A titanium alloy includes a nickel content controlled to a level sufficient to reduce incidence of strain induced porosity upon hot working the titanium alloy relative to incidence of strain induced porosity in a second alloy upon hot working, the second alloy comprising no greater than an impurities level of nickel and otherwise having an elemental composition identical to the titanium alloy.
## FIGURE 1

<table>
<thead>
<tr>
<th>Location</th>
<th>Position</th>
<th>Temp. °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-1</td>
<td>Center</td>
<td>1645°F</td>
</tr>
<tr>
<td>B-8</td>
<td>Center</td>
<td>1645°F</td>
</tr>
</tbody>
</table>

**BETA TRANSUS - LOM**
FIGURE 14

NO WORST

LOCATION: T4S(TYPICAL)  LOCATION: T4S(WORST)

LOCATION: T4MR(TYPICAL)  LOCATION: T4MR(WORST)

LOCATION: T4C(TYPICAL)  LOCATION: T4C(WORST)
FIGURE 19

MAG: 100X

LOCATION: B8S (TYPICAL)

LOCATION: B8S (WORST)

LOCATION: B8MR (TYPICAL)

LOCATION: B8MR (WORST)

LOCATION: B8C (TYPICAL)

LOCATION: B8C (WORST)
Multizone Testing Report

Size: 8"

Test Status: Approved

<table>
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<tr>
<th>Billet Information</th>
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<th>Noise</th>
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<tbody>
<tr>
<td>B-9</td>
<td>133.125</td>
<td>12</td>
</tr>
<tr>
<td>T-1</td>
<td>194.625</td>
<td>12</td>
</tr>
<tr>
<td>T-2</td>
<td>192</td>
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<td>12</td>
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<tr>
<td>T-7</td>
<td>175.75</td>
<td>12.8</td>
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Inspection Results

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<tr>
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<th>Non-rejectable Internal Indications</th>
<th>Rejectable Internal Indications</th>
<th>Results</th>
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<tbody>
<tr>
<td>B-9</td>
<td>0</td>
<td>0</td>
<td>Acceptable</td>
</tr>
<tr>
<td>T-1</td>
<td>0</td>
<td>0</td>
<td>Acceptable</td>
</tr>
<tr>
<td>T-2</td>
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<tr>
<td>T-7</td>
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<td>Acceptable</td>
</tr>
</tbody>
</table>

FIGURE 20
SIP by % Nickel

Heats Sequenced in Decreasing % Ni Content

350 PPM Ni

SIP Present?

- N
- Y

FIGURE 21
Figure 22: Ti-17 SIP versus Nickel Content

Two-sample T for Ni

SIP?  #  Mean  StDev
N    182  0.0486  0.0102
Y    55   0.03963 0.00734

Estimate for difference: 0.00994
P-Value = 0.000
Both use Pooled StDev = 0.00960

Boxplots of Ni by SIP
(marks are indicated by solid circles)

Analysis of Variance for Ni

Individual 95% CIs for Mean
Based on Pooled StDev

SIP?  #  Mean  StDev
N    182  0.040565 0.010182
Y    55   0.039022 0.007339

Pooled StDev = 0.00960

0.0229
0.0266
0.0306
TITANIUM ALLOYS, METHODS OF FORMING THE SAME, AND ARTICLES FORMED THEREFROM

TECHNICAL FIELD

[0001] The present invention relates to methods of making titanium alloys, titanium alloys produced therefrom, and articles formed from the alloys.

BACKGROUND

[0002] Certain titanium alloys possess particularly good properties for use in high performance components, such as biomedical and aerospace components. The high strength:to-weight ratios, toughness, corrosion resistance, and low creep rates of these alloys make them particularly well suited for use in high performance rotating components, such as discs and rotors in aircraft and land-based turbines. These desired properties, along with certain manufacturing considerations, such as welding and forming requirements, determine suitable alloy composition, structure, heat treatment, and level of process control in the alloy systems.

[0003] To provide the mechanical properties required under stringent user specifications, careful and strict control of the microstructure and casting and forging processes is generally required. Even slight adjustments in processing of titanium alloys can significantly affect microstructure, properties, and performance of forged titanium alloys. It is therefore necessary to inspect these alloy during various stages of manufacture to ensure that the desired integrity and mechanical properties are achieved in the forged product.

[0004] Much of the focus of testing and research on titanium alloys is directed at optimizing microstructure. At about 885°C, titanium undergoes an allotropic transformation from an alpha (α) phase, which has a close packed hexagonal crystal structure, to a beta (β) phase, which has a body-centered cubic structure. The β transus temperature can be raised or lowered by varying the identity and amount of alloying elements employed. For example, aluminum, tin, and zirconium are α-stabilizing agents, and vanadium, molybdenum, and tantalum are α-stabilizing agents. Other residual β stabilizers, such as nickel and iron, are thought to detrimentally affect properties of titanium alloys, such as creep, and typically are maintained at amounts that are as low as practicable, typically well below about 0.03 weight percent (See, e.g., P.A. Russo, J.R. Wood, R.N. Brousis, S.W. Marcinko, and S.R. Giangiordano, “Influence of Ni and Fe on the Creep of Beta Annealed Ti-6242S”, Titanium ’95: Sc. and Tech., 1075-1082). Typically, it is at the grain boundaries where defects may be sporadically found that develop during hot working (such as hot forging, extrusion, superplastic forming, and the like) of cast titanium alloy ingots to forged products. These defects may include the occurrence of small internal voids or pores, known as strain induced porosity (SIP). SIP is particularly detrimental to the integrity of the final forged article. Because high performance applications demand superior mechanical properties, the presence of even minor levels of SIP in forged titanium alloy articles may render them unsuitable for use in such applications. A frequent result is that the material is scrapped.

