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Economic Development Canada
Canadian Intellectual Property Office

CA 3020347 C 2022/03/08

(11)(21) **3 020 347**

(12) **BREVET CANADIEN**
CANADIAN PATENT

(13) **C**

(86) Date de dépôt PCT/PCT Filing Date: 2017/04/24
(87) Date publication PCT/PCT Publication Date: 2017/11/02
(45) Date de délivrance/Issue Date: 2022/03/08
(85) Entrée phase nationale/National Entry: 2018/10/05
(86) N° demande PCT/PCT Application No.: US 2017/029208
(87) N° publication PCT/PCT Publication No.: 2017/189459
(30) Priorité/Priority: 2016/04/25 (US62/327,244)

(51) Cl.Int./Int.Cl. *C22C 14/00* (2006.01),
B22F 3/105 (2006.01)

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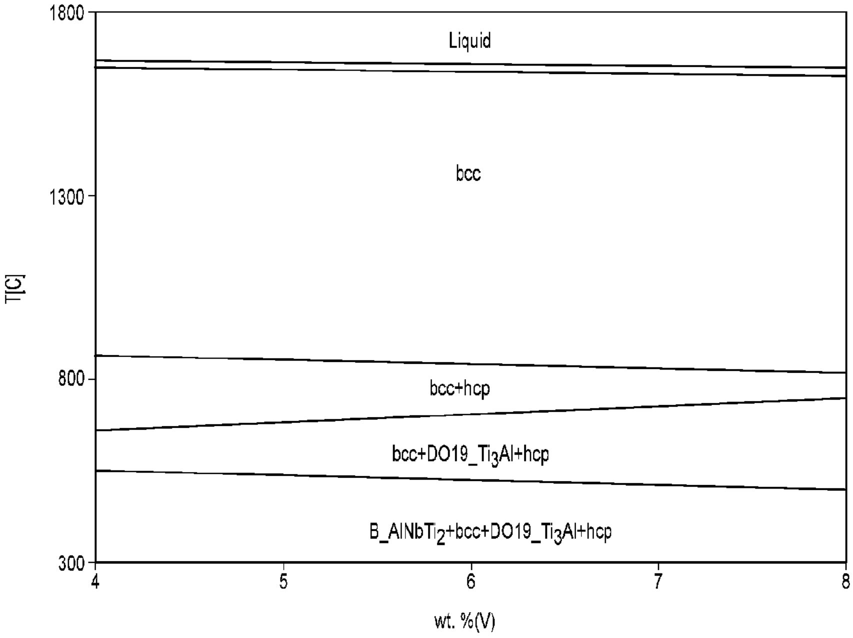
(54) Titre : MATERIAUX BCC EN TITANE, ALUMINIUM, NIOBIUM, VANADIUM ET MOLYBDENE, ET PRODUITS FABRIQUES A PARTIR DE CEUX-CI

(54) Title: BCC MATERIALS OF TITANIUM, ALUMINUM, NIOBIUM, VANADIUM, AND MOLYBDENUM, AND PRODUCTS MADE THEREFROM



(57) Abrégé/Abstract:
New beta-style (bcc) titanium alloys are disclosed. The new alloys generally include 4 - 8 wt. % Al, 4-8 wt. % Nb, 4-8 wt. % V, 1-5 wt. % Mo, optionally 2-6 wt. % Cr, the balance being titanium, optional incidental elements, and unavoidable impurities. The new alloys may realize an improved combination of properties as compared to conventional titanium alloys.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
02 November 2017 (02.11.2017)

WIPO | PCT

(10) **International Publication Number**
WO 2017/189459 A1

(51) **International Patent Classification:**
C22C 14/00 (2006.01) ***B33Y 70/00*** (2015.01)
B22F 3/105 (2006.01)

(21) **International Application Number:**
PCT/US2017/029208

(22) **International Filing Date:**
24 April 2017 (24.04.2017)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
62/327,244 25 April 2016 (25.04.2016) US

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(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC,

(54) **Title:** BCC MATERIALS OF TITANIUM, ALUMINUM, NIOBIUM, VANADIUM, AND MOLYBDENUM, AND PRODUCTS MADE THEREFROM

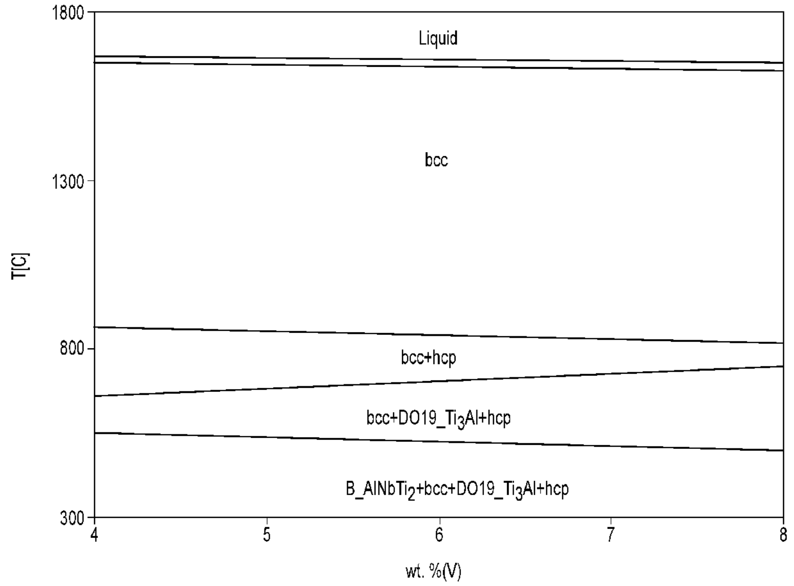

FIG.2b

(57) **Abstract:** New beta-style (bcc) titanium alloys are disclosed. The new alloys generally include 4 - 8 wt. % Al, 4-8 wt. % Nb, 4-8 wt. % V, 1-5 wt. % Mo, optionally 2-6 wt. % Cr, the balance being titanium, optional incidental elements, and unavoidable impurities. The new alloys may realize an improved combination of properties as compared to conventional titanium alloys.

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SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

Published:

— *with international search report (Art. 21(3))*

BCC MATERIALS OF TITANIUM, ALUMINUM, NIOBIUM, VANADIUM, AND MOLYBDENUM, AND PRODUCTS MADE THEREFROM

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 resistant properties. Pure titanium has an alpha (hcp) crystalline structure.

SUMMARY OF THE DISCLOSURE

[002] Broadly, the present patent application relates to new bcc (beta) materials (e.g., alloys) made from titanium, aluminum, niobium, vanadium, and molybdenum, optionally with chromium, having a single phase field of a body-centered cubic (bcc) solid solution structure immediately below the solidus temperature of the material ("the new materials"). As known to those skilled in the art, and as shown in FIG. 1, a body-centered cubic (bcc) unit cell has atoms at each of the eight corners of a cube plus one atom in the center of the cube. Each of the corner atoms is the corner of another cube so the corner atoms are shared among eight unit cells. Due to the unique compositions described herein, the new materials may realize a single phase field of a bcc solid solution structure immediately below the solidus temperature of the material. The new materials may also have a high liquidus point and a narrow equilibrium freezing range (e.g., for restricting microsegregation during solidification), making them suitable for production through conventional ingot processing, as well as powder metallurgy, shape casting, additive manufacturing, and combinations thereof (hybrid processing).

[003] The new materials generally have a bcc crystalline structure and include 4 - 8 wt. % Al, 4-8 wt. % Nb, 4-8 wt. % V, 1-5 wt. % Mo, optionally 2-6 wt. % Cr, the balance being titanium, optional incidental elements, and unavoidable impurities, wherein the material includes a sufficient amount of the titanium, aluminum, niobium, vanadium, molybdenum, and the optional chromium to realize the bcc crystalline structure. Some small fraction of alpha phase (hcp) may be present through a solid-state transformation at a low temperature in the alloy. The below table provides some non-limiting examples of useful new alloy materials.

Table 1 - Example Titanium Alloys

Ex. Alloy	*Al (wt. %)*	*Nb (wt. %)*	*V (wt. %)*	*Mo (wt. %)*	*Cr (optional) (wt. %)*	***Balance***
Alloy 1	4.0 - 8.0	4.0 - 8.0	4.0 - 8.0	1.0 - 5.0	2.0 - 6.0	Ti, any incidental elements and impurities
Alloy 2	4.5 - 7.5	4.5 - 7.5	4.5 - 7.5	1.5 - 4.5	2.5 - 5.5	Ti, any incidental elements and impurities
Alloy 3	5.0 - 7.0	5.0 - 7.0	5.0 - 7.0	2.0 - 4.0	3.0 - 5.0	Ti, any incidental elements and impurities

[004] As used herein, “alloying elements” means the elements of aluminum, niobium, vanadium, molybdenum, chromium (when used), and titanium of the alloy, and within the compositional limits defined herein. As used herein, “incidental elements” includes grain boundary modifiers, casting aids, and/or grain structure control materials, and the like, that may be used in the alloy, such as silicon, iron, yttrium, erbium, carbon, oxygen, and boron, among others. Such materials may have a low beta transus temperature, resulting in a stable solid solution strengthened matrix. In one embodiment, the beta transus temperature of the new alloys is not greater than 850°C. In one embodiment, the materials may optionally include a sufficient amount of one or more of the following elements to induce additional precipitates at elevated temperatures:

- Si: up to 1 wt. %
- Fe: up to 2 wt. %
- Y: up to 1 wt.
- Er: up to 1 wt. %
- C: up to 0.5 wt. %
- O: up to 0.5 wt. %
- B: up to 0.5 wt. %

While the amount of such optional additional element(s) in the material should be sufficient to induce the production of strengthening precipitates, the amount of such optional additional element(s) should also be restricted to avoid primary phase particles.

[005] As noted above, the new materials may have a beta (β) transus temperature not greater than 850 °C. Tables 1-2 provide some non-limiting examples of liquidus, solidus, equilibrium freezing range, non-equilibrium freezing range, beta transus, solvus, precipitate

phase and density for two invention alloys. One non-invention alloy (Ti-6Al-4V) is included for comparison purposes.

