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(54) **FERRITIC STAINLESS STEEL**

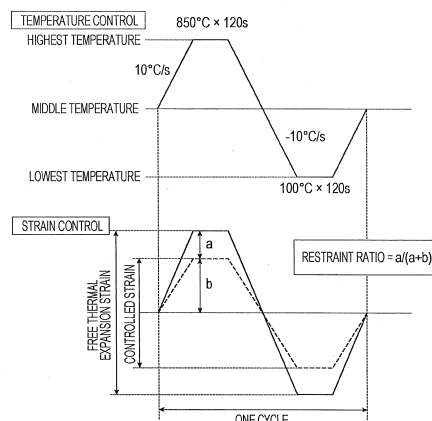
(57) Provided is a ferritic stainless steel having a good thermal fatigue property and oxidation resistance while minimizing the contents of Mo, W, and Nb which are expensive elements and minimizing the content of Cu which deteriorates oxidation resistance and workability.

A ferritic stainless steel comprises, in terms of % by mass, C: 0.020% or less, Si: 3.0% or less, Mn: 1.0% or less, P: 0.040% or less, S: 0.030% or less, Cr: 10.0% or more and less than 16.0%, N: 0.020% or less, Al: 1.4 to 4.0%, Ti: more than 0.15% and 0.5% or less, Ni: 0.05 to 0.5%, and the balance being Fe and unavoidable impurities, the ferritic stainless steel satisfying formula (1) below:

$$\text{Al}\%/\text{Cr}\% \geq 0.14 \quad \dots \quad (1)$$

where Al% and Cr% in the formula respectively denote an Al content and a Cr content (% by mass).

FIG. 2



Description

Technical Field

[0001] The present invention relates to ferritic stainless steel suitable for use in exhaust parts in high-temperature environments, such as exhaust pipes and catalyst cases (also known as converter cases) of automobiles and motorcycles and exhaust ducts of thermal power plants.

Background Art

[0002] Exhaust-system components such as exhaust manifolds, exhaust pipes, converter cases, and mufflers used as automobile exhaust parts are required to have a good thermal fatigue property and good oxidation resistance (hereinafter these properties are generally referred to as a "heat resistance property").

[0003] Currently, Cr-containing steel such as steel containing Nb and Si (for example, JFE 429EX (15-mass% Cr-0.9 mass% Si-0.4 mass% Nb) (hereinafter referred to as Nb-Si-containing steel)) is often used in usages that require such a heat resistance property. In particular, Nb is known to significantly improve heat resistance property. Steel containing Mo or W, that improves the heat resistance property, in addition to Nb (for example, SUS444 (18 mass% Cr-2 mass% Mo-0.5 mass% Nb)) has also emerged and is used in components that require a higher heat resistance property.

[0004] Patent Literature 1 discloses a stainless steel sheet, the heat resistance property of which has been increased by adding Ti, Cu, and B. Patent Literatures 2, 3, and 4 each disclose a heat-resistant ferritic stainless steel containing Al. Patent Literature 5 also discloses a ferritic stainless steel containing Al and having good oxidation resistance in the steam addition atmosphere.

Citation List

Patent Literature

[0005]

- PTL 1: Japanese Unexamined Patent Application Publication No. 2010-248620
- PTL 2: Japanese Unexamined Patent Application Publication No. 2009-68113
- PTL 3: Japanese Unexamined Patent Application Publication No. 2004-307918
- PTL 4: Japanese Unexamined Patent Application Publication No. 2001-316773
- PTL 5: Japanese Unexamined Patent Application Publication No. 2009-167443

Summary of Invention

Technical Problem

[0006] However, the technique described in Patent Literature 1 has a problem in that the required continuous oxidation resistance cannot be obtained due to occurrence of breakaway oxidation in a continuous oxidation test because of addition of Cu.

[0007] The techniques described in Patent Literatures 2 and 3 have Al added to the steel but have a problem in that they do not consider the thermal fatigue property. The technique described in Patent Literature 4 also has Al added to the steel but has a problem of occasionally failing to achieve required oxidation resistance due to breakaway oxidation in a continuous oxidation test, oxide scale separation in a cyclic oxidation test, and the like. The technique described in Patent Literature 5 also relates to the oxidation resistance in the steam addition atmosphere associated with addition of Al; however, there is a problem in that good cyclic oxidation resistance may not be obtained due to spalling of oxide scale occurring during cyclic oxidation.

[0008] From the viewpoint of alloy elements, Mo and W are expensive elements and may cause problems such as generating surface defects by deteriorating hot workability, and deteriorating workability. Nb is also an expensive element and increases the recrystallization temperature of the steel, requiring a high annealing temperature. Thus there is a problem of high production cost. Cu also has problems such as a deterioration in oxidation resistance and workability.

[0009] Accordingly, there is an expectation for development of steel that exhibits a high heat resistance property with minimum amounts of the aforementioned alloy elements added.

[0010] An object of the present invention is to provide a ferritic stainless steel that has a good thermal fatigue property and good oxidation resistance in the condition that the amounts of Mo, W, and Nb, which are expensive and deteriorate various properties, and Cu, which deteriorates oxidation resistance and workability, are minimized. Solution to Problem

[0011] The inventors have conducted extensive studies on the effects of the Al content and the Ti content on the thermal fatigue property and the effects of the contents of Cr and Ni and the Al/Cr content ratio on the oxidation resistance and found optimum content ranges for Al, Ti, Cr, and Ni. The present invention has been made based on this finding and further investigations and can be summarized as follows:

[1] A ferritic stainless steel comprising, in terms of % by mass, C: 0.020% or less, Si: 3.0% or less, Mn: 1.0% or less, P: 0.040% or less, S: 0.030% or less, Cr: 10.0% or more and less than 16.0%, N: 0.020% or less, Al: 1.4 to 4.0%, Ti: more than 0.15% and 0.5% or less, Ni: 0.05 to 0.5%, and the balance being Fe and unavoidable impurities, the ferritic stainless steel satisfying formula (1) below:

$$\text{Al\%/Cr\%} \geq 0.14 \quad (1)$$

where Al% and Cr% in the formula respectively denote an Al content and a Cr content (% by mass).

[2] The ferritic stainless steel described in [1], further comprising, in terms of % by mass, at least one selected from Nb: 0.01 to 0.15% and Cu: 0.01% or more and less than 0.4%.

[3] The ferritic stainless steel described in [1] or [2], further comprising, in terms of % by mass, at least one selected from Mo: 0.02 to 0.5% and W: 0.02 to 0.3%.

[4] The ferritic stainless steel described in any one of [1] to [3], further comprising, in terms of % by mass, at least one selected from REM: 0.001 to 0.1%, Zr: 0.01 to 0.5%, V: 0.01 to 0.5%, and Co: 0.01 to 0.5%.

[5] The ferritic stainless steel described in any one of [1] to [4], further comprising, in terms of % by mass, at least one selected from B: 0.0002 to 0.0050%, Mg: 0.0002 to 0.0020%, and Ca: 0.0005 to 0.0030%.

[0012] Note that the oxidation resistance means both continuous oxidation resistance and cyclic oxidation resistance. The continuous oxidation resistance is evaluated based on the weight gain by oxidation after the steel has been isothermally held at high temperature. The cyclic oxidation resistance is evaluated based on the weight gain by oxidation after heating and cooling are repeated and presence or absence of spalling of oxide scale.

[0013] If continuous oxidation resistance is insufficient, the amount of oxide scale increases during high-temperature use and the thickness of the base metal decreases. Thus, a good thermal fatigue property is not obtained. If cyclic oxidation resistance is low, spalling of oxide scale occurs during use and other parts downstream such as converters may be affected to bring a problem.

Advantageous Effects of Invention

[0014] According to the present invention, a ferritic stainless steel having a thermal fatigue property and oxidation resistance comparable or superior to Nb-Si-containing steels can be obtained while minimizing the Mo, W, Nb, and Cu contents; thus, the present invention is significantly useful for automotive exhaust parts.

Brief Description of Drawings

[0015]

[Fig. 1] A diagram illustrating a thermal fatigue test specimen.

[Fig. 2] A graph illustrating the temperature and constraint conditions in a thermal fatigue test.

[Fig. 3] A graph illustrating the effect of Al(%)/Cr(%) on continuous oxidation resistance (weight gain by oxidation).

[Fig. 4] A graph illustrating the effect of Al(%)/Cr(%) on cyclic oxidation resistance (weight gain by oxidation and presence/absence of scale separation).

Description of Embodiments

[0016] The reasons for limiting the respective features of the present invention are described below.

1. Regarding composition

[0017] The reason for limitations on the composition of the ferritic stainless steel according to the present invention will now be described. Note that % means % by mass.

