

LOW-HYDROGEN COATED ELECTRODE

FIELD OF THE INVENTION

The present invention relates to a low-hydrogen coated electrode for high-strength steel which can ensure resistance to low-temperature cracking and high toughness of a weld metal in welding the high-tensile steel having a tensile strength of 590 MPa class or more. In particular, the invention is directed to a low-hydrogen coated electrode which is suitable for welding by use of a direct current power source commonly used abroad, and which has excellent low-temperature fracture toughness until about -40°C .

BACKGROUND OF THE INVENTION

Many attempts have been made to construct a structure from a high-tensile steel for the purpose of reduction in weight together with increase in size of the structure. Large offshore structures for developing natural resources at cold regions, such as North Europe, are required to have improved fracture toughness at lower temperature of weld metal so as to ensure security.

Conventionally, the large offshore structure makes it difficult to ensure both strength and fracture toughness of weld beads, and thus the application of a high-strength steel to the structure is partly limited. The large offshore structure is manufactured solely using steel for a low-temperature having a tensile strength of 490 MPa class. Thus, for the purpose of entirely applying the high-tensile steel which is essential for reduction in weight of the structure, weld material that enables welding of the high-tensile steel is strongly desired to

be developed. In recent years, the offshore structures are mainly constructed abroad, and still have many parts to which an electric arc electrode is used abroad as weld material. Most of overseas power sources for the electric arc electrode are direct current. Thus, it is required to develop a low-hydrogen coated electrode for a high-tensile steel suitable for the direct current power source, specifically, a low-hydrogen coated electrode with excellent low-temperature fracture toughness.

The following techniques have hitherto been developed as a low-hydrogen coated electrode for a high-tensile steel. Japanese Patent No. 3154661 discloses a low-hydrogen coated electrode suitable for use in welding of steel responsive to low-temperature cracking, such as a low-Ni steel, or a high-tensile steel having a tensile strength of 780 MPa class or more. This conventional technique is directed to an ultra-low-hydrogen coated electrode which is a low oxygen type with good fracture toughness. The hydrogen content of the weld metal obtained from the coated electrode is equal to or less than 5 ml/100 g. In the technique, however, the temperature of a CTOD test, that is, the temperature determined by taking into consideration the fracture toughness, is -10°C or so which is high (insufficient). This conventional technique is not to improve the fracture toughness at an ultra-low temperature, such as -40°C , and does not take into consideration the use of a direct current power source at all. That is, the low-hydrogen coated electrode described in the above patent uses a power source for an alternating current. The low-hydrogen coated electrode cannot be applied to welding using the direct current power source as it is.

Japanese Unexamined Patent Publication No. Hei 08(1996)-257791 relates to a coated electrode that can provide weld metal with excellent low-temperature toughness and fracture toughness after stress-relief annealing in welding a high-tensile steel, for example, a high-tensile steel having a tensile strength of 590 MPa class or more. However, since the temperature of the fracture toughness test (CTOD test) is high, for example, up to -20 °C (insufficient), the technique disclosed does not improve the fracture toughness at an ultra-low temperature, such as -40 °C. Also, this conventional technique does not take into consideration the use of a direct current power source at all.

Japanese Patent Publication No. Hei 08(1996)-29431 discloses a low-hydrogen coated electrode for a high-tensile steel having a tensile strength of HT60 class or more, and for a low Ni steel for the purpose of obtaining good fracture toughness of weld metal. Although this technique improves a low-temperature impact value at temperatures from -20 to -60 °C as compared to other conventional techniques, the CTOD test is not performed at low-temperature, and thus the quality of fracture toughness is not clear. Also, this conventional technique does not take into consideration the use of a direct current power source.

Japanese Patent No. 3026899 discloses a low-hydrogen coated electrode adapted to obtain a high strength weld metal having a tensile strength of HT60 class or more for the purpose of improving low-temperature toughness of the weld metal. Although the coated electrode has an improved impact value of a V-notch impact test at -40 °C as compared to that of a conventional electrode, this technique does not perform the CTOD test at low temperature, and thus the quality of

fracture toughness is not clear. Also, this conventional technique does not take into consideration the use of a direct current power source at all.

As mentioned above, the related art has not developed the low-hydrogen coated electrode with excellent low-temperature fracture toughness and with an improved CTOD value (fracture toughness value) at -40 °C, and has not proposed a low-hydrogen coated electrode with excellent low-temperature fracture toughness for a direct current power source. In fact, problems caused in use of the direct current power source have not been recognized hitherto.

SUMMARY OF THE INVENTION

The present invention has been made in view of the forgoing problems, and it is an object of the present invention to provide a low-hydrogen coated electrode which exhibits an excellent CTOD value at low temperature and good low-temperature fracture toughness, and which is suitable as weld material for a high-tensile steel with a tensile strength of 590 MPa class or more, and also as weld material for a direct current.

The invention provides a low-hydrogen coated electrode including a steel core wire with a coating flux applied thereto. The steel core wire contains, relative to a total mass of the steel core wire, more than 0.05 % by mass but not more than 0.10 % by mass of C, 0.010 % by mass or less of P, 0.010 % by mass or less of S, and 0.005 % by mass or less of N, in which the P content, the S content, and the N content are defined as above. The coating flux contains, relative to a total mass of the coating flux, 15 to 28 % by mass of a metal carbonate in

terms of CO_2 , 4 to 9 % by mass of a metal fluoride in terms of F, 4.0 to 9.0 % by mass of SiO_2 , 0.5 to 5.0 % by mass of TiO_2 , 0.5 to 3.0 % by mass of Mg in terms of Mg as a single metal or an alloy, 1.0 to 7.0 % by mass of Si, 0.5 to 5.0 % by mass of Mn, 2.0 to 10.0 % by mass of Ni, 0.3 to 3.0 % by mass of Ti, 0.05 to 0.20 % by mass of B, 5.0 to 20.0 % by mass of Fe, 2.0 % by mass or less of Al_2O_3 , 0.1 % by mass or less of Mo, and 0.1 % by mass or less of Cr, in which the Al_2O_3 content, the Mo content, and the Cr content are defined as above. In addition to the above elements, the coating flux further contains an arc stabilizer, a slag formation agent, and a binder. A coating ratio of the coating flux is 25 to 45 % as a mass ratio of the coating flux relative to a total mass of the electrode.

