



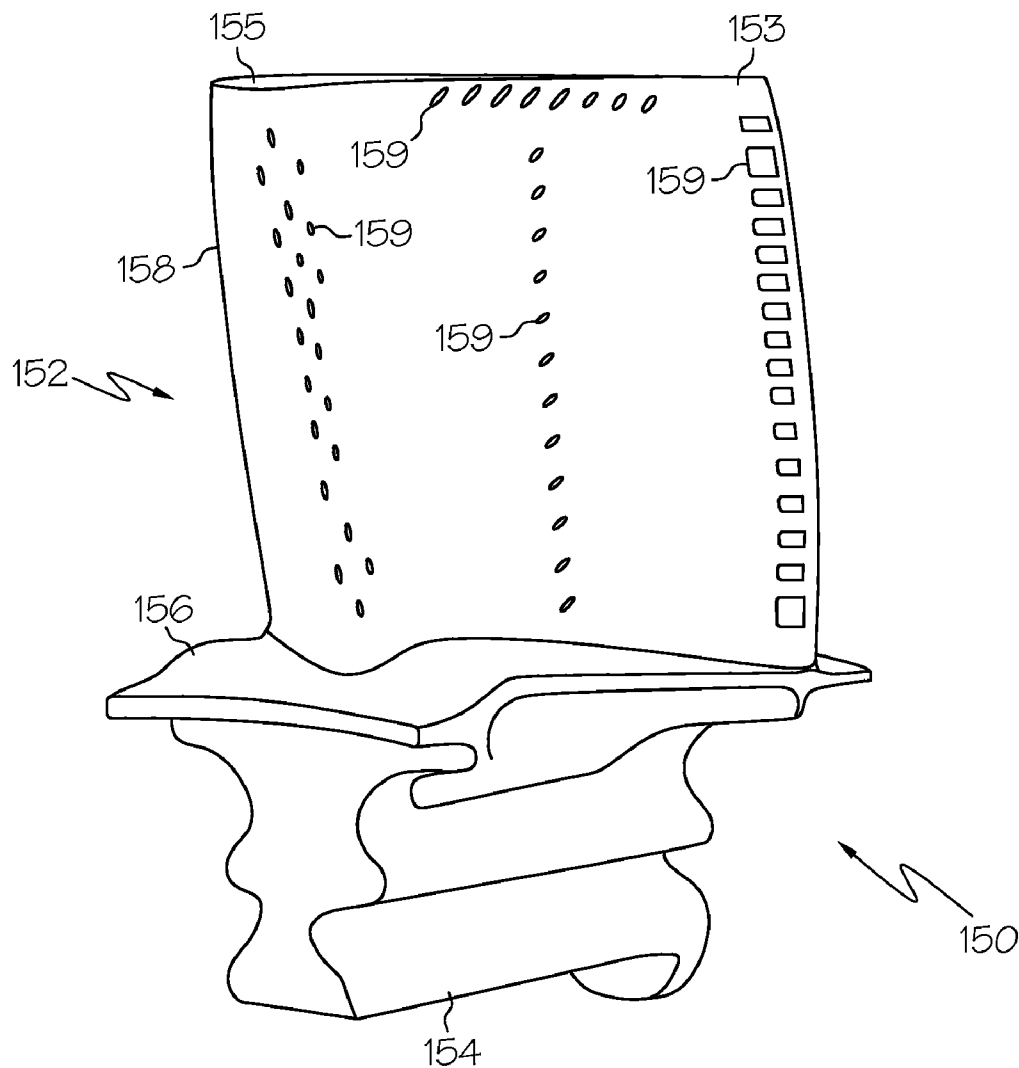
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Hu(10) **Pub. No.: US 2009/0185944 A1**(43) **Pub. Date: Jul. 23, 2009**(54) **SUPERALLOY COMPOSITIONS WITH
IMPROVED OXIDATION PERFORMANCE
AND GAS TURBINE COMPONENTS MADE
THEREFROM****Publication Classification**(51) **Int. Cl.**
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Correspondence Address:
**HONEYWELL INTERNATIONAL INC.
PATENT SERVICES
101 COLUMBIA ROAD, P O BOX 2245
MORRISTOWN, NJ 07962-2245 (US)**

(73) **Assignee: HONEYWELL
INTERNATIONAL, INC.,
Morristown, NJ (US)**(21) **Appl. No.: 12/017,101**(22) **Filed: Jan. 21, 2008**(57) **ABSTRACT**

Single crystal superalloy compositions and components made from such compositions are provided. One composition consists essentially of, in weight percent, from about 4 to about 7 percent chromium; from about 8 to about 12 percent cobalt; from about 1 to about 2.5 percent molybdenum; from about 3 to about 6 percent tungsten; from about 2 to about 4 percent rhenium; from about 5 to about 7 percent aluminum; from about 0 to about 1.5 percent titanium; from about 6 to about 10 percent tantalum; from about 0.08 to about 1.2 percent hafnium; no more than about 0.0002 percent sulfur; no more than about 0.007 percent zirconium; and the balance nickel.