[0005] Due to part to stringent user requirements for titanium alloys in aerospace components, extensive efforts have been made to improve the mechanical properties of titanium alloys for these applications. Attempts to reduce the incidence of SIP in forged titanium alloys have focused on alloy forming and deformation methods over a wide range of process parameters, including furnace time and temperature, forging speed, forging drafts, and the like. For example, prior investigators have examined the physical mechanisms that cause SIP, and have developed modified hot working practices aimed at reducing or preventing SIP formation. In particular, attempts have been made to reduce the incidence of SIP and improve the integrity of high performance titanium alloy aerospace components through adjustment of the process conditions used to melt and hot work the alloy. Examples of such attempts are described in: Prasad, et al., “Hot Deformation Mechanisms in Ti-6Al-4V with Transformed β Starting Microstructure: Commercial v. Extra Low Interstitial Grade”, Mater. Sci and Tech., 2000, 16, 1029-1036; and Tamirisakandala, et al., “Strain-Induced Porosity During Coggings of Extra-Low Interstitial Grade Ti-6Al-4V”, J. Mater. Sci. and Perf., 2001, 10(2), 125-127. These reported methods use various processing conditions, such as hot working temperatures, amount of deformation, and rate of cooling, to reportedly provide improved alloy properties.

[0006] Further improvements would be a welcome addition to the prior art processes in which control and monitoring of ingot casting and hot working conditions are intended to improve the characteristics of titanium alloys. More particularly, there is a continued need for approaches reducing the incidence of SIP in titanium alloys and providing greater integrity, physical properties, and performance in the articles formed therefrom.

SUMMARY

[0007] In one embodiment, the present invention provides a titanium alloy having anickel content controlled to a level no greater than 0.10 weight percent and sufficient to reduce the incidence of strain induced porosity upon hot working the titanium alloy relative to the incidence of strain induced porosity in a second alloy upon hot working. The second alloy includes no greater than an impurities level of nickel and otherwise has an elemental composition identical to the titanium alloy.

[0008] In another embodiment, the present invention provides a titanium alloy having greater than an impurities level of aluminum and having a nickel content controlled to a level sufficient to reduce the incidence of strain induced porosity upon hot working the titanium alloy relative to the incidence of strain induced porosity upon hot working a second alloy. The second alloy includes no greater than an impurities level of nickel and otherwise has an elemental composition identical to the titanium alloy.

[0009] In yet another embodiment, the present invention provides a titanium alloy including greater than an impurities level of aluminum and also including a nickel content added and controlled to at least 0.035 percent by weight.

[0010] In another embodiment, the present invention provides a titanium alloy having a nickel content controlled within the range 0.035 to 0.10 percent by weight.

[0011] The present invention also provides a method of making a titanium alloy. The method includes forming a melt comprising a source of titanium and a source of nickel.
The nickel content of the melt is controlled to a level no greater than 0.10 percent by weight and sufficient to reduce the incidence of strain induced porosity upon hot working the titanium alloy relative to the incidence of strain induced porosity in a second alloy upon hot working. The second alloy comprises no greater than an impurities level of nickel and otherwise has an elemental composition identical to the titanium alloy. The method also includes casting the melt.

[0012] In another embodiment, the present invention provides a method of making a titanium alloy including greater than an impurities level of aluminum. The method includes forming a melt comprising a source of titanium, a source of nickel, and a source of aluminum. The nickel content of the melt is controlled to at least 0.035 percent by weight. The method includes casting the melt.

[0013] In yet another embodiment, the present invention provides a method of making a titanium alloy. The method includes forming a melt having a source of titanium and a source of nickel. The source of nickel is at least one of virgin raw nickel, nickel pellets, nickel shot, nickel powder, and nickel-containing master alloy. The nickel content of the melt is controlled to no greater than 0.10 percent by weight. The method includes casting the melt.

