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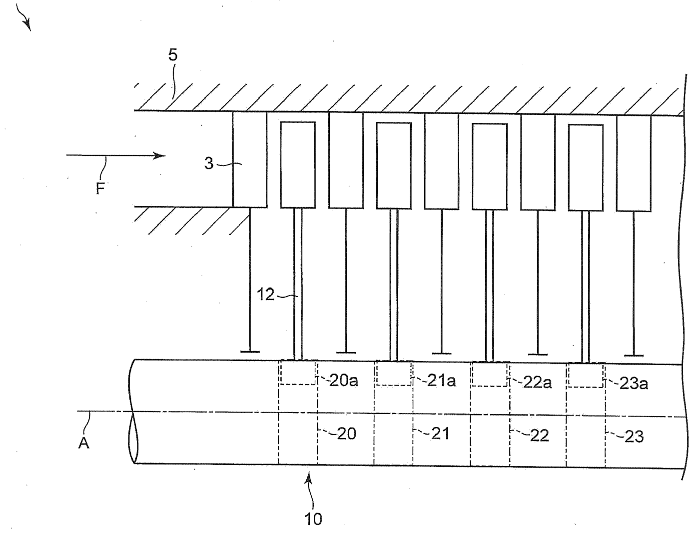
(54) METHOD OF MANUFACTURING ROTOR TO BE USED FOR STEAM TURBINE

(57) According to one embodiment, a method of manufacturing a steam turbine rotor (10) has a step of reducing the residual stress (2-2) of the target regions (20) of the rotor if compared with the other region.

FIG. 1



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Description

FIELD

[0001] Embodiments of the present invention relate to a method of manufacturing a rotor to be used for a steam turbine.

BACKGROUND

[0002] Steam turbines include those being used for geothermal power generation and also those to be used for geothermal power generation. For geothermal power generation, steam stored underground is fed to a steam turbine installed on the ground to drive the rotor of the steam turbine to rotate by steam force. The temperature of natural steam that is fed to steam turbines for geothermal power generation is lower than that of steam that is fed to steam turbines for ordinary thermal power generation and typically about 200 °C. Natural steam that is fed to steam turbines for geothermal power generation may contain corrosive gases such as hydrogen sulfide that corrode metals.

[0003] The rotors being employed for geothermal power generation can give rise to cracking due to hydrogen embrittlement (to be simply referred to as "hydrogen cracking" hereinafter). Therefore, materials for forming steam turbines (to be referred to as "rotor materials" hereinafter) are required to have an ability of not giving rise to cracking that is attributable to hydrogen embrittlement (to be referred to as "hydrogen cracking resistance" hereinafter) in addition to satisfactory mechanical properties in terms of tensile strength, yield strength and tenacity and corrosion resistance.

[0004] Thus, 1 to 2 % Cr-based materials prepared on the basis of 1 % CrMoV steel, which has a rich record of use as rotor material for steam turbines for thermal power generation, in order to provide improved toughness are being employed more often than not for steam turbines for geothermal power generation from the viewpoint of securing the hydrogen cracking resistance and the corrosion resistance that are required to rotors of the type under consideration as described above.

[0005] Meanwhile, of the rotor of a steam turbine for geothermal power generation, the regions that are initially exposed to natural steam may be operated in a highly corrosive environment if compared with the other region of the rotor. Those regions are accompanied by a problem that they are particularly liable to give rise to hydrogen cracking and such hydrogen cracking easily and quickly develops. Therefore, there is a strong demand for steam turbine rotors that show a particularly improved resistance against hydrogen cracking.

Brief Description of the Drawings

[0006]

FIG. 1 is a schematic illustration of the configuration of an exemplar rotor of a steam turbine of the first and second embodiments and a peripheral area of the rotor;

FIG. 2 is a table illustrating exemplar materials that can be used for the rotors of the steam turbines of the first and second embodiments according to the present invention;

FIG. 3 is a table illustrating the heat treatment conditions of the first and second embodiments of manufacturing method according to the present invention;

FIG. 4 is a table illustrating the results of determining the grain size (G.S. No.), the residual stress (maximum tensile stress) and the hydrogen cracking resistance of each of the sample materials that have been subjected to the heat treatments of the first and second embodiments of manufacturing method according to the present invention;

FIG. 5 is a table illustrating the heat treatment conditions of Comparative Examples; and

FIG. 6 is a table illustrating the results of determining the grain size (G.S. No.), the residual stress (maximum tensile stress) and the hydrogen cracking resistance of the sample materials that have been subjected to the heat treatments of Comparative Examples.

DETAILED DESCRIPTION

[0007] The problem to be solved by the present invention is to provide a method of manufacturing a rotor to be used for a steam turbine (to be referred to as steam turbine rotor hereinafter) that shows an improved hydrogen cracking resistance at predetermined regions that are the target of improvement.

[0008] Embodiments of the present invention can improve the hydrogen cracking resistance at predetermined regions of a steam turbine rotor that are the target of improvement.

[0009] Now, the present invention will be described in greater detail by referring to the accompanying drawings that illustrate preferred embodiments of the present invention.

[First Embodiment]

[0010] An exemplar steam turbine rotor, to which the first embodiment of manufacturing method according to the present invention is applicable, will be described below by referring to FIG. 1.

[0011] FIG. 1 is a schematic illustration of the steam turbine rotor of this embodiment and the configuration of peripheral regions thereof. Note that the lower side of the rotor blades, the fixed vanes and the casing are omitted in FIG. 1 for the purpose of easy understanding.

[0012] As shown in FIG. 1, steam turbine 1 is an axial flow type turbo fluid machinery that has a casing 5, to the inside of which fixed vanes 3 are coupled, and a steam turbine rotor (to be referred to simply as "rotor" hereinafter) 10 designed to rotate around a center axis of rotation (indicated by dotted chain line A in FIG. 1) in the casing 5. The rotor 10 has a substantially cylindrical shape and extends in the axial direction. A plurality of rotor blades 12 is arranged in the circumferential direction of the rotor 10. As viewed in the axial direction of the rotor 10 (the direction indicated by dotted chain line A in FIG. 1), the rotor blades 12 are arranged vis-a-vis the fixed vanes 3. The rotor blades 12 and the fixed vanes 3 form a plurality of turbine stages.

[0013] As indicated by arrow F in FIG. 1, steam is introduced into the steam turbine 1 from one axial side (to be referred to as upstream side hereinafter) of the rotor 10. The steam turbine 1 of this embodiment is employed for geothermal power generation and hence natural steam is introduced into the steam turbine 1. Natural steam contains corrosive gases such as hydrogen sulfide that corrode metals. Therefore, the rotor 10 is exposed to natural steam that contains corrosive gases.

[0014] Particularly, regions located near the turbine stages at the upstream side of the steam turbine 1 are those that are exposed to incoming natural steam as shown in FIG. 1. Therefore, those regions are required to show a particularly high hydrogen cracking resistance. For example, at the coupling portions 20a, 21 a, 22a and 23a where the turbine blades 12 that form the first through fourth turbine stages (to be referred to as blade-implanted sections hereinafter, which are indicated by broken lines in FIG. 1) are coupled, corrosive components of natural steam can be deposited and accumulated in the gaps surrounding those rotor blades 12. For this reason, hydrogen cracking is apt to occur at substantially cylindrical portions 20, 21, 22 and 23 (to be referred to as stage-portions hereinafter, which are indicated by chain double-dashed lines in FIG. 1) and include the blade-implanted portions 20a, 21 a, 22a and 23a respectively, if compared with the other region of the rotor.