[006] As shown, the beta (β) transus temperature of the two invention alloys is below 850°C, whereas the prior art Ti-6Al-4V alloy has a beta (β) transus temperature of 995°C. The two invention alloys also show reasonable equilibrium and non-equilibrium freezing ranges for minimizing hot cracking and microsegregation during manufacturing.

Table 1 - Additional Example Alloys (Calculated)

Alloy	Approx. Liquidus (°C)	Approx. Solidus (°C)	Approx. Equil. Freezing Range (°C)	Approx. Non-Equil. Freezing Range (°C)	Matrix Phase
Ti-6Al-6Nb-6V-3Mo	1657	1636	21	72	Beta+alpha
Ti-6Al-6Nb-6V-3Mo-4Cr	1667	1646	21	72	Beta+alpha
Ti-6Al-4V (Prior art)	1648	1631	17	66	Beta+alpha

Table 2 - Additional Example Alloys (cont.)

Alloy	Approx Beta transus (°C)	Precipitate Phase	Approx. Solvus (°C)	Density (g/cm^3)
Ti-6Al-6Nb-6V-3Mo	841	Ti_3Al (α2)	702	4.60
Ti-6Al-6Nb-6V-3Mo-4Cr	758	Ti_3Al (α2)	784	4.67
Ti-6Al-4V (Prior art)	995	Ti_3Al (α2)	551	4.41

[007] FIG. 2a shows the equilibrium phase fields of a Ti-3Mo-6Nb-6V-XAl alloy. The freezing range of the alloy is not affected by the Al content. The stability of hcp (α) increases with increasing Al content. However, the stability of Ti_3Al (α2) also increases with increasing Al content. The increased amount of Ti_3Al (α2) might degrade the ductility of the alloy. In one embodiment, an alloy include at least 4.5 wt. % Al. In another embodiment, an alloy includes at least 5.0 wt. % Al. In one embodiment, an alloy includes not greater than 7.5 wt. % Al. In another embodiment, an alloy includes not greater than 7.0 wt. % Al. In one approach, an alloy includes 5 - 7 wt. % Al.

[008] FIG. 2b shows the equilibrium phase fields of a Ti-6Al-3Mo-6Nb-XV alloy. The freezing range of the alloy is not affected by the V content. The stability of beta (β) increases with increasing V content. However, the stability of Ti_3Al (α2) also increases with increasing V content. The increased amount of Ti_3Al (α2) might degrade the ductility of the alloy. In

one embodiment, an alloy include at least 4.5 wt. % V. In another embodiment, an alloy includes at least 5.0 wt. % V. In one embodiment, an alloy includes not greater than 7.5 wt. % V. In another embodiment, an alloy includes not greater than 7.0 wt. % V. In one approach, an alloy includes 5 - 7 wt. % V.

[009] FIG. 2c shows the equilibrium phase fields of a Ti-6Al-3Mo-6V-XNb alloy. Niobium has a similar effect to vanadium on the phase stability of beta (β) and Ti_3Al (α2). In one embodiment, an alloy include at least 4.5 wt. % Nb. In another embodiment, an alloy includes at least 5.0 wt. % Nb. In one embodiment, an alloy includes not greater than 7.5 wt. % Nb. In another embodiment, an alloy includes not greater than 7.0 wt. % Nb. In one approach, an alloy includes 5 - 7 wt. % Nb.

[0010] FIG. 2d shows the equilibrium phase fields of a Ti-6Al-6V-6Nb-XMo alloy. The effect of Mo content on the phase stability of beta (β) and Ti_3Al (α2) is similar to that of V and Nb. In one embodiment, an alloy include at least 1.5 wt. % Mo. In another embodiment, an alloy includes at least 2.0 wt. % Mo. In one embodiment, an alloy includes not greater than 4.5 wt. % Mo. In another embodiment, an alloy includes not greater than 4.0 wt. % Mo. In one embodiment, an alloy includes 2 - 4 wt. % Mo.

[0011] FIG. 2e shows the equilibrium phase fields of a Ti-6Al-6V-6Nb-3Mo-XCr alloy. The addition of chromium continues stabilizing the beta (β) phase, i.e. facilitates a lower beta transus temperature. It is also noted that both Ti_3Al (α2) and hcp (α) phases are destabilized with increasing chromium content for a chromium content of greater than about 3 wt. % Cr. In one embodiment, an alloy include at least 2.5 wt. % Cr. In another embodiment, an alloy includes at least 3.0 wt. % Cr. In one embodiment, an alloy includes not greater than 5.5 wt. % Cr. In another embodiment, an alloy includes not greater than 5.0 wt. % Cr. In one embodiment, the titanium alloy comprises 3 - 5 wt. % Cr.

[0012] In one approach, and referring now to FIG. 3, a method of producing a new material includes the steps of (100) heating a mixture comprising Ti, Al, V, Nb, Mo, optionally with Cr, and within the scope of the compositions described above, above a liquidus temperature of the mixture, thereby forming a liquid, (200) cooling the mixture from above the liquidus temperature to below the solidus temperature, wherein, due to the cooling, the mixture forms a solid product having a bcc (body-centered cubic) solid solution structure (potentially with other phases due to microsegregation), and wherein the mixture comprises a sufficient amount of the Ti, the Al, the V, the Nb, and the Mo, optionally with the Cr, to realize the bcc solid solution structure, and (300) cooling the solid product to below a solvus temperature of precipitate phase(s) of the mixture, thereby forming one or more precipitate phases within the bcc solid solution structure of the solid product, wherein the mixture comprises a sufficient amount of the Ti, the Al, the V, the Nb, and the Mo, optionally with the Cr, to realize the precipitate phase(s) within the bcc solid solution structure. In one embodiment, the bcc solid solution is the first phase to form from the liquid.

[0013] In one embodiment, controlled cooling of the material is employed to facilitate realization of an appropriate end product. For instance, a method may include the step of (400) cooling the mixture to ambient temperature, and a method may include controlling rates of cooling during at least cooling steps (300) and (400) such that, upon conclusion of step (400), i.e., upon reaching ambient temperature, a crack-free ingot is realized. Controlled cooling may be accomplished by, for instance, using an appropriate water cooled casting mold.

[0014] As used herein, “ingot” means a cast product of any shape. The term “ingot” includes billet. As used herein, “crack-free ingot” means an ingot that is sufficiently free of cracks such that it can be used as a fabricating ingot. As used herein, “fabricating ingot” means an ingot suitable for subsequent working into a final product. The subsequent working may include, for instance, hot working and/or cold working via any of rolling, forging, extrusion, as well as stress relief by compression and/or stretching.

[0015] In one embodiment, a crack-free product, such as a crack-free ingot, may be processed, as appropriate, to obtain a final wrought product from the material. For instance, and referring now to FIGS. 3-4, steps (100) - (400) of FIG. 3, described above, may be considered a casting step (10), shown in FIG. 4, resulting in the above-described crack-free ingot. In other embodiments, the crack-free product may be a crack-free preform produced by, for instance, shape casting, additive manufacturing or powder metallurgy. In any event, the crack-free product may be further processed to obtain a wrought final product having the bcc solid solution structure, optionally with one or more of the precipitate phase(s) therein. This further processing may include any combination of dissolving (20) and working (30) steps, described below, as appropriate to achieve the final product form. Once the final product form is realized, the material may be precipitation hardened (40) to develop strengthening precipitates. The final product form may be a rolled product, an extruded product or a forged product, for instance.

[0016] With continued reference to FIG. 4, as a result of the casting step (10), the ingot may include some second phase particles. The method may therefore include one or more dissolving steps (20), where the ingot, an intermediate product form and/or the final product form are heated above the solvus temperature of the applicable precipitate(s) but below the solidus temperature of the material, thereby dissolving some of or all of the second phase particles. The dissolving step (20) may include soaking the material for a time sufficient to dissolve the applicable second phase particles. After the soak, the material may be cooled to ambient temperature for subsequent working. Alternatively, after the soak, the material may be immediately hot worked via the working step (30).

[0017] The working step (30) generally involves hot working and/or cold working the ingot and/or an intermediate product form. The hot working and/or cold working may include rolling, extrusion or forging of the material, for instance. The working (30) may occur before and/or after any dissolving step (20). For instance, after the conclusion of a dissolving step (20), the material may be allowed to cool to ambient temperature, and then reheated to an appropriate temperature for hot working. Alternatively, the material may be cold worked at around ambient temperatures. In some embodiments, the material may be hot worked, cooled to ambient, and then cold worked. In yet other embodiments, the hot working may commence after a soak of a dissolving step (20) so that reheating of the product is not required for hot working.

[0018] The working step (30) may result in precipitation of second phase particles. In this regard, any number of post-working dissolving steps (20) can be utilized, as appropriate, to dissolve some of or all of the second phase particles that may have formed due to the working step (30).

[0019] After any appropriate dissolving (20) and working (30) steps, the final product form may be precipitation hardened (40). The precipitation hardening (40) may include heating the final product form to above the applicable solvus temperature(s) for a time sufficient to dissolve at least some second phase particles precipitated due to the working, and then rapidly cooling the final product form to below the applicable solvus temperature(s) thereby forming precipitate particles. The precipitation hardening (40) will further include holding the product at the target temperature for a time sufficient to form strengthening precipitates, and then cooling the product to ambient temperature, thereby realizing a final heat treated product having strengthening precipitates therein. In one embodiment, the final heat treated product contains ≥ 0.5 vol. % of the strengthening precipitates. The strengthening precipitates are preferably located within the matrix of the bcc solid solution structure, thereby conferring strength to the product through interactions with dislocations.

[0020] Due to the structure and composition of the new materials, the new materials may realize an improved combination of properties, such as an improved combination of at least two of density, ductility, strength, and fracture toughness, among others. Thus, the new materials may find use in various applications, such as use in low temperature applications (e.g., low temperature vehicle application, such as for an automotive or aerospace component).