[0014] The present invention also provides an article of manufacture comprising a titanium alloy of the present invention. For example, the titanium alloy may include a nickel content controlled to a level no greater than 0.10 weight percent and sufficient to reduce the incidence of strain induced porosity upon hot working the titanium alloy relative to the incidence of strain induced porosity in a second alloy upon hot working. The second alloy comprises no greater than an impurities level of nickel and otherwise has an elemental composition identical to the titanium alloy.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] The characteristics and advantages of the present invention may be better understood by reference to the accompanying drawings, wherein:

[0016] FIG. 1 provides test results of eight billets formed by the embodiment of the method described in Example 2, and includes measured beta transus temperatures at the top of the first billet and at the bottom of the final billet;

[0017] FIGS. 2-10 are photomicrographs of the as-forged macrostructure taken on transverse sections from the top of each billet and the bottom of the final billet produced in Example 2;

[0018] FIGS. 11-19 are photomicrographs of the as-forged structure in the typical and worst conditions of each billet produced in Example 2;

[0019] FIG. 20 provides an ultrasonic inspection report on billets of the as-forged structure produced in Example 2;

[0020] FIG. 21 provides a statistical analysis of the nickel content in a Ti-17 alloy and its effect on strain induced porosity; and

[0021] FIG. 22 shows a statistical analysis of Ti-17 alloy heats with and without SIP versus the range of nickel contents.

DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

[0022] It is to be understood that certain descriptions of the present invention have been simplified to illustrate only those elements and limitations that are relevant to a clear understanding of the present invention, while eliminating, for purposes of clarity, other elements. Those of ordinary skill in the art, upon considering the present description of the invention, will recognize that other elements and/or limitations may be desirable in order to implement the present invention. However, because such other elements and/or limitations may be readily ascertained by one of ordinary skill upon considering the present description of the invention, and are not necessary for a complete understanding of the present invention, a discussion of such elements and limitations is not provided herein. For example, as discussed herein, certain embodiments of the titanium alloys of the present invention may be used in, for example, high performance aerospace applications, such as for parts of aircraft and land-based turbines. The manner of manufacturing aircraft and land-based turbines, for example, are generally understood by those of ordinary skill in the art and, accordingly, are not described in detail herein.

[0023] Furthermore, certain compositions within the present invention are generally described in the form of titanium alloys that may be used to produce certain high performance components and articles, such as parts for aircraft and land-based turbines. It will be understood, however, that the present invention may be embodied in forms and applied to end uses that are not specifically and expressly described herein. For example, one skilled in the art will appreciate that embodiments of the present invention may be incorporated into other high performance articles. Non-exhaustive examples of such other high performance articles include aircraft and airframe parts, rocket components and rocket motors, gas turbine engines, industrial land-based turbines, internal combustion engines, automobile and motorcycle components, automotive racing parts (such as, for example, valves, springs, and brakes), heat exchangers, equipment employed in the chemical and petrochemical industries, such as, for example, tanks, pipes, valves, pumps, and the like, biomedical implant components, surgical instruments, recreational equipment, sports equipment, architectural components, and building materials.

[0024] Other than in the examples herein, or unless otherwise expressly specified, all of the numerical ranges, amounts, values and percentages, such as those for amounts of materials, elemental contents, times and temperatures of reaction, ratios of amounts, and others, in the following portion of the specification and attached claims may be read as if prefaced by the words “about” even though the term “about” may not expressly appear with the value, amount, or range. Accordingly, unless indicated to the contrary, the numerical parameters set forth in the following specification and attached claims are approximations that may vary depending upon the desired properties sought to be obtained by the present invention. At the very least, and not as an attempt to limit the application of the doctrine of equivalents to the scope of the claims, each numerical parameter should at least be construed in light of the number of reported significant digits and by applying ordinary rounding techniques.

[0025] Notwithstanding that the numerical ranges and parameters set forth the broad scope of the invention are approximations, the numerical values set forth in the specific examples are reported as precisely as possible. Any numeri-
cal value, however, inherently contains error necessarily resulting from the standard deviation found in its underlying respective testing measurements. Furthermore, when numerical ranges are set forth herein, these ranges are inclusive of the recited range end points (i.e., end points may be used). When percentage by weight are used herein, the numerical values reported are relative to the total alloy weight.

As used herein, the following terms or phrases have the following meanings. The terms “controlled” and “controlling” mean having applied or applying, as the case may be, any method, technique, or practice of actively monitoring and adjusting the intentional addition of an ingredient to a melt, or of otherwise actively monitoring and adjusting the chemical composition of a melt, to achieve the result that the content of an element in the melt falls within an aim. The term “source” means any material suitable for use as an ingredient to a melt to provide a particular elemental constituent to the melt. The phrase “impurities level of nickel” means a nickel content of 150 ppm (0.015 percent by weight) or less. The phrase “impurities level of aluminum” means an aluminum content of 50 ppm (0.005 percent by weight) or less.

The present invention is directed, generally, to titanium materials, and more particularly, to titanium alloys and methods of making and employing the same. Certain of the titanium alloys within the present invention would have application in, for example, high performance components, such as discs and rotors for aircraft and land-based turbines and in certain biomedical devices. It has been found that the intentional addition of relatively small amounts of nickel (but greater than impurities levels of nickel) to titanium or titanium alloys reduces the incidence of voids or SIP during processing, particularly during hot working processes such as forging. For example, the inventors have determined that a reduced incidence of SIP during processing is exhibited in certain titanium alloys including greater than an impurities level of nickel when subjected to particular hot working conditions as set forth herein.

