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(54) Titre : TOLE D’ACIER A HAUTE RESISTANCE ET TUYAU D’ACIER A HAUTE RESISTANCE A DEFORMABILITE EXCELLENT ET METHODE DE FABRICATION

(54) Title: HIGH-STRENGTH STEEL SHEET AND HIGH-STRENGTH STEEL PIPE EXCELLENT IN DEFORMABILITY AND METHOD FOR PRODUCING THE SAME

(57) Abrégé/Abstract:
The present invention provides a line pipe of the API standard X60 to X100 class, the line pipe having excellent deformability as well as excellent low temperature toughness and high productivity, a steel plate used as the material of the steel pipe, and methods for producing the steel pipe and the steel plate. In particular, a high-strength steel plate excellent in deformability wherein a ferrite phase is dispersed finely and accounts for 5 to 40% in area percentage in a low temperature transformation structure mainly composed of a bainite phase and most grain sizes of the ferrite phase are smaller than the average grain size of the bainite phase; a high-strength steel pipe excellent in deformability, in particular, a large diameter steel pipe produced through forming the steel plate into a pipe shape, the steel pipe having the aforementioned structure and satisfying the conditions that YS/TS is 0.95 or less and YS x uEL is 5,000 or more; and methods for producing the steel plate and the steel pipe.
HIGH-STRENGTH STEEL SHEET AND HIGH-STRENGTH STEEL PIPE EXCELLENT IN DEFORMABILITY AND METHOD FOR PRODUCING THE SAME

ABSTRACT OF THE DISCLOSURE

The present invention provides a line pipe of the API standard X60 to X100 class, the line pipe having excellent deformability as well as excellent low temperature toughness and high productivity, a steel plate used as the material of the steel pipe, and methods for producing the steel pipe and the steel plate: in particular, a high-strength steel plate excellent in deformability wherein a ferrite phase is dispersed finely and accounts for 5 to 40% in area percentage in a low temperature transformation structure mainly composed of a bainite phase and most grain sizes of the ferrite phase are smaller than the average grain size of the bainite phase; a high-strength steel pipe excellent in deformability, in particular, a large diameter steel pipe produced through forming the steel plate into a pipe shape, the steel pipe having the aforementioned structure and satisfying the conditions that YS/TS is 0.95 or less and YS x uEL is 5,000 or more; and methods for producing the steel plate and the steel pipe.
BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to a steel pipe widely usable as a line pipe for transporting natural gas and crude oil and having a large tolerance for deformation of a pipeline caused by ground movement and the like, and to a steel sheet used as the material of the steel pipe.

2. Description of the Related Art

The importance of pipelines as a means of long-distance transportation of crude oil and natural gas has increased over the years. However, as the environment in which pipelines are constructed has diversified, problems have arisen in relation to the displacement and bending of pipelines in frozen soil regions caused by seasonal fluctuation of a ground level, the bending of pipelines laid on sea bottoms caused by water current, the displacement of pipelines caused by seismic ground movement and so forth. As a consequence, a steel pipe excellent in deformability and not susceptible to buckling and the like in the case of deformation has been sought. A large uniform elongation and a large work hardening coefficient are generally regarded as indices of good deformability.

As disclosed in Japanese Unexamined Patent Publication No. S63-286517 "Method for Producing Low-yield-ratio, High-tensile Steel", Japanese Unexamined Patent Publication No. H11-279700 "Steel Pipe Excellent in Buckling Resistance and Method for Producing the Same" and so on, methods have already been proposed for lowering a yield ratio (raising a work hardening coefficient) by rolling and then cooling, in air to the $\text{Ar}_3$ transformation temperature or below, to form ferrite
and then performing rapid cooling to form a dual-phase structure. The proposed methods are, however, unsuitable for a line pipe material of which good low temperature toughness is required, and, what is more, they involve another problem of low productivity when a process of cooling in air is included. In view of such a situation, a line pipe having a good deformability (a large uniform elongation), with high productivity to allow use for long-distance pipelines and low temperature toughness to allow use in cold regions not impaired, has been sought.

SUMMARY OF THE INVENTION

The present invention provides a line pipe of the API standard X60 to X100 class, the line pipe having excellent deformability as well as excellent low temperature toughness and high productivity, a steel plate used as the material of the steel pipe, and methods for producing the steel pipe and the steel plate.

The gist of the present invention, which is presented for solving the above problems, is as follows:

(1) A high-strength steel plate excellent in deformability, characterized in that: a ferrite phase is dispersed finely and accounts for 5 to 40% in area percentage in a low temperature transformation structure mainly composed of a bainite phase; and most grain sizes of the ferrite phase are smaller than the average grain size of said bainite phase.

(2) A high-strength steel plate excellent in deformability according to the item (1), characterized in that said steel plate contains, in its chemical composition, in mass:

C: 0.03 to 0.12%,
Si: 0.8% or less,
Mn: 0.8 to 2.5%,
P: 0.03% or less,
S: 0.01% or less,
Nb: 0.01 to 0.1%,
Ti: 0.005 to 0.03%,
Al: 0.1% or less, and
N: 0.008% or less,
so as to satisfy the expression Ti - 3.4N ≥ 0; and, in addition, one or more of
Ni: 1% or less,
Mo: 0.6% or less,
Cr: 1% or less,
Cu: 1% or less,
V: 0.1% or less,
Ca: 0.01% or less,
REM: 0.02% or less, and
Mg: 0.006% or less;
with the balance consisting of iron and unavoidable impurities.