C: 0.020% or less

[0018] Carbon (C) is an element effective for increasing the strength of steel but a deterioration in toughness and formability is significant at a C content exceeding 0.020%. Thus, in the present invention, the C content is to be 0.020% or less. From the viewpoint of ensuring the formability, the C content is preferably as low as possible and is preferably 0.015% or less and more preferably 0.010% or less. In order to ensure the strength required for exhaust parts, the C content is preferably 0.001% or more and more preferably 0.003% or more.

Si: 3.0% or less

[0019] Silicon (Si) is an important element for improving the oxidation resistance. This effect can be obtained at a Si content of 0.1% or more. The Si content is preferably 0.3% or more if higher oxidation resistance is required. However, at a content exceeding 3.0%, not only the workability is deteriorated but also separation of oxide scale occurs easily and the cyclic oxidation resistance is deteriorated. Accordingly, the Si content is to be 3.0% or less. The Si content is more preferably in the range of 0.3 to 2.0% and yet more preferably in the range of 0.5 to 1.0%.

Mn: 1.0% or less

[0020] Manganese (Mn) is an element that increases the strength of steel and also acts as a deoxidizer. It also has an effect of suppressing separation of oxide scale in the case where Si is added. In order to obtain such effects, the Mn content is preferably 0.1% or more. However, excessive Mn not only significantly increases the oxidizing speed but also tends to form γ phases easily at high temperature and deteriorates the heat resistance property. Accordingly, in the present invention, the Mn content is to be 1.0% or less. The Mn content is preferably in the range of 0.1 to 0.5% and more preferably in the range of 0.15 to 0.4%.

P: 0.040% or less

[0021] Phosphorus (P) is a harmful element that deteriorates the toughness and the P content is preferably as low as possible. In the present invention, the P content is to be 0.040% or less and preferably 0.030% or less.

S: 0.030% or less

[0022] Sulfur (S) deteriorates elongation and r value (Lankford value) to adversely affect formability, and further is a harmful element that deteriorates corrosion resistance, which is the basic property of stainless steel. Thus, the S content is preferably as low as possible. In the present invention, the S content is to be 0.030% or less, preferably 0.010% or less, and more preferably 0.005% or less.

Cr: 10.0% or more and less than 16.0%

[0023] Chromium (Cr) is an important element effective for improving corrosion resistance and oxidation resistance, which are the features of stainless steel. At a Cr content less than 10.0%, sufficient oxidation resistance cannot be obtained. On the other hand, Cr is an element that causes solid solution strengthening of steel at room temperature, hardens the steel, and deteriorates the ductility. When an Al-containing steel such as one according to the present invention contains 16.0% or more of Cr, these undesirable properties become significant and it becomes difficult to work the steel into a complicated shape, for example, an exhaust manifold. Accordingly, the Cr content is to be in the range of 10.0% or more and less than 16.0%. The Cr content is preferably in the range of 11.0 to 15.0% and more preferably in the range of 12.0 to 14.0%.

N: 0.020% or less

[0024] Nitrogen (N) is an element that deteriorates the toughness and formability of the steel and the deterioration in formability is significant if the N content exceeds 0.020%. The N content is thus to be 0.020% or less. From the viewpoints of ensuring toughness and formability, the N content is preferably as low as possible and is preferably 0.015% or less and more preferably 0.012% or less.

Al: 1.4 to 4.0%, Al%/Cr% $\geq$ 0.14

[0025] Aluminum (Al) is an important element for improving the thermal fatigue property. Aluminum acts as a solid

solution strengthening element and significantly improves the thermal fatigue property in a thermal fatigue test particularly in which the maximum temperature exceeds 700°C. This effect is obtained when the Al content is 1.4% or more.

[0026] Furthermore, Al produces oxide scale mainly composed of dense and stable Al_2O_3 and thus improves oxidation resistance. At an Al content less than 1.4%, the oxide scale is mainly composed of Cr oxides and a sufficient amount of Al_2O_3 is not produced. When the Al content is 1.4% or more and the Cr and Al contents satisfy $\text{Al}\%/\text{Cr}\% \geq 0.14$, dense and stable Al_2O_3 is produced and good oxidation resistance is achieved.

[0027] Among the results of Example 1 described below, steels particularly described in Table 2 were used to investigate the effect of $\text{Al}\%/\text{Cr}\%$ on the oxidation resistance. The effect of $\text{Al}\%/\text{Cr}\%$ on the weight gain by oxidation in a continuous oxidation test of holding specimens at 1050°C for 400 hours is shown in Fig. 3. When $\text{Al}\%/\text{Cr}\%$ is less than 0.14, breakaway oxidation (weight gain by oxidation $\geq 50 \text{ g/m}^2$) occurs although 1.4% or more Al is contained. In contrast, at $\text{Al}\%/\text{Cr}\%$ of 0.14 or more, breakaway oxidation does not occur.

[0028] The effect of $\text{Al}\%/\text{Cr}\%$ on the weight gain by oxidation in a cyclic oxidation test performed at 1050°C for 400 cycles is shown in Fig. 4. At $\text{Al}\%/\text{Cr}\%$ less than 0.14, breakaway oxidation (weight gain by oxidation $\geq 50 \text{ g/m}^2$) occurs although 1.4% or more of Al is contained and spalling of scale is also observed. In contrast, at $\text{Al}\%/\text{Cr}\%$ exceeding 0.14, neither breakaway oxidation nor spalling of scale occurs.

[0029] This is because when the value of $\text{Al}\%/\text{Cr}\%$ is less than 0.14, that is, when the ratio of the Cr content is large with respect to the Al content, Cr oxides are formed and inhibit formation of Al_2O_3 oxide layer and thus good oxidation resistance is not obtained. In contrast, as long as $\text{Al}\%/\text{Cr}\%$ is 0.14 or more, dense and stable Al_2O_3 oxide layer are preferentially formed rather than Cr oxides and thus good oxide resistance can be obtained. Accordingly, the Al content and the Cr content must satisfy $\text{Al}\%/\text{Cr}\% \geq 0.14$

[0030] As discussed above, Al has an effect of improving a thermal fatigue property and oxidation resistance. However, at an Al content exceeding 4.0%, steel hardens significantly, formability and toughness are significantly deteriorated, and thermal fatigue property is also deteriorated. Accordingly, the Al content is to be in the range of 1.4 to 4.0%. The Al content is preferably in the range of 1.5% to 3.5% and more preferably in the range of 2.0 to 3.0%.

Ti: more than 0.15% and 0.5% or less

[0031] Titanium (Ti) is an important element that fixes C and N and improves corrosion resistance, formability, and weld-zone intergranular corrosion resistance. Furthermore, when the Al content is 1.4% or more as in the present invention, Ti is an important element that prevents Al, which improves the thermal fatigue property, from precipitating as AlN so that Al can keep function as a solid solution strengthening element. The Ti content needs to be more than 0.15% in order to prevent formation of AlN. At a Ti content less than this, Al combines with N and forms AlN precipitates, the amount of dissolved Al is decreased, and a good thermal fatigue property is no longer obtained.

[0032] At a Ti content exceeding 0.15%, not only Ti forms Ti(C,N) precipitates but also Ti forms fine precipitates of FeTiP in grain boundaries. Ti(C,N) precipitates are coarse and do not contribute to strengthening of the steel, but fine precipitates of FeTiP in the grain boundaries strengthen the grain boundaries and improve the thermal fatigue property. Accordingly, the Ti content is to be more than 0.15%. On the other hand, excessive Ti will deteriorate toughness of steel and adhesion of oxide scale (cyclic oxidation resistance) and thus 0.5% is the upper limit. Accordingly, the Ti content is to be in the range of more than 0.15% and 0.5% or less. The Ti content is preferably in the range of 0.18 to 0.4% and more preferably in the range of 0.20 to 0.3%. The Ti content is favorably in the range of more than 0.15% and 0.50% or less, more favorably in the range of 0.18 to 0.40%, and yet more favorably in the range of 0.20 to 0.30%.

Ni: 0.05 to 0.5%

[0033] Nickel (Ni) is an important element in the present invention. Nickel not only improves toughness of the steel but also improves oxidation resistance, in particular, cyclic oxidation resistance, of Ti-containing steel. In order to obtain such effects, the Ni content needs to be 0.05% or more. At a Ni content of less than 0.05%, the cyclic oxidation resistance is insufficient. If the cyclic oxidation resistance is insufficient, oxide scale separates every time the temperature raising and falling and oxidation proceeds, resulting in thickness reduction of the base metal. Moreover, due to spalling of oxide scale, starting points of cracks are formed and thus a good thermal fatigue property is no longer obtained. On the other hand, Ni is an expensive element and is a strong γ -phase forming element; thus, excessive Ni will cause formation of γ phases at high temperatures and deteriorate the oxidation resistance. Accordingly, the upper limit is 0.5%. The Ni content is preferably in the range of 0.05 to 0.50%, more preferably in the range of 0.10 to 0.30%, and yet more preferably in the range of 0.15 to 0.25%.

