FLUX BASICITY INDEX INFLUENCE ON WELD METAL MICROSTRUCTURE MODIFICATION OF THE HSLA STEELS

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ABSTRACT

The flux oxygen potential and the deoxidizers content in the flux influence on low-alloy steels the microstructure modification welds metal was investigated. It was established that flux basicity, changing the deoxidation alloying system effects on weld metal structure forming processes and contributes to achieving the low-alloy steels welds highest strength and plasticity levels. It was shown that the welding flux oxygen potential reducing contributes to reducing the inclusions size formed in the weld metal. The use of fluxes with a higher basicity index in welding contributes to an increase the refractory inclusions content in the primary austenite grains. An increase the dispersed inclusions content in the primary austenite grains is accompanied by an acicular ferrite content increase in the weld metal structure and an increase in the weld metal resistance to brittle fracture.

KEYWORDS

Welding, metallography, microstructure, non-metallic inclusions, primary austenite, acicular ferrite, brittle fracture

1. INTRODUCTION

High Strength Low-alloy (HSLA) steels used for the welded structures manufacture must have, in addition to high strength and toughness, good weldability [1–3]. Current demand for construction, repair of larger diameter pipelines, building metal structures, and arrangement of railway and road transport facilities lead to increased requirements for rolled steel. Modern (HSLA) steels are characterized not only by a high strength level specifications but also by a low yield strength. A low yield strength means higher resistance to deformation and plastic instability [4,5] and helps prevent sudden failure. For example, API X-80 grade HSLA steels have to have a yield strength above 570 MPa, an impact energy of more than 100 J at minus 40°C, and a yield strength of less than 85%. However, it is much more difficult to maintain adequate values of the toughness-strength ratio for HSLA steels. The main difficulty lies in optimizing these properties because they are often inversely proportional, i.e. an increase in strength is achieved by reducing the viscosity level.

One way to solve this problem is to use a hard second phase in the microstructure. Numerous studies of the so-called dual-phase steels have shown that these steels have a low yield strength due to the hard martensite presence or bainite grains in a soft ferrite matrix microstructure [6,7]. In [8], the relationship between the second phase volume fraction and morphology and the yield strength was analyzed using the finite element method and it was concluded that the steel should have a soft matrix with about 50% volume fraction of the hard second phase to obtain a low yield strength. However, such dual-phase steels usually have low yield strength, which does not meet

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the requirements for HSLA X-80 steels category and above. In addition, the large difference in strength between the two phases can have a detrimental effect on fracture toughness, since cracks can easily initiate on the second phase solid particles at low temperatures. Recently, more attention has been paid to the acicular ferritic or bainite HSLA steels development [9–11]. However, the toughness of these steels is often disappointing. Therefore, new studies are needed on the microstructure composition influence on the possibility adequate combinations of strength, toughness and yield strength obtaining.

One of the possible ways to achieve such results in relation to strength category X80 steels weld metals is to modify the structure. The structure fragmentation due to the non-metallic inclusions formation in the weld metal has been widely studied and summarized in the relevant monographs, which show that for modifying the microstructure it is advisable to use finely dispersed non-metallic inclusions that have a crystal structure at the metal melt temperatures. Such inclusions include, for example, aluminum or titanium oxides.

The paper presents the research results concerning the possibility aluminum and titanium oxides for HSLA steels category X80 the weld metal composition to modify their microstructure in order to influence the weld metal yield strength and impact toughness.

2. MATERIALS AND METHODS

For the research there were manufactured type 1.3 butt joints according to ISO 15792-1:2000 with the arc welding method with. Solid wire ISO 16834-A - G 62 6 M Mn3Ni2.5CrMo and flux ISO 14171-A-S 55 6 AB was use. The base metal and welding wire chemical composition are given in Table 1.

