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(54) WEAR-RESISTANT STEEL SHEET HAVING EXCELLENT TOUGHNESS

(57) To achieve both the "wear resistance" and the "toughness" to high levels for a non-tempered material. A steel sheet: having a chemical composition containing, in terms of percentage by mass, from 0.60 to 1.25% of C, 0.50% or less of Si, from 0.30 to 1.20% of Mn, 0.030% or less of P, 0.030% or less of S, from 0.30 to 1.50% of Cr, from 0.10 to 0.50% of Nb, from 0 to 0.50% of Ti, from 0 to 0.50% of Mo, from 0 to 0.50% of V, from 0 to 2.00% of Ni, and the balance of Fe, with unavoidable impurities; having a metal structure containing a ferrite phase as a metal matrix having dispersed therein cementite particles and particles of a carbide containing one or more kind of Nb and Ti (which may be hereinafter referred to as a "Nb·Ti based carbide"); and having, on a cross sectional surface in parallel to a rolling direction and a thickness direction (i.e., an L cross section), a number density of the Nb·Ti based carbide particles having a circle equivalent diameter of 0.5 μm or more of from 3,000 to 9,000 per mm^2 and a number density of voids having a circle equivalent diameter of 1.0 μm or more of 1,250 per mm^2 or less.

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Description

Technical Field

[0001] The present invention relates to a wear-resistant steel sheet having a hard Nb·Ti based carbide dispersed therein, in which the steel sheet is particularly improved in toughness.

Background Art

[0002] An automobile component, a chain component of an industrial machine, a power transmission member, such as a gear, and a cutlery member, such as a rim saw and a band saw, for cutting wood and mowing are demanded to have wear resistance. In general, the wear resistance of a steel material is enhanced by increasing the hardness thereof. Accordingly, a steel material hardened through a heat treatment, such as quenching, and a steel material having a large content of an alloy element, such as carbon, are frequently used as a member with importance of wear resistance. That is, the hardness and the wear resistance of a steel material closely relate to each other, and as a measure for imparting wear resistance to a steel material, a method of increasing the hardness thereof has been generally employed.

[0003] For a cutlery member rotating at high speed, such as a rim saw, it is important that the member is not broken during use. For preventing the breakage, it is necessary to secure the toughness of the steel material. The hardening, which is advantageous for enhancing the wear resistance, is a factor deteriorating the toughness. Accordingly, the "wear resistance" and the "toughness" are in a trade-off relationship.

[0004] As for some cutlery members, such as a rim saw for mowing agricultural products, such as fruits, cereals, and cotton, the "toughness" advantageous for preventing breakage is attached more importance than the hardness since the wear thereof is relatively gradual. To the purpose of this type of cutlery members, a "non-tempered material" having a ferrite phase + spheroidized cementite structure is frequently applied rather than a "tempered material" hardened through a tempering heat treatment, such as quenching. However, there has been an enduring demand of prolongation of the lifetime of the product, and therefore there is an increasing demand of improvement of the wear resistance even in the purpose where the wear is relatively gradual. The establishment of a technique that achieves both the "wear resistance" and the "toughness" at high levels for a non-tempered material is demanded.

[0005] PTLs 1 and 2 describe that the wear resistance of a steel is enhanced through the hardening and the decrease in area ratio of the ferrite phase, which accelerates wear in a steel for hot forging. However, the steel targeted by the literatures has a ferrite-pearlite structure, which is inferior in toughness to the ferrite + spheroidized cementite structure.

[0006] PTL 3 describes a technique of providing a member for a machine structure capable of being used without a tempering heat treatment, by directly cutting a hot-rolled steel material imparted with high strength and high toughness through refinement of the crystal grains. However, for the purpose requiring wear resistance, a treatment of induction hardening and tempering is required.

[0007] PTL 4 describes a steel sheet of a rim saw that has both wear resistance and toughness through cladding a high carbon steel as a sheath material and a low carbon steel as a core material. However, the cladding process is required.

[0008] PTLs 5 and 6 describe a technique for enhancing the wear resistance by using dispersion of a hard Nb·Ti based carbide. The technique targets a tempered material that intends to achieve hardening through a quenching and tempering treatment. High wear resistance can be obtained, but a further improvement is demanded in toughness.

Citation List

Patent Literatures

[0009]

PTL 1: JP-A-10-137888
PTL 2: JP-A-2003-201536
PTL 3: JP-A-2011-195858
PTL 4: JP-A-60-82647
PTL 5: JP-A-2010-138453
PTL 6: JP-A-2013-136820

Summary of Invention

Technical Problem

[0010] An object of the invention is to achieve both the "wear resistance" and the "toughness" at high levels for a non-tempered material.