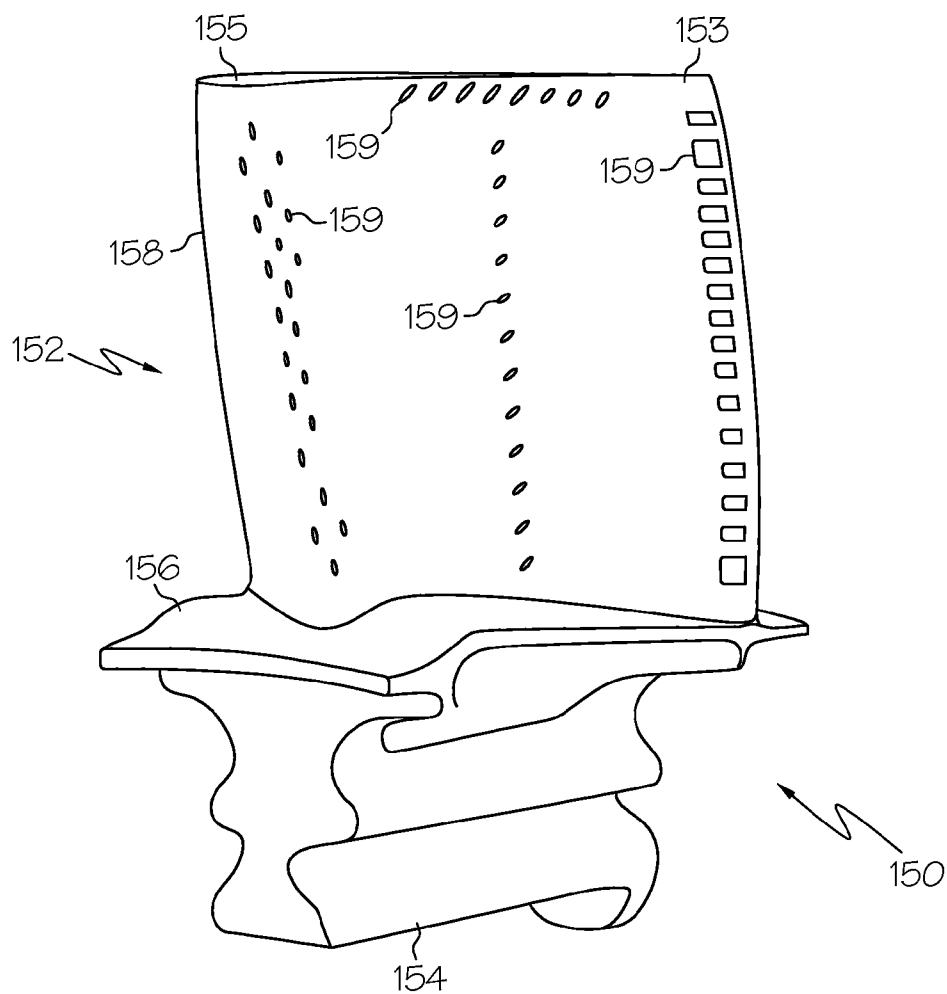


FIG. 1

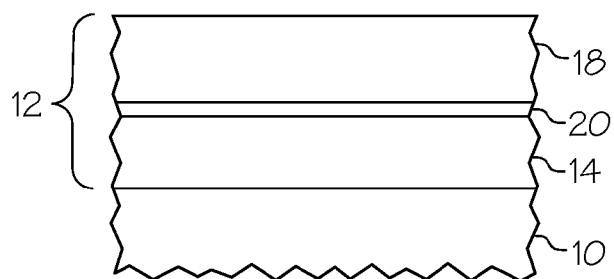


FIG. 2

**SUPERALLOY COMPOSITIONS WITH
IMPROVED OXIDATION PERFORMANCE
AND GAS TURBINE COMPONENTS MADE
THEREFROM**

FIELD OF THE INVENTION

[0001] The present invention generally relates to metallic materials for gas turbine engine applications, and more particularly relates to superalloy compositions with improved oxidation performance and components of gas turbine engines made therefrom.

BACKGROUND OF THE INVENTION

[0002] In an attempt to increase the efficiencies and performance of contemporary gas turbine engines generally, engineers have progressively pushed the engine environment to more extreme operating conditions. The harsh operating conditions of high temperature and pressure that are now frequently specified place increased demands on engine component-manufacturing technologies and new materials. Indeed the gradual improvement in engine design has come about in part due to the increased strength and durability of new materials that can withstand the operating conditions present in the modern gas turbine engine.

[0003] Turbine airfoils are key engine components that directly experience severe engine operation conditions. Turbine blades of turbine airfoils are thus designed and manufactured to perform under repeated cycles of high stress and high temperature. Turbine blades used in modern gas turbine engines are frequently cast from a class of materials known as precipitation-strengthening superalloys. These superalloys include nickel-, cobalt-, and iron-based alloys. In the cast form, turbine blades made from these superalloys include many desirable elevated-temperature properties such as elevated-temperature strength and good environment resistance. Advantageously, the strength displayed by this type of material remains even under stressful conditions, such as high temperature and high pressure, that are experienced during engine operation. The precipitation-strengthening superalloys are thus a preferred material for the manufacturing of turbine blades and vanes.

[0004] However, while the superalloys exhibit superior mechanical properties under high temperature and pressure conditions, they are subject to oxidation and corrosion attack by chemical degradation. The gases at high temperature and pressure in the turbine engine can lead to oxidation of the exposed superalloy substrates. High-pressure turbine (HPT) blades, that is, those turbine blades at the high pressure stages following the combustion stage of a gas turbine engine, are particularly subject to this kind of oxidation attack and erosion, particularly at the blade tip areas. Blade tips are also potential wear points. Oxidation is undesirable because it can lead to the gradual erosion of blade tip material, which affects the dimensional characteristic of the blade and its physical integrity. In general, eroded blade tips negatively affect engine performance.

