

LOW-HYDROGEN COVERED ELECTRODE

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a low-hydrogen covered electrode, which is a steel core wire covered with a low-hydrogen coating. More particularly, the present invention relates to a technique of improving the performance of a weld metal in shielded metal-arc welding.

2. Description of the Related Art

Various studies are being performed to improve the performance of weld metals in connection with low-hydrogen covered electrodes, which are steel core wires covered with a low-hydrogen coating (see, for example, Japanese Unexamined Patent Application Publications No. 3-285793, No. 7-251294, and No. 2010-227968). In a low-hydrogen covered electrode described in Japanese Unexamined Patent Application Publication No. 3-285793, in order to improve the toughness of a weld metal, the core wire has a particular N content and a particular C content, the coating contains particular amounts of CO₂, Mg, and acidic oxides, the coverage ranges from 26% to 45%, and the electrode has particular Mn, Ni, Al, and P contents.

In a low-hydrogen covered electrode described in Japanese Unexamined Patent Application Publication No. 7-251294, in order to improve the welding performance and the toughness and ductility of a weld metal by the introduction of Ni from the coating, Ni and a Ni alloy in the coating have a particular particle size and a particular composition. In a low-hydrogen covered electrode described in Japanese Unexamined Patent Application Publication No. 2010-227968, in order to improve the low-temperature fracture toughness of a weld metal in welding of a high-strength steel having a tensile strength of 590 MPa or more, the steel core wire and the coating have particular compositions.

Sour corrosion problems, such as sulfide stress corrosion cracking and hydrogen embrittlement, need to be dealt with in the exploitation of oil and gas resources and the transportation of oil and gas. To address these problems, the National Association of Corrosion Engineers (NACE) standards limit the Ni content of weld metals to 1% by mass or less. In the known low-hydrogen covered electrodes described above, however, Ni imparts toughness to weld metals, and weld metals have a Ni content of more than 1% by mass, which does not conform to the NACE standards.

In the low-hydrogen covered electrode described in Japanese Unexamined Patent

Application Publication No. 3-285793, the addition of metal Mg imparts toughness to the weld metal even at a low oxygen content. However, the addition of metal Mg induces the occurrence of spatters or deterioration of coatability, thereby adversely affecting welding performance.

SUMMARY OF THE INVENTION

Accordingly, it is a principal object of the present invention to provide a low-hydrogen covered electrode that can produce a weld metal having satisfactory low-temperature toughness even at a Ni content of 1% by mass or less.

A low-hydrogen covered electrode according to one aspect of the present invention includes a steel core wire covered with a coating. The coating coverage ranges from 10% to 40% by mass of the electrode. The coating contains a metal carbonate (based on CO₂): 10% to 30% by mass, a metal fluoride (based on F): 2% to 13% by mass, TiO₂: 1% to 7% by mass, at least one selected from the group consisting of Si, Si alloys, and Si oxides (based on Si): 1.9% to 11.7% by mass in total, Ni and/or a Ni alloy (based on Ni): 0.5% to 3.5% by mass in total, Mo and/or a Mo alloy (based on Mo): 0.11% to 0.45% by mass in total, at least one selected from the group consisting of B, B alloys, and B oxides (based on B): 0.02% to 0.25% by mass in total, Ti and/or a Ti alloy (based on Ti): 0.2% to 1.0% by mass in total, at least one selected from the group consisting of Al, Al alloys, Mg, and Mg alloys (based on Al and Mg): 0.2% to 1.8% by mass in total, Mn and/or a Mn alloy (based on Mn): 1% to 7% by mass, and Fe: 3% to 11% by mass, on a coating mass basis.

The coating may satisfy the following mathematical formula (A):

$$0.3 \leq \frac{[Ni] + [Ti] + [B]}{[Mo] + [Mn]} \leq 1.2$$

wherein [Ni] denotes the Ni and Ni alloy content (based on Ni), [Ti] denotes the Ti and Ti alloy content (based on Ti), [B] denotes the B, B alloy, and B oxide content (based on B), [Mo] denotes the Mo and Mo alloy content (based on Mo), and [Mn] denotes the Mn and Mn alloy content (based on Mn).

A low-hydrogen covered electrode according to one aspect of the present invention can be used in welding of a high-strength steel having a tensile strength of 550 MPa or more.

In accordance with the present invention, a low-hydrogen covered electrode having a particular coating composition and a particular coverage can produce a weld metal having satisfactory low-temperature toughness even at a Ni content of 1% by mass

or less.

BRIEF DESCRIPTION OF THE DRAWING

Figure 1 is a graph of the relationship between the ratio of the Mo and Mn content to the Ni, Ti, and B content of the coatings of covered electrodes according to Examples 1 to 15 and weld metal performance, wherein the horizontal axis represents the Mo and Mn content of the coating, and the vertical axis represents the Ni, Ti, and B content of the coating.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Embodiments of the present invention will be described in detail below. The present invention is not limited to these embodiments.

