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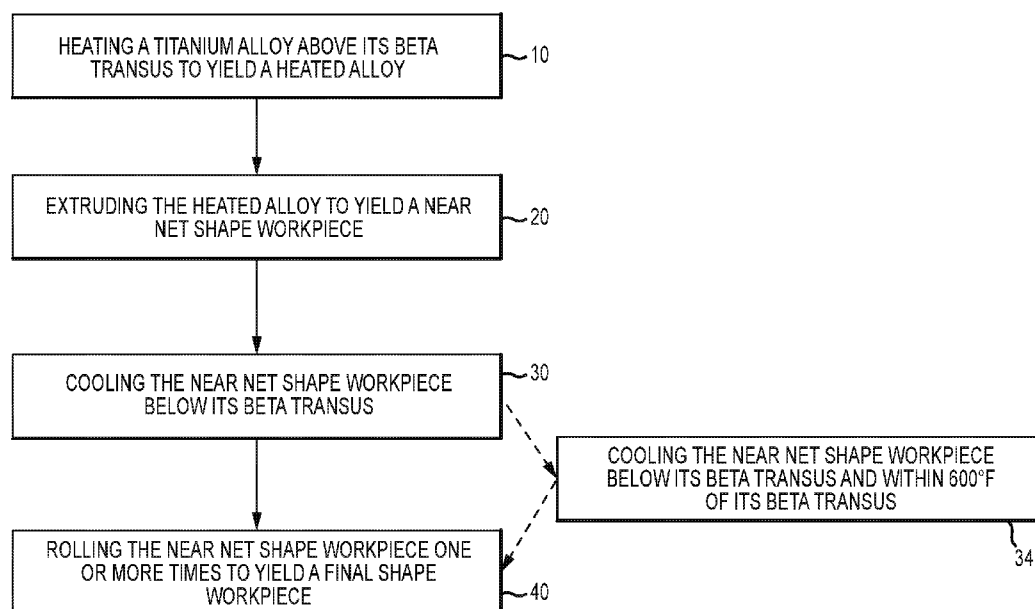


FIG.1

(57) Abstract: The present disclosure relates to methods of finishing extruded titanium alloy workpieces by generating an extruded near net shape workpiece, cooling the extruded near net shape workpiece to a cooled temperature below the beta transus temperature, and then rolling the extruded near net shape workpiece one or more times at a rolling temperature to yield a final shape workpiece with desired properties.

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IMPROVED METHODS FOR FINISHING EXTRUDED TITANIUM PRODUCTS**BACKGROUND**

[001] Titanium alloys are known for their low density (60% of that of steel) and their high strength. Additionally, titanium alloys may have good corrosion resistance properties. Pure titanium has an alpha (hcp) crystalline structure at room temperature.

SUMMARY OF THE DISCLOSURE

[002] Broadly, the present patent application relates to an improved process for forming a shaped titanium workpiece via a process that couples hot extrusion and one or more rolling steps. The new shaped workpieces may realize improved properties (e.g., improved strength; improved isotropic properties) as compared to conventional titanium materials.

[003] In one embodiment, a method of creating a titanium alloy workpiece may comprise (a) heating a cast ingot or wrought billet of a titanium alloy to a temperature above its beta transus temperature to yield a heated workpiece, (b) initiating extrusion of the heated workpiece while the heated workpiece is above the beta transus temperature, thereby generating an extruded near net shape workpiece, (c) cooling the extruded near net shape workpiece to a cooled temperature below the beta transus temperature, and (d) rolling the extruded near net shape workpiece one or more times at a rolling temperature to yield a final shape workpiece, wherein the rolling temperature is a temperature below an incipient melting temperature of the alloy and within 600°F (333°C) of the beta transus temperature. In some embodiments, the titanium alloy is an alpha-beta alloy, such as Ti-6Al-4V. In some embodiments, a thermal treatment, such as an anneal (e.g., a stress relief anneal) and/or a heat treatment, may be used before or after any of the extrusion and/or rolling steps to facilitate production of the final shape workpiece.

[004] In some embodiments, the method may further comprise after the heating step (a), protecting a surface of the heated workpiece with a protectant before the initiating extrusion step (b). The protectant may be a lubricant or parting agent, and in some embodiments the protectant may be removed before the rolling step (d).

[005] In some embodiments of the cooling step (c), the cooled temperature may be room temperature. In some embodiments, the method may further comprise, after the cooling step (c), cleaning / preparing the near net shape workpiece prior to the rolling step (d) to remove any protectant.

[006] In some embodiments, the rolling step (d) may further comprise rolling at a strain rate of from 0.1 s^{-1} to 100 s^{-1} . In some embodiments, the rolling step may comprise uniformly reducing the near net shape workpiece by a relative reduction of from 1% to 95%, thereby achieving the final shape workpiece. In some embodiments, the rolling step may comprise uniformly reducing the near net shape workpiece by a relative reduction of from 10% to 90%, thereby achieving the final shape workpiece. In some embodiments, the rolling step may comprise uniformly reducing the near net shape workpiece by a relative reduction of from 20% to 85%, thereby achieving the final shape workpiece. In some embodiments, the rolling step may comprise uniformly reducing the near net shape workpiece by a relative reduction of from 30% to 80%, thereby achieving the final shape workpiece. In some embodiments, the rolling step may comprise uniformly reducing the near net shape workpiece by a relative reduction of from 40% to 75%, thereby achieving the final shape workpiece. In some embodiments, the rolling step may comprise uniformly reducing the near net shape workpiece by a relative reduction of from 50% to 70%, thereby achieving the final shape workpiece. In some embodiments, the rolling step may comprise uniformly reducing the near net shape workpiece by a relative reduction of from 55% to 65%, thereby achieving the final shape workpiece.

[007] In some embodiments, the rolling step may comprise reducing a first section of the near net shape workpiece by a relative reduction of from 1% to 95%, thereby achieving a final shape workpiece with the first section being reduced. In some embodiments, the rolling step may comprise reducing a first section of the near net shape workpiece by a relative reduction of from 10% to 90%, thereby achieving a final shape workpiece with the first section being reduced. In some embodiments, the rolling step may comprise reducing a first section of the near net shape workpiece by a relative reduction of from 20% to 85%, thereby achieving a final shape workpiece with the first section being reduced. In some embodiments, the rolling step may comprise reducing a first section of the near net shape workpiece by a relative reduction of from 30% to 80%, thereby achieving a final shape workpiece with the first section being reduced. In some embodiments, the rolling step may comprise reducing a first section of the near net shape workpiece by a relative reduction of from 40% to 75%, thereby achieving a final shape workpiece with the first section being reduced. In some embodiments, the rolling step may comprise reducing a first section of the near net shape workpiece by a relative reduction of from 50% to 70%, thereby achieving a final shape workpiece with the first section being reduced. In some embodiments, the rolling step may comprise reducing a first section of the near net shape workpiece by a relative

reduction of from 55% to 65%, thereby achieving a final shape workpiece with the first section being reduced.

[008] In some embodiments, the rolling step may further comprise reducing at least a second section (different than the first section) of the near net shape workpiece by a relative reduction of from 1% to 95% thereby achieving the final shape workpiece with at least the first and second sections being reduced. In some embodiments, the rolling step may further comprise reducing at least a second section of the near net shape workpiece by a relative reduction of from 10% to 90% thereby achieving the final shape workpiece with at least the first and second sections being reduced. In some embodiments, the rolling step may further comprise reducing at least a second section of the near net shape workpiece by a relative reduction of from 20% to 85% thereby achieving the final shape workpiece with at least the first and second sections being reduced. In some embodiments, the rolling step may further comprise reducing at least a second section of the near net shape workpiece by a relative reduction of from 30% to 80% thereby achieving the final shape workpiece with at least the first and second sections being reduced. In some embodiments, the rolling step may further comprise reducing at least a second section of the near net shape workpiece by a relative reduction of from 40% to 75% thereby achieving the final shape workpiece with at least the first and second sections being reduced. In some embodiments, the rolling step may further comprise reducing at least a second section of the near net shape workpiece by a relative reduction of from 50% to 70% thereby achieving the final shape workpiece with at least the first and second sections being reduced. In some embodiments, the rolling step may further comprise reducing at least a second section of the near net shape workpiece by a relative reduction of from 55% to 65% thereby achieving the final shape workpiece with at least the first and second sections being reduced.

[009] In some embodiments, the rolling temperature may be a temperature above the beta transus temperature and below the incipient melting temperature. In some embodiments, the rolling temperature may be a temperature above the beta transus temperature and within 500°F (278°C) of the beta transus temperature. In some embodiments, the rolling temperature may be a temperature above the beta transus temperature and within 250°F (139°C) of the beta transus temperature. In some embodiments, the rolling temperature may be a temperature above the beta transus temperature and within 100°F (55.6°C) of the beta transus temperature. In some embodiments, the rolling temperature may be a temperature above the beta transus temperature and within 50°F (27.8°C) of the beta transus temperature. In yet other embodiments, the rolling temperature may be a temperature below the beta

transus temperature and within 600°F (333°C) of the beta transus temperature. In some embodiments, the rolling temperature may be a temperature below the beta transus temperature and within 300°F (167°C) of the beta transus temperature. In some embodiments, the rolling temperature may be a temperature below the beta transus temperature and within 100°F (55.6°C) of the beta transus temperature. In some embodiments, the rolling temperature may be a temperature below the beta transus temperature and within 50°F (27.8°C) of the beta transus temperature. In some embodiments, the rolling temperature is a temperature of more than 600°F (333°C) below the beta transus temperature, the rolling step (d) further comprising limiting a per pass reduction of each rolling step to prevent cracking or development of internal metallurgical defects in the final shape workpiece.

[0010] The new processes described herein may yield final shape workpieces having improved properties. In one approach, a new final shaped workpiece realizes at least 3% higher strength (TYS and/or UTS) (L) as compared to a referenced titanium alloy body, where the referenced titanium alloy body has the same composition as the final shape workpiece, and is in the same temper as the final shape workpiece, but is in the form of a sheet, strip or plate (e.g., as per AMS 4911, § 3.3.1-3.3.2), depending on thickness of the final shape workpiece. The final shape workpiece and the referenced titanium alloy body shall have the same final thickness, within acceptable commercial tolerances (e.g., AMS 2242). To produce a reference-version of the titanium alloy body in the same temper, one would generally provide the same thermal history to both the final shape workpiece and referenced titanium alloy body.

[0011] In one embodiment, a new final shaped workpiece realizes at least 5% higher tensile yield strength (TYS and/or UTS) (L) as compared to a referenced titanium alloy body. In one embodiment, a new final shaped workpiece realizes at least 7% higher tensile yield strength (TYS and/or UTS) (L) as compared to a referenced titanium alloy body. In one embodiment, a new final shaped workpiece realizes at least 9% higher tensile yield strength (TYS and/or UTS) (L) as compared to a referenced titanium alloy body. In one embodiment, a new final shaped workpiece realizes at least 11% higher tensile yield strength (TYS and/or UTS) (L) as compared to a referenced titanium alloy body. In one embodiment, a new final shaped workpiece realizes at least 12% higher tensile yield strength (TYS and/or UTS) (L) as compared to a referenced titanium alloy body. In one embodiment, a new final shaped workpiece realizes at least 13% higher tensile yield strength (TYS and/or UTS) (L) as compared to a referenced titanium alloy body.

[0012] In one embodiment, a new final shaped workpiece realizes at least 5% higher tensile yield strength (TYS and/or UTS) (LT) as compared to a referenced titanium alloy body. In one embodiment, a new final shaped workpiece realizes at least 7% higher tensile yield strength (TYS and/or UTS) (LT) as compared to a referenced titanium alloy body. In one embodiment, a new final shaped workpiece realizes at least 9% higher tensile yield strength (TYS and/or UTS) (LT) as compared to a referenced titanium alloy body. In one embodiment, a new final shaped workpiece realizes at least 11% higher tensile yield strength (TYS and/or UTS) (LT) as compared to a referenced titanium alloy body. In one embodiment, a new final shaped workpiece realizes at least 12% higher tensile yield strength (TYS and/or UTS) (LT) as compared to a referenced titanium alloy body. In one embodiment, a new final shaped workpiece realizes at least 13% higher tensile yield strength (TYS and/or UTS) (LT) as compared to a referenced titanium alloy body.

[0013] In one embodiment, a new final shaped workpiece realizes isotropic properties, wherein the tensile yield strength (TYS) in the LT direction is within 10 ksi of the tensile yield strength (TYS) in the L direction. In one embodiment, the TYS(LT) is within 8 ksi of the TYS(L). In one embodiment, the TYS(LT) is within 7 ksi of the TYS(L). In one embodiment, the TYS(LT) is within 6 ksi of the TYS(L). In one embodiment, the TYS(LT) is within 5 ksi of the TYS(L). In one embodiment, the TYS(LT) is within 4 ksi of the TYS(L). In one embodiment, the TYS(LT) is within 3 ksi of the TYS(L). Similar isotropic properties may also be realized relative to ultimate tensile strength (UTS).

