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(54) **TURBINE COMPONENTS FORMED OF TITANIUM ALLOYS**

(57) A turbine component comprised of a titanium alloy that has been modified from Ti-64 is provided. The modification preserves the desired properties of Ti-64 (e.g., relatively isotropic properties, a relatively low density, tolerance to FOD, repairability, and low cost) while

improving the thick section strength, HCF capability, creep strength, and low deformation following FOD to approach those beneficial aspects of Ti-17 and Ti-6246. Methods of forming such turbine components are also provided.

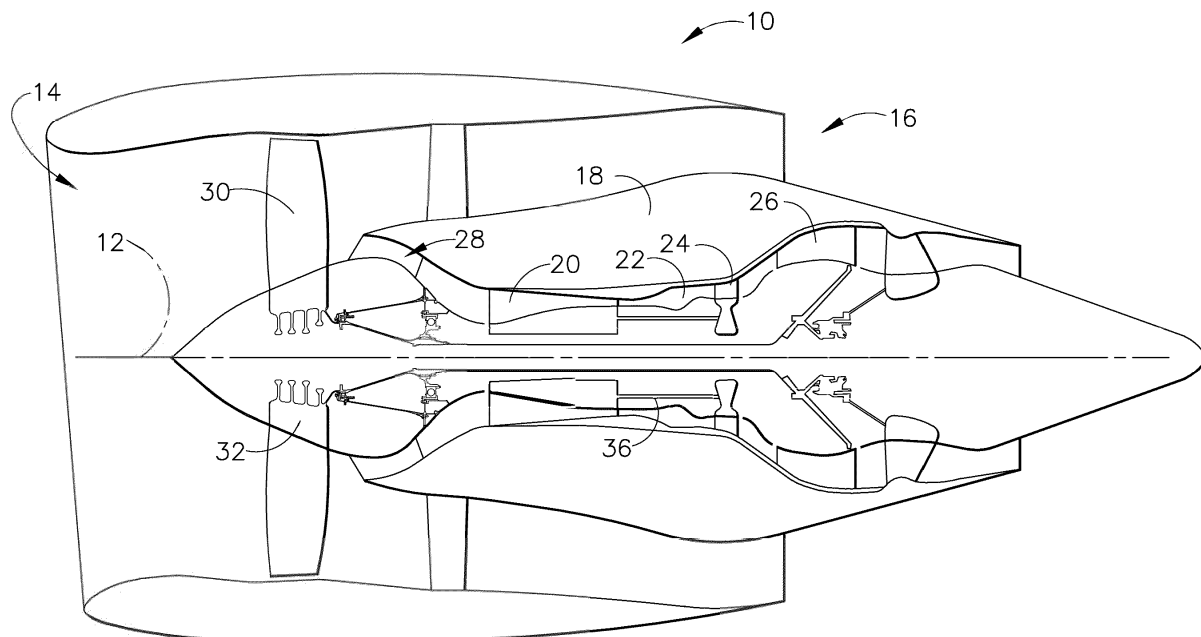


FIG. 1

Description

PRIORITY INFORMATION

5 **[0001]** The present application claims priority to U.S. Provisional Patent Application Serial Number 63/506,614 filed on June 7, 2023, which is incorporated by reference herein in its entirety for all purposes.

FIELD

10 **[0002]** The present application generally relates to components formed of titanium alloys. In particular, the components formed of titanium alloys disclosed herein are particularly suitable for use in rotary machines, such as gas turbines.

BACKGROUND

15 **[0003]** At least some known rotary machines such as, but not limited to, steam turbine engines and/or gas turbine engines, include various rotor assemblies, such as a fan assembly, a compressor, and/or turbines that each includes a rotor assembly. At least some known rotor assemblies include components such as, but not limited to, disks, shafts, spools, bladed disks ("bladed disks"), seals, and/or bladed integrated rings ("blings") and individual dovetail attached blades. Such components may be subjected to different temperatures depending on an axial position within the gas turbine engine.

20 **[0004]** For example, during operation, at least some known gas turbine engines may be subjected to an axial temperature gradient that extends along a central longitudinal axis of the engine. Generally, gas turbine engine components are exposed to lower operating temperatures towards a forward portion of the engine and higher operating temperatures towards an aft portion of the engine. As such, known rotor assemblies and/or rotor components are generally fabricated from materials capable of withstanding an expected maximum temperature at its intended position within the engine.

25 **[0005]** To accommodate different temperatures, different engine components have been forged with different alloys that have different material properties that enable the component to withstand different expected maximum radial and/or axial temperatures. More specifically, known rotary assemblies and/or rotary components are each generally forged from a single alloy that is capable of withstanding the expected maximum temperature of the entire rotary assembly and/or rotary component. For example, Ti-17 (Ti-5Al-4Mo-4Cr-2Sn-2Zr), Ti-6246 (Ti-6Al-2Sn-4Zr-6Mo), and Ti-64 (Ti-6Al-4V) can be utilized for rotary components within a gas turbine engine depending on the part's relative position within the engine.

30 **[0006]** Ti-64 is an alpha/beta processed titanium alloy that is highly manufacturable, has relatively isotropic properties, has a relatively low density, is tolerant to foreign object damage (FOD), is relatively easy to repair, and is relatively low cost. However, Ti-64 has limited thick section strength and high-cycle fatigue (HCF) capability. In contrast, Ti-17 and Ti-6246 are beta processed, are not as easily manufacturable, have more anisotropic properties (especially ductility) as a result of beta processing, have higher density, are not as tolerant to FOD, are not as easily repairable, and have a higher cost. However, Ti-17 and Ti-6246 have good thick section strength, have good HCF capability, and have a superior temperature capability than Ti-64.

35 **[0007]** As such, a need exists for a low-cost titanium alloy that has the good qualities of Ti-64 (e.g., relatively isotropic properties, a relatively low density, is tolerant to FOD, is repairable) with some of the benefits of Ti-17 and Ti-6246 (e.g., thick section strength and HCF).

BRIEF DESCRIPTION OF THE DRAWINGS

45 **[0008]** A full and enabling disclosure of the present disclosure, including the best mode thereof, directed to one of ordinary skill in the art, is set forth in the specification, which makes reference to the appended figures, in which:

50 FIG. 1 is a cross-sectional view of a gas turbine engine in accordance with an exemplary aspect of the present disclosure;

FIG. 2 is an isometric view of a bladed disk, as an example of a turbine component suitable for use in a gas turbine engine, such as shown in FIG. 1; and

FIG. 3 is a sectional view of two stages of a bladed disk showing an optional location of a weld zone, such as in the bladed disk of FIG. 2.

DEFINITIONS

55 **[0009]** The word "exemplary" is used herein to mean "serving as an example, instance, or illustration." Any implemen-

tation described herein as "exemplary" is not necessarily to be construed as preferred or advantageous over other implementations. Additionally, unless specifically identified otherwise, all embodiments described herein should be considered exemplary.

[0010] The singular forms "a", "an", and "the" include plural references unless the context clearly dictates otherwise.

[0011] The term "at least one of" in the context of, e.g., "at least one of A, B, and C" refers to only A, only B, only C, or any combination of A, B, and C.

[0012] The phrases "X to Y", "from X to Y", and "between X and Y" each refers to a range of values inclusive of the endpoints (i.e., refers to a range of values that includes both X and Y). Here and throughout the specification and claims, range limitations are combined and interchanged, such ranges are identified and include all the sub-ranges contained therein unless context or language indicates otherwise. For example, all ranges disclosed herein are inclusive of the endpoints, and the endpoints are independently combinable with each other.

[0013] As used herein, the term "substantially free" is understood to mean completely free of said constituent, or inclusive of trace amounts of same. "Trace amounts" are those quantitative levels of chemical constituent that are barely detectable and provide no benefit to the functional or aesthetic properties of the subject composition. The term "substantially free" also encompasses completely free.

[0014] The term "turbomachine" refers to a machine including one or more compressors, a heat generating section (e.g., a combustion section), and one or more turbines that together generate a torque output.

[0015] The term "gas turbine engine" refers to an engine having a turbomachine as all or a portion of its power source. Example gas turbine engines include turbofan engines, turboprop engines, turbojet engines, turboshaft engines, etc., as well as hybrid-electric versions of one or more of these engines.

[0016] Chemical elements are discussed in the present disclosure using their common chemical abbreviation, such as commonly found on a periodic table of elements. For example, hydrogen is represented by its common chemical abbreviation H; helium is represented by its common chemical abbreviation He; and so forth.

[0017] The term "yield strength" refers to the stress at which a material begins to exhibit plastic deformation (permanent deformation) without any increase in load. It is the point on the stress-strain curve where the material transitions from elastic deformation (reversible) to plastic deformation (irreversible). 0.2% yield strength is the strength measured at 0.2% plastic strain beyond yield strength. It is easier and more reproducible to measure than the yield strength. 0.2% yield strength is an important parameter in determining the structural integrity and stability of a material under load.

[0018] The term "ultimate tensile strength" ("UTS") is the maximum stress a material can withstand before fracturing or breaking. It is the highest point on the stress-strain curve and represents the material's maximum strength under tensile loading. Once the UTS is reached, the material experiences necking (localized deformation) and ultimately fails.

[0019] The term "plastic elongation" refers to a material's ability to plastically deform under tensile stress without fracturing. It is an important mechanical property that measures the extent to which a material can be permanently deformed without breaking. Ductile materials can undergo large plastic deformation before failure, while brittle materials tend to fracture without significant deformation. Plastic elongation is typically measured as the percentage increase in length between two marks placed on the gage length prior to the test and the final distance between the two marks after the test is completed and the two fractured specimen halves are fit back together. A higher plastic elongation indicates greater ductility, as it indicates that the metal can deform significantly before fracturing. Conversely, a lower plastic elongation suggests lower ductility, meaning the metal is more brittle and prone to fracture without significant plastic deformation.

[0020] The "reduction in area" (also expressed as "%RA") refers to a measurement quantifying the extent of deformation or plastic flow that occurs in a metal specimen during mechanical testing. When a metal specimen is subjected to tensile forces, it undergoes plastic deformation in the form of elongation and reduction in cross-sectional area. The reduction in area is a measurement of the decrease in the cross-sectional area of the specimen after it fractures or fails during the testing process. The reduction in area is typically expressed as a percentage and is calculated using the following formula: Reduction in Area = [(Original cross-sectional area - Final cross-sectional area) / Original cross-sectional area] x 100. A higher reduction in area indicates greater ductility, as it indicates that the metal can deform significantly before fracturing. Conversely, a lower reduction in area suggests lower ductility, meaning the metal is more brittle and prone to fracture without significant plastic deformation.

