavelength of from about 266 nm to about 10,640 nm (e.g., about 355 nm). The laser generator 50 can, in one or more suitable embodiments, be configured to generate a material removal laser 46 having a maximum power of from about 3 W to about 800 W (e.g., about 10 W), a laser pulse energy of from about 50 μ J to about 150 μ J (e.g., about 75 μ J), and a pulse repetition rate of from about 5 kHz to about 100 kHz (e.g., about 20kHz). One suitable embodiment of a material removal laser generator 50 is a Coherent AVIA-355X laser generator, available from Coherent Inc. of Santa Clara, CA.

[0050] A first segment 46a of the material removal laser 46 extends along the y axis from the laser generator 50 to the half wave plate 52. The half wave plate 52 changes a polarity of the laser 46 in a second segment 46b. The second segment 46b extends further along the y axis to the beam expander 34, which expands the size of

the laser 46 in a third segment 46c. The third segment 46c extends further along the y axis to a turning reflector 56. The turning reflector 56 turns the laser 46 so that a fourth segment 46d extends away from the turning reflector 56 along the z axis. The fourth segment 46d of the material removal laser 46 is received by a focusing lens 58, which focuses a fifth, cutting segment 46e at a focal point. In one or more embodiments, the focusing lens 58 has a focal length which focuses the welding segment 46e of the material removal laser 46 on a beam spot spaced apart from the focusing lens along the z axis. In certain embodiments, the focal length is from about 5 cm to about 20 cm (e.g., about 10 cm).

[0051] Preferably, the focal lengths of the cutting segment 46e and welding segment 26c and z axis positioning of the focusing lenses 42, 58 are such that the beam spots of the respective lasers 46, 26 are aligned with one another along the z axis. The focusing lens 58 is, like the focusing lens 42, mounted on the z movement stage 44 for conjoint movement along the z axis. As will be explained in further detail below, the beam spot of the material removal laser 46 is preferably aligned along the z axis with each new foil sheet F that is positioned on the platform 22 to sequentially remove material from each of the foil sheets. Aligning the beam spots of the two lasers 26, 46 enables alternating use of the material joining laser 26 and material removal laser 46 on a respective sheet of foil F without adjusting the z movement stage 44.

[0052] Various material removal atmospheres can be created at the foil sheet F from which material is being removed. For example, atmospheres of ambient air, compressed air, ambient argon, compressed argon, etc. may be suitable depending on the configuration of the laser system 16. In the illustrated embodiment, the laser system 16 includes a coaxial gas nozzle 60 at the distal end of the focusing lens 58. The gas nozzle 60 is configured to dispense a coaxial stream of compressed assisting gas along the z axis with the cutting segment 46e of the material removal laser. Any suitable assisting gas, such as argon, may be used without departing from the scope of the invention. The gas preferably blows away dross and debris created during material removal to achieve a clean cut and prevent oxidation.

[0053] As is the case for the material joining laser system 14, any suitable material removal movement system operatively connected to the controller may be used to move the material removal laser 46 and platform 22 relative to one another for removing material from specified locations of the foil sheets F to shape the foil sheets to

correspond in shape with the slices S of the part P. In the illustrated embodiment, the material removal movement system includes the x-y axis movement stage 23 and the z axis movement stage 44. An x-y movement stage may be preferable to a laser scanner for the material removal laser system so that the focusing lens and coaxial gas dispensing nozzle can be mounted relatively close to the foil sheets. As mentioned above, the x-y axis movement stage is operatively coupled to the platform 22 to move the platform 22 along the x and y axes, and the z axis movement stage 44 is operatively connected to the focusing lens 58 to move the focusing lens along the z axis. Movement of the focusing lens 58 along the z axis moves the material removal laser 46 along the z axis relative to the platform 22, and moreover, moves the beam spot of the material removal laser 46 relative to the foil sheets F stacked upon the platform 22.

[0054] The controller 20 is configured to control the material removal laser system 16, x-y axis movement stage 23, and z axis movement stage 44 to sequentially remove material from each foil sheet F after it is positioned on the platform 22. For example, in one embodiment, the controller 20 is configured to control the manufacturing system 10 to remove material from each foil sheet after it has been temporarily attached to the underlying layer, but before the material joining system 14 has permanently fused the respective sheet to its underlying layer. In other embodiments, the controller 20 is configured to control the manufacturing system 10 to remove material from each foil sheet F after being permanently fused to the underlying layer by the material joining laser system 14. In a preferred embodiment, the controller 20 is configured to adjust the z axis movement stage 44 each time a new foil sheet F is layered onto the platform 22 to position the beam spot in operative alignment with the respective foil sheet along the z axis. In one or more embodiments, the controller 20 is configured to receive shape data about each of the slices S of the part P and to use the shape data for each slice to control the x-y movement stage 23 to remove material from the respective sheet F, thereby shaping it to correspond in shape with the respective slice. In a preferred embodiment, the x-y movement stage 23 moves the platform 22 relative to the material removal laser 46 at from about 50 mm/min to about 350 mm/min (e.g., about 200 mm/min).

[0055] The cutting speed of the material removal laser system 16 affects the quality of the resulting part P. Referring to Fig. 7, in exemplary embodiments, the

material removal laser system 16 is configured to form one or more cuts 62 along one or more edge margins of the foil sheet F defining a location where material is removed. Preferably the material removal laser 46 is configured to form a cut in the foil sheet F with which it is operatively aligned without damaging the underlying layer. Where material is removed from foil by a laser, a heat affected zone 64 develops along the edge margins of the cuts 62. In one or more embodiments, the heat affected zone 64 has a width w_3 that is less than about 25 μm (e.g., about 20 μm). As shown in Fig. 7, the relatively small heat affected zone width produces relatively clean cuts 62, with minimal burring and visible thermal effects. Using multiple passes of the material removal laser 46 over the foil sheets F at higher cutting speeds is thought to produce higher quality cuts 62.

[0056] Referring to Fig. 8, an exemplary method 100 of using the additive manufacturing system 10 will now be described. In the following discussion, reference will be made to the controller 20, which controls various aspects of the foil sheet positioning system 12, material joining system 14, and material removal system 16. It will be understood that more than one control module may be used to control the method 100. For example, separate control modules (e.g., separate controllers) may be used to control the material joining laser system 14, material removal system 16, x-y movement stage 23, and z movement stage 44. Alternatively, a single control module may be used to implement the entire control system without departing from the scope of the invention. Moreover, various aspects of the method 100 that are described as being performed by the controller 20 may be performed manually without departing from the scope of the invention.

[0057] At an initial step 110 of the method 100, the controller 20 receives a three dimensional model of the part P. After receiving the model, the controller 20 uses shape slicing software to generate shape data from the model at step 112. The shape data divides the three dimensional model into separate models of the slices S of the part P. The controller 20 further converts the shape data into machine instructions for controlling the manufacturing system 10. It will be understood that the controller 20 could receive shape data or machine instructions from another source instead of compiling its own shape data and machine instructions using a three dimensional model.

[0058] At step 114, the user of the system 10 loads the substrate J onto the platform 22. After loading the substrate J onto the platform 22, the user loads a first one of the n foil sheets F onto the substrate J (i.e., the underlying layer of the first sheet) (step 116). If an automated foil loading system is used, the controller 20 can control the system in carrying out step 116. After the first foil sheet F is loaded onto the substrate J, the controller operates the z movement stage 44 to operatively align the material joining laser 26 and material removal laser 46 with the newly loaded foil sheet (step 118). The controller 20 then operates the material joining laser system 14 to temporarily attach the foil sheet F to the substrate J (step 120). As discussed above, the illustrated additive manufacturing system 10 temporarily attaches the foil sheets F to their underlying layers by spot welding, but other methods of temporarily attaching may also be used without departing from the scope of the invention.

[0059] With the foil sheet F temporarily attached to the substrate J, the controller 20 controls the material joining laser system 12 to join the sheet to the underlying layer in a substantially uniform manner (step 122). As discussed above, the controller 20 operates the laser generator 30 and scanner 40 to move the material joining laser 26 along the weld path Q, thereby creating substantially continuous fusion between the foil sheet F and the underlying layer across the interface therebetween. Preferably, the controller 20 prevents the material removal laser system 16 from generating the material removal laser 46 as the material joining laser system 14 is operating to join the foil sheet F to the underlying layer.

[0060] After joining the foil sheet F to the underlying layer, the controller 20 controls the material removal laser system 16 to remove material from the foil sheet to shape the foil sheet to correspond in shape with a corresponding slice S of the part P (step 124). The controller 20 preferably prevents the material joining laser system 14 from generating the material joining laser 26 during step 124. It will be understood that steps 122 and 124 could be reversed without departing from the scope of the invention. During step 124, the controller 20 uses the shape data about the slice S to move the x-y movement stage 23 to position the material removal laser 46 at locations along the foil sheet F where material must be removed. Any cut foil waste remaining on the machine may be manually or automatically removed from the foil loading system 12.

[0061] If, at decision block 126, the controller 20 determines that the part P is not completely manufactured, the method 100 returns to step 116. Another sheet F is

loaded onto the platform 22 atop an underlying layer. The controller 20 repeats steps 116-124 for respective sheets of foil F until the n sheets of foil form the n slices of the part P. In exemplary embodiments of the method 100, the resulting part P has good strength characteristics that lack substantial directional dependence.

