

FLUX-CORED WIRE FOR GAS-SHIELDED ARC WELDING

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a flux-cored wire used for gas-shielded arc welding of members to be welded made of mild steel or 490 MPa-class high tensile steel. More particularly, the present invention relates to a flux-cored wire for gas-shielded arc welding, the wire having the following advantages in that: good welding can be carried out at a high welding current without a drop of a molten metal in the vertical and upward progressing of welding; and a weld metal can be obtained which is excellent in the hot cracking resistance of the first layer in the one-side welding and Also excellent in the low temperature toughness in the high heat input welding.

2. Description of the Related Art

A flux-cored wire for gas-shielded arc welding is mainly used for welding members to be welded made of mild steel or 490MPa-class high tensile steel. An amount of the use of the flux-cored wires is increasing year by year, because the wires are excellent in the welding efficiency as well as bead appearances and the welding maneuverability, as compared with a solid wire.

However, the flux-cored wire for gas-shielded arc welding has a tendency in which a hot crack (a solidification crack) is likely to occur in the first layer forming a penetration bead in the one-side welding, because a welding speed of the wire is larger than that of a solid wire. In addition, in the high heat input welding with the input

welding heat of as high as 30 to 60 kJ/cm, it is difficult to secure a weld metal having the good toughness at a low temperature such as -20°C, because a metal oxide such as rutile is contained in a large amount in the wire, all of them not completely floating on as slag during welding, hence remaining as metallic inclusions in the weld metal. Further, when welding is carried out in the vertical and upward progressing of welding at the same welding current as that in the flat welding, a molten metal is likely to drop (a bead is likely to drop).

A flux-cored wire for gas-shielded arc welding in which the following improvements are simultaneously achieved has not conventionally proposed: improvement for a higher current in the vertical and upward progressing of welding; improvement for the hot cracking resistance of the first layer in the one-side welding; and improvement for the low temperature toughness in the high heat input welding.

Hence, an object of the present invention is to provide a flux-cored wire for gas-shielded arc welding used in the gas-shielded arc welding of members to be welded made of mild steel or 490 MPa-class high tensile steel, in which good welding can be carried out at a high welding current without a drop of a molten metal in the vertical and upward progressing of welding; and a weld metal can be obtained which is excellent in the hot cracking resistance of the first layer in one-side welding and further excellent in the low temperature toughness in the high heat input welding where a welding amount is increased.

SUMMARY OF THE INVENTION

The present invention administers the following technical means in order to solve the aforementioned challenge. That is, a flux-cored wire for gas-shielded arc welding with flux being filled in a steel tube made of mild steel or alloy steel, contains, based on the total mass of the wire, 4.5 to 7.0 mass% TiO_2 , 0.11 to 0.29 mass% Ti, 0.30 to 0.70 mass% Mg, 0.02 to 0.08 mass% C, 0.35 to 0.75 mass% Si, 2.20 to 2.85 mass% Mn, and 0.002 to 0.010 mass% B. Also, in the flux-cored wire for gas-shielded arc welding, MgO satisfies the following relation based on the above content of Mg: $[\text{MgO}] + [\text{Mg}] \times 1.66 \leq 2.5 \text{ mass\%}$, assuming contents of Mg and MgO are $[\text{Mg}]$ and $[\text{MgO}]$, respectively.

In the above flux-cored wire for gas-shielded arc welding, it is further preferable that the wire further contains Al_2O_3 so as to satisfy the following relations: $\text{Al} : \leq 0.5 \text{ mass\%}$ based on the total mass of the wire, and $[\text{Al}_2\text{O}_3] + [\text{Al}] \times 1.89 : 0.5 \text{ to } 1.0 \text{ mass\%}$, assuming contents of Al and Al_2O_3 are $[\text{Al}]$ and $[\text{Al}_2\text{O}_3]$, respectively.

Note that each content of the above Ti, Mg, and Al does not contain Ti, Mg, and Al present in the forms of oxides, respectively.

In the above flux-cored wire for gas-shielded arc welding, it is preferable that the wire further contains 0.2 to 1.0 mass% Ni based on the total mass of the wire.

According to the present invention having such features, a flux-cored wire for gas-shielded arc welding used for gas-shielded arc welding of members to be welded made of mild steel or 490 MPa-class high tensile steel, can be provided in which: good welding can be carried out at a high welding current without a drop of a molten metal in the

vertical and upward progressing of welding; and a weld metal can be obtained which is excellent in the hot cracking resistance of the first layer in one-side welding and Also excellent in the low temperature toughness in the high heat input welding where a welding amount is increased.