In the low-hydrogen coated electrode, the total amount of the SiO_2 , TiO_2 , and Al_2O_3 as an acidic oxide in the coating flux is preferably equal to or less than 12 % by mass.

Further, an "A" value determined by the following formula is 0.30 to 0.70:

$$A = ([C] \times 10 + 1.8 \times [\text{Si}] + [\text{Mn}]) / \{(1 + [\text{Ni}]) \times (0.5 + [\text{Ti}])\}$$

where [C] is a C content (% by mass), [Si] is a Si content (% by mass), [Mn] is a Mn content (% by mass), [Ni] is a Ni content (% by mass), and [Ti] is a Ti content (% by mass), relative to the total mass of the electrode.

According to the invention, the compositions of the steel core wire and coating flux of the low-hydrogen coated electrode are appropriately limited thereby to provide the coated electrode exhibiting the excellent low-temperature fracture toughness in welding a high-tensile steel having a tensile strength of 590 MPa class or more.

Thus, the reliability of weld joints for various types of steel structures can be greatly improved.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Some preferred embodiments of the invention will be described below in detail. An alternating current power source has been hitherto used widely as a weld power source for manual welding in Japan. Together with this, various electrodes for the alternating current power source have been proposed. In general, it is known that when an electrode designed for an alternating current power source is used in a direct current power source, an yield of alloy elements, such as Si, Mn, and C, into weld metal is decreased, which reduces the strength and toughness of the weld metal. Further, since the weld metal is likely to be affected by a magnetic field, the weldability is degraded. Thus, the electrode for the alternating current power source cannot be used for the direct current power source as it is. In order to solve the problems described above, the inventors have been dedicated themselves to studying and conducting experiments on a balance between compositions of a core wire and coating flux, and, as a result, found that a carbon content of a steel core wire used as an electrode for the direct current power source greatly affects the amount of oxygen in weld metal as compared to a carbon content of the coating flux. This finding is a new one that has never been obtained hitherto. That is, the inventors have found that the C content of the steel core wire is limited to more than 0.05 % by mass but not more than 0.10 % by mass, which effectively reduces the amount of oxygen in the weld metal thereby to make the weldability and mechanical performance better.

In order to ensure an adequate CTOD value (low-temperature fracture toughness) at $-40\text{ }^{\circ}\text{C}$ of a weld bead of a high-tensile steel having a tensile strength of 590 MPa class or more, the inventors have studied various alloy elements, and, as a result, found that the following conditions are essential. That is, first, it is necessary to ensure the strength of weld metal without containing an element for reducing the toughness. Second, in order to ensure the fracture toughness at $-40\text{ }^{\circ}\text{C}$, the structure of the weld metal needs to be made finer.

The inventors have studied by various experiments on coated electrodes which can provide weld metal satisfying these conditions, and, as a result, found that the following means are effective. First, in order to ensure the CTOD value (low-temperature fracture toughness) of the weld bead at $-40\text{ }^{\circ}\text{C}$, in the composition of the coating flux, a Cr content is 0.10 % by mass or less, a Mo content is 0.10 % by mass or less, and a Si content is 1.0 to 7.0 % by mass, thereby preventing reduction of the toughness, while a Mn content is 0.5 to 5.0 % by mass, and a Ni content is 2.0 to 10.0 % by mass, thereby ensuring the high strength. Furthermore, a B content of the coating flux composition is set to 0.05 to 0.20 % by mass, and a Ti content thereof is set to 0.3 to 3.0 % by mass, so that the composition of the weld metal has a microstructure of acicular ferrite thereby to increase the CTOD value (fracture toughness) at $-40\text{ }^{\circ}\text{C}$.

The following will first describe the reasons for addition and limitation of compositions included in the steel core wire of the low-hydrogen coated electrode in the invention.

"C: more than 0.05 % by mass but not more than 0.10 % by mass"

A carbon (C) content of the steel core wire is one of important factors in the invention. The inventors have found that a carbon content of the steel core wire used as an electrode for a direct current power source greatly affects the amount of oxygen in weld metal as compared to a carbon content of the coating flux. That is, when the C content of the steel core wire is high, the amount of oxygen in the weld metal can be reduced, which improves the toughness of the weld metal. Conventionally, as described in the above-mentioned patent publications, it is considered that the lower the carbon content of the steel core wire, the better the toughness of the weld metal (see, for example, a C content is preferably 0.05 % by mass or less per mass of the steel core wire: Japanese Patent No. 3154461, Japanese Unexamined Patent Publication No. Hei8(1996)-257791, and Japanese Unexamined Patent Publication No. Hei8(1996)-29431). For this reason, a steel core wire having a low carbon content has been used. In contrast, the inventors have found that a core wire having a certain carbon content is preferable in welding by the direct current power source so as to improve the toughness. For a C content of the steel core wire of 0.05 % by mass or less relative to the total mass of the steel core wire, the effect of improvement of the toughness is small, and the C content of weld metal obtained is reduced by the effect of decarbonizing at the direct current power source, which does not serve to improve the strength of the weld metal. For a C content exceeding 0.10 % by mass, a C content of the weld metal exceeds 0.08 % by mass, so that a high-carbon martensite is formed to reduce the toughness of the weld metal. Further, high-temperature cracking of the weld metal is likely to be caused. Accordingly, the C content of the steel core wire is limited to more

than 0.05 % by mass but not more than 0.10 % by mass relative to the total mass of the steel core wire.

"N: 0.005 % by mass or less"

The element N is an inevitable impurity in the steel core wire, and when an N content of the steel core wire exceeds 0.005 % by mass relative to the total mass of the steel core wire, an N content of the weld metal exceeds 0.008 % by mass to promote internal distortion of the weld metal, leading to reduction in toughness of the weld metal. Accordingly, the N content of the steel core wire is limited to 0.005 % by mass or less relative to the total mass of the steel core wire.

"P: 0.010 % by mass or less, S: 0.010 % by mass or less"

Elements P and S are segregated at the last coagulation portion to reduce the toughness of weld metal in welding, causing the high-temperature cracking. Thus, the P and S contents of the steel core wire are desirably as low as possible. But when the P and S contents are intended to be decreased, the manufacturing cost of the steel core wire may be increased. Thus, the P and S contents are respectively limited to 0.010 % by mass or less, which is a range little affecting the low-temperature toughness of the weld metal.