[0014] In one approach, a new final shaped workpiece may also realize good ductility. In one embodiment, a new final shaped workpiece realizes an elongation (L) of at least 6%. In one embodiment, a new final shaped workpiece realizes an elongation (LT) of at least 6%. In one embodiment, a new final shaped workpiece realizes an elongation (L) of at least 8%. In one embodiment, a new final shaped workpiece realizes an elongation (LT) of at least 8%. In one embodiment, a new final shaped workpiece realizes an elongation (L) of at least 10%. In one embodiment, a new final shaped workpiece realizes an elongation (LT) of at least 10%. In one embodiment, a new final shaped workpiece realizes an elongation (L) of at least 12%. In one embodiment, a new final shaped workpiece realizes an elongation (LT) of at least 12%. Any of the above elongations may be realized in both the L and LT directions.

[0015] The new processes described herein may give the final shape workpieces improved properties, which may have applicability in a variety of product applications. In one embodiment, the titanium alloy products may be used in an aerospace structural application. For instance, the titanium alloy products may be formed into various

components for use in the aerospace industry, such as floor beams, seat rails, and fuselage framing, among others. Many potential benefits could be realized in such components due to the improved tensile properties, improved bearing, and improved resistance to the initiation and growth of fatigue cracks, among others. Improved combinations of such properties can result in enhanced reliability, for instance. The titanium alloy workpieces may also be useful, for instance, in marine, automotive, and/or defense applications.

[0016] As noted above, the near net shape workpiece may be produced via an extrusion process. In other embodiments, the near net shape workpiece may be a forged product, a shape cast product, or an additively manufactured product instead of an extruded product. The processing techniques and parameters described herein, however, still apply to such near net shape workpieces made from forged products, shape cast products, or additively manufactured products.

Definitions

[0017] Titanium alloys are classified based on microstructures and chemistries into five classes: alpha, near-alpha, beta, near-beta and alpha-beta alloys. “Alpha” or “alpha phase” refers to a hexagonal close-packed (hcp) crystal structure. “Beta” or “beta phase” refers to a body-centered cubic (bcc) crystal structure. “Alpha alloys” are titanium alloys that have essentially no beta phase and may not be strengthened by heat treatment. “Beta alloys” are titanium alloys that retain the beta phase on initial cooling to room temperature, which may be heat treated and have high hardenability. “Near-beta alloys” are titanium alloys that start out as beta alloys but may partially revert to have some alpha phase upon heating or cold working. “Near-alpha alloys” are titanium alloys that form some limited beta phase on heating, but appear microstructurally similar to alpha alloys. “Alpha-beta alloys” are titanium alloys that consist of alpha phase and some retained beta phase, the amount of beta phase retained being dependent on the composition of the alloys and/or the presence of beta stabilizers (*e.g.*, V, Mo, Cr, Cu), the amount of beta phase being more than what is found in near-alpha alloys. Alpha-beta alloys may be strengthened by heat treatment (such as solution heat treatment) and/or aging.

[0018] Alpha-beta titanium alloys may be classified into a grade based on the composition of the alloy as determined by ASTM B348 (*e.g.*, grade 5 (which includes titanium alloys having approximately 6% Al and 4% V, such as Ti-6Al-4V), grade 6 (which includes titanium alloys having approximately 5% Al and 2.5% Sn), and grade 9 (which includes titanium alloys having approximately 3% Al and 2.5% V)). Alpha-beta titanium

alloys may also be directly classified by their chemical composition (*e.g.*, Ti-6Al-4V, Ti-6Al-6V-2Sn, Ti-Al-2Sn-4Zr-6Mo, Ti-6Al-2Mo-2Cr, and Ti-6Al-2Sn-4Zr-2Mo, among others).

[0019] As used herein, “Ti-6Al-4V” means a grade 5 alpha-beta titanium alloy comprising from about 5.5 wt. % Al to about 6.75 wt. % Al, from about 3.5 wt. % V to about 4.5 wt. % V, a maximum of 0.40 wt. % Fe, a maximum of 0.2 wt. % O, a maximum of 0.015 wt. % H, a maximum of 0.05 wt. % N, a maximum of 0.40 wt. % other impurities, and the balance being Ti. As may be appreciated, similar specifications exist for other titanium grades.

[0020] The “beta transus” is defined as the lowest equilibrium temperature at which the material is 100% beta phase. As demonstrated in FIG. 9, below the beta transus, titanium alloys may be a mixture of alpha and beta phase depending on the composition of the alloy. FIG. 9 can be found in Tamirisakandala, S., R. B. Bhat, and B. V. Vedam. “Recent advances in the deformation processing of titanium alloys.” *Journal of Materials Engineering and Performance* 12.6 (2003): 661-673.

[0021] As used herein, “cast ingot” means an ingot formed from a molten titanium alloy wherein the alloy may be melted one or more times during formation of the cast ingot.

[0022] As used herein, “wrought billet” means a billet of a titanium alloy formed from a cast ingot of the titanium alloy that has been worked (*e.g.*, by forging, rolling, or pilger) prior to or during formation of the billet.

[0023] As used herein, “extrusion” or “extruded” shall mean a process to create an extruded titanium alloy workpiece using direct or indirect extrusion. “Direct extrusion” or “directly extruded” means a process used to create an extruded titanium alloy workpiece by pushing a cast ingot or wrought billet of titanium alloy through a stationary die having a desired cross-section or shape. In contrast, “indirect extrusion” or “indirectly extruded” means a process used to create an extruded titanium alloy workpiece by pushing a die having a desired cross section or shape through a stationary cast ingot or wrought billet of titanium alloy.

[0024] As used herein, “near net shape workpiece” means an extruded titanium alloy workpiece, the shape of which, after one or more rolling steps, is sufficient to achieve a final shape workpiece (*e.g.*, in the shape of the final product provided to a customer). In some embodiments, the one or more rolling steps may reduce a physical feature of the near net shape workpiece such that the change in the physical feature from near net shape to final shape workpiece may be represented by the formula: $NNSWP(z) \times (1 - RR(\%)) = FSWP(z)$. $NNSWP(z)$ represents a value for a physical measurement, z , of the near net shape workpiece

(e.g., z may be a volume, a width, or a thickness), $RR(\%)$ means the percent reduction achieved in the physical measurement by the rolling, and $FSWP(z)$ means a value of the physical measurement in the final shape workpiece. In some embodiments, the one or more rolling steps may be sufficient to achieve a relative reduction in a thickness of the near net shape workpiece, wherein “relative reduction” is defined as a change in thickness in the near net shape workpiece after the one or more rolling steps divided by the thickness before the one or more rolling steps using the following formula: $R = (h_1 - h_2)/h_1$, where R is the relative reduction, h_1 is a measure of thickness before rolling, and h_2 is a measure of thickness after rolling. In other words, the relative reduction relates to the total reduction of the material’s thickness, irrespective of the number of rolling passes required to achieve the relative reduction. Typically, each rolling pass reduces a material’s thickness by not greater than 25%. In some embodiments, the relative reduction may be non-uniform, meaning the relative reduction may vary for different features or parts of the near net shape workpiece depending on the configuration of the rolling steps, or only one portion of the near net shape workpiece may be reduced. Alternatively, the relative reduction may be uniform across the entire workpiece, meaning the reduction of thickness is the same across the entire workpiece. Relative reduction (R) may mean a reduction of thickness of at least a part of the near net shape workpiece from 1 % to 95 %, such as any of the relative reductions described above. By way of a non-limiting example, a near net shape workpiece may be a near net shape c-channel shaped workpiece (as seen in FIG. 4C) having an initial thickness after extrusion of 0.255 inch (6.48 mm) across the entire c-channel shaped workpiece, having a final thickness after one or more rolling steps of 0.055 inch (1.40 mm), and having a relative reduction (R) of 78%.

[0025] As used herein, “rolling” means a metal forming process (step) in which an extruded titanium alloy product is passed through one or more rolls of a roller apparatus to reduce a volume or thickness of the product. As demonstrated in FIG. 8, a roller apparatus (800) may comprise multiple rolls (801), (802), (803) which may be arrayed in a manner so that the roller is configured to reduce a thickness in one or more dimensions of the extruded titanium alloy product. FIG. 8 can be found in Tamirisakandala, S., R. B. Bhat, and B. V. Vedam. “Recent advances in the deformation processing of titanium alloys.” *Journal of Materials Engineering and Performance* 12.6 (2003): 661-673.

[0026] As used herein, “final shape workpiece” means an extruded and rolled titanium workpiece having a desired volume or thickness and is suitable for its intended end-use purpose. In some embodiments, the final shape workpiece may be additionally finished via

machining or surface treatment. Some non-limiting examples of some final shape workpieces include a final shape pi-box final shape C channel. As used herein, “pi-box” means a material having a cross-section generally resembling the Greek letter pi (π).

[0027] As used herein, “stress relieve anneal” means a thermal treatment process at relative low temperature to relieve the stress in the product.

[0028] As used herein, “heat treatment” means a thermal process in which the material is heated to an elevated temperature to change the properties of the material. Some non-limiting examples of heat treatments useful in accordance with the methods described herein include a mill anneal, a near beta transus anneal, a recrystallization anneal, a solution heat treatment, and artificial aging, among others.

BRIEF DESCRIPTION OF THE DRAWINGS

[0029] FIGS. 1-3 are flow charts illustrating an embodiment of a method of creating a titanium alloy workpiece;

[0030] FIGS. 4A-4C demonstrate a C-channel shaped workpiece created by a method in accordance with the present disclosure;

[0031] FIGS. 5A-5C demonstrate a T-bracket shaped workpiece created by a method in accordance with the present disclosure;

[0032] FIGS. 6A-6C depicts an L-bracket shaped workpiece having a uniform relative reduction and a non-uniform thickness created by a method in accordance with the present disclosure;

[0033] FIGS. 7A-7C depicts an L-bracket shaped workpiece having a non-uniform thickness and a non-uniform relative reduction created by a method in accordance with the present disclosure;

[0034] FIG. 8 demonstrates an embodiment of a roller setup having three sets of rolls;

[0035] FIG. 9 illustrates a microstructural deformation mechanism map for a Ti-6Al-4V alloy;

[0036] FIGS. 10A and 10B are graphs demonstrating a relationship between room temperature strength and ductility as a function of cooling from a beta transus region;

[0037] FIGS. 11A and 11B demonstrate yield strengths between workpieces processed at various strain rates and at temperatures above (11A) and below (11B) a beta transus temperature;

[0038] FIGS. 12A and 12B demonstrate ultimate strengths between workpieces processed at various strain rates and at temperatures above (12A) and below (12B) a beta transus temperature;

[0039] FIGS. 13A and 13B demonstrate material elongations between workpieces processed at various strain rates and at temperatures above (13A) and below (13B) a beta transus temperature;

[0040] FIGS. 14A and 14B demonstrate a reduction of area between workpieces processed at various strain rates and at temperatures above (14A) and below (14B) a beta transus temperature;

[0041] FIG. 15 illustrates micrographs of materials of Example 2 in the extruded and rolled conditions in the longitudinal (L) and long transverse (T) directions; and

[0042] FIG. 16 illustrates fatigue crack propagation rates of materials of Example 2.

DETAILED DESCRIPTION

[0043] Reference will now be made in detail to the accompanying drawings, which at least assist in illustrating various pertinent embodiments of the new technology provided for by the present disclosure.

[0044] FIGS. 1-3 are flow charts of various embodiments of a method for creating a titanium workpiece in accordance with the present disclosure. The workpiece may be any shape capable of being extruded from a titanium alloy. In some embodiments, for example, the workpiece may be a C-channel bracket, a T bracket, H or I shapes, or an L bracket. The method comprises a first step of heating (10) a titanium alloy above its beta transus temperature to yield a heated workpiece. In some embodiments, the titanium alloy may be an alpha alloy, a beta alloy, or an alpha-beta alloy. In some embodiments, the alpha-beta alloy may be Ti-6Al-4V. In some embodiments, the titanium alloy comprises a cast ingot or a wrought billet.

[0045] In some embodiments, the method may further comprise, after the heating step (10), a protecting step, wherein a surface of the heated workpiece is coated with a protectant to protect the surface from damage that may occur during extrusion. In some embodiments, the protectant may comprise a lubricant (e.g., graphite, glass, a molten salt (e.g., a molten alkaline metal salt)), and/or a parting agent, such as a ceramic material (e.g., a ceramic powder).

[0046] The method further comprises a step of extruding (20) the heated workpiece to yield an extruded near net shape workpiece. In some embodiments, the extruding (20) may comprise direct extrusion. Alternatively, the extruding (20) may comprise indirect extrusion. In some embodiments, the extruding step (20) may comprise extruding the heated workpiece at a temperature above the alloy's beta transus temperature. In other embodiments, the

extruding step (20) may comprise initiating extrusion at a temperature above the alloy's beta transus temperature, wherein at least a portion of the extruding step (20) may be performed at a temperature below the alloy's beta transus temperature.

[0047] The method further comprises the step of cooling (30) the near net shape workpiece to a temperature below its beta transus temperature. In some embodiments, the cooling step (34) comprises cooling to a temperature within 600°F (333°C) of the alloy's beta transus. In some embodiments, the cooling (30) is to a temperature within 500°F (278°C) of the alloy's beta transus. In some embodiments, the cooling (30) is to a temperature of within 400°F (222°C) of the alloy's beta transus. In some embodiments, the cooling (30) is to a temperature of within 300°F (167°C) of the alloy's beta transus. In some embodiments, the cooling (30) is to a temperature of within 200°F (111°C) of the alloy's beta transus. In some embodiments, the cooling (30) is to a temperature of within 100°F (55.6°C) of the alloy's beta transus. In some embodiments, the cooling (30) is to a temperature of more than 600°F (333°C) below the alloy's beta transus. In some embodiments, as seen in FIG. 2 and FIG. 3, the cooling step (31) may comprise cooling the near net shape workpiece to any temperature below the alloy's beta transus, and in some embodiments the temperature may be room temperature.