(3) A high-strength steel pipe excellent in deformability, characterized in that: the ratio (YS/TS) of yield strength (YS) to tensile strength (TS) is 0.95 or less; and the product (YS x uEL) of yield strength (YS) and uniform elongation (uEL) is 5,000 or more.

(4) A high-strength steel pipe excellent in deformability according to the item (3), characterized in that the base material of said steel pipe has a structure wherein: a ferrite phase is dispersed finely and accounts for 5 to 40% in area percentage in a low temperature transformation structure mainly composed of a bainite phase; and that most grain sizes of the ferrite phase are smaller than the average grain size of said bainite phase.

(5) A high-strength steel pipe excellent in deformability according to the item (3) or (4), characterized in that the base material of said steel pipe contains, in its chemical composition in mass:
C: 0.03 to 0.12%,
Si: 0.8% or less,
Mn: 0.8 to 2.5%,
P: 0.03% or less,
S: 0.01% or less,
Nb: 0.01 to 0.1%,
Ti: 0.005 to 0.03%,
Al: 0.1% or less, and
N: 0.008% or less,
so as to satisfy the expression Ti - 3.4N ≥ 0; and,
in addition, one or more of
Ni: 1% or less,
Mo: 0.6% or less,
Cr: 1% or less,
Cu: 1% or less,
V: 0.1% or less,
Ca: 0.01% or less,
REM: 0.02% or less, and
Mg: 0.006% or less;
with the balance consisting of iron and unavoidable impurities.

(6) A method for producing a high-strength steel plate excellent in deformability, characterized by subjecting a steel slab, the steel slab containing, in mass:
C: 0.03 to 0.12%,
Si: 0.8% or less,
Mn: 0.8 to 2.5%,
P: 0.03% or less,
S: 0.01% or less,
Nb: 0.01 to 0.1%,
Ti: 0.005 to 0.03%,
Al: 0.1% or less, and
N: 0.008% or less,
so as to satisfy the expression Ti - 3.4N ≥ 0; and,
in addition, one or more of
Ni: 1% or less,
Mo: 0.6% or less,
Cr: 1% or less,
Cu: 1% or less,
V: 0.1% or less,
Ca: 0.01% or less,
REM: 0.02% or less, and
Mg: 0.006% or less;
with the balance consisting of iron and unavoidable
impurities, to a group of processes comprising the steps
of: reheating to the austenitic temperature range;
thereafter, rough rolling within the recrystallization
temperature range; subsequently, finish rolling at a
cumulative reduction ratio of 50% or more within the
unrecrystallization temperature range of 900°C or lower;
lightly accelerated cooling at a cooling rate of 5 to
20°C/sec. from a temperature not lower than the Ar,
transformation point to a temperature of 500°C to 600°C;
and, immediately thereafter, heavily accelerated cooling
at a cooling rate of 15°C/sec. or more and greater than
the cooling rate of the previous cooling to a temperature
not higher than 300°C.

(7) A method for producing a high-strength steel
plate excellent in deformability, characterized by
subjecting a steel slab, the steel slab containing, in mass:

C: 0.03 to 0.12%,
Si: 0.8% or less,
Mn: 0.8 to 2.5%,
P: 0.03% or less,
S: 0.01% or less,
Nb: 0.01 to 0.1%,
Ti: 0.005 to 0.03%,
Al: 0.1% or less, and
N: 0.008% or less,
so as to satisfy the expression Ti - 3.4N ≥ 0; and,
in addition, one or more of
Ni: 1% or less,
Mo: 0.6% or less,
Cr: 1% or less,
Cu: 1% or less,
V: 0.1% or less,
Ca: 0.01% or less,
REM: 0.02% or less, and
Mg: 0.006% or less;

with the balance consisting of iron and unavoidable

impurities, to a group of processes comprising the steps
of: reheating to the austenitic temperature range;
thereafter, rough rolling within the recrystallization
temperature range; subsequently, finish rolling at a
cumulative reduction ratio of 50% or more within the
unrecrystallization temperature range of 900°C or lower;
lightly accelerated cooling at a cooling rate of 5 to
20°C/sec. from a temperature not lower than the Ar1
transformation point to a temperature of 500°C to 600°C;
then, after holding the rolled steel plate at a constant
temperature or letting it cool in air for 30 sec. or
less, heavily accelerated cooling at a cooling rate of
15°C/sec. or more and greater than the cooling rate of
the previous cooling to a temperature not higher than
300°C.

(8) A method for producing a high-strength steel
pipe excellent in deformability, characterized by,

further: forming a steel sheet produced by either of the
methods according to the items (6) and (7) into a pipe
shape; and then welding the seam portion.

(9) A method for producing a high-strength steel
pipe excellent in deformability, characterized in that
the pipe production method in the item (8) is the UOE
process.

(10) A method for producing a high-strength steel
pipe excellent in deformability, characterized in that
the pipe production method in the item (8) is the bending
roll method.