Solution to Problem

[0011] According to the investigations by the present inventors, it has been found that in the technique of imparting wear resistance with a hard Nb·Ti based carbide as described in PTLs 5 and 6, the steel sheet before subjecting to a tempering heat treatment, such as quenching, (i.e., the non-tempered material) does not necessarily exhibit good toughness in this stage although the material is relatively soft. As a result of the detailed investigations, it has been found out that voids occur in the vicinity of the hard carbide particles in cold rolling, and the voids impair the toughness. Accordingly, the inventors have performed the studies for finding production condition that prevents the occurrence of voids. As a result, a tendency has been found that voids can be prevented from occurring by decreasing the cold rolling reduction ratio. As a result of the studies further performed, it has been found that in the case where cold rolling and annealing are repeated, there are cases where the toughness is significantly deteriorated when the cold rolling reduction ratio exceeds 35%. It has been found that a steel sheet having less occurrence of coarse voids can be obtained, and high toughness can be stably imparted thereto through such a process that intermediate cold rolling is performed at a relatively low rolling reduction ratio of 35% or less, then intermediate annealing is performed, and then final finish cold rolling is performed. In this case, it has been confirmed that the finish cold rolling reduction ratio is allowed to be up to approximately 60%. The invention has been achieved based on the knowledge.

[0012] The object can be achieved by a steel sheet: having a chemical composition containing, in terms of percentage by mass, from 0.60 to 1.25% of C, 0.50% or less of Si, from 0.30 to 1.20% of Mn, 0.030% or less of P, 0.030% or less of S, from 0.30 to 1.50% of Cr, from 0.10 to 0.50% of Nb, from 0 to 0.50% of Ti, from 0 to 0.50% of Mo, from 0 to 0.50% of V, from 0 to 2.00% of Ni, and the balance of Fe, with unavoidable impurities; having a metal structure containing a ferrite phase as a metal matrix having dispersed therein cementite particles and particles of a carbide containing one or more kind of Nb and Ti (which may be hereinafter referred to as a "Nb·Ti based carbide"); and having, on a cross sectional surface in parallel to a rolling direction and a thickness direction (i.e., an L cross section), a number density of the Nb·Ti based carbide particles having a circle equivalent diameter of 0.5 μm or more of from 3,000 to 9,000 per mm^2 and a number density of voids having a circle equivalent diameter of 1.0 μm or more of 1,250 per mm^2 or less. Herein, Ti, Mo, V, and Ni are arbitrary additional elements. The steel sheet may have a thickness, for example, of from 0.2 to 4.0 mm.

[0013] The "Nb·Ti based carbide" referred herein is a hard carbide containing one kind or two kinds of Nb and Ti as a metal element constituting the carbide. Examples of the type of Nb·Ti based carbide include a type mainly containing NbC, a type mainly containing TiC, and a type mainly containing (Nb,Ti)C. The invention targets a steel containing a prescribed amount of Nb, and therefore a hard carbide mainly containing NbC is formed in the case where the steel components do not include Ti. The Nb-containing hard carbide that does not contain Ti of this type is also referred to as "Nb·Ti based carbide" in the description herein. In the case where the steel components include Ti, the type mainly containing (Nb,Ti)C is formed, and in addition it is considered that the type mainly containing TiC and the type mainly containing NbC may be mixed therein depending on the Ti content. The steel matrix may also contain spheroidized cementite (Fe_3C) particles. Whether or not a certain carbide is the Nb·Ti based carbide can be confirmed by such an analysis method as EDX (energy dispersive X-ray spectrometry).

[0014] The voids are gaps existing between the surface of the Nb·Ti based carbide particles and the steel matrix. The number density of voids having a circle equivalent diameter of 1.0 μm or more can be obtained in the following manner.

[Method for obtaining Number Density of Voids]

[0015] The observation surface obtained by polishing the cross sectional surface in parallel to the rolling direction and the thickness direction (i.e., the L cross section) is observed with a confocal laser microscope, and on the observation image, the number of voids having a circle equivalent diameter of 1.0 μm or more among the voids adjacent to the Nb·Ti based carbide is counted, and a value obtained by dividing the total count number by the total observation area (mm^2) is designated as the number density (per mm^2) of the voids having a circle equivalent diameter of 1.0 μm or more. Herein, the observation area is 90 μm × 60 μm × 20 view fields. The void that partially protrudes out of the observation view field is designated as an object to be counted in the case where the part thereof appearing inside the view field has a circle equivalent diameter of 1.0 μm or more. The circle equivalent diameter of the void means the diameter of the circle that has the same area as the void on the observation image. The area of the void can be measured by processing the observation image with an image processing software.