DETAILED DESCRIPTION OF THE INVENTION

The present invention will be described in detail below. With an intention of solving the above challenge, the present inventors at first attempted to increase an amount of slag mainly made of rutile (TiO_2) in order to eliminate a drop of a molten metal in the vertical and upward progressing of welding. However, the hot cracking resistance of the first layer in the flat and one-Side welding was decreased, while a drop of a molten metal was prevented.

Thus, the inventors further investigated their study with regard to the cause and measures thereof and finally found out that a hot crack was likely to occur because of an increased amount of oxygen in a weld metal. Then, the inventors proceeded to take into consideration with regard to the measures for reducing an amount of oxygen while maintaining the amount of slag.

As a result, it has been found that an amount of oxygen in a weld metal can be reduced and thereby the hot cracking resistance can be improved while maintaining the amount of slag, by adding in the flux an alloy element which is converted to a slag element during welding, instead of adding a required amount of a slag-producing agent, such as TiO_2 and SiO_2 , from the beginning. In the present invention, adding Ti

and Mg is found to be effective, while Mn, Si, Al, Ti or Mg or the like is usually used as a deoxidation agent for a flux-cored wire.

The Ti has the following advantages in that: by acting as a deoxidation agent during welding and reducing an amount of oxygen in a weld metal, the hot cracking resistance of the first layer in the one-side welding can be improved; and with the produced TiO_2 acting as a slag element, a drop of a molten metal can be prevented in the vertical and upward progressing of welding. In addition, Ti has an advantage in that, by remaining slightly in a weld metal, the structure of a weld metal is made fine and the low temperature toughness in the high heat input welding can be improved.

The above Mg has the following great advantages in that: with Almost All Mg acting as a deoxidation agent without remaining in a weld metal, an amount of oxygen in a weld metal can be reduced; and hence, the hot cracking resistance of the first layer in the one-side welding can be improved. Further, MgO produced by a deoxidation action changes the equilibrium state between oxygen and a deoxidation agent, thereby promoting the deoxidation action.

Still further, the low temperature toughness of a weld metal can be improved in the high heat input welding of about 30 to 60 kJ/cm, by appropriately specifying contents of Mg, MgO , C, Si, Mn, and B.

Note that a flux-cored wire for gas-shielded arc welding according to the present invention is used when the shielding gas is CO_2 gas. A content percentage of the flux is suitable in the range of 10 to 18 mass% (based on the total mass of the wire).

Hereinafter, the flux-cored wire for gas-shielded arc welding

of the present invention will be described with regard to the composition thereof and the reasons for which the content percentage is numerically limited. If not specified, the ranges below are based on the total mass of the wire.

[TiO₂: 4.5 to 7.0 mass%]

TiO₂ acts as a slag-producing agent (slag-forming agent). When the content of TiO₂ is below 4.5 mass%, an amount of slag enough to support a molten metal so as to prevent the molten metal from dropping in the vertical and upward progressing of welding, cannot be secured, thereby a bead shape is not good. On the other hand, when the content of TiO₂ is beyond 7.0 mass%, an amount of oxygen in a weld metal is increased, thereby the hot cracking resistance of the first layer in the one-side welding is decreased, and the low temperature toughness is also decreased. Therefore, the content of TiO₂ should be specified as 4.5 to 7.0 mass%.

[Ti: 0.11 to 0.29 mass%]

As mentioned above, Ti has the following advantages in that: by acting as a deoxidation agent to reduce an amount of oxygen in a weld metal, the hot cracking resistance of the first layer in the one-side welding can be improved; and with the produced TiO₂ acting as a slag element, a drop of a molten metal can be prevented in the vertical and upward progressing of welding. In addition, Ti has an advantage in that, by remaining slightly in a weld metal, the structure of a weld metal is made fine and the low temperature toughness in the high heat input welding can be improved. In order to demonstrate such effects, Ti is required to be contained in an amount of 0.11 mass% or more. On the other hand, when the content of Ti is beyond 0.29 mass%, the toughness thereof

is decreased as the strength thereof increases, because Ti remains too much in the weld metal. Therefore, the content of Ti should be specified as 0.11 to 0.29 mass%. Further, the content thereof is preferably 0.20 mass% or less from the viewpoint of maintaining the good low temperature toughness.