[0034] The components described above are basic chemical components of a ferritic stainless steel of the present invention. The balance is Fe and unavoidable impurities. From the viewpoint of improving the heat resistance property, at least one selected from Nb and Cu may be contained as an optional element within the range described below.

Nb: 0.01 to 0.15%

[0035] Since Niobium (Nb) forms carbonitrides with C and N and then fixes C and N, Nb has an effect of improving corrosion resistance, formability, and weld-zone intergranular corrosion resistance as well as an effect of significantly increasing high-temperature strength to improve a thermal fatigue property and a high-temperature fatigue property. In order to achieve these effects, the Nb content is preferably 0.01% or more. However, using more than 0.15% of Nb will increase the production cost since Nb is an expensive element and increases the recrystallization temperature of the steel and the annealing temperature thus needs to be increased. Thus, if Nb is to be contained, the Nb content is preferably in the range of 0.01 to 0.15%. The Nb content is more preferably in the range of 0.02 to 0.12% and yet more preferably in the range of 0.05 to 0.10%.

Cu: 0.01% or more and less than 0.4%

[0036] Copper (Cu) is an element effective for improving a thermal fatigue property. In order to obtain such an effect, the Cu content is preferably 0.01% or more. However, at a Cu content of 0.4% or more, Cu inhibits generation of Al_2O_3 in oxide scale and deteriorates oxidation resistance. Accordingly, if Cu is to be contained, the Cu content is preferably in the range of 0.01% or more and less than 0.4%. The Cu content is more preferably in the range of 0.01 to 0.2% and more preferably in the range of 0.01 to 0.1%. The Cu content is favorably in the range of 0.01% or more and less than 0.40%, more favorably in the range of 0.01 to 0.20%, and yet more favorably in the range of 0.01 to 0.10%.

[0037] From the viewpoint of improving a heat resistance property, at least one selected from Mo and W may be

contained as an optional element within the ranges described below.

Mo: 0.02 to 0.5%

5 **[0038]** Molybdenum (Mo) is an element that increases the strength of steel by solid solution strengthening and then improves heat resistance. The Mo content is preferably 0.02% or more to obtain this effect. However, Mo is an expensive element and a Mo content exceeding 0.5% will deteriorate the oxidation resistance of a steel containing 1.4% or more of Al as in the present invention. Accordingly, if Mo is to be contained, the Mo content is preferably in the range of 0.02 to 0.5%, more preferably in the range of 0.02 to 0.3%, and yet more preferably in the range of 0.02 to 0.1%. The Mo content is favorably in the range of 0.02 to 0.50%, more favorably in the range of 0.02 to 0.30%, and yet more favorably in the range of 0.02 to 0.10%.

W: 0.02 to 0.3%

15 **[0039]** Tungsten (W) is an element that improves the strength of steel by solid solution strengthening and then improves the heat resistance property as with Mo. In order to obtain this effect, the W content is preferably 0.02% or more. However, W is also an expensive element as with Mo and, at a W content exceeding 0.3%, oxide scale generated during annealing is stabilized and it becomes difficult to remove scale by pickling after cold-roll annealing. Accordingly, if W is to be contained, the W content is preferably in the range of 0.02 to 0.3% and more preferably in the range of 0.02 to 0.1%.
20 The W content is favorably in the range of 0.02 to 0.30% and more favorably in the range of 0.02 to 0.10%.

[0040] From the viewpoint of improving a heat resistance property, at least one selected from REM, Zr, V, and Co may be contained as an optional element within the ranges described below.

REM: 0.001 to 0.10%

25 **[0041]** A rare earth element (REM) is an element that improves oxidation resistance and is contained as needed in the present invention. The REM content is preferably 0.001% or more to obtain the effect. However, at a REM content exceeding 0.10%, the steel becomes brittle. Thus, if REM is to be contained, the REM content is preferably in the range of 0.001 to 0.10%, more preferably in the range of 0.005 to 0.06%, and yet more preferably in the range of 0.01 to 0.05%.
30 The REM content is favorably in the range of 0.001 to 0.100%, more favorably in the range of 0.005 to 0.060%, and yet more favorably in the range of 0.010 to 0.050%.

Zr: 0.01 to 0.5%

35 **[0042]** Zirconium (Zr) is an element that improves oxidation resistance and is contained in the present invention, if desired. In order to obtain this effect, the Zr content is preferably 0.01% or more. At a Zr content exceeding 0.5%, Zr intermetallic compounds precipitate and the steel becomes brittle. Thus, if Zr is to be contained, the Zr content is preferably in the range of 0.01 to 0.5%, more preferably in the range of 0.02 to 0.1%, and yet more preferably in the range of 0.01 to 0.10%. The Zr content is favorably in the range of 0.01 to 0.50% and more favorably in the range of 0.02 to 0.10%.

V: 0.01 to 0.5%

40 **[0043]** Vanadium (V) is an element that improves oxidation resistance and further is effective for improving high-temperature strength. In order to obtain these effects, the V content is preferably 0.01% or more. At a V content exceeding 0.5%, coarse V(C,N) precipitates are formed and toughness is deteriorated. Accordingly, if V is to be contained, the V content is preferably in the range of 0.01 to 0.5%, more preferably in the range of 0.05 to 0.4%, and yet more preferably in the range of 0.10 to 0.25%. The V content is favorably in the range of 0.01 to 0.50% and more favorably in the range of 0.05 to 0.40%.

50 Co: 0.01 to 0.5%

[0044] Cobalt (Co) is an element effective for improving toughness and further improves high-temperature strength. In order to obtain this effect, the Co content is preferably 0.01% or more. However, Co is an expensive element and the effect is saturated at a Co content exceeding 0.5%. Thus, if Co is to be contained, the Co content is preferably in the range of 0.01 to 0.5%, more preferably in the range of 0.02 to 0.2%, and yet more preferably in the range of 0.02 to 0.1%.

[0045] The Co content is favorably in the range of 0.01 to 0.50%, more favorably in the range of 0.02 to 0.20%, and yet more favorably in the range of 0.02 to 0.10%.

[0046] Furthermore, from the viewpoints of improving formability and productivity, at least one selected from B, Mg,

and Ca may be contained as an optional element within the ranges described below.

B: 0.0002 to 0.0050%

[0047] Boron (B) is an element that improves workability, in particular, secondary working embrittlement. In order to obtain this effect, the B content is preferably 0.0002% or more. However, at a B content exceeding 0.0050%, the workability and toughness of the steel are deteriorated. Accordingly, if B is to be contained, the B content is preferably in the range of 0.0002 to 0.0050%, more preferably in the range of 0.0002 to 0.0030%, and yet more preferably in the range of 0.0002 to 0.0010%.

Mg: 0.0002 to 0.0020%

[0048] Magnesium (Mg) is an element that improves the equiaxed crystal ratio of a slab and is effective for improving workability and toughness. Magnesium also has an effect of suppressing coarsening of Ti carbonitrides in a steel that contains Ti as in the present invention. In order to obtain this effect, the Mg content is preferably 0.0002% or more. This is because coarsened Ti carbonitrides become starting points for brittle cracking and significantly deteriorates the toughness of the steel. However, at a Mg content exceeding 0.0020%, the surface quality of the steel is degraded. Accordingly, if Mg is to be contained, the Mg content is preferably in the range of 0.0002 to 0.0020%, more preferably in the range of 0.0002 to 0.0015%, and yet more preferably in the range of 0.0004 to 0.0010%.

Ca: 0.0005 to 0.0030%

[0049] Calcium (Ca) is a component effective for preventing clogging of casting nozzles caused by precipitation of Ti-based inclusions that are likely to occur during continuous casting. In order to obtain this effect, the Ca content is preferably 0.0005% or more. However, since surface defects are likely to occur, the Ca content needs to be 0.0030% or less to obtain satisfactory surface quality. Accordingly, if Ca is to be contained, the Ca content is preferably in the range of 0.0005 to 0.0030%, more preferably in the range of 0.0005% to 0.0020%, and yet more preferably in the range of 0.0005% to 0.0015%.

2. Regarding production method

[0050] A method for producing a ferritic stainless steel according to the present invention will now be described.