[0015] At the downstream side (not shown) of the steam turbine 1, on the other hand, natural steam works in the turbine stages at the downstream side and becomes condensed (liquefied) and drained. For this reason, the corrosive components of natural steam are not deposited in the blade-implanted portions that are located at the downstream side but discharged to the outside as they are condensed and drained. Therefore, hydrogen cracking is not apt to take place in the regions of the rotor 10 that are located at the downstream side of the steam turbine 1.

[0016] In the rotor 10 of this embodiment, the stage portions 20, 21, 22 and 23 respectively including the blade-implanted portions 20a, 21 a, 22a and 23a of the upstream side turbine stages of the steam turbine, into which geothermal steam flows, are regions that are particularly required to show an improved hydrogen cracking resistance. These regions will be referred to as "target regions" in the following description. Also in the following description, all the regions other than the predetermined target regions (stage portions) 20, 21, 22 and 23 will be referred to as "the other region"

[0017] Now, rotor materials that can be used for the method of manufacturing the steam turbine rotor of this embodiment will be described below by referring to FIG. 2. FIG. 2 is a table illustrating exemplar rotor materials that can be used for the steam turbine of this embodiment. Note that FIG. 2 shows the components of the rotor materials that were assessed (to be referred to as sample materials hereinafter) for the purpose of the present invention and the components of the rotor material defined in one of the appended claims for patent of this specification. The results of the heat treatment operations conducted on the sample materials A, B, C, D, E, F and G for this embodiment will be described hereinafter.

[0018] As shown in FIG. 2, steam turbine rotors are made of so-called ferritic alloy steels that contains iron (symbol of element: Fe) as principal component. Ferritic alloy steels listed in FIG. 2 contains, in mass %(in percentage by mass), carbon (symbol of element: C): 0.15 % to 0.33 %, silicon (symbol of element: Si): 0.03% to 0.20%, manganese (symbol of element: Mn): 0.5 % to 2.0 %, nickel (symbol of element: Ni): 0.1 % to 1.3 %, chromium (symbol of element: Cr): 0.9 % to 3.5 %, molybdenum (symbol of element: Mo): 0.1 % to 1.5 %, vanadium (symbol of element: V): 0.15 % to 0.35 % and tungsten (symbol of element: W) as optional component: 1.0 % or less. Note that a ferritic alloy steel of this embodiment may contains no tungsten.

[0019] Additionally, ferritic alloy steels may contain nitrogen (symbol of element: Ni): 0.005 % to 0.15 % in mass % if necessary for manufacturing it. Nitrogen improves hardenability of the material. If applied to a large steel ingot, nitrogen reduces production of ferrite in center regions of the steel ingot and hence the use of nitrogen is effective for producing a large rotor made of the rotor material. Furthermore, nitrogen is effective for raising the degree of strength of the rotor 10 as it incorporates into the matrix (principal metal, i.e. balance) of the material to produce solid solution and deposits as a carbonitride of Nb or Nb (C, N). Note that the material may further contain one or more impurities that unavoidably get into the material in the manufacturing process (to be referred to as unavoidable impurities hereinafter).

[0020] Now, the manufacturing method (heat treatment method) of this embodiment will be described below by referring to FIGS. 3 and 4. FIG. 3 is a table illustrating the heat treatment conditions of the manufacturing method of this embodiment. FIG. 4 is a table illustrating the results of determining the grain size, the residual stress (maximum tensile stress) and the hydrogen cracking resistance of each of the sample materials that were subjected to the heat treatments of the manufacturing method of this embodiment.

[0021] The above-described rotor material of this embodiment can be obtained by means of a well-known melting and manufacturing process and the obtained hot alloy steel is subjected to hot working such as forging. After such a hot working process, the various heat treatments of this embodiment are executed on the rotor material. The heat treatments include, for example, a quality heat treatment. A quality heat treatment is a heat treatment of tempering the material at a relatively high temperature after hardening the material by quenching in order to stabilize the material. This heat treatment will be referred to as "quality heat treatment" hereinafter.

(1) Pre-quality heat treatment annealing step

[0022] With the manufacturing method of this embodiment, the rotor material is subjected to annealing before the execution of the above-described quality heat treatment step. This annealing step will be described below by referring to FIGS. 3 and 4. In this step, the steam turbine rotor is heated to a predetermined temperature and held to the temperature before it is gradually cooled. As a result of the cooling, the rotor material is softened so that the strain in the inside can be removed. The annealing step that is conducted prior to the quality heat treatment is referred to as "pre-quality heat treatment annealing step" hereinafter. The pre-quality heat treatment annealing step is executed on the entire steam turbine rotor including the above-described target regions and the other region.

[0023] In the pre-quality heat treatment annealing step of this embodiment, the heating temperature for the annealing (to be simply referred to as "annealing temperature" hereinafter) is set to be within the range of 1,050 to 1,300°C. As an example, the annealing temperature may be set to be equal to 1,150°C or 1,050°C as shown in FIG. 3. In the pre-quality heat treatment annealing step, the rotor material is heated until the temperature of the rotor material gets to the annealing temperature, which may be set to be within the range of 1,150 to 1,300°C, and held to the annealing temperature for a predetermined period of time (to be referred to as holding time hereinafter) before it is gradually cooled at a sufficiently low cooling rate typically by furnace cooling or air cooling. Then, in the subsequent quenching step for the quality heat treatment, the crystal grains of the target regions are refined. Note that 5 hours is selected for the annealing temperature holding time of this embodiment.

[0024] 1,050°C is selected as the lower limit value of annealing temperature for the purpose of removing the strain that is given rise to during the hot working step including forging. Additionally, an annealing temperature not lower than 1,050°C is required to make course carbides and carbonitrides incorporate into the matrix (principal metal, i.e. balance) of the material to produce solid solution and obtain a homogeneous structure. If the annealing temperature is lower than 1,050°C, the quality heat treatment step that is executed after the pre-quality heat treatment annealing step cannot provide the quality level and the material characteristics that are required to the rotor material.

[0025] 1,300°C is selected as the upper limit value of annealing temperature because the service life of the annealing furnace is remarkably shortened when the annealing temperature exceeds the above value and hence such a high temperature is inappropriate for actual manufacturing operations. For the above reasons, the annealing temperature is set to be within the range of 1,050°C to 1,300°C. For the same reasons, the lower limit value and the upper limit value of annealing temperature are preferably set to be equal to 1,100°C and 1,250°C respectively.

[0026] As the pre-quality heat treatment annealing step is executed within the above-described temperature range, the strain within the rotor material is removed and a pearlite structure can be produced to a relative high ratio. When the ratio of the pearlite structure that is produced in the pre-quality heat treatment annealing step is high, crystal grains are refined to a large extent after the quality heat treatment, which will be described below. In other words, the step of micronizing crystal grains includes the above-described pre-quality heat treatment annealing step.

(2) Quality heat treatment

(2-1) Quenching step

[0027] In the quality heat treatment of this embodiment, firstly the structure of the rotor material is subjected to a quenching step so as to be austenitized. In this step, the rotor material is heated and held to a predetermined heating temperature (to be referred to as austenitizing temperature hereinafter), then the rotor material is rapidly cooled. As a result, the structure of the rotor material is austenitized. The step of austenitizing the structure by quenching is referred to simply as "quenching step" hereinafter.