[0005] Thermal barrier coatings (TBCs) may be used to protect the superalloy components of a gas turbine engine that are subjected to extremely high temperatures. Typical TBCs include those formed of yttria stabilized zirconia (YSZ) and yttria stabilized zirconia doped with other oxides such as Gd_2O_3 , TiO_2 , and the like. An effective TBC has a low thermal conductivity and strongly adheres to an underlying bond

coating, to which it is bonded under contemplated use conditions. To extend the service life of a TBC, an environment-resistant bond coating is commonly employed. Bond coatings typically are in the form of overlay coatings such as $MCrAlX$, where M is a metallic element such as nickel, cobalt, and/or a combination of both nickel and cobalt, and X is yttrium or other reactive and metallic elements. A bond coating also can be a diffusion coating such as a simple aluminide coating, a reactive element-modified aluminide coating, a platinum-modified aluminide coating or a reactive element-modified platinum aluminide coating. During exposure of TBCs to high temperature, such as during ordinary service use thereof, bond coatings of the type described above oxidize first to form a thermally grown oxide (TGO) that protects the underlying structure from further catastrophic oxidation. However, if the TGO layer grows too quickly and/or too thickly, adherence of the TBC to the bond coating can be compromised, and cracks between the TBC and the TGO as well as between the TGO and the bond coating form. This causes the TBC to prematurely spall off, thus decreasing the service life of the superalloy component.

[0006] Accordingly, it is desirable to provide an improved superalloy composition for gas turbine engine applications wherein the superalloy has improved oxidation performance. In addition, it is desirable to provide an improved superalloy that reacts with the bond coating to improve the life of both the bond coating and the overlying TBC. Furthermore, other desirable features and characteristics of the present invention will become apparent from the subsequent detailed description of the invention and the appended claims, taken in conjunction with the accompanying drawings and this background of the invention.

BRIEF SUMMARY OF THE INVENTION

[0007] In accordance with an exemplary embodiment of the present invention, a single crystal nickel-based superalloy composition is provided. The single crystal nickel-based superalloy composition consists essentially of, in weight percent, from about 4 to about 7 percent chromium; from about 8 to about 12 percent cobalt; from about 1 to about 2.5 percent molybdenum; from about 3 to about 6 percent tungsten; from about 2 to about 4 percent rhenium; from about 5 to about 7 percent aluminum; from about 0 to about 1.5 percent titanium; from about 6 to about 10 percent tantalum; from about 0.08 to about 1.2 percent hafnium; no more than about 0.0002 percent sulfur; no more than about 0.007 percent zirconium; and the balance nickel.

[0008] In accordance with an exemplary embodiment of the present invention, a single crystal nickel-based superalloy component is provided. The single crystal nickel-based superalloy component is fabricated of a single crystal composition consisting essentially of (in weight percent) from about 4 to about 7 percent chromium; from about 8 to about 12 percent cobalt; from about 1 to about 2.5 percent molybdenum; from about 3 to about 6 percent tungsten; from about 2 to about 4 percent rhenium; from about 5 to about 7 percent aluminum; from about 0 to about 1.5 percent titanium; from about 6 to about 10 percent tantalum; from about 0.08 to about 1.2 percent hafnium; no more than about 0.0002 percent sulfur; no more than about 0.007 percent zirconium; and the balance nickel.

[0009] In accordance with an exemplary embodiment of the present invention, a process for preparing a single crystal nickel-based superalloy component is provided. The method

comprises the steps of providing an alloy comprising (in weight percent) from about 4 to about 7 percent chromium; from about 8 to about 12 percent cobalt; from about 1 to about 2.5 percent molybdenum; from about 3 to about 6 percent tungsten; from about 2 to about 4 percent rhenium; from about 5 to about 7 percent aluminum; from about 0 to about 1.5 percent titanium; from about 6 to about 10 percent tantalum; from about 0.08 to about 1.2 percent hafnium; no more than about 0.0002 percent sulfur; no more than about 0.007 percent zirconium; and the balance nickel; and fabricating a single crystal component from the alloy.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The present invention will hereinafter be described in conjunction with the following drawing figures, wherein like numerals denote like elements, and wherein:

[0011] FIG. 1 is a perspective view of a gas turbine blade; and

[0012] FIG. 2 is a cross-sectional view of a protective coating system formed on a component of a gas turbine engine.

DETAILED DESCRIPTION OF THE INVENTION

[0013] The following detailed description of the invention is merely exemplary in nature and is not intended to limit the invention or the application and uses of the invention. Furthermore, there is no intention to be bound by any theory presented in the preceding background of the invention or the following detailed description of the invention.

[0014] The present invention includes an improved superalloy for a variety of substrates, including industrial gas turbine and aero-engine components. In one exemplary embodiment, the superalloy has a composition that results in improved resistance to oxidation compared to conventional superalloy compositions. In another exemplary embodiment, the reactive elements of the superalloy, such as hafnium and yttrium, diffuse into the bond coating to promote adherence of the TGO to the bond coating and improve its performance and hence the performance of an overlying thermal barrier coating.

[0015] As is shown in the figures for the purposes of illustration, the exemplary embodiments of the present invention are embodied in a single crystal nickel-based superalloy component such as, for example, a turbine blade or vane used in a gas turbine engine. FIG. 1 illustrates a turbine blade 150 that is exemplary of the types of components or substrates that are used in turbine engines, although turbine blades commonly have different shapes, dimensions and sizes depending on gas turbine engine models and applications. The illustrated blade 150 has an airfoil portion 152 including a pressure surface 153, an attachment or root portion 154, a leading edge 158 including a blade tip 155, and a platform 156. The blade 150 may be formed with a non-illustrated outer shroud attached to the tip 155. The blade 150 may have non-illustrated internal air-cooling passages that remove heat from the turbine airfoil. After the internal air has absorbed heat from the superalloy blade, the air is discharged into a combustion gas flow path through passages 159 in the airfoil wall.

