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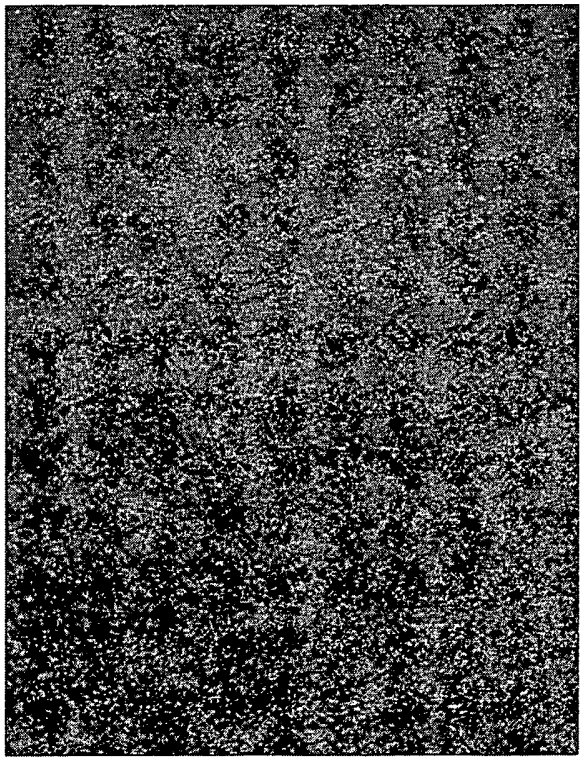
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(54) Title: METASTABLE BETA-TITANIUM ALLOYS AND METHODS OF PROCESSING THE SAME BY DIRECT AGING



(57) Abstract: Metastable beta titanium alloys and methods of processing metastable ß-titanium alloys are disclosed. For example, certain non-limiting embodiments relate to metastable β-titanium alloys, such as binary ß-titanium alloys comprising greater than 10 weight percent molybdenum, having tensile strengths of at least 150 ksi and elongations of at least 12 percent. Other non-limiting embodiments relate to methods of processing metastable β-titanium alloys, and more specifically, methods of processing binary ß-titanium alloys comprising greater than 10 weight percent molybdenum, wherein the method comprises hot working and direct aging the metastable β-titanium alloy at a temperature below the ß-transus temperature of the metastable ß-titanium alloy for a time sufficient to form α-phase precipitates in the metastable ß-titanium alloy. Articles of manufacture comprising binary β-titanium alloys according to various non-limiting embodiments disclosed herein are also disclosed.

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METASTABLE BETA-TITANIUM ALLOYS AND METHODS OF PROCESSING THE SAME BY DIRECT AGING

BACKGROUND

[0001] The present disclosure generally relates to metastable β-titanium alloys and methods of processing metastable β-titanium alloys. More specifically, certain embodiments of the present invention relate to binary metastable β-titanium alloys comprising greater than 10 weight percent molybdenum, and methods of processing such alloys by hot working and direct aging. Articles of manufacture made from the metastable β-titanium alloys disclosed herein are also provided.

[0002] Metastable beta-titanium (or "β-titanium") alloys generally have a desirable combination of ductility and biocompatibility that makes them particularly well suited for use in certain biomedical implant applications requiring custom fitting or contouring by the surgeon in an operating room. For example, solution treated (or "β-annealed") metastable β-titanium alloys that comprise a single-phase beta microstructure, such as binary β-titanium alloys comprising about 15 weight percent molybdenum ("Ti-15Mo"), have been successfully used in fracture fixation applications and have been found to have an ease of use approaching that of stainless steel commonly used in such applications. However, because the strength of solution treated Ti-15Mo alloys is relatively low, they are generally not well suited for use in applications requiring higher strength alloys, for example, hip joint prostheses. For example, conventional Ti-15Mo alloys that have been solution treated at a temperature near or above the β-transus temperature and subsequently cooled to room temperature without further aging, typically have an elongation of about 25 percent and a tensile strength of about 110 ksi. As used herein the terms "β-transus temperature," or "β-transus," refer to the minimum temperature above which equilibrium α-phase (or "alpha-phase") does not exist in the titanium alloy. *See e.g.,* ASM Materials Engineering Dictionary, J.R. Davis Ed., ASM International, Materials Park, OH (1992) at page 39, which is specifically incorporated by reference herein.

[0003] Although the tensile strength of a solution treated Ti-15Mo alloy can be increased by aging the alloy to precipitate α-phase (or alpha phase) within the β-phase microstructure, typically aging a solution treated Ti-15Mo alloy results in a dramatic decrease in the ductility of the alloy. For example, although not limiting herein, if a Ti-15Mo alloy is solution treated

at about 1472°F (800°C), rapidly cooled, and subsequently aged at a temperature ranging from 887°F (475°C) to 1337°F (725°C), an ultimate tensile strength ranging from about 150 ksi to about 200 ksi can be achieved. However, after aging as described, the alloy can have a percent elongation around 11% (for the 150 ksi material) to around 5% (for the 200 ksi material). *See* John Disegi, "AO ASIF Wrought Titanium-15% Molybdenum Implant Material," AO ASIF Materials Expert Group, 1st Ed., (Oct. 2003), which is specifically incorporated by reference herein. In this condition, the range of applications for which the Ti-15Mo alloy is suited can be limited due to the relatively low ductility of the alloy.

[0004] Further, since metastable β-titanium alloys tend to deform by twinning, rather than by the formation and movement of dislocations, these alloys generally cannot be strengthened to any significant degree by cold working (i.e., work hardening) alone.

[0005] Accordingly, there is a need for metastable β-titanium alloys, such as binary β-titanium alloys comprising greater than 10 weight percent molybdenum, having both good tensile properties (e.g., good ductility, tensile and/or yield strength) and/or good fatigue properties. There is also a need for a method of processing such alloys to achieve both good tensile properties and good fatigue properties.

BRIEF SUMMARY OF THE DISCLOSURE

[0006] Various non-limiting embodiments disclosed herein related to methods of processing metastable β-titanium alloys. For example, one non-limiting embodiment provides a method of processing a metastable β-titanium alloy comprising greater than 10 weight percent molybdenum, the method comprising hot working the metastable β-titanium alloy, and direct aging the metastable β-titanium alloy, wherein direct aging comprises heating the metastable β-titanium alloy in the hot worked condition at an aging temperature ranging from greater than 850°F to 1375°F for a time sufficient to form α-phase precipitates within the metastable β-titanium alloy.

[0007] Another non-limiting embodiment provides a method of processing a metastable β-titanium alloy comprising greater than 10 weight percent molybdenum, the method comprising hot working a metastable β-titanium alloy and direct aging the metastable β-titanium alloy, wherein direct aging comprises heating the metastable β-titanium alloy in the hot worked condition at a first aging temperature below the β-transus temperature of the metastable β-titanium alloy for a time sufficient to form and at least partially coarsen at least

one α-phase precipitate in at least a portion of the metastable β-titanium alloy; and subsequently heating the metastable β-titanium alloy at a second aging temperature that is lower than the first aging temperature for a time sufficient to form at least one additional α-phase precipitate in at least a portion of the metastable β-titanium alloy.

[0008] Another non-limiting embodiment provides a method of processing a metastable β-titanium alloy comprising greater than 10 weight percent molybdenum, the method comprising hot working a metastable β-titanium alloy and direct aging the metastable β-titanium alloy, wherein direct aging comprises heating the metastable β-titanium alloy in the hot worked condition at a first aging temperature ranging from 1225°F to 1375°F for at least 0.5 hours, and subsequently heating the metastable β-titanium alloy at a second aging temperature ranging from 850°F to 1000°F for at least 0.5 hours.