(11) A method for producing a high-strength hot-
rolled steel strip excellent in deformability,

characterized by subjecting a steel slab, the steel slab
containing, in mass:

C: 0.03 to 0.12%,
Si: 0.8% or less,
Mn: 0.8 to 2.5%,
P: 0.03% or less,
S: 0.01% or less,

5

Nb: 0.01 to 0.1%,
Ti: 0.005 to 0.03%,
Al: 0.1% or less, and
N: 0.008% or less,

so as to satisfy the expression Ti - 3.4N ≥ 0; and, in addition, one or more of

10

Ni: 1% or less,
Mo: 0.6% or less,
Cr: 1% or less,
Cu: 1% or less,

15

V: 0.1% or less,
Ca: 0.01% or less,
REM: 0.02% or less, and
Mg: 0.006% or less;

with the balance consisting of iron and unavoidable impurities, to a group of processes comprising the steps of: reheating to the austenitic temperature range; thereafter, rough rolling within the recrystallization temperature range; subsequently, finish rolling at a cumulative reduction ratio of 50% or more within the unrecrystallization temperature range of 900°C or lower; lightly accelerated cooling at a cooling rate of 5 to 20°C/sec. from a temperature not lower than the Ar₃ transformation point to a temperature of 500°C to 600°C; thereafter, heavily accelerated cooling at a cooling rate of 15°C/sec. or more to a temperature not higher than 300°C; and then coiling.

(12) A method for producing a high-strength steel pipe excellent in deformability, characterized by, further: continuously forming a hot-rolled steel strip produced by the method according to the item (11) into a cylindrical shape by the roll forming method; and then welding the butt portion by high-frequency resistance
welding or laser welding.

(13) A steel plate having tensile strength in the width direction of 517 MPa to 990 MPa comprising, in its chemical composition by mass,

C: 0.03 to 0.12%,
Si: 0.8% or less,
Mn: 0.8 to 2.5%,
P: 0.03% or less,
S: 0.01% or less,

Nb: 0.01 to 0.1%,
Ti: 0.005 to 0.03%,
Al: 0.1% or less, and
N: 0.008% or less,

so as to satisfy the expression

Ti - 3.4N ≥ 0, and one or more of:

Ni: 1% or less,
Mo: 0.6% or less,
Cr: 1% or less,
Cu: 1% or less,

V: 0.1% or less,
Ca: 0.01% or less,
REM: 0.02% or less, and
Mg: 0.006% or less, and

the balance being Fe and unavoidable impurities, wherein the steel plate has a high degree of deformability and comprises a low-temperature transformation structure having a ferrite phase which is composed of first grains and a bainite phase which is composed of second grains, the ferrite phase being finely dispersed and accounting for 5 to 40% in area percentage of the structure, wherein the sizes of the first grains are smaller than an average size of the second grains.
(14) A steel pipe having tensile strength in the circumferential direction of 517 MPa to 990 MPa comprising, in its chemical composition by mass,

\[
\begin{align*}
C &: \text{ 0.03 to 0.12}\%, \\
Si &: \text{ 0.8\% or less,} \\
Mn &: \text{ 0.8 to 2.5\%,} \\
P &: \text{ 0.03\% or less,} \\
S &: \text{ 0.01\% or less,} \\
Nb &: \text{ 0.01 to 0.1\%,} \\
Ti &: \text{ 0.005 to 0.03\%,} \\
Al &: \text{ 0.1\% or less, and} \\
N &: \text{ 0.008\% or less,} \\
\end{align*}
\]

so as to satisfy the expression

\[\text{Ti} - 3.4N \geq 0,\] 

and one or more of:

\[
\begin{align*}
\text{Ni} &: \text{ 1\% or less,} \\
\text{Mo} &: \text{ 0.6\% or less,} \\
\text{Cr} &: \text{ 1\% or less,} \\
\text{Cu} &: \text{ 1\% or less,} \\
\text{V} &: \text{ 0.1\% or less,} \\
\text{Ca} &: \text{ 0.01\% or less,} \\
\text{REM} &: \text{ 0.02\% or less, and} \\
\text{Mg} &: \text{ 0.006\% or less, and} \\
\end{align*}
\]

the balance being Fe and unavoidable impurities, wherein the steel pipe has a high degree of deformability wherein at least one portion has a ratio of yield strength (MPa) to tensile strength (MPa) of at most 0.95 and a yield strength (MPa) multiplied by uniform elongation (%) (YS x uEL) value of at least 5,000.
BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1(a) is a micrograph of the steel plate of the comparative example No. 15 described in Example.

Fig. 1(b) is a micrograph of the steel plate of the invention example No. 2.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention is hereafter explained in detail.

For realizing high deformability, it is essential, as stated in relation to the conventional technologies, to obtain a dual-phase structure wherein a soft phase exists in the structure of a steel material; this constitutes a basic principle. As a result of examining the problems of conventional technologies in detail, however, the present inventors have made it clear that, when a steel material was cooled in air to the Ar transformation point or below after rolling, coarse ferrite or lamellar ferrite formed and that caused separation to occur at a Charpy test fracture surface, and, as a consequence, absorbed energy decreased. (For reference, in Fig. 1(a), dark grains represent ferritic structure and gray portions represent bainitic structure. An identical structure is formed also when a steel plate is produced in the same manner as the comparative examples described later in the Examples.) Furthermore, the present inventors found that the conventional technologies required waiting until a steel plate was cooled in air to a prescribed temperature and thus they were inapplicable to the case of producing a large amount of product such as a line pipe.