[0048] In some embodiments, the method further comprises, after the cooling step, a cleaning / preparing step, wherein the near net shape workpiece is prepared for rolling by removing any residual protectant via the cleaning / preparing step. In some embodiments, the cleaning and/or preparing may comprise sandblasting some or all of the workpiece to remove protectant residue (*e.g.*, residual lubricant or parting agent) and to condition the surface for adherence. Dry powder or wet suspension may be applied to surface. Excess powder or suspension may be removed via mechanical or high velocity air means, leaving a thin layer of protectant.

[0049] Referring back to FIG. 1, the method further comprises one or more rolling steps (40), wherein the rolling comprises rolling the extruded near net shape workpiece one or more times at a rolling temperature to yield a final shape workpiece. In some embodiments, the rolling temperature is the same temperature for each of the one or more rolling steps. In some embodiments, the rolling temperature may be different for each of the one or more rolling steps. In some embodiments, the rolling temperature is a temperature below an incipient melting temperature of the alloy and within 600°F (333°C) of the beta transus temperature. In some embodiments, the rolling temperature is a temperature below the incipient melting temperature of the alloy and within 500°F (278°C) of the beta transus

temperature. In some embodiments, the rolling temperature is a temperature below the incipient melting temperature of the alloy and within 400°F (222°C) of the beta transus temperature. In some embodiments, the rolling temperature is a temperature below the incipient melting temperature of the alloy and within 300°F (167°C) of the beta transus temperature. In some embodiments, the rolling temperature is a temperature below the incipient melting temperature of the alloy and within 250°F (139°C) of the beta transus temperature. In some embodiments, the rolling temperature is a temperature below the incipient melting temperature of the alloy and within 100°F (55.6°C) of the beta transus temperature. In some embodiments, the rolling temperature is a temperature below the incipient melting temperature of the alloy and within 50°F (27.8°C) of the beta transus temperature. In some embodiments, the rolling temperature is a temperature below the beta transus temperature and within 600°F (333°C) of the beta transus temperature. In some embodiments, the rolling temperature is a temperature below the beta transus temperature and within 500°F (278°C) of the beta transus temperature. In some embodiments, the rolling temperature is a temperature below the beta transus temperature and within 400°F (222°C) of the beta transus temperature. In some embodiments, the rolling temperature is a temperature below the beta transus temperature and within 300°F (167°C) of the beta transus temperature. In some embodiments, the rolling temperature is a temperature below the beta transus temperature and within 250°F (139°C) of the beta transus temperature. In some embodiments, the rolling temperature is a temperature below the beta transus temperature and within 100°F (55.6°C) of the beta transus temperature. In some embodiments, the rolling temperature is a temperature below the beta transus temperature and within 50°F (27.8°C) of the beta transus temperature.

[0050] In some embodiments, the one or more rolling steps (40) comprise reducing one or more aspects or portions of the near net shape workpiece to yield a final shape workpiece having a relative reduction of from 1% to 95% in the one or more aspects or portions as compared to the near net shape workpiece. In some embodiments, only one section of the near net shape workpiece may be reduced. In some embodiments, more than one section of the near net shape workpiece may be reduced. In some embodiments, the total relative reduction may be from 1% to 95%. In some embodiments, the relative reduction may be not greater than 90% in total relative reduction. In some embodiments, the relative reduction may be not greater than 85% in total relative reduction. In some embodiments, the relative reduction may be not greater than 80% in total relative reduction. In some embodiments, the relative reduction may be not greater than 75% in total relative reduction. In some

embodiments, the relative reduction may be not greater than 70% in total relative reduction. In some embodiments, the relative reduction may be not greater than 65% in total relative reduction. In some embodiments, the relative reduction may be at least 1% in total relative reduction. In some embodiments, the relative reduction may be at least 10% in total relative reduction. In some embodiments, the relative reduction may be at least 20% in total relative reduction. In some embodiments, the relative reduction may be at least 30% in total relative reduction. In some embodiments, the relative reduction may be at least 40% in total relative reduction. In some embodiments, the relative reduction may be at least 50% in total relative reduction. In some embodiments, the relative reduction may be at least 55% in total relative reduction.

[0051] In some embodiments, the rolling may further comprise rolling at a strain rate of from 0.1 s^{-1} to 100 s^{-1} . In some embodiments, the strain rate may be a rate of from 1 s^{-1} to 100 s^{-1} . In some embodiments, the strain rate may be a rate of from 1 s^{-1} to 50 s^{-1} . In some embodiments, the strain rate may be a rate of from 1 s^{-1} to 10 s^{-1} .

[0052] In some embodiments, the relative reduction may be uniform, as may be seen in FIGS. 4A-4C, wherein all portions of the final shape workpiece have uniform relative reduction. FIG. 4A depicts an extruded C-channel bracket prior to the one or more rolling steps (40). FIG. 4B depicts the final shape workpiece, having uniform relative reduction as compared to the near net shape workpiece (as seen in FIG. 4C comparing the two shapes).

[0053] In some embodiments, as seen in FIGS. 4A-4C and FIGS. 5A-5C, the relative reduction may be uniform, and an absolute measure of the one or more aspects of the final shape workpiece may be the same across the entire final shape workpiece (*e.g.*, the thickness or volume may be the same throughout the entire final shape workpiece). FIG. 5A depicts an extruded T bracket prior to the one or more rolling steps (40). FIG. 5B depicts the final shape workpiece, having a uniform relative reduction as compared to the near net shape workpiece (as seen in FIG. 5C comparing the two shapes), and also having a uniform absolute measure of thickness throughout all portions of the final shape workpiece as a first section (501) has a same thickness as a thickness of a second section (502).

[0054] In some embodiments, as seen in FIGS. 6A-6C, the relative reduction may be uniform across the final shape workpiece, but the absolute measure of one or more aspects may differ (*e.g.*, a percent of reduction in thickness may be the same across the entire final shape workpiece, but the absolute thickness from portion to portion of the final shape workpiece may be different). FIG. 6A depicts an extruded L bracket prior to the one or more rolling steps (40). FIG. 6B depicts the final shape workpiece, having a uniform relative

reduction as compared to the near net shape workpiece (as seen in FIG. 6C comparing the two shapes), but having non-uniform thickness throughout portions of the final shape workpiece as a first section (601) has a different thickness from a second section (602).

[0055] In some embodiments, as seen in FIGS. 7A-7C, the relative reduction and the absolute measure may be non-uniform across the final shape workpiece. FIG. 7A depicts an extruded L bracket prior to the rolling steps (40). FIG. 7B depicts the final shape workpiece, having a non-uniform relative reduction as compared to the near net shape workpiece (as seen in FIG. 7C comparing the two shapes), and having non-uniform thickness throughout portions of the final shape workpiece as a first section (701) has a different thickness from a second section (702).

[0056] Referring back to FIG. 2, the method may further comprise the step of reheating (32) the near net shape workpiece after the cooling step (31), wherein the reheating (32) step comprises heating the extruded near net shape workpiece to a reheated temperature below an incipient melting temperature of the alloy and within 600°F (333°C) of its beta transus. In some embodiments, the reheated temperature is a temperature below the incipient melting temperature of the alloy and within 500°F (278°C) of its beta transus. In some embodiments, the reheated temperature is a temperature below the incipient melting temperature of the alloy and within 400°F (222°C) of its beta transus. In some embodiments, the reheated temperature is a temperature below the incipient melting temperature of the alloy and within 300°F (167°C) of its beta transus. In some embodiments, the reheated temperature is a temperature below the incipient melting temperature of the alloy and within 200°F (111°C) of its beta transus. In some embodiments, the reheated temperature is a temperature below the incipient melting temperature of the alloy and within 100°F (55.6°C) of its beta transus.

[0057] In some embodiments, after each rolling step of the one or more rolling steps (40), the near net shape workpiece may be reheated (32) to allow for a subsequent rolling step to be performed at the reheated temperature. In some embodiments, the near net shape workpiece may be alternatively cooled (31) and re-heated (32) between each rolling step of the one or more rolling steps (40). In some embodiments, all of the one or more rolling steps (40) may comprise a rolling temperature of more than 600°F (333°C) below the beta transus, wherein each of the one or more rolling steps (40) may further comprise limiting the relative reduction for each rolling step to prevent cracking or development of internal metallurgical defects in the final shape workpiece. In some embodiments, various adjustments to the time (*e.g.*, longer times) and/or temperature (*e.g.*, hotter temperatures) of the reheating can be adjusted to relieve residual stress, allow dislocation motion, and relaxation of

crystallographic texture. This may ensure that adequate ductility is maintained to tolerate deformation at lower temperatures.

[0058] In some embodiments, as seen in FIG. 3, the reheating step (33) may comprise heating the extruded near net shape workpiece to a temperature above its beta transus temperature and below its incipient melting temperature, wherein the reheating step (33) may be followed by one or more rolling steps (41) performed at a temperature above the alloy's beta transus temperature. In some embodiments, the near net shape workpiece may be reheated (33) if its temperature falls below the alloy's beta transus temperature during any given rolling step of the one or more rolling steps (41). In some embodiments, the method further comprises one or more other rolling steps (42), which may be performed below the alloy's beta transus temperature.

Example 1

[0059] Four Ti-6Al-4V samples were produced with an extrusion process and processed through four different manufacturing paths. The material selected had a mill measured beta transus (BT) of approximately 1810°F (988°C). There were two temperatures selected for processing: BT+50°F (28°C) (1860°F (1016°C)) and BT-10°F (5.6°C) (1800°F(982°C)). The temperature above the beta transus (BT) was limited to 50°F (28°C) above the beta transus to limit grain growth during heat up. The temperature below the beta transus was selected as an attempt to maintain product in the work window promising a globularization type conversion to end at 1775°F (968°C). Below the 1775°F (968°C) temperature the product may still breakdown into a worked structure, but it would be expected that this conversion would be dominated by lamellae kinking.

[0060] The processing speed of the roll reduction was selected as a high and low speed representing strain rates of 10 s^{-1} and 2.5 s^{-1} . Exit speeds of 20-30 inches/second (50.8-76.2 cm/second) in the high speed case, and 5-6 inches/second (12.7-15.2 cm/second) in the low speed case.

[0061] Extrusion samples were heated in a radiant heat furnace that was already pre-heated to the desired temperature. A track was added within the furnace to suspend samples within the furnace and align it with the entry of the rollers. Cold product was loaded onto the track and closed into the furnace for 8 minutes. Calculations showed that product was at temperature within 1-3 minutes, but additional time was used to ensure that furnace had time to homogenize after being opened and give some factor of safety for heating non-uniformity. After 8 minutes the product was pushed with a rigid arm along the track toward the roller

setup. Once in the roll bite, the product was pulled through by the spinning wheels. At the end of the channel a guiding structure was placed to both center the product entering the wheels and to prevent the possibility of the advancing arm from being able to reach the wheels.

[0062] The furnace was placed immediately adjacent the rolling device. Product was exposed to ambient air for a distance of 15 inches (38 cm) until the roll bite began. This provided a vehicle for cooling of the product, particularly in the final passes when the product was approaching 0.100 inch (2.54 mm) thick.

[0063] The four pieces were heated and run through four passes where they were reduced in equal increments from an extrusion of 0.205 to 0.100 inch (5.21 to 2.54 mm) thick. Each fin on the product was the same thickness, but could have been different. Following each pass the parts were allowed to fall into a tray to air cool.

[0064] The roller (depicted in FIG. 8) differed from a traditional 2 or 4 high rolling mill. In this case, the rollers were arranged to provide contact pressure on the primary (largest) surfaces of the product and be advanced independently to produce gaps between the different rollers. This type of roller design could be modified to produce channels, H's, L's, T's, and a variety of other structural members. With instances of small rollers and certain shapes, an interference will begin to occur with the bearing housings. Placing the bearing within the wheel and having only a powered sprocket on the side will alleviate much instance of interference. This also produces a more rigid structure for applying load. The use of larger wheels will also provide more space and increase the possible reduction per pass.

[0065] Following processing of the samples, a light anneal was performed on all samples, where the pieces were heated to 1325°F (718°C) (+/-25°F (14°C)) and held for 1 hour. The parts were then removed and allowed to air cool. This light anneal was primarily aimed at removing most of the built-up dislocations within crystals, and not aimed at changing resulting microstructure.

[0066] In some instances, glass was applied to the sample pieces to evaluate how well it performed as a lubricant or protectant in the rolling process. It was observed to build up in front of the roller until it went through as a large pool. All cases where glass was used experienced these types of defects. In the areas of glass pool indentation, the prior roughness remained as the incompressible liquid filled the surface profile. The same effect could also be seen when excessive amounts of dry lubricants (graphite, molybdenum disulfide, and/or hexagonal boron nitride) were applied to the rollers. In large quantities (vs. thin film) these materials behave like a fluid and can produce similar results as liquid glass. The best

surfaces may occur with either light amounts of dry lubricants on the rollers or simply light powdering of titanium dioxide on the piece with no additional roller lubricants.