[0021] The new materials described above can also be used to produce shape cast products or preforms. Shape cast products are those products that achieve their final or near final product form after the casting process. The new materials may be shape cast into any desired shape. In one embodiment, the new materials are shape cast into an automotive or aerospace component (e.g., shape cast into an engine component). After casting, the shape cast product may be subject to any appropriate dissolving (20) or precipitation hardening (40) steps, as described above. In one embodiment, a shape cast product consists essentially of the Ti, the Al, the V, the Nb, and the Mo, optionally with the Cr, and within the scope of the compositions described above. In one embodiment, the shape cast product includes $\geq$ 0.5 vol. % of strengthening precipitates.

[0022] While this patent application has generally been described as relating to bcc matrix alloy materials having one or more of the above enumerated precipitate phase(s) therein, it is to be appreciated that other hardening phases may be applicable to the new bcc matrix alloy materials, and all such hardening phases (coherent or incoherent) may find utility in the bcc alloy materials described herein.

Additive Manufacturing of New Materials

[0023] It is also possible to manufacture the new materials described above by additive manufacturing. As used herein, "additive manufacturing" means, "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies", as defined in ASTM F2792-12a entitled "Standard Terminology for Additively Manufacturing Technologies". The new materials may be manufactured via any appropriate additive manufacturing technique described in this ASTM standard, such as binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, or sheet lamination, among others.

[0024] In one embodiment, an additive manufacturing process includes depositing successive layers of one or more powders and then selectively melting and/or sintering the powders to create, layer-by-layer, an additively manufactured body (product). In one embodiment, an additive manufacturing processes uses one or more of Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM), among others. In one embodiment, an additive manufacturing process uses an EOSINT M 280 Direct Metal Laser Sintering (DMLS) additive manufacturing system, or comparable system, available from EOS GmbH (Robert-Stirling-Ring 1, 82152 Krailling/Munich, Germany).

[0025] As one example, a feedstock, such as a powder or wire, comprising (or consisting essentially of) the alloying elements and any optional incidental elements, and within the scope of the compositions described above, may be used in an additive manufacturing apparatus to produce an additively manufactured body comprising a bcc solid solution structure, optionally with precipitate phase(s) therein. In some embodiments, the additively manufactured body is a crack-free preform. The powders may be selectively heated above the liquidus temperature of the material, thereby forming a molten pool having the alloying elements and any optional incidental elements, followed by rapid solidification of the molten pool.

[0026] As noted above, additive manufacturing may be used to create, layer-by-layer, a metal product (e.g., an alloy product), such as via a metal powder bed. In one embodiment, a metal powder bed is used to create a product (e.g., a tailored alloy product). As used herein a "metal powder bed" and the like means a bed comprising a metal powder. During additive manufacturing, particles of the same or different compositions may melt (e.g., rapidly melt) and then solidify (e.g., in the absence of homogenous mixing). Thus, products having a homogenous or non-homogeneous microstructure may be produced. One embodiment of a method of making an additively manufactured body may include (a) dispersing a powder comprising the alloying elements and any optional incidental elements, (b) selectively heating a portion of the powder (e.g., via a laser) to a temperature above the liquidus temperature of the particular body to be formed, (c) forming a molten pool having the alloying elements and any optional incidental elements, and (d) cooling the molten pool at a cooling rate of at least 1000°C per second. In one embodiment, the cooling rate is at least 10,000°C per second. In another embodiment, the cooling rate is at least 100,000°C per second. In another embodiment, the cooling rate is at least 1,000,000°C per second. Steps (a)-(d) may be repeated as necessary until the body is completed, i.e., until the final additively manufactured body is formed / completed. The final additively manufactured body comprising the bcc solid solution structure, optionally with the precipitate phase(s) therein, may be of a complex geometry, or may be of a simple geometry (e.g., in the form of a sheet or plate). After or during production, an additively manufactured product may be deformed (e.g., by one or more of rolling, extruding, forging, stretching, compressing).

[0027] The powders used to additively manufacture a new material may be produced by atomizing a material (e.g., an ingot or melt) of the new material into powders of the appropriate dimensions relative to the additive manufacturing process to be used. As used herein, “powder” means a material comprising a plurality of particles. Powders may be used in a powder bed to produce a tailored alloy product via additive manufacturing. In one embodiment, the same general powder is used throughout the additive manufacturing process to produce a metal product. For instance, the final tailored metal product may comprise a single region / matrix produced by using generally the same metal powder during the additive manufacturing process. The final tailored metal product may alternatively comprise at least two separately produced distinct regions. In one embodiment, different metal powder bed types may be used to produce a metal product. For instance, a first metal powder bed may comprise a first metal powder and a second metal powder bed may comprise a second metal powder, different than the first metal powder. The first metal powder bed may be used to produce a first layer or portion of the alloy product, and the second metal powder bed may be used to produce a second layer or portion of the alloy product. As used herein, a “particle” means a minute fragment of matter having a size suitable for use in the powder of the powder bed (e.g., a size of from 5 microns to 100 microns). Particles may be produced, for example, via atomization.

[0028] The additively manufactured body may be subject to any appropriate dissolving (20), working (30) and/or precipitation hardening steps (40), as described above. If employed, the dissolving (20) and/or the working (30) steps may be conducted on an intermediate form of the additively manufactured body and/or may be conducted on a final form of the additively manufactured body. If employed, the precipitation hardening step (40) is generally conducted relative to the final form of the additively manufactured body. In one embodiment, an additively manufactured body consists essentially of the alloying elements and any incidental elements and impurities, such as any of the material compositions described above, optionally with ≥ 0.5 vol. % of precipitate phase(s) therein.

[0029] In another embodiment, the new material is a preform for subsequent working. A preform may be an ingot, a shape casting, an additively manufactured product, or a powder metallurgy product. In one embodiment, a preform is of a shape that is close to the final desired shape of the final product, but the preform is designed to allow for subsequent working to achieve the final product shape. Thus, the preform may be worked (30) such as by forging, rolling, or extrusion to produce an intermediate product or a final product, which intermediate or final product may be subject to any further appropriate dissolving (20), working (30) and/or precipitation hardening steps (40), as described above, to achieve the final product. In one embodiment, the working comprises hot isostatic pressing (hipping) to compress the part. In one embodiment, an alloy preform may be compressed and porosity may be reduced. In one embodiment, the hipping temperature is maintained below the incipient melting point of the alloy preform. In one embodiment, the preform may be a near net shape product.

[0030] In one approach, electron beam (EB) or plasma arc techniques are utilized to produce at least a portion of the additively manufactured body. Electron beam techniques may facilitate production of larger parts than readily produced via laser additive manufacturing techniques. In one embodiment, a method comprises feeding a small diameter wire (e.g., $\leq$ 2.54 mm in diameter) to the wire feeder portion of an electron beam gun. The wire may be of the compositions, described above. The electron beam (EB) heats the wire above the liquidus point of the body to be formed, followed by rapid solidification (e.g., at least 100°C per second) of the molten pool to form the deposited material. The wire could be fabricated by a conventional ingot process or by a powder consolidation process. These steps may be repeated as necessary until the final product is produced. Plasma arc wire feed may similarly be used with the alloys disclosed herein. In one embodiment, not illustrated, an electron beam (EB) or plasma arc additive manufacturing apparatus may employ multiple different wires with corresponding multiple different radiation sources, each of the wires and sources being fed and activated, as appropriate to provide the product having a metal matrix having the alloying elements and any optional incidental elements.

[0031] In another approach, a method may comprise (a) selectively spraying one or more metal powders towards or on a building substrate, (b) heating, via a radiation source, the metal powders, and optionally the building substrate, above the liquidus temperature of the product to be formed, thereby forming a molten pool, (c) cooling the molten pool, thereby forming a solid portion of the metal product, wherein the cooling comprises cooling at a cooling rate of at least 100°C per second. In one embodiment, the cooling rate is at least 1000°C per second. In another embodiment, the cooling rate is at least 10,000°C per second. The cooling step (c) may be accomplished by moving the radiation source away from the molten pool and/or by moving the building substrate having the molten pool away from the radiation source. Steps (a)-(c) may be repeated as necessary until the metal product is completed. The spraying step (a) may be accomplished via one or more nozzles, and the composition of the metal powders can be varied, as appropriate, to provide tailored final metal products having a metal matrix, the metal matrix having the alloying elements and any optional incidental elements. The composition of the metal powder being heated at any one time can be varied in real-time by using different powders in different nozzles and/or by varying the powder composition(s) provided to any one nozzle in real-time. The work piece can be any suitable substrate. In one embodiment, the building substrate is, itself, a metal product (e.g., an alloy product.)

[0032] As noted above, welding may be used to produce metal products (e.g., to produce alloy products). In one embodiment, the product is produced by a melting operation applied to pre-cursor materials in the form of a plurality of metal components of different composition. The pre-cursor materials may be presented in juxtaposition relative to one another to allow simultaneous melting and mixing. In one example, the melting occurs in the course of electric arc welding. In another example, the melting may be conducted by a laser or an electron beam during additive manufacturing. The melting operation results in the plurality of metal components mixing in a molten state and forming the metal product, such as in the form of an alloy. The pre-cursor materials may be provided in the form of a plurality of physically separate forms, such as a plurality of elongated strands or fibers of metals or metal alloys of different composition or an elongated strand or a tube of a first composition and an adjacent powder of a second composition, e.g., contained within the tube or a strand having one or more clad layers. The pre-cursor materials may be formed into a structure, e.g., a twisted or braided cable or wire having multiple strands or fibers or a tube with an outer shell and a powder contained in the lumen thereof. The structure may then be handled to subject a portion thereof, e.g., a tip, to the melting operation, e.g., by using it as a welding electrode or as a feed stock for additive manufacturing. When so used, the structure and its component pre-cursor materials may be melted, e.g., in a continuous or discrete process to form a weld bead or a line or dots of material deposited for additive manufacture.

[0033] In one embodiment, the metal product is a weld body or filler interposed between and joined to a material or material to the weld, e.g., two bodies of the same or different material or a body of a single material with an aperture that the filler at least partially fills. In another embodiment, the filler exhibits a transition zone of changing composition relative to the material to which it is welded, such that the resultant combination could be considered the alloy product.