[Mg: 0.30-0.70 mass%]

Mg acts as a deoxidation agent to reduce an amount of oxygen in a weld metal, enabling the hot cracking resistance of the first layer in the one-side welding to be improved and the low temperature toughness in the weld metal to be improved as well. When the content of Mg is below 0.30 mass%, such effects cannot be obtained; on the other hand, when exceeding 0.70 mass%, the cold-cracking resistance is decreased because of the decreased hygroscopic resistance. Therefore, the content of Mg should be specified as 0.30 to 0.70 mass%. Further, the content thereof is preferably 0.50 mass% or less from the viewpoint of maintaining the good cold cracking resistance.

[[MgO]+[Mg] × 1.66:≤ 2.5 mass%]

MgO, when added, is an element by which the redox constant is changed to promote an oxidation reaction, enabling an effect of deoxidation to be enhanced. However, MgO is also an element which promotes drops of a molten metal. Therefore, MgO is required to be contained in an amount which satisfies the following relation based on the content of Mg: $[MgO]+[Mg] \times 1.66 \leq 2.5$ mass%, more preferably in an amount which satisfies the following relation: $[MgO]+[Mg] \times 1.66 \leq 1.7$ mass%. When MgO is contained in an amount in which the value of

$[MgO] + [Mg] \times 1.66$ exceeds 2.5 mass% based on the content of Mg, a molten metal is likely to drop. In addition, in the horizontal welding, a defect, such as slag inclusion, is likely to occur because of an increased solidification temperature of slag. Note that the weight of Mg is multiplied by 1.66 when Mg is oxidized to MgO.

[C: 0.02-0.08 mass%]

C is an element necessary for securing the strength of a weld metal. When the content of C is below 0.02 mass%, the strength of a weld metal is not secured and the low-temperature toughness thereof is also decreased. On the other hand, when exceeding 0.08 mass%, the strength of a weld metal is increased while the low-temperature toughness is decreased. In addition, the cold-cracking resistance thereof is decreased and an amount of spatter produced is increased. Therefore, the content of C should be specified as 0.02 to 0.08 mass%.

[Si: 0.35 to 0.75 mass%]

Si acts as a deoxidation agent to adjust the strength of a weld metal and Also has an advantage in that Si enhances the viscosity of a weld metal to improve the weldability in the vertical and upward progressing of welding. When the content of Si is below 0.35 mass%, such effects cannot be obtained. On the other hand, when exceeding 0.75 mass%, the strength of a weld metal is increased and the low temperature toughness thereof is decreased. In addition, the cold-cracking resistance and the hot-cracking resistance are also decreased. Therefore, the content of Si should be specified as 0.35 to 0.75 mass%.

[Mn: 2.20-2.85 mass%]

Mn acts as a deoxidation agent and also has an advantage in that

Mn improves the strength and the low-temperature toughness of a weld metal. When the content of Mn is below 2.20 mass%, such effects cannot be fully demonstrated; on the other hand, when exceeding 2.85 mass%, the strength of a weld metal is conversely increased too much and the low-temperature toughness thereof is decreased and a cold crack is likely to occur. Therefore, the content of Mn should be specified as 2.20 to 2.85 mass%.

[B: 0.002-0.010 mass%]

B has an advantage in that the crystal grain of a weld metal is made fine, thereby the low-temperature toughness thereof is improved. When the content of B is below 0.002 mass%, an effect of improving the toughness cannot be fully obtained; on the other hand, when exceeding 0.010 mass%, the hot-cracking resistance is decreased. Therefore, the content of B should be specified as 0.002 to 0.010 mass%.

[Al: $\leq$ 0.5 mass%]

Al is changed to an oxide during welding and thereby increases a solidification temperature of slag, and thus a drop of a weld metal in the vertical and upward progressing of welding can be prevented. However, Al remains slightly in a weld metal and when an amount of the remaining Al is large, the toughness of a weld metal is decreased and an amount of spatter produced is increased. Therefore, the content of Al should be specified as 0.5 mass% or less.

[[Al₂O₃]+[Al] × 1.89: 0.5-1.0 mass%]

Al₂O₃ acts such that a solidification temperature of slag is increased, thereby Al₂O₃ has an advantage in that a drop of a molten metal

can be prevented in the vertical and upward progressing of welding. When Al_2O_3 is contained in an amount in which the value of the following relation : $[\text{Al}_2\text{O}_3] + [\text{Al}] \times 1.89$ is below 0.5 mass % based on the content of Al, the above effect of preventing a drop of a molten metal cannot be fully demonstrated. On the other hand, when the value of $[\text{Al}_2\text{O}_3] + [\text{Al}] \times 1.89$ exceeds 1.0 mass%, the peelability of slag is deteriorated because of the too much hardened slag, in addition to the fact that an arc becomes unstable and an amount of the slag produced is increased. Note that the weight of Al is multiplied by 1.89, when Al is oxidized to Al_2O_3 .