It is noted that a carbon steel core wire is normally used as the steel core wire, but a deoxidizing element, such as Si, Mn, or Ti, and an element, such as Ni, Cu, Nb, or V, can be added thereto in appropriate amounts if necessary.

Next, the reasons for addition and limitation of compositions included in the coating flux will be described.

"Metal Carbonate (in terms of CO_2): 15 to 28 % by mass"

A metal carbonate is a composition that can reduce an N content

and a hydrogen content of the weld metal. When a metal carbonate of the coating flux is less than 15 % by mass in terms of CO_2 relative to the total mass of the coating flux, the shielding effect of CO_2 becomes insufficient, so that an N content of the weld metal cannot be equal to or less than 0.008 % by mass, whereby the weld metal cannot obtain good resistance to cracking and toughness. That is, in order to obtain the excellent resistance to cracking and toughness of the weld metal, it is necessary to set the N content of the weld metal to 0.008 % by mass or less. For this reason, the sealability of the weld needs to be improved. Thus, a metal carbonate content is equal to or more than 15 % by mass in terms of CO_2 relative to the total mass of the coating flux. For a metal carbonate content of the coating flux exceeding 28 % by mass in terms of CO_2 , the viscosity of slag becomes excessive, which makes it difficult to perform vertical welding. Accordingly, the metal carbonate content of the coating flux is 15 to 28 % by mass in terms of CO_2 , relative to the total mass of the coating flux. The metal carbonate included in, for example, calcium carbonate, barium carbonate, or magnesium carbonate, is added to the flux.

The term "metal carbonate content (in terms of CO_2)" means a total mass of only CO_2 parts of metal carbonate molecules represented by % with respect to the total mass of coating flux.

"Metal Fluoride (in terms of F): 4 to 9 % by mass"

A metal fluoride is a composition that can obtain good weldability by adjusting the viscosity of slag. For a metal fluoride of the coating flux of less than 4 % by mass in terms of F, the viscosity of slag is excessively high to degrade the shape of a bead. In contrast, for a metal fluoride content of the coating flux exceeding 9 % by mass in

terms of F, the arc undesirably becomes unstable. Accordingly, the metal fluoride content of the coating flux is 4 to 9 % by mass in terms of F relative to the total mass of the coating flux. The metal fluoride included in, for example, calcium fluoride, sodium fluoride, barium fluoride, or aluminum fluoride, is added to the flux.

The term "metal fluoride content (in terms of F)" means a total mass of only F parts of metal fluoride molecules represented by % with respect to the total mass of the coating flux.

"Mg as Single Metal or Alloy (in terms of Mg): 0.5 to 3.0 % by mass"

A Mg element is an element which decreases the oxygen content of the weld metal, and which has a great effect of improving toughness of the weld metal as described above. When a Mg content (in terms of Mg) as the single metal or alloy of the coating flux is less than 0.5 % by mass relative to the total mass of the coating flux, it is difficult to set the oxygen content of the weld metal to 200 ppm or less, resulting in reduced toughness of the weld metal. In contrast, when a Mg content (in terms of Mg) as the single metal or alloy of the coating flux exceeds 3.0 % by mass, the spread of arc is degraded, which makes it difficult to perform welding. Accordingly, the element Mg serves as the single metal or alloy in the coating flux, and the Mg content (in terms of Mg) of the coating flux is 0.5 to 3.0 % by mass, relative to the total mass of the coating flux. The Mg element included in, for example, magnesium metal, AlMg, or nickel magnesium, can be added to the flux.

The term "Mg as a single metal or alloy (in terms of Mg)" means the mass of single Mg material, or a total mass of only Mg parts of the alloy represented by % with respect to the total mass of the coating flux.

"Si: 1.0 to 7.0 % by mass"

The element Si is a deoxidizing element. The element Si serves to improve the wettability between a molten pool and a base material in welding and to improve the weldability. For a Si content of less than 1.0 % by mass, the effect of deoxidizing is weak, and pores are likely to be generated in the weld metal, which cannot provide the effect of improving the weldability. In contrast, for a Si content exceeding 7.0 % by mass, a low-melting-point oxide is precipitated at a grain boundary to reduce the cracking resistance and toughness. Accordingly, the Si content is 1.0 to 7.0 % by mass. The element Si included in, for example, Fe-Si, is added to the flux.

"Mn: 0.5 to 5.0 % by mass"

The element Mn is a deoxidizing element which decreases the temperature of ferrite transformation to make ferrite particles finer, thereby enhancing the strength and toughness of the weld metal. For a Mn content of less than 0.5 % by mass, the weld metal cannot obtain the high strength and toughness. In contrast, for a Mn content exceeding 5.0 % by mass, the weld metal exhibits a lath structure, and has its toughness reduced. Accordingly, the Mn content is 0.5 to 5.0 % by mass. The element Mn included in, for example, metal Mn, Fe-Mn, or Fe-Si-Mn, is added to the flux.

"Ni: 2.0 to 10.0 % by mass"

The element Ni is an element enhancing the strength and toughness of the weld metal. For a Ni content of less than 2.0 % by mass, the weld metal having high toughness cannot be obtained. In contrast, for a Ni content exceeding 10.0 % by mass, the strength of the weld metal becomes excessively high, so that the toughness of the weld metal is

reduced. Accordingly, a Ni content is set to 2.0 to 10.0 % by mass. The element Ni included in, for example, metal Ni, Ni-Mg, or Fe-Ni, is added to the flux.

"Ti: 0.3 to 3.0 % by mass"

The element Ti is a deoxidizing element, and effective for improving the strength of the weld metal. The element Ti generates a fine spherical oxide, and thus is effective for making the structure of the weld metal finer. For a Ti content of less than 0.3 % by mass, the sufficient deoxidization and the effect of improvement of the strength of the weld metal are not exhibited. In contrast, for a Ti content exceeding 3.0 % by mass, the Ti content of the weld metal becomes excessively large, and hence the strength and hardness of the weld metal become excessively high, which results in reduction of toughness of the weld metal. Accordingly, the Ti content is set to 0.3 to 3.0 % by mass. The Ti element included in, for example, Fe-Ti and metal Ti, is added to the flux.