[0009] Another non-limiting embodiment provides a method of processing a metastable β-titanium alloy comprising greater than 10 weight percent molybdenum, the method comprising hot working the metastable β-titanium alloy to a reduction in area of at least 95% by at least one of hot rolling and hot extruding the metastable β-titanium alloy; and direct aging the metastable β-titanium alloy by heating the metastable β-titanium alloy in the hot worked condition at an aging temperature below the β-transus temperature of metastable β-titanium alloy for a time sufficient to form α-phase precipitates in the metastable β-titanium alloy.

[0010] Another non-limiting embodiment provides a method of processing a binary β-titanium alloy comprising greater than 10 weight percent molybdenum, the method comprising hot working the binary β-titanium alloy and direct aging the binary β-titanium alloy by heating the β-titanium alloy in the hot worked condition at an aging temperature below the β-transus temperature of binary β-titanium alloy for a time sufficient to form α-phase precipitates within the binary β-titanium alloy, wherein after processing, the binary β-titanium alloy has a tensile strength of at least 150 ksi and an elongation of at least 12 percent.

[0011] Other non-limiting embodiments of the present invention relate to binary β-titanium alloys. For example, one non-limiting embodiment provides a binary β-titanium alloy comprising greater than 10 weight percent molybdenum, wherein the binary β-titanium alloy is processed by hot working the binary β-titanium alloy and direct aging the binary β-

titanium alloy, wherein after processing, the binary β-titanium alloy has a tensile strength of at least 150 ksi and an elongation of at least 12 percent.

[0012] Another non-limiting embodiment provides a binary β-titanium alloy comprising greater than 10 weight percent molybdenum and having a tensile strength of at least 150 ksi and an elongation of at least 12 percent.

[0013] Other non-limiting embodiments disclosed herein relate to articles of manufacture made from binary β-titanium alloys. For example, one non-limiting embodiment provides an article of manufacture comprising a binary β-titanium alloy comprising greater than 10 weight percent molybdenum and having a tensile strength of at least 150 ksi and an elongation of at least 12 percent.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING(S)

[0014] Various embodiments disclosed herein will be better understood when read in conjunction with the drawings, in which:

Fig. 1 is a micrograph of a metastable β-titanium alloy processed using single-step direct aging process according to various non-limiting embodiments disclosed herein;

Fig. 2 is a micrograph of a metastable β-titanium alloy processed using two-step direct aging process according to various non-limiting embodiments disclosed herein; and

Fig. 3 is a plot of stress amplitude vs. cycles to failure for a Ti-15% Mo alloy processed according to various non-limiting embodiments disclosed herein.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE DISCLOSURE

[0015] As discussed above, embodiments of the present invention relate to metastable β-titanium alloys and methods of processing the same. More specifically, embodiments of the present invention relate to metastable β-titanium alloys, such as binary β-titanium alloys comprising greater than 10 weight percent molybdenum, and methods of processing such alloys to impart the alloys with desirable mechanical properties. As used herein, the term "metastable β-titanium alloys" means titanium alloys comprising sufficient amounts of β-stabilizing elements to retain an essentially 100% β-structure upon cooling from above the β-transus. Thus, metastable β-titanium alloys contain enough β-stabilizing elements to avoid passing through the martensite start (or "M_s") upon quenching, thereby avoiding the formation of martensite. Beta stabilizing elements (or β-stabilizers) are elements that are isomorphous with the body centered cubic ("bcc") β-titanium phase. Examples of β-

stabilizers include, but are not limited to, zirconium, tantalum, vanadium, molybdenum, and niobium. *See e.g.*, Metal Handbook, Desk Edition, 2nd Ed., J.R. Davis ed., ASM International, Materials Park, OH (1998) at pages 575-588, which are specifically incorporated by reference herein.

[0016] As previously discussed, in the solution treated condition, metastable β-titanium alloys comprise a single-phase β-microstructure. However, by appropriate heat treatment at temperatures below the β-transus, α-phase titanium having a hexagonal close-packed crystal structure can be formed or precipitated in the β-phase microstructure. While the formation of α-phase within the β-phase microstructure can improve the tensile strength of the alloy, it also generally results in a marked decrease in the ductility of the alloy. However, as discussed below in more detail, the inventors have found that when metastable β-titanium alloys are processed according to the various non-limiting embodiments disclosed herein, a metastable β-titanium alloy having both desirable tensile strength and ductility can be formed.

[0017] Metastable β-titanium alloys that are suitable for use in conjunction with the methods according to various non-limiting embodiments disclosed herein include, but are not limited to, metastable β-titanium alloys comprising greater than 10 weight percent molybdenum. Other metastable β-titanium alloys that are suitable for use in conjunction with the methods according to various non-limiting embodiments disclosed herein include, without limitation, metastable β-titanium alloys comprising from 11 weight percent molybdenum to 18 weight percent molybdenum. According to certain non-limiting embodiments, the metastable β-titanium alloy comprises at least 14 weight percent molybdenum, and more specifically, comprises from 14 weight percent to 16 weight percent molybdenum. Further, in addition to molybdenum, the metastable β-titanium alloys according to various non-limiting embodiments disclosed herein can comprise at least one other β-stabilizing element, such as zirconium, tantalum, vanadium, molybdenum, and niobium.

[0018] Further, according various non-limiting embodiments disclosed herein, the metastable β-titanium alloy can be a binary β-titanium alloy comprising greater than 10 weight percent molybdenum, and more specifically, comprising from 14 weight percent to 16 weight percent molybdenum. According other non-limiting embodiments, the metastable β-

titanium alloy is a binary β-titanium alloy comprising about 15 weight percent molybdenum. As used herein the term "binary β-titanium alloy" means a metastable β-titanium alloy that comprises two primary alloying elements. However, it will be appreciated by those skilled in the art that, in addition to the two primary alloying elements, binary alloy systems can comprise minor or impurity amounts of other elements or compounds that do not substantially change the thermodynamic equilibrium behavior of the system.

[0019] The metastable β-titanium alloys according to various non-limiting embodiments disclosed herein can be produced by any method generally known in the art for producing metastable β-titanium alloys. For example and without limitation, the metastable β-titanium alloy can be produced by a process comprising at least one of plasma arc cold hearth melting, vacuum arc remelting, and electron beam melting. Generally speaking, the plasma arc cold hearth melting process involves melting input stock that is either in the form of pressed compacts (called "pucks") formulated with virgin raw material, bulk solid revert (i.e., solid scrap metal), or a combination of both in a plasma arc cold hearth melting furnace (or " PAM" furnace). The resultant ingot can be rotary forged, press forged, or press forged and subsequently rotary forged to an intermediate size prior to hot working.

[0020] For example, according to certain non-limiting embodiments disclosed herein, the β-titanium alloy can be produced by plasma arc cold hearth melting. According to other non-limiting embodiments, the metastable β-titanium alloy can be produced by plasma arc cold hearth melting and vacuum arc remelting. More specifically, the β-titanium alloy can be produced by plasma arc cold hearth melting in a primary melting operation, and subsequently vacuum arc remelted in a secondary melting operation.

[0021] Methods of processing metastable β-titanium alloys according to various non-limiting embodiments of the present invention will now be discussed. One non-limiting embodiment disclosed herein provides a method of processing a metastable β-titanium alloy comprising greater than 10 weight percent molybdenum, the method comprising hot working the metastable β-titanium alloy to a reduction in area of at least 95% by at least one of hot rolling and hot extruding the metastable β-titanium alloy, and direct aging the metastable β-titanium alloy by heating the metastable β-titanium alloy in the hot worked condition at an aging temperature below the β-transus temperature of metastable β-titanium alloy for a time sufficient to form α-phase in the metastable β-titanium alloy.