As supported by the working examples set forth herein, titanium alloys believed to benefit from the intentional nickel addition described herein include commercial and semi-commercial grades and alloys of titanium that are well known in the art. Non-limiting examples of titanium alloys believed to benefit from the present invention include Commercially Pure Titanium (i.e., 98.5 percent by weight titanium or greater) (referred to as CP Ti), Commercially Pure Titanium with additions (i.e., 98 percent by weight titanium or greater) (such as, for example, CP Ti-Pd, CP Ti-Grades 12-16), Ti-6Al-4V (Ti-6-4), Ti-6Al-4V-ELI (extra low interstitial) (Ti-6-4-ELI), Ti-5Al-2.5Sn (Ti-5-2-5), Ti-5Al-2.5Sn (Ti-5-2-5-ELI), Ti-5Al-2.5Sn-ELI (Ti-5-2-5-ELI), Ti-5Al-2.5Sn-ELI (Ti-3-2-5), Ti-6Al-2.5Sn (Ti-6-2-5), Ti-6Al-2.5Sn (Ti-6-2-5), Ti-6Al-4 (Ti-6-4), Ti-6Al-4 (Ti-6-4), Ti-6Al-4 (Ti-6-4), Ti-6Al-4 (Ti-6-4), Ti-4Al (Ti-4-4-2), Ti-4Al-2Fe-3Al (Ti-4-2-3), Ti-15V-3Cr-3Al-3Sn (Ti-15-3-3-3), Ti-3Al-8V-6Cr-4Zr-4Mo (Ti-3-8-6-4-4), Ti-13V-11Cr-3Al (Ti-13-11-3), and Ti-5Al-2Sn-2Zr-4Mo-4Cr (Ti-17). With regard to each such titanium alloy, the elemental composition may be controlled to adjust the nickel content to a level providing a reduced incidence of SIP. As used herein, a “reduced incidence” or like language referring to SIP means that there is a statistically significant reduction in SIP formation when evaluated over a suitable number of test samples. As discussed in further detail herein, the several embodiments of the present invention discussed herein are believed to show exceptional reduction in the incidence of SIP with the intentional addition of a nickel-containing material to the melt and controlling the nickel content to a level greater than an impurities level.

When producing alloys within the present invention, the nickel content is controlled to fall within a range that reduces the incidence of SIP in formed articles of the alloy relative to a titanium alloy having only an impurities level of nickel. Typical impurities ranges for elements such as nickel are in the range of 0.001 to less than 0.015 percent by weight (10 to less than 150 ppm). In certain embodiments, titanium alloys within the present invention include a nickel content that is controlled within the range of 0.035 to 0.10 percent by weight (350 to 1000 ppm). The addition of nickel to the titanium alloys may be more narrowly controlled within the range of 0.035 to 0.065 percent by weight in certain embodiments, and in other embodiments is controlled to an amount of 0.055 percent by weight.

In making the titanium alloys of the present invention, the nickel content may be added to the melt as one or more of various sources including, for example, virgin raw nickel (substantially pure nickel), nickel-containing master alloys (i.e., metal alloys of known composition consisting of nickel in combination with one or more other elements, such as aluminum-nickel or titanium-nickel), and revert material including major or minor amounts of nickel. Available sources of virgin raw nickel include, for example, nickel pellets, nickel shot, and nickel powder. Sources of nickel revert material include, for example, nickel machining turnings, and solid titanium-containing revert material such as, for example, recycled scrap material from unsuitable titanium alloy melts, conversion of titanium ingots into product, forging or casting titanium components, and turnings from machining titanium articles.

As described in the Examples set forth herein, certain titanium alloys of the present invention may be made and processed by a method initially including reduction of titanium ore into sponge (a porous form of titanium metal). The sponge is melted along with sources of alloying ingredients and, for example, revert material, and cast to form an ingot. The ingot is subsequently remelted, cast, and forged into general mill products, such as billets, bars, plates, and the like, for secondary fabrication. The added revert may be previously melted titanium or titanium alloy and can be in the form of, for example, solid pieces or machining turnings.

With regard to preparing the melt, the titanium ore and other major components of the titanium alloy, if necessary, may be pulverized and mixed in any manner known to those of ordinary skill in the art. The raw ore may be pulverized, such as through crushing or shearing, and mixed such that titanium and all alloying agents are present in the desired amounts and ratios. Also, through appropriate selection of ingredients, other elements such as nitrogen, carbon, hydrogen, iron, and oxygen may be held to acceptable levels to obtain desired mechanical properties or to limit any adverse effect on the mechanical properties of the final alloy. The raw material is blended together in preparation for melting. The raw ingredients may be consolidated into a generally homogenous cylindrical or rectangular form via a series of manufacturing and melting processes.
cesses can include consumable melting, (e.g., vacuum arc remelting (VAR) or electro-slag remelting (ESR)), non-consumable melting (e.g., non-consumable electric arc, plasma cold hearth melting, or electron beam cold hearth melting), or a combination of any of these practices. As discussed above, the selection and addition of each of the raw ingredients to form the melt must be carefully controlled because of the effect these additions have on the properties of the alloy in the finished form.