[0016] In the steel sheet, the number density of the Nb·Ti based carbide particles having a circle equivalent diameter of 0.5 μm or more is more preferably from 3,000 to 9,000 per mm^2. The number density of the Nb-containing carbide particles can be obtained in the following manner.

[Method for obtaining Number Density of Nb·Ti based Carbide Particles]

[0017] The observation surface obtained by polishing and then etching the cross sectional surface in parallel to the rolling direction and the thickness direction (i.e., the L cross section) is observed with a confocal laser microscope, and on the observation image, the number of Nb·Ti based carbide particles having a circle equivalent diameter of 0.5 μm or more is counted, and a value obtained by dividing the total count number by the total observation area (mm^2) is designated as the number density (per mm^2) of the Nb·Ti based carbide particles having a circle equivalent diameter of 0.5 μm or more. Herein, the observation area is 90 μm × 60 μm × 20 view fields. The Nb·Ti based carbide particle that partially protrudes out of the observation view field is designated as an object to be counted in the case where the part thereof appearing inside the view field has a circle equivalent diameter of 0.5 μm or more. The circle equivalent diameter of the Nb·Ti based carbide particle means the diameter of the circle that has the same area as the Nb·Ti based carbide particle on the observation image. The area of the Nb·Ti based carbide particle can be measured by processing the observation image with an image processing software.

[0018] The steel plate can be produced, for example, by the following method.

[0019] A production method including, in this order:

a step of producing a cast piece while controlling a cooling rate in cooling a molten steel from a liquidus line temperature to a solidus line temperature to from 5 to 20°C/min (casting step);
a step of heating and retaining the cast piece to from 1,200 to 1,350°C for from 0.5 to 4 hours (cast piece heating step);
a step of performing hot rolling (hot rolling step);
a step of, depending on necessity, performing annealing by retaining a hot rolled steel sheet obtained in the hot rolling step at a temperature of 500°C or more and less than an Ac_1 point for from 10 to 50 hours, and then cooling (hot rolled steel sheet annealing step);
a step of performing once or more a procedure including cold rolling at a rolling reduction ratio of 35% or less, and then retaining at a temperature of 500°C or more and less than an Ac_1 point for from 10 to 50 hours and then cooling (intermediate cold rolling annealing step);
a step of performing cold rolling at a rolling reduction ratio of 60% or less (finish cold rolling step); and
a step of, depending on necessity, performing annealing by retaining at from 300 to 500°C for from 1 to 5 hours (stress relief annealing step).

[0020] The rolling reduction ratio is defined by the following expression (1).

$$\text{Rolling reduction ratio (\%)} = (h_0 - h_1) / h_0 \times 100 \quad (1)$$

[0021] Herein, h_0 represents the thickness (mm) before rolling, and h_1 represents the thickness (mm) after rolling.

Advantageous Effects of Invention

[0022] According to the invention, the toughness can be improved for a non-tempered material of a Nb-containing steel. The steel material has both excellent wear resistance and excellent toughness. For a cutlery member, such as a rim saw for mowing fruits, cereals, cotton, and the like, to which a non-tempered material has been applied, the effect of prolonging the lifetime can be obtained through the enhancement of the wear resistance. The deterioration of the toughness, which has been in a trade-off relationship to the enhancement of the wear resistance, can be suppressed.

Description of Embodiments

[Chemical Composition]

[0023] In the description herein, the "%" relating to the component elements of the steel means the "% by mass" unless otherwise indicated.

[0024] C is an element that is necessary for securing the strength of the steel sheet. A steel having a C content of 0.60% or more is targeted herein. An increased C content may increase coarse carbides, which may be a factor deteriorating the toughness. The C content is limited to 1.25% or less.

[0025] Si may be added as a deoxidizing agent in some cases, but a large amount thereof contained may deteriorate the toughness. The Si content is limited to 0.50% or less. The content may be generally controlled to a range of from 0.01 to 0.50%.

[0026] Mn is effective for enhancing the strength of the steel sheet, and a content thereof of 0.30% or more is secured. A large amount of Mn contained may cause hardening of the hot rolled steel sheet, which may be a factor deteriorating the productivity. The Mn content is limited to 1.20% or less, and may be managed to less than 1.00%.

[0027] P and S adversely affect the toughness, and the contents thereof are preferably small. P is limited to 0.030% or less, and S is limited to 0.030% or less. In general, P may be controlled to a range of 0.001% or more, and S may be controlled to a range of 0.0005% or more.

[0028] Cr is effective for enhancing the strength of the steel sheet, and a content thereof of 0.30% or more is secured. A large amount of Cr contained may be a factor deteriorating the toughness. The Cr content is limited to 1.50% or less.