[0016] FIG. 2 is a cross-sectional view of a portion of a component 10 upon which is disposed a protective coating system 12 fabricated in accordance with an exemplary embodiment of the present invention. The component 10 may be, for example, a turbine airfoil such as turbine blade 150 of FIG. 1. The protective coating system 12 overlies the com-

ponent 10 and any intermediate layers, and is formed of a bond coating 14, a thermal barrier coating 18, and any intermediate layers therebetween, such as a thermally grown oxide (TGO) 20. In one exemplary embodiment, the bond coating 14 is a diffusion aluminide coating that is formed by depositing an aluminum layer over the component 10, and by interdiffusing the aluminum layer with the superalloy substrate. In one embodiment, the bond coating is a simple diffusion aluminide. In another embodiment, the bond coating is a more complex diffusion aluminide that includes other metallic layers. In one embodiment, the other metallic layer is a platinum layer. In another embodiment, the other metallic layer is a hafnium and/or a zirconium layer. In yet another embodiment, the other metallic layer is a co-deposited hafnium, zirconium, and platinum layer. In another exemplary embodiment, the bond coating 14 is an overlay coating known as an MCrAlX coating, wherein M is cobalt, nickel, or combinations thereof. The X is hafnium, zirconium, yttrium, tantalum, rhenium, ruthenium, palladium, platinum, silicon, or combinations thereof. Some examples of MCrAlX compositions include NiCoCrAlY and CoNiCrAlY. In another exemplary embodiment, the bond coating 14 is a combination of two types of bond coatings, a diffusion aluminide coating formed on an MCrAlX coating. Thermal barrier coating 18 may comprise, for example, a partially stabilized zirconia-based thermal barrier coating, such as yttria stabilized zirconia (YSZ).

[0017] The component of the present invention, such as the turbine blade 150, is necessarily fabricated as a single crystal of superalloy, at least in the section comprising the airfoil 152. As used herein, a single crystal superalloy component is one in which substantially the entire component has a single crystallographic orientation through the load bearing portions, without the presence of high angle boundaries. Low angle boundaries, such as tilt or twist boundaries, are permitted within such a single crystal component, but are preferably not present. However, such low angle boundaries are often present after solidification and formation of the single crystal superalloy component, or after some deformation of the component during creep or other deformation process.

[0018] Other minor irregularities are also permitted within the scope of the term "single crystal." For example, small areas of high angle boundaries may be formed directly adjacent the coating during the diffusional interaction of the coating and the component, and during thermal cycling of the component. Small areas of high angle boundaries may also be formed in the root portion 154, particularly adjacent the contact surfaces with turbine wheel. Such minor amounts of deviation from a perfect single crystal, which are found in normal commercial production operations and use of the components, are within the scope of the term "single crystal" as used herein.

[0019] The completed article typically primarily comprises two phases, a precipitate formed within a matrix. The microstructure may also contain minor amounts of a eutectic region formed during solidification of the component and not dissolved during subsequent heat treatment procedures. As with the presence of low angle boundaries, small volume fractions of eutectic phase are tolerated within a single crystal material.

[0020] The single crystal superalloy components can be manufactured directly through vacuum-induction melting and casting processes. Any fabrication technique which produces a substantially single crystal article is operable in conjunction with the present invention. The preferred technique,

used to produce the single crystal components described in the examples herein, is the thermal gradient solidification method. Molten metal of the desired composition is poured into a heat resistant ceramic mold having essentially the desired shape of the final fabricated component. The mold and metal contained therein are placed within a furnace, induction heating coil, or other heating device to melt the metal, and the mold and molten metal are gradually cooled in a temperature gradient. In this process, metal adjacent the cooler end of the mold solidifies first, and the interface between the solidified and liquid metal gradually moves through the metal as cooling continues. Such gradient solidification can be accomplished by placing a chill block adjacent one end of the mold and then turning off the heat source, allowing the mold and molten metal to cool and solidify in a controlled desirable temperature gradient. Alternatively, the mold and molten metal can be gradually withdrawn from the heat source.

[0021] It is found that certain crystallographic orientations such as $\langle 001 \rangle$ grow to the exclusion of others during such a thermal gradient solidification process, so that a single grain becomes dominant throughout the article. Techniques have been developed to promote the formation of the single crystal orientation rapidly, so that substantially all the article has the same single crystal orientation. Such techniques include seeding whereby an oriented single crystal starting material is positioned adjacent the metal first solidified, so that the metal initially develops that orientation. Another approach is a geometrical selection process.

[0022] All other techniques for forming a single crystal are acceptable for use in conjunction with the present invention. For example, the liquid metal cooling process or cast may be used to fabricate single crystal turbine components. In this process, a nickel-based superalloy is melted and poured into a ceramic mold placed inside a multi-zone heater. For solidification, the cast components are immersed at a constant rate into a liquid tin bath.