[0028] In the quenching step of this embodiment, the austenitizing temperature of the target regions of the rotor that are particularly required to show a high hydrogen cracking resistance is set to a relatively low temperature if compared with the austenitizing temperature of the other region. More specifically, the austenitizing temperature of the other region is set to be within the range of 910 to 950°C. On the other hand, the austenitizing temperature of the target regions is set to be within the range of 880 to 910 °C that is lower than that of the other region. As the rotor material is subjected to a quenching step that is executed in the above-described austenitizing temperature ranges, the crystal grains of the target regions of the rotor can be refined if compared with the crystal grains of the other region. In other words, the step of micronizing crystal grains includes the above-described quenching step.

[0029] As shown in FIG. 3, the austenitizing temperature of the other region is set to be equal to 920°C whereas the austenitizing temperature of the target regions is set to be equal to 900°C is lower than that of the other region. In the quenching step, the rotor material is heated until it gets to the above-described austenitizing temperatures, and the austenitizing temperatures are held for a predetermined holding time before the rotor material is cooled rapidly by blowing atomized water to the rotor. Note that 5 hours is selected for the austenitizing temperature holding time of this embodiment.

[0030] If instances where the crystal grains of the target regions are refined are compared with instances where the crystal grains of the target regions are not refined, the service life until cracks take place due to hydrogen cracking of the target regions is same but the rate at which cracks develop (to be referred to as crack developing rate hereinafter) is reduced in the former instances. As the "crack developing rate" is reduced, the hydrogen cracking resistance of the target regions is improved.

[0031] While the effect of micronizing crystal grains in the rotor materials can be obtained if the austenitizing temperature of the target regions is lower than 880°C, carbonitrides incorporate into the matrix (principal metal, i.e. balance) of the material to produce solid solution only insufficiently so that the degree of strength and that of toughness that are required after the tempering step, which will be described hereinafter, are no longer achievable. Additionally, the use of a low austenitizing temperature can give rise to relatively large residual (tensile)stress. If, on the other hand, the austenitizing temperature of the target regions exceeds 910°C, it no longer differs from the austenitizing temperature of the other region. Then, it is no longer possible to provide a satisfactory degree of hydrogen cracking resistance that is required to the target regions. For the above-described reasons, the austenitizing temperature of the target regions, which particularly require an improved hydrogen cracking resistance, is set to be within the range of 880 to 910°C. For the same reasons, the lower limit value and the upper limit value of austenitizing temperature of the target regions are preferably set to be equal to 890°C and 905°C respectively.

[0032] The above-described austenitizing temperature is held for a predetermined period of time. Substantially, the rotor is cooled rapidly by spraying water to complete the quenching step.

(2-2) Tempering step

[0033] In the quality heat treatment of this embodiment, the rotor material is then subjected to a tempering step. In the tempering step that follows the above-described quenching step, the rotor material is heated again to a predetermined heating temperature (to be referred to as tempering temperature hereinafter) that is set to be lower than the austenitizing temperature and then cooled. As a result, the rotor material can acquire desired properties including toughness. The step in which the above-described tempering operations are executed is referred to as "tempering step" hereinafter. Note that the tempering step is denoted as "the first stage tempering" in FIG. 3.

[0034] In the tempering step of this embodiment, the tempering temperature of the target regions of the rotor that are required to show a particularly high hydrogen cracking resistance, is set to a high temperature if compared with the remaining region. The tempering temperature of the other region is set to be within the range of 600 to 660°C. On the other hand, the tempering temperature of the target regions is set to be within the range of 660 to 700°C that is higher than the temperature range for the other region. As the tempering step of this embodiment is executed at the above-described tempering temperature, the tempering step can reduce the residual stress (tension) that arises in the target regions of the rotor after tempering if compared with the other region. In other words, the step of reducing the residual stress of the target regions relative to the other region includes this tempering step (2-2).

[0035] As shown under "the first stage tempering" in FIG. 3, the tempering temperature of the target regions of this embodiment is set to be equal to 670°C, while the tempering temperature of the other region is set to be equal to 630°C. In the tempering step, the rotor material is heated until the above-described tempering temperatures are reached and the tempering temperatures are held for a predetermined period of time before the rotor material is cooled. Note that 20 hours is selected for the tempering temperature holding time.

[0036] The stress that acts on the rotor material include external stress (external force) and internal stress (residual stress). As the target regions that particularly require improvement in the hydrogen cracking resistance is tempered at a temperature within the range of 660 to 700°C that is higher than that of the other region, the residual stress (tension) in the target regions is reduced and hence the stress that acts on the rotor material is reduced so much. Then, as a result, the development of hydrogen cracking in the target regions can be controlled.

[0037] While the effect of reducing the residual stress (tension) can be obtained for above-described ferritic alloy steels when the tempering temperature of the target region is not lower than 660°C, the strength of the rotor falls when the tempering temperature exceeds 700°C. For these reasons, the tempering temperature of the target regions of the rotor that are required to show a particularly high hydrogen cracking resistance is set to be within the range of 660 to 700°C. For the same reasons, the lower limit value and the upper limit value of tempering temperature are preferably set to be equal to 665°C and 685°C respectively.

[0038] The technique of high-frequency induction heating can be employed as technique for making the tempering temperature of the target regions of a steam turbine rotor higher than the tempering temperature of the other region of the rotor. By heating only the target regions of the rotor, which particularly require an improved hydrogen cracking resistance, by means of the technique of high-frequency induction heating, the tempering temperature of the target regions can be made higher than that of the other region.

[Rotor material and heat treatment conditions]

[0039] The method of manufacturing a rotor to be used for the steam turbine (heat treatment method) of this embodiment will be described below by referring to FIGS. 2 through 6 in terms of the hydrogen cracking resistances of the various rotor materials to which the method was applied.

[0040] FIG. 2 is a table illustrating exemplar materials that can be used for the steam turbine rotor of this embodiment. It shows the components of each of the rotor materials (to be referred to as sample materials hereinafter) that were evaluated. The sample materials listed in FIG. 2 were provided in the form of three pieces of each of test sample steel ingots A, B, C, D, E, F and G that were ingoted by means of a vacuum induction melting furnace (VIM) and forged.

[0041] FIG. 3 is a table illustrating the heat treatment conditions of this embodiment of manufacturing method of the present invention. FIG. 4 is a table illustrating the results of determining the crystal grain size (G.S. No.), the residual stress (maximum tensile stress) and the hydrogen cracking resistance of each of the sample materials that were subjected to the heat treatments of the first embodiment of manufacturing method of the present invention. FIG. 5 is a table illustrating the heat treatment conditions of Comparative Examples. FIG. 6 is a table illustrating the results of determining the crystal grain size (G.S. No.), the residual stress (maximum tensile stress) and the hydrogen cracking resistance of the sample materials that were subjected to the heat treatments of Comparative Examples.

[0042] The crystal grain size (G.S. No.) of each of the sample materials including those of Comparative Examples was determined by comparing the austenite grain size as defined in prior JIS(Japanese Industrial Standard, Methods of austenite grain size determination for steel) with the Grain Size Standard Views for each of the samples. Note that, as the G.S. No. increases, the crystal grain size decreases.

[0043] For each of the samples, the residual stress (maximum tensile stress) is determined by means of formula (1) shown below and the X-ray stress measurement method.

$$N\lambda = 2d\sin\theta \qquad \ldots(1)$$

In the formula (1),
n: degree of diffraction,
λ: wavelength of X-ray,
d: crystal lattice spacing of material and
θ: angle of diffraction.