[0029] Nb forms considerably hard Nb·Ti based carbide particles in the steel through cooling process after casting, and contributes to the enhancement of the wear resistance, particularly the abrasive wear resistance. For sufficiently exhibiting the function, a Nb content of 0.10% or more is secured. However, a large amount of Nb added may cause an excessive formation amount of the Nb·Ti based carbide particles, which may be a factor deteriorating the toughness. As a result of the various investigations, the Nb content is necessarily limited to 0.50% or less, and may be managed to 0.45% or less.

[0030] Ti forms considerably hard Nb·Ti based carbide particles in the steel through cooling process after casting, and contributes to the enhancement of the wear resistance, as similar to Nb. Accordingly, Ti may be added depending on necessity. In this case, the Ti content is more effectively 0.01% or more. However, a large amount of Ti added may be a factor deteriorating the toughness. As a result of the various investigations, in the case where Ti is added, the addition thereof is necessarily performed in a content range of 0.50% or less. The Ti content may be managed to 0.30% or less.

[0031] Mo, V, and Ni are elements that are effective for enhancing the toughness. Accordingly, one or more kind thereof may be added depending on necessity. In this case, it is more effective that the content of Mo is 0.10% or more, the content of V is 0.10% or more, and the content of Ni is 0.10% or more. Even though these elements are added excessively, no further effect of enhancing the toughness corresponding to the cost is expected. The content ranges are preferably suppressed to 0.50% or less for Mo, 0.50% or less for V, and 2.00% or less for Ni.

[Metal Structure]

[0032] The invention intends to the achievement of both the wear resistance and the toughness of a non-tempered material, which is not subjected to the structure conditioning using the phase transformation (i.e., a so-called tempering heat treatment) represented by a quenching and tempering treatment and an austempering treatment. Accordingly, the steel sheet according to the invention has a ferrite phase as the metal matrix. The spheroidized cementite particles and the Nb·Ti based carbide particles are dispersed in the metal matrix.

[0033] The steel sheet has a decreased amount of voids occurring in the vicinity of the Nb·Ti based carbide particles in the cold rolling process. Specifically, the number density of voids having a circle equivalent diameter of 1.0 μm or more on the cross sectional surface in parallel to the rolling direction and the thickness direction (i.e., the L cross section) is suppressed to 1,250 per mm^2 or less, and more preferably 1,000 per mm^2 or less. The voids having a circle equivalent diameter of 1.0 μm or more among the voids of this type have been found to be a major factor deteriorating the toughness of the steel sheet that is a non-tempered material. With the Nb content and the Ti content that are suppressed to the proper ranges described above, a significant improvement effect of the toughness can be obtained by restricting the number density of voids having a circle equivalent diameter of 1.0 μm or more to 1,250 per mm^2 or less. The number density of voids having a circle equivalent diameter of 1.0 μm or more is more preferably 1,000 per mm^2 or less. A smaller occurrence of the voids is more advantageous for the improvement of the toughness, but excessive limitation of the voids may be a factor restricting the process for providing a cold rolled product having a proper thickness. In general, the number density of the voids having a circle equivalent diameter of 1.0 μm or more may be in a range of 300 per mm^2 or more. The reduction of the number density of the voids can be achieved, for example, by the production method having inserted thereto an intermediate cold rolling step at a relatively low rolling reduction ratio (which is described later).

[0034] The Nb·Ti based carbide particles exhibit a function enhancing the wear resistance. In particular, it is more effective that the number density of the Nb·Ti based carbide particles having a circle equivalent diameter of 0.5 μm or more is controlled to from 3,000 to 9,000 per mm^2. The number density of the Nb·Ti based carbide particles can be controlled by a known method for optimizing the cooling rate in casting and the heating temperature of the cast piece before hot rolling (for example, the technique described in PTL 5).

[Production Method]

[0035] The wear resistant steel sheet according to the invention can be produced, for example, by the following procedure.

[0036] Casting → Cast piece heating → Hot rolling → (Hot rolled steel sheet annealing) → Intermediate cold rolling → Intermediate annealing → Finish cold rolling → (stress relief annealing)

[0037] In this case, the procedure of the part (Intermediate cold rolling → Intermediate annealing) may be performed once or plural times. In the description herein, the procedure of (Intermediate cold rolling → Intermediate annealing) performed once or plural times is referred to as an "Intermediate cold rolling annealing step". A scale removing step, such as acid cleaning, may be inserted depending on necessity. The steps will be described below.

[Casting and Cast Piece Heating]

[0038] In the casting step, the Nb·Ti based carbide is formed in the cooling process. The size of the Nb·Ti based carbide formed can be controlled by the cooling rate of the cast piece and the cast piece heating temperature. For example, such a method is effective that the cooling rate in cooling the molten steel from the liquidus line temperature to the solidus line temperature is controlled to from 5 to 20°C/min, the retention time in a temperature range of from 1,500°C to 900°C is secured to 30 minutes or more, and the resulting cast piece is heated and retained to from 1,200 to 1,350°C for from 0.5 to 4.0 hours. The heating treatment of the cast piece may be performed by utilizing the heating of the cast piece before hot rolling.