[0021] Values disclosed for 0.2% yield strength, the ultimate tensile strength, plastic elongation, and the reduction in area are measured at room temperature (i.e., 20 °C to 25 °C) according to ASTM E8/E8M, also known as the Standard Test Methods for Tension Testing of Metallic Materials. ASTM E8/E8M is a widely used standard in the field of materials testing, including for alloy characterization, that provides guidelines for conducting tension tests to determine the mechanical properties of metallic materials. In addition to ASTM E8/E8M, all the tensile tests were run at a controlled strain rate of 0.005 in/in $\pm$ 0.002 in/in per minute. After the 0.2 percent yield point has been reached and the load has stabilized, the crosshead speed was 0.05 $\pm$ 0.01 in/in of the length of the reduced section of the specimen per minute. Plastic elongation and %RA were measured using the "fit-back method" whereby fracture surfaces of the failed specimens were fit back together to measure the length change and reduced cross area needed to calculate these parameters. All tensile

testing was performed on bars with a gage diameter of at least 0.14" and a gage length of at least 0.75".

[0022] The "ballistic impact resistance" refers to a material's ability to resist the penetration or deformation caused by projectiles or high-velocity impacts. It is particularly important in applications where protection against bullets, shrapnel, or other projectiles is required. Materials with high ballistic impact resistance are designed to absorb and dissipate the energy of the impact, reducing the damage caused by the projectile. The resistance to ballistic impact damage, or foreign object damage, was measured using a compressed ballistic rig firing approximately 4.45 mm diameter ball bearing Cr-steel alloy balls weighing 0.36g and having a hardness of 55 Rockwell C at speeds ranging from approximately 182.9 meters per second to approximately 304.8 meters per second into targets of the alloys under test, with the sample thickness of 0.762 mm. The extent of damage was quantified by summing the total radial crack length for crack(s) emanating from the impact site. For avoidance of doubt, only radial crack lengths are summed, while any circumferential cracking associated with the impact site was not considered.

[0023] The term "weight percent" (abbreviated herein as wt%) refers to the concentration of the amount of a particular element in the titanium alloy. The weight percent represents the proportion of the element's weight relative to the total weight of the titanium alloy, expressed as a percentage. Weight percent is calculated by dividing the weight of the element by the total weight of the titanium alloy and multiplying the result by 100.

DETAILED DESCRIPTION

[0024] Reference will now be made in detail to present embodiments of the disclosure, one or more examples of which are illustrated in the accompanying drawings. The detailed description uses numerical and letter designations to refer to features in the drawings. Like or similar designations in the drawings and description have been used to refer to like or similar parts of the disclosure.

[0025] A turbine component is generally provided that is comprised of a titanium alloy that has been modified from Ti-64 in order to preserve the desired properties of Ti-64 (e.g., relatively isotropic properties, a relatively low density, tolerance to FOD, repairability, and low cost) while improving the thick section strength, HCF capability, creep strength, and low deformation following FOD to approach those beneficial aspects of Ti-17 and Ti-6246. The cost of the new modified Ti-64 alloy can be minimized by designing the composition such that a high percentage of widely available Ti-64 recycled materials can be used. Additionally, the billet and forge processing approach may be kept as close to Ti-64 as possible in order to minimize cost, while allowing for a large scale production of such turbine components from the titanium alloy.

[0026] As stated, a turbine component within a turbofan engine, such as shown in FIG. 1, can be constructed from a titanium alloy. The titanium alloy includes 5.50 wt% to 6.90 wt% aluminum; 3.50 wt% to 4.50 wt% vanadium; 0.01 wt% to 0.03 wt% carbon; 0.20 wt% to 0.70 wt% iron; 1.00 wt% to 1.50 wt% molybdenum; 0.10 wt% to 0.30 wt% silicon; up to 0.21 wt% oxygen; up to 0.016 wt% nitrogen (e.g., up to 0.015 wt% nitrogen); and a balance of titanium. In particular embodiments, the titanium alloy has a 0.2% yield strength of 1000 MPa or greater (e.g., 1000 MPa to 1380.0 MPa), an ultimate tensile strength of 1060 MPa or greater (e.g., 1060 MPa to 1450 MPa), a plastic elongation of 15.0% or greater (e.g., 15.0% to 30.0%), a ballistic impact resistance measured by a crack length of 3.048 mm or less (e.g., 0 mm to 3.048 mm), a reduction in area that is 45 %RA or greater (e.g., 45 %RA to 75 %RA), or any combination of these properties.

[0027] Silicon (Si) is included within the titanium alloy to increase strength. It has been found that less than 0.10 wt% of Si does not impart sufficient strength to the titanium alloy. Additionally, it was found that more than 0.30 wt% Si results in poorer ballistic impact resistance, poorer plastic elongation, poorer reduction in area, or a combination thereof. Additionally, it was found that increased levels of Si above 0.30 wt% may result in Si segregation issues during large diameter ingot solidification that would be necessary for large scale production and manufacturing processes.

[0028] Iron (Fe) is included within the titanium alloy to enhance high-temperature strength and to increase the temperature width of the alpha + beta phase field, thereby increasing the hot working processing flexibility. It has been found that at least 0.20 wt% of Fe, in conjunction with 1.00 wt% to 1.50 wt% Mo, leads to a desired balance of strength and plastic elongation. However, Fe segregates strongly during solidification of large diameter ingots, and it was found that a maximum of 0.70 wt% of Fe avoids production issues in large scale production and manufacturing processes.

[0029] Molybdenum (Mo) is included within the titanium alloy to enhance high-temperature strength and creep resistance and to increase the temperature width of the alpha + beta phase field, thereby increasing the hot working processing flexibility. It has been found that at least 1.00 wt% Mo, in conjunction with 0.20 wt% to 0.70 wt% Fe, leads to a desired balance of strength and plastic elongation. However, the presence of too much Mo within the titanium alloy may degrade the plastic elongation, reduction in area and/or ballistic impact resistance of the titanium alloy. Thus, it has been found that more than 1.50 wt% degrades the plastic elongation, reduction in area and/or ballistic impact resistance of the titanium alloy beyond what would be desirable. Increased levels of Mo also lead to an increase in the titanium alloy density.

[0030] Nitrogen (N) is present in the titanium alloys due to inevitable pick-up during vacuum melting step(s) in the production of the titanium alloy. N will increase the strength and hardness of a titanium alloy. However, too much N present in the titanium alloy, such as above 0.016 wt% nitrogen (e.g., above 0.015 wt% nitrogen), leads to lower plastic

elongation, lower reduction in area, and/or lower ballistic impact resistance.

[0031] Oxygen (O) is naturally present in titanium alloys due to titanium's high oxidation rate and can be intentionally added to meet a desired chemistry. However, the amount of O present is minimized in the titanium alloys presently disclosed, as it has been found that more than 0.21 wt% O in the titanium alloy would lead to reduced plastic elongation, reduction in area, and/or ballistic impact resistance.

[0032] Carbon (C) is naturally present in titanium alloys due to low levels in the input materials used in formulation and can be intentionally added to meet a desired chemistry. A certain amount of C above 0.01 wt% is beneficial to 0.2 % yield strength and ultimate tensile strength without degrading plastic elongation, reduction in area and/or ballistic impact resistance; however, above 0.03 wt% of carbon present in the alloy leads to a reduction in plastic elongation, reduction in area and/or ballistic impact resistance.

[0033] In particular embodiments, other elements may be avoided from inclusion within the titanium alloy so as to avoid undesired characteristics. For example, the inclusion of certain elements may hinder large scale use, such as in a large scale manufacturing production of such turbine components.

[0034] While copper (Cu) may provide increased strength to a titanium alloy, it has been found that the presence of Cu results in severe segregation during large diameter ingot solidification and may lead to production chemistry and microstructural control issues at large-scale. Thus, the presence of Cu in the titanium alloy may form a non-homogeneous titanium alloy material that would not be suitable for manufacturing of turbine components with consistent composition within each component and across all the components. As such, the titanium alloy is substantially free from Cu to avoid these issues that would hinder use of the titanium alloy in large scale manufacturing settings.

[0035] While chromium (Cr) may provide increased strength to the titanium alloy, it has been found that the presence of Cr results in segregation during solidification and may lead to production chemistry and microstructural control issues at large-scale. Thus, the presence of Cr in the titanium alloy may form a non-homogeneous titanium alloy material that would not be suitable for manufacturing of turbine components with consistent composition within each component and across all the components. As such, the titanium alloy is substantially free from Cr (e.g., no more than any residual amount of Cr present due to Cr presence in the Ti sponge, such as no more than 500 wppm, e.g., no more than 200 wppm), in certain embodiments, to avoid these issues that would hinder use of the titanium alloy in large scale manufacturing settings.

[0036] While tin (Sn) may provide increased strength to the alloy, particularly at elevated temperatures, it was found that the presence of Sn results in decrease plastic elongation, a decrease in reduction in area, and a decrease in ballistic impact resistance. Thus, the titanium alloy is substantially free from Sn, in certain embodiments, to avoid these issues.

[0037] While nickel (Ni) may provide increased strength to the alloy, it was found that the presence of Ni results in segregation during solidification and may lead to production chemistry and microstructural control issues at large-scale. Thus, the presence of Ni in the titanium alloy may form a non-homogeneous titanium alloy material that would not be suitable for manufacturing of turbine components with consistent composition within each component and across all the components. As such, the titanium alloy is substantially free from Ni (e.g., no more than any residual amount of Ni present due to Ni presence in the Ti sponge, such as no more than 500 wppm, e.g., no more than 200 wppm), in certain embodiments, to avoid these issues that would hinder use of the titanium alloy in large scale manufacturing settings.

[0038] While zirconium (Zr) may provide increased strength to the titanium alloy, particularly at elevated temperatures, it has been found that the presence of Zr and Si in the titanium alloy forms a mixed $(\text{TiZr})_6\text{Si}_3$ silicide particle that will rapidly degrade plastic elongation, decrease the reduction in area, and decrease the ballistic impact resistance. Thus, the titanium alloy is substantially free from Zr, in certain embodiments, to avoid these issues.

[0039] While tungsten (W) may provide increased strength and creep strength to the titanium alloy, the inclusion of W may lead to a non-homogeneous alloy material because of W's relatively high density compared to Ti. Thus, the titanium alloy is substantially free from W, in certain embodiments, to avoid this issue.

[0040] In particular embodiments, the titanium alloy described herein may be forged from a section of cylindrical billet to a shape closer to the finished turbine component in one or more steps below the beta transus, which is the temperature on heating at which all the low temperature alpha, close-packed hexagonal phase disappears and the high temperature beta, body-centered cubic phase is present. The forging temperature may be below the beta transus temperature of the titanium alloy, and may be varied from 14 °C to 83 °C below the beta transus temperature.