[0022] Although not meant to be bound by any particular theory, hot working the metastable β-titanium alloy prior to aging in accordance with various non-limiting embodiments disclosed herein is believed by the inventors to be advantageous in increasing the level of work in the alloy and decreasing the grain size of the alloy. Generally speaking, the metastable β-titanium alloy can be hot worked to any percent reduction required to achieve the desired configuration of the alloy, as well as to impart a desired level of work into the β-phase microstructure. As discussed above, in one non-limiting embodiment the metastable β-titanium alloy can be hot worked to a reduction in area of at least 95%. According to another non-limiting embodiment the metastable β-titanium alloy can be hot worked to a reduction in area of at least 98%. According to still another non-limiting embodiment, the metastable β-titanium alloy can be hot worked to a reduction in area of 99%. According to still other non-limiting embodiments, the metastable β-titanium alloy can be hot worked to a reduction in area of at least 75%.

[0023] Further, as discussed above, according to one non-limiting embodiment, hot working the metastable β-titanium alloy can comprise at least one of hot rolling and hot extruding the metastable β-titanium alloy. For example, according to various non-limiting embodiments disclosed herein, hot working the metastable β-titanium alloy can comprise hot rolling the metastable β-titanium alloy at a roll temperature ranging from greater than 1100°F to 1725°F. Further, according to other non-limiting embodiments disclosed herein hot working the metastable β-titanium alloy can comprise hot extruding the metastable β-titanium alloy at a temperature ranging from 1000°F to 2000°F. For example, hot extruding the metastable β-titanium alloy can comprise welding a protective can made from stainless steel, titanium or other alloy or material around the metastable β-titanium alloy to be extruded (or "mult"), heating the canned mult to a selected extrusion temperature, and extruding the entire piece through an extrusion die. Other methods of hot working the metastable β-titanium alloy include, without limitation, those methods known in the art for hot working metastable β-titanium alloys - such as, hot forging or hot drawing.

[0024] As discussed above, after hot working the metastable β-titanium alloy, the alloy is direct aged. As used herein the term "aging" means heating the alloy at a temperature below the β-transus temperature for a period of time sufficient to form α-phase precipitates within

the β-phase microstructure. Further, as used herein, the term "direct aging" means aging an alloy that has been hot worked without solution treating the alloy prior to aging.

[0025] According to various non-limiting embodiments, direct aging the metastable β-titanium alloy can comprise a single-step direct aging process wherein the metastable β-titanium alloy is heated in the hot worked condition at an aging temperature below the β-transus temperature of the metastable β-titanium alloy for a time sufficient to form α-phase precipitates in the metastable β-titanium alloy. For example, although not limiting herein, according to various non-limiting embodiments, the aging temperature can range from 850°F to 1375°F, and can further range from greater than 900°F to 1200°F. According to other non-limiting embodiments, the aging temperature can range from 925°F to 1150°F and can still further range from 950°F to 1100°F.

[0026] One specific non-limiting embodiment provides a method of processing a β-titanium alloy comprising greater than 10 weight percent molybdenum, the method comprising hot working the metastable β-titanium alloy and direct aging the metastable β-titanium alloy, wherein direct aging comprises heating the metastable β-titanium alloy in the hot worked condition at an aging temperature ranging from 850°F to 1375°F for a time sufficient to form α-phase precipitates in the metastable β-titanium alloy.

[0027] As discussed above, according to various non-limiting embodiments, direct aging the metastable β-titanium alloy comprises heating the metastable β-titanium alloy in the hot worked condition for a time sufficient to form α-phase precipitates in the metastable β-titanium alloy. It will be appreciated by those skilled in the art that the precise time required to precipitate the α-phase precipitates in the metastable β-titanium alloy will depend upon several factors, such as, but not limited to, the size and configuration of the alloy, and the aging temperature(s) employed. For example, although not limiting herein, according to one non-limiting embodiment, direct aging the metastable β-titanium alloy can comprise heating the metastable β-titanium alloy at a temperature ranging from 850°F to 1375°F for at least 0.5 hours. According to another non-limiting embodiment, direct aging can comprise heating the metastable β-titanium alloy at a temperature ranging from 850°F to 1375°F for at least 2 hours. According to still another non-limiting embodiment, direct aging can comprise heating the metastable β-titanium alloy at a temperature ranging from 850°F to 1375°F for at least 4 hours. According to another non-limiting embodiment, direct aging can comprise

heating the metastable β-titanium alloy at a temperature ranging from 850°F to 1375°F for 0.5 to 5 hours.

[0028] After processing the metastable β-titanium alloy in accordance with various non-limiting embodiments disclosed herein, the metastable β-titanium alloy can have a tensile strength of at least 150 ksi, at least 170 ksi, at least 180 ksi or greater. Further, after processing the metastable β-titanium alloy in accordance with various non-limiting embodiment disclosed herein, the metastable β-titanium alloy can have an elongation of at least 10 percent, at least 12 percent, at least 15 percent, at least 17 percent and further can have an elongation of at least 20 percent.

[0029] As previously discussed, in the solution treated or β-annealed condition Ti-15Mo β-titanium alloys generally have elongations around 25% and tensile strengths around 110 ksi. Further, as previously discussed, while aging a solution treated Ti-15Mo alloy to form α-phase precipitates within the β-phase microstructure can result in an increase in the tensile strength of the alloy, aging generally decreases the ductility of the alloy. However, by direct aging metastable β-titanium alloys, such as Ti-15Mo, after hot working according to various non-limiting embodiments described herein, tensile strengths of at least 150 ksi and elongations of at least 12 percent can be achieved.

[0030] Although not meant to be bound by any particular theory, it is contemplated that by direct aging the metastable β-titanium alloy after hot working α-phase can be more uniformly formed or precipitated in the β-phase microstructure than if the alloy is solution treated prior to aging, thereby resulting in improved mechanical properties. For example, Figs. 1 and 2 show the microstructures of binary β-titanium alloys comprising about 15 weight percent molybdenum (i.e., Ti-15Mo) processed by a direct aging the alloy in the hot worked condition according to various non-limiting embodiments discussed herein. More specifically, Fig. 1 is a micrograph of a Ti-15Mo alloy that was hot worked and direct aged in a single-step direct aging process by hot rolling the alloy to a reduction in area of 99% and thereafter direct aging the alloy by heating the alloy in the hot worked condition at an aging temperature of about 950°F for about 4 hours, followed by air cooling. As shown in Fig. 1, the microstructure includes both α-phase precipitates 10 and α-lean (e.g., precipitate-free or untransformed β-phase) regions 12.

[0031] Fig. 2 is a micrograph of a Ti-15Mo alloy that was processed by a two-step direct aging process according to various non-limiting embodiments disclosed herein below. More

specifically, the Ti-15Mo alloy of Fig. 2 was hot rolled at a reduction in area of at least 99% and subsequently direct aged by heating the alloy in the hot worked condition at a first aging temperature of about 1275°F for about 2 hours, followed by water quenching, and subsequently heating the alloy at a second aging temperature of about 900°F for about 4 hours, followed by air cooling. As shown in Fig. 2, α-phase precipitates are generally uniformly distributed throughout the microstructure. Further, as discussed below in more detail, processing β-titanium alloys using a two-step direct aging process according to various non-limiting embodiments disclosed herein can be useful in producing β-titanium alloys having a microstructure with a uniform distribution of α-phase precipitates and essentially no untransformed (e.g., precipitate-free or α-lean) metastable phase regions.