[0044] According to Bragg's law for X-ray diffraction as expressed by the formula (1), the value of d (the crystal lattice spacing of the material) can be determined when θ (the angle of diffraction) is known. Then, the residual stress can be computationally determined by determining the strain from the difference between d and the standard crystal lattice spacing and using Young's modulus to Poisson's ratio.

[0045] Hydrogen cracking resistance refers to the resistance against cracking that is caused by the pressure of hydrogen gas that is produced due to a phenomenon that hydrogen produced as a result of corrosion of the material penetrates into the material, diffuses and concentrates along interfaces between the non-metallic inclusions and the matrix (principal metal, i.e. balance) so as to become hydrogen gas molecules.

[0046] The test for hydrogen cracking was conducted according to NACE Standard (TM0284, Evaluation of Pipeline and Pressure Vessel Steels for Resistance against Hydrogen-Induced Cracking). Each of the test pieces of the sample materials was immersed in a 5 % NaCl + 0.5 % acetic acid solution with pH4 for 96 hours at the test temperature of 24 ± 2.8 °C and subsequently cut to evaluate the cross portion and check for existence or non-existence of cracking. The size of the test pieces was 50 mm × 30 mm × 10 mm and three test pieces were employed for each of the sample materials. When all of the three test pieces of a sample material did not show any cracking, the sample material was rated as "hydrogen cracking resistance : O" and all the sample materials that were not rated as "O" were rated as "hydrogen cracking resistance: X".

[0047] As shown in FIGS. 3 and 4, when the pre-quality heat treatment annealing step, the quenching step and the tempering step (the first stage tempering and the second stage tempering) were executed under the heat treatment conditions of this embodiment, all the sample materials were rated as "hydrogen racking resistivity: O" at least at the target regions that are required to show a satisfactory hydrogen cracking resistance.

[0048] However, when at least any one of the pre-quality heat treatment annealing step, the quenching step and the tempering step (the first stage tempering and the second stage tempering) was conducted under the conditions where at least one of the heat treatment conditions of this embodiment was not satisfied, the target regions that are required to show a satisfactory hydrogen cracking resistance were rated as "hydrogen crack resistivity: X" as in the case of Comparative Examples shown in FIGS. 5 and 6.

[0049] Thus, it was proved that the method of manufacturing a steam turbine rotor of this embodiment provides the target regions of the turbine that are particularly required to show a satisfactory hydrogen cracking resistance with an excellent hydrogen cracking resistance.

[0050] As described above, the method of manufacturing a steam turbine rotor of this embodiment comprises a step of reducing the residual stress (2-2) of the target regions of the rotor if compared with the other region. As the residual stress that arises after the tempering step is reduced in the target regions than in the other region, the development of hydrogen cracking in the target regions can be controlled so that the hydrogen cracking resistance of the rotor can be improved.

[0051] The step of reducing the residual stress of this embodiment includes a tempering step (2-2) that is a step of tempering the rotor after the quenching the rotor. In the tempering step, the tempering temperature (the first stage tempering) is set high for the target regions of the steam turbine rotor if compared with the other region of the rotor as shown in the inventive examples 4, 5, 7 to 9, 12, 13, 15, 16, 18, 19, 21, 23, 25, 27 to 31, 34 to 40 and 42 in FIG. 3. As a result of selecting a tempering temperature in the above-described manner, the residual stress of the target regions can be reduced if compared with the other region.

[0052] Note that the tempering temperature of the target regions of the steam turbine rotor that is higher than that of the other region of the rotor is reached by high frequency induction heating in this embodiment. High frequency induction heating can make the tempering temperature of the target regions that require a particularly improved hydrogen cracking resistance in the rotor higher than that of the other region.

[0053] This embodiment further includes a step of refining crystal grains in the target regions if compared with the crystal grains of the other region. Thus, the strength and the toughness of the target regions can be improved and, at the same time, the crack developing rate can be reduced by refining crystal grains in the target regions.

[0054] "The step of refining crystal grains" of this embodiment includes a quenching step (2-1), which is a step where the rotor is subjected to quenching. The quenching step is executed before the tempering step (2-2). In the quenching step (2-1), the austenitizing temperature, which is the heating temperature, is set low for the target regions of the steam turbine rotor if compared with the other region of the rotor as shown in the inventive examples 2, 3, 19 to 21, 26 to 37, 41 and 42 in FIG. 3. As a result of selecting the austenitizing temperature in the above-described manner, crystal grains can be refined for the target regions if compared with the other region.

[0055] In this embodiment, the steam turbine rotor is formed by using a ferritic alloy steel that contains, in mass %, carbon: 0.15 % to 0.33 %, silicon: 0.03 % to 0.20 %, manganese: 0.5 % to 2.0 %, nickel: 0.1 % to 1.3 %, chromium: 0.9 % to 3.5 %, molybdenum:

> 0.1 % to 1.5 %, vanadium: 0.15 % to 0.35 %, nitrogen: 0.005 % to 0.015 % and tungsten as optional component: 1.0 % or less as shown in FIG. 2 for the sample materials A, B, C, D, E, F and G. As a result of using such a ferritic alloy steel for forming the rotor, it is possible to realize a rotor that hardly produces hydrogen cracking if exposed to highly corrosive gases such as hydrogen sulfide and, if it produces hydrogen cracking, cracks hardly develop.

[0056] The heating temperature for the tempering step, or the tempering temperature, is set to be within the range of 660 to 700°C for the target regions of the steam turbine rotor as shown in the inventive examples 4, 5, 7 to 9, 12, 13, 15, 16, 18, 19, 21, 23, 25, 27 to 31, 34 to 40 and 42 in FIG. 3. While the effect of reducing the residual stress (tension) can be obtained for above-described ferritic alloy steels when the tempering temperature of the target region is not lower than 660°C, the strength of the rotor falls when the tempering temperature exceeds 700°C. For this reason, the tempering temperature of the target regions of the rotor that are required to show a particularly high hydrogen cracking resistance is set to be within the range of 660 to 700°C to effectively reduce the residual stress, while reducing the extent of fall of the strength.

[0057] While the tempering temperature of the target regions is set to be equal to 670°C and the tempering temperature of the other region is set to be equal to 630°C for the tempering step of this embodiment, the tempering temperatures according to the present invention are by no means limited to the above specified values. For example, the tempering temperature of the target regions may be set to be equal to 630°C, which is equal to the tempering temperature of the other region.

[0058] The austenitizing temperature in the quenching step (2-1) of the target regions is set to be within the range of 880 to 910°C as shown in the inventive examples 2, 3, 19 to 21, 26 to 37, 41 and 42 in FIG. 3. If the austenitizing temperature is lower than 880°C, carbonitrides incorporate into the matrix (principal metal, i.e. balance) of the material to produce solid solution only insufficiently so that the degree of strength and that of toughness that are required after the tempering step, which will be described hereinafter, are hardly achievable. Additionally, the use of a low austenitizing temperature can give rise to relatively large residual stress. If, on the other hand, the austenitizing temperature exceeds 910°C, it is no longer possible to provide a satisfactory degree of hydrogen cracking resistance that is required to the target regions. For the above-described reasons, the austenitizing temperature of the target regions, which particularly require an improved hydrogen cracking resistance, is set to be within the range of 880 to 910°C to make it possible to refine their crystal grains, while securing the required degree of strength and that of toughness.