[Ni: 0.2-1.0 mass%]

Ni has an advantage in that Ni improves the low temperature toughness of a weld metal. When the content of Ni is below 0.2 mass%, the above effect of improving the toughness cannot be obtained. On the other hand, when Ni is contained in an amount exceeding 1.0 mass%, an effect proportional to the amount of addition cannot be obtained with regard to the impact performance thereof at around -40°C , and a production cost thereof is increased because of an expensive price of Ni as a raw material. Therefore, the content of Ni should be specified as 0.2 to 1.0 mass%.

Examples

Flux-cored wires for gas-shielded arc welding having their diameters of 1.4 mm with flux filled in steel tubes made of mild steel (JIS G 3141 SPCC), were produced (Examples No.1 to No.18 and Comparative Examples No.19 to 57). The content of flux of each wire is 14 mass%.

Chemical components of these wires are shown in Tables 1, 2, and 3. Chemical components other than the components shown in Tables 1 to 3 include a metal fluoride (0.05 to 1.50%), an alkali metal oxide (0.05 to 1.50%), ZrO_2 (1.50% or less) and SiO_2 (0.20 to 2.00%) besides Fe of the steel tubes; and the remainders thereof are filled with iron powder.

The following each welding test was carried out by using the above produced wires under the welding conditions shown in Table 4: (i) the vertical and upward progressing of welding, (ii) the flat butt welding for evaluating the low temperature toughness, (iii) the welding of the first layer in the flat butt and one-side welding for evaluating the hot-cracking resistance, and (iv) the flat butt welding for evaluating the cold-cracking resistance.

In the vertical and upward progressing of welding, the fillet welding was carried out in the position of the vertical upward progressing, and the degree of drops of a molten metal (whether a shape of a bead was good or not) was evaluated. In the evaluation, a shape of a bead having a good one without a convex shape in the delta weaving at a welding current of 180 A was represented by "o", while a shape having a bad one by "x". Further, in the delta weaving at a current of 220 A, a shape of a bead having a good one without a convex shape was represented by "o~◎", while, in the delta weaving at a current of 250 A, a shape of a bead having a good one without a convex shape was represented by "◎". The results of the evaluation are shown in Tables 5 and 6.

In the flat butt welding, the low temperature toughness in the high heat input welding, was evaluated. Charpy specimens were cut out

from the center position in the direction of the sheet thickness of a welding portion. Charpy absorption energy values at -40°C were measured by the Charpy impact test (the size of the specimens and the test method were complied with JIS Z3111). A mean value of three Charpy specimens was defined as the absorption energy at -40°C . In the evaluation, a value of the absorption energy at -40°C exceeding 100 J was represented by "◎", a value thereof in the range of 47 J to 100 J by "○", and a value thereof below 47 J by "×". The results of the evaluation are shown in Tables 5 and 6.

In the welding of the first layer in the flat butt and one-side welding (restraint cracking test), hot-cracking was checked by the radiographic test whether it was present or not after welding. In the evaluation, a welding portion of the first layer without a hot crack at a welding current of 230 A is represented by "○", while a welding portion of the first layer with a hot crack by "×". The results of the evaluation are shown in Tables 5 and 6. In addition, in a window type restraint weld cracking test for the flat butt welding, a cold crack was checked by the ultrasonic test whether it was present or not after welding. In the evaluation, a welding portion without a cold crack was represented by "○", while a welding portion with a cold crack "×". The results of the evaluation are shown in Tables 5 and 6.