The present inventors further devotedly studied methods for obtaining a dual-phase structure composed of a ferrite phase and a bainite phase and, as a result, discovered that: when a steel was cooled at a particular cooling rate, comparatively fine ferrite formed inside crystal grains and at grain boundaries; when the steel
was rapidly cooled thereafter to form a low temperature transformation structure mainly composed of a bainite phase, the difference in hardness between the structure thus obtained and the ferrite phase became large; and, as a result, both a high uniform elongation and a high strength could be realized and, in addition, the separation at a Charpy test was suppressed and a high absorbed energy could be obtained.

In order to avoid the deterioration of low temperature toughness, it is necessary that dispersed ferrite exists as shown in Fig. 1(b); neither the coarse ferrite nor the ferrite existing in the form of lamellar tiers. Here, it is necessary for most of the ferrite grains to be finer than the bainite grains that constitute the matrix phase; otherwise, the deterioration of toughness caused by the formation of ferrite becomes conspicuous. Here, that most of the ferrite grains are finer than the bainite grains that constitute the matrix phase means that the percentage of the ferrite grains larger than the average size of bainite grains is 10% or less in the ferrite phase.

In terms of actual numerical size, a desirable condition is that most of ferrite grains are several micrometers in size, mostly 10 μm or less. For reference, in Fig. 1(b), the portion encircled by a white solid line shows the grain size of the bainitic structure and the black particles are ferrite grains. This constitution is identical to the one obtained in an invention example in the Examples as described later. If the amount of a ferrite phase is below 5% in terms of area percentage, the effect of improving uniform elongation is not obtained but, if its amount is so large as to exceed 40%, high strength is not realized. For this reason, the area percentage of a ferrite phase is defined to be 5 to 40%.

Next, the reasons for limiting the amounts of the component chemical elements are explained hereafter. Any
of the amounts of the component chemical elements in the
description below is in mass percentage.

The amount of C is limited to 0.03 to 0.12%. Carbon
is very effective for increasing steel strength and, for
obtaining a desired strength, it must be added to at
least 0.03%. When the amount of C is too large, however,
low temperature toughness of a base material and a HAZ
and weldability are remarkably deteriorated, and, for
this reason, the upper limit of the amount of C is set at
0.12%. The larger the amount of C, the higher the
uniform elongation becomes, and, the smaller the amount
of C, the better the low temperature toughness and
weldability become. Thus, it is necessary to decide the
amount of C in consideration of a balance of required
characteristics.

Si is an element to be added for deoxidation and the
improvement of strength. However, when it is added in a
large quantity, HAZ toughness and field weldability are
remarkably deteriorated, and, for this reason, the upper
limit of its amount is set at 0.8%. Steel can be well
deoxidized using Al or Ti and, in this sense, it is not
always necessary to add Si, but, for stably obtaining a
deoxidizing effect, it is preferable to add Al, Ti and Si
by 0.01% or more in terms of a total content.

Mn is an indispensable element for making the
microstructure of the matrix phase of a steel according
to the present invention a structure mainly composed of
bainite and securing a good balance between strength and
low temperature toughness, and, for this reason, the
lower limit of its content is set at 0.8%. When the
amount of Mn is too large, however, it becomes difficult
to form ferrite in a dispersed manner, and, for this
reason, its upper limit is set at 2.5%.

Besides the above, a steel according to the present
invention contains Nb of 0.01 to 0.10% and Ti of 0.005 to
0.030% as obligatory elements.

Nb not only inhibits the recrystallization of
austenite during controlled rolling and forms a fine structure, but also contributes to the enhancement of hardenability and thus renders steel strong and tough. When the addition amount of Nb is too large, however, HAZ toughness and field weldability are adversely affected, and, for this reason, the upper limit of its amount is set at 0.10%.

Ti forms fine TiN, inhibits the coarsening of austenite grains during slab reheating and at a HAZ, thus makes a microstructure fine and improves the low temperature toughness of a base material and a HAZ. It also has a function of fixing solute N in the form of TiN. For these purposes, Ti is added by an amount equal to or larger than 3.4N (in mass %). Besides, when the amount of Al is small (0.005% or less, for instance), Ti brings about the effects of forming oxides, having the oxides act as nuclei for the formation of intra-granular ferrite in a HAZ and making the structure of the HAZ fine. For obtaining those effects of TiN, an addition of Ti to at least 0.005% is required. When the amount of Ti is too large, however, TiN becomes coarse and/or the precipitation hardening caused by TiC occurs, deteriorating low temperature toughness. For this reason, the upper limit of its content is set at 0.030%.

Al is an element usually contained in steel as a deoxidizing agent. It is effective also for making a structure fine. However, when the amount of Al exceeds 0.1%, Al-type nonmetallic inclusions increase, adversely affecting steel cleanliness, and, for this reason, the upper limit of its content is set at 0.1%. Steel can be deoxidized using Ti or Si, and, in this sense, it is not always necessary to add Al, but, for stably obtaining a deoxidizing effect, it is desirable to add Si, Ti and Al by 0.01% or more in terms of a total content.

N forms TiN and inhibits the coarsening of austenite grains during slab reheating and at a HAZ and, thus, improves the low temperature toughness of a base material
and a HAZ. It is desirable that the minimum N amount required for obtaining this effect is 0.001%. However, when solute N exists, dislocations are fixed by the effect of aging caused by the strain of forming work, and a yield point and yield point elongation come to appear clearly at a tensile test, significantly lowering deformability. It is therefore necessary to fix N in the form of TiN. When the amount of N is too large, TiN increases excessively and drawbacks such as surface defects and deterioration of toughness occur. For this reason, it is necessary to set the upper limit of its content at 0.008%.