[0033] To the major components of the melt are added small, but effective, amounts of nickel by way of a nickel source. The nickel content of the melt is controlled within a range sufficient to reduce SIP in formed articles of the alloy relative to a titanium alloy having a nickel content not exceeding an impurities level, but otherwise having the same chemistry as the melt. The intentional addition of nickel includes a formulation aim, such that the addition of raw materials meets the formulation aim. In certain embodiments of the present invention, the nickel content is controlled within the range of 0.035 to 0.10 percent by weight, may be more narrowly controlled within the range of 0.035 to 0.065 percent by weight, and in some embodiments is controlled to 0.050 percent by weight.

[0034] The addition of nickel is from a nickel source that may be, for example, virgin raw nickel, revert material, or a combination of virgin raw material and revert. For example, virgin raw nickel in the form of, for example, nickel pellets and nickel shot, along with nickel revert material in the form of, for example, turnings, may be added to the titanium melt at intentional, target levels as set forth herein to form the titanium alloy melt. Titanium turnings having nickel as a minor element at less than 1 percent by weight, and typically in the range of 0.08 to 0.20 percent by weight, have been found to be particularly beneficial, versus solid revert material such as, for example, recycled scrap material from previous titanium alloy melts. The remelting and casting into the finished shape for secondary fabrication are thereafter completed as known to those of ordinary skill in the art and as described in the Examples below. The final ingot is converted by hot working, e.g., forging or rolling at elevated temperatures, to a size than can be used to produce a desired final product. For example, the ingot may be forged using β and/or α-β forging practices well known to those skilled in the art. The hot working operation changes the physical shape and the internal structure of the titanium or titanium alloy to impart the desired physical, mechanical, and optical properties to the material. The invention operates during this hot working by changing the physical response of the titanium so that the formation of SIP is significantly reduced, and in some instances is substantially eliminated.

[0035] As illustrated in the Examples and the Figures, it has been found that intentionally adding nickel and controlling the nickel content of a titanium or titanium-alloy melt to meet a formulated range, which may be from 0.035 weight percent to 0.10 weight percent, can reduce or eliminate the formation of SIP during hot working. The invention has the most significance when applied to titanium alloys that are susceptible to SIP and can be used to significantly reduce or eliminate defects that cause material to be scrapped, resulting in significant cost savings. It is believed that the present understanding in the titanium industry is that the addition of nickel to titanium alloys is to be avoided because doing so could negatively affect the creep (high temperature plastic deformation under low mechanical loading) properties of certain titanium alloys.

[0036] The present invention may be further understood by reference to the following examples. The following examples are merely illustrative of the invention and are not intended to be limiting. Unless otherwise indicated, all parts are by weight.

Example 1

[0037] A 30 inch diameter round Plasma Arc Melted Single Vacuum Arc Remelted ingot of Ti-17, (i.e., the cast ingot of a titanium alloy having a nominal outer diameter of 30 inches) having a nickel content controlled to a 0.035 to 0.065 percent by weight range was primary melted using a plasma arc cold hearth method followed by a final melt using a vacuum consumable arc technique, and ingot-to-billet converted for the production of nominal 8 inch round premium quality beta finished Ti-17 forging billets.

Example 2

[0038] The ingot-to-billet conversion practice employed was as follows. A 30 inch diameter ingot was heated to a temperature above the β transus for purposes of homogenization, and then β forged to an intermediate size. The ingot was then heated to a temperature in the α+β phase range and approaching the β transus and forged to provide pre-strain for recrystallization. The ingot was then reheated to a temperature in the β field and forged to recrystallize the grain size. Through a series of 3 heating and forging operations, the product was forged to final size. The final forging operations were accomplished using a rotary forging machine (GFMM). The conversion process used a Round Corner Square (RCS) intermediate press forging geometry.

[0039] Based on the β transus, hydrogen, macro/microstructure, and multi-zone ultrasonic results, the billets produced from this heat did not exhibit SIP voiding and were considered acceptable for further fabrication. SIP was measured by immersion ultrasonic testing, wherein no indications of SIP were found in the billets during testing the heat.

Example 2

[0040] A 30 inch round ingot of Ti-17 was primary melted by the plasma cold hearth process followed by having a nickel source added to the melt and controlled to between 0.065 to 0.086 weight percent and remelted as set forth in Example 1. The ingot was ingot-to-billet converted to provide a nominal 8 inch round premium quality beta finished forging billets.

Example 4

[0041] The ingot-to-billet conversion practice employed was as follows. A 30 inch diameter ingot was heated to a temperature above the D transus for purposes of homogenization, and then β forged to an intermediate size. The ingot was then heated to a temperature in the α+β phase range and approaching the β transus and forged to provide pre-strain for recrystallization. The ingot was then reheated to a temperature in the β field and forged to recrystallize the β grain size. Through a series of β heating and forging operations, the product was forged to final size. The final forging operations were accomplished using a GFMM rotary forging machine. The surface of the intermediate forged product and final billets were conditioned by a combination of grinding and peeling. The heat yielded eight billets, labeled Billets 1-8, which are presented in FIG. 1 along with
the individual length of each billet in inches. This figure also reports center β transus temperatures from the top and bottom of the heat as determined by metallurgical techniques.