[0059] Finally, the above-described step of "refining crystal grains include the pre-quality heat treatment annealing step (1) that is an annealing step to be executed prior to the quenching step (2-1) and the pre-quality heat treatment annealing temperature, which is the heating temperature, is set to be within the range of 1,050 to 1,300°C for the pre-quality heat treatment annealing step (1). As the pre-quality heat treatment annealing step is executed within the above-described temperature range, a pearlite structure can be produced to a relatively high ratio. When the rotor material that shows a high ratio of the pearlite structure is subjected to the quenching step (2-1), crystal grains can be refined further.

[0060] While the tempering operation is conducted only once in the quality heat treatment of the above-described embodiment, the mode of conducting of the quality heat treatment according to the present invention is by no means limited to the above-described one. For example, the tempering step can suitably be executed twice in the quality heat treatment. Another mode of quality heat treatment will be described below.

[Second Embodiment]

[0061] The quality heat treatment of this embodiment will be described below. In this embodiment, the entire steam turbine rotor is subjected to tempering twice. Additionally, the austenitizing temperature in the quenching step for the quality heat treatment of this embodiment differs from that of the first embodiment as will be described in detail below. The arrangements that are common to this embodiment and also to the first embodiment will not be described below repeatedly.

(2-1 B) Quenching step

[0062] In the quenching step of this embodiment, the austenitizing temperature is set to be equal for both the target regions of the steam turbine rotor that are required to show a particularly high hydrogen cracking resistance and the other region. In other words, the entire rotor including the target regions and the other region is subjected to quenching at a uniform austenitizing temperature. The austenitizing temperature is set to be within the range of 910 to 950°C. However, a austenitizing temperature that is lower than that of the other region may be selected for the target regions as in the case of the first embodiment.

(2-2B) Two-stage tempering step

[0063] A two-stage tempering step is executed for the quality heat treatment of this embodiment. More specifically, the tempering step of the quality heat treatment of this embodiment includes the first stage tempering step (2-2B1) and the second stage tempering step (2-2B2). Note that the tempering temperature in the first stage tempering step is referred to as "the first stage tempering temperature" and the second stage tempering temperature is referred to as "the second stage tempering temperature" hereinafter.

(2-2B1) First stage tempering step

[0064] For the first stage tempering step, the first stage tempering temperature, which is the heating temperature, is set to be within the range of 600 to 700°C for both the target regions and the other region of the steam turbine rotor. Note that, in particular, a same temperature can be selected for both the first stage tempering temperature of the target regions and the first stage tempering temperature of the other region. This will be described below by referring to FIGS. 3 and 5.

[0065] As shown in FIGS. 3 and 5, 670 °C is selected for the first stage tempering temperature of the target regions and 630 °C is selected for the first stage tempering temperature of the other region. In the first stage tempering step, the rotor material is heated to the first stage tempering temperatures and then the first stage tempering temperatures are held to a predetermined holding time before the rotor material is cooled. Note that the first stage tempering temperature holding time is set to be equal to 20 hours.

[0066] Also note that the first stage tempering temperature of the target regions may be set to be equal to 630 °C, which is same as that of the other region. Alternatively, only the surface layers of the target regions may be heated to 670 °C, which is the first stage tempering temperature selected for the target regions.

[0067] For the first stage tempering step, the first stage tempering temperature of the target regions may be set to be equal to 670 °C, which is the highest allowable temperature and a technique of so-called gradient heating may suitably be employed. With gradient heating, the rotor material is heated such that the first stage tempering temperature is gradually lowered from the target regions toward the other region. Note that, for the first stage tempering step, the first stage tempering temperature of the other region is set to be equal to 630°C. When the technique of gradient heating is employed, it is no longer necessary to execute a heat treatment at "predetermined positions" of the rotor for the purpose of improving the strength of the rotor at those positions. After executing the above-described first stage tempering step (2-2B1), the second stage tempering step (2-2B2) will be executed.

(2-2B2) Second stage tempering step

[0068] For the second stage tempering step, the second stage tempering temperature, which is the heating temperature, is set to be within the range of 600 to 700°C for both the target regions and the other region of the steam turbine rotor. In the second stage tempering step, the rotor material is heated to the second stage tempering temperature and then the second stage tempering temperature is held for a predetermined holding time before the rotor material is cooled. Note that the second stage tempering temperature holding time is set to be equal to 20 hours. Also note that, in particular, a same temperature may be selected for both the second stage tempering temperature of the target regions and the second stage tempering temperature of the other region. For example, the second stage tempering temperature may be set to be equal to 630°C as shown in FIG. 3.

[0069] The second stage tempering temperature of the target regions may be set to a temperature level that is higher than that of the second stage tempering temperature of the other region. For example, as shown FIG. 3, the second stage tempering temperature of the target regions may be set to be equal to 670°, which is the highest allowable temperature and a technique of gradient heating may suitably be employed. With gradient heating, the second stage tempering temperature is gradually lowered from the target regions toward the other region.

[0070] When the technique of gradient heating is employed for the second stage tempering step, the target regions are heated to the second stage tempering temperature in the furnace. At this time, the other region are held to the outside of the furnace because the other region does not need the second stage tempering. With this arrangement for the other region, gradient heating of gradually lowering the second stage tempering temperature from the target regions toward the other region is realized.

[0071] As shown in the inventive examples 6 to 8, 10 to 27, 32 to 37 and 39 to 42 in FIG. 3, the tempering step (2-2B) of this embodiment is made to include the first stage tempering step (2-2B1) of heating the rotor material to the first stage tempering temperature, which is set to be within the range of 600 to 700°C, for tempering and the second stage tempering step (2-2B2) to be executed after the first stage tempering step (2-2B1) of heating the rotor material to the second tempering temperature, which is also set to be within the range of 600 to 700°C, for tempering.

[0072] The rotor material is mostly turned into a quenched bainite structure in the quenching step (2-1 B). If, however, the residual austenite structure is left, all the residual austenite structure is not turned into the tempered bainite structure in the next tempering step but the quenched bainite structure partly remains. Then, for this reason, the rotor material becomes a mixture of structures containing the tempered bainite structure in which the strength and the toughness are well balanced and the quenched bainite structure that shows a high strength and a low toughness. Then, strain is accumulated between the two structures to increase the residual stress.

[0073] However, the residual stress can be reduced by executing the two-stage tempering step (2-2B1) and (2-2B2) to completely turning the entire quenched bainite structure into the tempered bainite structure. This effect can be achieved when both the first tempering temperature and the second tempering temperature exceed 600°C but the rotor material does not show the required level of strength when the two tempering temperatures exceed 700°C. For this reason, both the first tempering temperature and the second tempering temperature of the target regions whose hydrogen cracking resistance particularly needs to be improved are limited within the range of 600 to 700°C and the tempering step is executed in two stages. With this arrangement, the residual stress can be reduced. Then, as a result, the occurrence of hydrogen cracking and the development of hydrogen cracking in the target regions can be controlled.

[0074] As shown in the inventive examples 4, 5, 7 to 9, 12 to 31, 34 to 40 and 42, at least one of the first stage tempering temperature and the second stage tempering temperature of the target region is set to show a value higher than that of the other region and the higher value is set to be within the range of 660 to 700°C. For ferritic alloy steels, the effect of reducing the residual stress can be achieved when the tempering temperature is not lower than 660°C. On the other hand, however, the strength of the rotor falls when the tempering temperature exceeds 700°C. Thus, when the tempering temperature of at least one of the first stage tempering step (2-2B1) and the second stage tempering step (2-2B2) is set to be within the range of 660 to 700°C for the target region, which is required to show a particularly high hydrogen cracking resistance, it is possible to reduce the extent of possible fall of the strength of the rotor and, at the same time, reduce the residual stress in the rotor.