[0062] Figure 9 is a photograph of an exemplary part 200 that was formed by performing the method 100 using the additive manufacturing system 10. The part 200 comprises n slices 202 that were each formed from a respective foil sheet F that had material removed therefrom the shape the sheet to correspond in shape with the respective slice. The slices 202 are stacked upon a substrate layer 204 along the z axis. And as discussed above, each slice 202 is joined to the underlying layer by a weld that extends along a weld path Q. The illustrated part 200 is embedded with a sensor 206. The process for forming a sensor embedded part 200 is substantially the same as discussed above for part P. Foil sheets along a certain segment of the z axis are shaped to define a channel for receiving the sensor 206. With the channel partially formed, the sensor 206 is positioned on the part 200 and subsequent foil sheets are formed atop the sensor to enclose the sensor in the part. In some instances, it is desirable to apply a buffer coating to the sensor before positioning it in the channel. It also may be desirable to dimension the channel larger than the sensor to create a gap between the part and sensor.

[0063] As shown in the photograph, the system 10 and method 100 produced a part 100 that has relatively smooth top and side surfaces. The surface roughness of the top surface was measured at a level of about 10 μm . The side surfaces are rougher than the top surfaces due to imperfections caused by manually stacking the foil sheets F atop one another along the z axis. It is believed that by incorporating an automated foil stacking system, the smoothness of the side surfaces can be improved.

[0064] Referring to Fig. 10, another 4-mm cube 300 was manufactured by the additive manufacturing system 10 according to the method 100. The cube 300 was subjected to micro-hardness testing to evaluate the effectiveness of the manufacturing system and method at producing high strength parts. The micro-hardness testing was generally performed according to the standard of ASTM E8/E8M 2009 edition, page 6, adapted for a smaller specimen. The micro-hardness of the raw foil was measured, along with the micro-hardness of the fabricated cube 300 at a matrix of 64 different points on its cross-section. The results of the micro-hardness testing are illustrated in

Fig. 10. The average micro-hardness for the fabricated part 300 is 339.8 kgf/mm² (Vickers hardness, Hv0.1/5) with the standard deviation of 20.8 kgf/mm². For the raw foil, the average micro-hardness is 283.8 kgf/mm² with the standard deviation of 13.9 kgf/mm². Thus, the fabricated part has improved micro-hardness as compared with the raw foil. The micro-hardness of the fabricated part is quite uniform throughout the volume of the part and the slight increase of the micro-hardness in the fabricated part as compared to the raw material is attributed to the fast cooling and the change of grain size and orientation due to solidification in laser welding (see Fig. 2(a)).

[0065] In addition to hardness, various samples of parts P fabricated using the system 10 and method 100 were tested for tensile strength. The results of the testing showed that the tensile strength of the parts in the x-y plane was greater than that of the original foil. For example, for a raw foil having an AISI 1010 tensile strength of about 551 MPa, the tested tensile strength of fabricated parts were found to be from about 950 MPa to about 1015 MPa. Along the vertical z axis, tested parts also show improved tensile strength as compared with the raw foil. For example, for a raw foil having an AIS 1010 tensile strength of about 551 MPa, the tested tensile strength of fabricated parts along the z axis was found to be from about 700 MPa to about 750 MPa. It is thought that the z axis tensile strength can be further improved by optimizing the process to minimize unwelded gaps between adjacent foil layers.

[0066] As shown in Figs. 11-13, the additive manufacturing system 10 and method 100 can be used to form metal parts 400, 500, 600 having a large variety of shapes, sizes, and arrangements.

[0067] When introducing elements of the present invention or the preferred embodiment(s) thereof, the articles "a", "an", "the" and "said" are intended to mean that there are one or more of the elements. The terms "comprising", "including" and "having" are intended to be inclusive and mean that there may be additional elements other than the listed elements.

[0068] In view of the above, it will be seen that the several objects of the invention are achieved and other advantageous results attained.

[0069] As various changes could be made in the above constructions, products, and methods without departing from the scope of the invention, it is intended that all matter contained in the above description and shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

WHAT IS CLAIMED IS:

1. A system for manufacturing a three-dimensional metal part comprising n slices from n foil sheets including a first foil sheet, an n th foil sheet, and plurality of intermediate foil sheets, the system comprising:

a base configured to support a substrate layer and the n foil sheets as each of the n foil sheets is sequentially stacked as another layer upon the substrate layer such that each of the n foil sheets engages a respective underlying layer comprising one of the substrate layer and another of the n foil sheets;

a material joining laser system configured to generate a material joining laser configured for joining any of the n foil sheets to the respective underlying layer;

a material removal laser system configured to generate a material removal laser configured to remove material from any of the n foil sheets; and

a controller configured to receive shape data indicative of a shape of each of the n slices of the three-dimensional metal part, the controller being further configured to perform the following steps after each of the n foil sheets is stacked upon the respective underlying layer:

control the material joining laser system to join the respective foil sheet to the respective underlying layer using the material joining laser; and

use the shape data to control the material removal laser system to remove material from the respective foil sheet to shape the respective foil sheet to correspond in shape with a respective slice of the metal part using the material removal laser.

2. A system as set forth in claim 1 further comprising a material removal movement system configured to selectively move at least one of the base and the material removal laser relative to the other of the base and the material removal laser along an x axis, a y axis, and a z axis, the controller being operatively connected to the material removal movement system to move said at least one of the base and the material removal laser relative to said other of the base and the material removal laser to position the material removal laser at one or more positions along one of the n foil sheets to remove material from said one of the n foil sheets to shape said one of the n foil sheets to correspond in shape with a respective slice of the metal part.

3. A system as set forth in claim 2 wherein the material removal movement system comprises an x-y axis movement stage operatively connected to the base to move the base along the x axis and the y axis and a z axis movement stage operatively connected to the material removal laser system to move at least a portion of the material removal laser system along the z axis and thereby move the material removal laser along the z axis.

4. A system as set forth in claim 1 further comprising a material joining movement system configured to selectively move at least one of the base and the material joining laser relative to the other of the base and the material joining laser along an x axis, a y axis, and a z axis, the controller being operatively connected to the material joining movement system to move said at least one of the base and the material joining laser relative to said other of the base and the material joining laser to cause the material joining laser to travel along one of the n foil sheets along a welding path, thereby joining said one of the n foil sheets to the respective underlying layer in a substantially uniform manner across said one of the n foil sheets.

5. A system as set forth in claim 4 wherein the material joining movement system comprises a laser scanner in optical communication with the material joining laser system to move the material joining laser relative to the base along the x axis and the y axis.

6. A system as set forth in claim 5 wherein the material joining movement system comprises a z axis movement stage operatively connected to the laser scanner to move the laser scanner relative to the base along the z axis and thereby move the material joining laser along the z axis.

7. A system as set forth in claim 1 wherein the material joining laser system is configured to generate the material joining laser to have a continuous wavelength.

8. A system as set forth in claim 1 wherein the material joining laser system is configured to generate the material joining laser to have a wavelength of from about 355 nm to about 10,600 nm.

9. A system as set forth in claim 1 wherein the material joining laser system is a fiber laser system.

10. A system as set forth in claim 1 wherein the material joining laser system is configured to generate the material joining laser to penetrate each of the n foil sheets in a keyhole penetration mode.

11. A system as set forth in claim 1 wherein each of the n foil sheets has a thickness and the material joining laser system is configured to generate the material joining laser to have a spot diameter, the spot diameter being less than or equal to the thickness.

12. A system as set forth in claim 1 wherein the material removal laser system is configured to pulse the material removal laser.

13. A system as set forth in claim 1 wherein the material removal laser system is configured to generate the material removal laser to have a wavelength of from about 266 nm to about 10,640 nm.

14. A system as set forth in claim 1 wherein the controller is configured to control the material joining laser system to spot weld each of the n foil sheets to the respective underlying layer to fix each of the n foil sheets in position on the respective underlying layer before joining each of the n foil sheets to the respective underlying layer in a substantially uniform manner across the respective one of the n foil sheets.

15. A system for manufacturing a three-dimensional metal part comprising n slices from n foil sheets including a first foil sheet, an nth foil sheet, and plurality of intermediate foil sheets, the system comprising:

a base configured to support a substrate layer and the n foil sheets as each of the n foil sheets is sequentially stacked as another layer upon the substrate layer such that each of the n foil sheets engages a respective underlying layer comprising one of the substrate layer and another of the n foil sheets;

a material removal system configured to remove material from any one or more of the n foil sheets;

a material joining laser system configured to generate a material joining laser configured for joining any of the n foil sheets to an underlying layer;

a material joining movement system configured to selectively move at least one of the base and the material joining laser relative to the other of the base and the material joining laser along at least an x axis and a y axis; and

a controller configured to receive shape data indicative of a shape of each of the n slices of the three-dimensional metal part, the controller being configured to control the material removal system to remove material from one or more of the n foil sheets to shape each of the n foil sheets to correspond in shape with a respective one of the n slices of the metal part, the controller being further configured to, after each one of the n foil sheets is stacked upon an underlying layer, control the material joining movement system to move said at least one of the base and the material joining laser relative to said other of the base and the material joining laser to cause the material joining laser to travel along a welding path along the respective foil sheet to join the respective foil sheet to the respective underlying layer in a substantially uniform manner across the respective foil sheet.