[0023] In accordance with an exemplary embodiment of the present invention, the single crystal superalloy has a composition in weight percent consisting essentially of from about 4 to about 7 percent chromium, from about 8 to about 12 percent cobalt, from about 1 to about 2.5 percent molybdenum, from about 3 to about 6 percent tungsten, from about 2 to about 4 percent rhenium, from about 5 to about 7 percent aluminum, from about 0 to about 1.5 percent titanium, from about 6 to about 10 percent tantalum, from about 0.08 to about 1.2 percent hafnium, no more than 0.0002 percent sulfur, no more than 0.007 zirconium, and balance in nickel totaling 100 percent. Further, in such composition the sum of the molybdenum plus tungsten plus rhenium is from about 8.4 to about 10.4 percent, and the sum of aluminum plus titanium plus tantalum is about 13.8 to about 15.7 percent. In another exemplary embodiment, the composition further includes from about 0.001 to about 0.015 percent yttrium, lanthanum, cerium or a combination thereof. In a further exemplary embodiment of the present invention, the composition also may comprise about 0.03 to about 0.10 percent carbon and about 0.003 to about 0.006 percent boron.

[0024] These alloying elements are selected to achieve a cooperative optimization of the physical and chemical as well as mechanical properties of the completed component, and to optimize the retention of such properties during the operating lifetime of the component. A consideration in the selection of the alloying ingredients is the attainment of creep strength

and phase stability as well as environmental resistance, and to achieve these goals the strengthening mechanisms of the single crystal component must be optimized. The preferred microstructure of the component, after heat treatment, is an array of gamma prime precipitates in a matrix. The matrix is nickel which has been strengthened by the addition of various solid-solution strengthening elements, and is termed gamma phase. Most elements have at least some solid solubility in nickel, but molybdenum, tungsten and rhenium have been found to be potent solid-solution strengtheners which do not have significant detrimental effects on other properties when used in controlled amounts, and in fact can promote the attainment of desirable properties. Molybdenum is present in an amount of from about 1 to about 2.5 weight percent, tungsten is present in an amount of from about 3 to about 6 weight percent, and rhenium is present in an amount of from about 2 to about 4 weight percent. The sum of these solid-solution strengthening elements should be from about 8.4 to about 10.4 percent. If too low a level of these alloying elements is used, the strength of the matrix is low. If excessively high levels are used, other properties such as hot corrosion resistance and oxidation resistance are reduced.

[0025] Rhenium has an additional benefit of refining the size of the precipitates, which contributes to improved strength of the gamma matrix. Rhenium also improves the creep strength of the gamma matrix and retards the rate of coarsening of the precipitates, during extended elevated temperature exposure.

[0026] In addition to solid-solution strengthening, the strength of the single crystal article is promoted by precipitation hardening due to the presence of the precipitates in the matrix. The precipitates are formed as compounds of nickel, aluminum, titanium and tantalum, the compound being known as gamma-prime phase and having a composition conventionally represented as $\text{Ni}_3(\text{Al}, \text{Ti}, \text{Ta})$. It is desirable that the volume fraction of the gamma-prime phase be maintained at a high level, preferably in the range of from about 65 to about 70 volume percent.

[0027] To achieve this quantity of the gamma-prime phase, aluminum is present in an amount of from about 5 to about 7 weight percent, titanium is present in an amount of from about 0 to about 1.5 weight percent, and tantalum is present in an amount of from about 6 to about 10 weight percent. If lower levels of these gamma-prime forming elements are utilized, the volume fraction of gamma-prime precipitate is low, with the result that the tensile and creep strengths are reduced below acceptable levels. If too high levels are used, the volume fraction of eutectic gamma-prime is excessively high. Since the eutectic gamma-prime is highly alloyed with refractory elements, the alloy becomes less responsive to a solution heat treat that dissolves all or most of the eutectic gamma-prime. Hence, the full potential strength of the alloy as a single crystal article cannot be realized. The tantalum content of the alloy improves the rupture life of the alloy because the high tantalum level also is effective in maintaining the desired volume fraction of the gamma-prime precipitate.

[0028] The sum of the aluminum plus titanium plus tantalum percentages is maintained in the range of from about 13.8 to about 15.7 weight percent. Lower levels result in the insufficient availability of gamma-prime forming elements, a low volume fraction of gamma-prime precipitate phase, and corresponding low strengths. Excessively high amounts of these three gamma-prime forming elements result in the formation

of topologically closepacked phases (TCP) such as P and R, and sigma phases, a brittle, undesirable precipitated constituent that may be formed during subsequent elevated temperature exposure of the article. It has been found that the simultaneous limitation of molybdenum plus tungsten plus rhenium to the range of from about 8.4 to about 10.4 percent, and the limitation of the sum of aluminum plus titanium plus tantalum to about 13.8 to about 15.7 percent, results in an optimum combination of strength of the article in creep loading, and chemical stability of the article to the formation of the undesirable sigma phase during extended elevated temperature exposure.

[0029] Chromium is present in the alloy in the amount of from about 4 to about 7 weight percent. The chromium promotes environmental resistance of the alloy to hot corrosion in the sulfur-containing hot gas of the gas turbine and to oxidation damage. Such inherent resistance to environmental damage is desirable in the article, even though it may be coated with a protective coating. Too low of a level of chromium results in insufficient protection against environmental attack, while too high of a level of chromium tends to promote formation of the undesirable brittle sigma phase.