[0051] Any appropriate common method for producing a ferritic stainless steel can be used to produce a stainless steel in the present invention without any limitation. For example, preferably, a steel is melted and refined in a known melting furnace such as a converter or an electric furnace and, optionally, subjected to secondary refining such as ladle refining or vacuum refining to prepare a steel having the aforementioned composition according to the present invention; the steel is then formed into a slab by a continuous casting method or an ingoting-slabbing method; and the slab is formed into a cold rolled-annealed sheet through steps of hot rolling, hot rolled sheet annealing, pickling, cold-rolling, finish-annealing, pickling, etc.

[0052] The cold rolling may be performed once, or two or more times with intermediate annealing performed in between. The steps of cold rolling, finish annealing, and pickling may be repeated. In some cases, the hot rolled sheet annealing may be omitted. In the cases where the surface of the steel sheet needs to be glossy, skin-pass rolling may be performed after cold rolling or finish annealing.

[0053] A more preferable production method involves specifying some of the conditions of performing the hot-rolling step and the cold rolling step. In steel making, it is preferable to produce a molten steel containing the aforementioned essential components and optional additive components by melting and refining with a converter, an electric furnace, or the like and by performing secondary refining by a vacuum oxygen decarburation method (VOD method) or an argon oxygen decarburation method (AOD method). The refined molten steel can be formed into a steel material by a known production method and a continuous casting method is preferable from the viewpoints of productivity and quality.

[0054] A steel material obtained by continuous casting is, for example, heated to 1000 to 1250°C and hot-rolled into a hot rolled sheet having a desired thickness. Certainly, the steel material can be worked into a form other than a sheet. If needed, this hot rolled sheet is subjected to batch annealing at 600 to 900°C or continuous annealing at 850°C to 1050°C and pickling, for example, to remove scale and thus a hot rolled sheet product is obtained. If needed, scale may be removed by shot blasting before pickling.

[0055] Further, in order to obtain a cold rolled-annealed sheet, the hot rolled-annealed sheet obtained as above is subjected to a cold rolling step to be a cold rolled sheet. In this cold rolling step, cold rolling may be performed two or more times with intermediate annealing in between as needed depending on the factors related to production. The total reduction in the cold rolling step in which cold rolling is performed once or two or more times is to be 60% or more and

preferably 70% or more.

[0056] The cold rolled sheet is then subjected to continuous annealing (finish annealing) at 850 to 1000°C and pickling to obtain a cold rolled-annealed sheet. Depending on the usage, the sheet may be moderately rolled (skin pass rolling or the like) after pickling so as to adjust the shape and quality of the steel sheet.

[0057] A hot rolled sheet product or a cold rolled-annealed sheet product produced as such is subjected to bending or the like depending on the usage so as to form exhaust pipes and catalyst cases of automobiles and motorcycles, exhaust ducts of thermal power plants, and parts (for example, separators, interconnectors, and reformers) related to fuel cells.

[0058] The method for welding these parts is not particularly limited. Common arc welding methods such as metal inert gas (MIG), metal active gas (MAG), and tungsten inert gas (TIG) welding methods, resistance welding methods such as spot welding and seam welding, and high-frequency resistance welding and high-frequency inductive welding used in such as an electric welding method can be applied.

EXAMPLE 1

[0059] Steel Nos. 1 to 80 (% means % by mass) having compositions shown in Tables 1-1 to 1-6 were prepared by melting in a vacuum melting furnace and cast to produce 30 kg steel ingots. Each ingot was heated to 1170°C and hot-rolled into a sheet bar having a thickness of 35 mm and a width of 150 mm. The sheet bar was halved, one segment was hot-forged into a square bar having a 30 mm x 30 mm cross section, annealed in the temperature range of 850 to 1000°C, and machined to prepare a thermal fatigue test specimen having dimensions shown in Fig. 1, and the specimen was subjected to a thermal fatigue test. Note that the annealing temperature was set within the range described above while monitoring the microstructure so that the temperature was suitable for the composition.

[0060] The other segment of the sheet bar was heated to 1050°C and hot-rolled into a hot rolled sheet having a thickness of 5 mm. Then annealing is performed in the temperature range of 850 to 1050°C and the scale on the surface was removed by pickling or polishing. At this stage, the presence or absence of the surface normality of the steel sheet was observed visually. The steel sheet was cold-rolled to a thickness of 2 mm and finish-annealed within the temperature range of 850 to 1000°C to be a cold rolled-annealed sheet. A specimen 30 mm in length and 20 mm in width was cut out from the cold rolled-annealed sheet. All six faces of the specimen were polished with a #320 emery paper and the specimen was subjected to a continuous oxidation test and a cyclic oxidation test described below.

1.1 Regarding thermal fatigue test

[0061] Fig. 2 shows a thermal fatigue test procedure. A thermal fatigue test specimen was repeatedly heated at a heating rate of 10 °C/s and cooled at a cooling rate of 10 °C/s between 100°C and 850°C and, simultaneously, strain was repeatedly applied to the specimen at a restraint ratio of 0.3 to measure the thermal fatigue lifetime. The holding time at 100°C and 850°C was 2 min each.

[0062] Here, the thermal fatigue lifetime was determined as follows according to the standard test method for high temperature and low-cycle fatigue testing set forth in Standard of the Society of Materials Science, Japan: , stress was calculated by dividing the load detected at 100°C by the cross-sectional area of the gauged portion of the specimen shown in Fig. 1, and the number of cycles on which the stress decreased to 75% of the stress on the fifth cycle was defined to be the thermal fatigue lifetime. For comparison, the same testing was performed on a Nb-Si-containing steel (15 mass% Cr-0.9 mass% Si-0.4 mass% Nb).

[0063] The evaluation standard of the thermal fatigue test was as follows: A specimen with a thermal fatigue lifetime equal to or longer than that of the Nb-Si-containing steel specimen(940 cycles) was evaluated as pass and a specimen with a thermal fatigue life less than 940 cycles was evaluated as fail. The evaluation results are shown in Tables 1-2, 1-4, and 1-6.

1.2 Regarding continuous oxidation test

[0064] The oxidation test specimen described above was held for 400 hours in an air atmosphere heated to 1050°C in a furnace, the difference in mass of the specimen between before and after the holding was measured, and the weight gain by oxidation per unit area (g/m²) was calculated. The test was performed twice on each specimen.

[0065] The evaluation standard of the continuous oxidation test was as follows: A specimen with an weight gain by oxidation of less than 50 g/m² after the continuous oxidation test was evaluated as pass and a specimen that underwent an weight gain by oxidation of 50 g/m² or more even once was evaluated as fail. The evaluation results are shown in Tables 1-2, 1-4, and 1-6.

1.3 Regarding cyclic oxidation test

[0066] The oxidation test specimen described above was subjected to 400 cycles of a heat treatment that included repetition of holding at 100°C x 1 min, heating to 1050°C, holding at 1050°C x 20 min and cooling to 100°C in air, and then the difference in mass of the specimen between before and after the test was measured. The weight gain by oxidation per unit area (g/m²) was calculated and the absence or presence of scale separating from the specimen surface (spalling of scale) was checked. In this test, the heating rate and the cooling rate were 5 °C/sec and 1.5 °C/sec, respectively.

[0067] Regarding the evaluation results of the cyclic oxidation test, a specimen in which spalling of the oxide scale was not observed on the specimen surface after the cyclic oxidation test was evaluated as pass, a specimen in which the spalling was observed was evaluated as fail, and a specimen in which breakaway oxidation (weight gain by oxidation of 50 g/m² or more) occurred was evaluated as fail (breakaway oxidation). The evaluation results are shown in Tables 1-2, 1-4, and 1-6.