16. A system as set forth in claim 15 wherein the material joining laser system is configured to form a weld in each foil sheet as it travels along the weld path, each weld having a width at a top surface of the respective foil sheet.

17. A system as set forth in claim 16 wherein each weld path includes a plurality of parallel path segments extending along the x axis and spaced apart along the y axis.

18. A system as set forth in claim 17 wherein the path segments of each weld path are spaced apart from one another along the y axis so that at least about 40% of the width of a segment of the respective weld formed along each path segment overlaps the width of an adjacent segment of the respective weld formed along an adjacent path segment at the top surface of each foil sheet.

19. A system as set forth in claim 15 wherein each of the n foil sheets has a thickness and each weld has a depth, the depth of each weld being at least about 130% of the thickness of the respective foil sheet.

20. A metal part comprising n slices including a first slice, an n th slice and a plurality of intermediate slices, each of the n slices being formed from a foil sheet having material removed therefrom to shape the respective foil sheet to correspond in shape with a respective one of the n slices, the n foil sheets being stacked atop one another along a z axis, the metal part further including a substrate layer underlying the n foil layers, each of the n foil sheets being joined to a respective underlying layer comprising one of the substrate layer and another of the n foil sheets by a respective laser weld, each weld extending along a weld path comprising a plurality of path segments, each of the path segments of each weld extending along an x axis and being spaced apart from one another along a y axis.

21. A metal part as set forth in claim 20 wherein each of the foil sheets has a top surface, a bottom surface, and a thickness extending between the top and bottom surfaces, each weld having a width along the top surface of the respective sheet of foil.

22. A metal part as set forth in claim 21 wherein the path segments of each weld are spaced apart from one another along the y axis so that at least about 40% the width of a segment of each weld formed along each path segment overlaps the width of an adjacent segment of the weld formed along an adjacent path segment.

23. A metal part as set forth in claim 21 wherein each weld has a depth, the depth of each weld being at least about 130% of the thickness of the respective foil sheet.

24. A metal part as set forth in claim 21 wherein each weld path is shaped and arranged so that each weld extends substantially continuously across the bottom surface of the respective sheet of foil.

25. A metal part as set forth in claim 20 wherein each of the foil sheets has a heat affected zone along an edge margin of the foil defining a location where material was removed from the respective foil sheet, each heat affected zone having a width that is less than about 25 micrometers.

26. A metal part as set forth in claim 20 wherein a sensor is embedded in the metal part.

27. A method of manufacturing a metal part comprising n slices from n foil sheets including a first foil sheet, an n th foil sheet, and a plurality of intermediate foil sheets, the method comprising:

sequentially stacking each of the n foil sheets on a substrate layer such that each of the n foil sheets engages a respective underlying layer comprising one of the substrate layer and another of the n foil sheets;

joining each of the n foil sheets to the respective underlying layer using a material joining laser after each respective sheet is stacked on the respective underlying layer; and

removing material from one or more of the n foil sheets to shape said one or more of the n foil sheets to correspond in shape with one or more respective slices of the metal part;

wherein said steps of joining each of the n foil sheets to the respective underlying layer and removing material from said one or more of the n foil sheets are controlled based on shape data indicative of a shape of each of the n slices of the metal part.

28. A method as set forth in claim 27 wherein said step of removing material from one or more of the n foil sheets is performed by a material removal laser.

29. A method as set forth in one of claims 27 and 28 wherein, for each of the n foil sheets, said step of joining the respective foil sheets to the respective underlying layer comprises moving one of the material joining laser and the respective foil sheet relative to the other of the material joining laser and the respective foil sheet to cause the material joining laser to travel along a welding path along the respective foil sheet to

join the respective foil sheet to the respective underlying layer in a substantially uniform manner across the respective foil sheet.