Further, in the present invention, the amounts of P and S, which are impurity elements, are restricted to 0.03% or less and 0.01% or less, respectively. This is mainly for the purpose of enhancing the low temperature toughness of a base material and a HAZ yet more. A reduction in the amount of P not only decreases the center segregation of a continuously cast slab but also prevents intergranular fracture and, thus, improves low temperature toughness. In the meantime, a reduction in the amount of S has the effects of reducing MnS, which is elongated during hot rolling, and improving ductility and toughness. It is therefore desirable to make the amounts of both P and S as small as possible. However, the amounts of these elements must be determined in consideration of the balance between required product characteristics and costs for their reduction.

Next, the purposes in adding Ni, Mo, Cr, Cu, V, Ca, REM and Mg are explained.

The principal purposes in adding these elements to basic component elements are to increase strength and toughness yet more and expand the size of the steel materials that can be produced, without hindering the excellent characteristics of the present invention. Therefore, the addition amounts of these elements should be restricted as a matter of course.
The purpose in adding Ni is to improve the low temperature toughness and field weldability of a steel according to the present invention, the steel having a low carbon content. The addition of Ni has less effect than the addition of Mn, Cr or Mo in forming a hardened structure harmful to low temperature toughness in a rolled structure (in particular, in the center segregation band of a continuously cast slab). When the addition amount of Ni is too large, however, not only economical efficiency is lowered but also HAZ toughness and field weldability are deteriorated, and, for this reason, the upper limit of its addition amount is set at 1.0%. The addition of Ni is effective also for preventing the Cu-induced cracking during continuous casting and hot rolling. For obtaining this effect, it is necessary to add Ni by not less than one third of a Cu amount. Note that Ni is an optional element and its addition is not obligatory but, to realize the effects of the Ni addition as described above stably, it is desirable to set the lower limit of its content at 0.1%.

The purpose in adding Mo is to improve steel hardenability and obtain high strength. Mo is effective also for inhibiting the recrystallization of austenite during controlled rolling and forming a fine austenitic structure, when added together with Nb. However, an excessive addition of Mo deteriorates HAZ toughness and field weldability and makes it difficult to form ferrite in a dispersed manner. For this reason, the upper limit of its amount is set at 0.6%. Note that Mo is an optional element and its addition is not obligatory but, for realizing the effects of the Mo addition as described above stably, it is desirable to set the lower limit of its content at 0.06%.

Cr increases the strength of a base material and a weld, but, when added excessively, it significantly deteriorates HAZ toughness and field weldability. For this reason, the upper limit of Cr amount is set at 1.0%.
Note that Cr is an optional element and its addition is not obligatory but, to realize the effects of the Cr addition as described above stably, it is desirable to set the lower limit of its content at 0.1%.

Cu increases the strength of a base material and a weld, but, when added excessively, it significantly deteriorates HAZ toughness and field weldability. For this reason, the upper limit of Cu amount is set at 1.0%.

Note that Cu is an optional element and its addition is not obligatory but, to realize the effects of the Cu addition as described above stably, it is desirable to set the lower limit of its content at 0.1%.

V has nearly the same effects as Nb does, but its effects are weaker than the effects of Nb. It also has an effect of inhibiting the softening of a weld. The upper limit of 0.10% is permissible from the viewpoints of HAZ toughness and field weldability, but a particularly desirable range of its addition is from 0.03 to 0.08%.

Ca and REM control the shape of sulfides (MnS) and improve low temperature toughness (the increase in an absorbed energy at a Charpy test, and so on). When Ca or REM is added in excess of 0.006 or 0.02%, respectively, a large amount of CaO-CaS or REM-CaS is formed and the compound forms large clusters or large inclusions, not only deteriorating steel cleanliness but also adversely affecting field weldability. For this reason, the upper limits of the addition of Ca and REM are set at 0.006 and 0.02%, respectively. In case of an ultra-high-strength line pipe, it is particularly effective to lower the amounts of S and O to 0.001% or less and 0.002% or less, respectively, and control the value of ESSP, which is defined as \( \text{ESSP} = (\text{Ca}) (1 - 124(\text{O}) ) / 1.25\text{S} \), so that the expression \( 0.5 \leq \text{ESSP} \leq 10.0 \) may be satisfied.

Note that Ca and REM are optional elements and their addition is not obligatory but, to realize the effects of the addition of Ca and REM as described above stably, it
is desirable to set the lower limits of the contents of Ca and REM at 0.001 and 0.002%, respectively.

Mg forms finely dispersed oxides, inhibits the grain coarsening in a weld heat-affected zone, and thus improves low temperature toughness. However, when added by 0.006% or more, it forms coarse oxides and inversely deteriorates toughness.

Note that Mg is an optional element and its addition is not obligatory but, to realize the effects of the Mg addition as described above stably, it is desirable to set the lower limit of its content at 0.0006%.