New materials consisting essentially of a bcc solid solution structure

[0034] While the above disclosure generally describes how to produce new bcc materials having precipitate phase(s) therein, it is also possible to produce a material consisting essentially of a bcc solid solution structure. For instance, after production of an ingot, a wrought body, a shape casting, or an additively manufactured body, as described above, the material may be homogenized, such as in a manner described relative to the dissolving step (20), above. With appropriate rapid cooling, precipitation of any second phase particles may be inhibited / restricted, thereby realizing a bcc solid solution material essentially free of any second phase particles, i.e., a material consisting essentially of a bcc solid solution structure.

Alloy Properties

[0035] The new materials may realize an improved combination of properties. In this section all mechanical properties are measured in the longitudinal (L) direction, unless otherwise specified.

[0036] In one approach, a new material realizes an as-cast tensile yield strength (TYS) of at least 715 MPa when tested in accordance with ASTM E8 at room temperature (RT). In one embodiment, a new material may realize an as-cast, RT TYS of at least 735 MPa. In another embodiment, a new material may realize an as-cast, RT TYS of at least 755 MPa. In yet another embodiment, a new material may realize an as-cast, RT TYS of at least 775 MPa. In another embodiment, a new material may realize an as-cast, RT TYS of at least 795 MPa. In yet another embodiment, a new material may realize an as-cast, RT TYS of at least 815 MPa. In another embodiment, a new material may realize an as-cast, RT TYS of at least 835 MPa. In yet another embodiment, a new material may realize an as-cast, RT TYS of at least 855 MPa. In another embodiment, a new material may realize an as-cast, RT TYS of at least 875 MPa. In yet another embodiment, a new material may realize an as-cast, RT TYS of at least 895 MPa. In another embodiment, a new material may realize an as-cast, RT TYS of at least 915 MPa. In yet another embodiment, a new material may realize an as-cast, RT TYS of at least 935 MPa. In another embodiment, a new material may realize an as-cast, RT TYS of at least 940 MPa. Higher strengths may be realized when chromium is employed. In any of these embodiments, a new material may realize an as-cast, RT elongation of at least 2.0 %. In any of these embodiments, a new material may realize an as-cast, RT elongation of at least 4.0 %. In any of these embodiments, a new material may realize an as-cast, RT elongation of at least 6.0 %. In any of these embodiments, a new material may realize an as-cast, RT elongation of at least 8.0 %. In any of these embodiments, a new material may realize an as-cast, RT elongation of at least 9.0 %.

[0037] In one approach, a new material may realize an as-cast ultimate tensile strength (UTS) of at least 880 MPa when tested in accordance with ASTM E8 at room temperature (RT). In one embodiment, a new material may realize an as-cast, RT UTS of at least 890 MPa. In another embodiment, a new material may realize an as-cast, RT UTS of at least 900 MPa. In yet another embodiment, a new material may realize an as-cast, RT UTS of at least 910 MPa. In another embodiment, a new material may realize an as-cast, RT UTS of at least 920 MPa. In yet another embodiment, a new material may realize an as-cast, RT UTS of at least 930 MPa. In another embodiment, a new material may realize an as-cast, RT UTS of at least 940 MPa. In yet another embodiment, a new material may realize an as-cast, RT UTS of at least 950 MPa. In another embodiment, a new material may realize an as-cast, RT UTS of at least 960 MPa. In yet another embodiment, a new material may realize an as-cast, RT UTS of at least 970 MPa. In another embodiment, a new material may realize an as-cast, RT UTS of at least 980 MPa. In any of these embodiments, a new material may realize an as-cast, RT elongation of at least 2.0 %. In any of these embodiments, a new material may realize an as-cast, RT elongation of at least 4.0 %. In any of these embodiments, a new material may realize an as-cast, RT elongation of at least 6.0 %. In any of these embodiments, a new material may realize an as-cast, RT elongation of at least 8.0 %. In any of these embodiments, a new material may realize an as-cast, RT elongation of at least 9.0 %.

[0038]

[0039] In one approach, a new material may realize a TYS of at least 1100 MPa in the heat treated condition, when tested in accordance with ASTM E8 at room temperature. In one embodiment, a new material may realize a heat treated, RT TYS of at least 1150 MPa. In another embodiment, a new material may realize a heat treated, RT TYS of at least 1200 MPa. In yet another embodiment, a new material may realize a heat treated, RT TYS of at least 1250 MPa. In another embodiment, a new material may realize a heat treated, RT TYS of at least 1300 MPa. In yet another embodiment, a new material may realize a heat treated, RT TYS of at least 1350 MPa. In another embodiment, a new material may realize a heat treated, RT TYS of at least 1400 MPa. In yet another embodiment, a new material may realize a heat treated, RT TYS of at least 1450 MPa. In another embodiment, a new material may realize a heat treated, RT TYS of at least 1500 MPa. In any of these embodiments, a new material may realize a heat treated, RT elongation of at least 1.0 %. In any of these embodiments, a new material may realize a heat treated, RT elongation of at least 2.0 %. In any of these embodiments, a new material may realize a heat treated, RT elongation of at least 3.0 %. In any of these embodiments, a new material may realize a heat treated, RT elongation of at least 4.0 %. In any of these embodiments, a new material may realize a heat treated, RT elongation of at least 5.0 %.

[0040] In one approach, a new material may realize a UTS of at least 1100 MPa in the heat treated condition, when tested in accordance with ASTM E8 at room temperature. In one embodiment, a new material may realize a heat treated, RT UTS of at least 1150 MPa. In another embodiment, a new material may realize a heat treated, RT UTS of at least 1200 MPa. In yet another embodiment, a new material may realize a heat treated, RT UTS of at least 1250 MPa. In another embodiment, a new material may realize a heat treated, RT UTS of at least 1300 MPa. In yet another embodiment, a new material may realize a heat treated, RT UTS of at least 1350 MPa. In another embodiment, a new material may realize a heat treated, RT UTS of at least 1400 MPa. In yet another embodiment, a new material may realize a heat treated, RT UTS of at least 1450 MPa. In yet another embodiment, a new material may realize a heat treated, RT UTS of at least 1500 MPa. In any of these embodiments, a new material may realize a heat treated, RT elongation of at least 1.0 %. In any of these embodiments, a new material may realize a heat treated, RT elongation of at least 2.0 %. In any of these embodiments, a new material may realize a heat treated, RT elongation of at least 3.0 %. In any of these embodiments, a new material may realize a heat treated, RT elongation of at least 4.0 %. In any of these embodiments, a new material may realize a heat treated, RT elongation of at least 5.0 %.

[0041] In one approach, the new materials may realize improved properties over a Ti-6Al-4V alloy of the same product form and heat treated condition when tested in accordance with ASTM E8 at room temperature. In one embodiment, the new materials may realize at least 5.0% higher room temperature TYS as compared to a Ti-6Al-4V product of the same product form and heat treated condition. In one embodiment, the new materials may realize at least 10% higher RT TYS as compared to a Ti-6Al-4V product of the same product form and heat treated condition. In one embodiment, the new materials may realize at least 20% higher RT TYS as compared to a Ti-6Al-4V product of the same product form and heat treated condition. In one embodiment, the new materials may realize at least 25% higher RT TYS as compared to a Ti-6Al-4V product of the same product form and heat treated condition. In one embodiment, the new materials may realize at least 30% higher RT TYS as compared to a Ti-6Al-4V product of the same product form and heat treated condition. In one embodiment, the new materials may realize at least 35% higher RT TYS as compared to a Ti-6Al-4V product of the same product form and heat treated condition. Similar results may be realized for ultimate tensile strength.

[0042] In one approach, the new materials may realize improved properties over a Ti-6Al-4V alloy of the same product form and heat treated condition when tested in accordance with ASTM E21 at 650°C. In one embodiment, the new materials may realize at least 1.0% higher TYS as compared to a Ti-6Al-4V product of the same product form and heat treated condition at 650°C. In one embodiment, the new materials may realize at least 2.0% higher TYS as compared to a Ti-6Al-4V product of the same product form and heat treated condition at 650°C. In one embodiment, the new materials may realize at least 3.0% higher TYS as compared to a Ti-6Al-4V product of the same product form and heat treated condition at 650°C. In one embodiment, the new materials may realize at least 4.0% higher TYS as compared to a Ti-6Al-4V product of the same product form and heat treated condition at 650°C. In one embodiment, the new materials may realize at least 5.0% higher TYS as compared to a Ti-6Al-4V product of the same product form and heat treated condition at 650°C. In any of these embodiments, the new materials may realize the higher TYS at equivalent elongation. Similar results may be realized for ultimate tensile strength.

BRIEF DESCRIPTION OF THE DRAWINGS

[0043] FIG. 1 is a schematic illustration of bcc, fcc, and hcp unit cells.

[0044] FIG. 2a is a graph showing the effect of Al content on the equilibrium phase fields of a Ti-3Mo-6Nb-6V-XAl alloy.

[0045] FIG. 2b is a graph showing the effect of V content on the equilibrium phase fields of a Ti-6Al-3Mo-6Nb-XV alloy.

[0046] FIG. 2c is a graph showing the effect of V content on the equilibrium phase field of Ti-6Al-3Mo-6V-XNb

[0047] FIG. 2d is a graph showing the effect of Mo content on the equilibrium phase fields of a Ti-6Al-6V-6Nb-XMo alloy.

[0048] FIG. 2e is a graph showing the effect of Cr content on the equilibrium phase fields of a Ti-6Al-6V-6Nb-3Mo-XCr alloy.

[0049] FIG. 3 is a flow chart of one embodiment of a method to produce a new material

[0050] FIG. 4 is a flow chart of one embodiment of a method to obtain a wrought product having a bcc solid solution structure with one of more precipitates therein.

