

TITLE

THERMO-MECHANICAL PROCESSING OF NICKEL-BASE ALLOYS

INVENTORS

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TECHNICAL FIELD

[0001] This disclosure relates to thermo-mechanical processing of nickel-
base alloys.

BACKGROUND

[0002] Nickel-base alloys are excellent engineering alloys in various applications because the alloys possess a number of advantageous material properties. For example, nickel-base alloys comprising chromium and iron additions have excellent resistance to corrosion in many aqueous media and high-temperature atmospheres. Nickel-base alloys also maintain metallurgical stability and high strength over a broad range of elevated temperatures, and do not form embrittling phases during long-term exposure to elevated temperatures. The combination of good creep and rupture strength, metallurgical stability, and corrosion resistance at high temperatures and over long service periods allows nickel-base alloys to function in applications involving aggressive environments and under severe operating conditions. For example, nickel-base alloys may find utility in engineering applications including: mineral acid production and processing equipment; coal-gasification units; petrochemical processing equipment; incinerators; steam generator tubes, baffles, tube sheets, and other hardware; and structural components in nuclear reactor power generation systems.

SUMMARY

[0003] In a non-limiting embodiment, a thermo-mechanical treatment process for nickel-base alloys comprises at least two heating steps and at least two working steps. A nickel-base alloy workpiece is heated in a first heating step to a temperature greater than the $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy. The heated nickel-base alloy workpiece is worked in a first working step to a reduction in area of 20% to 70% to provide a worked nickel-base alloy workpiece. The nickel-base alloy workpiece is at a temperature greater than the $M_{23}C_6$ carbide solvus temperature when the first working step begins. The worked nickel-base alloy workpiece is heated in a second heating step to a temperature greater than 1700°F (926°C) and less than the $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy. The worked nickel-base alloy workpiece is maintained at elevated temperature and not permitted to cool to ambient temperature between completion of the first working step and beginning the second heating step. The heated nickel-base alloy workpiece is worked in a second working step to a reduction in area of 20% to 70%. The nickel-base alloy workpiece is at a temperature greater than 1700°F (926°C) and less than the $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy when the second working step begins.

[0004] In another non-limiting embodiment, a thermo-mechanical treatment process for nickel-base alloys comprises at least two heating steps and at least two forging steps. A nickel-base alloy workpiece is heated in a first heating step to a temperature in the range of 2000°F to 2125°F (1093°C to 1163°C). The heated nickel-base alloy workpiece is rotary forged in a first forging step to a reduction in area of 30% to 70% to provide a forged nickel-base alloy workpiece. The heated nickel-base alloy workpiece is at a temperature in the range of 2000°F to 2125°F (1093°C to 1163°C) when the first forging step begins. The forged nickel-base alloy workpiece is heated in a second heating step to a temperature in the range of 1750°F to 1925°F (954°C to 1052°C). The forged nickel-base alloy workpiece is maintained at elevated temperature and not permitted to cool to ambient temperature between completion of the first forging step and beginning the second heating step. The heated nickel-base

alloy workpiece is rotary forged in a second forging step to a reduction in area of 20% to 70%. The heated nickel-base alloy ingot is at a temperature in the range of 1750°F to 1925°F (954°C to 1052°C) when the second rotary forging step begins.

[0005] It is understood that the invention disclosed and described in this specification is not limited to the embodiments summarized in this Summary.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Various features and characteristics of the non-limiting and non-exhaustive embodiments disclosed and described in this specification may be better understood by reference to the accompanying figures, in which:

[0007] Figures 1A and 1B are cross-sectional schematic diagrams of a rotary forging operation;

[0008] Figures 2A is a cross-sectional schematic diagram and Figure 2B is a perspective schematic diagram of a hot-forged and heat-treated long product having a ring-shaped region of abnormal grain growth; and

[0009] Figures 3A through 3D are metallographs of the cross-sectional macrostructure of regions of Alloy 690 long products showing various effects of thermo-mechanical processing according to various non-limiting embodiments described herein.

[0010] The reader will appreciate the foregoing details, as well as others, upon considering the following detailed description of various non-limiting and non-exhaustive embodiments according to the present disclosure.

DESCRIPTION

[0011] Various embodiments are described and illustrated in this specification to provide an overall understanding of the structure, function, operation, manufacture, and use of the disclosed processes and products. It is understood that

the various embodiments described and illustrated in this specification are non-limiting and non-exhaustive. Thus, the invention is not limited by the description of the various non-limiting and non-exhaustive embodiments disclosed in this specification. Rather, the invention is defined solely by the claims. The features and characteristics illustrated
5 and/or described in connection with various embodiments may be combined with the features and characteristics of other embodiments. Such modifications and variations are intended to be included within the scope of this specification. As such, the claims may be amended to recite any features or characteristics expressly or inherently described in, or otherwise expressly or inherently supported by, this specification.

10 Further, Applicant reserves the right to amend the claims to affirmatively disclaim features or characteristics that may be present in the prior art. Therefore, any such amendments comply with the requirements of 35 U.S.C. § 112, first paragraph, and 35 U.S.C. § 132(a). The various embodiments disclosed and described in this specification can comprise, consist of, or consist essentially of the features and characteristics as
15 variously described herein.

[0012] Any patent, publication, or other disclosure material identified herein is incorporated by reference into this specification in its entirety unless otherwise indicated, but only to the extent that the incorporated material does not conflict with existing definitions, statements, or other disclosure material expressly set forth in this
20 specification. As such, and to the extent necessary, the express disclosure as set forth in this specification supersedes any conflicting material incorporated by reference herein. Any material, or portion thereof, that is said to be incorporated by reference into this specification, but which conflicts with existing definitions, statements, or other disclosure material set forth herein, is only incorporated to the extent that no conflict
25 arises between that incorporated material and the existing disclosure material. Applicant reserves the right to amend this specification to expressly recite any subject matter, or portion thereof, incorporated by reference herein.

[0013] Reference throughout this specification to "various non-limiting embodiments," or the like, means that a particular feature or characteristic may be
30 included in an embodiment. Thus, use of the phrase "in various non-limiting

embodiments," or the like, in this specification does not necessarily refer to a common embodiment, and may refer to different embodiments. Further, the particular features or characteristics may be combined in any suitable manner in one or more embodiments. Thus, the particular features or characteristics illustrated or described in connection with
5 various embodiments may be combined, in whole or in part, with the features or characteristics of one or more other embodiments without limitation. Such modifications and variations are intended to be included within the scope of the present specification.