Non-metallic inclusions for structure modification were formed as an oxygen reaction result with aluminum and titanium atoms in the weld pool. To form non-metallic inclusions of different quantity, size, chemical composition and location in the structure, welding was carried out using three the basic flux modifications variant, which, due to the change in magnesium and silicon oxides the ratio, had different basicity indices: acidic flux (BI=0.67), neutral flux (BI=1.25) and basic flux (BI=2.35). The fluxes basicity was determined by the well-known IIW formula

$$\mathrm{BI} = \frac{Na_2O + K_2O + CaO + MgO}{SiO_2 + 0{,}5(Al_2O_3 + TiO_2)}$$

For the Al_2O_3 and TiO_2 type non-metallic inclusions formation in the welding bath metal melt, aluminum powder (0.5 wt.%) or ferrotitanium powder with a content of 75% titanium (0.4 wt.%), or an aluminum powder (0.5 wt.%) and ferrotitanium powder (0.2 wt.%) combination was added to the fluxes.

Welding was performed using a reverse polarity direct current with an input energy of 28 kJ/cm.

Tabel 1 The base metal and welding wire chemical composition

	Chemical composition, mas. %										
	C	Al	Si	Ti	Ni	Mn	Mo	Cr	Cu	S	P
Steel	0,088	0,011	0,253	0,005	2,16	0,44	0,27	0,40	0,47	0,005	0,010
Wire	0,02	0,002	0,16	0,004	2,29	0,62	0,17	0,17	0,20	0,010	0,011

Samples were taken from the weld metal to determine mechanical properties, as well as for metallographic studies in accordance with the ISO 15792-1:2000 requirements.

During metallographic studies, the metal microstructure components proportion, the alloying elements content in the solid solution, the non-metallic inclusions chemical composition and distribution were determined. The microstructure was studied by optical and electron metallography methods using a light microscope “Neophot-32” and a scanning electron microscope JSM-840 from “JEOL” equipped with a MicroCapture image capture board with subsequent image registration on a computer screen.

The microstructural components quantitative determination was carried out according to the IIW method. The alloying elements content in the solid solution and weld metal microstructure components were determined by the micro-X-ray spectral method using an energy-dispersive spectrometer LINK 860/500 from the company “Link System” and a wave-dispersive spectrometer ORTEC from the company “ORTEC” using a differential analysis program that allows determining the alloying elements content in microstructural components up to 0.5 μm in size.

The non-metallic inclusions composition analysis and their size distribution was carried out using a JSM EVO 50 electron microscope equipped with an INKA attachment for X-ray spectral analysis and a computer program for processing the obtained data.

3. RESULTS AND DISCUSSION

Table 2 shows the chemical composition determining spectral analysis results (except for the oxygen content) of the investigated welds metal. The oxygen content in the metal was determined by chromatographic analysis when the samples were completely melted. The analysis results refer to the last pass of the weld.

Table 2 The welds metal chemical composition

Weld metal *	Chemical elements content (mas. %) in weld metal									
	C	Al	Si	Ti	Ni	Mn	Mo	Cr	S	P	O
CA	0,032	0,007	0,84	0,001	2,40	0,84	0,19	0,12	0,009	0,004	0,63
CT	0,031	0,010	0,89	0,003	2,48	0,82	0,20	0,11	0,019	0,005	0.72
CTA	0,035	0,007	0,81	0,001	2,39	0,82	0,19	0,13	0,009	0,005	0,61
NA	0,036	0,011	0,35	0,003	2,32	0,84	0,18	0,18	0,009	0,007	0,18
NT	0,036	0,014	0,32	0,003	2,36	0,84	0,17	0,18	0,008	0,007	0,19
NTA	0,039	0,014	0,41	0,003	2,46	0,89	0,19	0,17	0,009	0,008	0,18
BA	0,037	0,023	0,13	0,005	2,43	0,55	0,17	0,17	0,009	0,005	0,14
BT	0,036	0,028	0,13	0,003	2,46	0,52	0,16	0,17	0,007	0,009	0,13
BTA	0,038	0,034	0,12	0,002	2,53	0,52	0,19	0,15	0,008	0,007	0,12

*Note: the weld symbol consists of two parts - the flux type designation (C-acidic, N-neutral, B-basic) and the deoxidizers designation in the flux composition (T-ferrotitanium, A-aluminum).