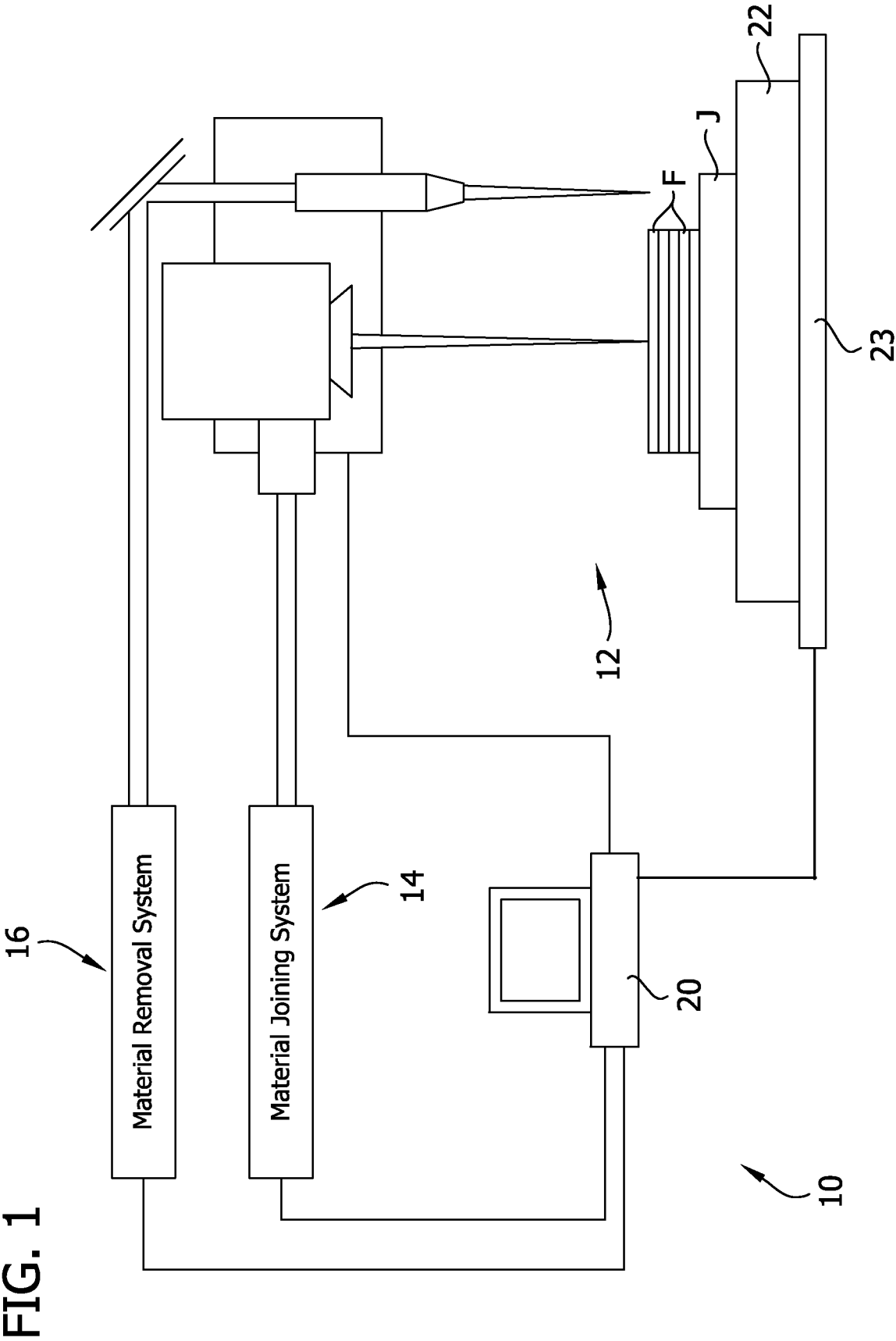


FIG. 2

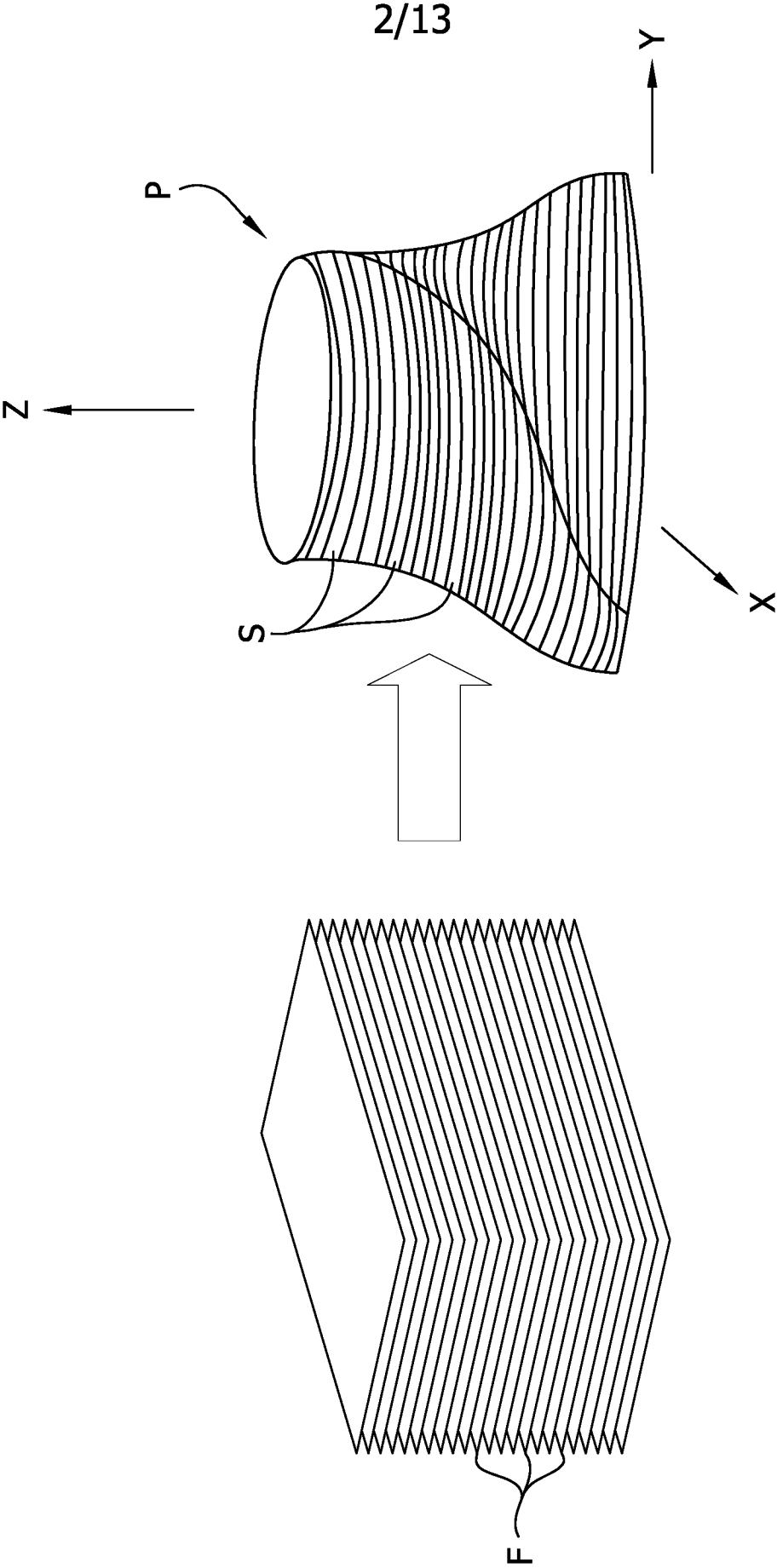


FIG. 3