[0014] In this specification, other than where otherwise indicated, all numerical parameters are to be understood as being prefaced and modified in all
10 instances by the term "about", in which the numerical parameters possess the inherent variability characteristic of the underlying measurement techniques used to determine the numerical value of the parameter. 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 described in the present description should at least be construed in light of
15 the number of reported significant digits and by applying ordinary rounding techniques.

[0015] Also, any numerical range recited in this specification is intended to include all sub-ranges of the same numerical precision subsumed within the recited range. For example, a range of "1.0 to 10.0" is intended to include all sub-ranges between (and including) the recited minimum value of 1.0 and the recited maximum
20 value of 10.0, that is, having a minimum value equal to or greater than 1.0 and a maximum value equal to or less than 10.0, such as, for example, 2.4 to 7.6. Any maximum numerical limitation recited in this specification is intended to include all lower numerical limitations subsumed therein and any minimum numerical limitation recited in this specification is intended to include all higher numerical limitations subsumed
25 therein. Accordingly, Applicant reserves the right to amend this specification, including the claims, to expressly recite any sub-range subsumed within the ranges expressly recited herein. All such ranges are intended to be inherently described in this specification such that amending to expressly recite any such sub-ranges would comply with the requirements of 35 U.S.C. § 112, first paragraph, and 35 U.S.C. § 132(a).

[0016] The grammatical articles "one", "a", "an", and "the", as used in this specification, are intended to include "at least one" or "one or more", unless otherwise indicated. Thus, the articles are used in this specification to refer to one or more than one (*i.e.*, to "at least one") of the grammatical objects of the article. By way of example, "a component" means one or more components, and thus, possibly, more than one component is contemplated and may be employed or used in an implementation of the described embodiments. Further, the use of a singular noun includes the plural, and the use of a plural noun includes the singular, unless the context of the usage requires otherwise.

[0017] The various embodiments disclosed and described in this specification are directed, in part, to the thermo-mechanical processing of nickel-base alloys. The thermo-mechanical processing disclosed and described in this specification may be used to produce nickel-base alloy products, such as, for example, bars, rods, slabs, rings, strips, plates, and the like. Products produced by the processes described in this specification may be characterized by a defined grain size and a defined precipitated carbide distribution.

[0018] Intergranular stress corrosion cracking (IGSCC) is a corrosion mechanism in which cracks form along the grain boundaries of a metallic material under tensile stress and exposed to a corrosive environment. The tensile stresses that promote IGSCC may be in the form of externally applied stresses to a metallic component in service and/or in the form of internal residual stresses in the metallic material. IGSCC is often encountered in applications involving aggressively corrosive environments, such as, for example, structural components in chemical processing equipment and pressurized water reactors (PWR) for nuclear power generation. Nickel-base alloys, such as, for example, Alloy 600 (UNS N06600) and Alloy 690 (UNS N06690), may be used in such applications due to the general corrosion resistance of such alloys. However, nickel-base alloys may nevertheless demonstrate IGSCC under high temperature and high pressure service conditions, for example, in aqueous or steam environments.

[0019] Certain thermo-mechanical treatment processes may be used to

reduce the susceptibility of nickel-base alloys to IGSCC in aggressively corrosive environments. Combinations of hot working and heat treatments may be used to produce nickel-base alloy products having defined grain sizes and carbide distributions

5 that increase IGSCC resistance. For example, nickel-base alloys including relatively high levels of chromium and iron, such as, for example, Alloy 600 and Alloy 690, may be thermo-mechanically processed by certain known methods to produce products having defined grain sizes with an intergranular distribution of precipitated $M_{23}C_6$ carbides and without chromium depletion in the grains. Intergranular precipitation of
10 $M_{23}C_6$ carbides between the grains in nickel-base alloys significantly reduces sensitization of the alloys in aggressively corrosive environments, which significantly increases resistance to IGSCC.

[0020] In various non-limiting embodiments, the processes described

herein may be used to thermo-mechanically treat nickel-base alloys such as, for
15 example, Alloy 600 and Alloy 690. For example, in various non-limiting embodiments, Alloy 690 workpieces treated according to embodiments of the thermo-mechanical processes described herein may have a chemical composition comprising (in percentage by total alloy weight/mass): at least 58.0% nickel; 27.0% to 31.0%

chromium; 7.0% to 11.0% iron; up to 0.5% manganese; up to 0.05% carbon; up to 0.5%
20 copper; up to 0.5% silicon; up to 0.015% sulfur; and incidental impurities. In various non-limiting embodiments, Alloy 690 workpieces treated according may have a chemical composition comprising any elemental sub-ranges subsumed within the elemental ranges described above. For example, an Alloy 690 workpiece treated according to embodiments of the thermo-mechanical processes described herein may
25 comprise (in percentage by total alloy weight/mass): at least 59.0% nickel; 28.0% to 30.0% chromium; 8.0% to 10.0% iron; up to 0.25% manganese; 0.010% to 0.040% carbon; up to 0.25% copper; up to 0.25% silicon; up to 0.010% sulfur; and incidental impurities. In various non-limiting embodiments, all elemental alloy constituents described in this specification as being "up to" a specified maximum amount also
30 include amounts "greater than zero to" the specified maximum amount.

[0021] In various non-limiting embodiments, nickel-base alloy ingots may be produced by vacuum induction melting (VIM) feed materials to produce an alloy comprising a chemical composition conforming to a predetermined compositional specification. For example, feed materials may be used to produce an alloy comprising
5 a chemical composition conforming to the specifications for Alloy 690 described above. The molten alloy produced by VIM, for example, may be cast into an initial ingot. In various non-limiting embodiments, the initial ingot may be used as an input electrode for one or more vacuum arc remelting (VAR) and/or electroslag remelting (ESR) operations to produce a refined ingot. In various non-limiting embodiments, other initial melting
10 and/or remelting operations known in the art, such as, for example, argon oxygen decarburization (AOD) and/or vacuum degassing, alone or in combination with VAR and/or ESR, may be used to produce nickel-base alloy ingots.

[0022] In various non-limiting embodiments, a nickel-base alloy ingot may be homogenized using standard heat treatment practices and/or forged to produce a
15 nickel-base alloy workpiece. For example, a nickel-base alloy ingot (in an as-cast, refined, or homogenized condition) may be press forged to produce a workpiece to be used as an input for subsequent thermo-mechanical processing operations. In various other non-limiting embodiments, a nickel-base alloy ingot (in an as-cast, refined, or homogenized condition) may be forge converted to a preform workpiece having any
20 shape and dimensions suitable for subsequent thermo-mechanical processing operations.