Table 1

Items	No.	Chemical components of wires (mass %)									*remainders Fe				
		TiO ₂	Ti	Mg	MgO	a	C	Si	Mn	B	Al	Al ₂ O ₃	b	Ni	Others
Examples	1	6.2	0.16	0.49	1.0	0.8	0.06	0.44	2.79	0.004	—	—	—	0.5	—
	2	4.5	0.29	0.62	1.2	2.2	0.05	0.61	2.82	0.006	—	—	—	—	SiO ₂ :0.42
	3	5.2	0.14	0.70	0.0	1.2	0.08	0.51	2.32	0.006	—	—	—	—	SiO ₂ :0.56
	4	6.1	0.25	0.55	0.2	1.1	0.04	0.68	2.72	0.007	—	—	—	—	—
	5	5.9	0.15	0.52	0.0	0.9	0.03	0.42	2.55	0.004	—	—	—	—	SiO ₂ :0.74
	6	4.7	0.29	0.68	1.4	2.5	0.08	0.67	2.67	0.010	—	—	—	—	ZrO ₂ :0.41
	7	7.0	0.11	0.30	0.0	0.5	0.07	0.75	2.83	0.009	—	1.0	1.0	—	SiO ₂ :0.77
	8	5.1	0.19	0.41	1.5	2.2	0.02	0.40	2.20	0.003	—	—	—	—	—
	9	6.7	0.19	0.38	1.2	1.8	0.05	0.36	2.66	0.005	—	—	—	—	—
	10	6.6	0.26	0.58	0.6	1.6	0.07	0.70	2.44	0.007	—	—	—	1.0	—
	11	5.7	0.16	0.64	0.6	1.7	0.04	0.67	2.85	0.008	0.1	0.3	0.6	—	ZrO ₂ :0.42
	12	4.8	0.26	0.42	0.2	0.9	0.02	0.62	2.51	0.002	—	—	—	—	—
	13	6.6	0.12	0.34	0.1	0.7	0.03	0.49	2.24	0.010	—	—	—	—	—
	14	6.2	0.16	0.37	0.9	1.5	0.05	0.41	2.81	0.008	0.4	0.3	0.9	—	—
	15	6.0	0.21	0.51	1.6	2.4	0.04	0.55	2.79	0.005	—	—	—	—	—
	16	5.0	0.25	0.45	1.6	2.3	0.02	0.59	2.59	0.006	—	—	—	—	—
	17	5.6	0.11	0.65	0.6	1.7	0.06	0.61	2.70	0.008	—	—	—	—	SiO ₂ :0.69
	18	6.6	0.25	0.35	0.9	1.5	0.05	0.68	2.29	0.010	—	—	—	—	—

(Note) a = [MgO] + [Mg] × 1.66 b = [Al₂O₃] + [Al] × 1.89

Table 2

Items	No.	Chemical components of wires (mass %)										*remainders Fe				
		TiO ₂	Ti	Mg	MgO	a	C	Si	Mn	B	Al	Al ₂ O ₃	b	Ni	Others	
Comparative Examples	19	4.8	0.10	0.52	0.2	1.1	0.06	0.39	2.81	0.005	—	—	—	—	—	
	20	6.9	0.30	0.43	1.0	1.7	0.08	0.35	2.20	0.002	—	—	—	—	—	
	21	7.1	0.11	0.70	0.3	1.5	0.02	0.75	2.85	0.010	—	—	—	—	—	
	22	6.4	0.15	0.70	1.8	3.0	0.03	0.67	2.44	0.009	—	—	—	—	SiO ₂ :0.49	
	23	4.6	0.08	0.70	0.2	1.4	0.05	0.61	2.81	0.008	—	—	—	—	—	
	24	5.1	0.12	0.64	1.3	2.4	0.03	0.30	2.79	0.006	—	—	—	—	ZrO ₂ :0.41	
	25	5.2	0.16	0.65	0.9	2.0	0.07	0.46	2.12	0.006	—	—	—	—	—	
	26	8.0	0.22	0.70	0.0	1.2	0.04	0.51	2.79	0.006	—	—	—	—	K ₂ O:0.03	
	27	4.9	0.12	0.22	1.0	1.4	0.02	0.37	2.46	0.009	0.2	0.2	0.6	—	K ₂ O:0.04	
	28	4.8	0.05	0.44	0.2	0.9	0.05	0.36	2.83	0.009	—	—	—	—	—	
	29	6.2	0.12	0.30	2.0	2.5	0.01	0.70	2.44	0.004	—	—	—	—	—	
	30	6.3	0.16	0.28	1.3	1.8	0.08	0.37	2.82	0.002	—	—	—	—	K ₂ O:0.07	
	31	6.3	0.21	0.70	1.6	2.8	0.04	0.42	2.46	0.006	—	—	—	0.5	ZrO ₂ :0.42	
	32	5.5	0.21	0.44	0.7	1.4	0.05	0.50	2.79	0.001	—	—	—	—	SiO ₂ :0.58	
	33	6.9	0.34	0.51	0.3	1.1	0.08	0.49	2.66	0.005	—	—	—	—	—	
	34	7.0	0.19	0.31	0.3	0.8	0.05	0.67	2.29	0.000	—	—	—	—	SiO ₂ :0.60	
	35	4.4	0.29	0.40	0.9	1.6	0.05	0.46	2.40	0.010	—	—	—	—	K ₂ O:0.06	
	36	6.3	0.15	0.57	1.1	2.0	0.05	0.34	2.77	0.003	—	—	—	—	SiO ₂ :0.62	
37	5.2	0.19	0.32	0.9	1.4	0.04	0.49	2.19	0.003	—	—	—	—	—		
38	7.0	0.19	0.32	3.0	3.5	0.04	0.40	2.59	0.010	0.8	0.4	1.9	—	—		