[0032] As discussed above, other non-limiting embodiments disclosed herein provide a method of processing a metastable β-titanium alloy comprising greater than 10 weight percent molybdenum, wherein the method comprises hot working the metastable β-titanium alloy and direct aging the metastable β-titanium alloy in a two-step direct aging process in which the metastable β-titanium alloy is heated in the hot worked condition at a first aging temperature below the β-transus temperature and subsequently heated at a second aging temperature below the first aging temperature.

[0033] For example, one specific non-limiting embodiment provides a method of processing a metastable β-titanium alloy comprising greater than 10 weight percent molybdenum, the method comprising hot working a metastable β-titanium alloy and direct aging the metastable β-titanium alloy, wherein direct aging comprises heating the metastable β-titanium alloy in the hot worked condition at a first aging temperature below the β-transus temperature of the metastable β-titanium alloy for a time sufficient to form and at least partially coarsen at least one α-phase precipitate in at least a portion of the metastable β-titanium alloy and subsequently heating the metastable β-titanium alloy at a second aging temperature that is lower than the first aging temperature for a time sufficient to form at least one additional α-phase precipitate in at least a portion of the metastable β-titanium alloy. Further, according to this non-limiting embodiment, after direct aging, the metastable β-titanium alloy can have a microstructure comprising at least one coarse α-phase precipitate and at least one fine α-phase precipitate.

[0034] Additionally, according to various non-limiting embodiments disclosed herein, direct aging the metastable β-titanium alloy can comprise heating at the first aging temperature for a time sufficient to form and at least partially coarsen α-phase precipitates in at least a portion of the metastable phase regions of the alloy, and subsequently heating at the second aging temperature for a time sufficient to form α-phase precipitates in the majority of the remaining metastable phase regions. Further, according to various non-limiting embodiments disclosed herein, the metastable β-titanium alloy can be aged at the second aging temperature for a time sufficient to form additional α-phase precipitates in essentially all of the remaining metastable phase regions of the alloy. As used herein, the term "metastable phase regions" with respect to the metastable β-titanium alloys refers to phase regions within the microstructure that are not thermodynamically favored (i.e., metastable or unstable) at the aging temperature and include, without limitation, β-phase regions as well as ω-phase regions within the microstructure of the alloy. Further, as used herein with respect to the formation of α-phase precipitates in the metastable phase regions, the term "majority" means greater than 50% percent of the remaining metastable phase regions are transformed by the formation of α-phase precipitates, and the term "essentially all" means greater than 90% of the remaining metastable phase regions are transformed by the formation of α-phase precipitates.

[0035] Although not limiting herein, the inventors have observed that by direct aging the hot worked metastable β-titanium alloy by heating at a first aging temperature below the β-transus temperature and subsequently heating the metastable β-titanium alloy at a second aging temperature that is lower than the first aging temperature, a microstructure having a distribution of coarse and fine α-phase precipitates can be formed. Although not limiting herein, it is contemplated by the inventors that metastable β-titanium alloys that are processed to avoid the retention of untransformed (e.g., precipitate-free or α-lean) metastable phase regions within the microstructure may have improved fatigue resistance and/or stress corrosion cracking resistance as compared to metastable β-titanium alloys with such untransformed regions. Further, although not limiting herein, it is contemplated that by transforming essentially all of the metastable phase regions in the microstructure to coarse and fine α-phase precipitates, the resultant alloy can have a desirable combination of mechanical properties such as tensile strength and ductility. As used herein, the term

"coarse" and "fine" with respect to the α-phase precipitates refers general to the grain size of the precipitates, with coarse α-phase precipitates having a larger average grain size than fine α-phase precipitates.

[0036] According to various non-limiting embodiments disclosed herein, the first aging temperature can range from 1225°F to 1375°F and the second aging temperature can range from 850°F to 1000°F. According to other non-limiting embodiments, the first aging temperature can range from greater than 1225°F to less than 1375°F. According to still other non-limiting embodiments, the first aging temperature can range from 1250°F to 1350°F, can further range from 1275°F to 1325°F, and can still further range from 1275°F to 1300°F.

[0037] Further, as discussed above, the metastable β-titanium alloy can be heated at the first aging temperature for a time sufficient to precipitate and at least partially coarsen α-phase precipitates in the metastable β-titanium alloy. It will be appreciated by those skilled in the art that the precise time required to precipitate and at least partially coarsen α-phase precipitates in the metastable β-titanium alloy will depend, in part, upon the size and configuration of the alloy, as well as the first aging temperature employed. According to various non-limiting embodiments disclosed herein, the β-titanium alloy can be heated at the first aging temperature for at least 0.5 hours. According to another non-limiting embodiment, the metastable β-titanium alloy can be heated at the first aging temperature for at least 2 hours. According to still other non-limiting embodiments, the metastable β-titanium alloy can be heated at the first aging temperature for a time ranging from 0.5 to 5 hours.

[0038] As discussed above, according to various non-limiting embodiments disclosed herein, the second aging temperature can range from 850°F to 1000°F. According to other non-limiting embodiments, the second aging temperature can range from greater than 850°F to 1000°F, can further range from 875°F to 1000°F, and can still further range from 900°F to 1000°F.

[0039] Additionally, as discussed above, the metastable β-titanium alloy can be heated at the second aging temperature for a time sufficient to form at least one additional α-phase precipitate in the metastable β-titanium alloy. While it will be appreciated by those skilled in the art that the exact time required to form such additional α-phase precipitates in the metastable β-titanium alloy will depend, in part, upon the size and configuration of the alloy as well as the second aging temperature employed, according to various non-limiting

embodiments disclosed herein, the metastable β-titanium alloy can be heated at the second aging temperature for at least 0.5 hour. According to another non-limiting embodiment, the metastable β-titanium alloy can be heated at the second aging temperature for at least 2 hours. According to still other non-limiting embodiments, the metastable β-titanium alloy can be heated at the second aging temperature for a time raging from 0.5 to 5 hours.

[0040] After processing the metastable β-titanium alloy using a two-step direct aging process in accordance with various non-limiting embodiments disclosed herein, the metastable β-titanium alloy can have a tensile strength of at least 150 ksi, at least 170 ksi, at least 180 ksi or greater. Further, after processing the metastable β-titanium alloy in accordance with various non-limiting embodiment disclosed herein, the metastable β-titanium alloy can have an elongation of at least 10 percent, at least 12 percent, at least 15 percent, at least 17 percent, and further can have an elongation of at least 20 percent.

[0041] Still other non-limiting embodiments disclosed herein provide a method of processing a binary β-titanium alloy comprising greater than 10 weight percent molybdenum, the method comprising hot working the binary β-titanium alloy and direct aging the binary β-titanium alloy at a temperature below the β-transus temperature of the binary β-titanium alloy for a time sufficient to form α-phase precipitates in the binary β-titanium alloy; wherein after processing, the binary β-titanium alloy has a tensile strength of at least 150 ksi and an elongation of 10 percent or greater. For example, after processing the binary β-titanium alloy can have a tensile strength of at least 150 ksi and an elongation of at least 12 percent, at least 15 percent, or at least 20 percent. Further, although not limiting herein, according to this non-limiting embodiment, after processing, the binary β-titanium alloy can have a tensile strength ranging from 150 ksi to 180 ksi and an elongation ranging from 12 percent to 20 percent. For example, according to one non-limiting embodiment, after processing, the binary β-titanium alloy can have a tensile strength of at least 170 ksi and an elongation of at least 15 percent. According to another non-limiting embodiment, after processing, the binary β-titanium alloy can have a tensile strength of at least 180 ksi and an elongation of at least 17 percent.