A low-hydrogen covered electrode according to an embodiment of the present invention includes a steel core wire covered with a coating, wherein the coating coverage ranges from 10% to 40% by mass of the electrode. The coating contains a metal carbonate (based on CO₂): 10% to 30% by mass, a metal fluoride (based on F): 2% to 13% by mass, TiO₂: 1% to 7% by mass, at least one selected from the group consisting of Si, Si alloys, and Si oxides (based on Si): 1.9% to 11.7% by mass in total, Ni and/or a Ni alloy (based on Ni): 0.5% to 3.5% by mass in total, Mo and/or a Mo alloy (based on Mo): 0.11% to 0.45% by mass in total, at least one selected from the group consisting of B, B alloys, and B oxides (based on B): 0.02% to 0.25% by mass in total, Ti and/or a Ti alloy (based on Ti): 0.2% to 1.0% by mass in total, at least one selected from the group consisting of Al, Al alloys, Mg, and Mg alloys (based on Al and Mg): 0.2% to 1.8% by mass in total, Mn and/or a Mn alloy (based on Mn): 1% to 7% by mass, and Fe: 3% to 11% by mass, on a coating mass basis.

[Steel Core Wire]

The type of steel core wire can be appropriately selected in a manner that depends on the base material and welding conditions. For example, when a high-strength steel having a tensile strength of 550 MPa or more is welded, a mild steel core wire is preferably used in terms of manufacturing and cost. One specific example of the mild steel core wire for use in the low-hydrogen covered electrode according to the present embodiment is SWRY 11 specified in JIS G3503.

[Coating Coverage Based on Mass of Electrode: 10% to 40% by mass]

The coating coverage (%) of covered electrodes is calculated from (mass of coating (% by mass)/mass of electrode (% by mass)) x 100. A coverage of less than 10% by mass

results in insufficient shielding, a high N content and a high hydrogen content of the weld metal, and low toughness and cracking resistance of the weld metal. A coverage of more than 40% by mass results in a long arc length and arc interruption. Thus, the coating coverage of a low-hydrogen covered electrode according to the present embodiment ranges from 10% to 40% by mass.

The reason for limiting the components of the coating of a low-hydrogen covered electrode according to the present embodiment will be described below. The component contents described below are based on the total mass of the coating.

[Metal Carbonate (Based on CO_2): 10% to 30% by Mass]

Metal carbonates can decompose during welding and produce CO_2 . Because of the shielding effect of CO_2 , metal carbonates can reduce the N content and the hydrogen content of the weld metal. However, a metal carbonate content of less than 10% by mass results in an insufficient shielding effect, and a metal carbonate content of more than 30% by mass results in frequent occurrence of spatters. Thus, the metal carbonate content ranges from 10% to 30% by mass based on CO_2 .

[Metal Fluoride (Based on F): 2% to 13% by Mass]

Metal fluorides are indispensable for maintaining porosity resistance and also act as slag forming agents. However, a metal fluoride content of less than 2% by mass results in low porosity resistance, and a metal fluoride content of more than 13% by mass results in unstable arc, making vertical upward welding difficult. Thus, the metal fluoride content ranges from 2% to 13% by mass based on F.

[TiO_2 : 1% to 7% by Mass]

TiO_2 is added as a slag forming agent in order to maintain workability in all positions, particularly vertical welding. However, a TiO_2 content of less than 1% by mass results in difficult vertical upward welding, and a TiO_2 content of more than 7% by mass results in an excessively high viscosity and low porosity resistance. Thus, the TiO_2 content ranges from 1% to 7% by mass.

[At Least One of Si, Si Alloys, and Si Oxides (Based on Si): 1.9% to 11.7% by Mass in Total]

Si added in the form of a metal or an alloy reacts with oxygen in the weld metal because of the deoxidation effect and produces SiO_2 . SiO_2 acts as a binder or a slag forming agent. Si added in the form of Si oxide also acts as a binder or a slag forming agent.

However, a Si, Si alloy, and Si oxide content of less than 1.9% by mass based on Si results in difficult vertical upward welding for the lack of slag. A Si, Si alloy, and Si

oxide content of more than 11.7% by mass based on Si results in the formation of glassy slag and low slag detachability. Thus, the Si, Si alloy, and Si oxide content ranges from 1.9% to 11.7% by mass based on Si.

The coating contains at least one of metal Si, Si alloys, and Si oxides. Examples of the Si alloys to be added to the coating include iron alloys, such as Fe-Si and Fe-Si-B.