DETAILED DESCRIPTION

Example 1: Testing of Invention and Conventional Alloys

[0051] Two invention alloys (Ti-6Al-3Mo-6Nb-6V, and Ti-6Al-3Mo-6Nb-6V-4Cr), and a conventional Ti-6Al-4V alloy were cast via arc melt casting into rods. After casting, mechanical properties of the as-cast alloys were measured in accordance with ASTM E8, the results of which are shown in Tables 3-5. Specimens of the Ti-6Al-3Mo-6Nb-6V and Ti-6Al-3Mo-6Nb-6V-4Cr alloys were heat treated at 500°C for 8 hours and then air cooled. The mechanical properties of the heat treated alloys were then tested, the results of which are shown in Table 4, below. All reported strength and elongation properties were from testing in the longitudinal (L) direction. Estimated toughness from the stress-strain curve produced during the mechanical property testing is also shown. Tensile properties at 650°C were also tested for the Ti-6Al-3Mo-6Nb-6V-4Cr alloy and are also provided in the Table 5, below.

Table 3 - Conventional Ti-6Al-4V Properties

Condition	TYS (MPa)	UTS (MPa)	Elong. (%)
RT As-Cast	715	881	11
As-Cast, Elevated Temp.	229	366	16

Table 4 - Ti-6Al-3Mo-6Nb-6V Properties

Condition	TYS (MPa)	UTS (MPa)	Elong. (%)
As-Cast	789	979	8
Heat Treated	N/A	937	N/A

Table 5 - Ti-6Al-3Mo-6Nb-6V-4Cr Properties

Condition	TYS (MPa)	UTS (MPa)	Elong. (%)
As-Cast	941	942	-
Heat Treated	1480	1488	-
As-Cast, Elevated Temp.	238	417	16
Heat Treated, Elevated Temp.	234	415	16

As shown, the new invention alloys realized improved properties as compared to the conventional alloy.

[0052] While various embodiments of the new technology described herein 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 presently disclosed technology.

THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A titanium alloy consisting of:

4 - 8 wt. % Al;

4 - 8 wt. % Nb;

4 - 8 wt. % V;

1 - 5 wt. % Mo;

optionally 2-6 wt. % Cr; and

optionally: up to 1 wt. % Si; up to 2 wt. % Fe; up to 1 wt. % Y; up to 1 wt. % Er; up to 0.5 wt. % C; up to 0.5 wt. % O; and up to 0.5 wt. % B;

the balance being Ti and unavoidable impurities;

wherein the titanium alloy is in the form of a titanium alloy body;

wherein the titanium alloy body is one of an ingot, a rolled product, an extrusion, a forging, a shape casting, or an additively manufactured product; and

wherein the titanium alloy body realizes a single phase field of a body-centered cubic (bcc) solid solution structure immediately below the solidus temperature of the titanium alloy body.

2. The titanium alloy of claim 1, wherein the titanium alloy includes a sufficient amount of the Ti, the Al, the Nb, the V, the Mo, and the optional Cr to realize a beta transus temperature of not greater than 850°C.

3. The titanium alloy of claim 1, wherein the alloy includes at least 4.5 wt. % Al, or at least 5.0 wt. % Al.

4. The titanium alloy of claim 1, wherein the alloy includes not greater than 7.5 wt. % Al, or not greater than 7.0 wt. % Al.

5. The titanium alloy of claim 1, wherein the alloy includes at least 4.5 wt. % Nb, or at least 5.0 wt. % Nb.

6. The titanium alloy of claim 1, wherein the alloy includes not greater than 7.5 wt. % Nb, or not greater than 7.0 wt. % Nb.

7. The titanium alloy of claim 1, wherein the alloy includes at least 4.5 wt. % V, or at least 5.0 wt. % V.

8. The titanium alloy of claim 1, wherein the alloy includes not greater than 7.5 wt. % V, or not greater than 7.0 wt. % V.

9. The titanium alloy of claim 1, wherein the alloy includes at least 1.5 wt. % Mo, or at least 2.0 wt. % Mo.

10. The titanium alloy of claim 1, wherein the alloy includes not greater than 4.5 wt. % Mo, or not greater than 4.0 wt. % Mo.

11. The titanium alloy of claim 1, wherein the alloy includes 2-6 wt. % Cr.

12. The titanium alloy of claim 11, wherein the alloy includes at least 2.5 wt. % Cr, or at least 3.0 wt. % Cr.

13. The titanium alloy of claim 11, wherein the alloy includes not greater than 5.5 wt. % Cr, or not greater than 5.0 wt. % Cr.

14. An alloy body comprising the titanium alloy of any one of claims 1-13, wherein the alloy body is in the form of an additively manufactured product.

15. A method comprising the steps of:

(a) using a feedstock in an additive manufacturing apparatus, wherein the feedstock consists of:

4 - 8 wt. % Al;
4 - 8 wt. % Nb;
4 - 8 wt. % V;
1 - 5 wt. % Mo;
optionally 2-6 wt. % Cr; and
optionally: up to 1 wt. % Si; up to 2 wt. % Fe; up to 1 wt. % Y; up to 1 wt. % Er; up to 0.5 wt. % C; up to 0.5 wt. % O; and up to 0.5 wt. % B;
the balance being Ti and unavoidable impurities;

(b) producing a metal product in the additive manufacturing apparatus using the feedstock;

wherein the metal product realizes a single phase field of a body-centered cubic (bcc) solid solution structure immediately below the solidus temperature of the metal product.

16. The method of claim 15, wherein the feedstock comprises a powder feedstock; and wherein the method comprises the steps of:

(a) dispersing a metal powder of the powder feedstock in a bed and/or spraying a metal powder of the powder feedstock towards or on a substrate;

(b) selectively heating a portion of the metal powder above its liquidus temperature, thereby forming a molten pool;

(c) cooling the molten pool, thereby forming a portion of the metal product, wherein the cooling comprises cooling at a cooling rate of at least 100°C per second; and

(d) repeating steps (a)-(c) until the metal product is completed.

17. The method of claim 15, wherein the feedstock comprises a wire feedstock; and wherein the method comprises the steps of:

(a) using a radiation source to heat the wire feedstock above its liquidus point, thereby creating a molten pool;

(b) cooling the molten pool at a cooling rate of at least 1000°C per second; and

(c) repeating steps (a)-(b) until the metal product is completed.

18. The method of claim 16 or claim 17, wherein the cooling rate is sufficient to form at least one precipitate phase.

19. The method of claim 18, wherein the at least one precipitate phase comprises Ti_3Al.

20. The method of any one of claims 18-19, wherein the metal product comprises at least 0.5 vol. % of the precipitate phase.

21. The method of claim 15, comprising the step of:

working the metal product.

22. The method of claim 21, wherein the metal product is a final additively manufactured body; and wherein the working step is working of the final additively manufactured body.

23. The method of claim 21, wherein the producing step comprises:

first producing a portion of the metal product using the feedstock; and

second producing another portion of the metal product using the feedstock; and

wherein the working step occurs at least after the first or second producing steps.

24. The method of claim 23, wherein the working step occurs between the first producing step and the second producing step.