"B: 0.05 to 0.20 % by mass"

The element B is effective for suppressing the formation of grain boundary ferrite, and is an element having strong hardenability. For a B content of less than 0.05 % by mass, the element B does not exhibit an effect of suppressing the formation of grain boundary ferrite, so that a metal structure of the weld metal becomes coarse. In contrast, for a B content exceeding 0.20 % by mass, the weld metal exhibits a lath structure, and has its toughness reduced. Accordingly, the B content is limited to 0.05 to 0.20 % by mass. The element B included in, for example, Fe-B, Fe-Si-B, or metal B, is added to the flux.

"Cr: 0.1 % by mass or less"

When a Cr content exceeds 0.1 % by mass, the quenching hardenability of the weld metal is reduced, and the low-temperature toughness thereof is drastically reduced due to the generation of crystallization of a δ ferrite phase. Accordingly, the Cr content is limited to 0.1 % by mass or less.

"Mo: 0.1 % by mass or less"

Like Cr, for a Mo content exceeding a specific value, a δ ferrite phase crystallizes out, and the low-temperature toughness of the weld metal is remarkably degraded. Accordingly, the Mo content is limited to 0.1 % by mass or less.

"Fe: 5.0 to 20.0 % by mass"

The element Fe is an element that influences the weldability and weld efficiency. For a Fe content of less than 5.0 % by mass, the weld efficiency is reduced, and the arc fluctuates to degrade the weldability. For a Fe content exceeding 20.0 % by mass, the shield effect is reduced, and the weldability is also reduced. Accordingly, the Fe content is 5.0 to 20.0 % by mass, and preferably 5.0 to 15.0 % by mass. The element Fe included in, for example, Fe-Mn, Fe-Si, or Fe powder, is added to the flux.

"SiO₂: 4.0 to 9.0 % by mass"

It is necessary to add SiO₂ which is an acidic oxide serving as a binder and a slag making material, to the coating flux. When a SiO₂ content of the coating flux exceeds 9.0 % by mass relative to the total mass of the coating flux, the slag became glassy, and the removability of the slag was degraded. In contrast, when a SiO₂ content of the coating flux is less than 4.0 % by mass relative to the total mass of the coating flux, the effect of the binder cannot be obtained. Accordingly, the

SiO₂ content of the coating flux is 4.0 to 9.0 % by mass relative to the total mass of the coating flux.

"TiO₂: 0.5 to 5.0 % by mass"

TiO₂ which is an acidic oxide can be added as a slag making material to the coating flux. When a TiO₂ content of the coating flux is less than 0.5 % by mass relative to the total mass of the coating flux, the weldability is degraded. When a TiO₂ content exceeds 5.0 % by mass, the viscosity of the slag is reduced, and the workability is degraded. Accordingly, in adding the TiO₂ to the coating flux, the TiO₂ content is 0.5 to 5.0 % by mass relative to the total mass of the coating flux.

"Al₂O₃: 2.0 % by mass or less"

Al₂O₃ which is an acidic oxide can be added as a slag making material to the coating flux. When the Al₂O₃ content of the coating flux exceeds 2.0 % by mass relative to the total mass of the coating flux, the slag becomes glassy, and the removability of the slag is degraded. Accordingly, in adding Al₂O₃ to the coating flux, the Al₂O₃ content is 2.0 % by mass or less relative to the total mass of the coating flux.

"Total Amount of SiO₂, TiO₂, and Al₂O₃ as Acidic Oxide: 12.0 % by mass or less"

In addition to SiO₂ as the slag making material, TiO₂, Al₂O₃, and the like which are acidic oxides, can be added to the coating flux. When the total amount of acidic oxides, including SiO₂, TiO₂, and Al₂O₃, in the coating flux exceeds 12.0 % by mass relative to the total mass of the coating flux, the slag basicity becomes insufficient, which makes it difficult to adjust an oxygen content of the weld metal to 200 ppm or less. When the oxygen content of the weld metal exceeds 200 ppm, the impact test performance (toughness) of the weld metal is degraded.

Accordingly, in adding the acidic oxide to the coating flux, the total amount of SiO_2 , TiO_2 , and Al_2O_3 is 12.0 % by mass or less relative to the total mass of the coating flux.

The following will describe a coating ratio of the coating flux to the coated electrode in the invention.

"Coating Ratio: 25 to 45 %"

The coating ratio regarding the coated electrode is calculated by the formula ((the mass of the coating flux/the total mass of the electrode) $\times$ 100). When a coating ratio is less than 25 %, the shielding is insufficient, and thus an N content and a hydrogen content of the weld metal are increased, which reduces the toughness and cracking resistance of the weld metal. In contrast, when the coating ratio exceeds 45 %, an arc length becomes long, and arc interruption occurs. Accordingly, the coating ratio of the coating flux in the coating electrode is 25 to 45 %.

$[A = ([C] \times 10 + 1.5 \times [Si] + [Mn]) / \{(4 + [Ni]) \times (0.5 + [Ti])\} : 0.30 \text{ to } 0.70]$

The elements C, Si, and Mn are elements that enhance the strength of weld beads. The element Ni is an element which improves the fracture toughness of a weld bead, while enhancing the toughness of the weld bead. The element Ti is an element which makes the structure of the weld bead finer to improve the toughness thereof. An "A" value is defined by the following formula:

"A" value = $([C] \times 10 + 1.5 \times [Si] + [Mn]) / (4 + [Ni]) \times (0.5 + [Ti])$
where [C] is a C content (% by mass), [Si] is a Si content (% by mass), [Mn] is a Mn content (% by mass), [Ni] is a Ni content (% by mass), and [Ti] is a Ti content (% by mass), relative to the total mass of the coated electrode. For an "A" value of less than 0.30, the strength

of the weld metal is reduced, and the CTOD value (fracture toughness) is also decreased. For an "A" value of more than 0.70, the strength is increased by the elements C, Si, Mn, and Ti, and the toughness is reduced due to relative shortage of the Ni content, which reduces the CTOD value (fracture toughness). Accordingly, the "A" value is preferably 0.30 to 0.70.

The "A" value is introduced as a result of taking into consideration the strength and toughness. An element for increasing the toughness is selected to correspond to a denominator of the "A" value, and an element for increasing the strength of the weld bead is selected to correspond to a numerator of the "A" value. The relationship between the "A" value and the CTOD value is organized. As a result, a very clear correlation therebetween is obtained. That is, when the "A" value is 0.30 to 0.70, the CTOD value is excellent. [Examples]

Examples of the low-hydrogen coated electrode according to the invention will be described specifically by comparison with Comparative Examples.