[0023] In various non-limiting embodiments, thermo-mechanical processing operations may comprise at least two heating steps and at least two working steps. A first heating step may comprise heating a nickel-base alloy workpiece to a
25 carbide supersolvus temperature. A first working step may comprise working (e.g., forging or rolling) the nickel-base alloy workpiece, wherein the nickel-base alloy workpiece is at a carbide supersolvus temperature when the working begins. A second heating step may comprise heating the nickel-base alloy workpiece to a carbide subsolvus temperature. A second working step may comprise working (e.g., forging or

rolling) the nickel-base alloy workpiece, wherein the nickel-base alloy workpiece is at a carbide subsolvus temperature when the working begins.

[0024] As used herein, including in the claims, the terms "first", "second", "before", "after", and the like, when used in connection with a step or operation, do not
5 exclude the possibility of prior, intervening, and/or subsequent steps or operations. For example, in various non-limiting embodiments, thermo-mechanical processing methods comprising "first" and "second" heating steps and "first" and "second" working steps may further comprise additional heating, working, and/or other steps before, between, and/or after the specified "first" and "second" heating steps and "first" and "second"
10 working steps.

[0025] As used herein, the term "carbide supersolvus temperature" refers to temperatures at least as great as the $M_{23}C_6$ carbide solvus temperature of an alloy. As used herein, the term "carbide subsolvus temperature" refers to temperatures less than the $M_{23}C_6$ carbide solvus temperature of an alloy. The $M_{23}C_6$ carbide solvus
15 temperature of an alloy is the lowest temperature at which essentially all of the carbon present in the alloy is in solid solution and the alloy does not comprise any metallographically observable $M_{23}C_6$ carbide phases or precipitates. The $M_{23}C_6$ carbide solvus temperature of an alloy depends upon the chemical composition of the alloy, particularly the carbon content. For example, the $M_{23}C_6$ carbide solvus temperature of
20 Alloy 690 may range from approximately 1915°F to 2115°F (1046°C to 1157°C) for carbon concentrations ranging from 0.02% to 0.05%, by weight, for a nominal composition of 29.0% chromium, 9.0% iron, 0.2% copper, 0.2% silicon, 0.2% manganese, 0.01% sulfur, 0.25 aluminum, 0.25 titanium, 0.008 nitrogen, and 60.842% to 60.872% nickel, calculated using JMatPro software, available from Sente Software,
25 Surrey, UK. Carbide solvus temperatures may be determined empirically or approximated using phase diagram calculation and materials property simulation software such as, for example, JMatPro software, or Pandat software, available from CompuTherm LLC, Madison, Wisconsin, USA.

[0026] As used herein, heating a workpiece "to" a specified temperature or temperature range indicates heating the workpiece for a time sufficient to bring the temperature of the entire workpiece, including the internal material portions of the workpiece, to the specified temperature or into the specified temperature range.

5 Likewise, a condition of a workpiece being heated "to" a specified temperature or temperature range indicates that the workpiece is heated for a time sufficient to bring the temperature of the entire workpiece, including the internal material portions of the workpiece, to the specified temperature or into the specified temperature range. The amount of time needed to heat a workpiece "to" a temperature or temperature range will
10 depend upon the shape and dimensions of the workpiece and the thermal conductivity of the workpiece material, for example.

[0027] As used herein, heating a workpiece for a specified period of time or time range "at" a specified temperature or temperature range (*i.e.*, time-at-temperature) indicates heating the workpiece for the specified time or time range
15 measured from the point when the surface temperature of the workpiece (measured, for example, using a thermocouple, pyrometer, or the like) reaches $\pm 25^{\circ}\text{F}$ ($\pm 14^{\circ}\text{C}$) of the specified temperature or temperature range. As used herein, a specified time-at-temperature does not include the pre-heating time to bring the surface temperature of the workpiece to within $\pm 25^{\circ}\text{F}$ ($\pm 14^{\circ}\text{C}$) of the specified temperature or temperature
20 range. As used herein, the term "furnace time" indicates the amount of time that a workpiece is maintained inside a controlled temperature environment such as, for example, a furnace, and does not include the time needed to bring the controlled temperature environment to the specified temperature or temperature range.

[0028] As used herein, forging, working, or conducting other mechanical
25 processing on a workpiece "at" a specified temperature or temperature range indicates that the temperature of the entire workpiece, including the internal material portions of the workpiece, is at the specified temperature or temperature range when the forging, working, or other mechanical processing begins. It is contemplated that surface cooling and/or adiabatic heating of a workpiece during forging, working, or like operations "at" a

specified temperature or temperature range may change the temperature of portions of a workpiece from that specified during the operation.

[0029] In various non-limiting embodiments, a thermo-mechanical treatment process comprises a first heating step comprising heating a nickel-base alloy workpiece to a temperature greater than the $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy. The heated nickel-base alloy workpiece may be worked to a reduction in area of 20% to 70% in a first working step to provide a worked nickel-base alloy workpiece. The heated nickel-base alloy workpiece may be at a temperature greater than the $M_{23}C_6$ carbide solvus temperature at the beginning of the first working step. The worked nickel-base alloy workpiece may be heated in a second heating step to a temperature greater than 1700°F (926°C) and less than the $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy. The worked nickel-base alloy workpiece may be maintained at elevated temperature and not permitted to cool to ambient temperature between completion of the first working step and the beginning of the second heating step. The nickel-base alloy workpiece may be worked to a second reduction in area of 20% to 70% in a second working step. The nickel-base alloy workpiece may be at a temperature greater than 1700°F (926°C) and less than the $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy at the beginning of the second working step. The nickel-base alloy workpiece may be air cooled to ambient temperature after completion of the second working step.

[0030] In various non-limiting embodiments, the first heating step, in which a nickel-base alloy workpiece is heated to a carbide supersolvus temperature, may comprise heating the nickel-base alloy workpiece in a furnace operating at 2000°F to 2125°F (1093°C to 1163°C) for at least 6.0 hours (360 minutes) time-at-temperature. A nickel-base alloy workpiece may be heated to a carbide supersolvus temperature by heating in a furnace operating at 2000°F to 2125°F (1093°C to 1163°C), or any sub-range subsumed therein such as, for example, 2000°F to 2100°F (1093°C to 1149°C), 2000°F to 2075°F (1093°C to 1135°C), 2000°F to 2050°F (1093°C to 1121°C), 2025°F

to 2075°F (1107°C to 1135°C), 2050°F to 2125°F (1121°C to 1163°C), 2050°F to 2100°F (1121°C to 1149°C), or the like.