[0042] Non-limiting methods of direct aging binary β-titanium alloys that can be used in conjunction with the above-mentioned non-limiting embodiment include those set forth above in detail. For example, although not limiting herein, according to the above-mentioned

non-limiting embodiment, direct aging the binary β-titanium alloy can comprise heating the binary β-titanium alloy in the hot worked condition at an aging temperature ranging from 850°F to 1375°F for at least 2 hours. In another example, direct aging the binary β-titanium alloy can comprise heating the binary β-titanium alloy in the hot worked condition at a first aging temperature ranging from greater than 1225°F to less than 1375°F for at least 1 hour; and subsequently heating the binary β-titanium alloy at a second aging temperature ranging from greater than 850°F to 1000°F for at least 2 hours.

[0043] Other embodiments disclosed herein relate to binary β-titanium alloys comprising from greater than 10 weight percent molybdenum, and more particularly comprise from 14 weight percent to 16 weight percent molybdenum, that are made in accordance with the various non-limiting methods discussed above. For example, one non-limiting embodiment provides a binary β-titanium alloy comprising greater than 10 weight percent molybdenum, wherein the binary β-titanium alloy is processed by hot working the binary β-titanium alloy and direct aging the binary β-titanium alloy and wherein after processing, the binary titanium alloy has a tensile strength of at least 150 ksi and an elongation of at least 12 percent. Non-limiting methods of direct aging binary β-titanium alloys that can be used in conjunction with the above-mentioned non-limiting embodiment include those set forth above in detail.

[0044] Suitable non-limiting methods of hot working binary β-titanium alloys that can be used in connection with this and other non-limiting embodiments disclosed herein are set forth above. For example, according various non-limiting embodiments, hot working the binary β-titanium alloy can comprise at least one of hot rolling and hot extruding the binary β-titanium alloy. Further, although not limiting herein, the binary β-titanium alloy can be hot worked to a reduction in area ranging from 95% to 99% in accordance with various non-limiting embodiments disclosed herein.

[0045] Other non-limiting embodiments disclosed herein provide a binary β-titanium alloy comprising greater than 10 weight percent molybdenum, and more particularly comprising 14 weight percent to 16 weight percent molybdenum, and having a tensile strength of at least 150 ksi and an elongation of at least 12 percent. Further, according to this non-limiting embodiment, the binary β-titanium alloy can have an elongation of at least 15% or at least 20%. Non-limiting methods of making the binary β-titanium alloys according to this and other non-limiting embodiments disclosed herein are set forth above.

[0046] Another non-limiting embodiment provides a binary β-titanium alloy comprising greater than 10 weight percent, and more particularly comprising from 14 weight percent to 16 weight percent molybdenum, wherein the binary β-titanium alloy has a tensile strength ranging from 150 ksi to 180 ksi and an elongation ranging from 12 percent to 20 percent. For example, according to one non-limiting embodiment, the binary β-titanium alloy can have a tensile strength of at least 170 ksi and an elongation of at least 15 percent. According to another non-limiting embodiment, the binary b-titanium alloy can have a tensile strength of at least 180 ksi and an elongation of at least 17 percent.

[0047] Further the metastable β-titanium alloys processed according to various non-limiting embodiments disclosed herein can have rotating beam fatigue strengths of at least 550 MPa (about 80 ksi). As used herein the term "rotating beam fatigue strength" means the maximum cyclical stress that a material can withstand for 10^7 cycles before failure occurs in a rotating beam fatigue test when tested at a frequency of 50 Hertz and R= -1. For example, one non-limiting embodiment provides a binary β-titanium alloy comprising greater than 10 weight percent and having a tensile strength of at least 150 ksi, an elongation of at least 12 percent, and a rotating beam fatigue strength of at least 550 MPa. Another non-limiting embodiment provides a binary β-titanium alloy comprising greater than 10 weight percent and having a tensile strength of at least 150 ksi, an elongation of at least 12 percent, and a rotating beam fatigue strength of at least 650 MPa (about 94 ksi).

[0048] Other embodiments disclosed herein are directed toward articles of manufacture comprising binary β-titanium-molybdenum alloys according to the various non-limiting embodiments set forth above. Non-limiting examples of articles of manufacture that can be formed from the binary β-titanium alloys disclosed herein can be selected from biomedical devices, such as, but not limited to femoral hip stems (or hip stems), femoral heads (modular balls), bone screws, cannulated screws (i.e., hollow screws), tibial trays (knee components), dental implants, and intermedullary nails; automotive components, such as, but not limited to valve lifters, retainers, tie rods, suspension springs, fasteners, and screws etc.; aerospace components, such as, but not limited to springs, fasteners, and components for satellite and other space applications; chemical processing components, such as, but not limited to valve bodies, pump casings, pump impellers, and vessel and pipe flanges; nautical components such as, but not limited to fasteners, screws, hatch covers, clips and connectors, ladders and handrails, wire, cable and other components for use in corrosive environments.

[0049] Various non-limiting embodiments of the present invention will now be illustrated by the following non-limiting examples.

EXAMPLES

Example 1

[0050] Allvac® Ti-15Mo Beta Titanium alloy, which is commercially available from ATI Allvac of Monroe, North Carolina was hot rolled at a percent reduction in area of 99% at rolling temperatures ranging from about 1200°F to about 1650°F. Samples of the hot rolled material were then direct aged using either a single-step or a two-step direct aging process as indicated below in Table I. Comparative samples were also obtained from the hot rolled material. As indicated in Table 1, however, the comparative samples were not direct aged after hot rolling.

Table I

Sample Number	First Aging Temp. (°F)	First Aging Time (Hours)	Second Aging Temp. (°F)	Second Aging Time (Hours)
Comparative	NA	NA	NA	NA
1	850	4	NA	NA
2	900	4	NA	NA
3	950	4	NA	NA
4	1275	2	NA	NA
5	1325	2	NA	NA
6	1375	2	NA	NA
7	1225	2	850	4
8	1225	2	900	4
9	1275	2	850	4
10	1275	2	900	4
11	1300	2	900	4
12	1325	2	850	4
13	1325	2	900	4
14	1325	2	950	4
15	1350	2	900	4
16	1375	2	850	4
17	1375	2	900	4

[0051] After processing according to Table I, samples were tensile tested from both the lead and the trail of the coil according to ASTM E21. The tensile testing results are set forth in Table II below, wherein the tabled values are averages of the two test results obtained for each sample (i.e., an average of the values obtained from the lead end sample and the trail end sample).

Table II

Sample Number	UTS (ksi)	0.2% YS (ksi)	Elong. (%)	ROA (%)
Comparative	137.6	121.9	18.5	77.5
1	229.4	226.9	3.0	11.0
2	213.8	209.3	5.0	17.5
3	179.4	170.2	19.0	67.0
4	120.7	116.8	24.5	79.0
5	125.8	121.7	21.5	78.0
6	132.8	125.3	19.0	74.5
7	135.3	126.9	22.0	78.8
8	141.2	133.3	22.0	78.9
9	188.8	182.5	10.0	26.9
10	169.0	161.6	17.3	53.2
11	180.3	172.2	16.5	70.7
12	209.7	205.5	7.5	14.3
13	192.9	184.9	11.5	45.4
14	159.4	144.5	20.0	74.3
15	200.2	196.3	9.5	34.9
16	224.7	221.7	4.5	14.4
17	206.8	202.3	8.3	26.5

[0052] As can be seen from the results in Table II, by processing the Ti-15Mo β-titanium alloys as described above and in accordance with various non-limiting embodiments disclosed herein, Ti-15Mo alloys having advantageous mechanical properties that can be used in a variety of applications can be produced.