First, coating fluxes containing various chemical compositions were respectively applied to steel core wires having respective compositions shown in the following Table 1 to manufacture coated electrodes. In Examples, the diameter of the steel core wire was 4 mm. Table 1 shows the compositions of the steel core wires used in respective Examples and Comparative Examples. Tables 2 to 4 show the types of the steel core wires, coating ratios, and compositions of coating fluxes, and "A" values of electrodes used in Examples and Comparative Examples of the invention. As shown in Tables 3 and 5,

another column about others include other compositions, such as BaO, Na₂O, Li₂O, Fe₂O₃, or ZrO₂.

Then, welding was carried out by using the coated electrode. At this time, the weldability was evaluated, and the mechanical quality of the weld metal was also evaluated. In Examples, a steel plate having a thickness of 60 mm and having an X groove formed therein was used as a weld base material. The steel plate was pre-heated at a temperature of 100 °C. Then, welding was performed on the groove in a downhand welding position at a heat input of welding of 25 kJ/cm, using a direct current power source as a power source at a weld current of 150A and at an arc voltage of 23 to 25 V. At this time, a steel plate having a tensile strength of 610 MPa class was used as a steel plate.

The mechanical quality of the weld metal was evaluated by measuring a 0.2 % proof stress, a tensile strength, a transition temperature v_{Trs} , and a CTOD value (fracture toughness) at -40 °C. Specifically, the proof stress and tensile strength of the weld metal were evaluated by taking a specimen for a tensile test from the obtained weld metal, and measuring a load on the specimen with respect to 0.2 % extension thereof, while measuring the maximum tensile strength of the specimen. Furthermore, the CTOD (Crack Tip Opening displacement) at -40 °C was measured based on the BS (British Standards) 5762.

The test results and evaluation results are shown in the following Tables 6 and 7. In a column regarding the evaluation result on the weldability, the mark O designates good workability, the mark Δ designates slightly bad workability, and the mark X designates bad workability. The total judgment was performed based on the weldability and the CTOD value.

[Table 1]

	Core wire No.	C	Si	Mn	P	S	N
Example	C1	0.06	0.03	0.28	0.007	0.003	0.002
	C2	0.10	0.03	0.41	0.004	0.003	0.002
	C3	0.07	0.03	0.33	0.010	0.003	0.004
	C4	0.06	0.03	0.35	0.004	0.010	0.002
	C5	0.08	0.02	0.35	0.005	0.005	0.005
Comparative example	C6	0.04	0.03	0.58	0.003	0.005	0.002
	C7	0.12	0.02	0.46	0.004	0.004	0.003
	C8	0.07	0.04	0.43	0.014	0.003	0.003
	C9	0.06	0.02	0.41	0.004	0.013	0.002
	C10	0.08	0.03	0.38	0.006	0.003	0.008

[Table 2]

Electrode No.	Core wire No.	Coating ratio	CaCO ₃	In terms of CO ₂	CaF ₂	In terms of F	Mg	Si	Mn	Ni	Ti	B	SiO ₂	TiO ₂	Al ₂ O ₃
E1	C1	26	46	20.2	14	6.8	2.5	5.2	2.6	6.2	0.8	0.12	7.2	1.4	0.3
E2	C2	45	52	22.9	16	7.8	2.2	2.0	2.5	6.3	0.8	0.14	5.9	1.8	0.7
E3	C2	28	34	15.0	17	8.3	2.5	5.2	2.7	6.2	1.5	0.15	5.8	2.1	0.5
E4	C1	30	63	27.7	10	4.9	0.9	3.6	2.8	5.4	1.5	0.08	4.5	1.4	0.3
E5	C3	33	51	22.4	9	4.4	2.3	6.1	2.6	7.0	0.7	0.15	5.6	2.1	1.3
E6	C3	30	46	20.2	18	8.8	1.3	4.5	2.6	6.3	0.6	0.15	5.2	1.3	1.2
E7	C5	43	47	20.7	14	6.8	0.5	4.5	3.1	5.2	0.7	0.13	4.9	3.6	0.5
E8	C4	40	46	20.2	15	7.3	3.0	4.2	1.9	5.3	1.4	0.15	6.0	1.0	0.9
E9	C3	39	52	22.9	13	6.3	2.9	1.3	2.9	7.2	0.7	0.14	7.2	2.6	0.7
E10	C2	37	48	21.1	14	6.8	2.4	6.8	2.4	3.2	0.6	0.14	6.3	2.2	1.3
E11	C4	41	52	22.9	13	6.3	2.3	4.2	0.6	7.2	0.8	0.15	7.6	1.8	0.7
E12	C5	36	46	20.2	14	6.8	2.1	3.9	4.8	4.1	0.9	0.15	5.7	3.3	1.2
E13	C3	35	50	22.0	15	7.3	2.0	5.3	3.0	2.3	0.7	0.14	6.7	1.7	0.8
E14	C1	38	46	20.2	10	4.9	2.0	4.2	0.9	9.7	0.8	0.18	6.7	1.9	1.4
E15	C1	41	51	22.4	14	6.8	2.4	4.0	2.5	5.4	0.6	0.15	6.6	2.7	1.3
E16	C2	35	43	18.9	17	8.3	1.6	3.9	3.2	4.2	2.8	0.16	6.5	2.0	0.8
E17	C3	35	46	20.2	15	7.3	1.8	6.1	4.3	6.1	0.7	0.06	6.5	1.4	0.4
E18	C2	36	43	18.9	16	7.8	1.9	5.1	2.6	9.0	0.8	0.19	7.1	1.5	0.9
E19	C4	41	47	20.7	15	7.3	2.0	4.8	2.4	6.7	0.7	0.16	4.3	1.6	0.4
E20	C5	34	43	18.9	14	6.8	1.6	4.6	2.0	8.3	0.9	0.15	8.8	1.5	0.6
E21	C3	32	45	19.8	17	8.3	2.5	4.5	3.1	5.3	1.1	0.10	6.5	0.6	0.7
E22	C5	34	43	18.9	15	7.3	2.3	4.4	2.3	6.8	0.8	0.16	4.7	4.8	0.7
E23	C4	35	44	19.4	15	7.3	2.4	4.5	2.4	6.0	0.8	0.15	6.9	2.0	1.8
E24	C5	32	42	18.5	16	7.8	2.5	4.5	3.0	5.4	1.0	0.12	8.6	3.2	0.7
E25	C2	40	51	22.4	14	6.8	2.4	4.3	2.9	5.7	0.7	0.14	6.5	1.3	0.3
E26	C3	42	48	21.1	14	6.8	2.3	5.0	2.8	5.5	0.8	0.14	5.8	2.4	0.5