[Table 1-1]

No.	Composition (mass%)													
	C	Si	Mn	P	S	Cr	N	Al	Ti	Cu	Ni	Nb	Mo	W
1	0.005	0.83	0.16	0.03	0.002	12.3	0.010	1.98	0.25	-	0.08	-	-	-
2	0.007	0.18	0.19	0.02	0.003	12.5	0.011	3.03	0.23	0.03	0.10	-	-	-
3	0.009	1.21	0.17	0.03	0.002	11.8	0.009	2.56	0.27	0.02	0.11	0.07	-	-
4	0.007	0.76	0.13	0.02	0.002	12.7	0.010	2.11	0.24	-	0.09	0.08	-	-
5	0.007	0.13	0.22	0.02	0.002	13.2	0.009	2.95	0.25	-	0.12	0.11	-	-
6	0.006	0.56	0.18	0.02	0.002	14.5	0.010	2.42	0.22	-	0.03	-	-	-
7	0.008	0.90	0.26	0.03	0.003	10.6	0.009	1.56	0.28	0.04	0.07	-	-	-
8	0.009	0.34	0.24	0.02	0.002	11.1	0.011	3.33	0.21	-	0.09	0.06	0.28	-
9	0.005	0.70	0.39	0.02	0.003	14.7	0.010	2.35	0.24	0.25	0.07	-	-	-
10	0.010	0.54	0.22	0.03	0.002	12.2	0.008	1.77	0.20	0.03	0.15	-	0.06	-
11	0.006	0.72	0.20	0.02	0.003	10.9	0.012	2.09	0.19	-	0.21	-	-	0.05
12	0.008	0.95	0.36	0.03	0.003	13.1	0.010	1.90	0.18	0.01	0.24	-	-	-
13	0.007	1.39	0.48	0.02	0.002	15.3	0.011	3.47	0.30	0.02	0.13	-	-	-
14	0.009	0.43	0.36	0.02	0.001	12.4	0.009	1.86	0.28	-	0.17	0.09	-	-
15	0.011	1.04	0.14	0.02	0.003	11.5	0.011	2.80	0.24	0.18	0.36	-	-	-
16	0.008	0.29	0.26	0.02	0.001	10.3	0.010	1.69	0.19	-	0.23	0.03	0.04	0.03
17	0.010	0.21	0.18	0.03	0.002	11.3	0.009	3.28	0.26	-	0.09	-	-	-
18	0.009	0.54	0.22	0.03	0.002	12.8	0.011	2.24	<u>0.14</u>	0.02	0.20	-	-	-
19	0.010	0.87	0.18	0.02	0.002	14.0	0.001	2.69	0.29	0.03	<u>0.02</u>	0.08	-	-
20	0.009	0.60	0.27	0.03	0.001	15.4	0.008	1.75	0.23	-	0.14	0.04	-	-
21	0.005	0.99	0.30	0.03	0.003	13.3	0.009	<u>0.89</u>	0.18	0.04	0.16	-	-	-
22	0.006	0.86	0.13	0.02	0.002	14.2	0.007	<u>4.12</u>	0.37	-	0.17	-	-	-
23	0.007	0.34	0.15	0.02	0.002	<u>9.4</u>	0.012	1.91	0.20	-	0.21	0.12	-	-
24	0.008	0.77	0.24	0.02	0.003	13.7	0.010	2.22	0.26	<u>1.06</u>	0.09	-	-	-
25	0.006	0.38	0.43	0.02	0.002	10.5	0.010	<u>0.02</u>	<u>0.15</u>	<u>1.26</u>	-	-	-	-
Note: Underlines indicate that specimens are outside the scope of the present invention.														

[Table 1-2]

No.	Composition (mass%)								Thermal fatigue test	Continuous oxidation test	Cyclic oxidation test	Note
	V	Co	Zr	REM	B	Ca	Mg	Al%/Cr%				
1	-	-	-	-	0.0002	0.0007	0.0005	0.16	Pass	Pass	Pass	Example
2	-	-	-	-	0.0003	0.0005	-	0.24	Pass	Pass	Pass	Example
3	-	-	-	-	0.0002	0.0011	0.0006	0.22	Pass	Pass	Pass	Example
4	-	-	-	-	0.0004	-	0.0010	0.17	Pass	Pass	Pass	Example
5	-	-	-	-	0.0003	-	0.0009	0.22	Pass	Pass	Pass	Example
6	-	-	-	-	0.0005	-	-	0.17	Pass	Pass	Pass	Example
7	-	-	-	-	0.0004	0.0010	0.0009	0.15	Pass	Pass	Pass	Example
8	-	-	-	-	0.0006	0.0009	0.0015	0.30	Pass	Pass	Pass	Example
9	-	-	-	-	0.0005	0.0008	0.0006	0.16	Pass	Pass	Pass	Example
10	-	-	-	-	0.0005	-	-	0.15	Pass	Pass	Pass	Example
11	-	-	-	-	0.0004	-	0.0007	0.19	Pass	Pass	Pass	Example
12	-	0.03	-	-	0.0006	0.0012	0.0003	0.15	Pass	Pass	Pass	Example
13	0.05	-	-	-	0.0009	0.0018	-	0.23	Pass	Pass	Pass	Example
14	-	-	0.06	-	0.0015	0.0002	0.0009	0.15	Pass	Pass	Pass	Example
15	0.19	-	-	-	0.0007	0.0007	0.0012	0.24	Pass	Pass	Pass	Example
16	-	-	-	-	0.0003	0.0009	0.0014	0.16	Pass	Pass	Pass	Example
17	-	-	-	0.01	0.0007	0.0008	0.0015	0.29	Pass	Pass	Pass	Example
18	-	-	-	-	0.0002	0.0010	0.0009	0.18	<u>Fail</u>	Pass	Pass	Comparative Example
19	-	-	-	-	0.0005	-	0.0008	0.19	Pass	Pass	<u>Fail</u>	Comparative Example
20	-	-	-	-	0.0004	0.0008	-	<u>0.11</u>	Pass	<u>Fail</u>	<u>Fail</u>	Comparative Example
21	-	-	-	-	0.0006	0.0009	0.0007	<u>0.07</u>	<u>Fail</u>	<u>Fail</u>	<u>Fail</u>	Comparative Example

(continued)

No.	Composition (mass%)							Thermal fatigue test	Continuous oxidation test	Cyclic oxidation test	Note
	V	Co	Zr	REM	B	Ca	Mg	Al%/Cr%			
22	-	-	-	-	0.0007	-	-	0.29	Pass	Pass	Comparative Example
23	-	-	-	-	0.0009	0.0005	0.0006	0.20	Fail	<u>Fail</u> (Breakaway oxidation)	Comparative Example
24	-	-	-	-	0.0010	0.0005	0.0006	0.16	Fail	<u>Fail</u> (Breakaway oxidation)	Comparative Example
25	-	-	-	-	0.0008	-	-	0.00	Fail	<u>Fail</u> (Breakaway oxidation)	Comparative Example
Note: Underlines indicate that specimens are outside the scope of the present invention.											

[Table 1-3]

No.	Composition (mass%)													
	C	Si	Mn	P	S	Cr	N	Al	Ti	Cu	Ni	Nb	Mo	W
26	0.007	0.73	0.33	0.02	0.001	14.3	0.012	2.38	<u>0.14</u>	-	0.10	-	-	-
27	0.005	0.50	0.26	0.03	0.001	<u>18.6</u>	0.009	1.94	0.18	0.13	0.11	-	-	-
28	0.006	1.95	0.40	0.02	0.001	15.6	0.009	<u>1.29</u>	0.18	-	0.08	-	-	-
29	0.009	0.41	0.82	0.02	0.001	15.4	0.008	2.55	0.26	-	<u>-</u>	0.01	-	-
30	0.008	0.83	0.38	0.03	0.003	14.9	0.009	0.02	0.01	-	0.22	0.46	-	-
31	0.010	0.11	0.16	0.02	0.002	12.1	0.011	2.97	0.26	-	0.08	-	-	-
32	0.008	0.58	0.26	0.03	0.003	13.9	0.010	2.11	0.24	-	0.11	-	-	-
33	0.009	0.32	0.39	0.02	0.001	10.4	0.009	3.44	0.18	-	0.12	-	-	-
34	0.008	1.47	0.18	0.02	0.002	15.7	0.012	2.89	0.29	-	0.15	-	-	-
35	0.010	0.20	0.35	0.02	0.002	13.1	0.009	2.56	0.25	-	0.13	-	-	-
36	0.008	0.77	0.22	0.02	0.001	12.3	0.011	2.03	0.39	-	0.10	-	-	-
37	0.009	0.98	0.15	0.03	0.002	11.2	0.011	1.57	0.30	-	0.09	-	-	-
38	0.007	0.55	0.19	0.01	0.003	12.5	0.012	1.86	0.29	-	0.05	0.08	-	-
39	0.009	0.89	0.24	0.02	0.002	12.8	0.010	2.08	0.18	-	0.08	-	0.28	-
40	0.010	0.30	0.16	0.02	0.002	13.3	0.010	2.92	0.24	-	0.11	-	-	-
41	0.007	0.13	0.23	0.02	0.002	14.5	0.012	3.05	0.23	-	0.13	-	-	-
42	0.009	0.10	0.27	0.03	0.002	15.5	0.011	3.44	0.24	-	0.11	-	-	-
43	0.011	1.47	0.31	0.02	0.001	10.9	0.011	2.22	0.25	0.36	0.12	-	-	-
44	0.008	0.26	0.18	0.02	0.002	10.5	0.009	2.98	0.27	-	0.14	-	-	-
45	0.007	0.78	0.26	0.02	0.003	12.7	0.008	2.53	0.19	-	0.09	-	-	-
46	0.009	1.11	0.25	0.02	0.002	11.9	0.010	2.87	0.20	-	0.22	-	0.15	-
47	0.010	0.82	0.21	0.02	0.003	13.6	0.011	3.66	0.26	0.27	0.19	0.09	-	-
48	0.009	0.14	0.19	0.02	0.002	12.4	0.010	3.14	0.25	-	0.09	-	-	-
49	0.010	0.33	0.28	0.03	0.001	13.0	0.012	2.69	0.23	-	0.08	-	0.19	-
50	0.007	1.45	0.30	0.02	0.001	12.7	0.010	1.90	0.27	-	0.23	-	-	0.04
Note: Underlines indicate that specimens are outside the scope of the present invention.														