[0075] As shown in the arrangement examples 13 to 27 in FIG. 3, a technique of gradient heating of gradually lowering the tempering temperature from the target regions toward the other region in at least one of the first stage tempering step (2-2B1) and the second stage tempering step (2-2B2) is employed. When the technique of gradient heating is employed, it is no longer necessary to execute a heat treatment at "predetermined positions" of the rotor for the purpose of improving the strength of the rotor at those positions.

[0076] As shown in the inventive examples 22 to 27 in FIG. 3, when the technique of gradient heating is employed for the above-described second tempering step, the target regions are heated to the second stage tempering temperature in the furnace for tempering but the other region are held to the outside of the furnace. "The other region" other than the target regions do not need to be tempered in the second tempering step. Therefore, "the other region" may be cooled in a state of being held to the outside of the furnace.

[0077] As shown in the inventive examples 6, 10, 11, 32, 33, 41 in FIG. 3, a same temperature may be selected for both the first stage tempering temperature of the target regions and the first stage tempering temperature of the other region and the first stage tempering temperature may be set to be within the range of 600 to 600°C, while a same temperature may be selected for both the second stage tempering temperature of the target regions and the second stage tempering temperature of the other region and the second stage tempering temperature may be set to be within the range of 600 to 660°C. With such a technique, it is possible to secure the hydrogen cracking resistance of the target regions as shown in FIG. 4.

[Other Embodiment(s)]

[0078] While the austenitizing temperature in the quenching step of each of the above-described embodiment is lower for the target regions that are required to show a particularly high hydrogen cracking resistance than for the other region, the present invention is by no means limited to such a difference in the austenitizing temperature. For example, as shown in the related tables, a same austenitizing temperature may alternatively be selected for both the target regions and the other region.

[0079] While the target regions that are required to show a particularly improved hydrogen cracking resistance are the stage-portions 20,21,22 and 23 ,which include the blade-implanted portions 20, 21, 22and 23 respectively, located at the upstream side of the steam turbine 1 as shown in FIG. 1 in the first embodiment, the target regions are not limited to such portions for the purpose of the present invention. Any portions of the rotor may be selected as target regions so long as corrosive components of steam can easily deposit there and those regions are required to show an improved hydrogen cracking resistance.

[0080] While certain embodiments have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the inventions. Indeed, the novel embodiments described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the embodiments described herein may be made without departing from the accompanying claims.

CLAUSES:

[0081]

Clause 1. A method of manufacturing a rotor to be used for forming a steam turbine, the method comprising:

a step of reducing the residual stress of predetermined target regions of the rotor relative to the other region.

Clause 2. The method according to clause 1, wherein the step of reducing the residual stress includes a tempering step of tempering the rotor at a tempering temperature; and
the tempering temperature being a heating temperature of the target regions is set to be higher than that of the other region in the tempering step.

Clause 3. The method according to clause 1, further comprising:

a step of refining crystal grains in the target regions relative to the other region.

Clause 4. The method according to clause 3, wherein the step of refining crystal grains includes a quenching step of quenching the rotor at an austenitizing temperature prior to the tempering step; and
the austenitizing temperature being a heating temperature of the target regions is set to be lower than that of the other region in the quenching step.

Clause 5. The method according to any one of clause 1 through 4, wherein
the rotor is made of a ferritic alloy steel containing,in mass%, carbon(C): 0.15 % to 0.33 %, silicon(Si): 0.03 % to 0.20 %, manganese(Mn): 0.5 % to 2.0 %, nickel(Ni): 0.1 % to 1.3 %, chromium(Cr): 0.9 % to 3.5 %, molybdenum(Mo): 0.1 % to 1.5 %, vanadium(V): 0.15 % to 0.35 % and tungsten(W)as optional component: 1.0 % or less.

Clause 6. The method according to clause 5, wherein the tempering temperature of the target regions is set to be within a range of 660 to 700 °C.

Clause 7. The method according to clause 6, wherein the austenitizing temperature of the target regions is set to be within the range of 880 to 900 °C.

Clause 8. The method according to clause 5, wherein the step of refining crystal grains includes a pre-quality heat treatment annealing step that is to be executed prior to the quenching step, and
a pre-quality heat treatment annealing temperature being a heating temperature for the pre-quality heat treatment annealing step is set to be within a range of 1,050 to 1,300 °C.

Clause 9. The method according to clause 5, wherein the tempering step includes:

a first stage tempering step of heating to a first stage tempering temperature set to be within a range of 600 to 700 °C for tempering; and
a second stage tempering step of heating to a second stage tempering temperature set to be within a range of 600 to 700 °C for tempering.

Clause 10. The method according to clause 9, wherein
at least one of the first stage tempering temperature and the second stage tempering temperature of the target regions is set at a tempering temperature higher than that of the other region,
the tempering temperature being set to be within a range of 660 to 700 °C.

Clause 11. The method according to clause 10, wherein
gradient heating of gradually lowering the tempering temperature from the target regions toward the other region is employed in at least one of the first stage tempering step and the second stage tempering temperature.

Clause 12. The method according to clause 11, wherein, when gradient heating is employed in the second stage tempering step, the target regions are heated to the second stage tempering temperature in a furnace while the other region is tempered in a state of being held to the outside of the furnace.

Clause 13. The method according to any one of clause 1 through 12, wherein
the steam turbine is to be used for geothermal power generation and the rotor is to be exposed to corrosive gases.

Claims

1. A method of manufacturing a rotor to be used for forming a steam turbine, the method comprising:

    a step of reducing the residual stress of predetermined target regions of the rotor relative to the other region, wherein the step of reducing the residual stress includes a tempering step of tempering the rotor at a tempering temperature, the tempering temperature being a heating temperature of the target regions which is set to be within a range of 660 to 700 °C and higher than that of the other region in the tempering step, and wherein the rotor is made of a ferritic alloy steel containing, in mass%, carbon(C): 0.15 % to 0.33 %, silicon(Si): 0.03 % to 0.20 %, manganese(Mn): 0.5 % to 2.0 %, nickel(Ni): 0.1 % to 1.3 %, chromium(Cr): 0.9 % to 3.5 %, molybdenum(Mo): 0.1 % to 1.5 %, vanadium(V): 0.15 % to 0.35 % and tungsten (W) as optional component: 1.0 % or less.

2. The method according to claim 1, wherein
the tempering step includes:

    a first stage tempering step of heating to a first stage tempering temperature set to be within a range of 600 to 700 °C for tempering; and
    a second stage tempering step of heating to a second stage tempering temperature set to be within a range of 600 to 700 °C for tempering.

3. The method according to claim 2, wherein
at least one of the first stage tempering temperature and the second stage tempering temperature of the target regions is set at a tempering temperature higher than that of the other region,
the tempering temperature being set to be within a range of 660 to 700 °C.

4. The method according to claim 3, wherein
gradient heating of gradually lowering the tempering temperature from the target regions toward the other region is employed in at least one of the first stage tempering step and the second stage tempering temperature.

5. The method according to claim 4, wherein,
when gradient heating is employed in the second stage tempering step, the target regions are heated to the second stage tempering temperature in a furnace while the other region is held to the outside of the furnace.

6. The method as in any one of claims 1 to 5, wherein the steam turbine is to be used for geothermal power generation and the rotor is to be exposed to corrosive gases.