[0041] The forged shape may be solution heat treated at a temperature closer to the beta transus than the forging temperature to control the volume fractions of primary alpha phase and the beta phase. For example, the solution temperature may be varied typically from 17 °C to 69 °C below the beta transus temperature and the solution time should be for at least 1 hour.

[0042] It is well known that increasing the cooling rate following solution heat treatment may result in an increase in 0.2% yield strength and ultimate tensile strength. For the purposes of this application, all alloys were solution heat treated and cooled at a rate of approximately 208 °C/min corresponding to about 80 mm section size in a component that is water quenched from solution heat treatment. Accordingly, all the tensile properties measured and reported here correspond to those tensile properties expected in large section size components, on the order of 101.6 mm, that would

be liquid quenched (e.g. water, oil, polymer, etc.) or gas cooled (e.g. air, helium, etc.) following solution heat treatment. It is well known that higher strengths may be achieved via increasing cooling rate following solution heat treatment. The post-solution cooling rate at any location in a heat treated component may be directly measured using embedded thermocouples, or estimated using a finite element model, or some combination of both. The post-solution cooling rate may be measured and/or calculated between a temperature of approximately 28 °C below the solution temperature to 83 °C below the solution temperature.

[0043] Following solution heat treatment and cooling, the component may be overaged at 537.8 °C to 760 °C for at least 1.5 hours (e.g., 2 hours) in order to minimize remaining residual stresses from the solution heat treatment and cooling while retaining the balance of 0.2% yield strength, ultimate tensile strength, plastic elongation, reduction in area and ballistic impact resistance. Through these processing methods, the desired characteristics of the titanium alloy may be achieved, such as a 0.2% yield strength of 1000 MPa or greater (e.g., 1000 MPa to 1380 MPa), an ultimate tensile strength of 1060 MPa or greater (e.g., 1060 MPa to 1450 MPa), a plastic elongation of 15.0% or greater (e.g., 15.0% to 30.0%), a ballistic impact resistance measured by a crack length of 3.048 mm or less (e.g., 0 mm to 3.048 mm), a reduction in area that is 45 %RA or greater (e.g., 45 %RA to 75 %RA), or any combination of these properties discussed above.

[0044] As stated, the titanium alloy described herein may be utilized for forming a turbine component, such as for use in an exemplary turbofan engine. FIG. 1 is a schematic illustration of an exemplary turbofan engine 10 having a central rotational axis 12. In the exemplary embodiment, turbofan engine 10 includes an air intake side 14 and an exhaust side 16. Turbofan engine 10 also includes a core gas turbine engine 18 that includes a high-pressure compressor 20, a combustor 22, and a high-pressure turbine 24. Moreover, turbofan engine 10 includes a low-pressure turbine 26 that is disposed axially downstream from core gas turbine engine 18, and a fan assembly 28 that is disposed axially upstream from core gas turbine engine 22. Fan assembly 28 includes an array of fan blades 30 extending radially outward from a rotor hub 32. Furthermore, turbofan engine 10 includes a first rotor shaft 34 disposed between fan assembly 28 and the low-pressure turbine 26, and a second rotor shaft 36 disposed between high-pressure compressor 20 and high-pressure turbine 24 such that fan assembly 28, high-pressure compressor 20, high-pressure turbine 24, and low-pressure turbine 26 are in serial flow communication and co-axially aligned with respect to central rotational axis 12 of turbofan engine 10.

[0045] During operation, air enters through intake side 14 and flows through fan assembly 28 to high-pressure compressor 20. Compressed air is delivered to combustor 22. Airflow from combustor 22 drives high-pressure turbine 24 and low-pressure turbine 26 prior to exiting turbofan engine 10 through exhaust side 16.

[0046] High-pressure compressor 20, combustor 22, high-pressure turbine 24, and low-pressure turbine 26 each include at least one rotor assembly. Rotary or rotor assemblies are generally subjected to different temperatures depending on their relative axial position within turbofan engine 10. For example, in the exemplary embodiment, turbofan engine 10 has generally cooler operating temperatures towards forward fan assembly 28 and hotter operating temperatures towards aft high-pressure compressor 20. As such, rotor components within high-pressure compressor 20 are generally fabricated from materials that are capable of withstanding higher temperatures as compared to fabrication materials for rotor components of fan assembly 28.

[0047] While turbofan engine 10, represents one member of the class of rotary machines, other members include land-based gas turbines, turbojets, turboshaft engines, unducted engines, unducted fans, fixed-wing and propeller rotors, and the like, as well as distributed propulsors such as distributed fans or pods, and the like. The turbine component formed of the titanium alloy described herein may be in form of a rotary machine part(s) useful in operating such rotary machines. Exemplary rotary machine parts include, for example, a disk, bladed disk, airfoil, blade, vane, integral bladed rotor, frame, fairing, seal, gearbox, case, mount, shaft, and the like.

[0048] FIG. 2 shows an example of a turbine component that may be constructed from a titanium alloy, depicting an isometric view of a single stage bladed disk 50, alternatively known as an integrally bladed rotor. The bladed disk 50 has a hub 52 that circumscribes the central rotational axis 12, reference also the axis 12 of turbofan engine 10 of FIG. 1. Extending substantially radially from hub 52 are airfoils 60. In the high-pressure compressor 20 of FIG. 1, to optimize the bladed disk for performance parameters such as, for example, fatigue life, FOD tolerance, and creep strength, a bi-metallic bladed disk, where the hub 52 and airfoils 60 are different alloys, may be preferred. The airfoil 60 may be solid state welded to the hub 52 utilizing processes such as translation friction welding or linear friction welding. Therefore, it may be desirable to select a material that provides excellent thick section properties for the hub 52, and excellent fatigue properties in relatively small section sizes and FOD properties for the airfoil 60.

[0049] In the exemplary embodiment shown in FIG. 2, hub 52 is made from a titanium alloy as described herein, with the airfoil 60 being made from a commercially available, or conventional, materials with desirable fatigue life performance, such as, for example Ti-64. After welding, the interface between hub 52 and airfoil 60 can be referred to as the weld or heat affected zone 70. In this zone 70, a mix of hub and airfoil alloys are present, along with a wide range of microstructures. This mix of alloys and range of microstructures may compromise the thick section fatigue, FOD, etc. of the portion of the bladed disk 50.

[0050] In another exemplary embodiment, hub 52 and airfoil 60 are both made from the same titanium alloy of the present disclosure, or made from separate example titanium alloys of the present disclosure. In the case of the hub 52 and airfoil 60 being the same titanium alloy, in zone 70, no mix of hub and airfoil alloys are present, but a wide range of microstructures exists. This range of microstructures may again compromise the thick section fatigue, FOD, etc. of the portion of the bladed disk 50.

[0051] To optimize the mass of rotating components (via eliminating bolted joints), and to take advantage of higher temperature materials, in a high pressure compressor 20, shown in FIG. 1, adjacent stages of bladed disks may be inertia welded. Similar to the bi-metallic hub/airfoil, it may be desirable to have a front bladed disk stage made from a first material and an aft stage bladed disk made from a second material. As shown in FIG. 3, the front bladed disk stage 80 may be made from an example titanium alloy of the present disclosure and the aft bladed disk stage 90 may be made from conventional material, such as, for example Ti-17. Again the weld zone or heat affected zone 70 is present and a mix of front bladed disk and aft bladed disk alloys are present, along with a wide range of microstructures in zone 70, representing an area of reduced material properties.

[0052] In other exemplary embodiments, adjacent front bladed disk stage 80 and aft bladed disk stage 90 are both made from the same titanium alloy of the present disclosure, or may be made from separate example titanium alloy of the present disclosure.

[0053] Furthermore, for the embodiments described by FIG. 2 and FIG. 3, any example titanium alloy of the present disclosure may be used alone or in combination with commercially available alloys for one or more of the airfoil 60, hub 52, bladed disk 50, front stage bladed disk 80 or back stage bladed disk 90. Although FIG. 3 describes two stages, more than two stages of bladed disks may be contemplated.

[0054] While materials may be selected for these properties alone, consideration should be made for recovering material property loss due to the weld-induced thermal environment seen in a translation friction welding or linear friction welding via post treatment, such as, for example, furnace heat treatment. As will be discussed below, the titanium alloy of the present disclosure pairs well with commercially available titanium alloys, allowing manufacturers to take full advantage of this bi-metallic material property benefit by, for example, better matching heat treatment temperatures and processing between the hub 52 material and airfoil 60 material and between the materials of adjacent bladed disk stages 80 and 90. These benefits can also be realized when the titanium alloy of the present disclosure is welded with itself, not only with commercially available titanium alloys. In the case of a translation friction welded bi-metallic bladed disk, use of the titanium alloy of the present disclosure as the hub in place of beta processed Ti-17 or beta processed Ti-6246, and Ti-64 as the airfoil will result in a better matching of flow stresses and microstructures between the titanium alloy of the hub and the Ti-64 alloy airfoil. This may result in a solid state weld having a lower tendency to form defects during or following the welding process.

[0055] Example components may have a thick section, be cast and wrought, or be a structural aerospace casting, or the like.

EXAMPLES

[0056] Exemplary alloys (E-1 to E-20) were created according to the chemistries shown in Table 1. These Exemplary Alloys were formed via an open die forge process designed to re-create a typical production billet conversion process; first hot working the as-cast ingot above the beta transus, followed by sub-transus hot working that resulted in beta recrystallization as the material was subsequently re-heated above the beta transus and further hot worked, followed by water quenching. Finally, the material was re-heated to below the beta transus and hot worked to final diameter. All hot working was accomplished using open die forging, like that used in large-scale production ingot to billet processing, with the intent that the microstructure and texture of the sub-scale materials was representative of larger, production-scale material.

[0057] Comparative alloys are discussed below and shown in Tables 2, 3A, and 3B. The alloys of Table 1, Table 2, Table 3A, and Table 3B were cooled from alpha + beta solution heat treatment at 208 °C/minute. These alloys were measured to determine the 0.2%YS, the UTS, the % plastic elongation, and the % reduction in area, according to ASTM E8/E8M at 23 °C.