[Hot Rolling and (Hot Rolled Steel Sheet Annealing)]

[0039] The hot rolling condition may be, for example, a finish rolling temperature of from 800 to 900°C and a coiling temperature of 750°C or less. The hot rolled steel sheet annealing may be performed depending on necessity. In the case where the hot rolled steel sheet annealing is performed, a condition of retaining at a temperature range of 500°C or more and less than an Ac_1 point, for example, for from 10 to 50 hours may be adopted. The number density of the Nb·Ti based carbide particle having a circle equivalent diameter of 0.5 μm or more on the L cross section of the steel sheet can be controlled to from 3,000 to 9,000 per mm^2 by the casting and cast piece heating conditions and the hot rolling conditions described above. The number density of the Nb·Ti based carbide particle in this stage is substantially reflected to the steel sheet after the finish cold rolling.

[Intermediate Cold Rolling]

[0040] The sheet material as the intermediate product is subjected to a relatively mild cold rolling at a rolling reduction ratio of 35% or less. This cold rolling is referred to as the "intermediate cold rolling" in the description herein since the cold rolling is performed before the final finish cold rolling. It has been found that the voids are difficult to grow in the finish cold rolling in the case where the intermediate cold rolling reduction ratio is 35% or less. The mechanism therefor has not yet been sufficiently clarified, and can be considered as follows. Specifically, the Nb·Ti based carbide particles do not undergo plastic deformation due to the extremely high hardness thereof, thereby forming voids around the Nb·Ti based carbide particles in cold rolling, but fine voids disappear during annealing, and thus the toughness is not deteriorated in the case where the voids formed are sufficiently small. However, in the case where the intermediate cold rolling reduction ratio exceeds 35%, there are cases where coarse voids that do not disappear during annealing occur, and the voids grow in finish cold rolling to increase the number density of voids having a circle equivalent diameter of 1.0 μm or more, which deteriorate the toughness. This influence is increased by increasing the intermediate cold rolling reduction ratio, and in particular, the toughness is considerably deteriorated when the intermediate cold rolling reduction ratio exceeds 45%. Furthermore, even with the intermediate cold rolling reduction ratio in a range of more than 35% and 45% or less, in the case where the intermediate cold rolling and the intermediate annealing are repeated plural times, such a case is found that the toughness is considerably deteriorated due to the repetition of the stay of the voids that do not disappear during annealing the intermediate annealing and the growth of the voids in cold rolling. Accordingly, the intermediate cold rolling is performed at a rolling reduction ratio in a range of 35% or less for sufficiently removing the voids occurring around the Nb·Ti based carbide particles by annealing. In the intermediate cold rolling, however, it is efficient to secure a rolling reduction ratio, for example, of 10% or more, and the rolling reduction ratio may be managed to 15% or more, but the effect of this step provided may not be sufficiently achieved when the rolling reduction ratio is too low.

[Intermediate Annealing]

[0041] The steel sheet having been subjected to the intermediate cold rolling is subjected to annealing. This annealing is referred to as "intermediate annealing" in the description herein since the annealing is performed before the finish cold rolling. The heating and retaining temperature of the intermediate annealing is 500°C or more and less than the Ac_1 point. The disappearnce of the voids occurring in the intermediate cold rolling sufficiently proceeds by retaining at that temperature. The spheroidization of cementite also proceeds. At a temperature lower than 500°C, the removal of the voids becomes insufficient. The spheroidization of cementite may also become insufficient in some cases. In the case where the temperature is increased to the Ac_1 point or more, an austenite phase is formed to fail to provide a structure state having a ferrite phase as the metal matrix. The heating and retaining time in the intermediate annealing (i.e., the period of time where the material temperature is in a range of 500°C or more and less than the Ac_1 point) is preferably from 10 to 50 hours.

[0042] The procedure of (Intermediate cold rolling → Intermediate annealing) may be performed plural times depending on necessity. In this case, the rolling reduction ratio is 35% or less in each of the intermediate cold rolling, and the heating and retaining temperature and the heating and retaining time in each of the intermediate annealing are as described above.

[Finish Cold Rolling]

[0043] The steel sheet after the intermediate annealing is subjected to cold rolling. This cold rolling is referred to as "finish cold rolling" in the description herein since the cold rolling is a process for decreasing the thickness to the final target thickness. The final cold rolling reduction ratio is necessarily 60% or less. With a rolling reduction ratio larger than this value, voids tend to occur excessively even through the intermediate cold rolling and the intermediate annealing have been performed under the proper conditions. Consequently, it may be difficult to improve stably the toughness of the steel sheet. The finish cold rolling is effective for improving the final shape (flatness) of the steel sheet. For achieving that, a rolling reduction ratio, for example, of 10% or more is preferably secured. The final thickness may be set in a range, for example, of from 0.2 to 4.0 mm.