[Table 1-4]

No.	Composition (mass%)								Thermal fatigue test	Continuous oxidation test	Cyclic oxidation test	Note
	V	Co	Zr	REM	B	Ca	Mg	Al%/Cr%				
26	-	-	-	-	-	-	-	0.17	Fail	Pass	Pass	Comparative Example
27	0.06	-	-	-	-	-	-	0.10	Pass	Fail	Fail	Comparative Example
28	0.22	-	-	-	-	-	-	0.08	Pass	Fail	Fail	Comparative Example
29	0.09	-	-	-	-	-	-	0.17	Pass	Pass	Fail	Comparative Example
30	-	-	-	-	0.0005	-	-	0.00	Pass	Fail	Fail (Breakaway oxidation)	Conventional example (Nb-Si-containing)
31	-	-	-	-	-	-	-	0.25	Pass	Pass	Pass	Example
32	-	-	-	-	-	-	-	0.15	Pass	Pass	Pass	Example
33	-	-	-	-	-	-	-	0.33	Pass	Pass	Pass	Example
34	-	-	-	-	-	-	-	0.18	Pass	Pass	Pass	Example
35	-	-	-	-	-	-	-	0.20	Pass	Pass	Pass	Example
36	-	-	-	-	-	-	-	0.17	Pass	Pass	Pass	Example
37	-	-	-	-	-	-	-	0.14	Pass	Pass	Pass	Example
38	-	-	-	-	-	-	-	0.15	Pass	Pass	Pass	Example
39	-	-	-	-	-	-	-	0.16	Pass	Pass	Pass	Example
40	-	-	0.07	-	-	-	-	0.22	Pass	Pass	Pass	Example
41	-	-	-	-	-	0.0011	-	0.21	Pass	Pass	Pass	Example
42	-	-	-	-	-	-	0.0008	0.22	Pass	Pass	Pass	Example
43	-	-	-	-	-	-	-	0.20	Pass	Pass	Pass	Example
44	0.13	-	-	-	-	-	-	0.28	Pass	Pass	Pass	Example
45	-	0.04	-	-	-	-	-	0.20	Pass	Pass	Pass	Example
46	-	0.05	-	-	-	-	-	0.24	Pass	Pass	Pass	Example
47	-	-	-	-	-	-	-	0.27	Pass	Pass	Pass	Example
48	-	-	-	-	-	0.0009	0.0010	0.25	Pass	Pass	Pass	Example
49	-	0.10	-	-	0.0005	0.0007	0.0008	0.21	Pass	Pass	Pass	Example

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(continued)

No.	Composition (mass%)							Thermal fatigue test	Continuous oxidation test	Cyclic oxidation test	Note
	V	Co	Zr	REM	B	Ca	Mg	Al%/Cr%			
50	-	-	-	-	-	-	-	<u>0.15</u>	Pass	Pass	Example
Note: Underlines indicate that specimens are outside the scope of the present invention.											

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[Table 1-5]

No.	Composition (mass%)													
	C	Si	Mn	P	S	Cr	N	Al	Ti	Cu	Ni	Nb	Mo	W
51	0.008	0.51	0.31	0.03	0.002	10.1	0.010	2.37	0.31	-	0.22	-	-	-
52	0.011	0.77	0.28	0.02	0.002	14.9	0.008	2.23	0.25	-	0.18	-	-	-
53	0.009	0.48	0.17	0.02	0.002	14.3	0.012	2.37	0.24	-	0.17	-	-	-
54	0.012	0.34	0.12	0.03	0.002	11.6	0.008	2.00	0.17	-	0.25	0.07	0.05	-
55	0.009	1.11	0.46	0.02	0.002	14.0	0.011	3.00	0.29	-	0.28	0.06	-	0.03
56	0.010	0.87	0.16	0.02	0.001	12.9	0.011	3.91	0.27	0.18	0.20	-	0.21	
57	0.012	0.83	0.57	0.02	0.001	14.8	0.008	2.14	0.21	0.22	0.21	-	-	0.10
58	0.005	0.55	0.24	0.02	0.002	14.1	0.008	2.44	0.19	-	0.23	0.11	-	-
59	0.004	1.57	0.23	0.02	0.001	12.3	0.010	1.84	0.23	-	0.12	0.08	-	-
60	0.009	0.48	0.45	0.02	0.002	10.4	0.009	1.47	0.26	-	0.07	0.09	-	-
61	0.008	0.77	0.37	0.03	0.001	13.8	0.007	2.01	0.28	-	0.20	0.12	-	-
62	0.010	0.91	0.31	0.02	0.001	11.1	0.009	2.43	0.24	0.15	0.06	-	-	-
63	0.009	2.04	0.20	0.01	0.002	11.5	0.010	3.69	0.21	0.24	0.08	-	-	-
64	0.008	0.79	0.15	0.02	0.002	15.2	0.011	3.09	0.19	0.33	0.11	-	-	-
65	0.006	1.09	0.28	0.02	0.002	12.8	0.007	2.97	0.28	0.29	0.17	-	-	-
66	0.007	0.86	0.13	0.02	0.002	11.8	0.011	1.81	0.20	-	0.24	0.08	0.04	-
67	0.009	0.17	0.96	0.02	0.002	15.2	0.009	2.74	0.19	-	0.08	0.10	0.13	-
68	0.011	0.79	0.18	0.03	0.001	14.8	0.011	3.53	0.22	-	0.14	0.09	0.14	-
69	0.012	0.31	0.59	0.01	0.002	10.5	0.010	2.05	0.24	0.21	0.21	-	0.09	-
70	0.010	0.64	0.22	0.02	0.002	12.4	0.010	2.31	0.28	0.23	0.11	-	0.20	-
71	0.009	0.39	0.77	0.03	0.001	11.5	0.010	3.20	0.26	0.34	0.26	-	0.31	-
72	0.008	0.64	0.17	0.02	0.002	13.8	0.011	2.54	0.23	-	0.08	-	0.02	-
73	0.009	0.73	0.13	0.02	0.001	14.2	0.012	2.88	0.27	-	0.19	-	0.02	-
74	0.006	0.40	0.25	0.01	0.002	11.8	0.012	2.01	0.20	-	0.15	-	-	0.02
75	0.010	0.58	0.31	0.02	0.002	15.0	0.010	3.13	0.25	-	0.11	-	-	0.03
76	0.006	1.23	0.17	0.02	0.001	15.5	0.010	2.03	0.21	-	0.09	-	-	-
77	0.007	0.78	0.33	0.02	0.002	14.2	0.010	1.84	0.30	-	0.10	-	-	-
78	0.007	0.38	0.31	0.02	0.003	11.1	0.011	1.48	0.28	-	0.12	-	-	-
79	0.009	0.99	0.20	0.01	0.002	13.3	0.009	1.56	0.26	-	0.11	-	-	-
80	0.008	1.46	0.56	0.03	0.002	14.6	0.011	1.79	0.26	-	0.06	-	-	-

[Table 1-6]

No.	Composition (mass%)							Thermal fatigue test	Continuous oxidation test	Cyclic oxidation test	Note
	V	Co	Zr	REM	B	Ca	Mg				
							Al%/Cr%				
51	-	-	-	0.02	-	-	-	Pass	Pass	Pass	Example
52	0.05	0.03	-	-	-	-	-	Pass	Pass	Pass	Example
53	-	0.06	0.04	-	-	-	-	Pass	Pass	Pass	Example
54	-	-	-	-	-	-	-	Pass	Pass	Pass	Example
55	-	-	-	-	-	-	-	Pass	Pass	Pass	Example
56	-	-	-	-	-	-	-	Pass	Pass	Pass	Example
57	-	-	-	-	-	-	-	Pass	Pass	Pass	Example
58	-	-	-	0.04	-	-	-	Pass	Pass	Pass	Example
59	-	-	0.05	-	-	-	-	Pass	Pass	Pass	Example
60	-	0.03	-	-	-	-	-	Pass	Pass	Pass	Example
61	0.09	-	-	-	-	-	-	Pass	Pass	Pass	Example
62	-	-	-	0.05	-	-	-	Pass	Pass	Pass	Example
63	-	-	0.03	-	-	-	-	Pass	Pass	Pass	Example
64	-	0.04	-	-	-	-	-	Pass	Pass	Pass	Example
65	0.19	-	-	-	-	-	-	Pass	Pass	Pass	Example
66	-	-	0.02	-	-	-	-	Pass	Pass	Pass	Example
67	0.11	-	-	-	-	-	-	Pass	Pass	Pass	Example
68	-	0.05	-	-	-	-	-	Pass	Pass	Pass	Example
69	-	-	0.07	-	-	-	-	Pass	Pass	Pass	Example
70	0.17	-	-	-	-	-	-	Pass	Pass	Pass	Example
71	-	0.06	-	-	-	-	-	Pass	Pass	Pass	Example
72	0.01	-	-	-	-	-	-	Pass	Pass	Pass	Example
73	0.02	-	-	-	0.0002	-	-	Pass	Pass	Pass	Example
74	0.03	-	-	-	-	-	-	Pass	Pass	Pass	Example