[Ni and/or Ni Alloy (Based on Ni): 0.5% to 3.5% by Mass in Total]

Ni and Ni alloys are effective in improving the proof stress and low-temperature toughness of the weld metal. However, a Ni and Ni alloy content of less than 0.5% by mass results in a decrease in this effect, and a Ni and Ni alloy content of more than 3.5% by mass results in frequent occurrence of hot cracking (solidification cracking). Thus, the Ni and Ni alloy content ranges from 0.5% to 3.5% by mass based on Ni.

In order to improve the proof stress and low-temperature toughness of the weld metal, the Ni and Ni alloy content is preferably 1.0% by mass or more. In order to improve hot cracking resistance, the Ni and Ni alloy content is preferably 3.0% by mass or less. The Ni and Ni alloy content of the coating of a low-hydrogen covered electrode according to the present embodiment is preferably controlled so that the Ni content of the weld metal is 1% by mass or less in conformity with the NACE standards.

The coating contains at least one of metal Ni and Ni alloys. The Ni component added to the coating is generally in the form of a metal Ni powder or a Ni alloy powder, such as a Ni-Mg powder.

[Mo and/or Mo Alloy (Based on Mo): 0.11% to 0.45% by Mass in Total]

Mo and Mo alloys are effective in ensuring the hardenability of the weld metal. However, a Mo and Mo alloy content of less than 0.11% by mass results in a decrease in this effect, and a Mo and Mo alloy content of more than 0.45% by mass results in significantly high hardenability and low toughness of the weld metal. Thus, the Mo and Mo alloy content ranges from 0.11% to 0.45% by mass based on Mo.

In order to improve the hardenability and strength of the weld metal, the Mo and Mo alloy content is preferably 0.15% by mass or more. In order to impart toughness to the weld metal, the Mo and Mo alloy content is preferably 0.40% by mass or less. The coating contains at least one of metal Mo and Mo alloys. The Mo component added to the coating is generally in the form of an iron alloy, such as Fe-Mo.

[At Least One of B, B Alloys, and B Oxides (Based on B): 0.02% to 0.25% by Mass in Total]

B, B alloys, and B oxides segregate in prior γ grain boundaries and reduce the formation of grain boundary ferrite, thereby improving the toughness of the weld metal.

However, a B, B alloy, and B oxide content of less than 0.02% by mass based on B results in an insufficient improvement in the toughness of the weld metal. A B, B alloy, and B oxide content of more than 0.25% by mass based on B results in low hot cracking resistance of the weld metal. Thus, the B, B alloy, and B oxide content ranges from 0.02% to 0.25% by mass based on B.

In order to further enhance the effect of improving toughness, the B, B alloy, and B oxide content is preferably 0.06% by mass or more. In order to improve hot cracking resistance, the B, B alloy, and B oxide content is preferably 0.20% by mass or less. The coating contains at least one of metal B, B alloys, and B oxides. The B component added to the coating is generally in the form of an Fe alloy, such as Fe-Si-B, or a B oxide.

[Ti and/or Ti Alloy (Based on Ti): 0.2% to 1.0% by Mass in Total]

Ti and Ti alloys are present as an oxide or solid solution in the weld metal. As nuclei of acicular ferrite in prior γ grains, a Ti oxide contributes to improved toughness of the weld metal. More specifically, the addition of Ti or a Ti alloy to the coating results in the formation of acicular ferrite having Ti oxide nuclei in prior γ grains. Acicular ferrite contributes to the formation of finer structures and improves the toughness of the weld metal.

However, a Ti and Ti alloy content of less than 0.2% by mass results in insufficient formation of acicular ferrite and low toughness of the weld metal because of the coarsening of ferrite. A Ti and Ti alloy content of more than 1.0% by mass results in excessive formation of Ti solid solution, an excessively high strength of the weld metal, and low toughness of the weld metal. Thus, the Ti and Ti alloy content ranges from 0.2% to 1.0% by mass based on Ti.

In order to improve the toughness of the weld metal, the Ti and Ti alloy content is preferably 0.4% by mass or more. In order to enhance the effect of inhibiting toughness degradation, the Ti and Ti alloy content is preferably 0.8% by mass or less. The coating contains at least one of metal Ti and Ti alloys. The Ti component added to the coating is generally in the form of an Fe alloy, such as Fe-Ti.

[At Least One of Al, Al Alloys, Mg, and Mg Alloys (Based on Al and Mg): 0.2% to 1.8% by Mass in Total]

Al, Al alloys, Mg, and Mg alloys, which are strong deoxidizers, can reduce the oxygen content of the weld metal and improve the toughness of the weld metal. However, an Al, Al alloy, Mg, and Mg alloy content of less than 0.2% by mass results in an insufficient effect of reducing the oxygen content. An Al, Al alloy, Mg, and Mg alloy content of more than 1.8% by mass results in frequent occurrence of spatters and poor

welding performance.