[0058] The 23°C 0.2% YS data from the alloys shown in Table 1 were input into a multiple linear regression statistical model using commercially available statistical analysis package (MiniTab V. 20.2). The following elements were determined to be statistically significant using a p-test with a >95% confidence level for each element's statistical significance: Al, O, Fe, Si, Mo. The model for yield strength prediction is shown in Equation 1:

$$0.2\% \text{ YS (MPa)} = 469.3 + 48.8 \cdot \text{Al (wt\%)} + 748 \cdot \text{O (wt\%)} + 96.1 \cdot \text{Fe (wt\%)} + 188 \cdot \text{Si (wt\%)} + 57.7 \cdot \text{Mo (wt\%)} \quad \text{equation 1}$$

[0059] For high strength Ti alloy applications, it is desirable for a candidate alloy to have 0.2% YS $\geq$ 1000 MPa at 23°C.

[0060] The 23°C UTS data from the alloys shown in Table 1 were input into a multiple linear regression statistical model using commercially available statistical analysis package (MiniTab V. 20.2). The following elements were determined to be statistically significant using a p-test with a >95% confidence level for each element's statistical significance: Al, O, Fe, Si, Mo. The model for Ultimate tensile strength prediction is shown in Equation 2:

$$\text{UTS (Mpa)} = 612.1 + 39.2 \cdot \text{Al (wt\%)} + 666 \cdot \text{O (wt\%)} + 74.6 \cdot \text{Fe (wt\%)} + 202 \cdot \text{Si (wt\%)} + 41.6 \cdot \text{Mo (wt\%)} \quad \text{equation 2}$$

[0061] For high strength Ti alloy applications, it is desirable for a candidate alloy to have UTS $\geq$ 1060 MPa at 23°C.

[0062] The 23°C %Plastic Elongation (%EL) from the alloys shown in Table 1 were input into a multiple linear regression statistical model using commercially available statistical analysis package (MiniTab V20.2). Note, the statistical analysis was performed using Log(10) transformation of the % plastic elongation values, as is standard practice for lognormally distributed data (J Chen, Z Wang et al., Int. J. Plast. 152 (2022) 103260). The following elements were determined to be statistically significant using a p-test with a >95% confidence level for each element's statistical significance: Fe, Si, Mo. The model for yield strength prediction is shown in Equation 3:

Equation 3

$$\text{EL (\%)} = 10^{(1.149 + 0.211 \cdot \text{Fe (wt\%)} - 0.514 \cdot \text{Si (wt\%)} + 0.076 \cdot \text{Mo (wt\%)})}$$

[0063] For high strength Ti alloy applications, it is desirable for a candidate alloy to have % plastic elongation $\geq$ 15.0% at 23°C.

[0064] The 23°C % Reduction in Area (%RA) from the alloys shown in Table 1 were input into a multiple linear regression statistical model using commercially available statistical analysis package (MiniTab V20.2). Note, the statistical analysis was performed using Log(10) transformation of the % reduction in area values, as is standard practice for lognormally distributed data (J Chen, Z Wang et al., Int. J. Plast. 152 (2022) 103260). The following elements were determined to be statistically significant using a p-test with a >95% confidence level for each element's statistical significance: Fe, Si, Mo. The model for yield strength prediction is shown in Equation 4:

Equation 4

$$\text{RA (\%)} = 10^{(1.560 + 0.195 \cdot \text{Fe (wt\%)} - 0.663 \cdot \text{Si (wt\%)} + 0.139 \cdot \text{Mo (wt\%)})}$$

[0065] For high strength Ti alloy applications, it is desirable for a candidate alloy to have % reduction in area $\geq$ 45.0% at 23°C.

[0066] In certain embodiments, it is desirable for high strength Ti alloys to have both high strength ($\geq$ 1000 MPa 0.2% YS, according to Equation 1) as well as high % plastic elongation ($\geq$ 15.0%, according to Equation 3).

[0067] Comparative alloys (C-1 to C-20) were also created according to the chemistries shown in Table 2. These Comparative Alloys were open die forged as with the exemplary alloys of Table 1. The alloys of Table 2 were measured for their respective properties according to ASTM E8/E8M at 23 °C. As shown in the results of Table 2, these comparative alloys did not meet the specifications of the desired titanium alloy.

[0068] Comparative alloys (C-21 to C-50) were also created according to the chemistries shown in Table 3A, and comparative alloys (C-51 to C-66) were also created according to the chemistries shown in Table 3B. As shown in the results of Tables 3A and 3B, these comparative alloys did not meet the specifications of the desired titanium alloy.

[0069] The alloy data from U.S. Patent Publication Number 2017/0268091 is shown recreated in Table 4, as comparative alloys (Comp-A to Comp-M). The alloys of Table 4 were cast as ingots and then extruded down to final size in the alpha/beta phase field, not following a typical open-die forge billet process. It is likely that this extrusion process resulted in a different combination of 0.2% yield strength, ultimate tensile strength, % plastic elongation and % reduction in area due to differences in texture induced by the extrusion process. This process is completely different than what could be used in large scale manufacturing production. Thus, while alloy Comp-G meets some of the targeted alloy characteristics, the predicted elongation is low for an alloy that would be processed according to an open die forge process, as utilized with the Exemplary Alloys of Table 1. Thus, it is believed that the alloy Comp-G would lead to an alloy with reduced elongation than shown in Table 4 during large-scale processes. While alloy Comp-J meets some of the targeted alloy characteristics, the presence of copper is problematic for the alloy Comp -J's use in a large scale manner. That is, the presence of copper would result in severe segregation during large diameter ingot solidification and would lead to

production chemistry and microstructural control issues at large-scale.

Table 1: Exemplary Alloys (tested at 23 °C)

Alloy Ref.	Al (wt%)	V (wt%)	C (wt%)	O (wt%)	Fe (wt%)	Si (wt%)	Cu (wt%)	Mo (wt%)	Sn (wt%)	N (wt%)	.2% YS (MPa)	UTS (MPa)	EI (%)	RA (%)	Log (EL) (RA)	Log (BI) (RA)	FPS BI (mm)	FPS BI (mm)	CIR (°C/mi n)	Test Temp (°C)	YS Model (MPa)	UTS Model (MPa)	EL Model (%)	RA Model (%)	BI Model (mm)
E-1	6.75	4.09	0.01	0.21	0.49	0.15	0	1.28	0	0.005	1122	1159	17.8	46.4	1.25	1.67	0.0	0.0	191	23	1105	1137	18.7	54.2	0.5
E-2	6.75	4.09	0.01	0.21	0.49	0.15	0	1.28	0	0.005	1094	1129	18.7	50.9	1.27	1.71	0.0	0.0	191	23	1105	1137	18.7	54.2	0.5
E-3	6.75	4.09	0.01	0.21	0.49	0.15	0	1.28	0	0.005	1109	1121	16.3	47.9	1.21	1.68	0.0	0.0	191	23	1105	1137	18.7	54.2	0.5
E-4	6.74	4.06	0.03	0.16	0.54	0.16	0	1.32	0	0.005	1088	1130	17.9	48.9	1.25	1.69	0.0	0.0	191	23	1076	1110	19.1	55.3	2.6
E-5	6.74	4.06	0.03	0.16	0.54	0.16	0	1.32	0	0.005	1087	1127	18.1	48	1.26	1.68	0.0	0.0	191	23	1076	1110	19.1	55.3	2.6
E-6	6.85	4.11	0.03	0.20	0.5	0.25	0	1.25	0	0.005	1125	1160	17.1	45.5	1.23	1.66	0.0	0.0	191	23	1111	1146	16.6	46.3	13.7
E-7	6.85	4.11	0.03	0.20	0.5	0.25	0	1.25	0	0.005	1127	1164	17.1	45.4	1.23	1.66	0.0	0.0	191	23	1111	1146	16.6	46.3	13.7
E-8	6.36	4.09	0.03	0.16	0.54	0.26	0	1.3	0	0.004	1059	1097	16.9	50	1.23	1.70	0.0	0.0	191	23	1075	1114	16.9	47.1	7.5
E-9	6.35	4.09	0.03	0.16	0.54	0.26	0	1.3	0	0.004	1031	1071	18	52	1.26	1.72	0.0	0.0	191	23	1075	1114	16.9	47.1	7.5
E-10	6.35	4.09	0.03	0.16	0.54	0.26	0	1.3	0	0.004	1024	1065	16.2	48.4	1.21	1.68	0.0	0.0	191	23	1075	1114	16.9	47.1	7.5
E-11	5.94	3.9	0.01	0.14	0.49	0.14	0	1.14	0	0.004	1011	1056	17.8	54.7	1.25	1.74	0.0	0.0	191	23	1003	1050	18.5	52.6	1.3
E-12	5.94	3.9	0.01	0.14	0.49	0.14	0	1.14	0	0.004	1019	1062	18.5	48.9	1.27	1.69	0.0	0.0	191	23	1003	1050	18.5	52.6	1.3
E-13	6.44	3.83	0.02	0.16	0.48	0.18	0	1.13	0	0.005	1042	1084	18.1	49.6	1.26	1.70	0.0	0.0	191	23	1048	1090	17.5	49.1	0.5
E-14	6.44	3.83	0.02	0.16	0.48	0.18	0	1.13	0	0.005	1038	1075	17.8	53.1	1.25	1.73	0.0	0.0	191	23	1048	1090	17.5	49.1	0.5
E-15	6.89	3.89	0.01	0.14	0.48	0.22	0	1.12	0	0.006	1076	1117	17.9	48	1.25	1.68	0.0	0.0	191	23	1062	1102	16.7	46.0	0.2
E-16	6.89	3.89	0.01	0.14	0.48	0.22	0	1.12	0	0.006	1082	1122	17.4	47.3	1.24	1.67	0.0	0.0	191	23	1062	1102	16.7	46.0	0.2
E-17	5.99	3.8	0.03	0.19	0.48	0.14	0	1.14	0	0.006	1069	1107	17.9	50.7	1.25	1.71	0.0	0.0	191	23	1042	1085	18.4	52.3	3.3
E-18	5.99	3.8	0.03	0.19	0.48	0.14	0	1.14	0	0.006	1073	1114	17.9	54	1.25	1.73	0.0	0.0	191	23	1042	1085	18.4	52.3	3.3
E-19	5.96	4.1	0.01	0.20	0.53	0.26	0	1.24	0	0.016	1058	1102	17.2	49.3	1.24	1.69	0.0	0.0	191	23	1081	1123	16.7	46.0	2.5
E-20	5.96	4.1	0.01	0.20	0.53	0.26	0	1.24	0	0.016	1045	1089	17.4	48.8	1.24	1.69	0.0	0.0	191	23	1081	1123	16.7	46.0	2.5

Table 2: Comparative Alloys (tested at 23 °C)