[0067] A less common method of secondary hot working of alpha/beta titanium alloys is beta processing. In this method, the working occurs above the beta transus temperature. This results in an acicular alpha phase or Widmanstatten microstructure. Lamellar microstructure results in higher fracture toughness, fatigue crack propagation resistance and creep resistance. Minor debits occur in strength, ductility. A major benefit of beta hot working, which includes beta forging and beta extrusion, is a lowered flow stress and improved die or feature fill. The extrusion of titanium is predominantly performed above the beta transition temperature to achieve the increase in formability of titanium in spite of an increase in grain size. The cooling rate from above the beta transus following recrystallization has significant impact on the formation of the Widmanstatten microstructure. During this cooling the alpha grains are formed in platelets/basketweave patterns within the prior beta grains. A faster cooling rate reduces the thickness of grain boundary alpha phase and produces as fine of transformed microstructure within prior grains as possible. This helps preserve later sub-transus hot workability. This also has an impact on room temperature properties as may be seen in FIGS. 10A and 10B. FIGS. 10A and 10B can be found in Sieniawski, J., Ziaja, W., Kubiak, K. and Motyka, M., 2013. Microstructure and mechanical properties of high strength two-phase titanium alloys. *Titanium Alloys-Advances in Properties Control*, pp.69-80.

[0068] There exists an optimum cooling rate as the material crosses the beta transus for Ti-6Al-4V. Ideally a 4-9°C per second cooling rate is desired to achieve the optimum of ductility yet still high strength. Going above 9 °C per second may result in the formation of thinner alpha lamellae and result in higher strength but lower ductility. Cooling faster than 18°C per second results in the formation of Martensite. This further reduces ductility with a minor increase in strength.

[0069] **Above Beta Transus Processing**

[0070] Two samples were processed above the beta transus for each reduction pass. The representation of material properties in relation to reduction amount illustrates how properties change through the various passes of rolling. The strength trends for the two samples at various stages in the post extrusion rolling process are given in FIG. 11A. Looking at the yield and ultimate strength plots in FIG. 12A, it is seen that both processing conditions yield strengthening, however the piece with lower strain rate demonstrates significantly higher yield and ultimate strength improvements. Some level of texturing is also observed in the test

results. As may be seen in FIGS. 13A and 14A, a general decrease in both elongation and reduction in area was observed in all cases. The slower processed sample demonstrated a significantly lower elongation than the faster processed piece. The performing of work above the recrystallization temperature suggests that the most likely root cause lies in the cooling rate. Examining the microstructure lends some explanation to the observed behavior.

[0071] The microstructure of the as-extruded material is characteristic of what is seen from an extrusion. Standard practice of air cooling on significantly thicker product produces a cooling rate in the 2-7°C per second and higher levels of ductility from the Widmanstatten microstructure. It typically takes a water quench to achieve Martensite in Ti-6Al-4V for extruded product. The microstructure after the four pass demonstrated a.) larger prior beta grains and b.) partially Martensitic structure versus the unidirectional bundles of the extrusion. Without being limited to any one theory, it could be as a result of the rapid cooling of the thin sections by both radiation and conduction losses to the rollers.

[0072] Conduction cooling effects might explain why the effects are more pronounced in the slower processed pieces where the contact time is longer. The loss of ductility is not desirable in aerospace structures, however this could be managed through warmer rolls, higher set point temperature, improved management of environment leading to and from the roll bite. A heated exit zone would allow slowed cooling during the initial cooling to form the desired microstructure. A mixed (below beta transus and above beta transus processing steps) would likely produce the best combination of properties of beta worked material.

[0073] **Below Beta Transus Processing**

[0074] When imparting work below the beta transus, texture can arise in the material. Texture is the imparting of directionality within the material, and arises from working in one predominant direction. In the production of strip, which sees large amounts of work in one direction, production is enabled by either using alloys with higher cold workability, such as commercially pure grades, or performing a beta anneal following hot working and between cold working passes to relieve directionality. Following hot rolling of strip prior to annealing, transverse ductility was un-measurable and brittle behavior was observed in transverse directions compared to lateral direction of rolling. Additionally, the presence of anisotropy in titanium increases the susceptibility to stress corrosion cracking in aqueous solutions.

[0075] Contrary to expectation, when evaluating the sub-beta processed pieces little anisotropy was seen in the material's strength. Longitudinal and transverse yield and

ultimate properties correlated very strongly, particularly when processed at slow strain rates. As seen in FIGS. 11B and 12B, the samples produced at a slower strain rate exhibited a higher strengthening effect than at the higher temperatures, and material produced through the below beta transus working was nearly isotropic in terms of ultimate strength. In spite of relatively limited texture demonstrated in mechanical testing, there is significant occurrence of grain elongation in the longitudinal direction (see FIG. 13B). The data corresponding to FIGS. 11A-14B is provided in Table 1, below.

Table 1 - Data of FIGS. 11A - 14B

Sample (Speed) (Direction)	RR (%)	TYS ksi	UTS ksi	TYS MPa	UTS MPa	Elong. (%)	Reduction of Area (%)
Sample A (Fast) (L)	0%	127.7	143.6	880.5	990.1	12%	22%
Sample A (Fast) (L)	12.5%	130.9	148.5	902.5	1023.9	10%	19%
Sample A (Fast) (L)	26.7%	134.2	150.6	925.3	1038.4	11%	18%
Sample A (Fast) (L)	39.7%	136.8	151.3	943.2	1043.2	10%	15%
Sample A (Fast) (L)	51.9%	137.4	152.8	947.3	1053.5	10%	16%
Sample A (Slow) (L)	0%	127.7	143.6	880.5	990.1	12%	22%
Sample A (Slow) (L)	11.1%	131.7	148.0	908.0	1020.4	12%	22%
Sample A (Slow) (L)	25.0%	136.6	154.6	941.8	1065.9	10%	13%
Sample A (Slow) (L)	34.7%	145.1	157.8	1000.4	1088.0	5%	13%
Sample A (Slow) (L)	46.9%	147.6	164.0	1017.7	1130.7	6%	17%
Sample A (Fast) (LT)	0%	128.2	146.0	883.9	1006.6	15%	31%
Sample A (Fast) (LT)	12.4%	132.5	146.9	913.6	1012.8	10%	22%
Sample A (Fast) (LT)	29.2%	132.5	148.5	913.6	1023.9	9%	16%
Sample A (Fast) (LT)	41.9%	133.5	146.9	920.5	1012.8	10%	17%
Sample A (Fast) (LT)	52.8%	129.4	149.2	892.2	1028.7	6%	16%
Sample A (Slow) (LT)	0%	128.2	146.0	883.9	1006.6	15%	31%
Sample A (Slow) (LT)	11.6%	132.2	146.9	911.5	1012.8	11%	26%
Sample A (Slow) (LT)	25.3%	132.9	150.7	916.3	1039.0	9%	10%
Sample A (Slow) (LT)	34.7%	138.9	152.4	957.7	1050.8	5%	19%
Sample A (Slow) (LT)	46.7%	144.1	157.0	993.5	1082.5	5%	19%
Sample B (Fast) (L)	0%	127.7	143.6	880.5	990.1	12%	22%
Sample B (Fast) (L)	11.8%	129.1	143.5	890.1	989.4	11%	21%
Sample B (Fast) (L)	30.9%	130.3	145.3	898.4	1001.8	11%	24%
Sample B (Fast) (L)	43.4%	132.0	146.8	910.1	1012.2	10%	20%
Sample B (Fast) (L)	56.1%	133.3	150.9	919.1	1040.4	10%	25%
Sample B (Slow) (L)	0%	127.7	143.6	880.5	990.1	12%	22%
Sample B (Slow) (L)	12.2%	135.5	149.8	934.2	1032.8	12%	21%
Sample B (Slow) (L)	27.5%	142.9	155.9	985.3	1074.9	10%	21%
Sample B (Slow) (L)	38.3%	148.3	159.8	1022.5	1101.8	11%	33%
Sample B (Fast) (LT)	0%	128.2	146.0	883.9	1006.6	15%	31%

Sample (Speed) (Direction)	RR (%)	TYS ksi	UTS ksi	TYS MPa	UTS MPa	Elong. (%)	Reduction of Area (%)
Sample B (Fast) (LT)	12.3%	120.3	141.8	829.4	977.7	16%	32%
Sample B (Fast) (LT)	30.5%	133.1	145.4	917.7	1002.5	13%	31%
Sample B (Fast) (LT)	42.5%	137.8	149.3	950.1	1029.4	11%	33%
Sample B (Fast) (LT)	56.2%	142.1	152.3	979.7	1050.1	13%	29%
Sample B (Slow) (LT)	0%	128.2	146.0	883.9	1006.6	15%	31%
Sample B (Slow) (LT)	11.1%	134.8	148.9	929.4	1026.6	10%	25%
Sample B (Slow) (LT)	26.6%	143.1	154.9	986.6	1068.0	9%	27%
Sample B (Slow) (LT)	37.4%	149.0	158.4	1027.3	1092.1	7%	27%

* Fast $\approx$ 20-30 inches/second exit speed; Slow $\approx$ 5-6 inches/second exit speed

** Sample A rolled at 1860°F (1016°C); Sample B rolled at 1800°F (982°C)

Example 2

[0076] Several Ti-6Al-4V alloys were extruded as strips (4 inches (10.2 cm) wide) and then rolled to various final thicknesses due to various rolling reductions, which are shown in Table 2, below. Sample 1 was processed to a 55% reduction, Sample 2 was processed to a 65% reduction, and Sample 3 was processed to a 75% reduction. The initial thickness of the extruded strips was 0.3 inch (7.62 mm). The extruding step was performed at 2200°F (1204°C). The rolling reduction steps were performed at 1750°F (954°C). A light anneal (for stress relief) was performed at 1450°F (788°C) for 30 minutes before allowing the samples to air cool. Mechanical properties of the final strips were then tested, the results of which are provided below.

[0077] Strength and elongation properties were measured in accordance with ASTM E8, the results of which are presented in Table 2. All strength values are provided in ksi / (MPa).

Table 2 - Room Temp. Properties of Example 2 Alloys

Property	Sample 1 (55% RR)	Sample 2 (65% RR)	Sample 3 (75% RR)
TYS (L)	129.1 (890.1)	141.5 (975.6)	137.8 (950.1)
UTS (L)	144.7 (997.3)	155.8 (1074)	153.3 (1057)
Elong. (L)	11.5%	11%	12%
TYS (LT)	135.3 (932.9)	144.9 (999.1)	145.5 (1016)
UTS (LT)	148.4 (1023)	157.0 (1083)	160.3 (1105)
Elong. (LT)	11%	11%	12.5%

The sample materials realize significantly higher strength as compared to conventional Ti-6Al-4V products (*see, e.g.*, AMS 4928 and AMS 4911). Further, the materials realize isotropic properties with about 65% rolling reduction, realizing less than 5 ksi strength differential between the L and LT directions.

[0078] Elevated temperature tensile properties were measured for Sample 2 (relative reduction of 65%) at 600°F (316°C) in accordance to ASTM E21, the results of which are presented in Table 3.

Table 3 - Elev. Temp. Properties of Example 2 Alloys

Property	Sample 2 (65% RR)
TYS (L)	92 (634)
UTS (L)	110.2 (759.8)
Elong. (L)	14.5%
TYS (LT)	92.2 (635)
UTS (L)	106.0 (730.8)
Elong. (LT)	12.5%

[0079] Fatigue measurements were performed on Sample 2 (relative reduction of 65%) in accordance to ASTM E466, the results of which are provided in Table 4.

Table 4: Measurement of Fatigue at $K_t = 2.3$ (open hole) and 30 Hz for Sample 2 (65% RR)

Stress (MPa)	Cycles to Failure
410	113,106
200	3,000,000 (discontinued)

[0080] Bearing measurements were performed on Sample 2 (relative reduction of 65%) in accordance to ASTM E238, the results of which are presented in Table 5.

Table 5: Measurement of Bearing at $e/D = 1.5$ for Sample 2 (65% RR)

Strength Measurement	Strength Value ksi/(MPa)
Ultimate	242.9 (1675)

Strength Measurement	Strength Value ksi/(MPa)
Ultimate	242.9 (1675)
Yield	209.3 (1443)

[0081] Grain elongation in the axial direction, was observed in both high and low strain rate cases. Microstructure taken within the vertical section and viewed in tangential direction demonstrated lengthening in the longitudinal direction of the prior beta grains. As illustrated, the extrusion has a beta worked microstructure, whereas the extruded plus rolled materials have an alpha-beta worked microstructure in accordance with the AMS standards.

[0082] FIG. 16 illustrates fatigue crack propagation rates performed in accordance of ASTM E647, under test conditions of a stress ratio of 0.10, a frequency of 10 Hz, room temperature, and laboratory atmospheric air. The fatigue crack growth results are consistent with AMS standards relative to alpha-beta sheet products.

[0083] While various embodiments of the present disclosure have been described in detail, it is apparent that modifications and adaptations of those embodiments will occur to those skilled in the art. However, it is to be expressly understood that such modifications and adaptations are within the spirit and scope of the present disclosure.