FIG. 1

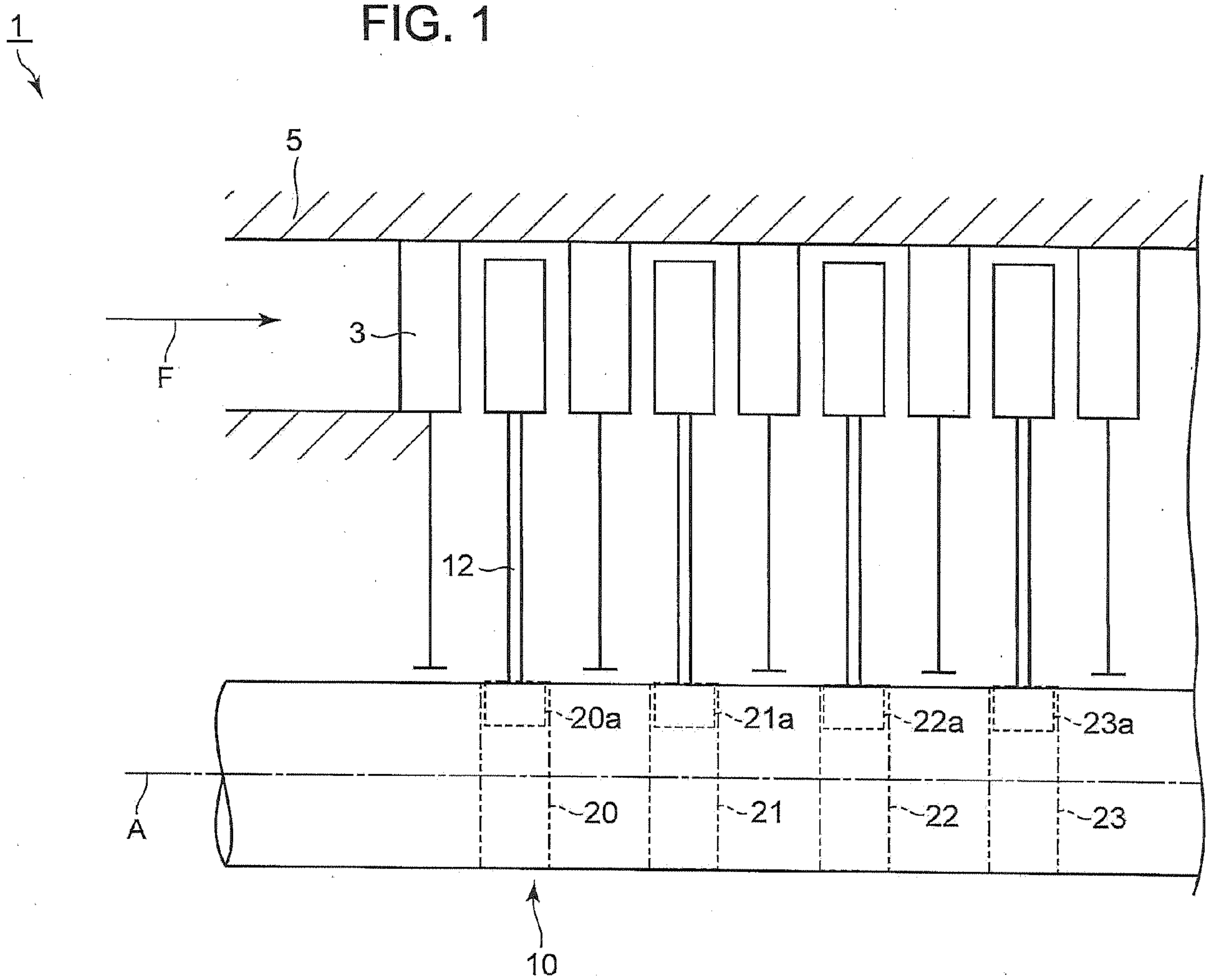

FIG. 2

[mass%]

	C	Si	Mn	Ni	Cr	Mo	V	N	W	Fe
CLAIMS	0.15 to 0.33	0.03 to 0.20	0.5 to 2.0	0.1 to 1.3	0.9 to 3.5	0.1 to 1.5	0.15 to 0.35	0.005 to 0.015	1.0 or less	Balance
Sample A	0.24	0.15	0.8	0.9	2.3	0.8	0.24	0.008	0.01	Balance
Sample B	0.25	0.15	0.7	0.9	2.2	0.8	0.25	0.009	0.01	Balance
Sample C	0.24	0.13	0.8	0.8	2.3	0.7	0.24	0.009	0.02	Balance
Sample D	0.25	0.17	0.7	1	2.3	0.8	0.24	0.008	0.01	Balance
Sample E	0.25	0.15	0.6	0.8	2.3	0.8	0.25	0.008	0.01	Balance
Sample F	0.24	0.14	0.8	0.8	2.2	0.7	0.24	0.009	0.01	Balance
Sample G	0.24	0.13	0.7	0.7	2.3	0.8	0.23	0.008	0.3	Balance

FIG. 3

Invantive Example	Sample	Pre-quality heat treatment annealing step		Quenching step			The first stage tempering step		The second stage tempering step	
		Annealing temperature [°C] *1	Cooling method	Austinitizing temperature [°C] *2		Cooling method	Tempering temperature [°C] *3		Tempering temperature [°C] *4	
				Target	The other		Target	The other	Target	The other
1	A	1150	Furnace	920	920	Spraying water	630	630	–	–
2	A	1050	Air	900	920	Spraying water	630	630	–	–
3	A	1150	Furnace	900	920	Spraying water	630	630	–	–
4	A	1150	Furnace	920	920	Spraying water	670	630	–	–
5	A	1150	Furnace	920	920	Spraying water	670 (Surface layer only)	630	–	–
6	A	1150	Furnace	920	920	Spraying water	630	630	630	630
7	A	1150	Furnace	920	920	Spraying water	670	630	630	630
8	A	1150	Furnace	920	920	Spraying water	670 (Surface layer only)	630	630	630
9	A	1050	Air	920	920	Spraying water	670	630	–	–
10	A	1050	Air	920	920	Spraying water	630	630	630	630
11	B	1150	Furnace	920	920	Spraying water	630	630	630	630
12	B	1050	Air	920	920	Spraying water	670	630	630	630
13	B	1050	Air	920	920	Spraying water	Gradient heating 670 (max)	630	630	630
14	B	1050	Air	920	920	Spraying water	630	630	Gradient heating 670 (max)	630
15	B	1050	Air	920	920	Spraying water	Gradient heating 670 (max)	630	Gradient heating 670 (max)	630
16	B	1150	Furnace	920	920	Spraying water	Gradient heating 670 (max)	630	630	630
17	B	1150	Furnace	920	920	Spraying water	630	630	Gradient heating 670 (max)	630
18	B	1150	Furnace	920	920	Spraying water	Gradient heating 670 (max)	630	Gradient heating 670 (max)	630
19	B	1150	Furnace	900	920	Spraying water	Gradient heating 670 (max)	630	630	630
20	B	1150	Furnace	900	920	Spraying water	630	630	Gradient heating 670 (max)	630
21	C	1150	Furnace	900	920	Spraying water	Gradient heating 670 (max)	630	Gradient heating 670 (max)	630
22	C	1050	Air	920	920	Spraying water	630	630	Gradient heating 670 (max)	Outside of furnace
23	C	1050	Air	920	920	Spraying water	Gradient heating 670 (max)	630	Gradient heating 670 (max)	Outside of furnace
24	C	1150	Furnace	920	920	Spraying water	630	630	Gradient heating 670 (max)	Outside of furnace
25	C	1150	Furnace	920	920	Spraying water	Gradient heating 670 (max)	630	Gradient heating 670 (max)	Outside of furnace
26	C	1150	Furnace	900	920	Spraying water	630	630	Gradient heating 670 (max)	Outside of furnace
27	C	1150	Furnace	900	920	Spraying water	Gradient heating 670 (max)	630	Gradient heating 670 (max)	Outside of furnace
28	C	1050	Air	900	920	Spraying water	670	630	–	–
29	C	1150	Furnace	900	920	Spraying water	670	630	–	–
30	C	1050	Air	900	920	Spraying water	670 (Surface layer only)	630	–	–
31	D	1150	Furnace	900	920	Spraying water	670 (Surface layer only)	630	–	–
32	D	1050	Air	900	920	Spraying water	630	630	630	630
33	D	1150	Furnace	900	920	Spraying water	630	630	630	630
34	D	1050	Air	900	920	Spraying water	670	630	630	630
35	D	1150	Furnace	900	920	Spraying water	670	630	630	630
36	D	1050	Air	900	920	Spraying water	670 (Surface layer only)	630	630	630
37	D	1150	Furnace	900	920	Spraying water	670 (Surface layer only)	630	630	630
38	G	1150	Furnace	920	920	Spraying water	670	630	–	–
39	G	1150	Furnace	920	920	Spraying water	670	630	630	630
40	G	1050	Air	920	920	Spraying water	670	630	630	630
41	G	1050	Air	900	920	Spraying water	630	630	630	630
42	G	1150	Furnace	900	920	Spraying water	670	630	630	630