Alloy Ref.	Al (wt%)	V (wt%)	C (wt%)	O (wt%)	Fe (wt%)	Si (wt%)	Cu (wt%)	Mo (wt%)	Sn (wt%)	N (wt%)	.2%YS (MPa)	UTS (MPa)	EI (%)	RA (%)	Log (EL)	Log (RA)	FPS BI (mm)	600 FPS BI (mm)	C/R (°C/mil n)	Test Temp (°C)	YS Model (MPa)	UTS Model (MPa)	EL Model (%)	RA Model (%)	BI Model (mm)
C-1	6.12	3.76	0.03	0.17	0.21	0.00	0.00	0.00	0.00	0.002	913	982	13.3	37.0	1.12	1.57	1.7	0.0	191	23	915	981	15.6	39.9	0.0
C-2	6.12	3.76	0.03	0.17	0.21	0.00	0.00	0.00	0.00	0.002	920	985	13.4	35.1	1.13	1.55	1.7	0.0	191	23	915	981	15.6	39.9	0.0
C-3	6.23	3.88	0.02	0.19	0.19	0.43	0.00	0.00	0.00	0.002	1038	1110	7.8	15.4	0.89	1.19	7.8	26.0	191	23	1015	1084	9.3	20.5	19.0
C-4	6.23	3.88	0.02	0.19	0.19	0.43	0.00	0.00	0.00	0.002	1030	1105	11.4	25.9	1.06	1.41	7.8	26.0	191	23	1015	1084	9.3	20.5	19.0
C-5	6.21	3.88	0.02	0.20	0.20	0.23	0.00	0.00	0.00	0.002	1003	1069	11.2	28.8	1.05	1.48	0.0	2.9	191	23	984	1050	11.8	28.0	5.8
C-6	6.21	3.88	0.02	0.20	0.20	0.23	0.00	0.00	0.00	0.002	1007	1070	12.9	28.3	1.11	1.45	0.0	2.9	191	23	984	1050	11.8	28.0	5.8
C-7	6.08	3.84	0.03	0.19	0.21	0.68	0.00	0.00	0.00	0.003	1052	1121	2.5	3.7	0.40	0.57	17.8	40.2	191	23	1056	1130	7.0	14.1	64.9
C-8	6.08	3.84	0.03	0.19	0.21	0.68	0.00	0.00	0.00	0.003	1067	1141	11.1	26.5	1.05	1.42	17.8	40.2	191	23	1056	1130	7.0	14.1	64.9
C-9	6.10	4.08	0.03	0.19	0.50	0.49	0.00	0.49	0.00	0.011	1074	1138	9.1	17.3	0.96	1.24	1.3	13.3	191	23	1078	1134	11.0	25.2	35.1
C-10	6.10	4.08	0.03	0.19	0.50	0.49	0.00	0.49	0.00	0.011	1089	1149	9.0	18.0	0.95	1.26	1.3	13.3	191	23	1078	1134	11.0	25.2	35.1
C-11	6.33	3.95	0.03	0.21	0.22	0.00	0.00	0.00	0.00	0.007	938	989	15.0	38.0	1.18	1.59	0.0	0.0	191	23	956	1017	15.7	40.1	1.0
C-12	6.33	3.95	0.03	0.21	0.22	0.00	0.00	0.00	0.00	0.007	921	981	17.0	38.4	1.23	1.58	0.0	0.0	191	23	956	1017	15.7	40.1	1.0
C-13	6.64	4.00	0.03	0.19	0.22	0.45	0.00	0.00	0.00	0.002	999	1058	13.6	33.7	1.13	1.53	6.5	21.2	191	23	1041	1106	9.2	20.2	30.0
C-14	6.64	4.00	0.03	0.19	0.22	0.45	0.00	0.00	0.00	0.002	1017	1076	13.0	29.4	1.11	1.47	6.5	21.2	191	23	1041	1106	9.2	20.2	30.0
C-15	6.26	3.64	0.02	0.19	0.91	0.43	0.00	0.00	0.00	0.002	1098	1155	14.5	32.7	1.16	1.51	12.4	40.2	191	23	1085	1139	13.2	28.3	19.0
C-16	6.26	3.64	0.02	0.19	0.91	0.43	0.00	0.00	0.00	0.002	1081	1133	14.6	35.5	1.16	1.55	12.4	40.2	191	23	1085	1139	13.2	28.3	19.0
C-17	6.36	3.93	0.02	0.20	0.20	0.46	0.00	0.98	0.00	0.005	1091	1140	11.7	34.8	1.07	1.54	25.8	47.4	191	23	1092	1143	10.7	26.9	24.9
C-18	6.36	3.93	0.02	0.20	0.20	0.46	0.00	0.98	0.00	0.005	1088	1139	11.4	34.4	1.08	1.54	25.8	47.4	191	23	1092	1143	10.7	26.9	24.9
C-19	6.51	4.13	0.05	0.22	0.20	0.32	0.00	1.00	0.00	0.006	1094	1142	13.7	35.0	1.14	1.54	12.1	101.6	191	23	1089	1135	12.7	33.5	44.4
C-20	6.51	4.13	0.05	0.22	0.20	0.32	0.00	1.00	0.00	0.006	1102	1154	14.1	36.9	1.15	1.57	12.1	101.6	191	23	1089	1135	12.7	33.5	44.4

Table 3A: Comparative Alloys (tested at 23 °C)

Alloy Ref.	Al (wt%)	V (wt%)	C (wt%)	O (wt%)	Fe (wt%)	Si (wt%)	Cu (wt%)	Mo (wt%)	Sn (wt%)	N (wt%)	.2%YS (MPa)	UTS (MPa)	EI (%)	RA (%)	Log (EL)	Log (RA)
C-21	6.36	4.14	0.03	0.19	0.20		0.22			0.002	959	1020	12.0	31.5	1.08	1.50
C-22	6.36	4.14	0.03	0.19	0.20		0.22			0.002	967	1028	14.5	40.6	1.16	1.61
C-23	6.25	3.92	0.02	0.18	0.21	0.67	0.20			0.002	1078	1145	8.1	15.1	0.91	1.18
C-24	6.25	3.92	0.02	0.18	0.21	0.67	0.20			0.002	1085	1156	8.3	15.3	0.92	1.18
C-25	6.22	3.85	0.03	0.17	0.22		1.38			0.002	1027	1089	8.5	15.6	0.93	1.19
C-26	6.22	3.85	0.03	0.17	0.22		1.38			0.002	1031	1096	8.2	15.9	0.91	1.20
C-27	6.21	4.10	0.03	0.19	0.22	0.30	1.48			0.002	1075	1135	7.4	17.0	0.87	1.23
C-28	6.21	4.10	0.03	0.19	0.22	0.30	1.48			0.002	1078	1144	9.1	19.0	0.96	1.28
C-29	6.10	3.96	0.03	0.19	0.21		0.78			0.009	984	1036	10.3	21.1	1.01	1.32
C-30	6.10	3.96	0.03	0.19	0.21		0.78			0.009	985	1036	11.7	24.0	1.07	1.38
C-31	6.08	4.10	0.03	0.20	0.22	0.50	0.85			0.008	1091	1142	3.8	0.0	0.58	n/a
C-32	6.08	4.10	0.03	0.20	0.22	0.5	0.85			0.008	1096	1153	4.2	6.2	0.62	0.79
C-33	6.34	4.08	0.09	0.19	0.51	0.49		0.51		0.010	1101	1165	7.6	9.2	0.88	0.96
C-34	6.34	4.08	0.09	0.19	0.51	0.49		0.51		0.010	1102	1164	8.4	12.1	0.92	1.08
C-35	6.32	4.15	0.10	0.18	0.22		0.87			0.007	1032	1089	7.3	12.5	0.86	1.10
C-36	6.32	4.15	0.10	0.18	0.22		0.87			0.007	1040	1094	9.4	18.1	0.97	1.26
C-31	6.24	4.15	0.09	0.18	0.22	0.52	0.86			0.006	113.5	1194	3.9	6.2	0.59	0.19
C-38	6.24	4.15	0.09	0.18	0.22	0.52	0.86			0.006	1126	1182	3.8	6.2	0.58	0.79
C-39	6.23	4.08	0.12	0.17	0.52		0.85	0.50		0.006	1064	1118	9.5	23.0	0.98	1.36
C-40	6.23	4.08	0.12	0.17	0.52		0.85	0.5		0.006	1069	1120	13.8	27.2	1.14	1.43
C-41	6.21	4.12	0.09	0.15	0.52	0.56	0.88	0.51		0.007	1179	1233	3.0	5.8	0.48	0.76
C-42	6.21	4.12	0.09	0.15	0.52	0.56	0.88	0.51		0.007	1175	1230	4.2	5	0.62	0.70
C-43	6.23	4.03	0.09	0.21	0.21	0.50				0.007	1051	1122	10.1	20.2	1.00	1.31
C-44	6.23	4.03	0.09	0.21	0.21	0.5				0.007	1051	1117	10.2	23.8	1.01	1.38
C-45	6.24	4.18	0.04	0.23	0.52		0.87	0.54		0.011	1027	1080	10.7	22.3	1.03	1.35

(continued)

Alloy Ref.	Al (wt%)	V (wt%)	C (wt%)	O (wt%)	Fe (wt%)	Si (wt%)	Cu (wt%)	Mo (wt%)	Sn (wt%)	N (wt%)	.2% YS (MPa)	UTS (MPa)	EI (%)	RA (%)	Log (EL)	Log (RA)
C-46	6.24	4.18	0.04	0.23	0.52		0.87	0.54		0.011	1048	1102	11.4	23.1	1.06	1.36
C-47	6.21	4.16	0.03	0.20	0.52	0.56	0.86	0.52		0.007	1215	1273	3.4	0.0	0.53	n/a
C-48	6.21	4.16	0.03	0.20	0.52	0.56	0.86	0.52		0.007	1149	1202	7.2	10.9	0.86	1.04
C-49	6.32	4.21	0.03	0.18	0.52	0.57	0.86	0.52	1.91	0.006	1189	1252	3.6	4.4	0.56	0.64
C-50	6.32	4.21	0.03	0.18	0.52	0.57	0.86	0.52	1.91	0.006	1185	1245	4	10.5	0.60	1.02

Table 3B: Comparative Alloys (tested at 23 °C)