Table 3 shows the results of weld metal samples testing to determine mechanical properties.

When conducting metallographic studies, the microstructure composition (Table 4), the non-metallic inclusions (NMI) total content and their size distribution (Table 5), as well as their chemical composition (Table 6) were determined. Fig. 1 shows the metal microstructure samples in the last pass center of the welds at a 2 mm distance from the upper edge. The volume fraction determining results of the non-metallic inclusions in the primary austenite grain body and in the boundaries are given in Table 7.

Table 3. The welds metal mechanical properties

Weld metal	Upper strength level Rm	Yield strength level Re	Relative elongation A_5	Relative narrowing Z	Actual fracture stress $S_к$	Impact toughness (KCV) at temperature	
						-40 ^{0}C	-60 ^{0}C
	МПа	МПа	%	%	МПа	J/cm^2	
CA	666 662 664	565 558 562	21 22 24	56 56 55	1514 1505 1510	85 77 69	22 22 10
NA	678 682 679	560 567 563	22 24 23	64 66 65	1883 2006 1890	93 75 68	49 39 38
BA	759 768 761	652 673 666	19 22 20	49 56 52	1488 1745 1505	22 15 10	12 7 6
CT	669 680 672	541 555 550	23 20 22	58 56 57	1593 1545 1559	21 17 15	9 9 9
NT	680 680 677	566 562 563	25 22 24	62 62 61	1789 1789 1767	61 56 49	37 12 10
BT	740 740 735	601 591 588	18 18 17	51 49 47	1510 1451 1478	33 25 19	19 8 7
CTA	633 637 635	555 548 553	22 22 20	53 53 51	1347 1355 1344	35 30 28	12 9 9
NTA	623 623 620	529 514 524	29 25 27	73 71 72	2307 2148 2245	74 70 67	48 48 47
BTA	682 700 694	624 650 545	21 24 23	71 70 69	2352 2333 2347	150 131 120	118 115 106

Table. 4.Weld metal microstructure content

Weld metal	* Volume fraction of the structural component, %					
	PF	WF	AF	OSF	DOSF	MAC-Fase
CA	16…20	10	31…37	14…15	24…27	5,4
CT	18…20	9…12	25…34	16…27	20…23	5,0
CTA	15…20	6…7	44…48	24…25	20…27	3,4
NA	13…19	3…5	40…45	17…20	23…25	4,0
NT	13…17	3…9	46…49	13…19	16…18	5,0
NTA	13…22	7	43…46	13…18	6…14	2,3
BA	10…15	3	50…55	16…27	17…21	2,5
BT	10…13	4	48…50	12…25	32…37	3,5
BTA	6…12	2	48…51	11…15	36…38	2,4

*Note: PF – polygonal ferrite, WF – Widmanstätte ferrite, AF – acicular ferrite, OSF – ferrite with an ordered second phase, DOSF – ferrite with a disordered second phase, MAC – martensite-austenite-carbide.

Table 5. Size distribution of non-metallic inclusions in metal welds.