*1 Holding time: 5hr *2 Holding time: 5hr *3 Holding time: 20hr *4 Holding time: 20hr

FIG. 4

Inventive Example	Sample	Grain size [G.S.No.]		(Maximum tensile) Residual stress [MPa]		Hydrogen cracking resistance	
		Target	The other	Target	The other	Target	The other
1	A	4.8		98		○	
2	A	2.7	1.6	95	102	○	X
3	A	6.1	4.6	104	99	○	○
4	A	4.5	4.5	80	97	○	○
5	A	4.5	4.7	76	103	○	○
6	A	4.7		77		○	
7	A	4.8	4.8	48	79	○	○
8	A	4.5	4.8	45	82	○	○
9	A	1.7	1.4	78	105	○	X
10	A	1.5		83		○	
11	B	4.7		80		○	
12	B	1.4	1.6	45	78	○	○
13	B	1.6	1.7	47	81	○	X
14	B	1.6	1.5	45	84	○	X
15	B	1.5	1.7	47	77	○	X
16	B	4.8	4.5	52	79	○	○
17	B	4.5	4.6	55	83	○	○
18	B	4.5	4.9	43	80	○	○
19	B	6.0	4.6	46	82	○	○
20	B	6.2	4.5	52	85	○	○
21	C	6.4	4.7	50	81	○	○
22	C	1.4	1.6	81	103	○	X
23	C	1.5	1.8	46	98	○	X
24	C	4.7	4.8	84	95	○	○
25	C	4.5	4.5	51	99	○	○
26	C	5.9	4.6	78	104	○	○
27	C	5.8	4.5	47	108	○	○
28	C	2.8	1.8	77	96	○	X
29	C	6.2	4.3	83	94	○	○
30	C	2.8	1.8	81	99	○	X
31	D	6.0	4.4	85	103	○	○
32	D	2.5	1.5	85	80	○	X
33	D	5.9	4.6	75	77	○	○
34	D	2.7	2	44	74	○	X
35	D	6.3	4.3	48	84	○	○
36	D	2.9	1.9	50	81	○	X
37	D	6.1	4.5	46	83	○	○
38	G	4.3	4.3	75	83	○	○
39	G	4.5	4.5	52	82	○	○
40	G	1.5	1.5	50	84	○	○
41	G	2.3	1.8	80	81	○	X
42	G	6.1	4.5	50	87	○	○

FIG. 5

Comparative Example	Sample	Pre-quality heat treatment annealing step		Quenching step			The first stage tempering		The second stage tempering	
		Annealing temperature [°C] *1	Cooling method	Austinitizing temperature [°C] *2		Cooling method	Tempering temperature [°C] *3		Tempering temperature [°C] *4	
				Target	The other		Target	The other	Target	The other
1	E	1050	Air	920	920	Spraying water	630	630	—	—
2	E	1000	Furnace	920	920	Spraying water	630	630	—	—
3	E	1050	Air	850	850	Spraying water	630	630	—	—
4	E	1000	Furnace	850	850	Spraying water	630	630	—	—
5	E	1150	Furnace	920	920	Spraying water	640	630	—	—
6	E	1150	Furnace	920	920	Spraying water	640 (Surface layer only)	630	—	—
7	E	1150	Furnace	920	920	Spraying water	580	580	630	630
8	E	1150	Furnace	920	920	Spraying water	630	630	580	580
9	E	1050	Air	920	920	Spraying water	640	630	—	—
10	E	1050	Air	920	920	Spraying water	580	580	630	630
11	F	1050	Air	920	920	Spraying water	630	630	580	580
12	F	1150	Furnace	920	920	Spraying water	580	580	630	630
13	F	1150	Furnace	920	920	Spraying water	630	630	580	580
14	F	1150	Furnace	850	920	Spraying water	630	630	630	630
15	F	1150	Furnace	850	920	Spraying water	580	580	630	630
16	F	1150	Furnace	920	920	Spraying water	580	580	Gradient heating 670(max)	Outside of furnace
17	F	1150	Furnace	850	920	Spraying water	630	630	Gradient heating 670(max)	Outside of furnace
18	F	1150	Furnace	850	920	Spraying water	580	580	Gradient heating 670(max)	Outside of furnace
19	G	1150	Furnace	920	920	Spraying water	640	630	—	—
20	G	1050	Air	920	920	Spraying water	580	580	630	630
21	G	1150	Furnace	850	920	Spraying water	580	580	630	630

*1 Holding time: 5hr *2 Holding time: 5hr *3 Holding time: 20hr *4 Holding time: 20hr

FIG. 6

Comparative Example	Sample	Grain size (G.S.No.)		(Maximum tensile) Residual stress [Mpa]		Hydrogen cracking resistance	
		Target	The other	Target	The other	Target	The other
1	E	1.5		103		X	
2	E	1.4		97		X	
3	E	3.5		152		X	
4	E	3.2		158		X	
5	E	4.7	4.6	143	132	X	X
6	E	4.6	4.4	140	130	X	X
7	E	4.6		156		X	
8	E	4.9		160		X	
9	E	1.3	1.5	154	129	X	X
10	E	1.7		150		X	
11	F	1.5		146		X	
12	F	4.6		120		X	
13	F	5.0		117		X	
14	F	6.1	4.6	115	110	X	X
15	F	5.8	4.8	127	130	X	X
16	F	4.4	4.5	122	134	X	X
17	F	6.4	4.5	118	138	X	X
18	F	6.2	4.9	154	166	X	X
19	G	4.5	4.6	138	129	X	X
20	G	1.9		145		X	
21	G	5.5	5.0	120	133	X	X

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EUROPEAN SEARCH REPORT

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The present search report has been drawn up for all claims

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Place of search	Date of completion of the search	Examiner
Munich	10 January 2017	Abrasonis, Gintautas

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Place of search	Date of completion of the search	Examiner
Munich	10 January 2017	Abrasonis, Gintautas

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