Example 2

[0053] A Ti-15Mo ingot was melted, forged and rolled at ATI Allvac. Titanium sponge was blended with pure molybdenum powder to produce compacts for melting a 1360 kg ingot. A plasma cold hearth melting process was used to maintain a shallow melt pool and homogeneity during the primary melt. The plasma melted primary ingot measured 430 mm in diameter. A secondary ingot was subsequently melted to 530 mm in diameter by VAR. The results from chemical analysis of the secondary ingot are presented along with the composition limits set by ASTM F 2066 (Table III). Two values are given for the product analysis when differences were detected between the composition of the top and bottom of the secondary ingot. The β-transus of the ingot was approximately 790°C (about 1454°F).

Table III:

Element	ASTM F 2066 Limit, weight %	Ti-15%Mo

Nitrogen	0.05	0.001 to 0.002
Carbon	0.10	0.006
Hydrogen	0.015	0.0017
Iron	0.10	0.02
Oxygen	0.20	0.15 to 0.16
Molybdenum	14 to 16	14.82 to 15.20
Titanium	balance	balance

[0054] The double melted, 530 mm diameter Ti-15Mo ingot was rotary forged to 100 mm diameter billet using a multi-step process. The final reduction step of this process was conducted above the β-transus temperature, and the resultant microstructure was an equiaxed, β-annealed condition. The 100 mm billet material was subsequently processed into bars using four different processing conditions (A-D) as discussed below. Processing conditions A-C, involved hot working and direct aging, while processing condition D, involved hot working followed by a β-solution treatment.

[0055] For processing conditions A and D, the 100 mm billet was hot rolled at temperature of approximately 1575°F (i.e., above the β-transus temperature of the Ti-15Mo alloy) to form a 25 mm diameter round bar (approximately a 94% reduction in area) using a continuous rolling mill. For processing condition B, the 100 mm billet was prepared by hot rolling at a temperature of approximately 1500°F (i.e., above the β-transus temperature of the Ti-15Mo alloy) to a form a 1" x 3" (25 mm x 75 mm) rectangular bar (approximately a 76% reduction in area) using a hand rolling mill. For processing condition C, the 100 mm billet was prepared as discussed above for processing condition B, however, the hot rolling temperature was approximately 1200°F (i.e., below the β-transus temperature of the Ti-15Mo alloy).

[0056] After hot working as discussed above, the materials were processed and tested as discussed below by Zimmer, Inc. See also Brian Marquardt & Ravi Shetty "*Beta Titanium Alloy Processed for High Strength Orthopaedic Applications*" to be published in Symposium on Titanium, Niobium, Zirconium, and Tantalum for Medical and Surgical Applications, JAI 9012, Vol. XX, No. X; and Brian Marquardt, "*Characterization of Ti-15Mo for Orthopaedic Applications*" to be published in β-Titanium Alloys of the 00's: Corrosion and Biomedical, Proceedings of the TMS Annual Meeting (2005).

[0057] In processing condition A, B and C, after hot rolling, the hot rolled materials were aged in a vacuum furnace at a first aging temperature high in the alpha/beta phase field and subsequently cooled using a fan assisted argon gas quench. Thereafter, the materials were

aged at second aging temperature of 480°C (about 896°F) for 4 hours. In processing condition D, after hot rolling, the hot rolled material was β-solution treated at a temperature of 810°C for 1 hour in an air furnace, followed by water quenching.

[0058] After processing, samples of materials processed using conditions A, B, C, and D were observed using an optical microscope. The material processed using condition A was observed to have banded microstructure with regions of equiaxed prior beta grains and globular alpha grains separated by regions of recovered beta grains and elongated alpha. The microstructure of the material processed using condition B showed little to no evidence of recrystallization. The alpha phase was elongated in some areas but it often appeared in a partially globularized form along variants of the prior beta grains. The material processed using condition C had a fully recrystallized and uniformly refined microstructure, wherein the recrystallized prior beta grains and globular alpha were roughly equivalent in size to the recrystallized regions in the banded structure of the material processed using condition A. The average prior beta grain size was approximately 2 μm while the globular alpha was typically 1 μm or less. The material processed using condition D was observed to have an equiaxed beta grain structure 'free' of alpha phase, wherein the beta grain size was approximately 100 μm.

[0059] Smooth tensile tests were conducted on specimen obtained from materials processed using conditions A, B, C, and D in accordance to ASTM E-8 at a strain rate of 0.005 per minute through the 0.2% yield strength and a head rate of 1.3 mm per minute to failure. The smooth tensile specimens were machined and tested at Metcut Research. The smooth test specimen configuration had nominal gage dimensions of 6.35 mm diameter by 34.5 mm length. The results of the tensile tests are shown below in Table IV.

[0060] Rotating beam fatigue testing were also conducted on specimen obtained from materials processed using conditions A, B and C. The rotating beam fatigue specimen were machined at Metcut Research and tested at Zimmer, Inc. using a Model RBF 200 made by Fatigue Dynamics of Dearborn, MI. The specimen configuration had a nominal gage diameter of 4.76 mm. The R ratio of the test was -1 and the frequency was 50 Hertz. The results of the rotating beam fatigue tests are shown in Fig. 3.

Table IV:

Processing Condition	UTS MPa	0.2% YS MPa	Elong.%	RA %
A	1280	1210	14	59

B	1290	1240	9	32
C	1320	1290	9	32
D	770	610	38	80

[0061] As can be seen from the data in Table IV, the materials processed by hot working and direct aging (i.e., processing conditions A-C), had UTS values at or above 1280 MPa (about 186 ksi), 0.2% YS values at or above 1210 MPa (about 175 ksi), and elongations ranging from 9-14%. As expected, the material processed using processing condition D (i.e., hot working followed by β-solution treatment) had lower UTS and 2%YS than the direct aged materials values but higher elongations.

[0062] As can be seen from Fig. 3, the materials processed using conditions A and C had rotating beam fatigue strengths greater than about 600 MPa, and the material processed using condition B has a rotating beam fatigue strength greater than about 500 MPa.

Example 3:

[0063] A round billet of Allvac® Ti-15Mo Beta Titanium alloy having a diameter of 4" was hot rolled to form a round bar having 0.5" diameter. The rolling temperature was approximately 1700°F. The hot rolled alloy was then aged in a two-step direct aging process by heating the hot rolled alloy at a first aging temperature of 1275°F for 2 hours, water quenching the alloy, and subsequently heating the alloy at a second aging temperature of 900°F for 4 hours. After heating at the second aging temperature, the alloy was air cooled to room temperature.

[0064] Subsequently, five tensile test samples (labeled 1 to 5 in Table V) were obtained from the aged alloy and the samples were tested at room temperature in accordance with ASTM E8. The results of this testing are set forth below in Table V:

Table V:

Sample	Modulus (GPa)	0.2% Offset YS (MPa)	UTS (MPa)	Elong. (%)	RA (%)
1	108	1136	1190	19.54	62.18
2	112	1205	1256	20.38	58.61
3	111	1216	1265	20.38	59.89
4	115	1267	1311	19.46	56.96
5	112	1206	1252	20.29	61.97
Mean	112 +/- 2	1206 +/- 47	1255 +/- 43	20.01 +/- 0.47	59.92 +/- 2.22

[0065] It is to be understood that the present description illustrates aspects of the invention relevant to a clear understanding of the invention. Certain aspects of the invention that would be apparent to those of ordinary skill in the art and that, therefore, would not facilitate a better understanding of the invention have not been presented in order to simplify the present description. Although the present invention has been described in connection with certain embodiments, the present invention is not limited to the particular embodiments disclosed, but is intended to cover modifications that are within the spirit and scope of the invention as defined by the appended claims.

