EFFECT OF YTTRIUM ON REDISTRIBUTION OF HYDROGEN AND STRUCTURE OF WELD METAL IN ARC WELDING OF HIGH-STRENGTH STEELS

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Transfer of yttrium into deposited high-strength low-alloy metal in welding with flux-cored wire in a shielding gas atmosphere and with covered electrodes of the basic type was investigated. Thermal desorption analysis revealed interaction of yttrium with dissolved hydrogen to form residual hydrogen depending on the concentration of yttrium. The effect of yttrium on microstructure of deposited low-alloy steel and mechanical properties of metal is shown.

Keywords: *arc welding, high-strength low-alloy steels, modification of weld metal, yttrium, redistribution of hydrogen, thermal desorption analysis of hydrogen, structure, mechanical properties*

It is a known fact [1–6] that yttrium and other rare-earth metals (REM) are used for microalloying and modification of steels and welds to improve their mechanical properties. In addition, yttrium, cerium, lanthanum, neodymium and praseodymium form compounds with hydrogen, thus decreasing the flake-sensitivity of steels [7].

Application of REMs in welding consumables to improve performance of the weld metal is described in studies [4–6]. Of special interest are the investigations aimed at decreasing the sensitivity of the welds and welded joints on high-strength low-alloy (HSLA) steels to hydrogen-induced cracking. The attempts to redistribute hydrogen absorbed by the weld pool are reported in studies [6, 8, 9]. However, the quantity of the investigations conducted is small, and their results contain a number of contradictory data concerning the effect of the REM additions on behaviour of hydrogen in the weld metal.

This study considers investigations of the effect of yttrium on the probability of redistribution of absorbed hydrogen between the diffusible and residual forms, as well as of the peculiarities of variations in structure and mechanical properties of the weld metal. Because of a high affinity of yttrium for oxygen, the effect of adding yttrium to the weld pool metal by using a flux-cored wire designed for gas-shielded welding was compared with that by using covered electrodes. The yttrium content of the weld metal was determined by using a high-sensitivity emission spectrometer with inductively coupled plasma iCAP 6000. Chemical composition of the metal was determined by using the «Spectrovak-1000» device. The content of diffusible hydrogen in the weld metal was measured, according to requirements of GOST 23338–91, by the chromatographic method using gas-analyser OB 2781P.

The content of residual hydrogen in weld metal samples was measured in the automatic mode by the thermal desorption method described in study [10] and upgraded to measure the content of residual hy-

Table 1. Chemical composition (wt.%) of deposited metal depending on yttrium content of flux-cored wire

Flux-cored wire	Yttrium content of wire	C	Si	Mn	Al	Ti	Y	Hydrogen concentration, ml/100 g	
								$[H]_{diff.\ d.m}$	$[H]_{res}$
P1 (PPAN 70)	0	0.08	0.71	1.6	<0.05	<0.08	0	$\frac{2.2–4.4}{3.5\times3}$	0.6
P2	0.3	0.08	0.74	1.7	<0.05	<0.08	0.008	$\frac{4.6–5.0}{4.7\times3}$	0.5
P3	0.8	0.09	0.90	1.8	0.11	0.064	0.013	$\frac{6.1–6.8}{6.3\times3}$	0.9
P4	1.6	0.10	0.95	1.7	0.15	0.250	0.055	$\frac{6.7–8.7}{7.7\times2}$	6.0

Note. Here and in Table 6, the numerator gives extreme values of $[H]_{diff.\ d.m}$, and the denominator — mean values over the indicated number of samples.

Table 2. Distribution of hydrogen in metal deposited with flux-cored wires in argon atmosphere

Flux-cored wire	$[H]_{diff.\ d.m}$, ml/100 g	$[H]_{res}$, ml/100 g
P1	3.8	0.2
P2	4.9	0.2
P3	4.8	1.9
P4	4.6	4.6

drogen $[H]_{res}$ and investigate thermal desorption of hydrogen from metals.

Transfer of yttrium into the weld metal and redistribution of absorbed hydrogen in welding with the 1.6 mm diameter flux-cored wire PP-AN 70 with the Fe–Y system alloy added to its core were investigated. Welding in high-purity argon was carried out at a reverse-polarity current of 220 A. Table 1 gives chemical composition of the multilayer deposited metal depending on the content of yttrium in the wire, diffusible hydrogen in the deposited metal, $[H]_{diff.\ d.m}$, and $[H]_{res}$ in the one-layer welds.

Below we give results of analysis of non-metallic inclusions in a sample made by welding with wire P4. Chemical composition of non-metallic inclusions was determined with scanning electron microscope «Jeol ISM-32CF» and dispersive energy analyser INCA Energy 350 of the «Oxford Instruments» Company (Great Britain). Non-metallic inclusions in the sample deposited with wire P4 had the following chemical composition, wt.%: 21.8 Y, 41.0 O, 13.7 Mn, 4.0 Si, 1.8 Al, 15.1 Ti, 2.6 S.