Thus, the Al, Al alloy, Mg, and Mg alloy content ranges from 0.2% to 1.8% by mass based on Al and Mg. The coating contains at least one of Al, Al alloys, Mg, and Mg alloys. [Mn and/or Mn Alloy (Based on Mn): 1% to 7% by Mass]

Mn and Mn alloys are added to impart strength to the weld metal and for deoxidation. Mn and Mn alloys are also important in producing tough weld metals. However, a Mn and Mn alloy content of less than 1% by mass results in a low strength and low toughness of the weld metal. A Mn and Mn alloy content of more than 7% by mass results in high hardenability and low toughness of the weld metal.

Thus, the Mn and Mn alloy content ranges from 1% to 7% by mass based on Mn. In order to impart strength and toughness to the weld metal, the Mn and Mn alloy content is preferably 3% by mass or more. In order to enhance the effect of inhibiting toughness degradation, the Mn and Mn alloy content is preferably 5% by mass or less. The coating contains at least one of metal Mn and Mn alloys. The Mn component added to the coating is generally in the form of an iron alloy, such as Fe-Mn, or metal Mn. [Fe: 3% to 11% by Mass]

Fe acts as a slag forming agent and an arc stabilizer. However, an Fe content of less than 3% by mass results in excessive slag formation and frequent occurrence of weld defects, such as slag inclusion. An Fe content of more than 11% by mass makes it difficult to add the desired amounts of essential alloy components described above. Thus, the Fe content ranges from 3% to 11% by mass. The Fe component added to the coating is in the form of an iron powder or an Fe alloy.

$$[(\text{Ni}) + (\text{Ti}) + (\text{B})]/[(\text{Mo}) + (\text{Mn})]: 0.3 \text{ to } 1.2]$$

Ni, Ti, and B are effective in improving the low-temperature toughness of the weld metal. Mo and Mn are effective in improving the strength of the weld metal. In order to improve both the strength and the low-temperature toughness of the weld metal, the present inventors extensively studied the blend ratios of these elements. As a result, the present inventors found that a particular ratio of the Ni, Ti, and B content to the Mo and Mn content results in improvement not only in the low-temperature toughness and strength of the weld metal but also in the hot cracking resistance of the weld metal and slag detachability.

More specifically, in a low-hydrogen covered electrode according to the present embodiment, the ratio of the Ni, Ti, and B content to the Mo and Mn content preferably satisfies the following mathematical formula 2. In the mathematical formula 2, [Ni] denotes the Ni and Ni alloy content (based on Ni), [Ti] denotes the Ti and Ti alloy

content (based on Ti), [B] denotes the B, B alloy, and B oxide content (based on B), [Mo] denotes the Mo and Mo alloy content (based on Mo), and [Mn] denotes the Mn and Mn alloy content.

$$0.3 \leq \frac{[Ni] + [Ti] + [B]}{[Mo] + [Mn]} \leq 1.2$$

When the ratio of the Ni, Ti, and B content to the Mo and Mn content $(([Ni] + [Ti] + [B])/([Mo] + [Mn]))$ is less than 0.3, this may increase the hardenability of the weld metal, resulting in a high strength or low toughness of the weld metal. When the ratio of the Ni, Ti, and B content to the Mo and Mn content $(([Ni] + [Ti] + [B])/([Mo] + [Mn]))$ is more than 1.2, this may result in a low strength of the weld metal due to poor hardenability or low hot cracking resistance or slag detachability.

When the ratio of the Ni, Ti, and B content to the Mo and Mn content $(([Ni] + [Ti] + [B])/([Mo] + [Mn]))$ ranges from 0.3 to 1.2, the addition of Ni and the addition of Ti and B in combination suppress the coarsening of the structure due to a structure control effect and increase the toughness of the weld metal while the weld metal maintains satisfactory hardenability and strength. The addition can also prevent the occurrence of hot cracking and improve welding performance, such as slag detachability. Thus, a weld metal having satisfactory low-temperature toughness, strength, and hot cracking resistance can be produced even at a Ni content of 1% by mass or less.

The ratio of the Ni, Ti, and B content to the Mo and Mn content $(([Ni] + [Ti] + [B])/([Mo] + [Mn]))$ is preferably 0.4 or more. This reduces an excessive increase in the strength of the weld metal and enhances the effect of preventing toughness degradation. In order to improve hot cracking resistance and avoid low slag detachability, the ratio of the Ni, Ti, and B content to the Mo and Mn content $(([Ni] + [Ti] + [B])/([Mo] + [Mn]))$ is more preferably 0.9 or less.

[Other Components]

In addition to the components described above, the coating may contain an organic substance, such as starch, pulp, and/or cellulose, and/or an inorganic substance, such as potassium silicate and/or sodium silicate, as a binder. The binder content preferably ranges from 0.2% to 4.0% by mass of the coating in order to improve workability. It is desirable that the coating contain substantially no silicate containing water of crystallization, such as mica, talc, or sericite, because such a silicate increases the hydrogen content of the weld metal.