[0031] In various non-limiting embodiments, the second heating step, in which a worked nickel-base alloy workpiece is heated to a carbide subsolvus temperature, may comprise heating the nickel-base alloy workpiece in a furnace operating at a temperature greater than 1700°F (926°C) and less than the $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy for greater than 2.0 hours (120 minutes) furnace time. A nickel-base alloy workpiece may be heated to a carbide subsolvus temperature by heating in a furnace operating at 1700°F to 1950°F (926°C to 1066°C), or any sub-range subsumed therein such as, for example, 1750°F to 1925°F (954°C to 1052°C), 1750°F to 1825°F (954°C to 996°C), 1825°F to 1925°F (996°C to 1052°C), 1775°F to 1900°F (968°C to 1038°C), 1800°F to 1875°F (982°C to 1024°C), 1800°F to 1850°F (982°C to 1010°C), or the like. In various embodiments, the second heating step may comprise heating a nickel-base alloy workpiece in a furnace operating at a carbide subsolvus temperature for greater than 2.0 hours (120 minutes) to 10.0 hours (600 minutes) furnace time, or any sub-range subsumed therein such as, for example, 2.5 to 8.0 hours (150-480 minutes), 3.0 to 10.0 hours (180-600 minutes), 3.0 to 8.0 hours (180-480 minutes), 4.0 to 8.0 hours (240-480 minutes), 5.0 to 8.0 hours (300-480 minutes), or the like.

[0032] In various non-limiting embodiments, a nickel-base alloy workpiece may be maintained at elevated temperature and not permitted to cool to room temperature between completion of the first working step and the beginning of the second heating step. For example, a nickel-base alloy workpiece may be maintained at temperatures no less than a temperature that is 300°F (167°C) below the $M_{23}C_6$ carbide solvus temperature of the alloy. In various non-limiting embodiments, a nickel-base alloy workpiece may be maintained at temperatures no less than a temperature that is 200°F (111°C), 150°F (83°C), or 100°F (56°C) below the $M_{23}C_6$ carbide solvus temperature of the alloy. In various non-limiting embodiments, a nickel-base alloy workpiece may be maintained at a temperature of at least 1700°F (926°C) between

completion of the first working step and the beginning of the second heating step. In various non-limiting embodiments, a nickel-base alloy workpiece may be maintained at a temperature of at least 1750°F (954°C), 1800°F (982°C), 1850°F (1010°C), 1900°F (1038°C), or 1950°F (1066°C) between completion of the first working step and the
5 beginning of the second heating step.

[0033] In various non-limiting embodiments, the first working step, the second working step, and any subsequent working steps, may together reduce the cross-sectional area of a workpiece by 40% to 95% relative to the cross-sectional area of the workpiece before the first working step. The first working step, the second
10 working step, and any subsequent working steps, may independently produce reductions in area of 20% to 70%, or any sub-range subsumed therein such as, for example, 30% to 70%, 40% to 60%, 45% to 55%, or the like. The reduction in area produced by the first working step is calculated based on the initial cross-sectional area of the workpiece before the first working step. The reduction in area produced by the
15 second working step is calculated based on the as-worked cross-sectional area produced by the first working step. The reduction in area of any subsequent working step may be calculated based on the as-worked cross-sectional area produced by the preceding working step.

[0034] In various non-limiting embodiments, the first working step, the
20 second working step, and any subsequent working steps, may independently comprise one or more passes through the equipment used to perform the particular working step. For example, a first working step may comprise one or more passes through a rotary forge to reduce the cross-sectional area of a workpiece by 20% to 70%, and a second working step may comprise one or more passes through the rotary forge to reduce the
25 cross-sectional area of the workpiece by 20% to 70% relative to the as-worked cross-sectional area of the workpiece produced by the first working step. The total reduction in area produced by the first working step and the second working step may be 40% to 95% relative to the area of the workpiece before the first working step. The reduction in area produced by each individual pass through the rotary forge may be, for example,

5% to 25% relative to the intermediate cross-sectional area produced by the preceding pass.

[0035] In various non-limiting embodiments, a heated nickel-base alloy workpiece may be at a temperature greater than the $M_{23}C_6$ carbide solvus temperature at the beginning of the first working step, and a heated nickel-base alloy workpiece may be at a temperature greater than 1700°F (926°C) and less than the $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy at the beginning of the second working step. In various non-limiting embodiments, a heated nickel-base alloy workpiece may be at a temperature greater than the $M_{23}C_6$ carbide solvus temperature during the entire first working step. In various non-limiting embodiments, a heated nickel-base alloy workpiece may be at a temperature greater than 1700°F (926°C) and less than the $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy during the entire second working step. For example, the dies, anvils, and/or rolls used to perform a working operation may be heated to minimize or eliminate heat loss due to conduction from the surfaces of the workpiece in contact with the working dies, anvils, and/or rolls. Further, adiabatic heating of deforming workpiece material during working steps may compensate, at least in part, for loss of heat from the workpiece.

[0036] In various non-limiting embodiments, the first working step and the second working step may independently comprise one or more forging or rolling operations such as, for example, flat rolling, ring rolling, roll forming, press forging, extrusion, rotary forging, and the like. In various embodiments, the first working step and the second working step may each comprise one or more rotary forging passes.

[0037] As used herein, the term "rotary forging" refers to the working of elongated workpieces such as, for example, tubes, bars, and rods, using two or more anvils/dies to compressively deform the workpiece perpendicular to the long axis of the workpiece, thereby decreasing the cross-sectional area of the workpiece and increasing the length of the workpiece to produce long products. A rotary forging operation 100 is illustrated in Figures 1A and 1B in which a cylindrical bar/rod-type workpiece 102 is compressively deformed by anvils/dies 104, thereby decreasing the cross-sectional

area of the workpiece and increasing the length of the workpiece. Rotary forging produces solid or tubular long products with constant or varying cross-sections along their length. Rotary forging, also known as rotary swaging or radial forging, is not to be confused with orbital (*i.e.*, rocking die) forging in which a workpiece is pressed between
5 a non-rotating flat anvil/die and a swiveling (rocking) die with a conical working face that makes orbital, spiral, planetary, or straight-line motions.