(continued)

No.	Composition (mass%)							Thermal fatigue test	Continuous oxidation test	Cyclic oxidation test	Note
	V	Co	Zr	REM	B	Ca	Mg				
75	-	0.02	-	-	-	-	-	Pass	Pass	Pass	Example
76	-	-	-	-	-	-	-	Pass	<u>Fail</u>	<u>Fail</u>	Comparative Example
77	-	-	-	-	-	-	-	Pass	<u>Fail</u>	<u>Fail</u>	Comparative Example
78	-	-	-	-	-	-	-	Pass	<u>Fail</u>	<u>Fail</u>	Comparative Example
79	-	-	-	-	-	-	-	Pass	<u>Fail</u>	<u>Fail</u>	Comparative Example
80	-	-	-	-	-	-	-	Pass	<u>Fail</u>	<u>Fail</u>	Comparative Example

[0068] Referring to Tables 1-1 to 1-6, Example Nos. 1 to 17 and Example Nos. 31 to 75 of the present invention all had a good thermal fatigue property, good continuous oxidation resistance, and good cyclic oxidation resistance. Hot rolled, annealed, and pickled steel sheets of examples of the present invention had no defects on surfaces and had good surface quality.

[0069] In contrast, Comparative Example No. 18 had a low Ti content of 0.14% and thus failed in thermal fatigue property. Comparative Example No. 19 had a low Ni content of 0.02% and failed in cyclic oxidation resistance. Comparative Examples No. 20 and Nos. 76 to 80 had an Al%/Cr% value being lower than 0.14 and thus failed in oxidation resistance (both continuous and cyclic). Comparative Example No. 21 had a low Al content of 0.89% and thus failed in thermal fatigue property (850°C); moreover, Comparative Example No. 21 had a low Al%/Cr% value of 0.07 and thus failed in oxidation resistance (both continuous and cyclic). Comparative Example No. 22 had a high Al content of 4.12% and thus failed in thermal fatigue property. Comparative Example No. 23 had a low Cr content of 9.4% and thus failed in oxidation resistance (both continuous and cyclic). Comparative Example No. 24 had a high Cu content of 1.06% and thus failed in oxidation resistance (both continuous and cyclic).

[0070] Comparative Example No. 25 had a low Al content and a low Ti content and thus failed in thermal fatigue property. Moreover, since the Cu content was as high as 1.25%, oxidation resistance (both continuous and cyclic) was evaluated as fail and since Ni was not contained, the cyclic oxidation property was evaluated as fail. Comparative Example No. 26 had a low Ti content and thus failed in thermal fatigue property. Comparative Examples No. 27 and No. 28 had a small Al%/Cr% value and thus failed in oxidation resistance (both continuous and cyclic). Comparative Example No. 29 did not contain Ni and thus failed in cyclic oxidation property.

[0071] Accordingly, it is clear that the steels within the range of the present invention have good thermal fatigue properties and oxidation resistance.

Industrial Applicability

[0072] A steel according to the present invention is not only suitable for use in exhaust parts of automobiles, etc., but also suitable for use in exhaust parts of thermal power plants and solid oxide-type fuel cell parts that require similar properties.

Claims

1. A ferritic stainless steel comprising, in terms of % by mass, C: 0.020% or less, Si: 3.0% or less, Mn: 1.0% or less, P: 0.040% or less, S: 0.030% or less, Cr: 10.0% or more and less than 16.0%, N: 0.020% or less, Al: 1.4 to 4.0%, Ti: more than 0.15% and 0.5% or less, Ni: 0.05 to 0.5%, and the balance being Fe and unavoidable impurities, the ferritic stainless steel satisfying formula (1) below:

$$\text{Al\%/Cr\%} \geq 0.14 \quad \cdots \quad (1)$$

where Al% and Cr% in the formula respectively denote an Al content and a Cr content (% by mass).

2. The ferritic stainless steel according to Claim 1, further comprising, in terms of % by mass, at least one selected from Nb: 0.01 to 0.15% and Cu: 0.01% or more and less than 0.4%.
3. The ferritic stainless steel according to Claim 1 or 2, further comprising, in terms of % by mass, at least one selected from Mo: 0.02 to 0.5% and W: 0.02 to 0.3%.
4. The ferritic stainless steel according to any one of Claims 1 to 3, further comprising, in terms of % by mass, at least one selected from REM: 0.001 to 0.10%, Zr: 0.01 to 0.5%, V: 0.01 to 0.5%, and Co: 0.01 to 0.5%.
5. The ferritic stainless steel according to any one of Claims 1 to 4, further comprising, in terms of % by mass, at least one selected from B: 0.0002 to 0.0050%, Mg: 0.0002 to 0.0020%, and Ca: 0.0005 to 0.0030%.