The coating may contain Na₂O and/or K₂O as an arc stabilizer. The arc stabilizer

content preferably ranges from 0.5% to 4.0% by mass of the coating in order to improve workability.

[Manufacturing Method]

A low-hydrogen covered electrode according to the present embodiment is manufactured by covering a steel core wire with a coating having the composition described above using a common electrode coating machine such that the coverage ranges from 10% to 40% by mass. In order to improve workability, the coating preferably contains a binder, for example, water glass, such as sodium silicate and/or potassium silicate. The steel core wire covered with the coating is then baked at a temperature in the range of 350°C to 550°C to remove water in the coating, thereby forming a low-hydrogen covered electrode. The steel core wire may be SWRY 11 specified in JIS G3503 as described above.

As described in detail above, a low-hydrogen covered electrode having a particular coating composition and a particular coverage according to the present embodiment can produce a weld metal having satisfactory low-temperature toughness even at a Ni content of 1% by mass or less. This low-hydrogen covered electrode also has high welding performance and is particularly suitable for welding of a high-strength steel having a tensile strength of 550 MPa or more.

When the coating composition has a ratio of the Ni, Ti, and B content to the Mo and Mn content that satisfies the mathematical formula 2, this can lower the brittle fracture transition temperature and reduce strength degradation. Thus, the resulting weld metal can have high low-temperature toughness and strength. The weld metal may have a Ni content that conforms to the NACE standards and have improved hot cracking resistance. This can further improve the safety of structures used in low-temperature environments.

EXAMPLES

The advantages of the present invention will be more specifically described with reference to examples and comparative examples of the present invention. In the present example, a mild steel core wire (having a diameter of 4.0 mm and a length of 400 mm) was covered with a coating having the composition listed in the following Table 1 using an electrode coating machine. The coating was baked at 470°C for approximately one hour. Low-hydrogen covered electrodes according to Examples and Comparative Examples were thus manufactured. The coverages of the electrodes according to Examples and Comparative Examples are listed in Table 1. In Table 1, the coatings No. 1 to No. 15 are within the scope of the present invention, and the coatings No. 16 to No.

22 are outside the scope of the present invention.

[Table 1]

No.	Cover age (% by mass)	Coating composition (% by mass)																	(Ni+Ti+B) (Mo+Mn)		
		Metal carbonate				Metal fluoride		Si component				TiO ₂	Ni	Mo	B	Al-Mg		Ti		Mn	Fe
		CaCO ₃	BaCO ₃	Based on CO ₂	CaF ₂	Based on F	SiO ₂	Si	Based on Si	Al	Mg										
1	28	36	13	21	15	7	6.0	4.0	6.8	4	2.1	0.25	0.10	0.6	0.3	0.6	4	7	0.7		
2	25	41	-	15	18	9	10.0	3.0	7.7	2	0.6	0.11	0.05	0.6	0.6	0.4	1	11	0.9		
3	40	38	9	18	4	2	5.0	3.0	5.3	5	3.0	0.34	0.25	0.1	0.1	0.3	3	3	1.1		
4	30	52	-	26	12	6	7.0	7.0	10.3	5	1.8	0.27	0.15	0.5	1.0	0.5	6	8	0.4		
5	10	45	-	19	26	13	2.0	6.0	6.9	1	0.5	0.12	0.02	1.0	0.8	0.7	4	5	0.3		
6	18	46	6	23	20	10	8.0	1.0	4.7	7	3.3	0.45	0.20	0.7	0.4	0.5	7	9	0.5		
7	20	38	-	12	10	5	8.0	5.0	8.7	6	3.5	0.20	0.18	0.2	0.6	0.2	3	10	1.2		
8	27	37	-	11	8	4	9.0	4.0	8.2	3	3.0	0.12	0.05	1.0	0.3	0.5	2	10	2.2		
9	30	46	-	20	16	8	8.0	5.0	8.7	2	0.5	0.30	0.17	0.8	0.8	0.7	7	6	0.2		
10	18	46	8	25	18	9	7.0	3.0	6.3	6	1.0	0.45	0.20	0.9	0.2	0.5	7	9	0.2		
11	20	41	-	15	14	7	6.0	1.0	3.8	4	3.2	0.20	0.23	0.5	0.3	1.0	3	10	1.4		
12	26	39	-	10	6	6	7.0	5.0	8.3	5	2.0	0.15	0.04	-	0.2	0.5	4	8	0.6		
13	35	41	-	18	17	9	4.0	5.0	6.9	6	0.5	0.35	0.12	-	1.8	1.0	2	11	0.7		
14	24	40	7	26	20	5	8.0	3.0	6.7	7	0.9	0.25	0.20	0.2	-	0.8	5	11	0.4		
15	22	40	-	14	10	11	3.0	4.0	5.4	5	2.2	0.30	0.13	1.8	-	1.0	5	8	0.6		
16	24	31	-	5	22	11	4	-	1.87	3	1.2	0.40	-	0.5	0.5	0.3	10	6	0.1		
17	22	36	13	20	40	20	7	4	7.3	2	-	0.33	0.12	-	-	3.0	4	10	0.7		
18	8	43	-	17	16	8	10	4	8.7	-	0.5	0.45	0.12	1.0	2.0	0.5	0	5	2.5		
19	30	46	11	28	20	10	-	7	7.0	5	5.0	0.80	0.15	0.9	0.8	0.5	5	7	1.0		
20	26	39	-	13	-	-	4	10	11.9	7	3.5	0.25	0.40	0.2	0.5	0.7	2	20	2.0		
21	45	63	-	37	14	7	9	2	6.2	10	1.8	0.30	0.20	0.1	0.3	0.6	3	-	0.8		
22	36	44	-	18	18	9	15	5	12.0	5	3.2	-	0.08	0.8	0.8	-	6	8	0.5		