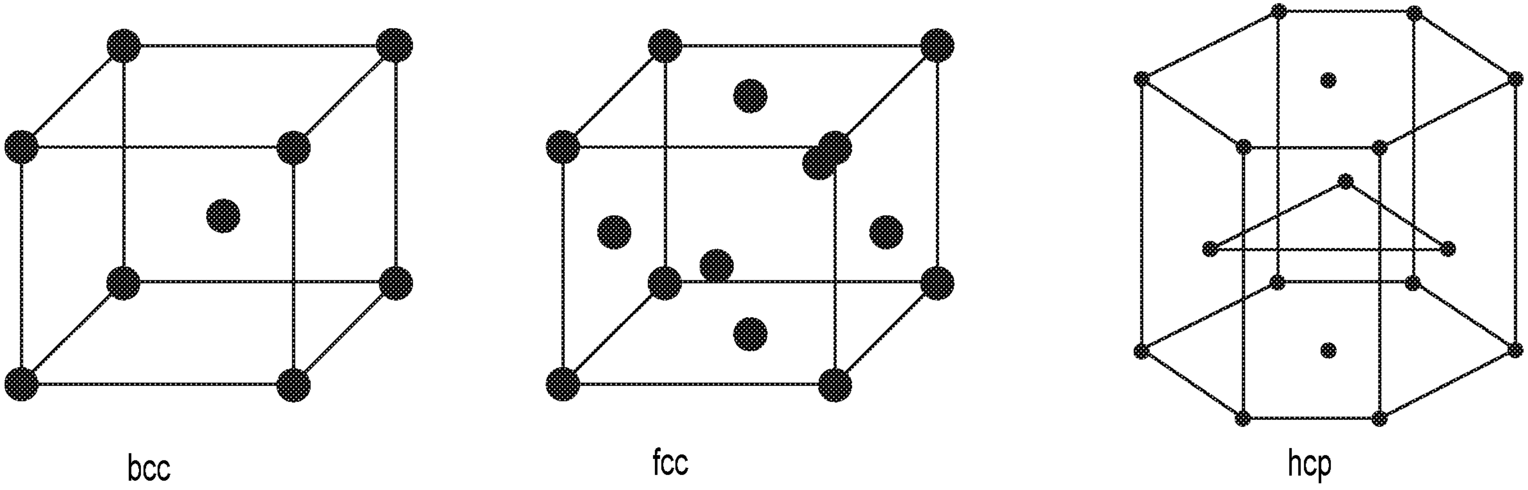


FIG.1

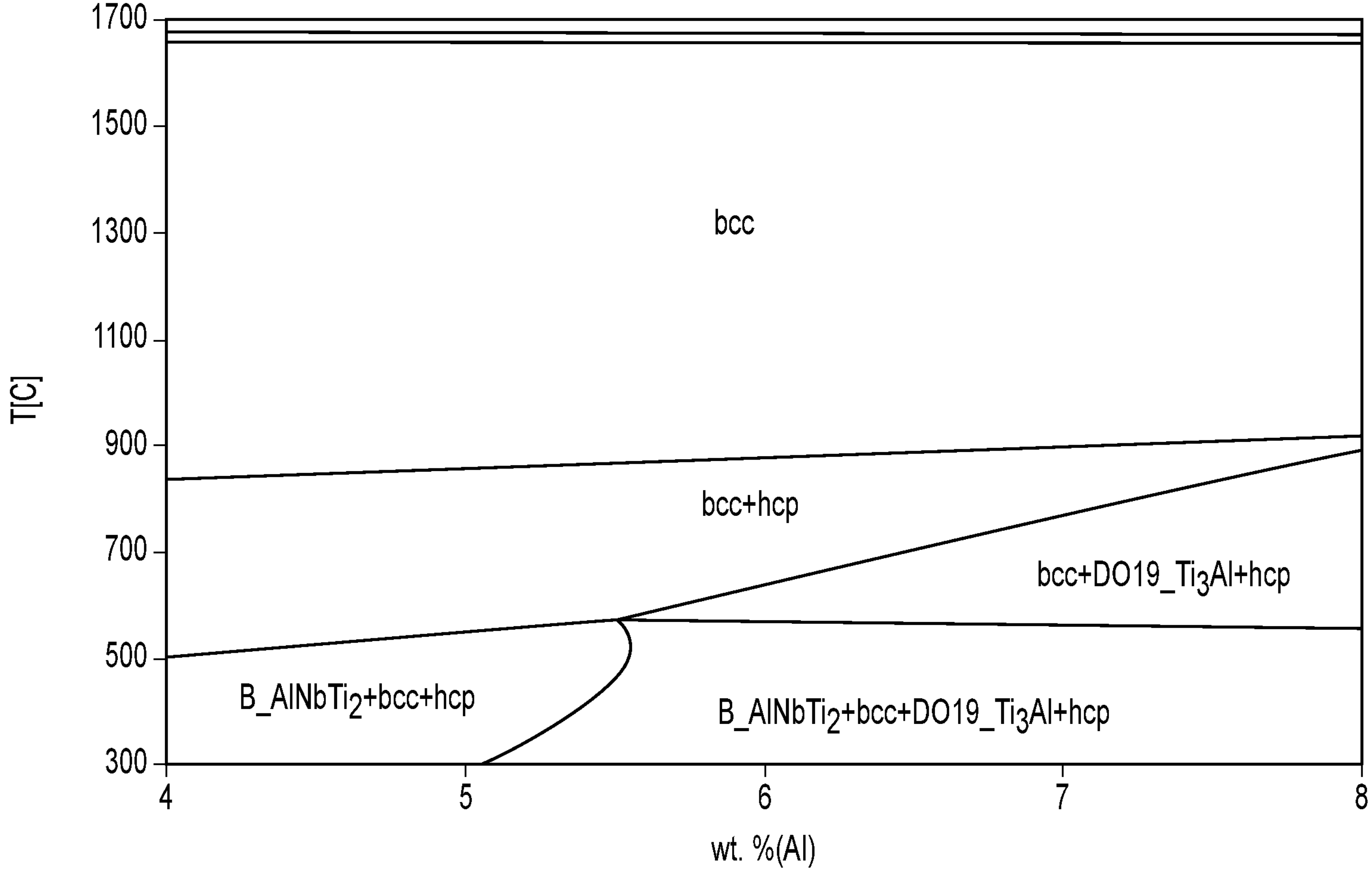

1700
1500
1300
1100
900
700
500
300
T[C]
4
5
6
7
8
wt. %(Al)
bcc
bcc+hcp
bcc+DO19_Ti$_3$Al+hcp
B_AlNbTi$_2$+bcc+hcp
B_AlNbTi$_2$+bcc+DO19_Ti$_3$Al+hcp

FIG.2a

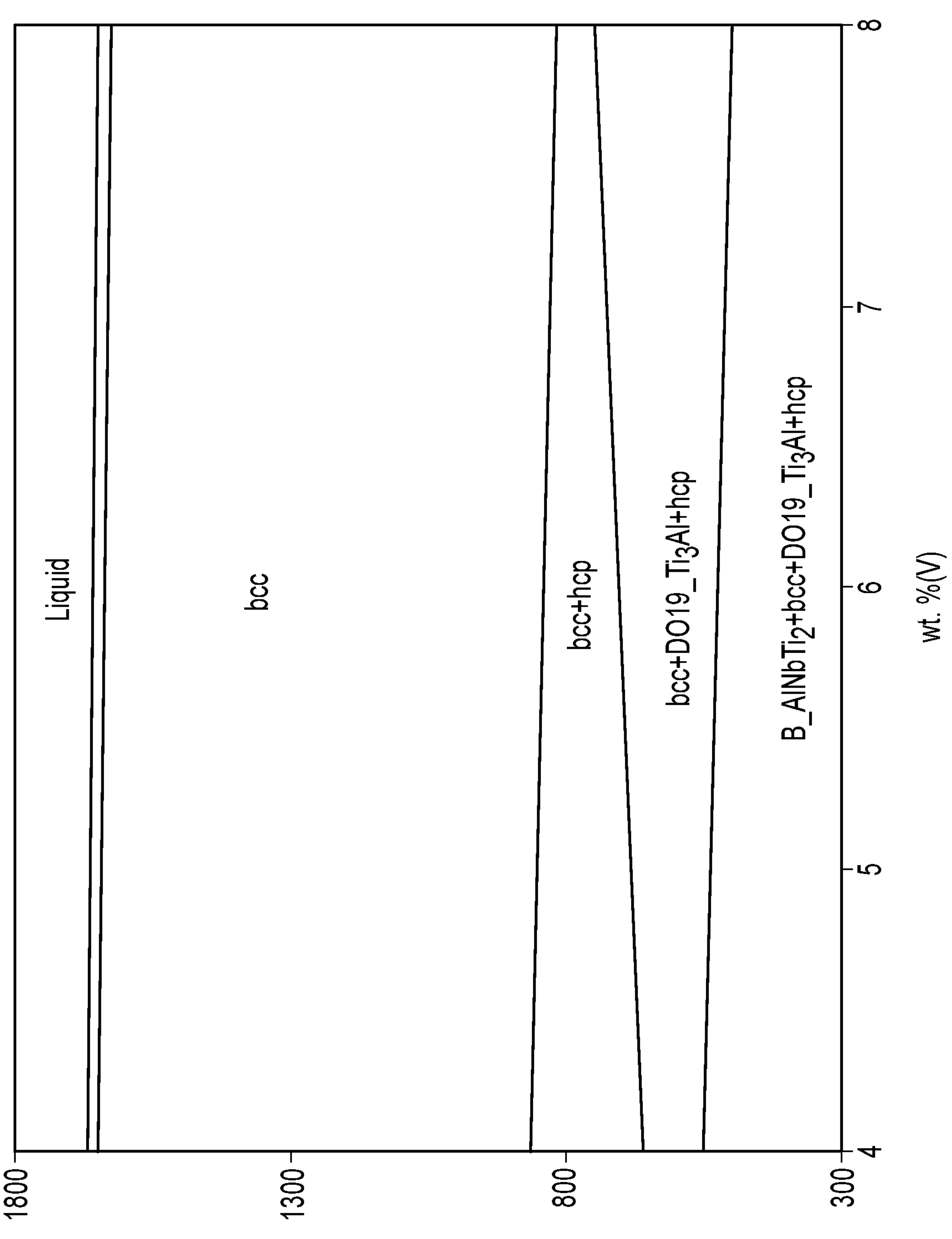

Liquid
bcc
bcc+hcp
bcc+DO19_Ti_3Al+hcp
B_AlNbTi_2+bcc+DO19_Ti_3Al+hcp
T[C]
1800
1300
800
300
4
5
6
7
8
wt. %(V)