(Note) a = [MgO] + [Mg] × 1.66 b = [Al₂O₃] + [Al] × 1.89

Table 3

Items	No.	Chemical Components of wires (mass %)										*remainders Fe			
		TiO ₂	Ti	Mg	MgO	a	C	Si	Mn	B	Al	Al ₂ O ₃	b	Ni	Others
Comparative Examples	39	4.0	0.11	0.32	0.1	0.6	0.06	0.68	2.72	0.007	—	—	—	—	—
	40	6.5	0.22	0.30	2.4	2.9	0.03	0.60	2.78	0.007	—	—	—	—	SiO ₂ :0.66
	41	6.0	0.24	0.70	0.3	1.5	0.08	0.74	2.86	0.004	—	—	—	—	K ₂ O:0.05
	42	5.1	0.20	0.42	0.7	1.4	0.03	0.72	2.22	0.011	—	—	—	—	SiO ₂ :0.80
	43	4.2	0.11	0.35	0.2	0.8	0.02	0.55	2.51	0.008	—	—	—	—	—
	44	5.9	0.19	0.41	0.9	1.6	0.06	0.80	2.32	0.002	0.1	0.4	0.6	—	SiO ₂ :0.70
	45	4.5	0.11	0.58	0.0	1.0	0.09	0.55	2.82	0.006	—	—	—	—	—
	46	5.9	0.14	0.56	0.5	1.4	0.05	0.76	2.32	0.010	—	—	—	—	SiO ₂ :0.72
	47	4.8	0.22	0.71	0.2	1.4	0.04	0.75	2.29	0.006	—	—	—	—	SiO ₂ :0.73
	48	6.1	0.11	0.52	0.7	1.6	0.02	0.39	2.24	0.015	—	—	—	1.3	—
	49	6.4	0.19	0.74	0.8	2.0	0.05	0.55	2.85	0.005	—	—	—	—	Na ₂ O:0.03
	50	5.0	0.15	0.42	0.7	1.4	0.02	0.35	2.90	0.004	—	—	—	—	SiO ₂ :0.76
	51	3.5	0.29	0.31	0.7	1.2	0.04	0.39	2.62	0.004	—	0.4	0.4	—	—
	52	4.5	0.15	0.38	2.5	3.1	0.05	0.60	2.62	0.010	—	—	—	—	SiO ₂ :0.78
	53	4.8	0.28	0.44	1.2	1.9	0.11	0.71	2.57	0.006	—	—	—	—	Na ₂ O:0.04
	54	4.5	0.18	0.80	0.9	2.2	0.06	0.59	2.29	0.002	—	—	—	—	—
	55	6.5	0.22	0.32	1.2	1.7	0.08	0.28	2.81	0.006	0.1	—	0.2	—	—
	56	5.5	0.25	0.39	0.2	0.8	0.07	0.42	2.17	0.008	—	—	—	0.1	—
	57	6.2	0.18	0.61	0.1	1.1	0.02	0.50	2.32	0.016	—	—	—	1.1	—