The covered electrodes according to Examples and Comparative Examples thus manufactured were tested with respect to various properties. Each test will be specifically described below.

<Test 1: All-Weld Metal Welding>

A steel sheet having the composition listed in the following Table 2 (the remainder were Fe and incidental impurities) was used as a base material. The steel sheet was welded with each of the covered electrodes according to Examples and Comparative Examples under the conditions listed in the following Table 3. The mechanical properties and chemical components of the weld metal were examined using the test methods listed in the following Table 4. With respect to mechanical properties, a 0.2% proof stress of 460 MPa or more, a tensile strength of 560 MPa or more, and an absorbed energy of 47 J or more at -60°C are acceptable.

[Table 2]

Base material	Thickness (mm)	Chemical component (% by mass)									
		C	Si	Mn	P	S	Ni	Cr	Mo	Ti	B
SM490A	20	0.15	0.32	1.34	0.010	0.001	0.01	0.03	-	-	-

[Table 3]

Groove shape	20° V groove Root gap: 16 mm With backing strip
Material to be welded	Covered electrode of Examples and Comparative Examples Rod diameter: 4.0 mm
Buttering	Buttering two layers within groove and steel backing of material to be welded.
Welding position	Flat welding
Welding conditions	Electric current: 140 to 150 A, Voltage: appropriate Welding heat input: 1.5 to 2.5 kJ/mm
Number of laminated layers	8 layers 16 passes
Preheating and interpass temperature	90 to 110°C

[Table 4]

Mechanical properties	Tensile test	JIS Z3111 A1 test specimen Sampling position: Center of weld metal and center of thickness Test temperature: room temperature (20 to 23°C)
	Impact test	JIS Z3111 4 test specimen Sampling position: Center of weld metal and center of thickness Test temperature: -60°C
Chemical component analysis		Analysis method: JIS G 1253 and JIS Z 2613 Analysis position: Center of weld metal and center of thickness

<Test 2: Vertical Upward Welding Test>

The steel sheet having the composition listed in Table 2 was used as a base material. Vertical upward welding of the steel sheet was performed with the covered electrodes according to Examples and Comparative Examples under the conditions listed in the following Table 5. The welding performance was evaluated in terms of "smoothness on the surface of bead", "equality in leg length", and "bead wetting".

[Table 5]

Groove shape	T-type fillet welding
Steel sheet size	Flat sheet: thickness 20 mm × width 100 mm × length 450 mm
Material to be welded	Covered electrodes of Examples and Comparative Examples Rod diameter: 4.0 mm
Welding position	Vertical upward fillet welding
Welding conditions	Electric current: 120 to 130 A, Voltage: appropriate
Preheating and interpass temperature	Room temperature

<Test 3: Fillet Welding Test>

The steel sheet having the composition listed in Table 2 was used as a base material. Fillet welding of the steel sheet was performed with the covered electrodes according to Examples and Comparative Examples under the conditions listed in the following Table 6. The welding performance was evaluated in terms of "slag detachability", "occurrence of spatters", and "porosity resistance".

[Table 6]

Groove shape	T-type fillet welding
Base material	A steel sheet coated with 15 μm of an inorganic zinc primer was subjected to the test.
Steel sheet size	Flat sheet: thickness 20 mm $\times$ width 100 mm $\times$ length 450 mm
Material to be welded	Covered electrodes of Examples and Comparative Examples Rod diameter: 4.0 mm
Welding position	Horizontal fillet welding
Welding conditions	Electric current: 150 A
Number of laminated layers	1 layer 1 pass (both sides were welded)
Preheating temperature	Room temperature to 100°C

<Test 4: Hot Cracking Resistance>

The steel sheet having the composition listed in Table 2 was used as a base material. The steel sheet was welded with the covered electrodes according to Examples and Comparative Examples under the conditions listed in the following Table 7. The hot cracking resistance of the weld metal was evaluated in the Fisco test. A "cracking ratio (%)" of 10% or less is acceptable. The "cracking ratio (%)", as used herein, refers to the ratio of the crack length to the weld bead length (except 10 mm of a crater) (= crack length/weld bead length).