[Table 3]

Electrode No.	Total of acidic oxides	Remainder			Others	A value
		Cr	Mo	Fe		
E1	8.9	0.02	0.02	10.5	3.1	0.43
E2	8.4	0.03	0.03	5.1	4.5	0.41
E3	8.4	0.03	0.05	18.4	3.9	0.64
E4	6.2	0.03	0.05	5.6	0.8	0.53
E5	9.0	0.05	0.04	11.3	0.8	0.53
E6	7.7	0.02	0.06	8.9	3.9	0.41
E7	9.0	0.03	0.05	8.6	7.2	0.63
E8	7.9	0.05	0.04	9.7	5.4	0.67
E9	10.5	0.08	0.05	6.3	2.9	0.29
E10	9.8	0.04	0.04	10.4	2.2	0.78
E11	10.1	0.03	0.05	5.8	3.8	0.41
E12	10.2	0.07	0.04	10.0	3.7	0.69
E13	9.2	0.06	0.05	9.4	2.9	0.70
E14	10.0	0.05	0.04	9.6	6.5	0.35
E15	10.6	0.06	0.05	6.3	2.9	0.48
E16	9.3	0.04	0.06	7.9	6.8	1.11
E17	8.3	0.03	0.05	9.5	2.1	0.66
E18	9.5	0.05	0.03	7.6	4.2	0.50
E19	6.3	0.05	0.07	8.4	6.4	0.53
E20	10.9	0.05	0.06	6.2	8.2	0.45
E21	7.8	0.03	0.04	8.4	5.1	0.58
E22	10.2	0.06	0.06	9.6	5.3	0.47
E23	10.7	0.07	0.05	9.2	4.7	0.49
E24	12.5	0.03	0.05	9.4	3.5	0.56
E25	8.1	0.08	0.05	7.6	3.0	0.57
E26	8.7	0.03	0.08	8.3	4.4	0.66

[Table 4]

Electrode No.	Core wire No.	Coating ratio	CaCO ₃	In terms of CO ₂	CaF ₂	In terms of F	Mg	Si	Mn	Ni	Ti	B	SiO ₂	TiO ₂	Al ₂ O ₃
T1	C2	22	51	22.4	16	7.8	2.8	3.2	4.1	3.9	1.4	0.14	5.1	3.2	0.4
T2	C4	49	46	20.2	17	8.3	2.2	3.2	3.2	5.5	1.1	0.15	4.5	3.3	0.3
T3	C3	32	32	14.1	22	10.7	2.1	6.0	3.5	7.6	1.4	0.10	6.9	2.1	0.5
T4	C2	36	64	28.2	10	4.9	2.6	3.2	2.5	3.2	0.9	0.14	5.6	1.0	0.7
T5	C1	39	56	24.6	7	3.4	2.5	6.4	3.0	9.3	0.9	0.08	5.5	2.6	0.8
T6	C5	37	38	16.7	20	9.7	2.8	4.6	3.5	5.6	1.0	0.06	4.9	3.1	0.6
T7	C4	34	42	18.5	14	6.8	0.3	5.4	3.6	5.4	0.8	0.08	6.7	2.6	0.8
T8	C5	31	39	17.2	17	8.3	3.5	6.0	4.1	6.6	1.1	0.13	6.5	2.6	0.8
T9	C2	30	46	20.2	15	7.3	2.1	0.8	4.3	5.4	1.8	0.12	5.7	3.1	0.6
T10	C1	34	51	22.4	14	6.8	2.6	7.4	4.4	2.8	1.4	0.15	4.9	2.1	0.7
T11	C1	32	53	23.3	13	6.3	2.5	7.2	0.3	4.6	1.6	0.07	4.5	1.7	1.4
T12	C2	35	48	21.1	14	6.8	0.9	2.5	5.4	6.5	1.3	0.09	5.4	2.6	1.3
T13	C4	35	49	21.6	16	7.8	2.4	6.1	3.6	1.6	1.0	0.14	7.3	2.2	1.2
T14	C5	34	47	20.7	15	7.3	2.0	1.7	2.5	10.5	0.9	0.13	6.1	1.4	0.9
T15	C3	38	49	21.6	14	6.8	1.8	5.0	4.5	4.6	0.2	0.15	7.3	2.4	0.5
T16	C1	39	43	18.9	16	7.8	1.6	5.6	3.5	5.7	3.3	0.16	6.8	2.1	0.6
T17	C2	29	46	20.2	14	6.8	1.7	4.5	3.7	6.4	0.9	0.03	5.6	2.1	0.8
T18	C2	32	51	22.4	13	6.3	2.1	4.7	3.7	4.2	1.0	0.22	5.4	2.5	0.8
T19	C1	33	47	20.7	16	7.8	2.2	2.4	3.2	3.2	1.3	0.17	3.5	1.6	1.0
T20	C3	34	44	19.4	17	8.3	2.1	4.6	3.1	4.0	0.8	0.06	9.5	1.9	0.4
T21	C2	33	46	20.2	18	8.8	1.7	5.6	2.4	5.0	1.4	0.09	6.3	0.3	0.9
T22	C4	36	45	19.8	16	7.8	1.4	6.3	1.4	6.3	1.1	0.13	5.3	5.3	1.2
T23	C3	35	43	18.9	14	6.8	1.3	2.6	1.9	5.5	1.2	0.15	7.3	2.1	2.4
T24	C5	35	38	16.7	15	7.3	2.4	6.5	3.1	6.3	0.8	0.15	5.7	4.5	0.4
T25	C4	37	45	19.8	15	7.3	2.2	5.0	3.5	4.5	0.8	0.13	5.3	1.5	0.7
T26	C6	35	46	20.2	14	6.8	2.0	4.5	3.3	7.5	1.7	0.09	7.0	2.4	0.5
T27	C7	37	46	20.2	15	7.3	2.1	6.3	3.6	5.2	1.0	0.11	6.5	2.5	1.3