[0030] Cobalt is present in the alloy in the amount of from about 8 to about 12 percent. The addition of elemental cobalt increases solubility of gamma matrix, thus inhibiting the formation of TCP phases like sigma phase-containing refractory elements, thus allowing these elements to be present for the reasons previously discussed. A too low cobalt level has an insufficient inhibiting effect, while a too high cobalt level increases undesirably the solubility of the gamma-prime precipitates in the gamma matrix, reduces solvus temperature of gamma prime, and reduces oxidation resistance. Such increased solubility tends to reduce the volume fraction of the gamma-prime precipitates, thereby decreasing the strength of the article. However, it is found that, in combination with the ranges of the other alloying elements, the relatively higher level of cobalt in the exemplary embodiments of this invention is not detrimental in the present articles.

[0031] In one exemplary embodiment, hafnium is present in an amount of from about 0.08 to about 1.2 weight percent. In another exemplary embodiment, hafnium is present in an amount of from about 0.08 to about 0.12 weight percent. In yet another exemplary embodiment, hafnium is present in an amount of from about 0.15 to about 1.2 weight percent. Hafnium promotes resistance to environmental damage by oxidation. In addition, hafnium can diffuse into the bond coating 14 illustrated in FIG. 2 and slow the growth rate of the TGO on the bond coating, which can dramatically improve the bond coating performance. Thus, in combination with the other alloying elements in the indicated ranges, the presence of hafnium promotes optimized alloy and thermal barrier coating performance.

[0032] In addition, exemplary embodiments of the present invention minimize the amount of elemental sulfur within the composition to no more than 0.0002 percent. A high level of sulfur tends to migrate to the free surfaces of the component, thereby dramatically decreasing oxidation and corrosion performance of the superalloy and the coating. In one exemplary embodiment, the composition also includes yttria, lanthanum, cerium or a combination thereof, which react with the sulfur to form stable compounds that minimize the amount of sulfur that can migrate to the free surface of the component. Accordingly, by minimizing the amount of sulfur in the composition and, optionally, binding the sulfur to some reactive

elements that prevent migration of the sulfur, the oxidation properties of the composition are greatly improved.

[0033] In another exemplary embodiment, the composition includes from about 0.03 to about 0.10 percent carbon and from about 0.003 to about 0.006 percent boron. Typically, carbon and boron are absent from single crystal superalloy compositions. However, in the exemplary embodiments of the present invention, carbon and boron are present in the disclosed amounts to accommodate both high angle and low angle boundaries.

[0034] The selection of the ranges of the alloying elements also leads to an improved ability to heat treat the cast single crystal articles. In the process for preparing a single crystal component of the invention, an alloy of the desired composition is formed and then a single crystal is prepared from the alloy composition. Without further processing, the microstructure of the resulting single crystal contains gamma-prime precipitates (referred to as cooling gamma-prime) having a variety of sizes. A further solution treat and age heat treatment procedure is performed, wherein the material in the gamma-prime precipitate phase is dissolved into the gamma matrix in solution heat treatment, and then reprecipitated in an aging treatment conducted at a lower temperature.

[0035] To place the gamma-prime phase into solution, the single crystal piece must be heated to a temperature which is greater than the solvus temperature of the gamma-prime phase, but less than the melting temperature of the alloy. The melting temperature, termed the solidus for a composition which melts over a temperature range, should be sufficiently greater than the solvus temperature so that the single crystal piece may be heated and maintained within the temperature range between the solvus and the solidus for a time sufficiently long to dissolve the gamma-prime precipitate phase into the gamma matrix. The solidus temperature is typically about 2,400° F. (about 1315.56° C.) to 2,450° F. (about 1343.33° C.) and accurate control to within a few degrees in commercial heat treating equipment is simply not possible. It is therefore preferred that the solidus be at least about 15° F. (about 8.3° C.) greater than the solvus temperature for the gamma-prime precipitates.

[0036] Both the solvus temperature and solidus temperature are altered by changes in the amounts of the elements contained within the alloy. Generally, greater amounts of the alloying elements reduce the solidus temperature and cause it to approach the solvus temperature, thereby making commercial heat treatment procedures impractical to perform. The composition of the present alloy has been selected with this consideration in mind, and the optimized levels of molybdenum, titanium, carbon, boron, zirconium, and tungsten all reduce the depression of the solidus temperature, largely without detrimental effects on other properties.

[0037] The "heat treatment window" or difference between the gamma-prime solvus and the alloy solidus temperatures preferably is at least at 15° F. (about 8.3° C.), and more preferably is greater than about 50° F. (about 27.8° C.). In a preferred heat treatment of the cast single crystal components, the components are solution heat treated at a temperature of about 2,415° F. (about 1323.89° C) for a period of about three hours, to dissolve the gamma-prime precipitate phase formed during solidification, into the gamma matrix. The solution heat treatment may be accomplished at any temperature within the heat treatment window between the gamma-prime solvus and the solidus temperatures. Greater temperatures allow shorter heat treatment times. However, the heat

treatment temperature is not typically pushed to a maximum level, to allow a margin of error in the heat treatment equipment. After the heat treating process is completed, the solution heat treated single crystal components are rapidly cooled to supersaturate the matrix with the gamma-prime forming elements. A fast argon fan cool to a temperature of less than about 1,000° F. (about 537.78° C.) has been found sufficient to achieve the necessary supersaturation. Excessively high cooling rates may not be achieved in all commercial heat treat furnaces, while excessively low cooling rates would not provide the necessary supersaturation.