[Table 7]

Groove shape	90° Y Groove Root face: 10 mm Root gap: 2.4 mm
Wire	Covered electrodes of Examples and Comparative Examples Rod diameter: 4.0 mm
Welding position	Flat welding
Welding conditions	150 A
Number of laminated layers	1 layer 1 pass (both sides were welded)
Preheating temperature	Room temperature (20 to 23°C)
Number of repetitions	2

The following Table 8 lists the composition of the weld metal for the covered

electrodes according to Examples and Comparative Examples. The following Table 9 lists the other evaluation results. The remainder of the weld metal composition listed in Table 8 were Fe and incidental impurities. In the "welding performance" in Table 9, circles represent good, and crosses represent poor. Even one "cross" or "fail" in these evaluation items was regarded as a fail (cross mark) in the "overall rating".

[Table 8]

	No.	Chemical component (% by mass)									
		C	Si	Mn	Ni	Mo	Ti	Al	B	O	N
Example	1	0.06	0.31	1.45	0.58	0.10	0.016	0.010	0.0026	0.025	0.0070
	2	0.07	0.28	1.32	0.17	0.04	0.014	0.005	0.0014	0.030	0.0075
	3	0.06	0.29	1.40	0.83	0.14	0.010	0.003	0.0052	0.026	0.0064
	4	0.05	0.38	1.48	0.50	0.11	0.015	0.004	0.0038	0.024	0.0077
	5	0.06	0.35	1.44	0.14	0.05	0.020	0.004	0.0006	0.028	0.0080
	6	0.07	0.24	1.54	0.91	0.20	0.016	0.006	0.0046	0.026	0.0065
	7	0.06	0.33	1.40	0.97	0.09	0.008	0.005	0.0044	0.025	0.0073
	8	0.05	0.32	1.36	0.83	0.04	0.016	0.007	0.0015	0.028	0.0067
	9	0.06	0.33	1.53	0.14	0.12	0.021	0.004	0.0042	0.026	0.0071
	10	0.05	0.29	1.56	0.28	0.18	0.014	0.009	0.0045	0.024	0.0069
	11	0.07	0.25	1.40	0.88	0.08	0.026	0.008	0.0050	0.025	0.0070
	12	0.05	0.32	1.44	0.57	0.06	0.016	0.001	0.0013	0.027	0.0067
	13	0.07	0.30	1.37	0.99	0.16	0.025	0.001	0.0028	0.025	0.0062
	14	0.06	0.31	1.50	0.27	0.09	0.020	0.005	0.0043	0.026	0.0070
	15	0.06	0.27	1.51	0.59	0.12	0.026	0.014	0.0031	0.026	0.0066
Comparative Example	16	0.06	0.20	1.82	0.33	0.15	0.008	0.010	-	0.029	0.0150
	17	0.07	0.30	1.43	-	0.13	0.072	-	0.0031	0.037	0.0083
	18	0.05	0.31	1.00	0.15	0.18	0.015	0.035	0.0030	0.026	0.0180
	19	0.06	0.37	1.47	1.38	0.35	0.017	0.013	0.0040	0.025	0.0061
	20	0.07	0.45	1.35	0.96	0.10	0.021	0.003	0.0105	0.025	0.0075
	21	0.06	0.26	1.39	0.51	0.12	0.020	0.009	0.0045	0.026	0.0087
	22	0.07	0.34	1.50	0.88	-	-	0.003	0.0021	0.030	0.0072

[Table 9]