[Stress Relief Annealing]

[0044] After the finish cold rolling, stress relief annealing may be performed depending on necessity. The strength level can be regulated by controlling the heating temperature and the retention time corresponding to the chemical composition and the finish cold rolling reduction ratio. The heating temperature of the stress relief annealing is set to a range of from 300 to 500°C. The heating and retaining time of the intermediate annealing (i.e., the period of time where the material temperature is in a range of from 300°C to 500°C) is preferably from 1 to 5 hours.

Examples

[0045] Steels having the chemical compositions shown in Table 1 were melted, and test materials of steel sheets were obtained through the procedure of Casting → Cast piece heating → Hot rolling → Intermediate cold rolling → Intermediate annealing → Finish cold rolling → Stress relief annealing.

[0046] In casting, a cast piece was obtained by controlling the cooling rate of the molten steel during cooling from the liquidus line temperature to the solidus line temperature to from 5 to 20°C/min. The cast piece was heated and retained at from 1,250 to 1,350°C for 1 hour and then extracted, and was then subjected to hot rolling. The hot rolling condition was a finish rolling temperature (i.e., a rolling temperature of the final pass of the hot rolling) of 850°C and a coiling temperature of 590°C, and a hot rolled steel sheet having a thickness of 7.0 mm was obtained. For making uniform the thicknesses of the test materials obtained by the experiments with various cold rolling reduction ratios in the later step, the thickness of the hot rolled steel sheet was controlled to 3.1 mm (for 40% rolling), 4.2 mm (for 55% rolling), and 6.3 mm (for 70% rolling) through grinding process, so as to prepare intermediate sheet materials.

[0047] The intermediate sheet materials each were subjected to intermediate cold rolling at a rolling reduction ratio of 20%, and then subjected to intermediate annealing at 550°C for 17 hours. The sheet material after the intermediate annealing was subjected to finish cold rolling at the rolling reduction ratio shown in Table 2, so as to provide a cold rolled steel sheet having a thickness of 1.5 mm. Thereafter, stress relief annealing was performed by retaining at a temperature that was set to a range of from 300 to 450°C to provide a hardness of 32±2 HRC corresponding to the composition and the cold rolling reduction ratio, for 3 hours, and thus the test material was obtained.

Table 1

Steel	Chemical composition (% by mass)											Note
	C	Si	Mn	P	S	Cr	Nb	Ti	Mo	V	Ni	
A	0.85	0.19	0.41	0.009	0.003	0.50	0.17	-	-	-	-	invention steel
B	0.91	0.32	0.55	0.020	0.005	0.82	0.35	0.21	-	-	-	invention steel
C	0.63	0.18	0.97	0.015	0.004	1.27	0.41	-	-	0.33	-	invention steel
D	1.15	0.07	0.78	0.011	0.010	0.73	0.26	-	0.24	-	-	invention steel
E	1.06	0.25	0.36	0.019	0.004	1.06	0.19	0.15	-	-	0.86	invention steel
F	0.85	0.18	0.49	0.016	0.009	0.60	-	-	-	-	-	comparative steel
G	0.46	0.45	0.81	0.019	0.005	0.47	0.24	-	0.12	-	-	comparative steel
H	0.72	0.22	0.63	0.028	0.006	1.13	0.06	0.71	-	-	-	comparative steel
I	0.98	0.14	0.51	0.028	0.006	0.54	0.71	-	-	-	-	comparative steel

Shaded cell: outside the scope of invention

[0048] For each of the test materials, the metal structure on the cross sectional surface in parallel to the rolling direction and the thickness direction (i.e., the L cross section) was observed. As a result, all the test materials each had a metal structure containing a ferrite phase as the metal matrix having dispersed therein the spheroidized cementite particles and the Nb·Ti based carbide particles.

[0049] The L cross section of each of the test materials was observed with a confocal laser microscope (OLS 3000, produced by Olympus Corporation), and the number density of the Nb·Ti based carbide particles having a circle equivalent diameter of 0.5 μm or more and the number density of the voids having a circle equivalent diameter of 1.0 μm or more were measured. The measurement was performed according to the "Method for obtaining Number Density of Nb·Ti based Carbide Particles" and the "Method for obtaining Number Density of Voids" described above. The test materials each were subjected to the wear resistance test and the impact test according to the following manners.