[0038] In various non-limiting embodiments, a thermo-mechanical treatment process may comprise a first heating step comprising heating an Alloy 690 workpiece to a temperature greater than the $M_{23}C_6$ carbide solvus temperature of the
10 alloy. For example, the first heating step may comprise heating an Alloy 690 workpiece to a temperature in the range of 2000°F to 2125°F (1093°C to 1163°C). In various non-limiting embodiments, the Alloy 690 workpiece may have a chemical composition comprising, by weight, up to 0.05% carbon; 27.0% to 31.0% chromium; up to 0.5% copper; 7.0% to 11.0% iron; up to 0.5% manganese; up to 0.015% sulfur; up to 0.5%
15 silicon; at least 58% nickel; and incidental impurities.

[0039] The heated Alloy 690 workpiece may be rotary forged to a reduction in area of 20% to 70% in a first forging step comprising one or more rotary forging passes. The heated Alloy 690 workpiece may be at a temperature greater than the $M_{23}C_6$ carbide solvus temperature at the beginning of the first forging step, such as,
20 for example, at a temperature in the range of 2000°F to 2125°F (1093°C to 1163°C) when the first forging step begins. The forged Alloy 690 workpiece may be heated in a second heating step to a temperature greater than 1700°F (926°C) and less than the $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy. For example, the second heating step may comprise heating a forged Alloy 690 workpiece to a temperature in the
25 range of 1750°F to 1925°F (954°C to 1052°C). The forged Alloy 690 workpiece may be maintained at a temperature of at least 1700°F (926°C) between completion of the first forging step and the beginning of the second heating step.

[0040] The heated Alloy 690 workpiece may be rotary forged to a second reduction in area of 20% to 70% in a second forging step comprising one or more rotary

5 forging passes. The heated Alloy 690 workpiece may be at a temperature greater than 1700°F (926°C) and less than the $M_{23}C_6$ carbide solvus temperature at the beginning of the second forging step, such as, for example, at a temperature in the range of 1750°F to 1925°F when the second forging step begins. The Alloy 690 workpiece may be air cooled to ambient temperature after completion of the second forging step.

10 [0041] In various non-limiting embodiments, nickel-base alloy workpieces, such as, for example, Alloy 690 workpieces, may be further heat treated after the at least two heating steps and the at least two working steps. For example, nickel-base alloy workpieces may be annealed at a temperature of at least 1800°F (982°C), but no greater than the $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy, for at least 3.0 hours time-at-temperature. In various non-limiting embodiments, nickel-base alloy workpieces may be annealed at a temperature of 1800°F to 2000°F (982°C to 1093°C), or any sub-range subsumed therein, such as, for example, 1840°F to 1960°F (1004°C to 1071°C), 1850°F to 1950°F (1010°C to 1066°C), 1875°F to 1925°F (1024°C to 1052°C), or the like. In various non-limiting embodiments, nickel-base alloy workpieces may be annealed for at least 4.0 hours time-at-temperature. In various non-limiting embodiments, nickel-base alloy workpieces may be water quenched after annealing heat treatment.

20 [0042] In various non-limiting embodiments, nickel-base alloy workpieces, such as, for example, Alloy 690 workpieces, may be aged after the at least two heating steps and the at least two working steps. For example, nickel-base alloy workpieces may be aged at a temperature of 1300°F to 1400°F (704°C to 760°C) for at least 3.0 hours time-at-temperature. In various non-limiting embodiments, nickel-base alloy workpieces may be aged at a temperature of 1300°F to 1400°F (704°C to 760°C), or 25 any sub-range subsumed therein, such as, for example, 1325°F to 1375°F (718°C to 746°C), 1310°F to 1360°F (710°C to 738°C), or the like. In various non-limiting embodiments, nickel-base alloy workpieces may be aged for at least 4.0 hours time-at-temperature. In various non-limiting embodiments, nickel-base alloy workpieces may be air cooled after aging heat treatment.

[0043] In various non-limiting embodiments, nickel-base alloy workpieces may be annealed and aged. For example, after the at least two heating steps and the at least two working steps, nickel-base alloy workpieces may be air cooled to ambient temperature and then annealed at a temperature of at least 1800°F (982°C), but no greater than the $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy, for at least 3.0 hours time-at-temperature. The nickel-base alloy workpieces may be water quenched after annealing heat treatment and then aged at a temperature of 1300°F to 1400°F (704°C to 760°C) for at least 3.0 hours time-at-temperature.

[0044] The processes described herein may be used, for example, to produce forged and/or rolled products. For example, in various non-limiting embodiments, the at least two heating steps and the at least two working steps convert preform workpieces into products including long products, such as, for example, round bar and rod, rectangular bar and rod, hexagonal bar and rod, forged rectangular long products, and rolled rectangular long products. The processes disclosed herein may be used, for example, to produce long products with constant or varying cross-sections along their length. In embodiments producing long products having varying cross-sections along their length, the first working step and the second working step may together reduce the cross-sectional area of a workpiece by 40% to 95% at one or more locations along the length of the long product. In addition, the processes disclosed herein may be used, for example, to produce rotary forged tubes.

[0045] In various non-limiting embodiments, products produced by the processes described herein may satisfy the requirements of ASTM B166-08: *Standard Specification for Nickel-Chromium-Iron Alloys (UNS N06600, N06601, N06603, N06690, N06693, N06025, N06045, and N06696) and Nickel-Chromium-Cobalt-Molybdenum Alloy (UNS N06617) Rod, Bar, and Wire* (2008), and ASME SB-166: *Specification for Nickel-Chromium-Iron Alloys (UNS N06600, N06601, N06603, N06690, N06693, N06025, N06045, and N06696) and Nickel-Chromium-Cobalt-Molybdenum Alloy (UNS N06617) Rod, Bar, and Wire* (2007), which are incorporated by reference into this specification.

[0046] In various non-limiting embodiments, products produced by the processes described herein may have a grain size of ASTM No. 3.0 to 9.0, determined in accordance with ASTM E 112 - 10: *Standard Test Methods for Determining Average Grain Size* (2010), which is incorporated by reference into this specification. In various non-limiting embodiments, products produced by the processes described herein may have a grain size in the range of ASTM No. 3.0 to 9.0, or any sub-range subsumed therein such as, for example, ASTM No. 3.0 to 8.0, 3.5 to 7.5, 4.0 to 7.0, 4.5 to 6.5, 3.0 to 7.0, 3.0 to 6.0, or the like. In various non-limiting embodiments, products produced by the processes described herein may comprise intergranular $M_{23}C_6$ carbide precipitates uniformly distributed on the grain boundaries. In various non-limiting embodiments, products produced by the processes described herein may comprise minimal metallographically observable intragranular $M_{23}C_6$ carbide precipitates. In various non-limiting embodiments, products produced by the processes described herein may lack metallographically observable intragranular $M_{23}C_6$ carbide precipitates.