[0038] Following the solution heat treatment and supersaturation cooling, the solution heat treated single crystal articles are aged to precipitate the gamma-prime precipitates within the single crystal gamma matrix. The aging heat treatment can be combined with the coating treatment. As noted previously, gas turbine components are typically coated with a corrosion- and oxidation-resistant coating and thermal barrier coating prior to use. During the coating procedure, the component being coated is heated to elevated temperature. A typical coating treatment requires heating the component to a temperature of about 1,950° F. (about 1065.56° C.) for about four hours. This heat treatment causes some precipitation of the gamma-prime phase within the gamma matrix, thus accomplishing in part the aging heat treatment. The aging heat treatment may be completed by a further elevated temperature exposure, separate from the coating procedure. A sufficient additional aging heat treatment is accomplished at a temperature of about 1,600° F. (about 871.11 ° C.) for a time of from about four to about twenty hours, following the heat treatment at 1,950° F. (about 1065.56° C.) for four hours. The aging heat treatment is not limited to this preferred heat treatment sequence, but instead may be accomplished by any acceptable approach which precipitates the desired volume fraction of gamma-prime particles within the gamma matrix, the precipitation occurring from the supersaturated heat treated single crystal matrix.

[0039] The microstructure of the as-solidified single crystals includes irregular gamma-prime particles and regions of gamma-prime eutectic phase. The solution heat treatment dissolves the irregular gamma-prime particles and most or all the gamma-prime eutectic constituent into the gamma matrix. The subsequent aging treatment precipitates an array of gamma-prime precipitates having a generally cuboidal shape and somewhat uniform size. The gamma-prime precipitates vary from about 0.3 to about 0.6 micrometers in size.

[0040] The following examples are presented to illustrate aspects and features of various embodiments of the present invention, and are not to be taken as limiting the invention in any respect.

EXAMPLE 1

In Weight Percent

[0041]

Co	9.8-10.2
Cr	5.2-5.4
Mo	1.6-1.8
W	4.8-5.2
Re	2.8-3.2
Ta	8.0-9.0
Al	5.0-5.4

-continued

Ti	0.9-1.1
Hf	0.08-0.12
S	≤0.0002
Zr	≤0.007
Others	La: 0.001-0.013
Ni	Balance

EXAMPLE 2

In Weight Percent

[0042]

Co	9.8-10.2
Cr	5.2-5.4
Mo	1.6-1.8
W	4.8-5.2
Re	2.8-3.2
Ta	8.0-9.0
Al	5.0-5.4
Ti	0.9-1.1
Hf	0.08-0.12
S	≤0.0002
Zr	≤0.007
Others	Y: 0.001-0.013
Ni	Balance

EXAMPLE 3

In Weight Percent

[0043]

Co	9.8-10.2
Cr	5.2-5.4
Mo	1.6-1.8
W	4.8-5.2
Re	2.8-3.2
Ta	8.0-9.0
Al	5.0-5.4
Ti	0.9-1.1
Hf	0.08-0.12
S	≤0.0002
Zr	≤0.007
Others	La and Y (combined weight percent): 0.001-0.013; C: 0.03-0.06; B: 0.004-0.006
Ni	Balance

EXAMPLE 4

In Weight Percent

[0044]

Co	9.8-10.2
Cr	5.2-5.4
Mo	1.6-1.8
W	4.8-5.2
Re	2.8-3.2
Ta	8.0-9.0
Al	5.0-5.4

-continued

Ti	0.9-1.1
Hf	0.08-0.12
S	≤0.0002
Zr	≤0.007
Others	La and Y (combined weight percent): 0.001-0.013
Ni	Balance

EXAMPLE 5

In Weight Percent

[0045]

Co	9.8-10.2
Cr	5.2-5.4
Mo	1.6-1.8
W	4.8-5.2
Re	2.8-3.2
Ta	7.3-8.5
Al	5.0-5.4
Ti	0.9-1.1
Hf	0.15-1.2
S	≤0.0002
Zr	≤0.007
Others	Y: 0.001-0.013; C: 0.03-0.09; B: 0.004-0.006
Ni	Balance

EXAMPLE 6

In Weight Percent

[0046]

Co	9.8-10.2
Cr	5.2-5.4
Mo	1.6-1.8
W	4.8-5.2
Re	2.8-3.2
Ta	7.3-8.5
Al	5.0-5.4
Ti	0.9-1.1
Hf	0.15-1.2
S	≤0.0002
Zr	≤0.007
Others	La and Y (combined weight percent): 0.001-0.013
Ni	Balance

EXAMPLE 7

In Weight Percent

[0047]

Co	9.8-10.2
Cr	5.2-5.4
Mo	1.6-1.8
W	4.8-5.2
Re	2.8-3.2
Ta	7.3-8.5
Al	5.0-5.4
Ti	0.9-1.1
Hf	0.15-1.2

-continued

S	≤0.0002
Zr	≤0.007
Others	La and Y (combined weight percent): 0.001-0.013; C: 0.03-0.09; B: 0.004-0.006
Ni	Balance

EXAMPLE 8

In Weight Percent

[0048]

Co	9.8-10.2
Cr	5.2-5.4
Mo	1.6-1.8
W	4.8-5.2
Re	2.8-3.2
Ta	7.3-8.5
Al	5.0-5.4
Ti	0.9-1.1
Hf	0.15-1.2
S	≤0.0002
Zr	≤0.007
Others	C: 0.03-0.09; B: 0.004-0.006
Ni	Balance

EXAMPLE 9

In Weight Percent

[0049]

Co	9.3-9.8
Cr	6.3-6.7
Mo	1.6-2.0
W	5.3-5.7
Re	2.8-3.2
Ta	6.8-7.2
Al	6.1-6.4
Hf	0.13-0.17
S	≤0.0002
Zr	≤0.007
Others	La and Y (combined weight percent): 0.001-0.013; C: 0.03-0.07; B: 0.004-0.006
Ni	Balance