T28	C8	42	53	23.3	11	5.4	2.4	4.5	2.6	5.6	1.1	0.10	6.6	1.8	0.8
T29	C9	32	47	20.7	13	6.3	1.6	5.7	2.4	5.2	1.0	0.09	6.9	1.6	0.6
T30	C10	34	43	18.9	14	6.8	1.6	4.6	2.5	7.2	1.3	0.08	7.4	1.3	0.9

[Table 5]

Electrode No.	Total of acidic oxides	Remainder			Others	A value
		Cr	Mo	Fe		
T1	8.7	0.04	0.03	5.6	3.1	0.51
T2	8.1	0.03	0.02	10.5	3.0	0.69
T3	9.5	0.05	0.05	13.1	2.6	0.70
T4	7.3	0.02	0.04	5.3	0.8	0.57
T5	8.9	0.04	0.03	5.2	0.6	0.61
T6	8.6	0.05	0.04	6.7	9.1	0.66
T7	10.1	0.06	0.04	11.4	6.8	0.61
T8	9.9	0.05	0.04	8.2	4.4	0.68
T9	9.4	0.05	0.04	11.8	3.2	0.49
T10	7.7	0.05	0.05	5.5	3.0	1.16
T11	7.6	0.07	0.04	7.4	2.6	0.77
T12	9.3	0.07	0.03	6.4	5.5	0.63
T13	10.7	0.06	0.06	6.1	3.2	0.95
T14	8.4	0.07	0.07	6.2	5.5	0.27
T15	10.2	0.04	0.07	6.5	3.9	0.52
T16	9.5	0.05	0.06	8.2	3.3	1.49
T17	8.5	0.06	0.08	5.6	8.5	0.53
T18	8.7	0.04	0.03	5.4	5.9	0.68
T19	6.1	0.03	0.05	9.6	8.8	0.53
T20	11.8	0.03	0.04	6.7	5.8	0.59
T21	7.5	0.04	0.03	7.4	4.8	0.77
T22	11.8	0.05	0.05	7.2	3.3	0.65
T23	11.8	0.04	0.04	11.3	7.2	0.42
T24	10.6	0.14	0.04	8.4	8.6	0.66
T25	7.5	0.05	0.15	6.3	9.9	0.66
T26	9.9	0.07	0.04	6.7	4.2	0.69
T27	10.3	0.08	0.03	6.3	4.0	0.87
T28	9.2	0.06	0.02	8.3	2.1	0.70
T29	9.1	0.06	0.05	7.3	7.5	0.61
T30	9.6	0.05	0.06	9.5	6.5	0.59

[Table 6]

Electrode No.	Weldability	0.2% proof stress (MPa)	Tensile strength (MPa)	Weld metal oxygen content (% by mass)	vTrs (°C)	CTOD at -40°C (mm)	Total judgment
E1	○	524	632	0.018	-90	0.45	○
E2	○	565	688	0.019	-95	0.34	○
E3	○	526	645	0.020	-85	0.52	○
E4	○	521	632	0.016	-80	0.43	○
E5	○	533	641	0.019	-105	0.45	○
E6	○	532	631	0.016	-110	0.69	○
E7	○	524	626	0.016	-100	0.69	○
E8	○	516	642	0.017	-105	0.56	○
E9	○	524	625	0.018	-110	0.32	△
E10	○	590	682	0.015	-90	0.35	△
E11	○	528	631	0.019	-100	0.52	○
E12	○	583	692	0.017	-90	0.38	○
E13	○	523	627	0.016	-85	0.34	△
E14	○	574	678	0.016	-95	0.47	○
E15	○	523	629	0.016	-110	0.51	○
E16	○	620	708	0.015	-80	0.28	△
E17	○	523	643	0.017	-100	0.54	○
E18	○	528	643	0.017	-105	0.57	○
E19	○	531	638	0.016	-100	0.62	○
E20	○	527	643	0.020	-95	0.53	○
E21	○	528	632	0.016	-100	0.49	○
E22	○	532	635	0.016	-105	0.57	○
E23	○	524	645	0.016	-100	0.61	○
E24	○	526	632	0.024	-80	0.36	△
E25	○	552	663	0.017	-100	0.41	○
E26	○	563	675	0.017	-85	0.39	○

[Table 7]

Electrode No.	Weldability	0.2% proof stress (MPa)	Tensile strength (MPa)	Weld metal oxygen content (% by mass)	vTrs (°C)	CTOD at -40°C (mm)	Total judgment
T1	○	465	586	0.019	-80	-	×
T2	×	-	-	-	-	-	×
T3	○	527	632	0.022	-70	0.12	×
T4	×	-	-	-	-	-	×
T5	×	-	-	-	-	-	×
T6	×	-	-	-	-	-	×
T7	○	510	625	0.025	-65	0.08	×
T8	×	-	-	-	-	-	×
T9	△	485	598	0.020	-90	-	×
T10	○	534	649	0.016	-85	0.08	×
T11	○	487	591	0.017	-90	-	×
T12	○	541	653	0.016	-80	0.07	×
T13	○	492	601	0.016	-75	-	×
T14	○	548	652	0.017	-90	0.09	×
T15	○	501	602	0.020	-85	-	×
T16	○	540	672	0.016	-80	0.06	×
T17	○	532	640	0.017	-90	0.09	×
T18	○	535	636	0.017	-85	0.08	×
T19	×	-	-	-	-	-	×
T20	×	-	-	-	-	-	×
T21	×	-	-	-	-	-	×
T22	×	-	-	-	-	-	×
T23	×	-	-	-	-	-	×
T24	○	551	667	0.017	-65	0.07	×
T25	○	562	673	0.017	-70	0.07	×
T26	○	486	587	0.020	-95	-	×
T27	○	532	638	0.016	-90	0.14	×
T28	○	513	623	0.017	-85	0.08	×
T29	○	526	632	0.016	-80	0.09	×
T30	○	532	629	0.016	-85	0.09	×

As shown in Tables 2 to 7 described above, Examples E1 to E26 had excellent weldability because the chemical compositions of steel core wires and coating fluxes, and the coating ratios thereof fell within the scope of the invention. Further, Examples E1 to E26 had excellent

strength and fracture toughness because the hydrogen content and oxygen content of the weld metal were sufficiently reduced. The CTOD value at -40 °C was sufficiently high, for example, 0.28 mm or more.