Increase in the yttrium content of the flux-cored wire core and its high deoxidising ability lead to increase in the content of silicon, aluminium and titanium in the weld metal, as well as to increase in the content of $[H]_{diff.\ d.m}$ and particularly $[H]_{res}$ in the weld metal obtained by using wires P3 and P4 (Table 1).

Supposedly, the content of hydrogen absorbed by the weld pool grows because of the presence of hydrogen in the Fe–Y system alloy and its hydration in manufacture and storage of the wires.

The content of diffusible hydrogen $[H]_{diff}$ was measured in samples of the weld pool metal taken

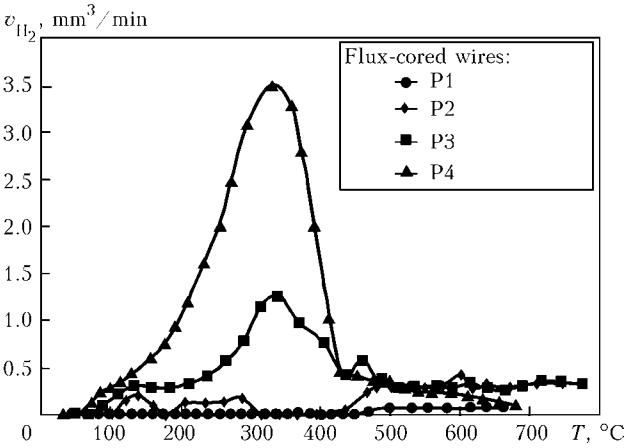

Figure 1. Spectrum of thermal desorption of residual hydrogen from samples taken into quartz ampoule (average sample heating rate — about 7 deg/min)

with a quartz tube in deposition of the fourth layer (Table 2), and thermal desorption analysis of $[H]_{res}$ was carried out to study in more detail the probability of redistribution of absorbed hydrogen depending on the yttrium content of the metal. The samples were cooled in water every 1–2 s and stored in liquid nitrogen before analysis.

The high content of $[H]_{res}$ takes place at an yttrium content of 0.013 to 0.053 wt.%, resulting in a peak of residual hydrogen (Figure 1) with a maximal temperature of 340–350 °C.

It is a known fact [11] that decomposition of yttrium hydride $YH_{1.6}$ during heating occurs in two stages — at temperatures of 360–410 and 1100–1300 °C. Yttrium monohydride transforms into yttrium metal at the second stage during heating. At an yttrium content of 0.013 wt.% or more, it is contained in non-metallic inclusions and iron solution in the weld [12], this leading to formation of the bond of dissolved hydrogen and yttrium.

Experiments on welding with basic electrodes were carried out by adding FeY (Y = 26 wt.%) or AlNiY (Y = 13.3 wt.%) into the electrode coverings.

Tables 3 and 4 give chemical compositions of the multilayer metal deposited with the experimental electrodes at a reverse polarity direct current of 160–170 A. Increasing the content of FeY and AlNiY in a covering causes a small increase in the yttrium content of the deposited metal with both series of electrodes,

Table 3. Chemical composition (wt.%) of metal deposited with electrodes containing FeY in their coverings

Electrode index	Y content of covering	C	Si	Mn	S	P	Cr	Ni	Mo	V	Al	Ti	Y
IP 1	0	0.043	0.274	0.98	0.007	0.015	0.88	2.36	0.45	0.18	0.007	0.005	–
IP 2	0.026	0.041	0.276	0.99	0.006	0.014	0.86	2.35	0.45	0.18	0.006	0.006	0.0001
IP 3	0.052	0.044	0.256	0.99	0.007	0.016	1.02	2.37	0.46	0.18	0.006	0.006	0.0001
IP 4	0.078	0.044	0.281	1.02	0.006	0.015	0.77	2.35	0.47	0.18	0.006	0.007	0.0001
IP 5	0.156	0.044	0.252	1.00	0.005	0.015	0.94	2.53	0.53	0.18	0.007	0.007	0.0002
IP 6	0.260	0.048	0.280	1.02	0.006	0.015	0.85	2.38	0.44	0.17	0.006	0.007	0.0006

Table 4. Chemical composition (wt.%) of metal deposited with electrodes containing AlNiY in their coverings

Electrode index	Y content of covering	C	Si	Mn	S	P	Cr	Ni	Mo	V	Al	Ti	Y
IP 7	0	0.035	0.278	0.95	0.005	0.012	0.83	2.14	0.45	0.21	0.007	0.005	–
IP 8	0.043	0.035	0.320	1.00	0.006	0.014	0.87	2.33	0.46	0.21	0.008	0.007	0.0001
IP 9	0.128	0.048	0.381	1.08	0.006	0.013	0.88	2.32	0.47	0.16	0.009	0.009	0.0001
IP 10	0.212	0.042	0.466	1.18	0.007	0.014	0.88	2.39	0.48	0.16	0.011	0.008	0.0001
IP 11	0.320	0.046	0.571	1.25	0.007	0.015	0.93	2.45	0.51	0.23	0.015	0.009	0.0002