Weld metal	Nonmetal content (%) with size, mkm									V_{nmi}
	≤ 0,5	0,5…1,0	1,1…1,5	1,6…2,0	2,1…2,5	2,6…3,0	3,1…3,5	3,6…4,5	4,6…6,0	
CA	18,6	37,0	21,2	10,5	5,4	2,0	1,7	1,4	0,2	0,65
CT	25,1	37,5	18,7	9,0	4,6	1,9	1,4	0,7	0,1	0,75
CTA	18,1	34,3	17,9	14,2	5,5	4,5	1,2	1,5	0,4	0,60
NA	19,5	50,8	20,5	5,6	2,2	0,7	0,6	0,3	0	0,20
NT	21,9	50,8	19,3	4,6	2,2	1,0	0	0	0	0,21
NTA	19,2	46,9	19,1	7,9	3,27	1,5	1,5	0,6	0	0,18
BA	22,9	50,0	17,2	7,5	2,2	0,2	0	0	0	0,15
BT	22,1	44,3	19,9	6,2	1,7	1,0	0,2	0,2	0	0,14
BTA	20,1	51,2	19,8	5,5	1,7	1,1	0,3	0	0	0,12

Table 6 Nonmetal inclusions chemical composition

Flux type	Alloyed elements content in nonmetal inclusions, mas. %					
	Al	Ti	Si	Mn	Ni	Mo
Acid	2,6	1,0	51,0	43,2	0,0	0,1
Neutral	11,5	3,6	21,4	62,9	0,0	0,5
Basic	27,2	2,0	20,5	49.7	0,0	0,5

Table 7. The non-metallic inclusions content at the boundaries and in the body of primary austenite grains.

Weld metal	The NMI proportion at the grain boundary, %	The NMI proportion in the grain body, %	Coefficient F	Average NMI size in the grain body, µm	Average NMI size at the grain boundary, µm
CA	1,398	0,971	0,590	0,590	0,382
CT	1,127	0,895	0,557	0,557	0,395
CTA	1,381	1,023	0,574	0,574	0,323
NA	0,401	0,155	0,529	0,529	0,289
NT	0,372	0,172	0,683	0,683	0,249
NTA	0,341	0,192	0,639	0,639	0,295
BA	0,385	0,124	0,754	0,754	0,253
BT	0,330	0,103	0,762	0,762	0,279
BTA	0,304	0,136	0,691	0,723	0,288

The experiments to determine the primary austenite grains average size were performed. The results show (Table.) that with a decrease in the flux oxygen potential the primary austenite grain size in the deposited metal samples increases. This circumstance is apparently associated with a change in the non-metallic inclusions volume fraction (Table 5) and its distribution between the inclusions located in the grain body and the inclusions located at the grain boundaries of primary austenite. In addition, it was found that the inclusions volume fraction at the primary austenite grain boundary is higher than the volume fraction inside the grain (Fig. 2). In [12], it was proposed to estimate the non-uniformity of the NMI distribution using the coefficient F, which is the ratio:

$$F = V_B / (V_B + V_I), \qquad (2)$$

where V_B and V_I are the NMI volume fractions on boundaries and inside the primary austenite grains, respectively, referred to a unit area.

The coefficient F, associated with their uneven distribution, and in most of the investigated welds, it was 0.6…0.7. The coefficients F value obtained in our investigation were somewhat lower than in work [12], in which the F factor was 0.7…0.8. The difference in the NMI distribution between the boundary and the primary austenite grains internal regions is apparently associated with both a higher heat input (4.2 kJ/mm in our work versus 2.5 kJ/mm used in work [12]), and with the difference in the used fluxes basicity.

4. DISCUSSION OF THE OBTAINED DATA

In the low-alloyed welds metal, the acicular ferrite structure has the most optimal strength and toughness indicators combination. For the processes which occurring in the weld metal better understanding, it is advisable to consider separately the study results of the factors related to non-metallic inclusions complex influence and the results of alloying elements content in the main structural components analysis.