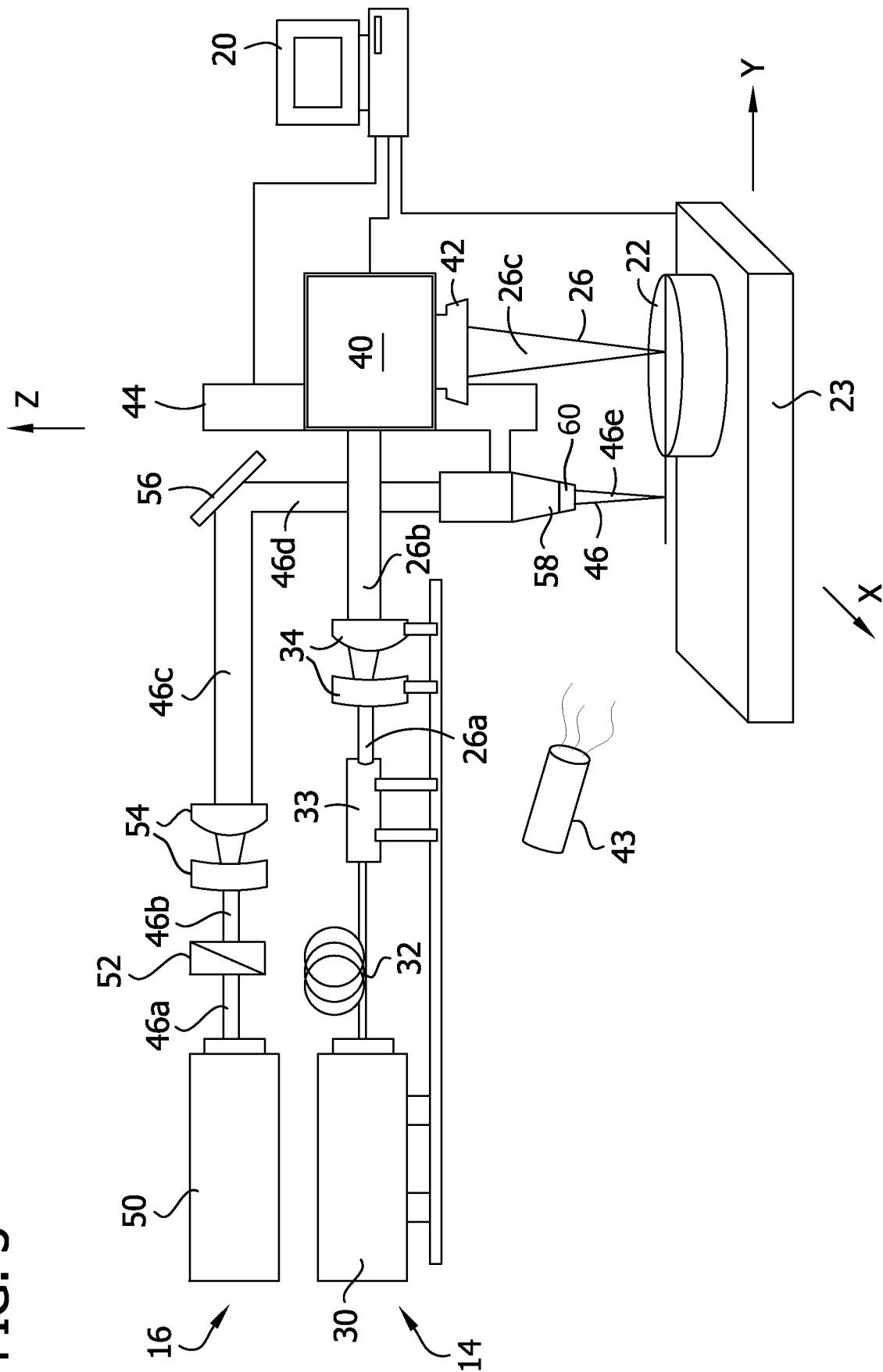
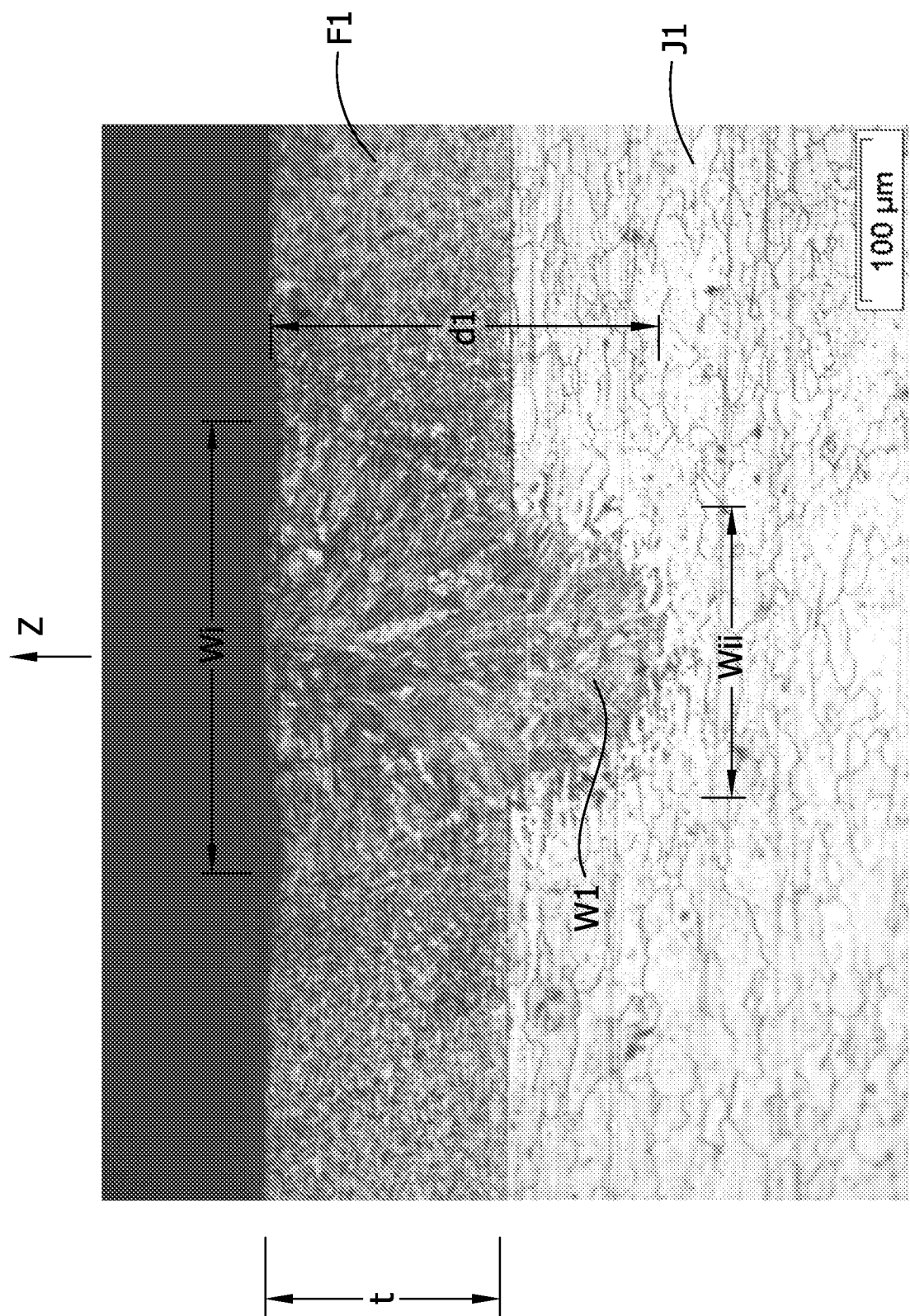
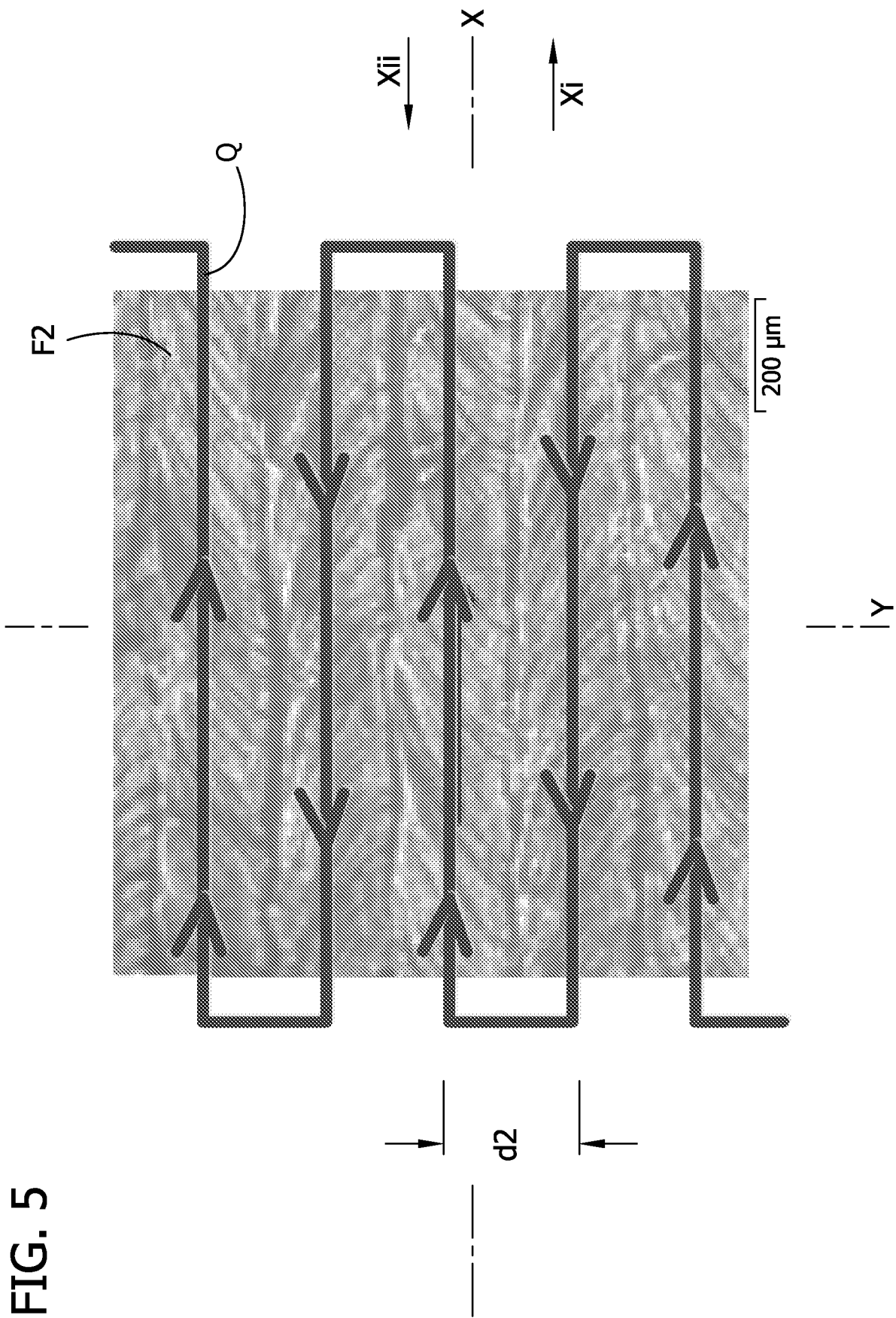