[0050] Accordingly, single crystal nickel-based superalloy compositions for hot-section components of gas turbine engines, such as gas turbine blades and vanes, have been provided. The compositions provide such components with mechanical, phase stability, and environmental properties superior to those of prior art superalloy materials. In addition, the compositions provide such components with improved oxidation resistance. While at least one exemplary embodiment has been presented in the foregoing detailed description of the invention, it should be appreciated that a vast number of variations exist. It should also be appreciated that the exemplary embodiment or exemplary embodiments are only examples, and are not intended to limit the scope, applicability, or configuration of the invention in any way. Rather, the foregoing detailed description will provide those skilled in the art with a convenient road map for implementing an exemplary embodiment of the invention, it being understood

that various changes may be made in the function and arrangement of elements described in an exemplary embodiment without departing from the scope of the invention as set forth in the appended claims and their legal equivalents.

What is claimed is:

1. A single crystal nickel-based superalloy composition consisting essentially of, in weight percent:

from about 4 to about 7 percent chromium;
from about 8 to about 12 percent cobalt;
from about 1 to about 2.5 percent molybdenum;
from about 3 to about 6 percent tungsten;
from about 2 to about 4 percent rhenium;
from about 5 to about 7 percent aluminum;
from about 0 to about 1.5 percent titanium;
from about 6 to about 10 percent tantalum;
from about 0.08 to about 1.2 percent hafnium;
no more than about 0.0002 percent sulfur;
no more than about 0.007 percent zirconium; and
the balance nickel.

2. The single crystal nickel-based superalloy composition of claim 1, further consisting essentially of (in weight percent) from about 0.001 to about 0.015 weight percent of one selected from the group consisting of yttrium, lanthanum, cerium, and a combination thereof.

3. The single crystal nickel-based superalloy composition of claim 2, further consisting essentially of (in weight percent) from about 0.03 to about 0.10 percent carbon and from about 0.003 to about 0.006 percent boron.

4. The single crystal nickel-based superalloy composition of claim 1, wherein a sum of the molybdenum, tungsten, and rhenium is from about 8.4 to about 10.4 weight percent.

5. The single crystal nickel-based superalloy composition of claim 1, wherein a sum of aluminum, titanium, and tantalum is about 13.8 to about 15.7 weight percent.

6. The single crystal nickel-based superalloy composition of claim 1, wherein the percentage of hafnium is from about 0.08 to about 0.12 weight percent.

7. The single crystal nickel-based superalloy composition of claim 1, wherein the percentage of hafnium is from about 0.15 to about 1.2 weight percent.

8. A single crystal nickel-based superalloy component fabricated of a single crystal composition consisting essentially of (in weight percent):

from about 4 to about 7 percent chromium;
from about 8 to about 12 percent cobalt;
from about 1 to about 2.5 percent molybdenum;
from about 3 to about 6 percent tungsten;
from about 2 to about 4 percent rhenium;
from about 5 to about 7 percent aluminum;
from about 0 to about 1.5 percent titanium;
from about 6 to about 10 percent tantalum;
from about 0.08 to about 1.2 percent hafnium;
no more than about 0.0002 percent sulfur;

no more than about 0.007 percent zirconium; and
the balance nickel.

9. The single crystal nickel-based superalloy component of claim 8, wherein the single crystal nickel-based superalloy component is a turbine blade.

10. The single crystal nickel-based superalloy component of claim 8, wherein the single crystal nickel-based superalloy component is a vane.

11. The single crystal nickel-based superalloy component of claim 8, further consisting essentially of (in weight percent) from about 0.001 to about 0.015 weight percent of one selected from the group consisting of yttrium, lanthanum, cerium, and a combination thereof.

12. The single crystal nickel-based superalloy component of claim 10, further consisting essentially of (in weight percent) from about 0.03 to about 0.10 percent carbon and from about 0.003 to about 0.006 percent boron.

13. The single crystal nickel-based superalloy component of claim 8, wherein the percentage of hafnium is from about 0.08 to about 0.12 percent.

14. The single crystal nickel-based superalloy component of claim 8, wherein the percentage of hafnium is from about 0.15 to about 1.2 percent.

15. A process for preparing a single crystal nickel-based superalloy component, the method comprising the steps of:

providing an alloy comprising (in weight percent):

from about 4 to about 7 percent chromium;
from about 8 to about 12 percent cobalt;
from about 1 to about 2.5 percent molybdenum;
from about 3 to about 6 percent tungsten;
from about 2 to about 4 percent rhenium;
from about 5 to about 7 percent aluminum;
from about 0 to about 1.5 percent titanium;
from about 6 to about 10 percent tantalum;
from about 0.08 to about 1.2 percent hafnium;
no more than about 0.0002 percent sulfur;
no more than about 0.007 percent zirconium; and
the balance nickel; and

fabricating a single crystal component from the alloy.

16. The process of claim 15, wherein the step of providing an alloy comprises the step of providing an alloy further comprising (in weight percent) from about 0.001 to about 0.015 weight percent of one selected from the group consisting of yttrium, lanthanum, cerium, and a combination thereof.

17. The process of claim 16, wherein the step of providing an alloy comprises the step of providing an alloy further comprising (in weight percent) from about 0.03 to about 0.10 percent carbon and from about 0.003 to about 0.006 percent boron.

18. The process of claim 15, wherein the step of fabricating a single crystal component from the alloy comprises the step of fabricating a turbine blade and a vane from the alloy.

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