(Note) a = [MgO] + [Mg] × 1.66 b = [Al₂O₃] + [Al] × 1.89

Table 4

(i) Vertical and upward progressing of welding (Evaluation for drops of molten metal) • Specimen : JIS G 3106 SM490A (Thickness 12 mm) • Fillet welding in T butt welding • Rod operation : Delta weaving • Welding current : 180A, 220A, 250A • Shield-gas : CO₂, Flow Rate: 25 L/min
(ii) Flat butt welding (Evaluation for low temperature toughness) • Specimen : JIS G 3106 SM400B (Thickness 40 mm) • Multilayer welding in V butt welding • Joint geometry : Single V groove with a groove angle of 40°, Root gap: 5 mm • Welding current: 350 A, Welding heat input:30-60 kJ/cm • Shield gas : CO₂, Flow rate:25 L/min
(iii) Welding of first layer in flat butt and one-side welding (Evaluation for hot cracking resistance) • Specimen : JIS G 3106 SM400B (Thickness 40mm) • Joint geometry : Single V groove with a groove angle of 40°, Root gap: 5 mm • Backing material : FBB-3 (Made by Kobe Steel, Ltd. Solid flux type with glass tape) • Welding current : 230 A (Welding speed 25 cm/min) 260 A (Welding speed 35 cm/min) • Shield gas : CO₂, Flow rate 25 L/min
(iv) Window type restraint weld cracking for flat butt welding (Evaluation for cold cracking resistance) • Specimen : JIS G 3106 SM490A (Thickness 50 mm) • Multilayer welding in V butt welding • Joint geometry : Single V groove with a groove angle of 40°, Root gap 5 mm • Welding Current : 350 A, Welding heat input : About 15 kJ/cm • Preheating · Interpass temperature : 75±10°C • Shield gas : CO₂, Flow rate 25 L/min

Table 5

Items	No.	Hot cracking resistance	Weldability in vertical and upward progressing of welding	Low temperature toughness	Cold cracking resistance
Examples	1	○	○	◎	○
	2	○	○	○	○
	3	○	○~◎	○	○
	4	○	○~◎	○	○
	5	○	○~◎	○	○
	6	○	○	○	○
	7	○	◎	○	○
	8	○	○	○	○
	9	○	○	○	○
	10	○	○~◎	◎	○
	11	○	◎	○	○
	12	○	○~◎	○	○
	13	○	○~◎	○	○
	14	○	◎	○	○
	15	○	○	○	○
	16	○	○	○	○
	17	○	○~◎	○	○
	18	○	○~◎	○	○

Table 6

Items	No.	Hot cracking resistance	Weldability in vertical and upward progressing of welding	Low temperature toughness	Cold cracking resistance	Others
Comparative Examples	19	x	o~o	x	o	
	20	o	o~o	x	o	
	21	x	o~o	x	o	
	22	o	x	o	o	
	23	x	o~o	x	o	
	24	o	x	o	o	
	25	o	o	x	o	
	26	x	o~o	x	o	
	27	x	o	x	o	
	28	x	o~o	x	o	
	29	o	o	x	o	
	30	x	o	x	o	
	31	o	x	o	o	
	32	o	o~o	x	o	
	33	o	o~o	x	o	
	34	o	o~o	x	o	
	35	o	x	o	o	
	36	o	x	o	o	
	37	o	o~o	x	o	
	38	o	x	o	o	Spatter amount increased Arc unstable Peelability of slag decreased
	39	o	x	o	o	
	40	o	x	o	o	
	41	o	o~o	x	x	
	42	x	o~o	o	o	
	43	o	x	o	o	
	44	x	o	x	x	Spatter amount increased
	45	o	o~o	x	x	
	46	x	o~o	x	x	
	47	o	o~o	o	x	
	48	x	o~o	o	o	Cost up
	49	o	o	o	x	
	50	o	o~o	x	x	
	51	o	x	o	o	
	52	o	x	o	x	
	53	o	o	x	x	Spatter amount increased
	54	o	o	o	x	
	55	o	x	o	o	
	56	o	o~o	x	o	
	57	x	o~o	o	o	Cost up

Referring to the results of Comparative Examples, Comparative Examples No.21 and No.26 had hot cracks in their first layers in the one-side welding and also had the decreased low temperature toughness in the high heat input welding, because their contents of TiO_2 were beyond the upper limit. Comparative Examples No. 35, 39, 43, and 51 had bad shapes of beads with convex shapes in the vertical and upward progressing of welding, because their contents of TiO_2 were below the lower limit. Comparative Examples No. 20 and 33 had the increased strength of the weld metals and the decreased low temperature toughness in the high heat input welding, because their contents of Ti were beyond the upper limit. Comparative Examples Nos. 19, 22, and 28 had hot cracks in their first layers in the one-side welding and had the decreased low temperature toughness in the high heat input welding, because their contents of Ti were below the lower limit. Comparative Examples No. 47, 49, and 54 had cold cracks, because their contents of Mg were beyond the upper limit. Comparative Examples No. 27, and 30 had hot cracks in their first layers in the one-side welding and had the decreased low temperature toughness in the high heat input welding, because their contents of Mg were below the lower limit. The above Comparative Example No. 27 had the good weldability in the vertical and upward progressing of welding, because Al and Al_2O_3 were added therein. Comparative Examples No. 45 and 53 had the increased strength of the weld metals and the low-temperature toughness in the high heat input welding, because their contents of C were beyond the upper limit. Also, cold cracks occurred. Comparative Example No. 29 had the decreased low temperature toughness in the high heat input welding, because the content of C was below the lower limit.