Alloy Ref.	Al (wt%)	V (wt%)	C (wt%)	O (wt%)	Fe (wt%)	Si (wt%)	Cu (wt%)	Mo (wt%)	Sn (wt%)	N (wt%)	.2%YS (MPa)	UTS (MPa)	EI (%)	RA (%)	Log (EL)	Log (RA)
C-51	6.37	4.01	0.03	0.18	0.22	0.02	0.86			0.003	1023,	1068	14.8	40.7	1.17	1.61
C-52	6.37	4.01	0.03	0.18	0.22	0.02	0.86			0.003	1010	1058	15	39.6	1.18	1.60
C-53	6.31	3.90	0.03	0.20	0.19	0.44	0.80			0.003	1125	1177	11.1	26.5	1.05	1.42
G-54	6.31	3.90	0.03	0.20	0.19	0.44	0.80			0.003	1135	1189	9.4	28.0	0.97	1.45
C-55	6.44	3.89	0.03	0.19	0.99	0.02	0.8.2			0.006	1081	1128	13.9	42.3	1.14	1.63
C-56	6.44	3.89	0.03	0.19	0.99	0.02	0.8.2			0.006	1070	1122	13.5	37.8	1.13	1.58
C-57	6.34	3.86	0.03	0.19	0.20	0.02	0.83	0.97		0.003	1061	1104	15.1	42.7	1.18	1.63
C-58	6.34	3.86	0.03	0.19	0.20	0.02	0.83	0.97		0.003	1055	1100	12.9	42.6	1.11	1.63
C-59	6.14	3.74	0.03	0.18	0.45	0.45	0.75	0.46		0.001	1123	1175	12.1	31.5	1.08	1.50
C-60	6.14	3.74	0.03	0.18	0.45	0.45	0.75	0.46		0.001	1121	1172	12.8	31.5	1.11	1.50
C-61	6.02	3.57	0.05	0.18	0.44	0.44	0.75	0.44	1.82	0.007	1158	1212	12.5	29.7	1.10	1.47
C-62	6.02	3.57	0.05	0.18	0.44	0.44	0.75	0.44	1.82	0.007	1162	1215	12.6	28.6	1.10	1.46
C-63	6.22	3.66	0.11	0.18	0.48	0.44	0.75	0.46		0.005	1170	1173	1.4.	2.7	0.15	0.43
C-64	6.22	3.66	0.11	0.18	0.48	0.44	0.75	0.46		0.005	1134	1178	6.0	13.2	0.78	1.12
C-65	6.53	4.09	0.05	0.22	0.54	0.37	0.27	0.51		0.007	1149	1189	13.1	31.3	1.12	1.50
C-66	6.53	4.09	0.05	0.22	0.54	0.37	0.27	0.51		0.007	1139	1180	13.8	36.9	1.14	1.57

Table 4: Comparative Examples

	Al (wt%)	V (wt%)	C (wt%)	O (wt%)	Fe (wt%)	Si (wt%)	Mo (wt%)	N (wt%)	Cu (wt%)	Pred 0.2% YS (Mpa)	Pred EL (%)	Measured 0.2% YS		Measured UTS		Measured %EI	
												111C/ min	333C/ min	111C/ min	333C/ min	111C/ min	333C/min
Comp-A	6.715	3.98	0.014	0.159	0.178	0.021	0.003	0.009	0.004	938	15.0	861	887	972	997	17.0	19.5
Comp-B	6.943	4.15	0.026	0.206	0.21	0.02	0.002	0.008	0.002	987	15.2	900	958	1012	1057	17.0	17.0
Comp-C	7.293	3.918	0.018	0.201	0.173	0.031	0.002	0.387	0.003	999	14.8						
Comp-D	7.573	3.993	0.019	0.227	0.195	0.019	0.002	0.415	0.003	1032	15.1						
Comp-E	6.638	4.028	0.044	0.159	0.18	0.019	0.002	0.008	0.003	934	15.0						
Comp-F	6.693	4.003	0.102	0.179	0.183	0.016	0.003	0.008	0.003	951	15.1	940	966	1074	1088	17.0	17.0
Comp-G	6.693	3.91	0.039	0.18	0.36	0.508	0.358	0.009	0.004	1082	9.8	1042	1069	1131	1152	17.0	16.5
Comp-H	6.423	3.765	0.082	0.184	0.443	0.673	0.465	0.019	0.758	1117	8.6	1202	1214	1282	1262	9.5	3.9
Comp-I	6.603	3.913	0.025	0.157	0.52	0.028	0.56	0.009	0.005	997	19.3		947		1115	0.0	19.0
Comp-J	6.61	3.85	0.074	0.173	0.455	0.022	0.495	0.01	0.77	999	18.6	1070	1101	1145	1176	17.0	11.7
Comp-K	6.683	3.923	0.014	0.153	0.175	0.635	0.003	0.009	0.002	1047	7.3	1006	1048	1105	1145	17.0	15.0
Comp-L	6.605	3.93	0.019	0.159	0.173	0.023	0.002	0.009	0.308	932	14.9	914	957	1005	1031	19.0	18.0
Comp-M	6.708	3.89	0.019	0.143	0.188	0.02	0.003	0.009	0.004	926	15.1	885	989	1002	1027	19.0	17.0

[0070] Further aspects are provided by the subject matter of the following clauses:

[0071] A turbine component comprising a titanium alloy, wherein the titanium alloy comprises: 5.50 wt% to 6.90 wt% aluminum; 3.50 wt% to 4.50 wt% vanadium; 0.01 wt% to 0.03 wt% carbon; 0.20 wt% to 0.70 wt% iron; 1.00 wt% to 1.50 wt% molybdenum; 0.10 wt% to 0.30 wt% silicon; up to 0.21 wt% oxygen; up to 0.016 wt% nitrogen (e.g., up to 0.015 wt% nitrogen); and a balance of titanium, wherein the titanium alloy is substantially free from copper.

[0072] A turbine component comprising a titanium alloy, wherein the titanium alloy comprises: 5.50 wt% to 6.90 wt% aluminum; 3.50 wt% to 4.50 wt% vanadium; 0.01 wt% to 0.03 wt% carbon; 0.20 wt% to 0.70 wt% iron; 1.00 wt% to 1.50 wt% molybdenum; 0.10 wt% to 0.30 wt% silicon; up to 0.21 wt% oxygen; up to 0.016 wt% nitrogen (e.g., up to 0.015 wt% nitrogen); and a balance of titanium, wherein the Al, O, Fe, Si, Mo are present in amounts that result in a predicted 23 °C 0.2% yield strength ≥ 1000 MPa according to the formula: $469.3 + 48.8 \cdot \text{Al (wt\%)} + 748 \cdot \text{O (wt\%)} + 96.1 \cdot \text{Fe (wt\%)} + 188 \cdot \text{Si (wt\%)} + 57.7 \cdot \text{Mo (wt\%)}$, and/or wherein the Fe, Si, Mo are present in amounts that result in a predicted 23 °C % plastic elongation $\geq 15.0\%$ according to the formula: $10^{(1.149 + 0.211 \cdot \text{Fe (wt\%)} - 0.514 \cdot \text{Si (wt\%)} + 0.076 \cdot \text{Mo (wt\%)})}$.

[0073] The turbine component as in any preceding clause, wherein the titanium alloy is substantially free from copper.

[0074] The turbine component as in any preceding clause, wherein the titanium alloy has a 0.2% yield strength of 1000 MPa or greater.

[0075] The turbine component as in any preceding clause, wherein the titanium alloy has a 0.2% yield strength of 1000 MPa to 1380 MPa.

[0076] The turbine component as in any preceding clause, wherein the titanium alloy has an ultimate tensile strength of 1060 MPa or greater.

[0077] The turbine component as in any preceding clause, wherein the titanium alloy has an ultimate tensile strength of 1060 MPa to 1450 MPa.

[0078] The turbine component as in any preceding clause, wherein the titanium alloy has a plastic elongation of 15.0% or greater.

[0079] The turbine component as in any preceding clause, wherein the titanium alloy has a plastic elongation of 15.0% to 30.0%.

[0080] The turbine component as in any preceding clause, wherein the titanium alloy has a ballistic impact resistance measured by a crack length of 3.048 mm or less.

[0081] The turbine component as in any preceding clause, wherein the titanium alloy has a ballistic impact resistance measured by a crack length of 0 mm to 3.048 mm.

[0082] The turbine component as in any preceding clause, wherein the turbine component has a reduction in area that is 45 %RA or greater.

[0083] The turbine component as in any preceding clause, wherein the turbine component has a reduction in area that is 45 %RA to 75 %RA.

[0084] The turbine component as in any preceding clause, wherein the titanium alloy has a 0.2% yield strength of 1000 MPa or greater, an ultimate tensile strength of 1060 MPa or greater, a plastic elongation of 15.0% or greater and a reduction in area that is 45 %RA or greater.

[0085] The turbine component as in any preceding clause, wherein the titanium alloy has a 0.2% yield strength of 1000 MPa to 1380 MPa, an ultimate tensile strength of 1060 MPa to 1450 MPa, a ductility of 15.0% to 30.0%, and a reduction in area that is 45 %RA to 75 %RA.

[0086] The turbine component as in any preceding clause, wherein the titanium alloy is substantially free from chromium.

[0087] The turbine component as in any preceding clause, wherein the titanium alloy is substantially free from tin.

[0088] The turbine component as in any preceding clause, wherein the titanium alloy is substantially free from nickel.

[0089] The turbine component as in any preceding clause, wherein the titanium alloy is substantially free from zirconium.

[0090] The turbine component as in any preceding clause, wherein the titanium alloy is substantially free from tungsten.

[0091] The turbine component as in any preceding clause, wherein the titanium alloy is substantially free from any other elements.

[0092] The turbine component as in any preceding clause, wherein the Al, O, Fe, Si, Mo are present in amounts that result in a predicted 23 °C 0.2% yield strength ≥ 1000 MPa according to the formula: $469.3 + 48.8 \cdot \text{Al (wt\%)} + 748 \cdot \text{O (wt\%)} + 96.1 \cdot \text{Fe (wt\%)} + 188 \cdot \text{Si (wt\%)} + 57.7 \cdot \text{Mo (wt\%)}$.

[0093] The turbine component as in any preceding clause, wherein the Fe, Si, Mo are present in amounts that result in a predicted 23 °C % plastic elongation $\geq 15.0\%$ according to the formula: $10^{(1.149 + 0.211 \cdot \text{Fe (wt\%)} - 0.514 \cdot \text{Si (wt\%)} + 0.076 \cdot \text{Mo (wt\%)})}$.

[0094] The turbine component as in any preceding clause, wherein the Al, O, Fe, Si, Mo are present in amounts that result in a predicted 23 °C 0.2% yield strength ≥ 1000 MPa according to the formula: $469.3 + 48.8 \cdot \text{Al (wt\%)} + 748 \cdot \text{O (wt\%)} + 96.1 \cdot \text{Fe (wt\%)} + 188 \cdot \text{Si (wt\%)} + 57.7 \cdot \text{Mo (wt\%)}$, and wherein the Fe, Si, Mo are present in amounts that result in a predicted 23 °C % plastic elongation $\geq 15.0\%$ according to the formula: $10^{(1.149 + 0.211 \cdot \text{Fe (wt\%)} - 0.514 \cdot \text{Si (wt\%)} + 0.076 \cdot \text{Mo (wt\%)})}$.