FIG.2b

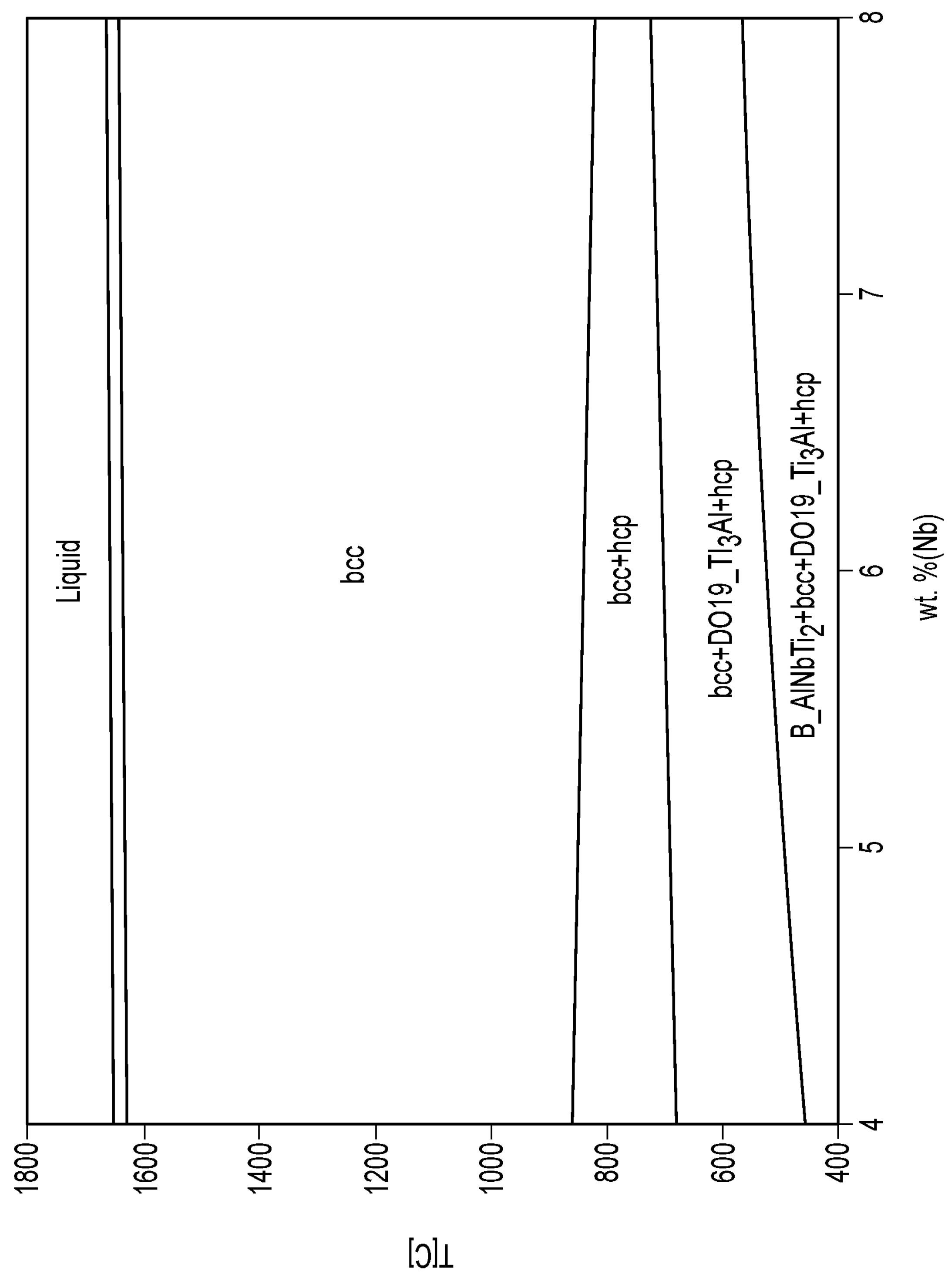

Liquid
bcc
bcc+hcp
bcc+DO19_Tl3Al+hcp
B_AlNbTi2+bcc+DO19_Ti3Al+hcp
T[C]
1800
1600
1400
1200
1000
800
600
400
4
5
6
7
8
wt. %(Nb)

FIG.2c

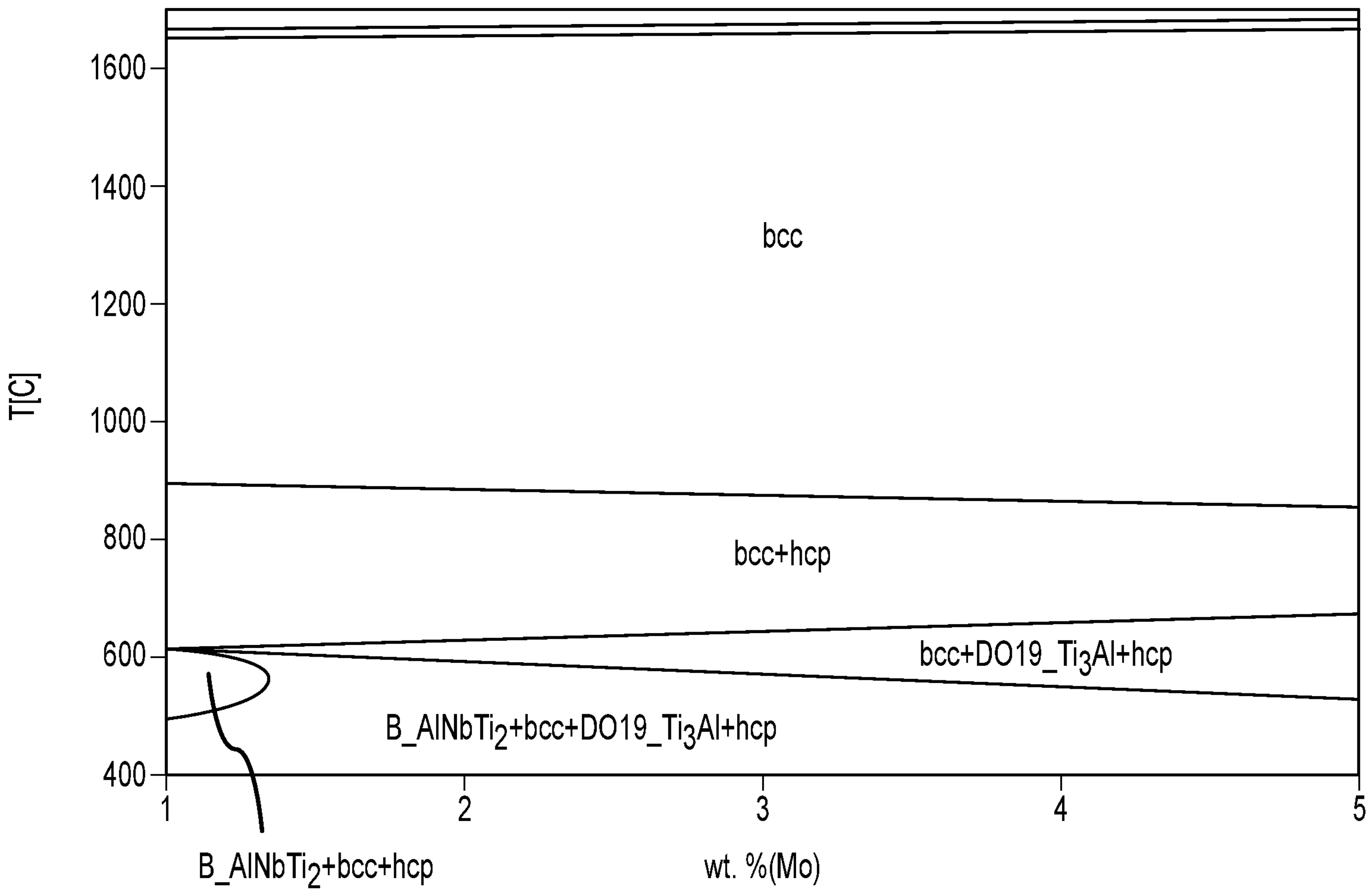

T[C]
1600
1400
1200
1000
800
600
400
1
2
3
4
5
wt. %(Mo)
bcc
bcc+hcp
bcc+DO19_Ti3Al+hcp
B_AlNbTi2+bcc+DO19_Ti3Al+hcp
B_AlNbTi2+bcc+hcp

FIG.2d

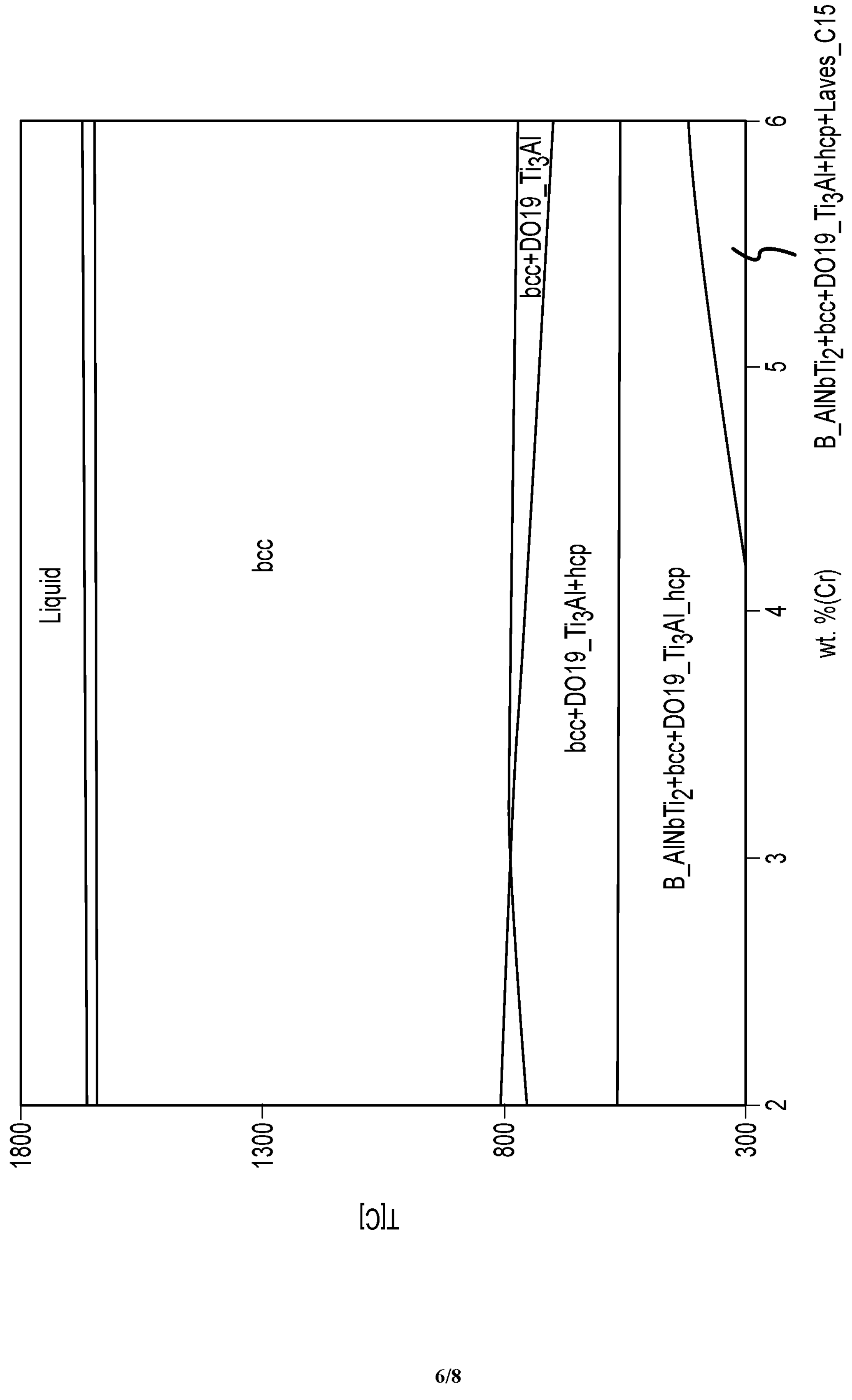

T[C]
1800
1300
800
300
2
3
4
5
6
wt. %(Cr)
Liquid
bcc
bcc+DO19_Ti_3Al
bcc+DO19_Ti_3Al+hcp
B_AlNbTi_2+bcc+DO19_Ti_3Al_hcp
B_AlNbTi_2+bcc+DO19_Ti_3Al+hcp+Laves_C15