[0042] A ¾ inch thick sample was taken from the top of every billet and the bottom of the bottommost billet throughout the heat. (The top of Billet 1, for example, is referred to herein and in the Figures as “T-1” or “T1”, while the bottom of Billet 8, for example, is referred to as “B-8” or “B8”). The β transus temperatures of T-1 and B-8 were measured at the center position using light optical microscopy (LOM). The ¾ inch thick samples were faced, blue etched and evaluated for the presence of segregation and macro grain size and found acceptable to specification. Photomicrographs of the as-forged structure are provided in Figs. 2-10. For Billet 8, two photomicrographs were prepared, identified as T-8 (Fig. 9) and B-8 (Fig. 10), at the top and bottom, respectively, of the billet.

[0043] From each of the nine macro-samples, shown in Figs. 2-10, metallurgical specimens were taken at surface, mid-radius, and center locations of each billet and examined in the longitudinal direction. Micros were polished and etched for structure and evaluated per specification and found acceptable. Representative as-forged photomicrographs (100X) in the typical and worst conditions are included in Figs. 11-19. TIS, TIMR and TIC in Fig. 11, for example, refer to the surface, mid-radius and center specimens, respectively, of the macro-sample of the top of Billet 1. In Figs. 11-19, those conditions referred to as “worst” refer to the poorest micro sample portion found in the specimen, wherein the largest agglomeration of material (known as coarse α) was found.

[0044] Hydrogen levels were tested and met requirements at the mid-radius location on the B-8 billet (bottom of bottommost billet) at 48 ppm.

[0045] All billets were immersion multizone ultrasonically inspected and found acceptable as set forth in Fig. 20. Based on the applied forging technique, β transus results, macro/microstructure, hydrogen content, and multizone ultrasonic test results, the billets produced were considered acceptable for use in further fabrication. Each billet lacked any detected SIP.

[0046] Other investigation confirmed that the addition of small, but effective, amounts of nickel to titanium or titanium alloys reduces the tendency of the alloyed material to form voids or SIP during manufacture, particularly during hot working processes. The reduced SIP formation during processing may be obtained from titanium alloy materials that are a combination of major components and one or more minor components at particular hot working conditions, as set forth herein. In certain embodiments, the titanium alloy of the present invention includes a nickel content that is controlled within the range of 0.035 to 0.10 percent by weight. The addition of nickel to the titanium alloys may be more narrowly controlled within the range of 0.035 to 0.065 percent by weight, and in some embodiments is controlled in an amount of 0.050 percent by weight.

[0047] As illustrated in Fig. 21, a study of the incidence of SIP formation in nickel-containing Ti-17 alloys reveals that in alloys having nickel content of at least 0.035 percent by weight, 31 of 33 heats (94%) exhibited no SIP formation. In contrast, in alloys having nickel content below 0.035 percent by weight, 12 of 30 heats (40%) exhibited SIP.

[0048] Test results provided in Fig. 22 show statistical analysis of nickel-containing Ti-17 alloy heats with and without SIP versus the range of nickel contents. The two sample T test for the heats is graphically illustrated in the boxplots. Data in Fig. 22 shows that there is a statistically significant difference in nickel content (P-value less than 0.01) between heats with and without SIP. As set forth in Fig. 22, there is a 100 percent confidence level (P-value equal to 0) of this difference. Heats considered in the statistical study of Fig. 22 having nickel content within the amounts and ranges set forth herein did not exhibit detectable SIP, while a substantial fraction of heats with lower nickel levels did exhibit SIP.

[0049] It will be appreciated by those of ordinary skill in the art that the improved characteristics of the alloys of the present invention would be expected to provide a higher yield of usable material and a lower scrap rate when fashioned into billets for use in certain high performance products. Embodiments of the present invention experience reduced incidence of SIP and, therefore, may be particularly suited for applications having stringent user specifications. It will also be appreciated by those skilled in the art that changes could be made to the embodiments described herein without departing from the broad concept of the invention. It is understood, therefore, that this 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.