CLAIMS**What is claimed is:**

1. A method of creating a titanium alloy workpiece comprising:
 - a. heating a cast ingot or wrought billet of a titanium alloy to a temperature above its beta transus temperature to yield a heated workpiece;
 - b. initiating extrusion of the heated workpiece while the heated workpiece is above the beta transus temperature, thereby generating an extruded near net shape workpiece;
 - c. cooling the extruded near net shape workpiece to a cooled temperature below the beta transus temperature; and
 - d. rolling the extruded near net shape workpiece one or more times at one or more rolling temperatures to yield a final shape workpiece, wherein the rolling temperature is below an incipient melting temperature of the alloy and within 600°F (333°C) of the beta transus temperature.
2. The method of claim 1, wherein the titanium alloy is an alpha-beta titanium alloy.
3. The method of claim 1, further comprising after the heating step (a), protecting a surface of the heated workpiece with a protectant.
4. The method of claim 3, wherein the protectant is a lubricant or parting agent.
5. The method of claim 3, wherein the method further comprises, after the cooling step (c), cleaning the near net shape workpiece prior to the rolling step (d) to remove any protectant.
6. The method of claim 1, wherein the cooled temperature is within 500°F (278°C) of the beta transus temperature.
7. The method of claim 1, wherein the cooled temperature is within 100°F (55.6°C) of the beta transus temperature.
8. The method of claim 1, wherein the cooled temperature is room temperature.
9. The method of claim 1, wherein the rolling temperature is above the beta transus temperature and below the incipient melting temperature.
10. The method of claim 1, wherein the rolling temperature is above the beta transus temperature and within 50°F (27.8°C) of the beta transus temperature.
11. The method of claim 1, wherein the rolling temperature is below the beta transus temperature and within 600°F (333°C) of the beta transus temperature.
12. The method of claim 1, wherein the rolling temperature is below the beta transus temperature and within 50°F (27.8°C) of the beta transus temperature.

13. The method of claim 1, wherein the rolling step (d) further comprises rolling at a strain rate of from 0.1 s^{-1} to 100 s^{-1} .
14. The method of claim 1, wherein the rolling step comprises uniformly reducing the near net shape workpiece by a relative reduction of from 1% to 95%, thereby achieving the final shape workpiece.
15. The method of claim 14, wherein the relative reduction is from 40 to 75%.
16. The method of claim 1, wherein the rolling step comprises reducing a first section of the near net shape workpiece by a first relative reduction of from 1% to 95%, thereby achieving a final shape workpiece with the first section being reduced.
17. The method of claim 16, wherein the rolling step further comprises reducing at least a second section of the near net shape workpiece by a second relative reduction of from 1% to 95% thereby achieving the final shape workpiece with at least the first and second sections being reduced, wherein the first relative reduction is different than the second relative reduction.
18. The method of claim 1, wherein the final shape workpiece realizes at least 3% higher tensile yield strength (L) over a referenced titanium alloy body; wherein the referenced titanium alloy body has the same composition as the final shape workpiece, and is in the same temper as the final shape workpiece.
19. The method of claim 18, wherein the final shape workpiece comprises isotropic strength properties, wherein the tensile yield strength in the LT direction is within 10 ksi of the tensile yield strength in the L direction.
20. The method of claim 19, wherein the final shape workpiece realizes an elongation (L) of at least 6% and an elongation (LT) of at least 6%.

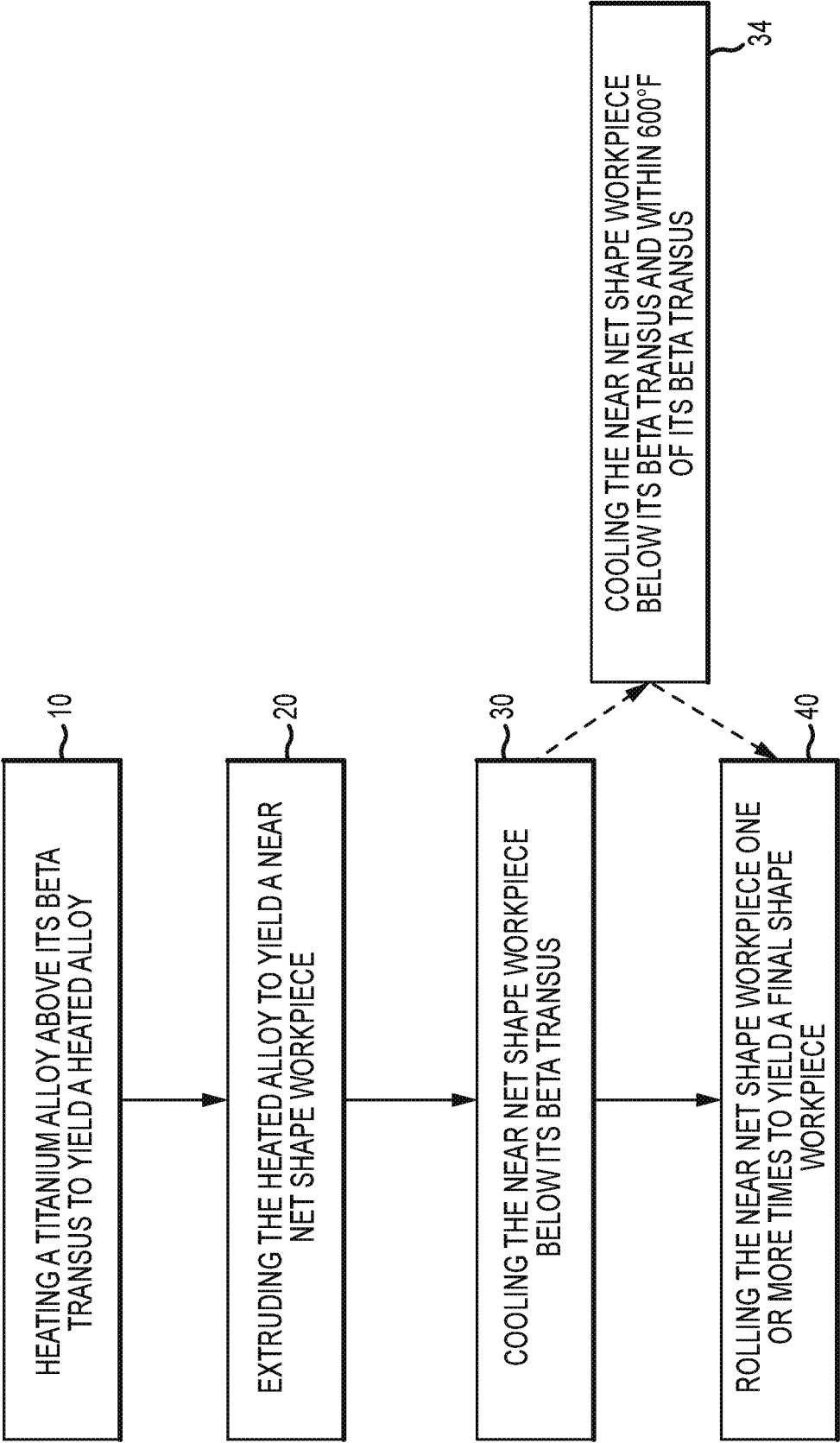


FIG.1

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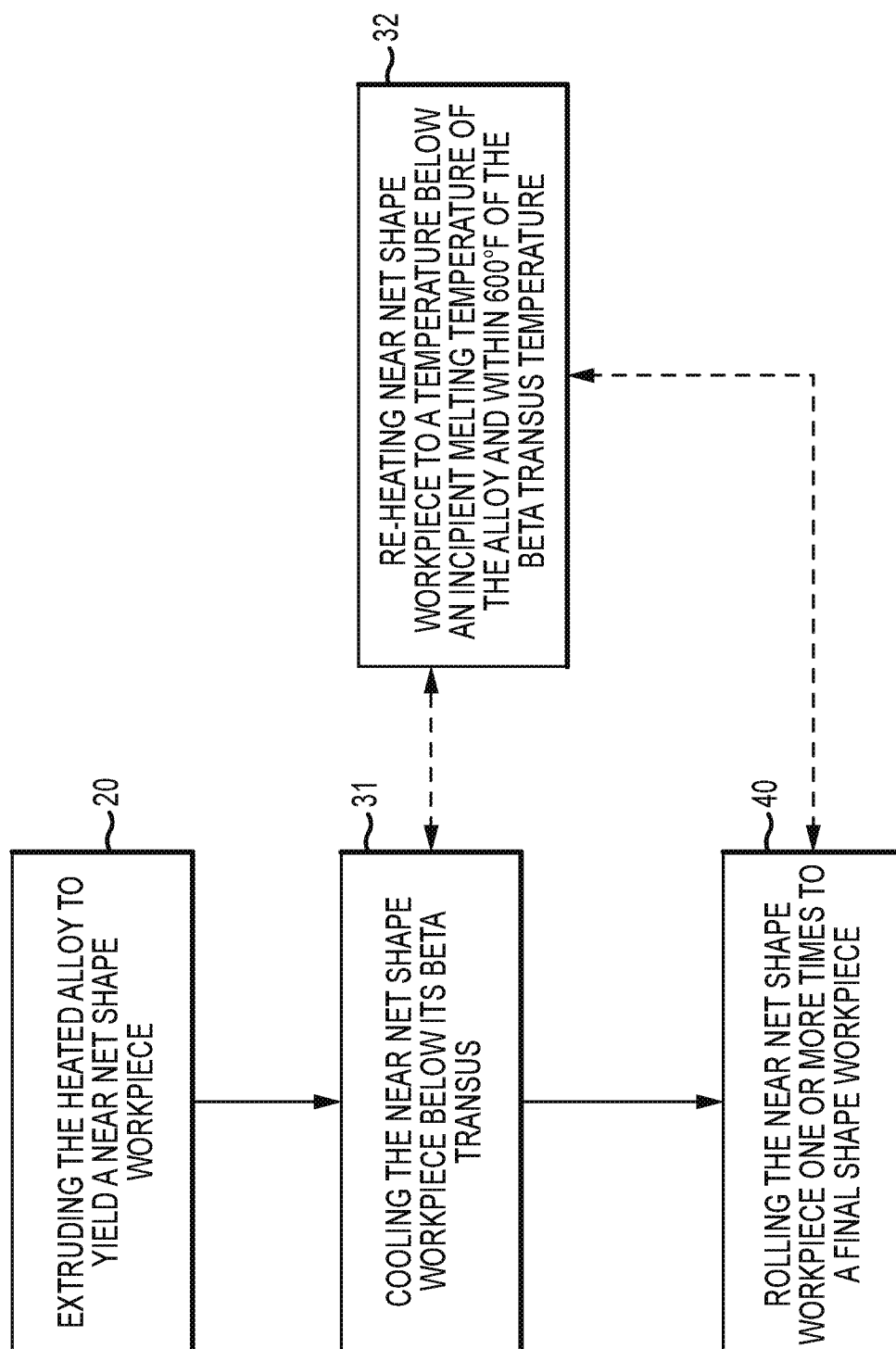