CLAIMS

We claim:

1. A method of processing a metastable β-titanium alloy comprising greater than 10 weight percent molybdenum, the method comprising:

hot working the metastable β-titanium alloy; and

direct aging the metastable β-titanium alloy, wherein direct aging comprises heating the metastable β-titanium alloy in the hot worked condition at an aging temperature ranging from 850°F to 1375°F for a time sufficient to form α-phase precipitates within the metastable β-titanium alloy.

2. The method of claim 1 wherein the metastable β-titanium alloy is a binary titanium-molybdenum alloy comprising from 14 weight percent to 16 weight percent molybdenum.

3. The method of claim 1 wherein hot working the metastable β-titanium alloy comprises one of: hot rolling the metastable β-titanium alloy at a roll temperature ranging from greater than 1100°F to 1725°F and hot extruding the metastable β-titanium alloy at a temperature ranging from 1000°F to 2000°F.

4. The method of claim 1 wherein the metastable β-titanium alloy is hot worked to a percent reduction in area ranging from 95% to 99%.

5. The method of claim 1 wherein the aging temperature ranges from greater than 900°F to 1200°F.

6. The method of claim 1 wherein the aging temperature ranges from 925°F to 1150°F.

7. The method of claim 1 wherein the aging temperature ranges from 950°F to 1100°F.

8. The method of claim 1 wherein prior to hot working the metastable β-titanium alloy, the metastable β-titanium alloy is produced by a process comprising at least one of plasma arc cold hearth melting and vacuum arc remelting.

9. The method of claim 1 wherein after processing, the metastable β-titanium alloy has a tensile strength of at least 150 ksi.

10. The method of claim 1 wherein after processing, the metastable β-titanium alloy has a tensile strength of at least 170 ksi.

11. The method of claim 1 wherein after processing, the metastable β-titanium alloy has a tensile strength of at least 180 ksi.

12. The method of claim 1 wherein after processing, the metastable β-titanium alloy has an elongation of at least 12 percent.

13. The method of claim 1 wherein after processing, the metastable β-titanium alloy has an elongation of at least 15 percent.

14. The method of claim 1 wherein after processing, the metastable β-titanium alloy has an elongation of at least 20 percent.

15. A method of processing a metastable β-titanium alloy comprising greater than 10 weight percent molybdenum, the method comprising:

hot working a metastable β-titanium alloy; and

direct aging the metastable β-titanium alloy, wherein direct aging comprises:

heating the metastable β-titanium alloy in the hot worked condition at a first aging temperature below the β-transus temperature of the metastable β-titanium alloy for a time sufficient to form and at least partially coarsen at least one α-phase precipitate within at least a portion of the metastable β-titanium alloy; and subsequently

heating the metastable β-titanium alloy at a second aging temperature that is lower than the first aging temperature for a time sufficient to form at least one additional α-phase precipitate within at least a portion of the metastable β-titanium alloy.

16. The method of claim 15 wherein the metastable β-titanium alloy is a binary titanium-molybdenum alloy comprising from 14 weight percent to 16 weight percent molybdenum.

17. The method of claim 15 wherein hot working the metastable β-titanium alloy comprises one of: hot rolling the metastable β-titanium alloy at a roll temperature ranging from greater than 1100°F to 1725°F and hot extruding the metastable β-titanium alloy at a temperature ranging from 1000°F to 2000°F.

18. The method of claim 15 wherein the metastable β-titanium alloy is hot worked to a reduction in area of ranging from 95% to 99%.

19. The method of claim 15 wherein the first aging temperature ranges from 1225°F to 1375°F.

20. The method of claim 15 wherein the first aging temperature ranges from 1250°F to 1350°F.

21. The method of claim 15 wherein the first aging temperature ranges from 1275°F to 1325°F.

22. The method of claim 15 wherein the first aging temperature ranges from 1275°F to 1300°F.

23. The method of claim 15 wherein the second aging temperature ranges from 850°F to 1000°F.

24. The method of claim 15 wherein the second aging temperature ranges from 875°F to 1000°F.

25. The method of claim 15 wherein the second aging temperature ranges from 900°F to 1000°F.

26. The method of claim 15 wherein prior to direct aging the metastable β-titanium alloy has a microstructure comprising metastable phase regions, and

heating the metastable β-titanium alloy at the first aging temperature comprises heating the metastable β-titanium alloy for a time sufficient to form and at least partially coarsen α-phases precipitate within at least a portion of the metastable phase regions; and

heating the metastable β-titanium alloy at a second aging temperature comprises heating the metastable β-titanium alloy for a time sufficient to form α-phase precipitates within a majority of remaining metastable phase regions in the metastable β-titanium alloy.

27. The method of claim 26 wherein heating the metastable β-titanium alloy at a second aging temperature comprises heating the metastable β-titanium alloy for a time sufficient to form α-phase precipitates within essentially all of the remaining metastable phase regions in the metastable β-titanium alloy.

28. The method of claim 15 wherein after processing, the metastable β-titanium alloy has a microstructure comprising at least one coarse α-phase precipitate and at least one fine α-phase precipitate.

29. The method of claim 15 wherein after processing, the metastable β-titanium alloy has a tensile strength of at least 150 ksi.

30. The method of claim 15 wherein after processing, the metastable β-titanium alloy has a tensile strength of at least 170 ksi.

31. The method of claim 15 wherein after processing, the metastable β-titanium alloy has a tensile strength of at least 180 ksi.

32. The method of claim 15 wherein after processing, the metastable β-titanium alloy has an elongation of at least 12 percent.

33. The method of claim 15 wherein after processing, the metastable β-titanium alloy has an elongation of at least 15 percent.

34. The method of claim 15 wherein after processing, the metastable β-titanium alloy has an elongation of at least 20 percent.

35. The method of claim 15 wherein after processing, the binary β-titanium alloy has a rotating beam fatigue strength of at least 550 MPa.

36. The method of claim 15 wherein after processing, the binary β-titanium alloy has a rotating beam fatigue strength of at least 650 MPa.

37. The method of claim 15 wherein prior to hot working the metastable β-titanium alloy, the metastable β-titanium alloy is produced by a process comprising at least one of plasma arc cold hearth melting and vacuum arc remelting.

38. A method of processing a metastable β-titanium alloy comprising greater than 10 weight percent molybdenum, the method comprising:

hot working a metastable β-titanium alloy; and

direct aging the metastable β-titanium alloy, wherein direct aging comprises:

heating the metastable β-titanium alloy in the hot worked condition at a first aging temperature ranging from 1225°F to 1375°F for at least 0.5 hours; and subsequently

heating the metastable β-titanium alloy at a second aging temperature ranging from 850°F to 1000°F for at least 0.5 hours.

39. A method of processing a metastable β-titanium alloy comprising greater than 10 weight percent molybdenum, the method comprising:

hot working the metastable β-titanium alloy to a reduction in area of at least 95 percent by at least one of hot rolling and hot extruding the metastable β-titanium alloy; and

direct aging the metastable β-titanium alloy by heating the metastable β-titanium alloy in the hot worked condition at an aging temperature below the β-transus temperature of metastable β-titanium alloy for a time sufficient to form α-phase precipitates within the metastable β-titanium alloy.