FIG.2e

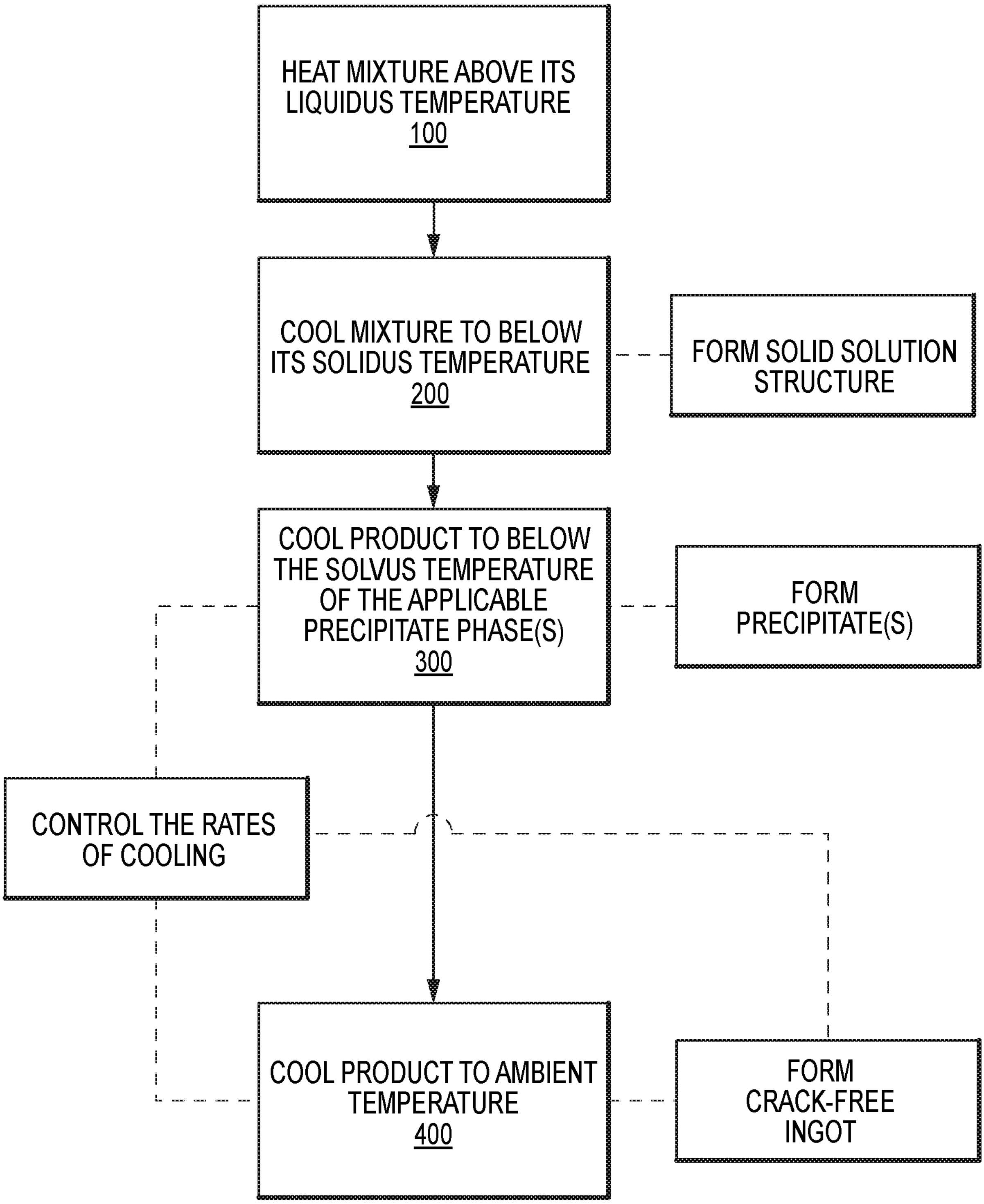

HEAT MIXTURE ABOVE ITS LIQUIDUS TEMPERATURE
100
COOL MIXTURE TO BELOW ITS SOLIDUS TEMPERATURE
200
FORM SOLID SOLUTION STRUCTURE
COOL PRODUCT TO BELOW THE SOLVUS TEMPERATURE OF THE APPLICABLE PRECIPITATE PHASE(S)
300
FORM PRECIPITATE(S)
CONTROL THE RATES OF COOLING
COOL PRODUCT TO AMBIENT TEMPERATURE
400
FORM CRACK-FREE INGOT

FIG.3

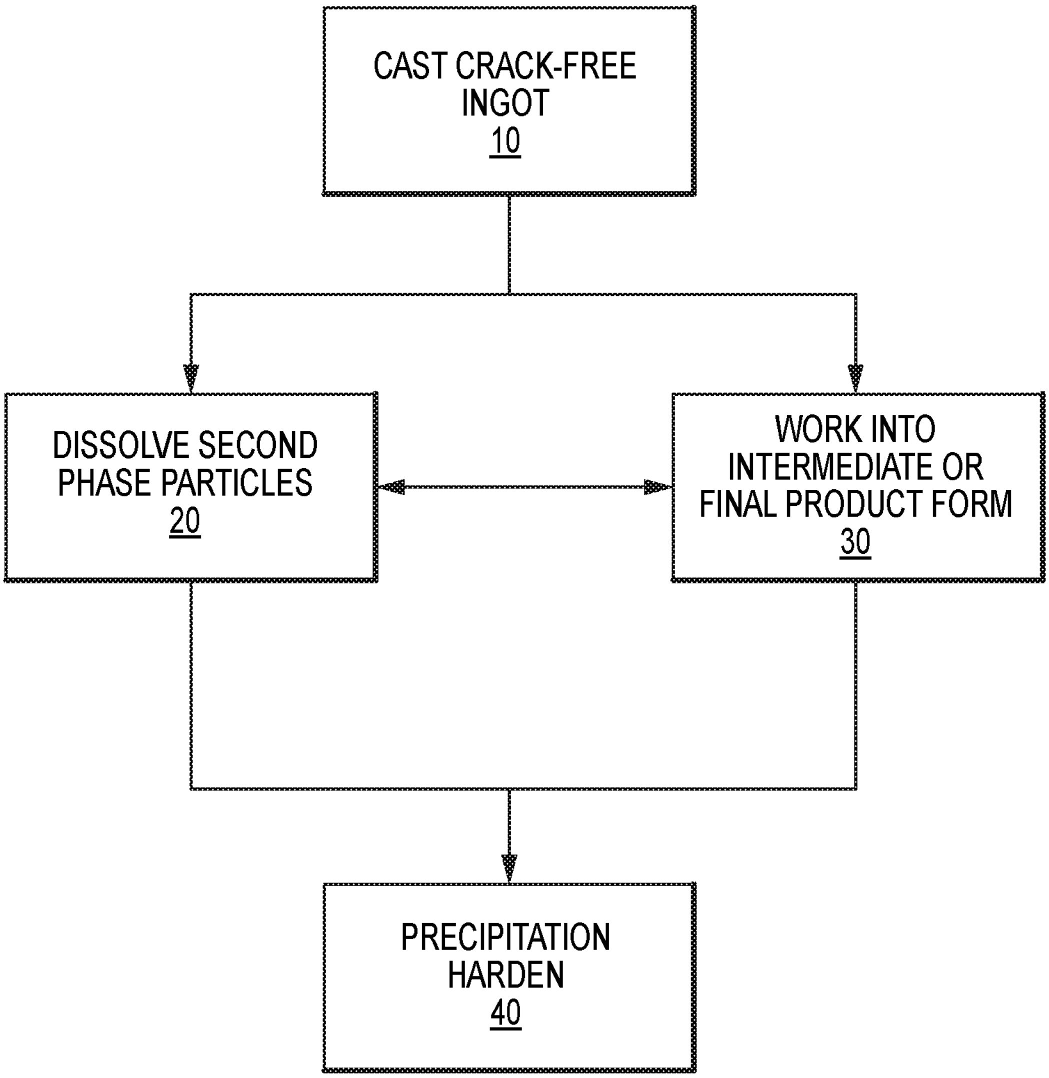
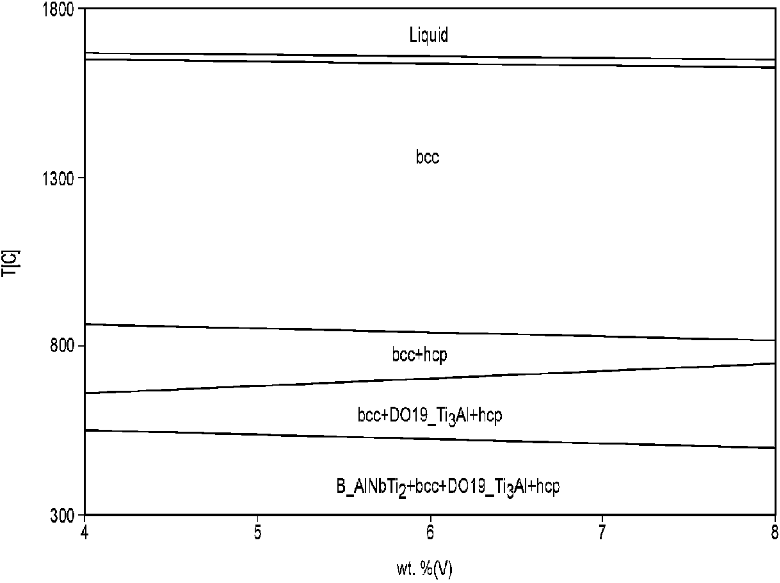

CAST CRACK-FREE INGOT
10
DISSOLVE SECOND PHASE PARTICLES
20
WORK INTO INTERMEDIATE OR FINAL PRODUCT FORM
30
PRECIPITATION HARDEN
40

FIG.4


Liquid
bcc
bcc+hcp
bcc+DO19_Ti3Al+hcp
B_AlNbTi2+bcc+DO19_Ti3Al+hcp
1800
1300
800
300
T[C]
4
5
6
7
8
wt. %(V)