FIG. 2

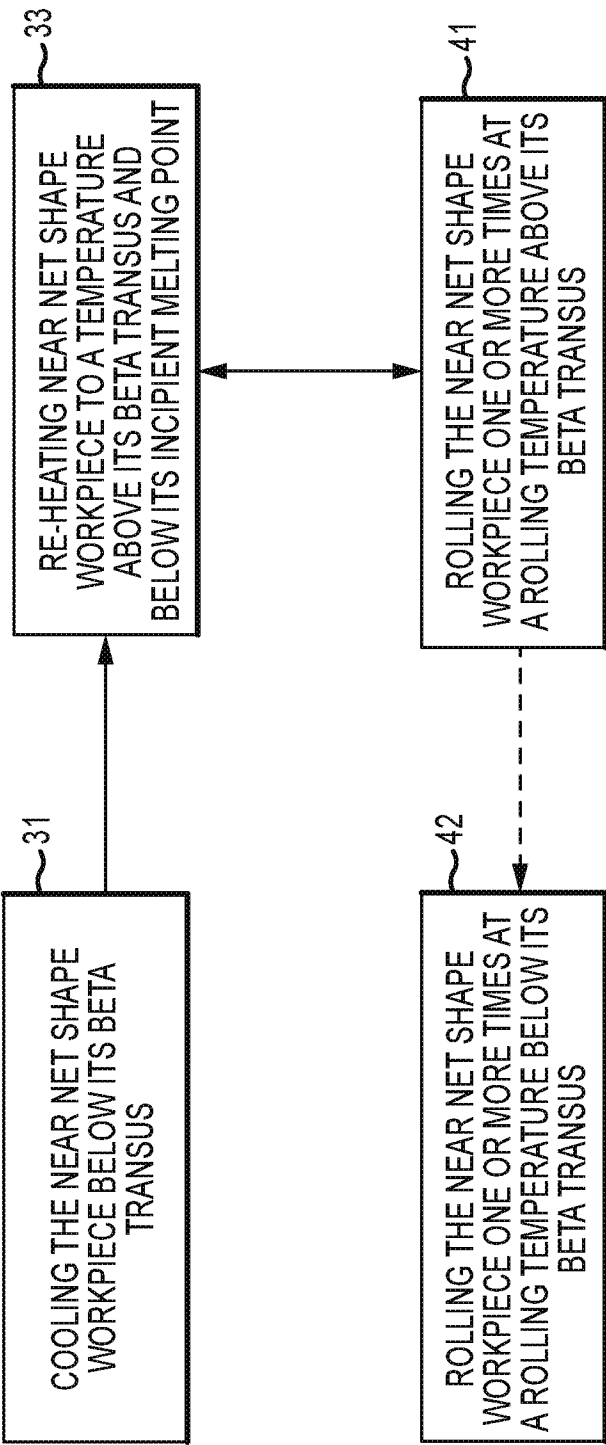


FIG.3

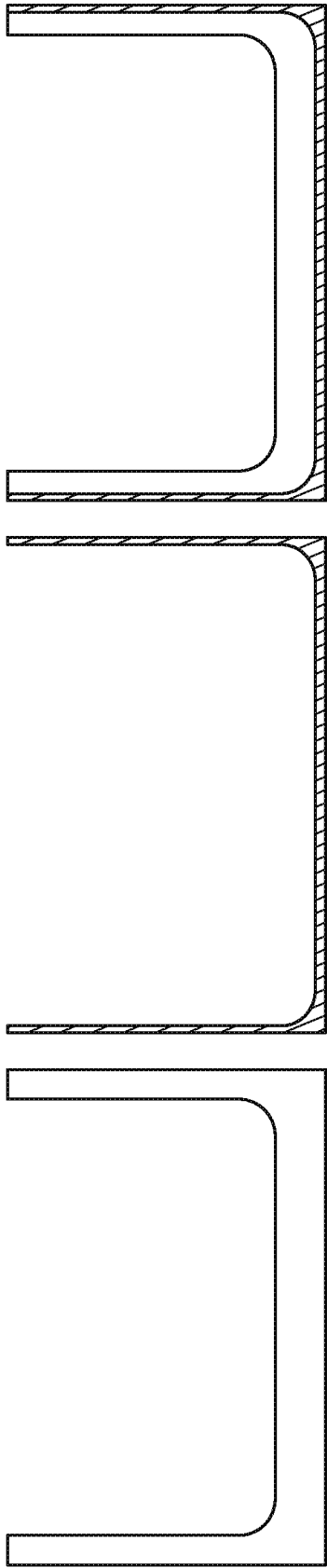


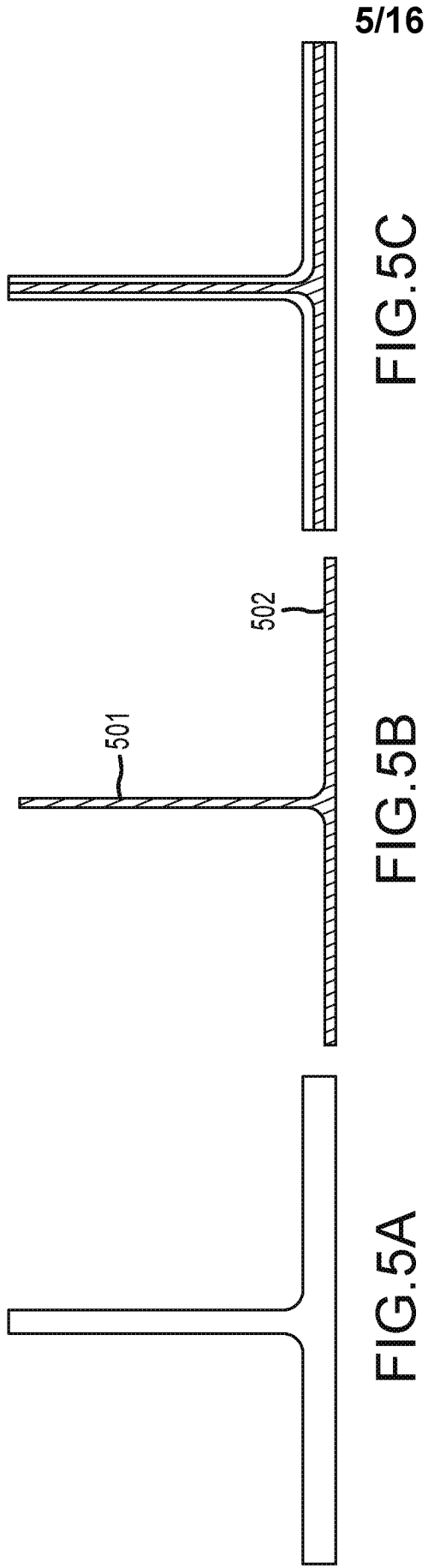
FIG. 4A

FIG. 4B

FIG. 4C

- A - EXTRUSION THICKNESS: 0.255 inch (6.48 mm)
- B - FINAL THICKNESS: 0.055 inch (1.40 mm)
- C - RELATIVE REDUCTION (R): 78%

TITANIUM C-CHANNEL BRACKET (NOT TO SCALE)
USE: IN MANY OF THE SAME USES THAT STAINLESS STEEL ENGINEERED STRUCTURAL SHAPES WOULD BE USED



A - EXTRUSION THIN SECTION: 0.210 inch (5.33 mm)
B - FINISHED SECTION: 0.075 inch (1.91 mm)
C - RELATIVE REDUCTION (R): 64%

TITANIUM T BRACKET (NOT TO SCALE)
USE: STRUCTURAL BRACKET

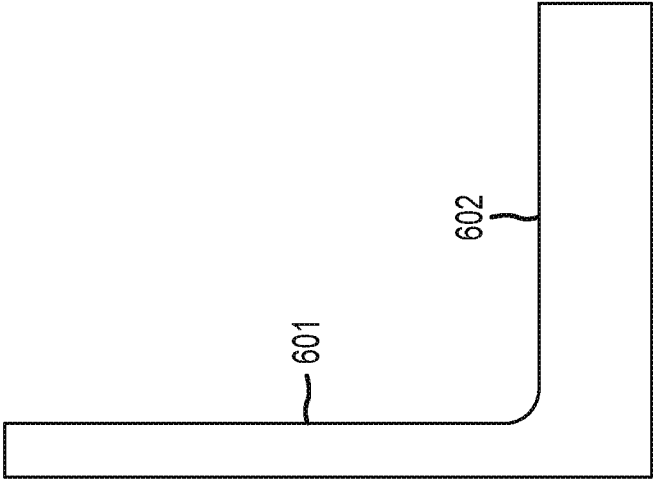


FIG. 6A

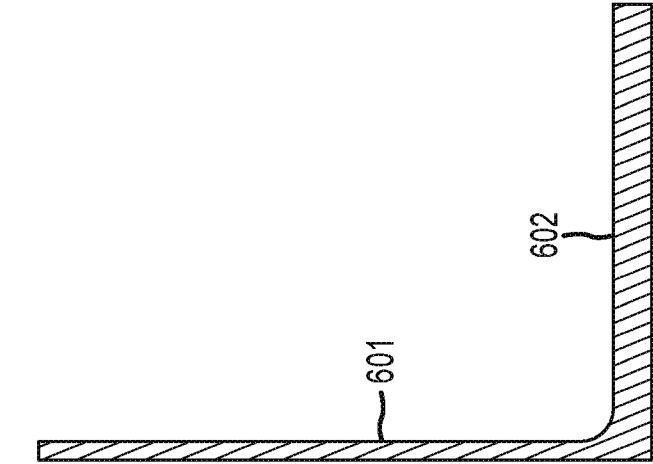


FIG. 6B

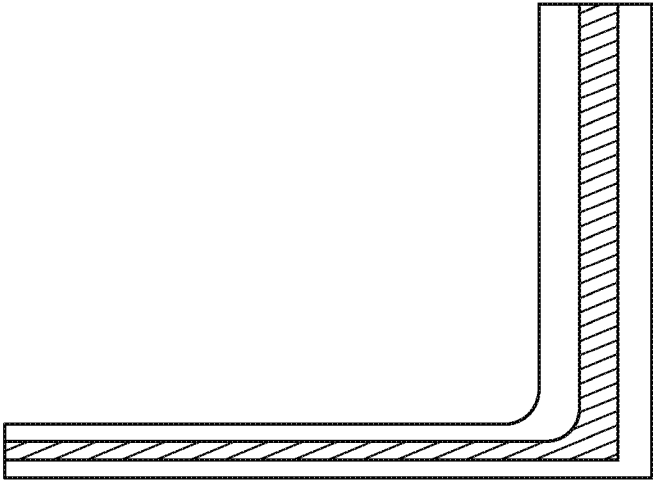


FIG. 6C

A - EXTRUSION FIRST SECTION: 0.225 inch (6.48 mm)
B - FINISHED FIRST SECTION: 0.075 inch (1.91 mm)
A - EXTRUSION THICK SECTION: 0.375 inch (9.53 mm)
B - FINISHED THICK SECTION: 0.125 inch (3.18 mm)
C - RELATIVE REDUCTION (R): BOTH SECTIONS 67%

TITANIUM L BRACKET UNIFORM RELATIVE REDUCTION (NOT TO SCALE)
USE: STRUCTURAL ATTACHMENT IN AEROSPACE FRAMING
(I.E. JOINING FRAME COMPONENTS TO CFRP PANELS)

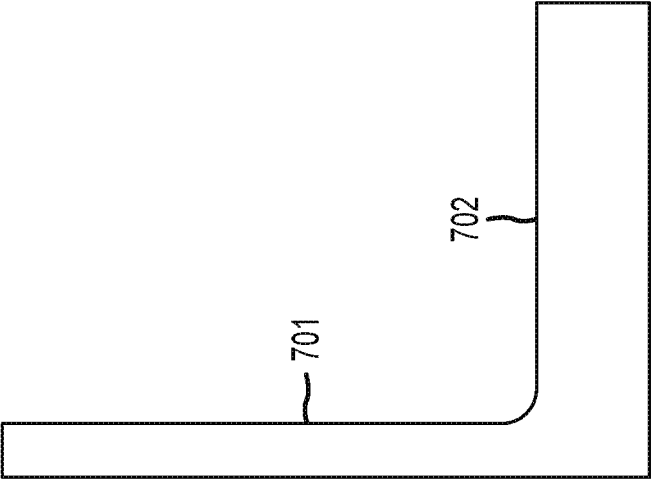


FIG. 7A

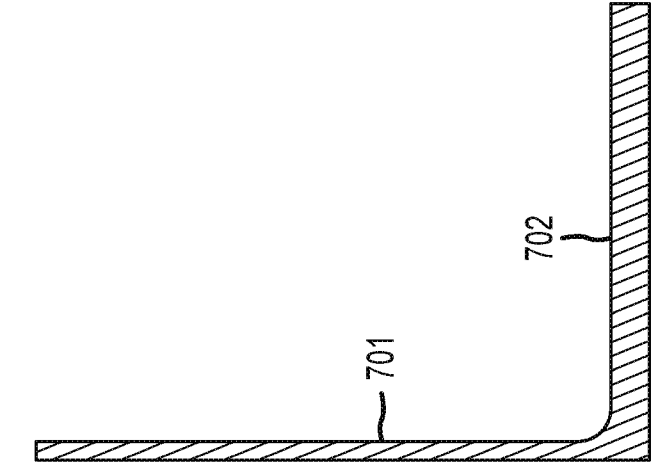


FIG. 7B

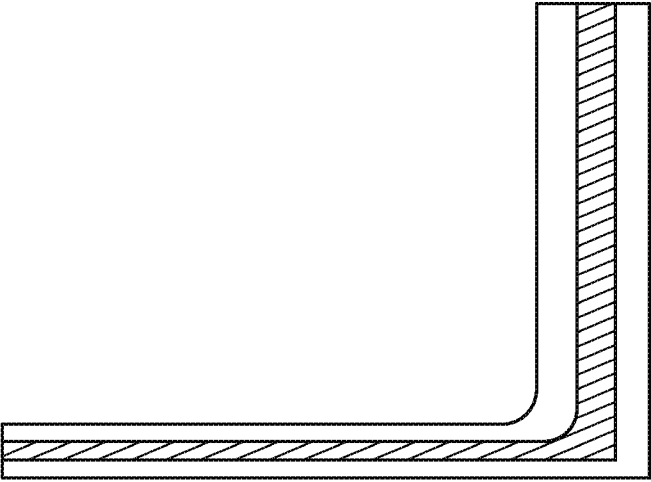


FIG. 7C

- A - EXTRUSION FIRST SECTION: 0.225 inch (5.72 mm)
- B - FINISHED FIRST SECTION: 0.075 inch (1.91 mm)
- A - EXTRUSION THICK SECTION: 0.210 inch (5.33 mm)
- B - FINISHED THICK SECTION: 0.075 inch (1.91 mm)
- C - RELATIVE REDUCTION (R): FIRST SECTION: 67%
- C - RELATIVE REDUCTION (R): SECOND SECTION: 64%

TITANIUM L BRACKET — NON-UNIFORM RELATIVE REDUCTION
(NOT TO SCALE)