Comparative Examples No. 44, and 46 had hot cracks in their first layers in the one-side welding and had the decreased low temperature toughness in the high heat input welding, because their contents of Si were beyond the upper limit. Also, cold cracks occurred. The above Comparative Example No. 44 had the excellent weldability in the vertical and upward progressing of welding, because Al_2O_3 and Al were added therein.

Comparative Examples No. 24, 36, and 55 had bad shapes of beads with convex shapes in the vertical and upward progressing of welding, because their contents of Si were below the lower limit. The above Comparative Example No. 55 had a bad shape of bead with a convex shape in the vertical and upward progressing of welding, because the content of Si was below the lower limit despite addition of Al_2O_3 . Comparative Examples No. 41 and 50 had the increased strength of the weld metals and the decreased low temperature toughness in the high heat input welding, and had cold cracks, because their contents of Mn were beyond the upper limit.

Comparative Examples No. 25, 37, and 56 had the decreased low temperature toughness in the high heat input welding, because their contents of Mn were below the lower limit. The Comparative Examples No. 56 had the decreased low temperature toughness in the high heat input welding, because the content of Mn was below the lower limit despite addition of Ni. Comparative Examples No. 42, 48, and 57 had cold cracks in their first layers in the one-side welding, because their contents of B were beyond the upper limit. The above Comparative Example 57 had the good low temperature toughness in the high heat input welding, because Ni was added therein. Comparative Examples No. 32 and 34 had the decreased low temperature toughness in the high heat input welding, because their

contents of B were below the lower limit. Comparative Examples No. 22, 31, 38, 40, and 52 had bad shapes of beads with convex shapes in the vertical and upward progressing of welding, because their contents of MgO were beyond the specified value. The above Comparative Example No. 31 had the good low temperature toughness in the high heat input welding, because Ni was added therein. The Comparative Example No. 38 had a larger amount of spatter produced, because the content of Al was beyond the upper limit, and had an unstable arc and the deteriorated peelability of the slag, because the total (b) of Al and Al_2O_3 was beyond the upper limit. Contrary to these results, in Examples No. 1 to 18, good welding was able to be carried out at high welding currents without a drop of molten metals in the vertical and upward progressing of welding, as shown in Table 5. In addition, Examples No. 1 to 18 had the excellent hot cracking resistance of the first layers in the one-side welding, and weld metals excellent in the low temperature toughness were obtained in the high heat input welding where a welding amount was increased. In addition, Examples No. 1 to 18 had the good cold cracking resistances.

WHAT IS CLAIMED IS:

1. A flux-cored wire for gas-shielded arc welding with flux being filled in a steel tube made of mild steel or alloy steel, the wire comprising, based on the total mass of the wire:

4.5 to 7.0 mass% TiO_2 ,
0.11 to 0.29 mass% Ti,
0.30 to 0.70 mass% Mg,
0.02 to 0.08 mass% C,
0.35 to 0.75 mass% Si,
2.20 to 2.85 mass% Mn, and
0.002 to 0.010 mass% B,

wherein MgO satisfies the following relation based on the above content of Mg: $[\text{MgO}] + [\text{Mg}] \times 1.66 \leq 2.5 \text{ mass\%}$, assuming contents of Mg and MgO are $[\text{Mg}]$ and $[\text{MgO}]$, respectively.

2. The flux-cored wire for gas-shielded arc welding according to claim 1, wherein the wire contains Al_2O_3 so as to satisfy the following relations: $\text{Al} \leq 0.5 \text{ mass\%}$ based on the total mass of the wire, and $[\text{Al}_2\text{O}_3] + [\text{Al}] \times 1.89: 0.5 \text{ to } 1.0 \text{ mass\%}$, assuming contents of Al and Al_2O_3 are $[\text{Al}]$ and $[\text{Al}_2\text{O}_3]$, respectively.

3. The flux-cored wire for gas-shielded arc welding according to claim 1 or 2, wherein the wire further contains 0.2 to 1.0 mass% Ni based on the total mass of the wire.