[Wear Resistance Test]

[0050] A test piece having a friction surface having a circular shape with a diameter of 10 mm was cut out from the test material, and tested with a pin-on-disk type wear tester. As a wearing material, WA (alumina) abrasive grains having a grain size of #3000 defined by JIS R6001 was prepared. The abrasive grains were mixed with 300 mL of water per 50 g thereof, so as to prepare a polishing liquid. The test piece was fixed to a specimen holder, and the surface of the test piece was pressed on a flat surface of a rotor having a buffing abrasive cloth adhered onto the surface of a steel circular disk, under a test load F of 5 N, with a sufficient amount of the polishing liquid supplied thereto, and the wear test was performed under condition of a friction speed of 0.4 m/s and a friction length L of 750 m. The volume of the material that was lost through wear was calculated from the difference in thickness of the specimen before and after the test, and was designated as the wear weight reduction W (mm^3). The specific wear amount C ($mm^3/(Nm)$) was obtained according to the following expression (2).

$$\text{Specific wear amount } C = \text{Wear weight loss } W / (\text{Test load } F \times \text{Friction length } L) \qquad (2)$$

[0051] The abrasive grains have a hardness of approximately 1,600 HV. The wear test simulates abrasive wear caused by invasion of fine sand. For a steel material having a hardness regulated to 32±2 HRC, a specific wear amount C of 5.0×10^{-4} mm^3/Nm or less by this test can be judged as having excellent wear resistance. Accordingly, a specimen that had a specific wear amount C of 5.0×10^{-4} $mm^3/(Nm)$ or less by this test was judged as pass (good wear resistance).

[Impact Test]

[0052] From each of the test materials, a 2 mm U-notch impact test piece (length of test piece: 55 mm, height of test piece: 10 mm, width of test piece (thickness) : 1.5 mm, impact direction: rolling direction) was produced, and measured for the Charpy impact value at ordinary temperature (23°C) by a method according to JIS Z2242:2005. The number of tests n was 5, and the lowest value (worst value) among them was designated as the impact value of the test material. In consideration of the use as a material of a high-speed rotation cutlery member (such as a rim saw for mowing agricultural products), to which a non-tempered material can be applied, the impact value by this test is desirably 50 J/cm^2 or more. Accordingly, a specimen that had an impact value of 50 J/cm^2 or more by this test was judged as pass (good toughness).

Table 2

No.	Steel	Finish cold rolling reduction ratio (%)	Number density of Nb·Ti based carbide of 0.5 μm or more (per mm²)	Number density of voids of 1.0 μm or more (per mm²)	Wear resistance	Toughness	Class
					Specific wear amount (× 10^{-4} $mm^3/(Nm)$)	Impact value (J/cm^2)	
1	A	40	3129	372	4.56	88	example of invention
2	A	55	3108	704	4.82	84	example of invention
3	B	40	7216	455	3.90	70	example of invention
4	B	55	7212	861	3.88	58	example of invention
5	B	70	7208	1394	3.90	44	comparative example
6	C	40	5133	313	4.36	81	example of invention
7	C	55	5126	592	4.27	76	example of invention
8	D	40	5845	525	4.08	63	example of invention
9	D	55	5810	992	3.90	54	example of invention
10	D	70	5820	1607	4.02	43	comparative example
11	E	40	6037	478	4.38	70	example of invention
12	E	55	6001	904	4.37	60	example of invention
13	E	70	6012	1465	4.37	45	comparative example
14	F	40	0	366	7.26	94	comparative example
15	F	55	0	692	7.46	91	comparative example
16	F	70	0	1121	7.25	83	comparative example
17	G	40	2495	206	6.07	98	comparative example
18	G	55	2481	390	5.95	96	comparative example
19	G	70	2488	631	5.83	87	comparative example
20	H	55	9829	1299	3.55	44	comparative example
21	H	70	9803	2104	3.46	25	comparative example
22	I	55	10744	1282	3.48	29	comparative example
23	I	70	10692	2077	3.25	10	comparative example

Shaded cell: outside the scope of invention
Underline: insufficient property

[0053] The materials of the invention had less voids, and were excellent in toughness and excellent in wear resistance. Accordingly, for a non-tempered material, a non-tempered material having both excellent wear resistance and excellent roughness was achieved.

[0054] On the other hand, Nos. 5, 10, and 13 as comparative examples had an increased amount of voids having a circle equivalent diameter of 1.0 μm or more due to the high finish cold rolling reduction ratio, and were inferior in toughness. Nos. 14 to 16 as comparative examples contained no hard Nb·Ti based carbide formed due to the use of the steel containing no Nb, and were inferior in wear resistance. Nos. 17 to 19 as comparative examples were insufficient in formation of the hard Nb·Ti based carbide due to the use of the steel having a small C content, and were insufficient in enhancement of the wear resistance. In Nos. 20 and 21 using the steel having an excessive Ti content and Nos. 22 and 23 using the steel having an excessive Nb content, the amount of the Nb·Ti based carbide formed was large, and associated thereto, the amount of voids having a circle equivalent diameter of 1.0 μm was increased. As a result, the toughness was not improved.