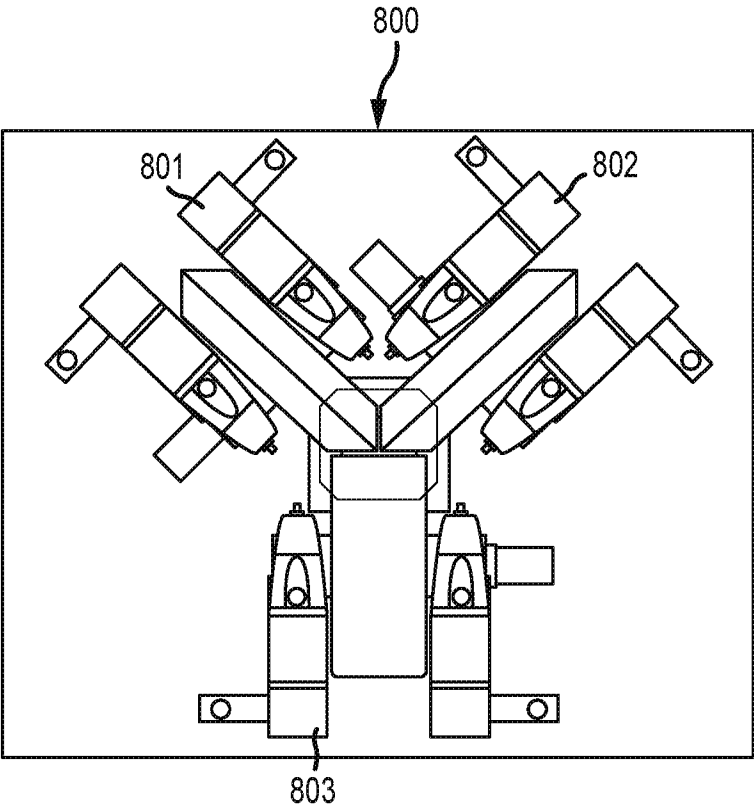


FIG.8

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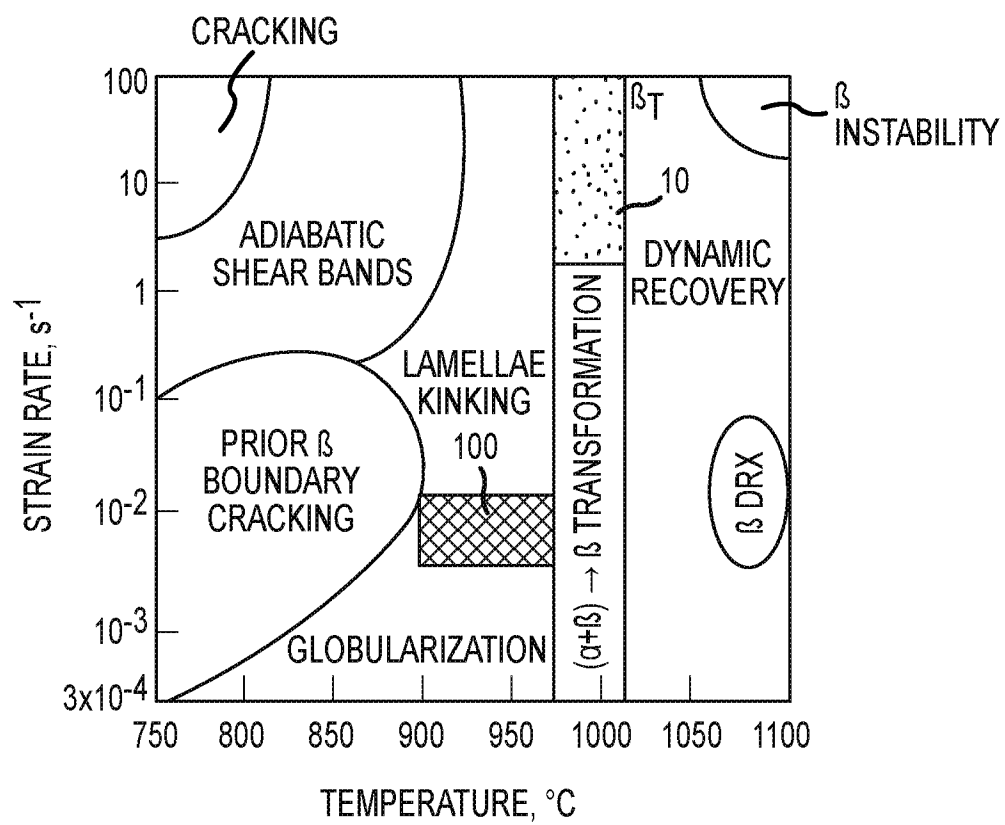