In contrast, in Comparative Example T1, the coating ratio was less than the lower limit of the scope of the invention, thus making the strength of the weld metal insufficient, whereby a CTOD test was cancelled. In Comparative Example T2, the coating ratio was equal to or more than the upper limit of the scope of the invention, thus reducing the weldability, whereby the test was cancelled. In Comparative Example T3, the metal carbonate content of the coating flux was equal to or less than a prescribed range of the invention, so that the oxygen content of the weld metal was increased thereby to reduce the fracture toughness. In Comparative Example T4, the metal carbonate content of the coating flux exceeded the upper limit of the prescribed range of the invention, so that the shape of a bead became convex.

In Comparative Example T5, the fluoride content of the coating flux was less than the lower limit of the prescribed range of the invention, so that the shape of a bead became convex. In Comparative Example T6, since the fluoride content of the coating flux exceeded the upper limit of a prescribed range of the invention, the arc became unstable, which degraded the weldability.

In Comparative Example T7, since the Mg content of the coating flux was less than the lower limit of a prescribed range of the invention, the weld metal had the higher oxygen content, and thus did not obtain good fracture toughness. In Comparative Example T8, since the Mg content of the coating flux exceeded the upper limit of the prescribed range of the invention, the arc became stronger, which degraded the

weldability.

In Comparative Examples T9, T11, T13, and T15, the Si content, the Mn content, the Ni content, and the Ti content of the respective coating fluxes were less than the lower limits of the respective prescribed ranges of the invention, so that the tensile strength of each weld metal was insufficient. In Comparative Examples T10, T12, T14, and T16, the Si content, the Mn content, the Ni content, and the Ti content of the respective coating fluxes exceeded the upper limits of the respective prescribed ranges of the invention, so that the tensile strength of each weld metal was increased, while the fracture toughness thereof was degraded.

In Comparative Examples T17 and T18, the B contents of the coating fluxes were less than the lower limit, and equal to or more than the upper limit of the prescribed range of the invention, respectively. These comparative examples did not exhibit the effect of making the structure finer, and thus reduced the fracture toughness of the weld metals. In Comparative Examples T19 and T21, the SiO_2 content and the TiO_2 content of the respective coating fluxes were less than the respective lower limits of the prescribed ranges of the invention, respectively, whereby the amount of slag was small and the weldability became worse. In Comparative Examples T20 and T23, the SiO_2 content and the Al_2O_3 content of the respective coating fluxes exceeded the upper limits of the prescribed ranges of the invention, respectively, which made the removability of the slag worse and degraded the weldability. In Comparative Example T22, the TiO_2 content of the coating flux exceeded the upper limit of the prescribed range of the invention, which made the shape of the bead convex, and degraded the weldability. In

Comparative Example T24, since the total amount of acidic oxides in the coating flux exceeded the upper limit of the prescribed range of the invention, the oxygen content of the weld metal became higher, and the fracture toughness thereof was reduced.

Since in Comparative Examples T24 and T25, the Cr content and Mo content of the respective coating fluxes exceeded the upper limits thereof, the low-temperature toughness and the fracture toughness were low. In Comparative Example T26, the C content of the steel core wire was equal to or less than the lower limit of the scope of the invention, whereby the tensile strength of the weld metal became insufficient and the oxygen content of the weld metal was increased. Then, a CTOD test was cancelled. In Comparative Examples T27 to T30, since the elements C, P, S, and N of the respective steel core wires exceeded the upper limits of the scope of the invention, the low-temperature toughness and fracture toughness of each weld metal were reduced. Comparative Examples T1 to T30 described above had the maximum CTOD value of 0.14 mm at -40 °C, which was much lower than the CTOD value of the invention at -40 °C.

Examples having the total evaluation of Δ were five examples E9, E10, E13, E16, and E24. In these Examples, the CTOD value was equal to or less than 0.36 mm. The reasons for such evaluations were as follows: in E24, the total amount of acidic oxides was excessively large; in E10 and E16, the "A" value was excessively large; in E9, the "A" value was excessively small and the value of A13 takes the upper limit in a preferable range of "A" value.

What is claimed is:

1. A low-hydrogen coated electrode, comprising a steel core wire with a coating flux applied thereto,

wherein the steel core wire contains, relative to a total mass of the steel core wire,

more than 0.05 % by mass but not more than 0.10 % by mass of C,

0.010 % by mass or less of P,

0.010 % by mass or less of S, and

0.005 % by mass or less of N,

wherein the coating flux contains, relative to a total mass of the coating flux,

15 to 28 % by mass of a metal carbonate in terms of CO_2 ,

4 to 9 % by mass of a metal fluoride in terms of F,

4.0 to 9.0 % by mass of SiO_2 ,

0.5 to 5.0 % by mass of TiO_2 ,

0.5 to 3.0 % by mass of Mg in terms of Mg as a single metal or an alloy,

1.0 to 7.0 % by mass of Si,

0.5 to 5.0 % by mass of Mn,

2.0 to 10.0 % by mass of Ni,

0.3 to 3.0 % by mass of Ti,

0.05 to 0.20 % by mass of B,

5.0 to 20.0 % by mass of Fe,

2.0 % by mass or less of Al_2O_3 ,

0.1 % by mass or less of Mo, and

0.1 % by mass or less of Cr, said Al_2O_3 content, said Mo content, and said Cr content being defined as above,

wherein, in addition to the above elements, the coating flux further contains an arc stabilizer, a slag formation agent, and a binder, and

wherein a coating ratio of the coating flux is 25 to 45 % as a mass ratio of the coating flux relative to a total mass of the electrode.

2. The low-hydrogen coated electrode according to claim 1, wherein the total amount of the SiO_2 , TiO_2 , and Al_2O_3 as an acidic oxide in the coating flux is equal to or less than 12 % by mass.

3. The low-hydrogen coated electrode according to claim 1 or 2, wherein an A value determined by the following formula is 0.30 to 0.70:

$$A = ([C] \times 10 + 1.8 \times [\text{Si}] + [\text{Mn}]) / \{(1 + [\text{Ni}]) \times (0.5 + [\text{Ti}])\}$$

where [C] is a C content (% by mass), [Si] is a Si content (% by mass), [Mn] is a Mn content (% by mass), [Ni] is a Ni content (% by mass), and [Ti] is a Ti content (% by mass), relative to the total mass of the electrode.