Even if a steel has a chemical composition as described above, a desired structure is not obtained unless appropriate production conditions are adopted. Theoretically, the method for obtaining a bainitic structure in which fine ferrite is dispersed is: to form austenite grains flattened in the thickness direction by processing recrystallized grains within an unrecrystallization temperature range; and to cool the steel at a cooling rate that allows ferrite to form in fine grains and then to transform the rest of the structure into a low temperature transformation structure by rapidly cooling. A structure obtained by low temperature transformation of a steel of this kind is generally referred to as bainite, bainitic ferrite or the like, but here it is collectively referred to as bainite.

A steel slab having a chemical composition specified in the present invention is reheated to the austenite temperature range of about 1,050°C to 1,250°C, then rough-rolled within the recrystallization temperature range, and subsequently finish-rolled so that the cumulative reduction ratio is 50% or more within the unrecrystallization temperature range of 900°C or lower temperatures. Then, the rolled steel plate is subjected to moderately accelerated cooling, as the first stage of cooling, at a cooling rate of about 5 to 20°C/sec. from a temperature not lower than the Ar, transformation point
to a temperature of 500°C to 600°C, and, by so doing, fine ferrite forms in a dispersed manner. A cooling rate under which fine ferrite is formed in a dispersed manner varies depending on the chemical composition of a steel, but the cooling rate can be determined by confirming beforehand with a simple test rolling applied to each steel grade. As the formation of ferrite is completed at 500°C to 600°C in the moderately accelerated cooling of the first stage cooling, a low temperature transformation structure mainly composed of a bainite phase is obtained by, further, subjecting the steel sheet to rapid accelerated cooling and having the rest of the structure transform at a low temperature. For obtaining a dual-phase structure composed of a ferrite phase and a bainite phase, it is necessary to make the cooling rate of the second stage cooling higher than that of the first stage cooling, and a sufficient low temperature transformation is not generated if the cooling rate of the second stage cooling is lower than 15°C/sec. For this reason, the second stage cooling is determined to be a rapid accelerated cooling having a cooling rate greater than that of the first stage cooling and not lower than 15°C/sec. A desirable cooling rate is about 30°C/sec. or higher. Note that a cooling rate mentioned herein is an average cooling rate at a thickness center. Note also that, if the second stage cooling is stopped at 300°C or higher, the low temperature transformation does not complete sufficiently, and, therefore, it is necessary to cool a steel plate to 300°C or lower.

In the case of producing a hot-rolled steel strip, it is necessary to coil the strip at 300°C or lower after the second stage cooling.

It is desirable to carry out the first stage cooling and the second stage cooling consecutively. However, depending on the layout of the cooling apparatuses, there may be a case where the first stage cooling and the second stage cooling are carried out in a discontinued
manner between the apparatuses. In such a case, too, it is necessary to hold a steel material at a constant temperature or let it cool in air for about 30 sec. or less between the first stage cooling and the second stage cooling.

A steel plate thus produced is further formed into a pipe shape, a seam portion is welded, and a steel pipe is manufactured.

In a method for producing a pipe using a steel plate, the UOE method or the bending roll method usually applied to steel pipe production can be employed and arc welding, laser welding or the like can be employed as a method for welding a butt portion.

In a method for producing a pipe using a steel strip, on the other hand, high frequency resistance welding or laser welding can be used after forming the strip by roll forming. As the uniform elongation of a steel plate tends to be lowered by forming work, it is desirable to carry out the forming work under as low a strain as possible.

A steel pipe thus formed is the steel pipe wherein: the base material has a structure wherein a ferrite phase is dispersed finely and accounts for 5 to 40% in area percentage in a low temperature transformation structure mainly composed of a bainite phase and the most grain sizes of the ferrite phase are smaller than the average grain size of the bainite phase; and, further, the steel pipe satisfies the conditions that the ratio \( \frac{YS}{TS} \) of yield strength \( (YS) \) to tensile strength \( (TS) \) is 0.95 or less and the product \( (YS \times uEL) \) of yield strength \( (YS) \) and uniform elongation \( (uEL) \) is 5,000 or more.

The above conditions are important for a large diameter steel pipe used for an application as envisaged in the present invention. If the value of \( \frac{YS}{TS} \) exceeds 0.95, as strength is low and deformation resistance is low, buckling and the like occur when deformation is imposed. If the value of \( YS \times uEL \) is less than 5,000,
uniform elongation is low and deformability is deteriorated. Therefore, a large diameter steel pipe excellent in deformability and uniform elongation according to the present invention is required to satisfy the expressions $YS/TS \leq 0.95$ and $YS \times uEL \geq 5,000$.

Example 1

Steels having the chemical compositions satisfying the requirements of the present invention as shown in Table 1 were melted and refined, rolled and cooled under the conditions shown in Table 2, then formed into steel pipes, and the mechanical properties of the pipes thus obtained were evaluated. The structures of the base materials and the mechanical properties of the steel pipes are shown in Table 3.

The uniform elongation ($uEL$) in the longitudinal direction of the steel pipes was measured as an index of deformability. Here, in view of the fact that uniform elongation tended to increase as strength decreased, deformability was evaluated as good even though strength was low when the product ($YS \times uEL$) of yield strength ($YS$) and uniform elongation ($uEL$) was 5,000 or more. As another index of the deformability of the steel pipes, the results of buckling tests are also shown.

As seen in Table 3, all inventive examples (Nos. 1 to 14) had structures wherein the ferrite phases accounted for 5 to 40% and few ferrite grains (10% or less) had sizes larger than the average grain sizes of the bainite phases, and their mechanical properties satisfied the expressions $YS/TS \leq 0.95$ and $YS \times uEL \geq 5,000$. As a result, the buckling strains were 1% or more and excellent deformability was realized.