The issue of the NMI influence on the acicular ferrite retention in the welds structure is addressed by a large number of works, among which fundamental research can be distinguished [10-12]. The these works authors conclude that, firstly, with an increase in the NMI volume fraction in the weld metal, the acicular ferrite content in their structure decreases, and secondly, for this structural component formation in the weld metal, the most preferable are finely dispersed manganese aluminosilicates inclusions, as well as inclusions with an increased titanium content. The data obtained as a studies result performed show that in the weld metal with an ultra-low carbon content case, a slightly different dependence is observed. An increase in the flux's oxygen potential leads to an increase in the NMI volume fraction in the welds metal (Table 3), while the acicular ferrite content in their structure, although decreasing, remains at a fairly high level (Table 5). As can be seen from the data presented in Table 6, in the weld metal obtained during submerged arc welding with Al or Ti alloying system, a decrease in the silicon content in acicular ferrite is accompanied by an increase in the of acicular ferrite proportion in the structure, and in the using fluxes with the Al+Ti alloying system case, the acicular ferrite content remains practically at the same level regardless of the flux basicity.

Such an ambiguous the structural component alloying level effect on its content in the metal is usually associated with a change in the temperature interval γ—α transformation characteristic points coordinate.

It is known [13] that the change in the temperature interval γ—α transformation characteristic points can be traced by considering changes in the primary austenite grain size. For this purpose, we performed experiments to determine the primary austenite grains average size. The results shown in Fig. 3 show that with a decrease in the flux oxygen potential, the primary austenite grain size in the deposited metal increases. This circumstance, in our opinion, is associated with a change in the NMI volume fraction (Table 3) and its distribution within the primary austenite grain.

As expected, the NMI volume fraction at the boundary and inside the primary austenite grain is higher when using an acid flux, compared to neutral and basic fluxes (Table 3). Comparing the data given in Table 7 and Fig. 3, we can conclude that in general, an increase in the NMI content at the primary austenite boundary compared to their content in the internal grains volumes leads to a decrease in the austenite grains size. When using weld pool deoxidation with aluminum and titanium, the NMI content inside the grain is higher than when using these deoxidizers separately, which is explained by the metal complex deoxidation effect.

For deoxidation reactions, an oxide activity decrease in the metal leads to a corresponding decrease in the oxygen content in the solution. In the complex deoxidation case, oxides of complex composition are formed in the weld pool, which have lower activity in the melt compared to pure aluminum or titanium oxides, as a result, for Al and Ti alloyed welds, compared to welds alloyed only with Al or only with Ti, the total NMI content in the metal decreases (Table 3) and the proportion of inclusions located inside the grains increases (Table 7). Silicon, which entering to bath from welding materials, participates in the deoxidation process as contributes to the complex aluminosilicate's formation, which have a relatively high melting point.

The weld pool refinement by NMI is determined by the interfacial tension value at the inclusion/slag boundary. The interfacial tension at the aluminum oxide inclusion type boundary with steel is about 1300 mN/m, and the manganese aluminosilicate inclusion type is 600 mN/m [13], therefore, with complex deoxidation in the weld metal, the silicate inclusions assimilation by slag increases and decreases, as a result the more refractory inclusions role such as aluminosilicates and titanium oxides in the weld metal secondary structure formation increases markedly.

5. CONCLUSIONS

Thus, summarizing the above, the following conclusions can be drawn:

1. The conditions for the weld metal structure formation are significantly influenced by the welding material oxygen potential and the weld pool deoxidation system choice.
2. Reducing the welding flux oxygen potential contributes to a change in the NMI size the weld metal.
3. The use of fluxes with a higher basicity index in welding contributes to an increase in the refractory inclusions content in the primary austenite grains.
4. An increase in the dispersed inclusions content in the primary austenite grains is accompanied by an increase in the acicular ferrite content in the weld metal structure and an increase in the weld metal resistance to brittle fracture.
5. Changing the alloying system, deoxidation and flux basicity affects the structure forming in the weld metal and contributes to achieving the highest strength and ductility indicators of low-alloy steels weld metal.

CONFLICTS OF INTEREST

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Author declare absence the involvement of anyone other than the author who: i) has an interest in the outcome of the work; ii) is affiliated to an organization with such an interest; or iii) was employed or paid by a funder, in the commissioning, conception, planning, design, conduct, or analysis of the work, the preparation or editing of the manuscript, or the decision to publish.

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