Claims

1. A steel sheet: having a chemical composition containing, in terms of percentage by mass, from 0.60 to 1.25% of C, 0.50% or less of Si, from 0.30 to 1.20% of Mn, 0.030% or less of P, 0.030% or less of S, from 0.30 to 1.50% of Cr, from 0.10 to 0.50% of Nb, from 0 to 0.50% of Ti, from 0 to 0.50% of Mo, from 0 to 0.50% of V, from 0 to 2.00% of Ni, and the balance of Fe, with unavoidable impurities; having a metal structure containing a ferrite phase as a metal matrix having dispersed therein cementite particles and particles of a carbide containing one or more kind of Nb and Ti (which is hereinafter referred to as a "Nb·Ti based carbide"); and having, on a cross sectional surface in parallel to a rolling direction and a thickness direction (i.e., an L cross section), a number density of the Nb·Ti based carbide particles having a circle equivalent diameter of 0.5 μm or more of from 3,000 to 9,000 per mm^2 and a number density of voids having a circle equivalent diameter of 1.0 μm or more of 1,250 per mm^2 or less.

2. A method for producing the steel sheet according to claim 1, comprising, in this order:

   a step of producing a cast piece while controlling a cooling rate in cooling a molten steel from a liquidus line temperature to a solidus line temperature to from 5 to 20°C/min (casting step);
   a step of heating and retaining the cast piece to from 1,200 to 1,350°C for from 0.5 to 4 hours (cast piece heating step);
   a step of performing hot rolling (hot rolling step);
   a step of performing once or more a procedure including cold rolling at a rolling reduction ratio of 35% or less, and then retaining at a temperature of 500°C or more and less than an Ac_1 point for from 10 to 50 hours and then cooling (intermediate cold rolling annealing step); and
   a step of performing cold rolling at a rolling reduction ratio of 60% or less (finish cold rolling step).

3. The method for producing the steel sheet according to claim 2, further comprising, between the hot rolling step and the intermediate cold rolling and annealing step:
   a step of performing annealing by retaining a hot rolled steel sheet obtained in the hot rolling step at a temperature of 500°C or more and less than an Ac_1 point for from 10 to 50 hours, and then cooling (hot rolled steel sheet annealing step).

4. The method for producing the steel sheet according to claim 2 or 3, further comprising, after the finish cold rolling step:
   a step of performing annealing by retaining at from 300 to 500°C for from 1 to 5 hours (stress relief annealing step) .

INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2017/030614

A. CLASSIFICATION OF SUBJECT MATTER
Int.Cl. C22C38/00(2006.01)i, C21D9/46(2006.01)i, C22C38/50(2006.01)i

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)
Int.Cl. C22C38/00-C22C38/60, C21D8/02, C21D9/46

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Published examined utility model applications of Japan	1922-1996
Published unexamined utility model applications of Japan	1971-2017
Registered utility model specifications of Japan	1996-2017
Published registered utility model applications of Japan	1994-2017

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.
A	JP 2015-190037 A (NISSHIN STEEL CO., LTD.) 02 November 2015 (Family: none)	1-4
A	JP 2011-12316 A (NIPPON STEEL CORPORATION) 20 January 2011 (Family: none)	1-4
A	JP 2001-59128 A (NISSHIN STEEL CO., LTD.) 06 March 2001 (Family: none)	1-4

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

* Special categories of cited documents:
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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
10.11.2017	28.11.2017

Name and mailing address of the ISA/	Authorized officer
Japan Patent Office 3-4-3, Kasumigaseki, Chiyoda-ku, Tokyo 100-8915, Japan	Telephone No.

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2017/030614

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 2009-215612 A (NISSHIN STEEL CO., LTD.) 24 September 2009 (Family: none)	1-4
A	JP 2016-222990 A (NIPPON STEEL & SUMITOMO METAL CORPORATION) 28 December 2016 (Family: none)	1-4
A	CN 103173685 A (BAOSTEEL GROUP XINJIANG BAYI IRON & STEEL CO., LTD.) 26 June 2013 (Family: none)	1-4
E, X	JP 2017-190494 A (NISSHIN STEEL CO., LTD.) 19 October 2017 (Family: none)	1-4

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REFERENCES CITED IN THE DESCRIPTION

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- JP 2003201536 A **[0009]**
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- JP 60082647 A **[0009]**
- JP 2010138453 A **[0009]**
- JP 2013136820 A **[0009]**