FIG.9

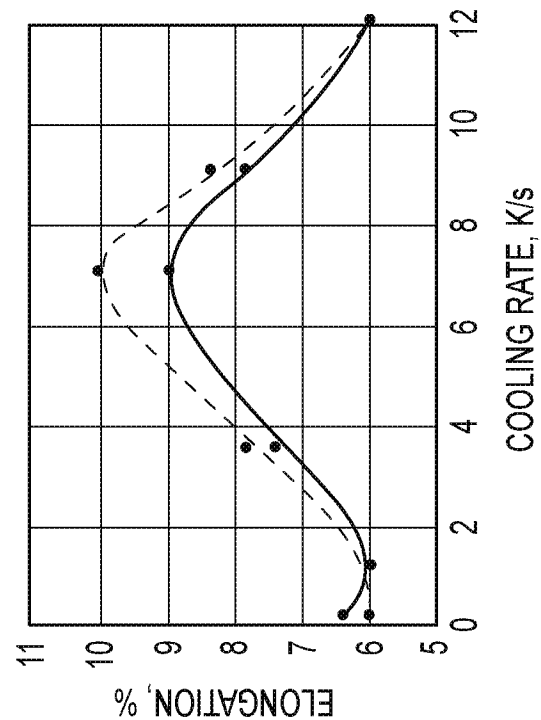


FIG.10B

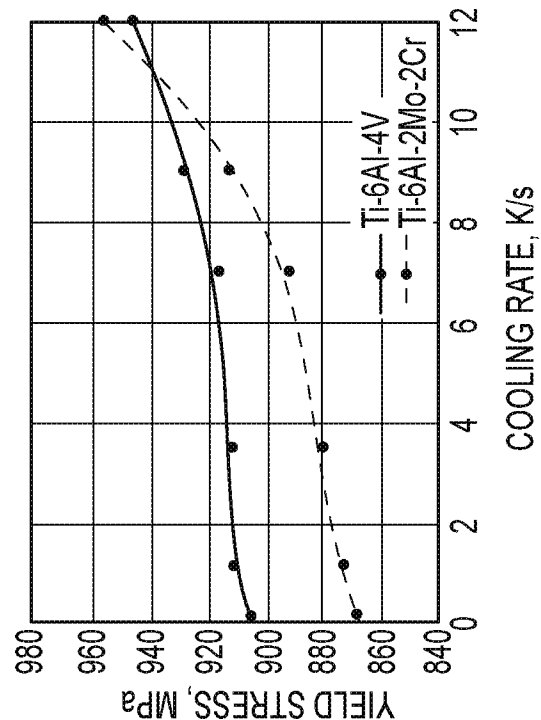


FIG.10A

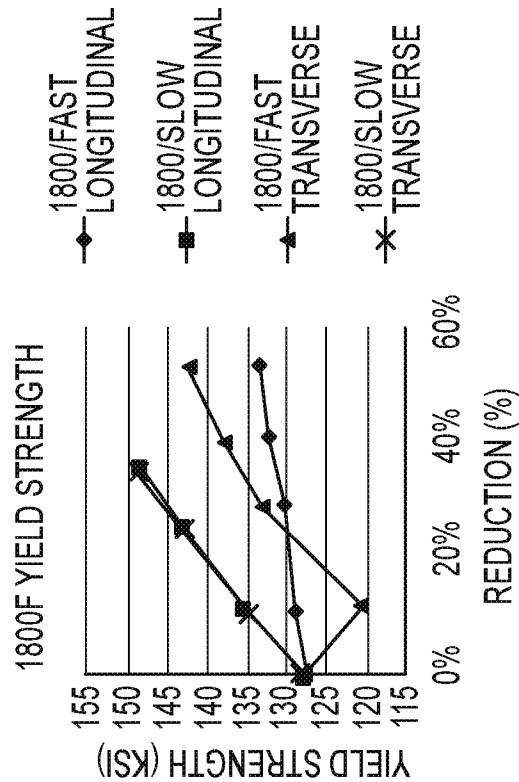


FIG.11B

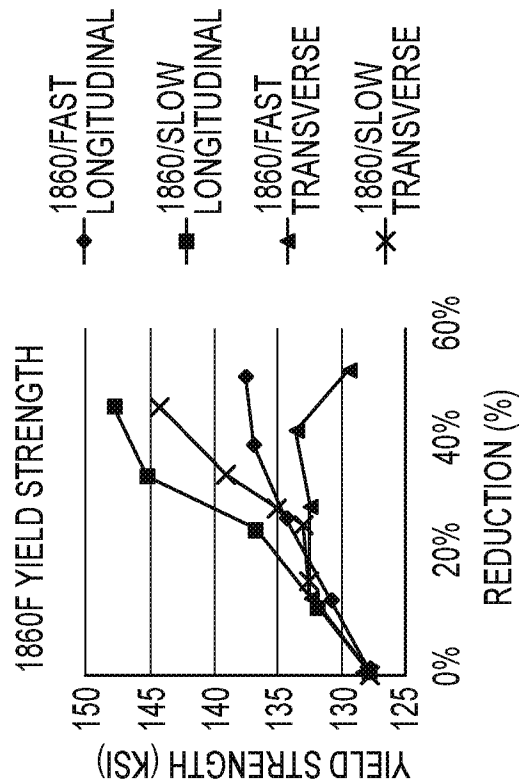


FIG.11A

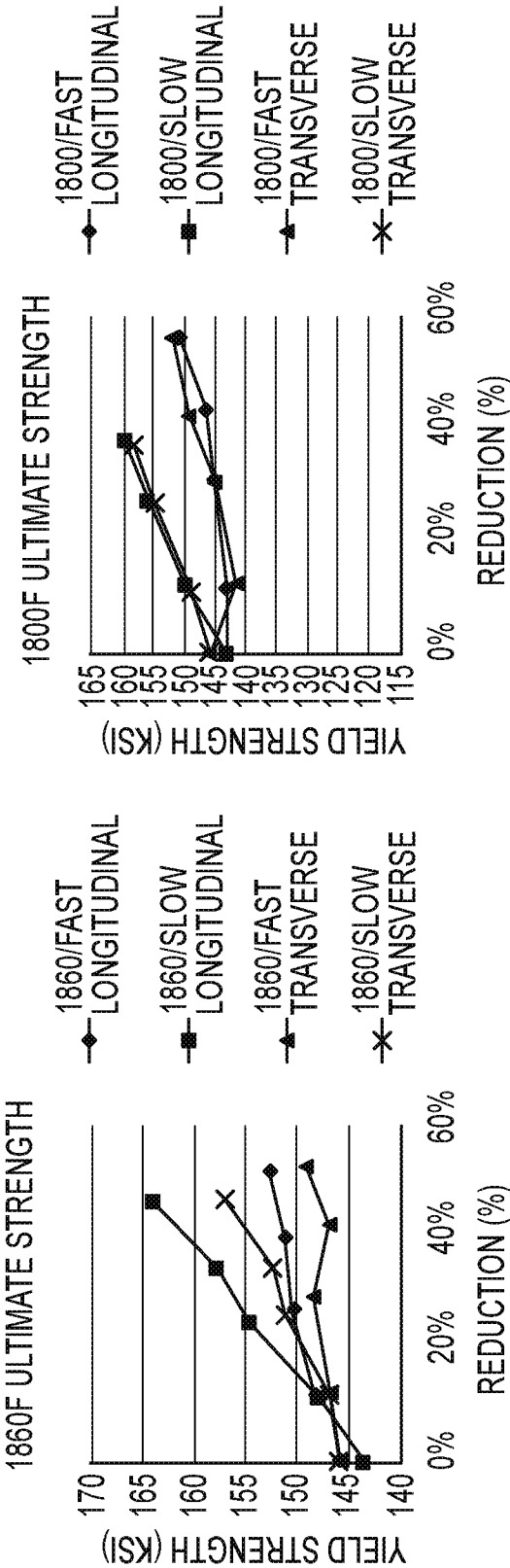


FIG.12A

FIG.12B

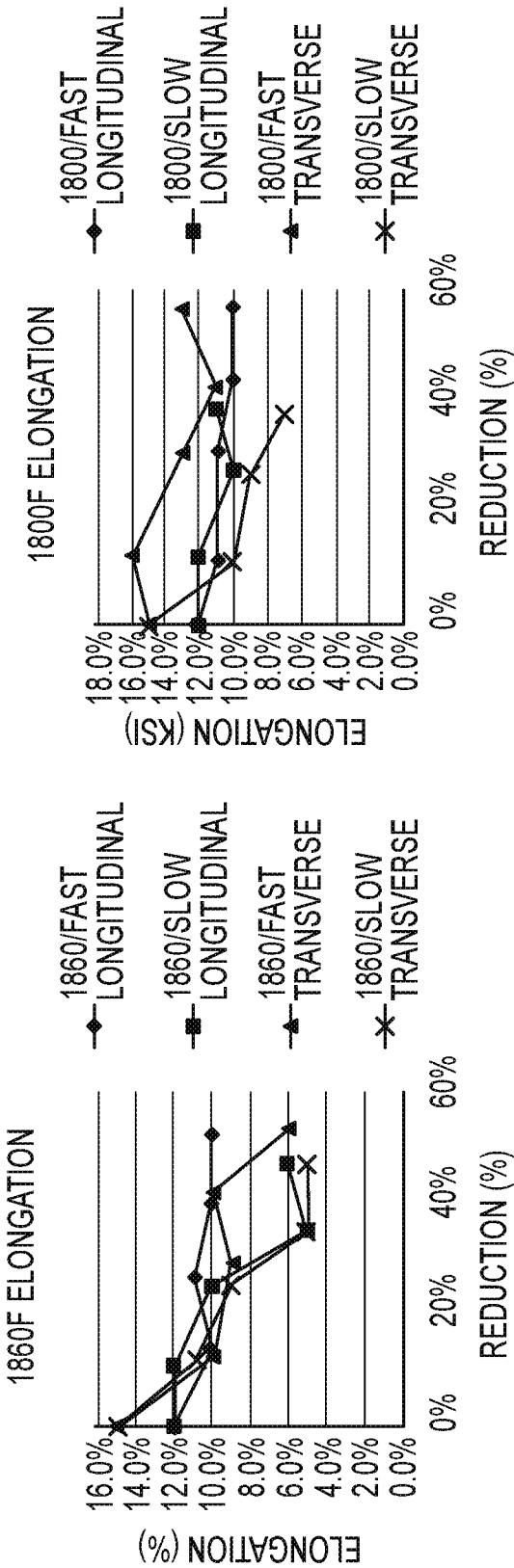


FIG.13B

FIG.13A

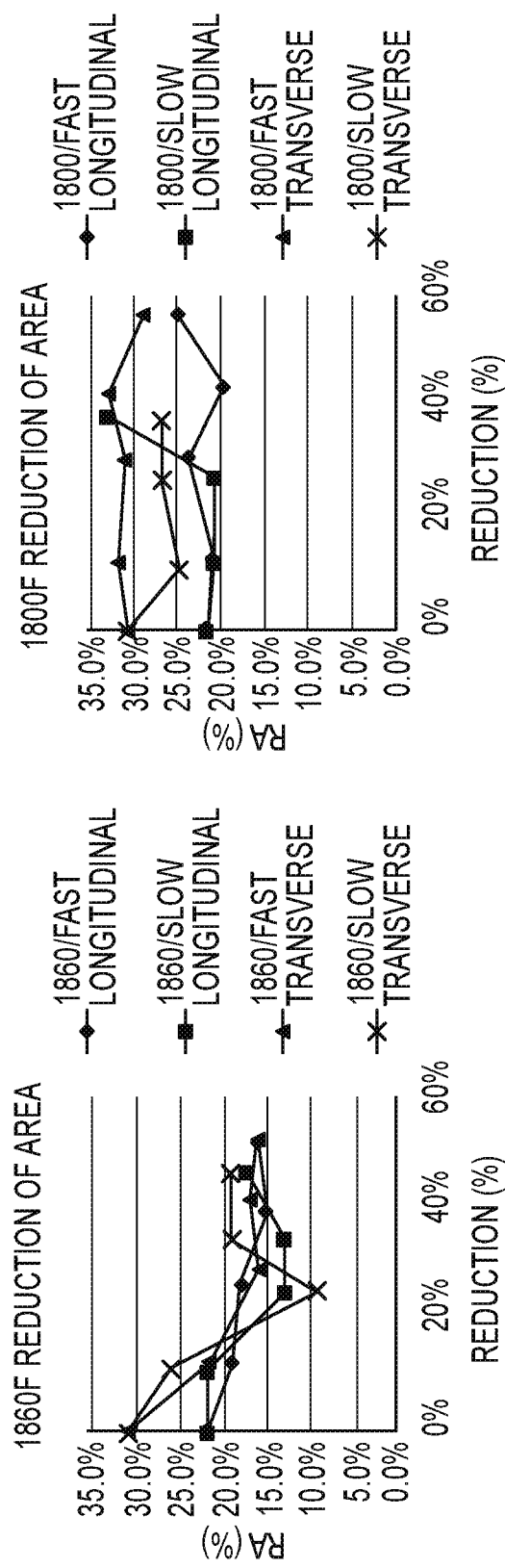


FIG.14B

FIG.14A

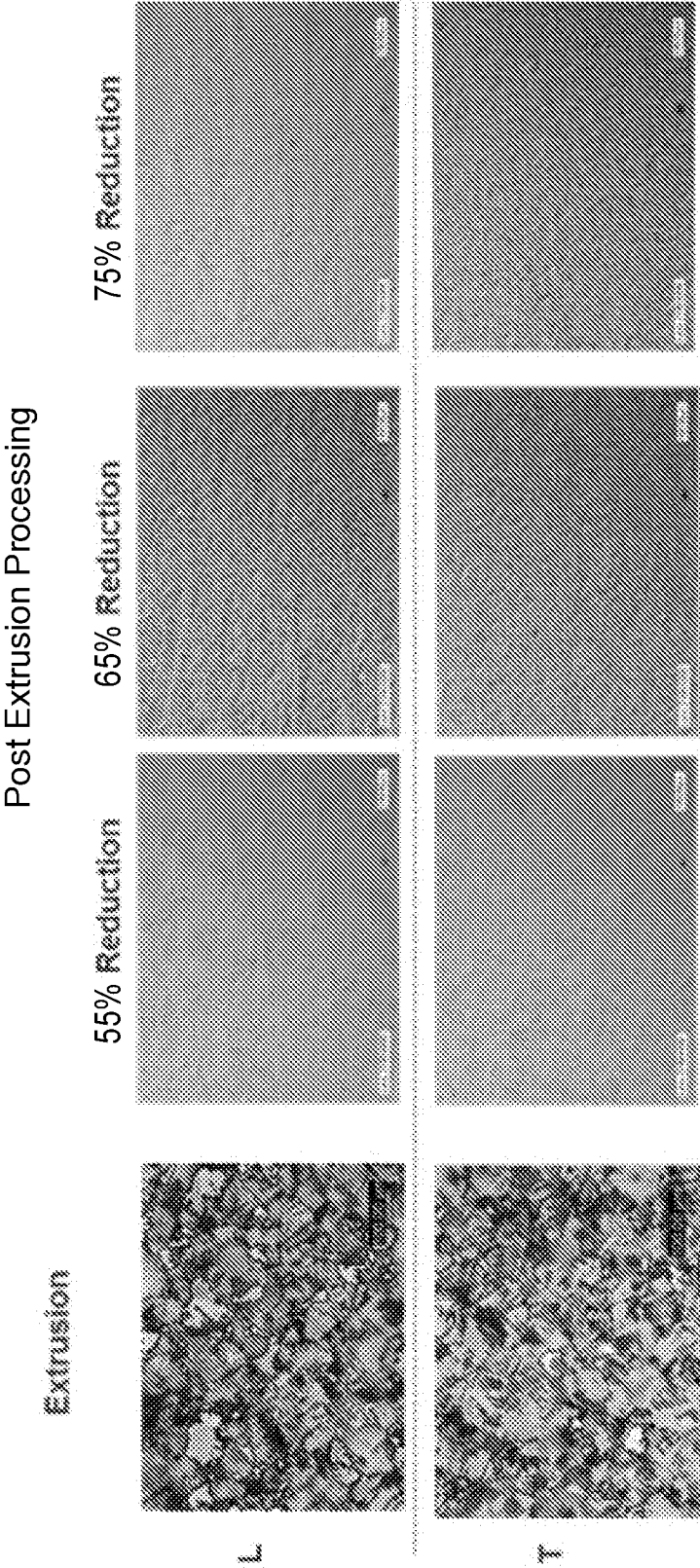


FIG.15

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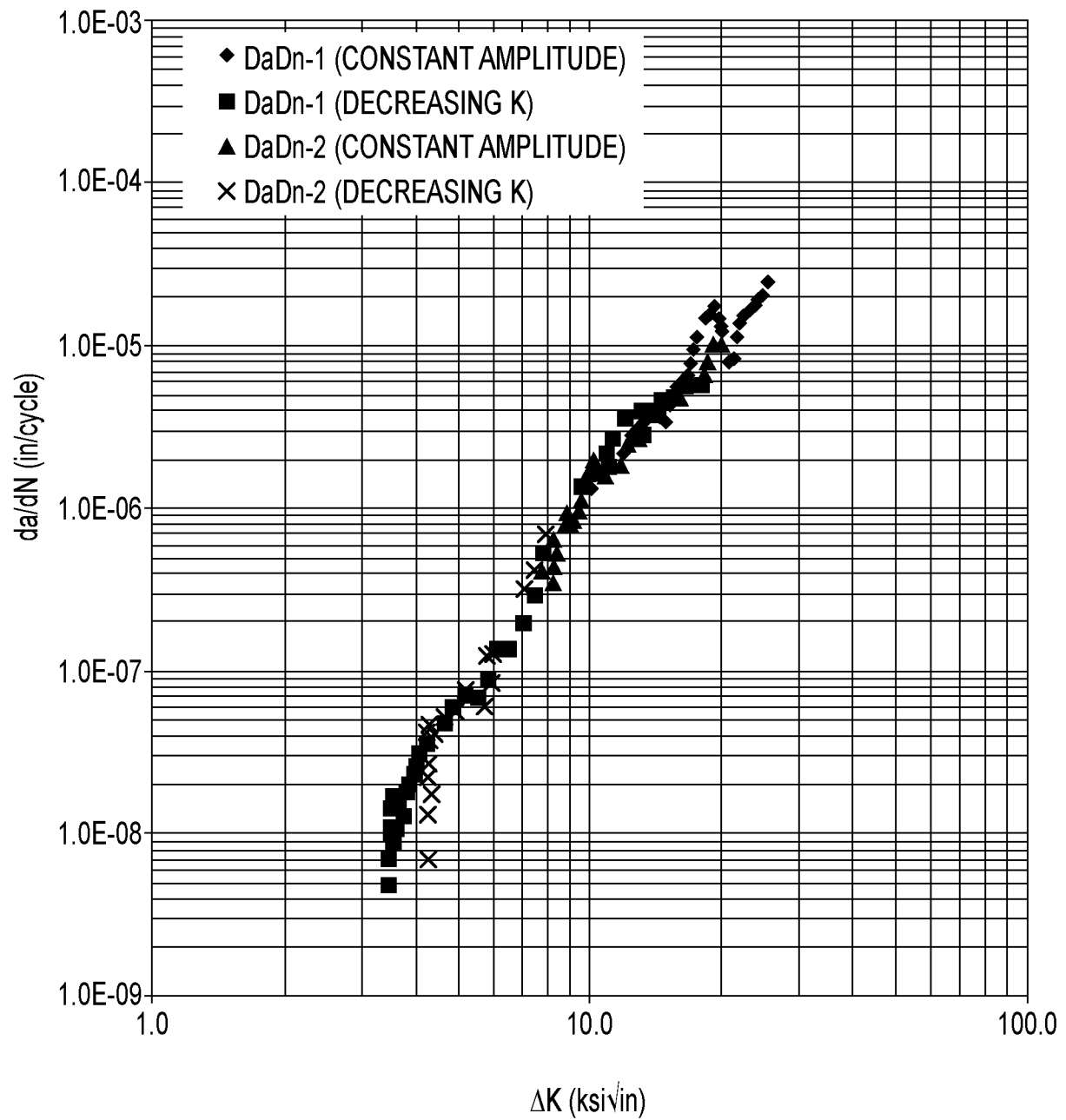


FIG. 16

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2017/029064**A. CLASSIFICATION OF SUBJECT MATTER****C22F 1/18(2006.01)i, B21B 1/092(2006.01)i, B21B 3/00(2006.01)i**

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)

C22F 1/18; B22F 3/26; C22C 14/00; B23K 35/02; B21B 1/46; B21B 1/092; B21B 3/00

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & keywords: titanium, alloy, extrusion, rolling, ingot, billet, beta transus temperature, cooling

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2007-0193018 A1 (DAVIS et al.) 23 August 2007 See paragraphs [0036]-[0041], [0058]-[0062], [0074]-[0078] and claims 1, 2, 6, 13, 23, 30.	1, 2, 6-20
Y		3-5
Y	US 2012-0269671 A1 (DRING, KEVIN) 25 October 2012 see paragraphs [0021], [0026] and claims 16, 23.	3-5
A	US 2011-0180188 A1 (BRYAN, DAVID J.) 28 July 2011 See paragraphs [0037], [0066] and claims 1, 4-12.	1-20
A	US 2013-0014865 A1 (HANUSIAK et al.) 17 January 2013 See paragraph [0016] and claims 1, 5-10.	1-20
A	US 5281285 A (MARQUARDT, BRIAN J.) 25 January 1994 See column 6, line 42 - column 7, line 39.	1-20



Further documents are listed in the continuation of Box C.



See patent family annex.

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"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

13 July 2017 (13.07.2017)

Date of mailing of the international search report

25 July 2017 (25.07.2017)

Name and mailing address of the ISA/KR

International Application Division

Korean Intellectual Property Office

189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea



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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2017/029064

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datePatent family
member(s)Publication
date

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23/01/2013

None