	No.	Mechanical properties			Welding performance							Overall rating	
		0.2% proof stress (MPa)	Tensile strength (MPa)	Absorbed energy (J)	Vertical upward welding			Slag detachability	Occurrence of spatters	Porosity resistance	Cracking ratio (%)		
					Smoothness on the surface of bead	Equality in leg length	Bead wetting						
Example	1	518	608	169	○	○	○	○	○	○	○	2	◎
	2	470	568	102	○	○	○	○	○	○	○	3	◎
	3	533	625	127	○	○	○	○	○	○	○	1	◎
	4	510	600	154	○	○	○	○	○	○	○	2	◎
	5	484	585	108	○	○	○	○	○	○	○	3	◎
	6	556	653	95	○	○	○	○	○	○	○	4	◎
	7	534	630	100	○	○	○	○	○	○	○	3	◎
	8	470	555	148	○	○	○	○	○	○	○	7	○
	9	534	648	62	○	○	○	○	○	○	○	6	○
	10	530	626	55	○	○	○	○	○	○	○	5	○
	11	460	565	98	○	○	○	○	○	○	○	4	○
	12	555	638	118	○	○	○	○	○	○	○	3	◎
	13	520	616	166	○	○	○	○	○	○	○	4	◎
	14	507	596	145	○	○	○	○	○	○	○	2	◎
	15	515	600	174	○	○	○	○	○	○	○	2	◎
Comparative Example	16	620	734	40	×	×	×	×	×	○	○	2	×
	17	472	567	32	×	×	×	×	○	○	○	3	×
	18	397	506	46	×	×	×	×	×	×	○	11	×
	19	598	707	30	×	×	×	×	×	○	○	24	×
	20	428	526	22	○	○	○	○	×	○	×	38	×
	21	515	632	118	○	○	○	○	×	×	×	2	×
	22	467	554	94	○	○	○	○	×	○	○	1	×
Target value		≥460	≥550	≥47J									

Tables 8 and 9 show that the covered electrodes according to Comparative Examples 16 to 22, which had coating compositions and coverages outside the scope of the present invention, had poor welding performance. The weld metals resulting from the covered electrodes according to Comparative Examples 16 to 20 also had poor mechanical properties.

In contrast, the covered electrodes according to Examples 1 to 15, which included the coatings within the scope of the present invention, had satisfactory welding performance and produced weld metals having satisfactory mechanical properties. In particular, the covered electrodes according to Examples 1 to 7 and 12 to 15, which included the coatings having a ratio of the Ni, Ti, and B content to the Mo and Mn content ($([Ni] + [Ti] + [B])/([Mo] + [Mn])$) in the range of 0.3 to 1.2, had excellent results for all the evaluation items.

Figure is a graph of the relationship between the ratio of the Mo and Mn content to the Ni, Ti, and B content of the coatings of the covered electrodes according to Examples 1 to 15 and their weld metal performance, wherein the horizontal axis represents the Mo and Mn content of the coatings, and the vertical axis represents the Ni, Ti, and B content of the coatings. The figure shows that the covered electrodes that included the coatings having a ratio of the Ni, Ti, and B content to the Mo and Mn content ($([Ni] + [Ti] + [B])/([Mo] + [Mn])$) of less than 0.3 had lower toughness than the covered electrodes in which the ratio was 0.3 or more. The figure also shows that the covered electrodes that included the coatings having a ratio of the Ni, Ti, and B content to the Mo and Mn content ($([Ni] + [Ti] + [B])/([Mo] + [Mn])$) of more than 1.2 tended to have lower strength than the covered electrodes in which the ratio was 1.2 or less.

These results show that the present invention can produce a weld metal having satisfactory low-temperature toughness even at a Ni content of 1% by mass or less.

WHAT IS CLAIMED IS:

1. A low-hydrogen covered electrode including a steel core wire covered with a coating, wherein
the coating coverage ranges from 10% to 40% by mass of the electrode, and
the coating contains on a coating mass basis
a metal carbonate (based on CO₂): 10% to 30% by mass,
a metal fluoride (based on F): 2% to 13% by mass,
TiO₂: 1% to 7% by mass,
at least one selected from the group consisting of Si, Si alloys, and Si oxides (based on Si): 1.9% to 11.7% by mass in total,
Ni and/or a Ni alloy (based on Ni): 0.5% to 3.5% by mass in total,
Mo and/or a Mo alloy (based on Mo): 0.11% to 0.45% by mass in total,
at least one selected from the group consisting of B, B alloys, and B oxides (based on B): 0.02% to 0.25% by mass in total,
Ti and/or a Ti alloy (based on Ti): 0.2% to 1.0% by mass in total,
at least one selected from the group consisting of Al, Al alloys, Mg, and Mg alloys (based on Al and Mg): 0.2% to 1.8% by mass in total,
Mn and/or a Mn alloy (based on Mn): 1% to 7% by mass, and
Fe: 3% to 11% by mass.

2. The low-hydrogen covered electrode according to Claim 1, wherein the coating satisfies the following mathematical formula (A): wherein [Ni] denotes the Ni and Ni alloy content (based on Ni), [Ti] denotes the Ti and Ti alloy content (based on Ti), [B] denotes the B, B alloy, and B oxide content (based on B), [Mo] denotes the Mo and Mo alloy content (based on Mo), and [Mn] denotes the Mn and Mn alloy content (based on Mn).

$$0.3 \leq \frac{[Ni] + [Ti] + [B]}{[Mo] + [Mn]} \leq 1.2 \cdots (A)$$

3. The low-hydrogen covered electrode according to Claim 1 or 2, for use in welding of a high-strength steel having a tensile strength of 550 MPa or more.