We claim:
1. A titanium alloy having a nickel content controlled to a level no greater than 0.10 weight percent and sufficient to reduce incidence of strain induced porosity upon hot working the titanium alloy relative to incidence of strain induced porosity in a second alloy upon hot working, the second alloy comprising no greater than an impurities level of nickel and otherwise having an elemental composition identical to the titanium alloy.
2. The titanium alloy of claim 1, wherein the nickel content is controlled to at least 0.035 percent by weight.
3. The titanium alloy of claim 2, wherein the nickel content is controlled within the range 0.035 to 0.10 percent by weight.
4. The titanium alloy of claim 3, wherein the nickel content is controlled within the range 0.035 to 0.065 percent by weight.
5. The titanium alloy of claim 4, wherein the nickel content is controlled to 0.05 percent by weight.
6. The titanium alloy of claim 1, wherein the titanium alloy comprises greater than an impurities level of aluminum.
7. The titanium alloy of claim 1, wherein, with the exception of nickel content, the elemental composition of the titanium alloy is that of a material selected from the group consisting of Commercially Pure Titanium, Commercially Pure Titanium with additions, Ti-6AI-4V, Ti-6AI-4V-ELI, Ti-5AI-2.5Sn, Ti-5AI-2.5Sn-ELI, Ti-3Al-2.5Sn, Ti-6AI-6V-2Sn, Ti-6AI-7Nb, Ti-7Al-4Mo, Ti-4Al-4Mo-2Sn, Ti-10V-2Fe-3Al, Ti-15V-3Cr-3Al-3Sn, Ti-3Al-8V-6Cr-4Zr-4Mo, Ti-13V-11Cr-3Al, and Ti-5AI-2Sn-2Zr-4Mo-4Cr.
8. The titanium alloy of claim 1, wherein a source of the nickel content in the titanium alloy is at least one material
selected from the group consisting of virgin raw nickel, nickel-containing revert, nickel pellets, nickel shot, nickel powder, nickel-containing master alloy, and nickel-containing turnings.

9. A titanium alloy comprising greater than an impurities level of aluminum and having a nickel content controlled to a level sufficient to reduce incidence of strain induced porosity upon hot working the titanium alloy relative to incidence of strain induced porosity upon hot working a second alloy, the second alloy comprising no greater than an impurities level of nickel and otherwise having an elemental composition identical to the titanium alloy.

10. The titanium alloy of claim 9, wherein the nickel content is controlled to at least 0.035 percent by weight.

11. The titanium alloy of claim 10, wherein the nickel content is controlled within the range 0.035 to 0.10 percent by weight.

12. The titanium alloy of claim 11, wherein the nickel content is controlled within the range 0.035 to 0.065 percent by weight.

13. The titanium alloy of claim 12, wherein the nickel content is controlled to 0.05 percent by weight.

14. The titanium alloy of claim 9, wherein, with the exception of nickel content, the elemental composition of the titanium alloy is that of a material selected from the group consisting of Commercially Pure Titanium, Commercially Pure Titanium with additions, Ti-6Al-4V, Ti-6Al-4V-ELI, Ti-5Al-2.5Sn, Ti-5Al-2.5Sn-ELI, Ti-3Al-2.5Sn, Ti-6Al-6V-2Sn, Ti-6Al-7Nb, Ti-7Al-4Mo, Ti-4Al-4Mo-2Sn, Ti-10V-2Fe-3Al, Ti-15V-3Cr-3Al-3Sn, Ti-3Al8V6Cr4Zr4Mo, Ti-13V-11Cr-3Al, and Ti-5Al-2Sn-2Zr-4Mo-4Cr.

15. The titanium alloy of claim 9, wherein a source of the nickel content is at least one material selected from the group consisting of virgin raw nickel, nickel-containing revert, nickel pellets, nickel shot, nickel powder, nickel-containing master alloy, and nickel-containing turnings.

16. A titanium alloy comprising greater than an impurities level of aluminum and a nickel content added and controlled to at least 0.035 percent by weight.

17. The titanium alloy of claim 16, wherein the nickel content is controlled within the range 0.035 to 0.10 percent by weight.

18. The titanium alloy of claim 17, wherein the nickel content is controlled within the range 0.035 to 0.065 percent by weight.

19. The titanium alloy of claim 18, wherein the nickel content is controlled to 0.05 percent by weight.

20. The titanium alloy of claim 16, wherein, with the exception of nickel content, the elemental composition of the alloy is that of a material selected from the group consisting of Commercially Pure Titanium, Commercially Pure Titanium with additions, Ti-6Al-4V, Ti-6Al-4V-ELI, Ti-5Al-2.5Sn, Ti-5Al-2.5Sn-ELI, Ti-3Al-2.5Sn, Ti-6Al-6V-2Sn, Ti-6Al-7Nb, Ti-7Al-4Mo, Ti-4Al-4Mo-2Sn, Ti-10V-2Fe-3Al, Ti-15V-3Cr-3Al-3Sn, Ti-3Al8V6Cr4Zr4Mo, Ti-13V-11Cr-3Al, and Ti-5Al-2Sn-2Zr-4Mo-4Cr.

21. A titanium alloy comprising a nickel content added and controlled within the range 0.035 to 0.10 percent by weight.

22. The titanium alloy of claim 21, wherein the nickel content is controlled within the range 0.035 to 0.065 percent by weight.

23. The titanium alloy of claim 22, wherein the nickel content is controlled to 0.050 percent by weight.

24. The titanium alloy of claim 21 wherein, with the exception of nickel content, the elemental composition of the titanium alloy is that of a material selected from the group consisting of Commercially Pure Titanium, Commercially Pure Titanium with additions, Ti-6Al-4V, Ti-6Al-4V-ELI, Ti-5Al-2.5Sn, Ti-5Al-2.5Sn-ELI, Ti-3Al-2.5Sn, Ti-6Al-6V-2Sn, Ti-6Al-7Nb, Ti-7Al-4Mo, Ti-4Al-4Mo-2Sn, Ti-10V-2Fe-3Al, Ti-15V-3Cr-3Al-3Sn, Ti-3Al8V6Cr4Zr4Mo, Ti-13V-11Cr-3Al, and Ti-5Al-2Sn-2Zr-4Mo-4Cr.