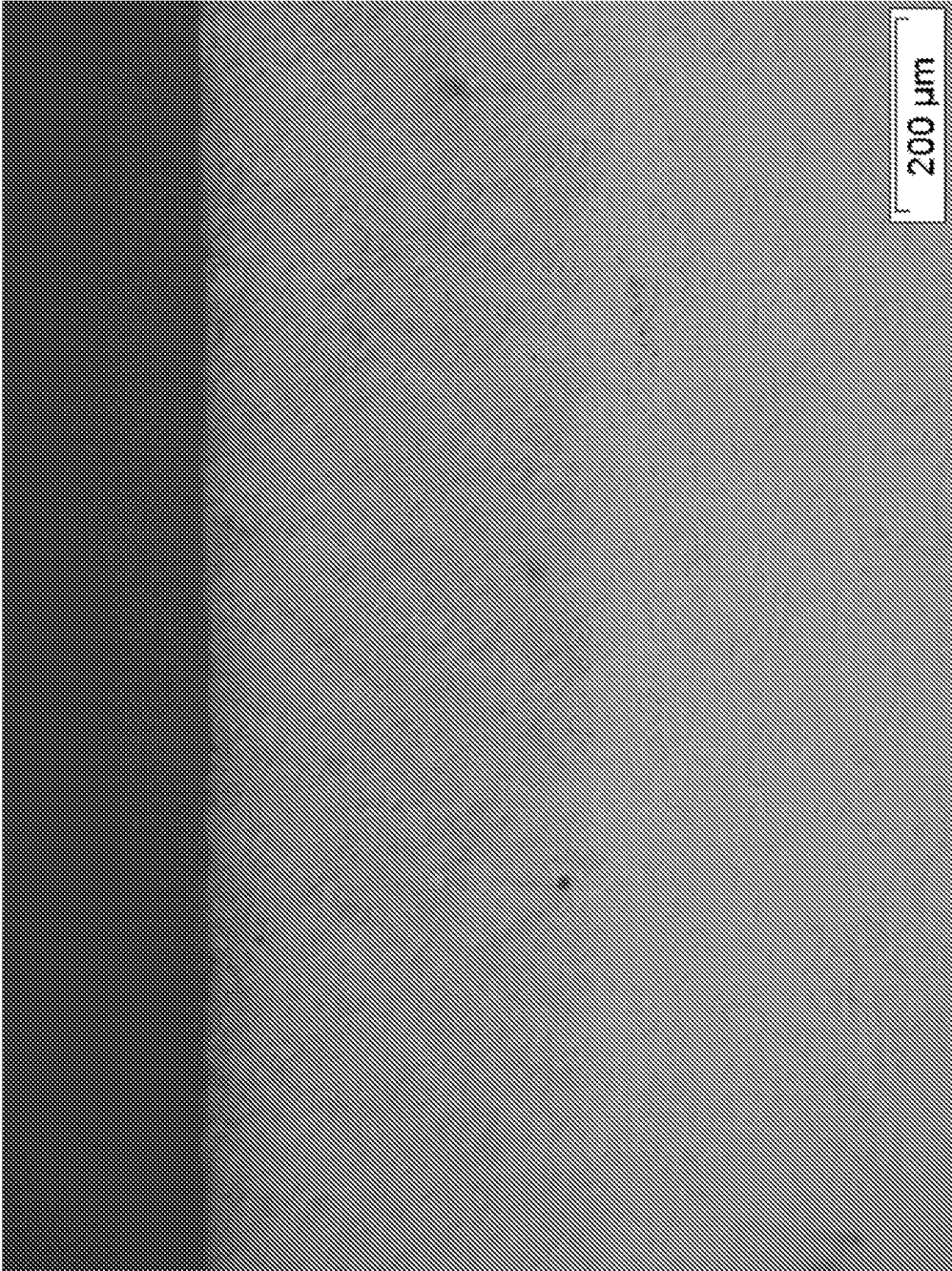
FIG. 4





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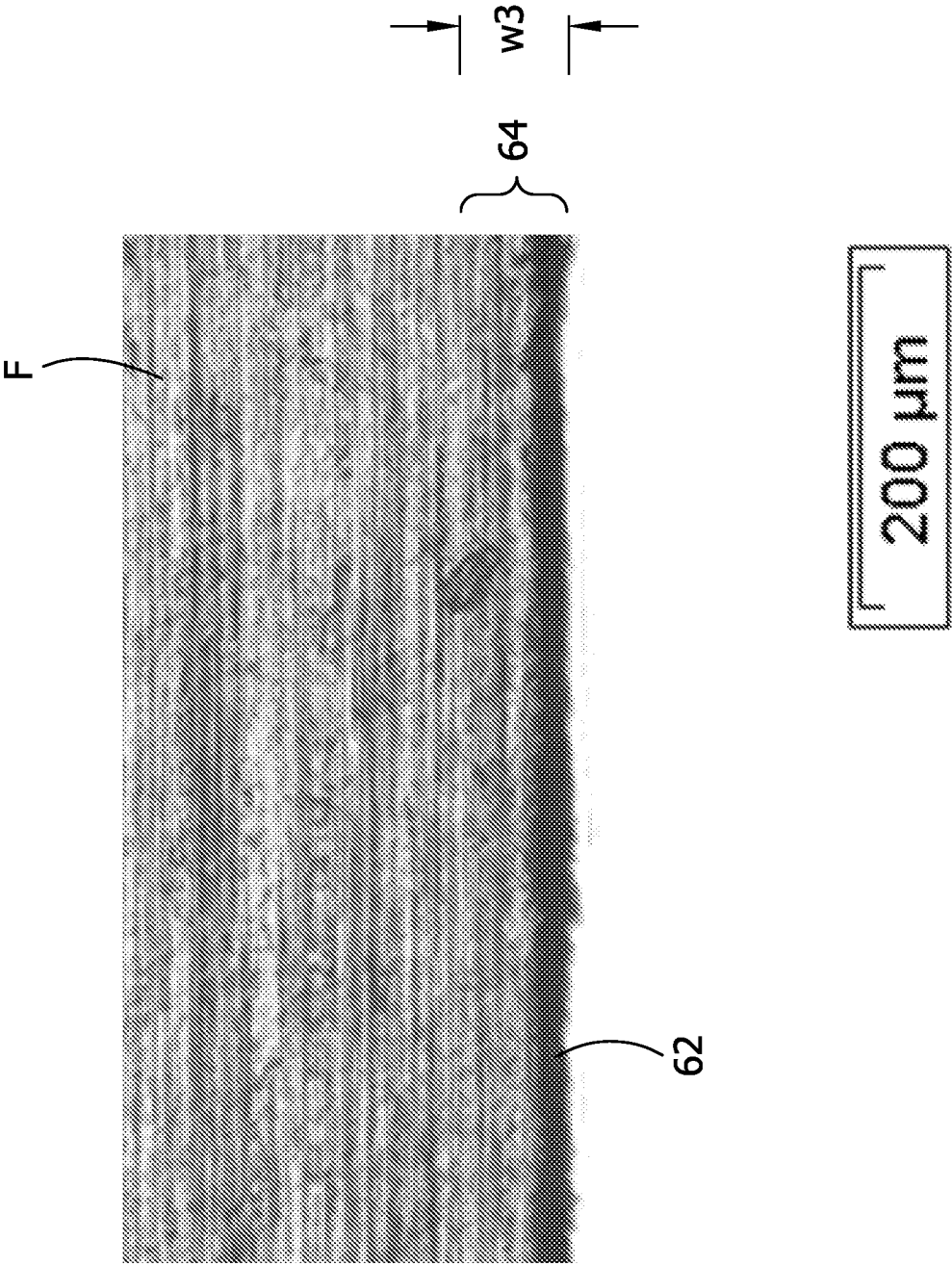
E3 E4