In contrast, comparative examples (Nos. 15 to 17) did not satisfy either of the conditions of the ferrite grain size and the conditions of mechanical properties ($YS/TS \leq 0.95$ and $YS \times uEL \geq 5,000$), the conditions being defined in the present invention. As a result,
their buckling strains were as low as 1% or less. In the
results of tensile tests, the stress-strain curves of the
comparative examples clearly demonstrated the yield point
drops and the existence of yield point elongation caused
the instability of plasticity, and therefore the
deformability of these steel pipes were significantly
deteriorated.

As seen in Table 2, comparative example No. 15 was
directly subjected to the rapid accelerated cooling
without being subjected to a lightly accelerated cooling
from a cooling start temperature of not lower than the
Ar₃ transformation point to a temperature of 500°C to
600°C. As a result, the example had a single-phase
structure mainly composed of a bainite phase and
therefore its uniform elongation was small. In
comparative example No. 16, the water-cooling termination
temperature was high and, as a result, the structure
formed through low temperature transformation did not
develop sufficiently. As a result, the dual-phase
structure of ferrite and bainite did not form and uniform
elongation was low. In comparative example No. 17, the
cooling rate at the rapid accelerated cooling of the
second stage was low and, as a consequence, the structure
formed through low temperature transformation, the
structure being mainly composed of a bainite phase, did
not develop sufficiently. As a result, the dual-phase
structure of ferrite and bainite did not form and uniform
elongation was low.
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Ar₃ point is the transformation temperature of a steel sheet 15 to 20 mm in thickness under cooling in air or equivalent.

Ceq = C + Mn/6 + (Ni + Cu)/15 + (Cr + Mo + V)/5
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<th>Average cooling temperature of first stage cooling (°C)</th>
<th>Cooling termination temperature of second stage cooling (°C)</th>
<th>Time between first and second stages of cooling (sec)</th>
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*1) Fraction in ferrite phase of ferrite grains larger than average grain size of bainite phase
1. A steel plate having tensile strength in the width direction of 517 MPa to 990 MPa comprising, in its chemical composition by mass,

\[
\begin{align*}
C & : 0.03 \text{ to } 0.12\%, \\
Si & : 0.8\% \text{ or less}, \\
Mn & : 0.8 \text{ to } 2.5\%, \\
P & : 0.03\% \text{ or less}, \\
S & : 0.01\% \text{ or less}, \\
Nb & : 0.01 \text{ to } 0.1\%, \\
Ti & : 0.005 \text{ to } 0.03\%, \\
Al & : 0.1\% \text{ or less}, \text{ and} \\
N & : 0.008\% \text{ or less}, \\
\end{align*}
\]

so as to satisfy the expression

\[\text{Ti} - 3.4N \geq 0,\] and one or more of:

\[
\begin{align*}
N & : 1\% \text{ or less}, \\
Mo & : 0.6\% \text{ or less}, \\
Cr & : 1\% \text{ or less}, \\
Cu & : 1\% \text{ or less}, \\
V & : 0.1\% \text{ or less}, \\
Ca & : 0.01\% \text{ or less}, \\
REM & : 0.02\% \text{ or less}, \text{ and} \\
Mg & : 0.006\% \text{ or less}, \text{ and}
\end{align*}
\]

the balance being Fe and unavoidable impurities, wherein the steel plate has a high degree of deformability and comprises a low-temperature transformation structure having a ferrite phase which is composed of first grains and a bainite phase which is composed of second grains, the ferrite phase being finely dispersed and accounting for 5 to 40\% in area percentage of the structure, wherein the sizes of the first grains are smaller than an average size of the second grains.
2. A steel pipe having tensile strength in the circumferential direction of 517 MPa to 990 MPa comprising, in its chemical composition by mass,

C: 0.03 to 0.12%,
Si: 0.8% or less,
Mn: 0.8 to 2.5%,
P: 0.03% or less,
S: 0.01% or less,
Nb: 0.01 to 0.1%,
Ti: 0.005 to 0.03%,
Al: 0.1% or less, and
N: 0.008% or less,
so as to satisfy the expression

\[ Ti - 3.4N \geq 0, \]

and one or more of:

Ni: 1% or less,
Mo: 0.6% or less,
Cr: 1% or less,
Cu: 1% or less,
V: 0.1% or less,
Ca: 0.01% or less,
REM: 0.02% or less, and
Mg: 0.006% or less, and

the balance being Fe and unavoidable impurities, wherein the steel pipe has a high degree of deformability wherein at least one portion has a ratio of yield strength (MPa) to tensile strength (MPa) of at most 0.95 and a yield strength (MPa) multiplied by uniform elongation (%) (YS x uEL) value of at least 5,000.

3. A steel pipe according to claim 2, wherein the at least one portion is formed from a base material which has a low temperature transformation structure, the structure comprising:

a finely dispersed ferrite phase which is composed of first grains and accounts for 5% to 40% in an area percentage of the structure, and
a bainite phase which is composed of second
grains, and

wherein sizes of the first grains are
smaller than an average size of second grains.