FIG. 1

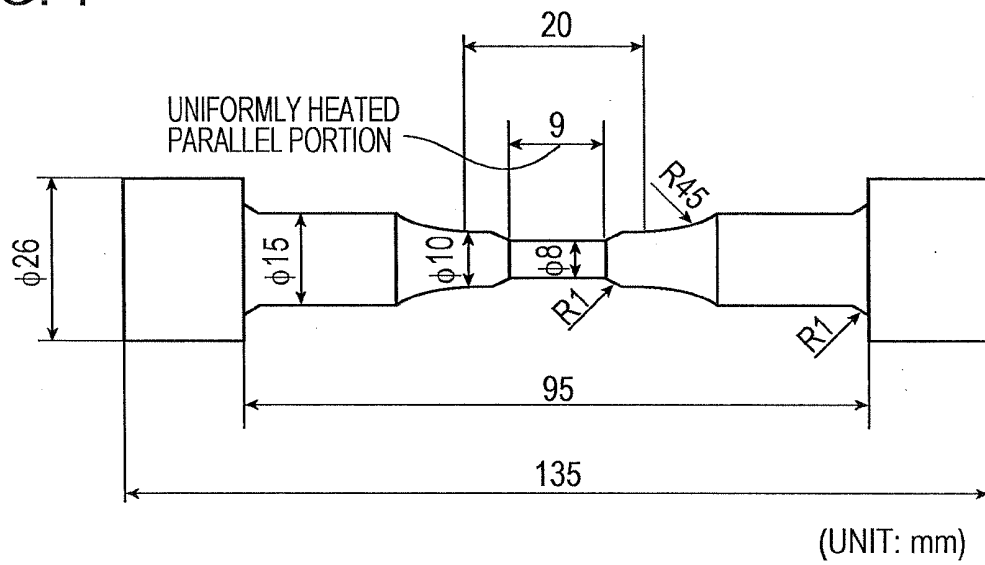


FIG. 2

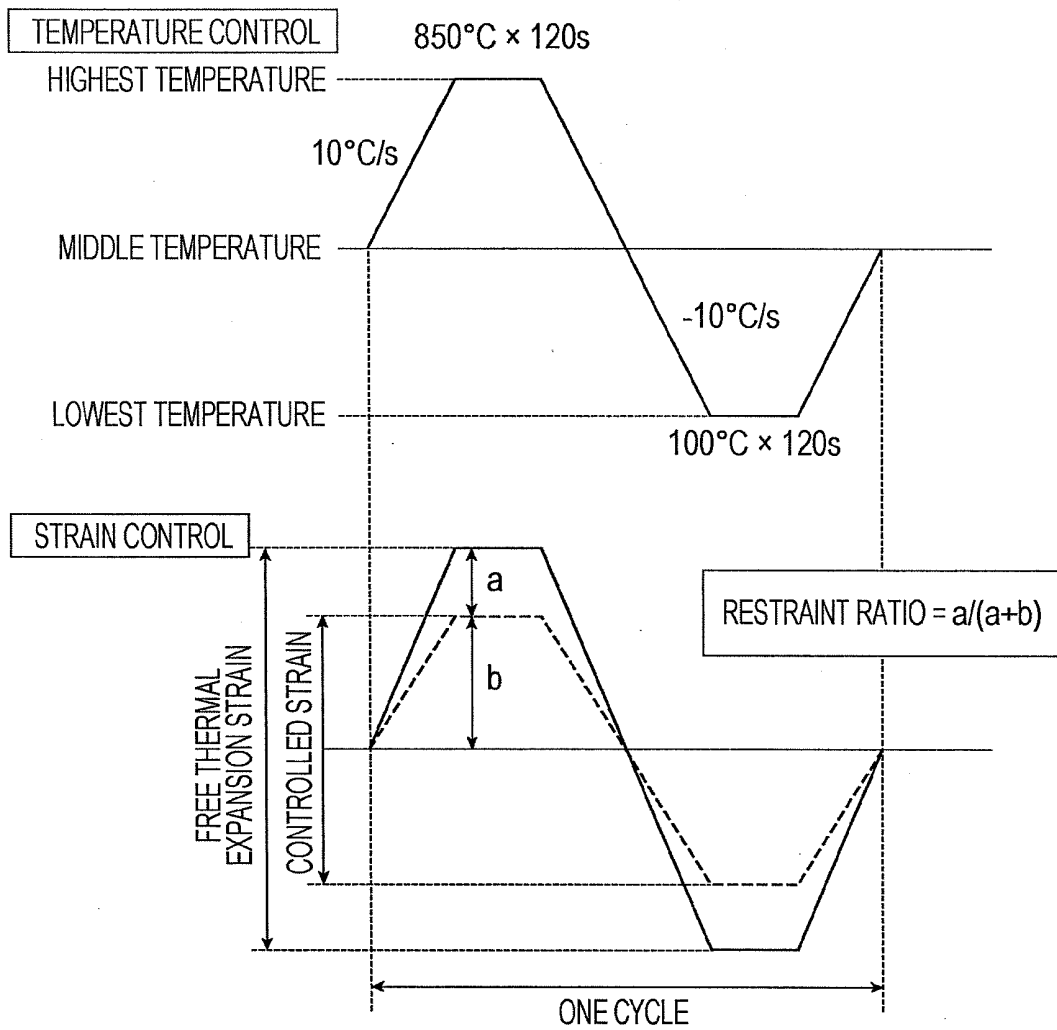


FIG. 3

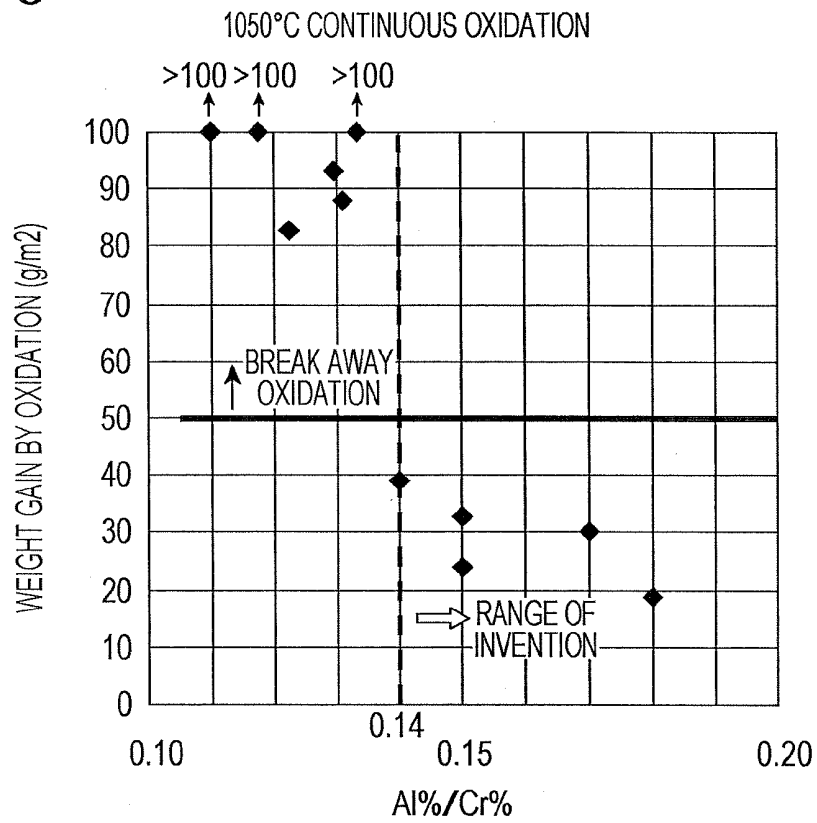
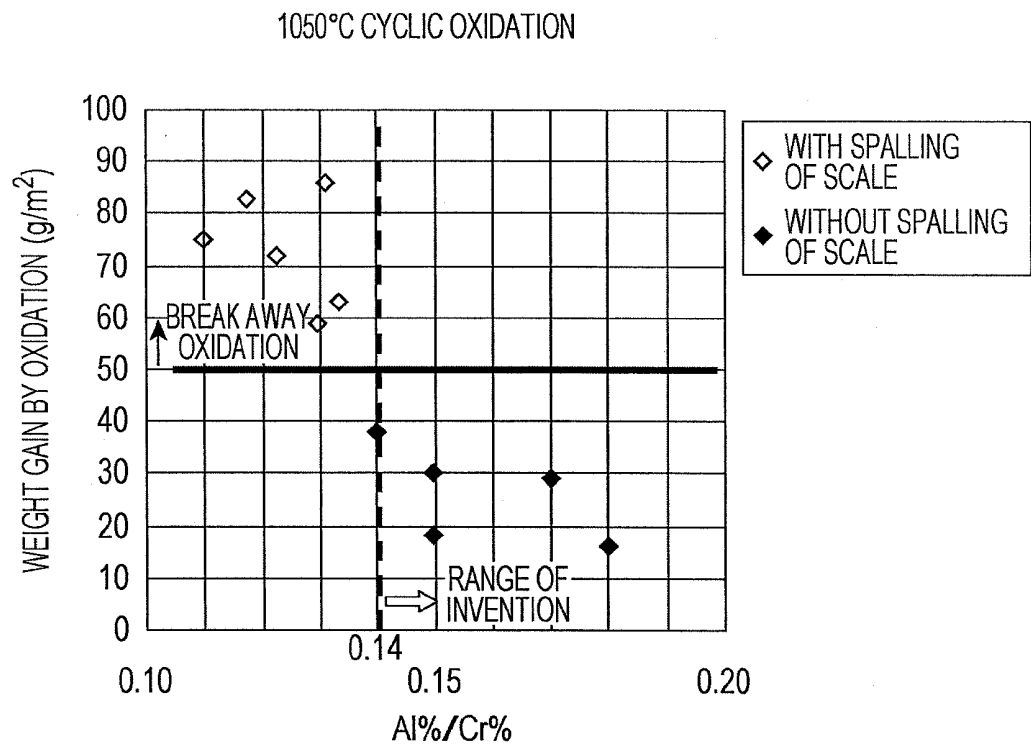


FIG. 4



INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2013/005486

A. CLASSIFICATION OF SUBJECT MATTER

C22C38/00(2006.01)i, C22C38/50(2006.01)i, C22C38/54(2006.01)i, C21D9/46
(2006.01)n

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
C22C38/00, C22C38/50, C22C38/54, C21D9/46

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Jitsuyo Shinan Koho 1922-1996 Jitsuyo Shinan Toroku Koho 1996-2013
Kokai Jitsuyo Shinan Koho 1971-2013 Toroku Jitsuyo Shinan Koho 1994-2013

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	JP 2011-256436 A (Nisshin Steel Co., Ltd.), 22 December 2011 (22.12.2011), table 1, steel type no. 15 (Family: none)	1 2-5
X	JP 2009-68113 A (Nippon Steel & Sumikin Stainless Steel Corp.), 02 April 2009 (02.04.2009), claims; paragraph [0046]; table 1, steel no. AF (Family: none)	1-5
X A	JP 2011-179088 A (Nisshin Steel Co., Ltd.), 15 September 2011 (15.09.2011), claims; table 1, steel no. 4, 13, 14 (Family: none)	1, 5 2-4

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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Date of the actual completion of the international search
03 December, 2013 (03.12.13)

Date of mailing of the international search report
10 December, 2013 (10.12.13)

Name and mailing address of the ISA/
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INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2013/005486

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 2008-156692 A (Nisshin Steel Co., Ltd.), 10 July 2008 (10.07.2008), entire text (Family: none)	1-5

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REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- JP 2010248620 A [0005]
- JP 2009068113 A [0005]
- JP 2004307918 A [0005]
- JP 2001316773 A [0005]
- JP 2009167443 A [0005]