J

FIG. 6

FIG. 7



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FIG. 8

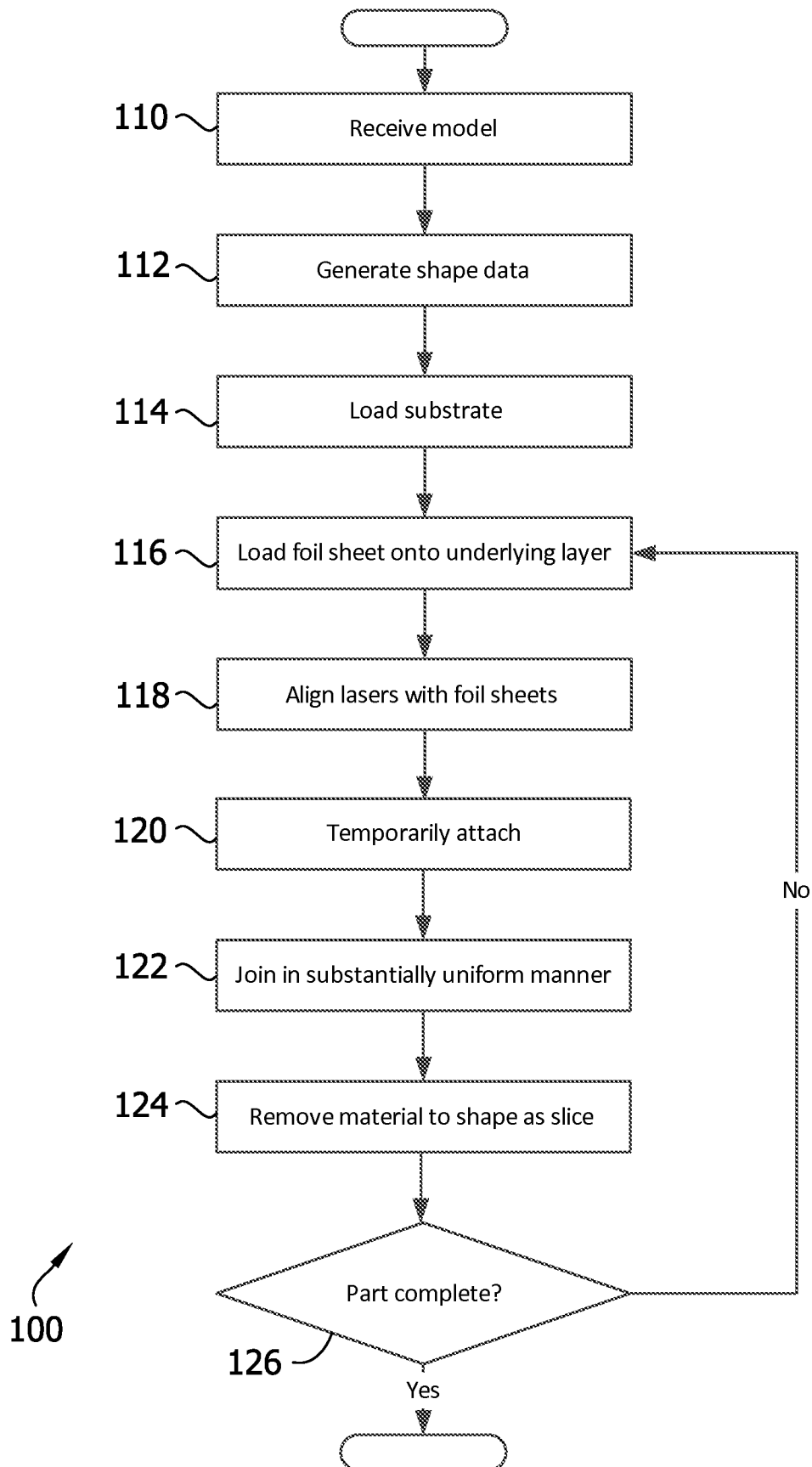


FIG. 9

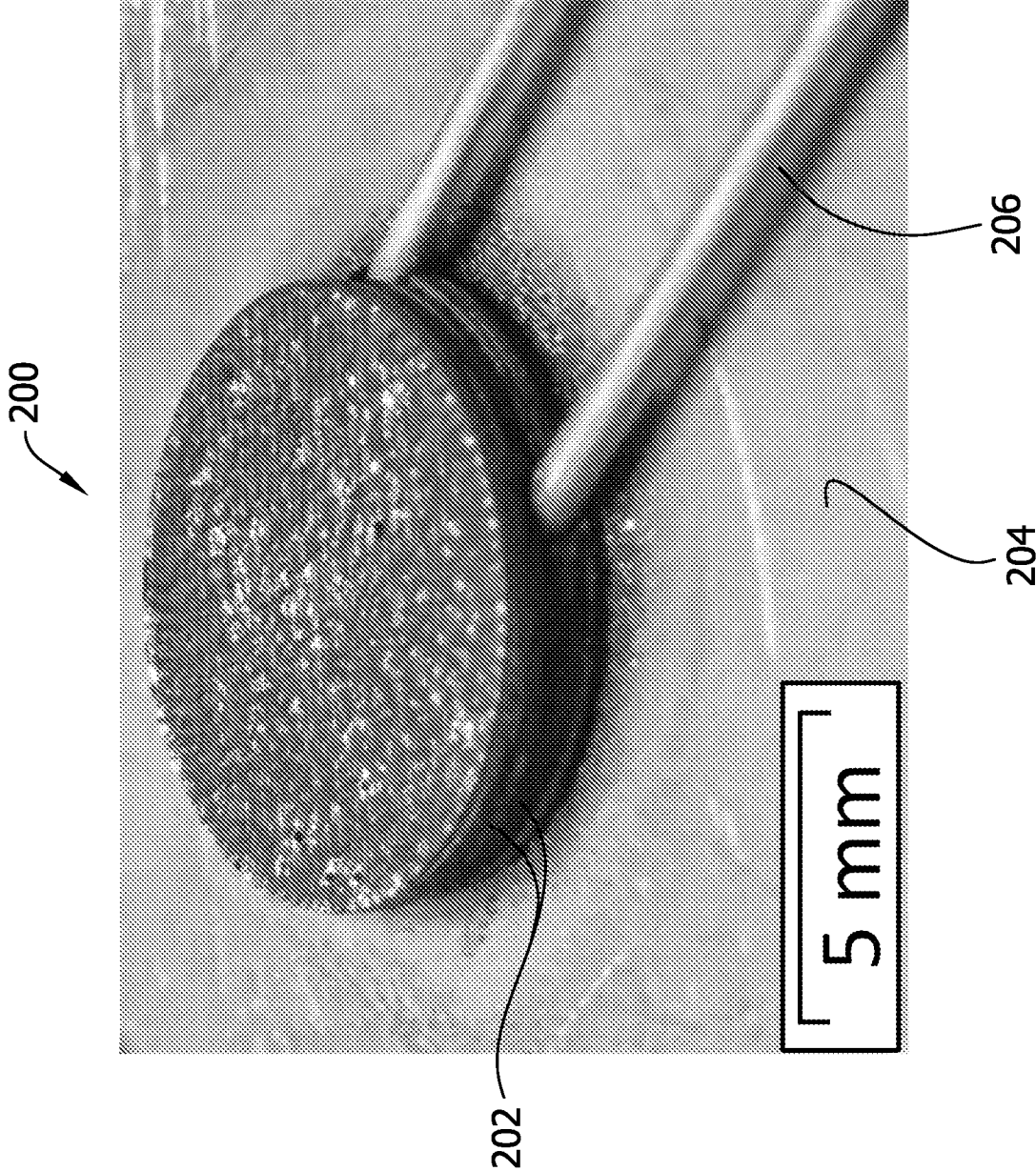
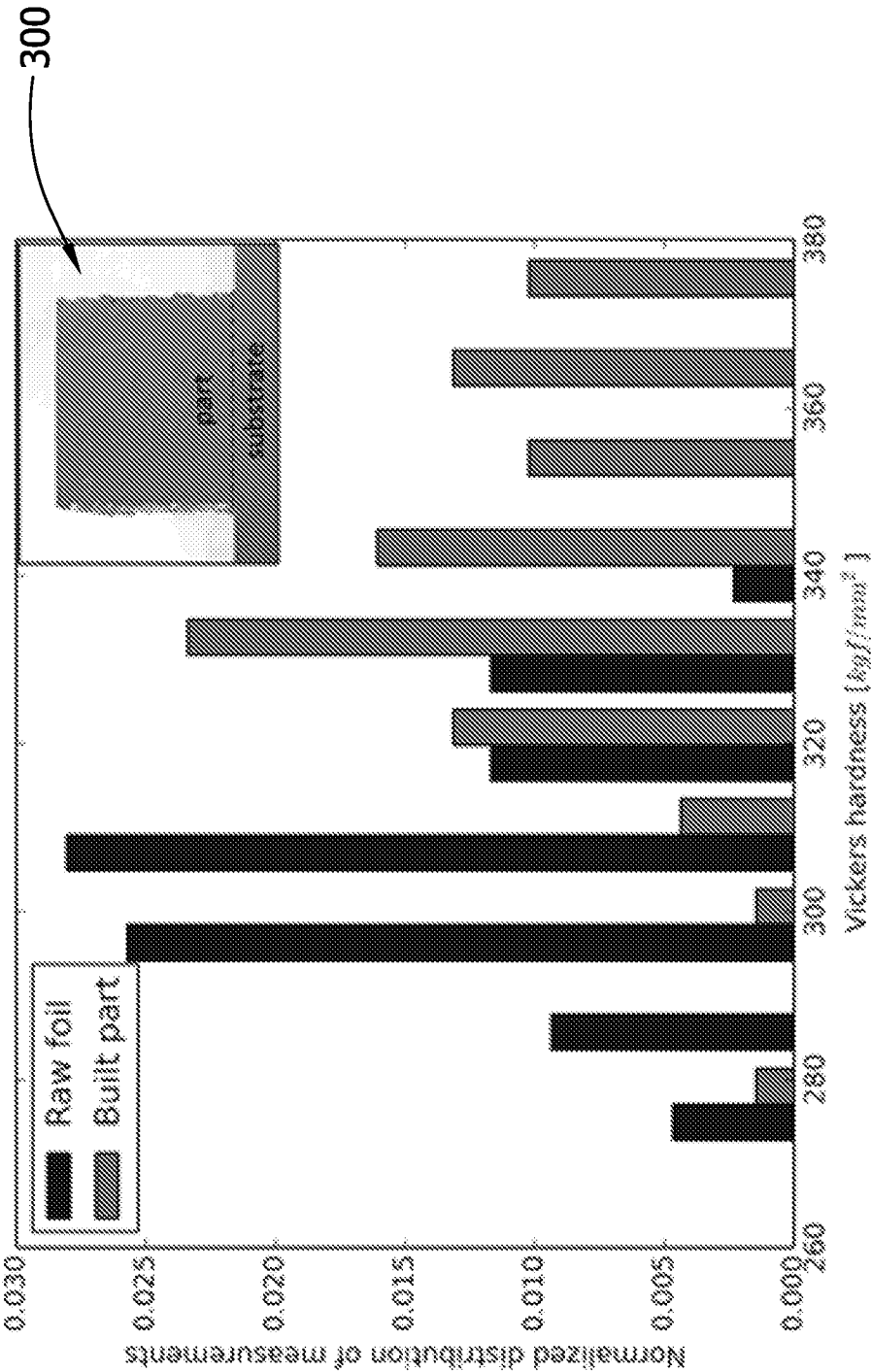