[0095] The turbine component as in any preceding clause, wherein the titanium alloy comprises 3.80 wt% to 4.43 wt%

vanadium.

[0096] The turbine component as in any preceding clause, wherein the titanium alloy comprises 0.45 wt% to 0.57 wt% iron.

[0097] The turbine component as in any preceding clause, wherein the titanium alloy comprises 0.14 wt% to 0.28 wt% silicon.

[0098] The turbine component as in any preceding clause, wherein the titanium alloy consists essentially of: 5.50 wt% to 6.90 wt% aluminum; 3.50 wt% to 4.50 wt% vanadium; 0.01 wt% to 0.03 wt% carbon; 0.20 wt% to 0.70 wt% iron; 1.00 wt% to 1.50 wt% molybdenum; 0.10 wt% to 0.30 wt% silicon; up to 0.21 wt% oxygen; up to 0.016 wt% nitrogen (e.g., up to 0.015 wt% nitrogen); and a balance of titanium.

[0099] The turbine component as in any preceding clause, wherein the titanium alloy consists of: 5.50 wt% to 6.90 wt% aluminum; 3.50 wt% to 4.50 wt% vanadium; 0.01 wt% to 0.03 wt% carbon; 0.20 wt% to 0.70 wt% iron; 1.00 wt% to 1.50 wt% molybdenum; 0.10 wt% to 0.30 wt% silicon; up to 0.21 wt% oxygen; up to 0.016 wt% nitrogen (e.g., up to 0.015 wt% nitrogen); and a balance of titanium.

[0100] A turbine component comprising a titanium alloy, wherein the titanium alloy consists essentially of: 5.50 wt% to 6.90 wt% aluminum; 3.50 wt% to 4.50 wt% vanadium; 0.01 wt% to 0.03 wt% carbon; 0.20 wt% to 0.70 wt% iron; 1.00 wt% to 1.50 wt% molybdenum; 0.10 wt% to 0.30 wt% silicon; up to 0.21 wt% oxygen; up to 0.016 wt% nitrogen (e.g., up to 0.015 wt% nitrogen); and a balance of titanium.

[0101] A turbine component comprising a titanium alloy, wherein the titanium alloy consists of: 5.50 wt% to 6.90 wt% aluminum; 3.50 wt% to 4.50 wt% vanadium; 0.01 wt% to 0.03 wt% carbon; 0.20 wt% to 0.70 wt% iron; 1.00 wt% to 1.50 wt% molybdenum; 0.10 wt% to 0.30 wt% silicon; up to 0.21 wt% oxygen; up to 0.016 wt% nitrogen (e.g., up to 0.015 wt% nitrogen); and a balance of titanium.

[0102] The turbine component as in any preceding clause, wherein the titanium alloy has a 0.2% yield strength of 1000 MPa or greater.

[0103] The turbine component as in any preceding clause, wherein the titanium alloy has a 0.2% yield strength of 1000 MPa to 1380 MPa.

[0104] The turbine component as in any preceding clause, wherein the titanium alloy has an ultimate tensile strength of 1060 MPa or greater.

[0105] The turbine component as in any preceding clause, wherein the titanium alloy has an ultimate tensile strength of 1060 MPa to 1450 MPa.

[0106] The turbine component as in any preceding clause, wherein the titanium alloy has a plastic elongation of 15.0% or greater.

[0107] The turbine component as in any preceding clause, wherein the titanium alloy has a plastic elongation of 15.0% to 30.0%.

[0108] The turbine component as in any preceding clause, wherein the titanium alloy has a ballistic impact resistance measured by a crack length of 3.048 mm or less.

[0109] The turbine component as in any preceding clause, wherein the titanium alloy has a ballistic impact resistance measured by a crack length of 0 mm to 3.048 mm.

[0110] The turbine component as in any preceding clause, wherein the turbine component has a reduction in area that is 45 %RA or greater.

[0111] The turbine component as in any preceding clause, wherein the turbine component has a reduction in area that is 45 %RA to 75 %RA.

[0112] The turbine component as in any preceding clause, wherein the titanium alloy has a 0.2% yield strength of 1000 MPa or greater, an ultimate tensile strength of 1060 MPa or greater, a plastic elongation of 15.0% or greater, a crack length of 3.048 mm or less, and a reduction in area that is 45 %RA or greater.

[0113] The turbine component as in any preceding clause, wherein the titanium alloy has a 0.2% yield strength of 1000 MPa to 1380 MPa, an ultimate tensile strength of 1060 MPa to 1450 MPa, a ductility of 15.0% to 30.0%, a ballistic impact resistance measured by a crack length of 0 to 3.048 mm, and a reduction in area that is 45 %RA to 75 %RA.

[0114] A method of forming the turbine component of any preceding clause.

[0115] A method of forming a turbine component, the method comprising: forging a titanium alloy into the turbine component, wherein the titanium alloy comprises: 5.50 wt% to 6.90 wt% aluminum; 3.50 wt% to 4.50 wt% vanadium; 0.01 wt% to 0.03 wt% carbon; 0.20 wt% to 0.70 wt% iron; 1.00 wt% to 1.50 wt% molybdenum; 0.10 wt% to 0.30 wt% silicon; up to 0.21 wt% oxygen; up to 0.016 wt% nitrogen (e.g., up to 0.015 wt% nitrogen); and a balance of titanium, wherein the titanium alloy is substantially free from copper.

[0116] A method of forming a turbine component, the method comprising: forging a titanium alloy into the turbine component, wherein the titanium alloy comprises: 5.50 wt% to 6.90 wt% aluminum; 3.50 wt% to 4.50 wt% vanadium; 0.01 wt% to 0.03 wt% carbon; 0.20 wt% to 0.70 wt% iron; 1.00 wt% to 1.50 wt% molybdenum; 0.10 wt% to 0.30 wt% silicon; up to 0.21 wt% oxygen; up to 0.016 wt% nitrogen (e.g., up to 0.015 wt% nitrogen); and a balance of titanium, wherein the Al, O, Fe, Si, Mo are present in amounts that result in a predicted 23 °C 0.2% yield strength $\geq$ 1000 MPa

according to the formula: $469.3 + 48.8 \cdot \text{Al (wt\%)} + 748 \cdot \text{O (wt\%)} + 96.1 \cdot \text{Fe (wt\%)} + 188 \cdot \text{Si (wt\%)} + 57.7 \cdot \text{Mo (wt\%)}$, and/or wherein the Fe, Si, Mo are present in amounts that result in a predicted 23 °C % plastic elongation $\geq 15.0\%$ according to the formula: $10^{(1.149 + 0.211 \cdot \text{Fe (wt\%)} - 0.514 \cdot \text{Si (wt\%)} + 0.076 \cdot \text{Mo (wt\%)})}$

[0117] The method of any preceding clause, wherein forging the titanium alloy into the turbine component comprises: forging the titanium alloy at a forging temperature that is below a beta transus temperature of the titanium alloy.

[0118] The method of any preceding clause, wherein the method comprises: heat treating the titanium alloy.

[0119] The method of any preceding clause, wherein the method comprises: solution heat treating the titanium alloy at a heat treatment temperature that is below a beta transus temperature of the titanium alloy.

[0120] The method of any preceding clause, wherein the heat treatment temperature is above a forging temperature, wherein the titanium alloy is held at the heat treatment temperature for at least 1 hour.

[0121] The method of any preceding clause, wherein the method comprises: after heat treating the titanium alloy, cooling the titanium alloy to form the turbine component.

[0122] The method of any preceding clause, wherein cooling the titanium alloy is performed with at cooling rate from the heat treatment temperature of 208 °C/min.

[0123] The method of any preceding clause, further comprising: following solution heat treatment and cooling, heating the titanium alloy to an overage heat treatment temperature of 538 °C to 760 °C for at least 1.5 hours.

[0124] The method of any preceding clause, wherein the titanium alloy has a 0.2% yield strength of 1000 MPa or greater.

[0125] The method of any preceding clause, wherein the titanium alloy has an ultimate tensile strength of 1060 MPa or greater.

[0126] The method of any preceding clause, wherein the titanium alloy has a plastic elongation of 15.0% or greater.

[0127] The method of any preceding clause, wherein the titanium alloy has a ballistic impact resistance measured by a crack length of 3.048 mm or less.

[0128] The method of any preceding clause, wherein the titanium alloy has a reduction in area that is 45 %RA or greater.

[0129] A titanium alloy formed according to the method of any preceding clause.

[0130] This written description uses examples to disclose the present disclosure, including the best mode, and also to enable any person skilled in the art to practice the disclosure, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the disclosure is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they include structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

Claims

1. A turbine component comprising a titanium alloy, wherein the titanium alloy comprises:

5.50 wt% to 6.90 wt% aluminum;
3.50 wt% to 4.50 wt% vanadium;
0.01 wt% to 0.03 wt% carbon;
0.20 wt% to 0.70 wt% iron;
1.00 wt% to 1.50 wt% molybdenum;
0.10 wt% to 0.30 wt% silicon;
up to 0.21 wt% oxygen;
up to 0.016 wt% nitrogen; and
a balance of titanium,

wherein the Al, O, Fe, Si, Mo are present in amounts that result in a predicted 23 °C 0.2% yield strength ≥ 1000 MPa according to the formula: $469.3 + 48.8 \cdot \text{Al (wt\%)} + 748 \cdot \text{O (wt\%)} + 96.1 \cdot \text{Fe (wt\%)} + 188 \cdot \text{Si (wt\%)} + 57.7 \cdot \text{Mo (wt\%)}$, or

wherein the Fe, Si, Mo are present in amounts that result in a predicted 23 °C % plastic elongation $\geq 15.0\%$ according to the formula: $10^{(1.149 + 0.211 \cdot \text{Fe (wt\%)} - 0.514 \cdot \text{Si (wt\%)} + 0.076 \cdot \text{Mo (wt\%)})}$.

2. The turbine component as in claim 1, wherein the titanium alloy is substantially free from copper.

3. The turbine component as in claim 1 or 2, wherein the titanium alloy has a 0.2% yield strength of 1000 MPa to 1380 MPa, and wherein the titanium alloy has a plastic elongation of 15.0% to 30.0%.

4. The turbine component as in any preceding claim, wherein the titanium alloy has an ultimate tensile strength of 1060 MPa to 1450 MPa.