4. A method for producing a high-strength steel plate excellent
in deformability, characterized by subjecting a steel slab, the
steel slab containing, in mass:

C : 0.03 to 0.12%,
Si: 0.8% or less,
Mn: 0.8 to 2.5%,
P : 0.03% or less,
S : 0.01% or less,
Nb: 0.01 to 0.1%,
Ti: 0.005 to 0.03%,
Al: 0.1% or less, and
N : 0.008% or less,

so as to satisfy the expression Ti - 3.4N ≥ 0; and,
in addition, one or more of

Ni: 1% or less,
Mo: 0.6% or less,
Cr: 1% or less,
Cu: 1% or less,
V : 0.1% or less,
Ca: 0.01% or less,
REM: 0.02% or less, and
Mg: 0.006% or less;

with the balance consisting of iron and unavoidable impurities,
to a group of processes comprising the steps of: reheating to the
austenitic temperature range; thereafter, rough rolling within
the recrystallization temperature range; subsequently, finish
rolling at a cumulative reduction ratio of 50% or more within the
unrecrystallization temperature range of 900°C or lower; lightly
accelerated cooling at a cooling rate of 5 to 20°C/sec. from a
temperature not lower than the Ar₃ transformation point to a
temperature of 500°C to 600°C; and, immediately thereafter,
heavily accelerated cooling at a cooling rate of 15°C/sec. or
more and greater than the cooling rate of the previous cooling to
a temperature not higher than 300°C.

5. A method for producing a high-strength steel plate excellent
in deformability, characterized by subjecting a steel slab, the
steel slab containing, in mass:

C : 0.03 to 0.12%,
Si: 0.8% or less,
Mn: 0.8 to 2.5%,
P : 0.03% or less,
S : 0.01% or less,
Nb: 0.01 to 0.1%,
Ti: 0.005 to 0.03%,
Al: 0.1% or less, and
N : 0.008% or less,

so as to satisfy the expression Ti - 3.4N ≥ 0; and, in addition,
one or more of

Ni: 1% or less,
Mo: 0.6% or less,
Cr: 1% or less,
Cu: 1% or less,
V : 0.1% or less,
Ca: 0.01% or less,
REM: 0.02% or less, and
Mg: 0.006% or less;

with the balance consisting of iron and unavoidable impurities,
to a group of processes comprising the steps of: reheating to the
austenitic temperature range; thereafter, rough rolling within
the recrystallization temperature range; subsequently, finish
rolling at a cumulative reduction ratio of 50% or more within the
unrecrystallization temperature range of 900°C or lower; lightly
accelerated cooling at a cooling rate of 5 to 20°C/sec. from a
temperature not lower than the Ar, transformation point to a
temperature of 500°C to 600°C; then, after holding the rolled
steel plate at a constant temperature or letting it cool in air
for 30 sec. or less, heavily accelerated cooling at a cooling
rate of 15°C/sec. or more and greater than the cooling rate of
the previous cooling to a temperature not higher than 300°C.

6. A method for producing a high-strength steel pipe excellent
   in deformability, characterized by, further: forming a steel
   sheet produced by either of the methods according to claims 4
   and 5 into a pipe shape; and then welding the seam portion.

7. A method for producing a high-strength steel pipe excellent
   in deformability, characterized in that the pipe production
   method in claim 6 is the UOE process.

8. A method for producing a high-strength steel pipe excellent
   in deformability, characterized in that the pipe production
   method in claim 6 is the bending roll method.

9. A method for producing a high-strength hot-rolled steel
   strip excellent in deformability, characterized by subjecting a
   steel slab, the steel slab containing, in mass:
   \[ C : \ 0.03 \text{ to } 0.12\%, \]
   \[ Si : \ 0.8\% \text{ or less,} \]
   \[ Mn : \ 0.8 \text{ to } 2.5\%, \]
   \[ P : \ 0.03\% \text{ or less,} \]
   \[ S : \ 0.01\% \text{ or less,} \]
   \[ Nb : \ 0.01 \text{ to } 0.1\%, \]
   \[ Ti : \ 0.005 \text{ to } 0.03\%, \]
   \[ Al : \ 0.1\% \text{ or less, and} \]
   \[ N : \ 0.008\% \text{ or less,} \]
   so as to satisfy the expression \( Ti - 3.4N \geq 0; \) and,
in addition, one or more of

Ni: 1% or less,
Mo: 0.6% or less,
Cr: 1% or less,
Cu: 1% or less,
V: 0.1% or less,
Ca: 0.01% or less,
REM: 0.02% or less, and
Mg: 0.006% or less;

with the balance consisting of iron and unavoidable impurities, to a group of processes comprising the steps of: reheating to the austenitic temperature range; thereafter, rough rolling within the recrystallization temperature range; subsequently, finish rolling at a cumulative reduction ratio of 50% or more within the unrecrystallization temperature range of 900°C or lower; lightly accelerated cooling at a cooling rate of 5 to 20°C/sec. from a temperature not lower than the Ar₃ transformation point to a temperature of 500°C to 600°C; thereafter, heavily accelerated cooling at a cooling rate of 15°C/sec. or more to a temperature not higher than 300°C; and then coiling.

10. A method for producing a high-strength steel pipe excellent in deformability, characterized by, further: continuously forming a hot-rolled steel strip produced by the method according to claim 9 into a cylindrical shape by the roll forming method; and then welding the seam portion by high-frequency electric resistance welding or laser welding.
Unscannable items received with this application (Request original documents in File Prep. Section on the 10th floor)