25. A method of making a titanium alloy, the method comprising:

forming a melt comprising a source of titanium and a source of nickel;

controlling the nickel content of the melt to a level no greater than 0.10 percent by weight and sufficient to reduce incidence of strain induced porosity upon hot working the titanium alloy relative to incidence of strain induced porosity in a second alloy upon hot working, the second alloy comprising no greater than an impurities level of nickel and otherwise having an elemental composition identical to the titanium alloy;

and casting the melt.

26. The method of claim 25, wherein the nickel content is controlled within the range 0.035 to 0.10 percent by weight.

27. The method of claim 26, wherein the nickel content is controlled within the range of 0.035 to 0.065 percent by weight.

28. The method of claim 27, wherein the nickel content is controlled to 0.050 percent by weight.

29. The method of claim 25, wherein the titanium alloy comprises greater than an impurities level of aluminum.

30. The method of claim 25, wherein, with the exception of nickel content, the elemental composition of the alloy is that of a material selected from the group consisting of Commercially Pure Titanium, Commercially Pure Titanium with additions, Ti-6Al-4V, Ti-6Al-4V-ELI, Ti-5Al-2.5Sn, Ti-5Al-2.5Sn-ELI, Ti-3Al-2.5Sn, Ti-6Al-6V-2Sn, Ti-6Al-7Nb, Ti-7Al-4Mo, Ti-4Al-4Mo-2Sn, Ti-10V-2Fe-3Al, Ti-15V-3Cr-3Al-3Sn, Ti-3Al8V6Cr4Zr4Mo, Ti-13V-11Cr-3Al, and Ti-5Al-2Sn-2Zr-4Mo-4Cr.

31. The method of claim 25, wherein the source of the nickel is at least one material selected from the group consisting of virgin raw nickel, nickel-containing revert, nickel pellets, nickel shot, nickel powder, nickel containing master alloys, and nickel-containing turnings.

32. A method of making a titanium alloy including greater than an impurities level of aluminum, the method comprising:

forming a melt comprising a source of titanium, a source of nickel, and a source of aluminum;

controlling the nickel content of the melt to at least 0.035 percent by weight; and

casting the melt.

33. The method of claim 32, wherein the nickel content is controlled within the range 0.035 to 0.10 percent by weight.

34. The method of claim 33, wherein the nickel content is controlled within the range of 0.035 to 0.065 percent by weight.

35. The method of claim 34, wherein the nickel content is controlled to 0.05 percent by weight.
36. The method of claim 32, wherein the source of nickel is at least one material selected from the group consisting of virgin raw nickel, nickel-containing revert, nickel pellets, nickel shot, nickel powder, nickel-containing master alloys, and nickel-containing turnings.

37. A method of making a titanium alloy, the method comprising:

- forming a melt comprising a source of titanium and a source of nickel, wherein the source of nickel is at least one of virgin raw nickel, nickel pellets, nickel shot, nickel powder, and nickel-containing master alloy;
- actively controlling the nickel content of the melt to no greater than 0.10 percent by weight; and
- casting the melt.

38. The method of claim 37, wherein the nickel content is controlled within the range 0.035 to 0.10 percent by weight.

39. The method of claim 38, wherein the nickel content is controlled within the range 0.035 to 0.065 percent by weight.

40. The method of claim 39, wherein the nickel content is controlled to 0.05 percent by weight.

41. The method of claim 37, wherein the titanium alloy includes greater than an impurities level of aluminum.

42. The method of claim 37, wherein, with the exception of nickel content, the elemental composition of the titanium alloy is that of a material selected from the group consisting of Commercially Pure Titanium, Commercially Pure Titanium with additions, Ti-6Al-4V, Ti-6Al-4V-ELI, Ti-5Al-2.5Sn, Ti-5Al-2.5Sn-ELI, Ti-3Al-2.5Sn, Ti 6Al-6V-2Sn, Ti-6Al-7Nb, Ti-7Al-4Mo, Ti-4Al-4Mo-2Sn, Ti-10V-2Fe-3Al, Ti-15V-3Cr-3Al-3Sn, Ti-3Al-8V-6Cr-4Zr-4Mo, Ti-13V-11Cr-3Al, and Ti-5Al-2Sn-2Zr-4Mo-4Cr.

43. An article of manufacture comprising the titanium alloy of claim 1.

44. The article of manufacture of claim 43, wherein the article of manufacture is selected from the group consisting of turbines, aircraft and airframe parts, rocket components, motors, engines, automobile and motorcycle components, automotive racing components, valves, springs, brakes, heat exchangers, industrial equipment, tanks, pipes, valves, pumps, biomedical implant components, surgical instruments, recreational equipment, sports equipment, architectural components, and building materials.

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