[0047] The microstructural carbide distribution may be determined metallographically, for example, by using scanning electron microscopy (SEM) to evaluate chemically etched (*e.g.*, bromine-methanol etch solution) specimens of nickel-base alloy processed according to various non-limiting embodiments described herein. For example, in various non-limiting embodiments, products produced by the processes described herein, when evaluated using SEM at 500x magnification, may comprise intergranular $M_{23}C_6$ carbide precipitates uniformly distributed on all observable grain boundaries and comprise minimal, or lack, observable intragranular $M_{23}C_6$ carbide precipitates. In various non-limiting embodiments, products produced by the processes described herein comprise equiaxed grains with a grain size of ASTM No. 3.0 to 9.0, a uniform grain size distribution, intergranular $M_{23}C_6$ carbide precipitates uniformly distributed on metallographically observable grain boundaries, and minimal metallographically observable intragranular $M_{23}C_6$ carbide precipitates.

[0048] The processes described herein reduce or eliminate abnormal grain growth that creates a non-uniform grain size distribution on a macroscopic scale. To control the grain size within specified limits, nickel-base alloy workpieces, such as, for

example, Alloy 690 workpieces, may be hot worked at temperatures above both the recrystallization temperature and the carbide solvus temperature of the alloy, *i.e.*, working at supersolvus temperatures. However, subsequent heat treatments to produce a uniform distribution of intergranular $M_{23}C_6$ carbide precipitates often cause an abnormal and non-uniform grain growth in sections of the macrostructure of the workpieces. For example, hot-worked rods and round bars of nickel-base alloy such as, for example, Alloy 690, tend to develop a ring-shaped region of abnormal grain growth through the cross-section of the product. Figures 2A and 2B schematically illustrate a long product 200 such as, for example, a rod or round bar of nickel-base alloy such as Alloy 690. The long product 200 includes a ring-shaped region 205 of abnormal grain growth through the cross-section of the product.

[0049] While not wishing to be bound by theory, it is believed that hot working at supersolvus temperatures to control grain size produces an intrinsic internal strain in the workpieces that causes the abnormal grain growth. The intrinsic internal strain is believed to be caused by differential thermal expansion of the workpiece during hot working and cooling after the hot working. The surface material of the workpieces cools much more rapidly than the internal material, particularly the material toward the center of the workpiece, when in contact with working dies/anvils and during subsequent cooling. This establishes a sharp temperature differential between the cooler surface and near-surface material and the hotter internal material. The temperature differential results in differential thermal expansion from the high temperature in the center to the low temperature at the surface of the hot-worked product, which is believed to produce an intrinsic internal strain in the material. During subsequent heat treatments to produce a uniform distribution of intergranular $M_{23}C_6$ carbide precipitates, the internal strain is believed to drive the abnormal grain growth, which localizes in the regions of the internal strain caused by the differential thermal expansion during cooling. This is believed to result in the observed ring-shaped regions of abnormal and non-uniform grain growth in the macrostructure of the products.

[0050] These deleterious regions of abnormal grain growth may be mitigated by working nickel-base alloy workpieces such as, for example, Alloy 690

workpieces, at temperatures below the carbide solvus temperature of the alloy, *i.e.*, at subsolvus temperatures. However, after working at subsolvus temperatures, subsequent heat treatments to produce a uniform distribution of intergranular $M_{23}C_6$ carbide precipitates often causes unacceptable grain growth throughout the entire workpiece. The grain size is difficult to control and the heat treatments often produce grain sizes greater than ASTM No. 3.0 (*i.e.*, ASTM Nos. less than 3.0.). Further, all of the carbides are not dissolved during working at subsolvus temperatures. As a result, the intergranular carbide distribution produced during subsequent heat treatments often includes large stringers of grain boundary carbides that were present between the large grains in the preform workpieces and that did not dissolve before, during, or after working at subsolvus temperatures.

[0051] The processes described herein reduce or eliminate the abnormal grain growth that creates a non-uniform grain size distribution on a macroscopic scale, and produce products having equiaxed grains with a grain size of ASTM No. 3.0 to 9.0, a uniform grain size distribution, intergranular $M_{23}C_6$ carbide precipitates uniformly distributed on the grain boundaries, and minimal intragranular $M_{23}C_6$ carbide precipitates. In the first of the at least two heating steps, a nickel-base alloy workpiece is heated to a carbide supersolvus temperature, which dissolves all of the $M_{23}C_6$ carbides present in the preform workpiece. In the first of the at least two working steps, the nickel-base alloy workpiece is worked at a carbide supersolvus temperature, for example, to a reduction in area of 20% to 70%. The working at the carbide supersolvus temperature prevents carbide precipitation and produces a uniform grain size distribution with grain sizes in the range of ASTM No. 3.0 to 9.0.

[0052] In the second of the at least two heating steps, the nickel-base alloy workpiece is heated to a carbide subsolvus temperature. The workpiece stabilizes at the subsolvus temperatures and is not permitted to cool to ambient temperature between the first working step and the second heating step. This minimizes any carbide precipitation because the workpiece material does not cool through the critical "nose" region of the time-temperature-transformation (TTT) curve of the material, at which the kinetics of carbide precipitation are the fastest. Nucleation and precipitation of carbides

is very slow at carbide subsolvus temperatures within approximately 300°F (167°C) of the carbide solvus temperature, for example. This prevents uncontrolled carbide precipitation. In the second of the at least two working steps, the nickel-base alloy workpiece is worked at a carbide subsolvus temperature, for example, to a reduction in
5 area of 20% to 70%. The working at the carbide subsolvus temperature reduces the differential thermal expansion and intrinsic internal strain in the material that is believed to cause abnormal grain growth during subsequent heat treatments.

[0053] The non-limiting and non-exhaustive examples that follow are intended to further describe various non-limiting and non-exhaustive embodiments
10 without restricting the scope of the embodiments described in this specification.