FIG. 10



11/13

400

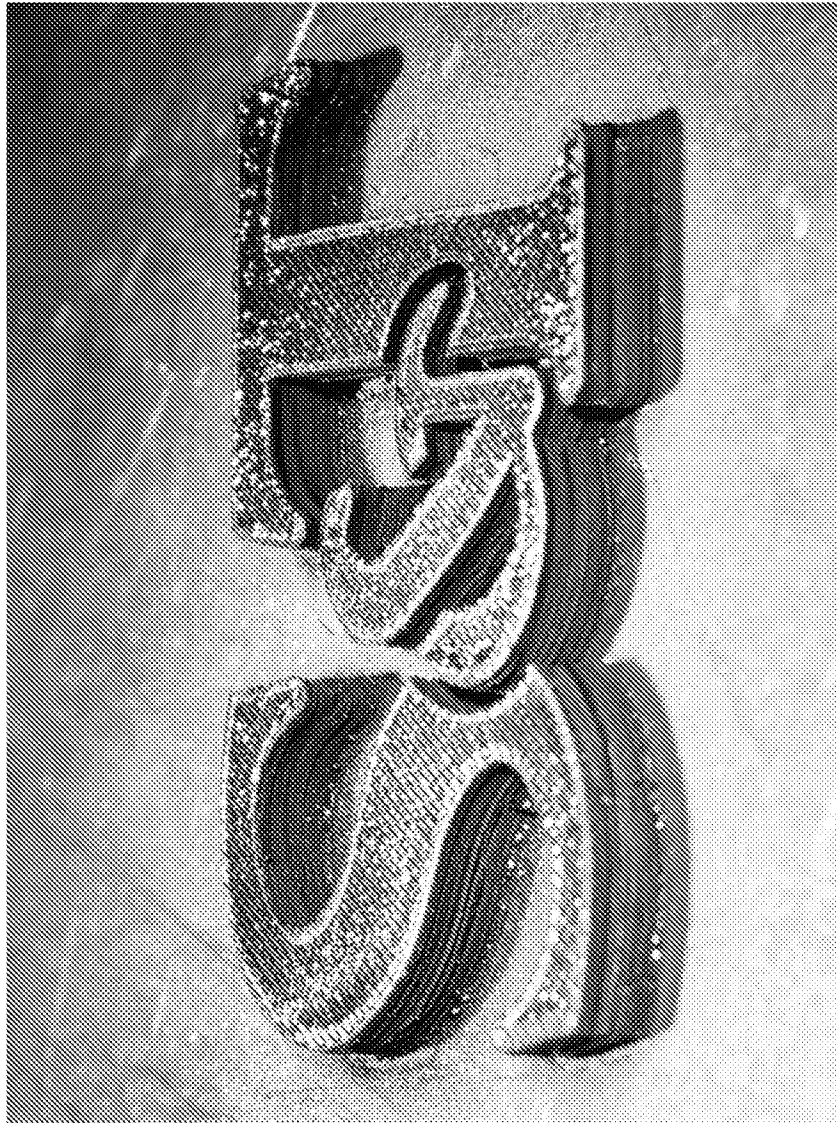


FIG. 11

500

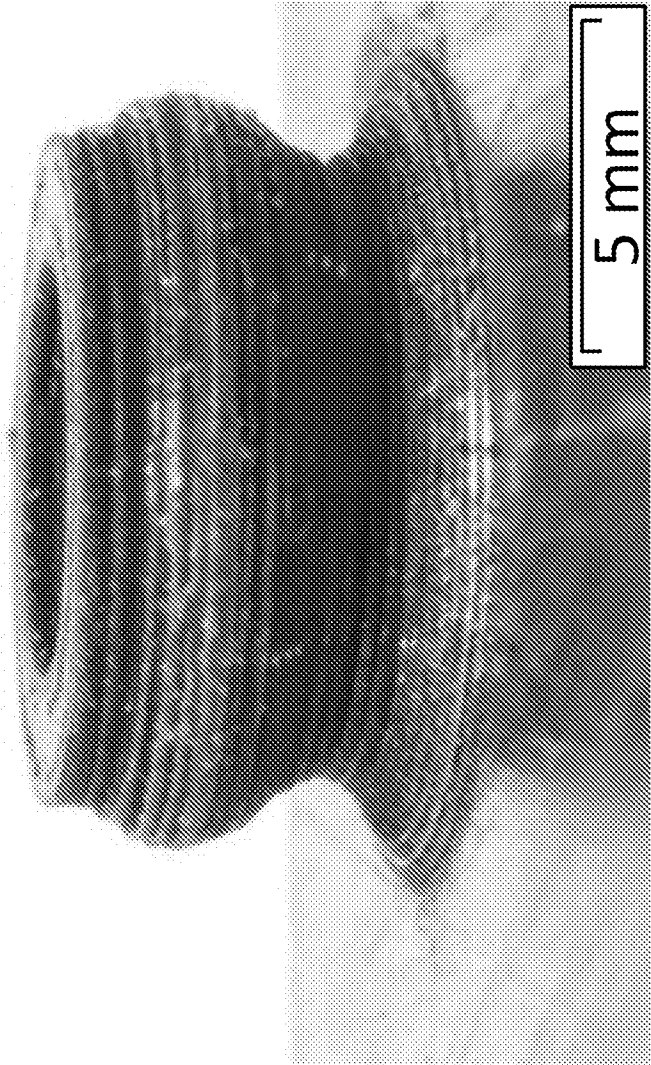


FIG. 12

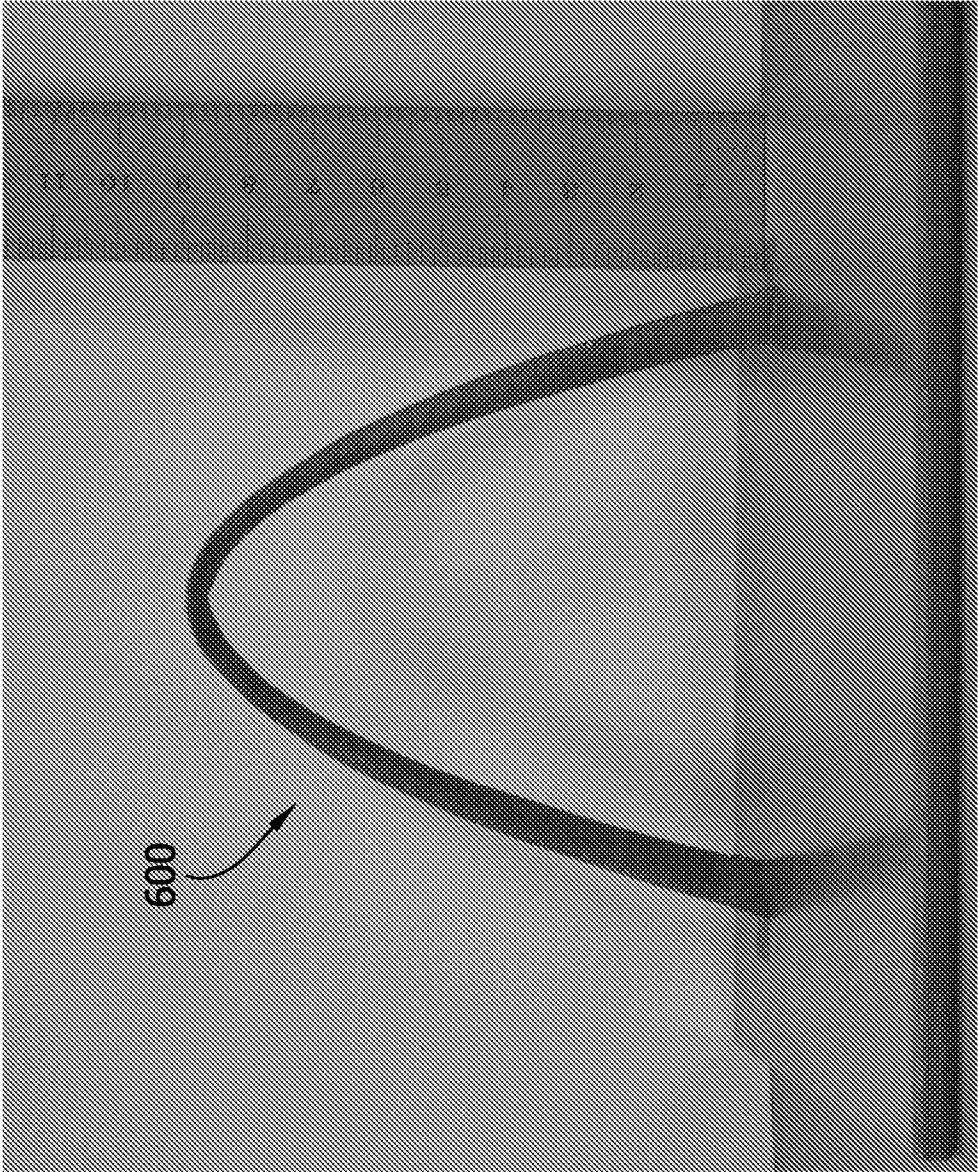


FIG. 13

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 15/55366

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - B23K 26/20, 26/21, 26/38 (2015.01)

CPC - B23K 26/20, 26/21, 26/38

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

CPC: B23K 26/20, 26/21, 26/38

IPC(8): B23K 26/20, 26/21, 26/38 (2015.01)

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

CPC: B29C 65/16, 67/0051, 67/0074, 2043/403; B33Y 10/00, 30/00; B23P 15/00; B23K 26/20, 26/21, 26/351, 26/36, 26/38; IPC(8): B23K 26/20, 26/21, 26/38 (2015.01); USPC: 228/141.1, 160; 156/272.8; 219/121.63, 124.64; 700/98, 118, 119; 264/400, 405, 482, 497

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

PatBase; PubWEST; Google

Search Terms Used: metal additive, manufacturing, foil sheet, laser, stack, y, z, axis, axes, cut, shape, weld, laser, 3d, three dimensional, laminate, continuous wavelength, keyhole, mode, embed, sensor

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2015/0136318 A1 (TIEFEL) 21 May 2015 (21.05.2015), entire document especially Figs 7-8; paras [0025]-[0028], [0038], [0078], [0108]-[0113]	27-29 ----- 1-26
Y	US 2015/0137412 A1 (SCHALANSKY) 21 May 2015 (21.05.2015), entire document especially Figs 1A-1B; paras [0029]-[0030]	1-19
Y	US 2011/0062221 A1 (JOHNSON) 17 March 2011 (17.03.2011), entire document especially Fig 3; paras [0035]-[0036], [0039]-[0040]	17, 18, 20-26
Y	US 2007/0170158 A1 (GREIG) 26 July 2007 (26.07.2007), entire document especially paras [0022], [0024], [0040]	3, 8
Y	US 2015/0121962 A1 (JIANG et al.) 07 May 2015 (07.05.2015), entire document especially Abstract; paras [0026], [0028]	7
Y	US 2015/0142160 A1 (OHNISHI) 21 May 2015 (21.05.2015), entire document especially para [0051]	13
Y	US 2008/0116175 A1 (BALLERINNI et al.) 22 May 2008 (22.05.2008), entire document especially Fig 3b; paras [0035], [0056]	10
Y	US 2005/0109740 A1 (BECKER et al.) 26 May 2005 (26.05.2005), entire document especially paras [0012]-[0014], [0026]-[0028]	14
Y	JP 2007/000888 A (Nisshin Steel Co LTD) 11 January 2007 (11.01.2007), Abstract	11



Further documents are listed in the continuation of Box C.



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Date of the actual completion of the international search

05 December 2015 (05.12.2015)

Date of mailing of the international search report

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INTERNATIONAL SEARCH REPORT

International application No.

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C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2013/0105447 A1 (HAAKE) 02 May 2013 (02.05.2013), entire document especially Fig 10	18, 22
Y	US 2013/0088074 A1 (DENNEY) 11 April 2013 (11.04.2013), entire document especially Fig 1; para [0027]	19, 23, 25
Y	US 6,450,393 B1 (DOUMANIDIS et al.) 17 September 2002 (17.09.2002), entire document especially col 16, lns 31-51	26