5. The turbine component as in any preceding claim, wherein the titanium alloy has a plastic elongation of 15.0% to 30.0%.
6. The turbine component as in any preceding claim, wherein the titanium alloy has a ballistic impact resistance measured by a crack length of 3.048 mm or less.
7. The turbine component as in any preceding claim, wherein the titanium alloy has a ballistic impact resistance measured by a crack length of 0 mm to 3.048 mm.
8. The turbine component as in any preceding claim, wherein the turbine component has a reduction in area that is 45 %RA to 75 %RA.
9. The turbine component as in any preceding claim, wherein the titanium alloy is substantially free from chromium, tin, nickel, zirconium, and tungsten.
10. The turbine component as in any preceding claim, wherein the titanium alloy is substantially free from any other elements.
11. The turbine component as in any preceding claim, wherein the titanium alloy comprises 3.80 wt% to 4.43 wt% vanadium.
12. The turbine component as in any preceding claim, wherein the titanium alloy comprises 0.45 wt% to 0.57 wt% iron.
13. The turbine component as in any preceding claim, wherein the titanium alloy comprises 0.14 wt% to 0.28 wt% silicon.
14. The turbine component as in any preceding claim, wherein the titanium alloy consists of:
 - 5.50 wt% to 6.90 wt% aluminum;
 - 3.50 wt% to 4.50 wt% vanadium;
 - 0.01 wt% to 0.03 wt% carbon;
 - 0.20 wt% to 0.70 wt% iron;
 - 1.00 wt% to 1.50 wt% molybdenum;
 - 0.10 wt% to 0.30 wt% silicon;
 - up to 0.21 wt% oxygen;
 - up to 0.016 wt% nitrogen; and
 - a balance of titanium.
15. A method of forming a turbine component, the method comprising: forging the titanium alloy of any preceding claim into the turbine component.

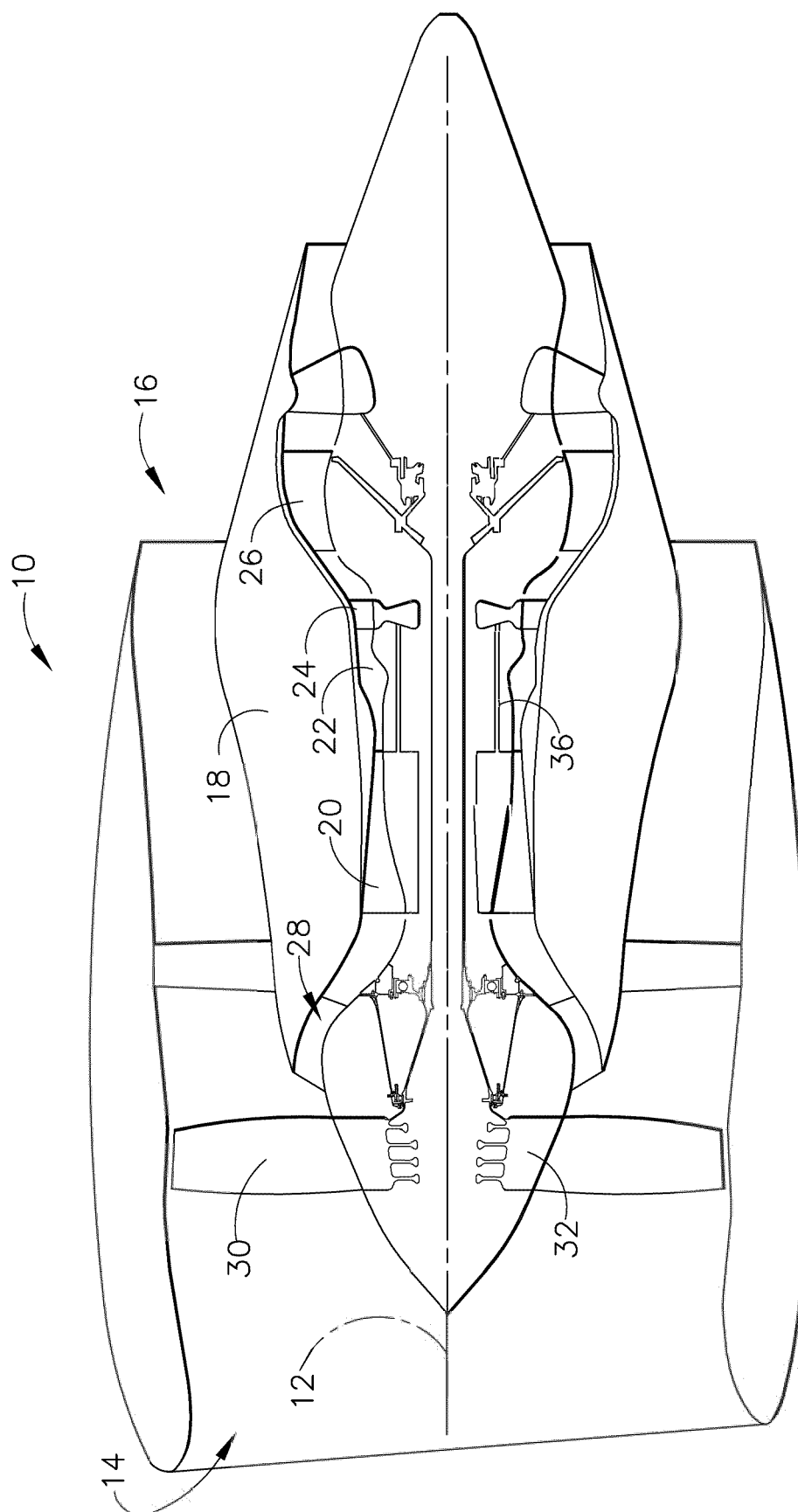


Fig. 1

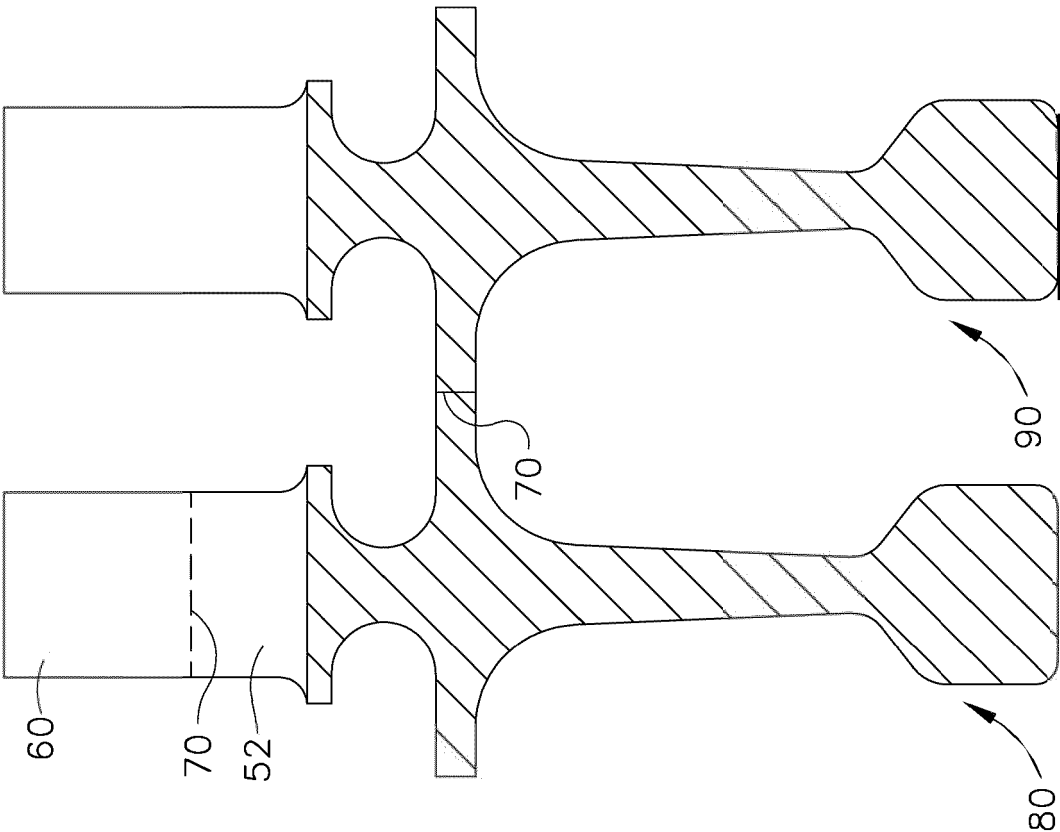


FIG. 3

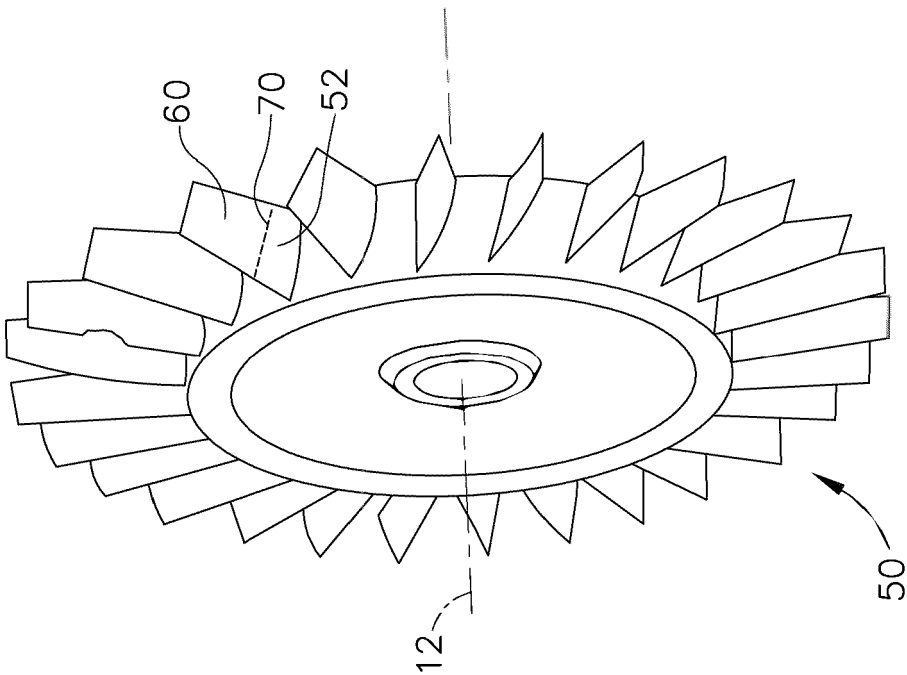


FIG. 2



EUROPEAN SEARCH REPORT

Application Number

EP 24 18 0240

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			C22C C22F F01D
The present search report has been drawn up for all claims			
Place of search The Hague		Date of completion of the search 16 October 2024	Examiner Neibecker, Pascal
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