40. A method of processing a binary β-titanium alloy comprising greater than 10 weight percent molybdenum, the method comprising:

hot working the binary β-titanium alloy; and

direct aging the binary β-titanium alloy by heating the β-titanium alloy in the hot worked condition at an aging temperature below the β -transus temperature of the binary β-titanium alloy for a time sufficient to form α-phase precipitates within the binary β-titanium alloy;

wherein after processing, the binary β-titanium alloy has a tensile strength of at least 150 ksi and an elongation of at least 12 percent.

41. The method of claim 40 wherein direct aging the binary β-titanium alloy comprises one of a single-step direct aging process and a two-step direct aging process.

42. The method claim 40 wherein after processing, the binary β-titanium alloy has a tensile strength ranging from 150 ksi to 180 ksi and an elongation ranging from 12 percent to 20 percent.

43. The method claim 40 wherein after processing, the binary β-titanium alloy has a tensile strength of at least 170 ksi and an elongation of at least 15 percent.

44. The method claim 40 wherein after processing, the binary β-titanium alloy has a tensile strength of at least 180 ksi and an elongation of at least 17 percent.

45. A binary β-titanium alloy comprising greater than 10 weight percent molybdenum and having a tensile strength of at least 150 ksi and an elongation of at least 12 percent.

46. The binary β-titanium alloy of claim 45 wherein the binary β-titanium alloy has an elongation of at least 20 percent.

47. The binary β-titanium alloy of claim 45 wherein the binary β-titanium alloy has a tensile strength ranging from 150 ksi to 180 ksi and an elongation ranging from 12 percent to 20 percent.

48. The binary β-titanium alloy of claim 45 wherein the binary β-titanium alloy has a tensile strength of at least 170 ksi and an elongation of at least 15 percent.

49. The binary β-titanium alloy of claim 45 wherein the binary β-titanium alloy has a tensile strength of at least 180 ksi and an elongation of at least 17 percent.

50. The binary β-titanium alloy of claim 45 wherein the binary β-titanium alloy has a rotating beam fatigue strength of at least 650 MPa.

51. An article of manufacture comprising a binary β-titanium alloy according to claim 45.

52. The article of manufacture of claim 45 wherein the article of manufacture is selected from the group consisting of biomedical components; automotive components; aerospace components; chemical processing components; and nautical components.

53. The article of manufacture of claim 52 wherein biomedical components are selected from the group consisting of hip stems, femoral heads, bone screws, cannulated screws, tibial trays, dental implants, intermedullary nails, valve lifters, retainers, tie rods, suspension springs, fasteners, screws, valve bodies, pump casings, pump impellers, vessels, pipe flanges, fasteners, screws, hatch covers, clips, connectors, ladders, handrails, wires, and cables.

Fig. 1:



Fig. 2:

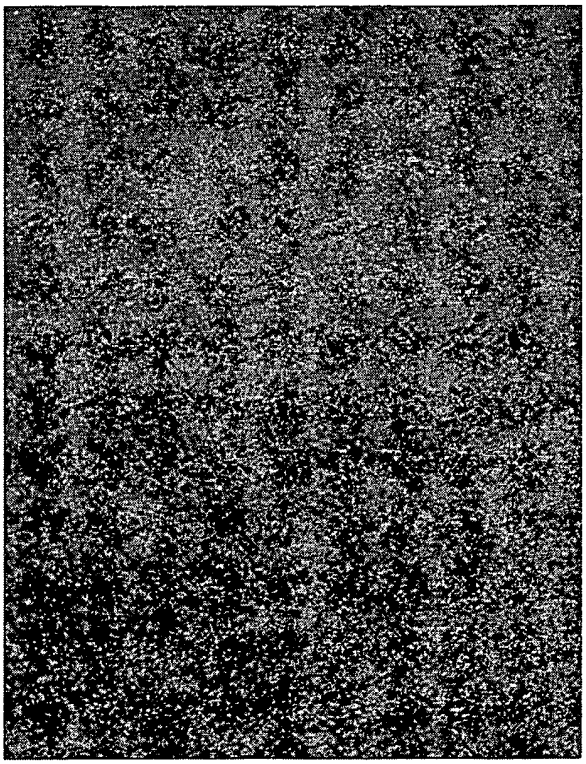
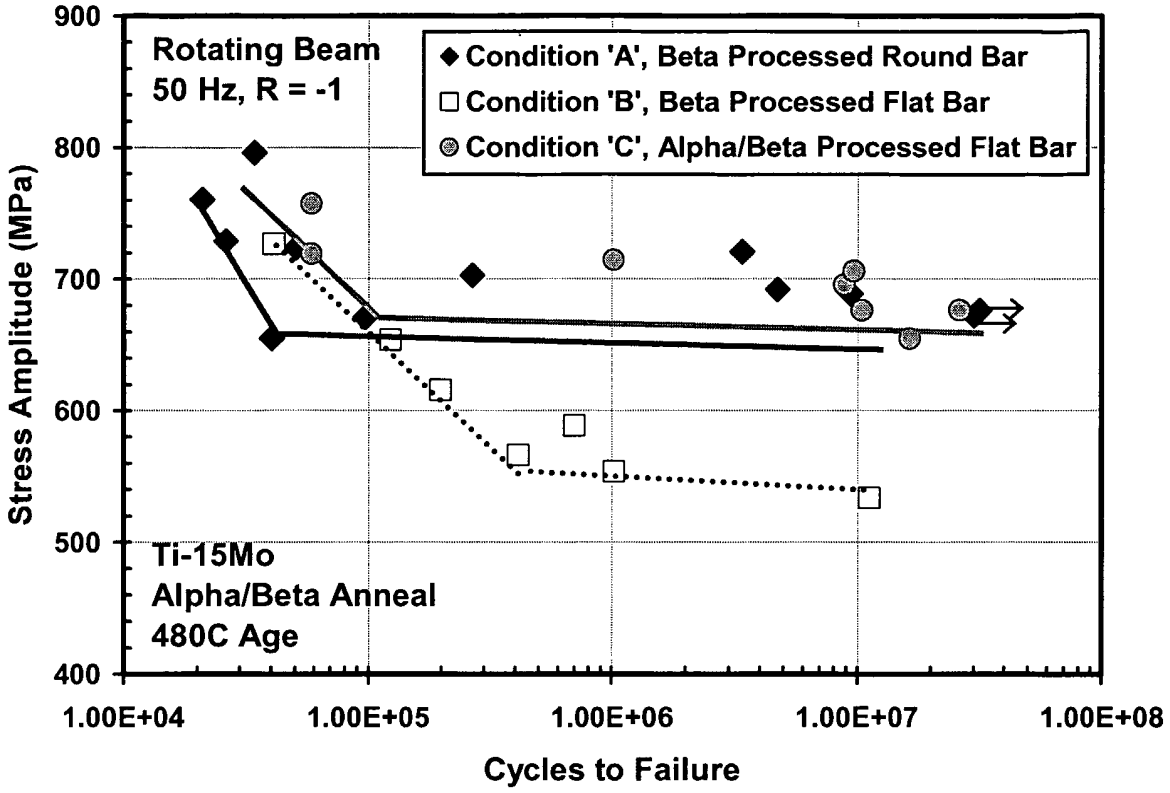


Fig 3:


Rotating Beam
50 Hz, R = -1
Condition 'A', Beta Processed Round Bar
Condition 'B', Beta Processed Flat Bar
Condition 'C', Alpha/Beta Processed Flat Bar
Ti-15Mo
Alpha/Beta Anneal
480C Age
Stress Amplitude (MPa)
900
800
700
600
500
400
1.00E+04
1.00E+05
1.00E+06
1.00E+07
1.00E+08
Cycles to Failure