EXAMPLES

[0054] Heats of Alloy 690 were prepared by melting feed materials using VIM. The chemical compositions of the Alloy 690 heats were in compliance with ASTM B166-08: *Standard Specification for Nickel-Chromium-Iron Alloys (UNS N06600, N06601, N06603, N06690, N06693, N06025, N06045, and N06696) and Nickel-Chromium-Cobalt-Molybdenum Alloy (UNS N06617) Rod, Bar, and Wire* (2008) and ASME SB-166: *Specification for Nickel-Chromium-Iron Alloys (UNS N06600, N06601, N06603, N06690, N06693, N06025, N06045, and N06696) and Nickel-Chromium-Cobalt-Molybdenum Alloy (UNS N06617) Rod, Bar, and Wire* (2007), which are incorporated by reference herein.

[0055] The VIM heats were cast into initial ingots that were used as input electrodes for ESR. The ESR operation produced refined cylindrical ingots having diameters of approximately 20 inches (508 millimeters). The 20-inch ESR ingots were homogenized using standard practices and press forged to produce cylindrical workpieces having diameters of approximately 14 inches (356 millimeters).

[0056] The workpieces were thermo-mechanically treated according to non-limiting embodiments of the processes described herein comprising two heating steps and two working steps. In a first heating step, the workpieces were heated in a furnace operating at 2000°F to 2050°F (1093°C to 1121°C) for at least 6 hours time-at-temperature. In a first working step, the heated workpieces were rotary forged to approximately 9.6 inch (243 millimeter) diameters, which corresponds to a reduction in area of approximately 53%. The first working step comprised four passes through the rotary forge, each pass producing an approximately 17% to 18% reduction in area. The entire workpiece was at a temperature in the range of approximately 2000°F to 2050°F when the first working step began. During the rotary forging passes, the to-die and off-die surface temperatures of the workpieces were maintained in the range of 1700°F to 2050°F (926°C to 1121°C) for all four (4) passes.

[0057] After completion of the rotary forging, the surface temperatures of the workpieces were not permitted to cool to ambient temperature and the workpieces

were immediately charged into a furnace operating at 1825°F (996°C). In a second heating step, the forged workpieces were heated in the furnace for approximately 1.0 hour, 2.0 hours, 4.0 hours, or 8.0 hours furnace time. In a second working step, the heated workpieces were rotary forged a second time to approximately 7.2 inch (182 millimeter) diameters, which corresponds to a reduction in area of approximately 44% relative to the intermediate 9.6 inch (243 millimeter) diameters. The second working step comprised three passes through the rotary forge, each pass producing a 17% to 18% reduction in area. The entire workpiece was at a temperature of approximately 1825°F (996°C) when the second working step began. During the second working step, the to-die and off-die surface temperatures of the workpiece were maintained in the range of 1700°F to 2050°F (926°C to 1121°C) for all three passes. The workpieces were air cooled to ambient temperature after completion of the second working step. The total reduction in area produced by the two working steps was approximately 74%.

[0058] The twice-heated and twice-rotary-forged workpieces were annealed at 1875°F (1024°C) for four (4) hours time-at-temperature followed by a water quench to ambient temperature. The quenched workpieces were aged at 1340°F for four (4) hours time-at-temperature and air cooled to ambient temperature.

[0059] Cross-sections of the workpieces were etched using standard practices and the macrostructure evaluated metallographically. Figure 3A is a metallograph of a cross-section of a workpiece heated for approximately 1 hour furnace time in a furnace operating at 1825°F (996°C) between the first working step and the second working step. Figure 3B is a metallograph of a cross-section of a workpiece heated for approximately 2 hours furnace time in a furnace operating at 1825°F (996°C) between the first working step and the second working step. Figure 3C is a metallograph of a cross-section of a workpiece heated for approximately 4 hours furnace time in a furnace operating at 1825°F (996°C) between the first working step and the second working step. Figure 3D is a metallograph of a cross-section of a workpiece heated for approximately 8 hours furnace time in a furnace operating at 1825°F (996°C) between the first working step and the second working step.

[0060] As shown in Figures 3A and 3B, the workpieces heated for approximately 1 hour and 2 hours furnace time in a furnace operating at 1825°F (996°C) developed a ring-shaped region of abnormal grain growth. As shown in Figures 3C and 3D, the workpieces heated for approximately 4 hours and 8 hours furnace time in a furnace operating at 1825°F (996°C) did not exhibit any abnormal grain growth. The grain size of the workpieces heated for approximately 4 hours and 8 hours furnace time was in the range of ASTM No. 3.0 to 8.0, determined in accordance with ASTM E 112-10. The workpieces formed intergranular $M_{23}C_6$ carbide precipitates uniformly distributed on the grain boundaries and exhibited minimal intragranular $M_{23}C_6$ carbide precipitation.

[0061] The processes described in this specification produce nickel-base alloy products having a microstructure and macrostructure that provides superior properties for critical engineering applications such as, for example, structural components in chemical processing equipment and PWRs for nuclear power generation. This specification has been written with reference to various non-limiting and non-exhaustive embodiments. However, it will be recognized by persons having ordinary skill in the art that various substitutions, modifications, or combinations of any of the disclosed embodiments (or portions thereof) may be made within the scope of this specification. Thus, it is contemplated and understood that this specification supports additional embodiments not expressly set forth herein. Such embodiments may be obtained, for example, by combining, modifying, or reorganizing any of the disclosed steps, components, elements, features, aspects, characteristics, limitations, and the like, of the various non-limiting embodiments described in this specification. In this manner, Applicant reserves the right to amend the claims during prosecution to add features as variously described in this specification, and such amendments comply with the requirements of 35 U.S.C. § 112, first paragraph, and 35 U.S.C. § 132(a).

CLAIMS

What is claimed is:

5 1. A process comprising:

 a first heating step comprising heating a nickel-base alloy workpiece to a temperature in the range of 2000°F to 2125°F;

 a first forging step comprising rotary forging the heated nickel-base alloy workpiece to a reduction in area of 30% to 70%, wherein the nickel-base alloy
10 workpiece is at a temperature in the range of 2000°F to 2125°F when the first forging step begins;

 a second heating step comprising heating the rotary-forged nickel-base alloy workpiece to a temperature in the range of 1750°F to 1925°F, wherein the rotary-forged nickel-base alloy workpiece is maintained at elevated temperature and not permitted to
15 cool to ambient temperature between completion of the first forging step and beginning of the second heating step; and

 a second forging step comprising rotary forging the heated nickel-base alloy workpiece to a reduction in area of 20% to 70%, wherein the nickel-base alloy workpiece is at a temperature in the range of 1750°F to 1925°F when the second
20 forging step begins;

 wherein the nickel-base alloy workpiece comprises, by weight, up to 0.05% carbon, 27.0% to 31.0% chromium, up to 0.5% copper, 7.0% to 11.0% iron, up to 0.5% manganese, up to 0.015% sulfur, up to 0.5% silicon, at least 58% nickel, and incidental impurities.

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 2. The process of claim 1, wherein the first heating step comprises heating the nickel-base alloy workpiece in a furnace operating at 2000°F to 2125°F for at least 6.0 hours time-at-temperature.

3. The process of claim 1, wherein the second heating step comprises heating the rotary-forged nickel-base alloy workpiece in a furnace operating at 1750°F to 1925°F for greater than 2.0 hours furnace time.

5 4. The process of claim 1, wherein the second heating step comprises heating the rotary-forged nickel-base alloy workpiece in a furnace operating at 1750°F to 1925°F for 3.0 hours to 10.0 hours furnace time.

10 5. The process of claim 1, wherein the second heating step comprises heating the rotary-forged nickel-base alloy workpiece in a furnace operating at 1750°F to 1925°F for 4.0 hours to 8.0 hours furnace time.

6. The process of claim 1, further comprising:
vacuum induction melting feed materials to form a nickel-base alloy ingot;
15 remelting the nickel-base alloy ingot to form a refined nickel-base alloy ingot, wherein the remelting comprises at least one remelting operation selected from the group consisting of vacuum arc remelting and electroslag remelting; and
press forging the refined nickel-base alloy ingot to form the nickel-base alloy workpiece.

20 7. The process of claim 1, further comprising, after the two heating steps and the two forging steps:

heating the nickel-base alloy workpiece at a temperature of at least 1800°F, but no greater than a $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy, for at least
25 3.0 hours time-at-temperature; and
water quenching the workpiece.

8. The process of claim 1, further comprising, after the two heating steps and the two forging steps:

aging the nickel-base alloy workpiece at a temperature of 1300°F to 1400°F for at least 3.0 hours time-at-temperature; and
air cooling the workpiece.

5 9. A product produced by the process of claim 1, the product selected from the group consisting of a rod and a round bar.

10 10. The product of claim 9, wherein the product comprises equiaxed grains with a grain size of ASTM No. 3.0 to 9.0, a uniform grain size distribution, intergranular $M_{23}C_6$ carbide precipitates uniformly distributed on metallographically observable grain boundaries, and substantially no metallographically observable intragranular $M_{23}C_6$ carbide precipitates.

15 11. A process comprising:
a first heating step comprising heating a nickel-base alloy workpiece to a temperature greater than a $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy;
a first working step comprising working the heated nickel-base alloy workpiece to a reduction in area of 20% to 70%, wherein the nickel-base alloy workpiece is at a temperature greater than a $M_{23}C_6$ carbide solvus temperature when the first working
20 step begins;

a second heating step comprising heating the worked nickel-base alloy workpiece to a temperature greater than 1700°F and less than the $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy, wherein the as-worked nickel-base alloy workpiece is maintained at elevated temperature and not permitted to cool to ambient temperature
25 between completion of the first working step and beginning of the second heating step;
and

a second working step comprising working the heated nickel-base alloy workpiece to a second reduction in area of 20% to 70%, wherein the nickel-base alloy workpiece is at a temperature greater than 1700°F and less than the $M_{23}C_6$ carbide
30 solvus temperature of the nickel-base alloy when the second working step begins.

12. The process of claim 11, wherein the nickel-base alloy workpiece comprises, by weight, up to 0.05% carbon; 27.0% to 31.0% chromium; up to 0.5% copper; 7.0% to 11.0% iron; up to 0.5% manganese; up to 0.015% sulfur; up to 0.5% silicon; at least 58% nickel; and incidental impurities.

5

13. The process of claim 11, wherein the nickel-base alloy workpiece comprises, by weight, up to 0.05% carbon; 28.0% to 30.0% chromium; up to 0.25% copper; 8.0% to 10.0% iron; up to 0.25% manganese; up to 0.010% sulfur; up to 0.25% silicon; at least 58% nickel; and incidental impurities.

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14. The process of claim 11, wherein the first working step and the second working step independently comprise at least one operation selected from the group consisting of flat rolling, ring rolling, roll forming, press forging, extruding, and rotary forging.

15

15. The process of claim 11, wherein the first working step and the second working step comprise rotary forging.

16. The process of claim 11, wherein the first heating step comprises heating the nickel-base alloy workpiece in a furnace operating at 2000°F to 2125°F for at least 3.0 hours time-at-temperature.

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17. The process of claim 11, wherein second heating step comprises heating the nickel-base alloy workpiece in a furnace operating at 1750°F to 1925°F for greater than 2.0 hours furnace time.

25

18. The process of claim 11, wherein the second heating step comprises heating the nickel-base alloy workpiece in a furnace operating at 1750°F to 1925°F for 3.0 hours to 10.0 hours furnace time.

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19. The process of claim 11, wherein the second heating step comprises heating the rotary-forged nickel-base alloy workpiece in a furnace operating at 1750°F to 1925°F for 4.0 hours to 8.0 hours furnace time.

5 20. The process of claim 11, further comprising:
vacuum induction melting feed materials to form a nickel-base alloy ingot;
remelting the nickel-base alloy ingot to form a refined nickel-base alloy ingot,
wherein the remelting comprises at least one remelting operation selected from the
group consisting of vacuum arc remelting and electroslag remelting; and
10 press forging the refined nickel-base alloy ingot to form the nickel-base alloy
workpiece.

21. The process of claim 11, further comprising, after the two heating steps
and the two working steps:

15 heating the nickel-base alloy workpiece at a temperature of at least 1800°F, but
no greater than a $M_{23}C_6$ carbide solvus temperature of the nickel-base alloy, for at least
3.0 hours time-at-temperature; and
water quenching the workpiece.

20 22. The process of claim 11, further comprising, after the two heating steps
and the two forging steps:

aging the nickel-base alloy workpiece at a temperature of 1300°F to 1400°F for at
least 3.0 hours time-at-temperature; and
air cooling the workpiece to ambient temperature.

25 23. A product produced by the process of claim 11.

24. The product of claim 23, wherein the product comprises a long product
selected from the group consisting of a rod, a round bar, and a rectangular bar.

25. The product of claim 23, wherein the product comprises equiaxed grains with a grain size of ASTM No. 3.0 to 9.0, a uniform grain size distribution, intergranular $M_{23}C_6$ carbide precipitates uniformly distributed on metallographically observable grain boundaries, and substantially no metallographically observable intragranular $M_{23}C_6$ carbide precipitates.
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