Table 5. Chemical composition (wt.%) of metal deposited with electrodes containing FeY + AMP in their coverings

Electrode index	AMP and Y content of covering	C	Si	Mn	S	P	Cr	Mo	V	Al	Ti	Y
IP 12	–	0.079	0.278	1.20	0.015	0.021	0.94	0.45	0.21	0.007	0.016	–
IP 13	1.5 AMP	0.081	0.347	1.30	0.015	0.024	0.98	0.44	0.23	0.009	0.017	–
IP 14	0.56 Y 1.5 AMP	0.090	0.376	1.29	0.013	0.021	0.94	0.44	0.23	0.009	0.017	0.0006
IP 15	3.0 AMP	0.087	0.490	1.42	0.013	0.022	0.98	0.45	0.24	0.013	0.022	–
IP 16	0.56 Y 3.0 AMP	0.097	0.460	1.41	0.013	0.025	0.99	0.46	0.23	0.013	0.025	0.0010

the content of $[H]_{res}$ remaining almost unchanged (Figure 2).

The probability of increase in transfer of yttrium into the weld metal by adding strong deoxidisers, i.e. aluminium and magnesium, into the coverings was evaluated in a series of experiments on welding by using electrodes with Fe–Y + AMP added into their coverings.

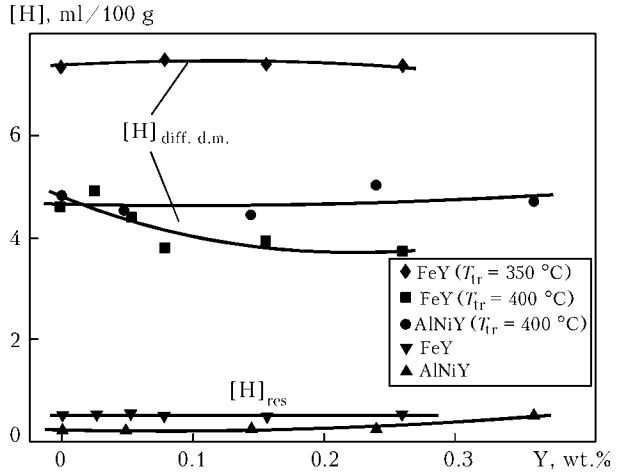

Figure 2. Contents of $[H]_{diff. d.m}$ and $[H]_{res}$ versus content of yttrium in electrode covering

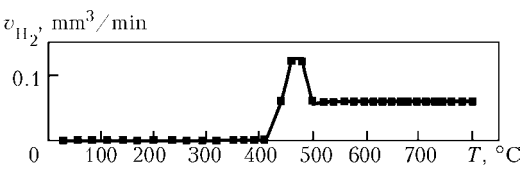

Figure 3. Spectrum of thermal desorption of residual hydrogen from deposited metal of one-layer weld made with electrode IP 16

Table 5 gives chemical composition of the multilayer metal deposited at a reverse polarity direct current of 160–170 A, and Table 6 — results of measurements of the $[H]_{diff. d.m}$ and $[H]_{res}$ contents.

Adding the aluminium-magnesium powder (AMP) into the electrode coverings leads to a substantial increase in the contents of silicon, manganese, aluminium, titanium and yttrium (Table 5). The content of $[H]_{res}$ remains almost unchanged (Table 6), and there is no peak of hydrogen in a 340 °C temperature range in the thermal desorption spectrum (Figure 3).

Adding yttrium together with AMP to the electrode coverings allows increasing the yttrium content of the weld metal to 0.001 wt.%. However, no redistribution of hydrogen was observed in this case.

Table 6. Content of hydrogen in weld metal obtained with electrodes containing FeY + AMP in their coverings

Electrode index	$[H]_{diff. d.m}$, ml/100 g	$[H]_{res}$ in heating to 800 °C, ml/100 g
IP 12 (basic)	$\frac{3.8–4.1}{3.9×3}$	0.5
IP 13 (1.5 wt.% AMP)	$\frac{3.9–4.2}{4.0×3}$	0.5
IP 14 (0.56 wt.% Y, 1.5 wt.% AMP)	4.9×3	0.7
IP 15 (3 wt.% AMP)	$\frac{5.0–5.2}{5.1×3}$	0.3
IP 14 (0.56 wt.% Y, 3 wt.% AMP)	$\frac{5.5–5.7}{5.6×3}$	0.5

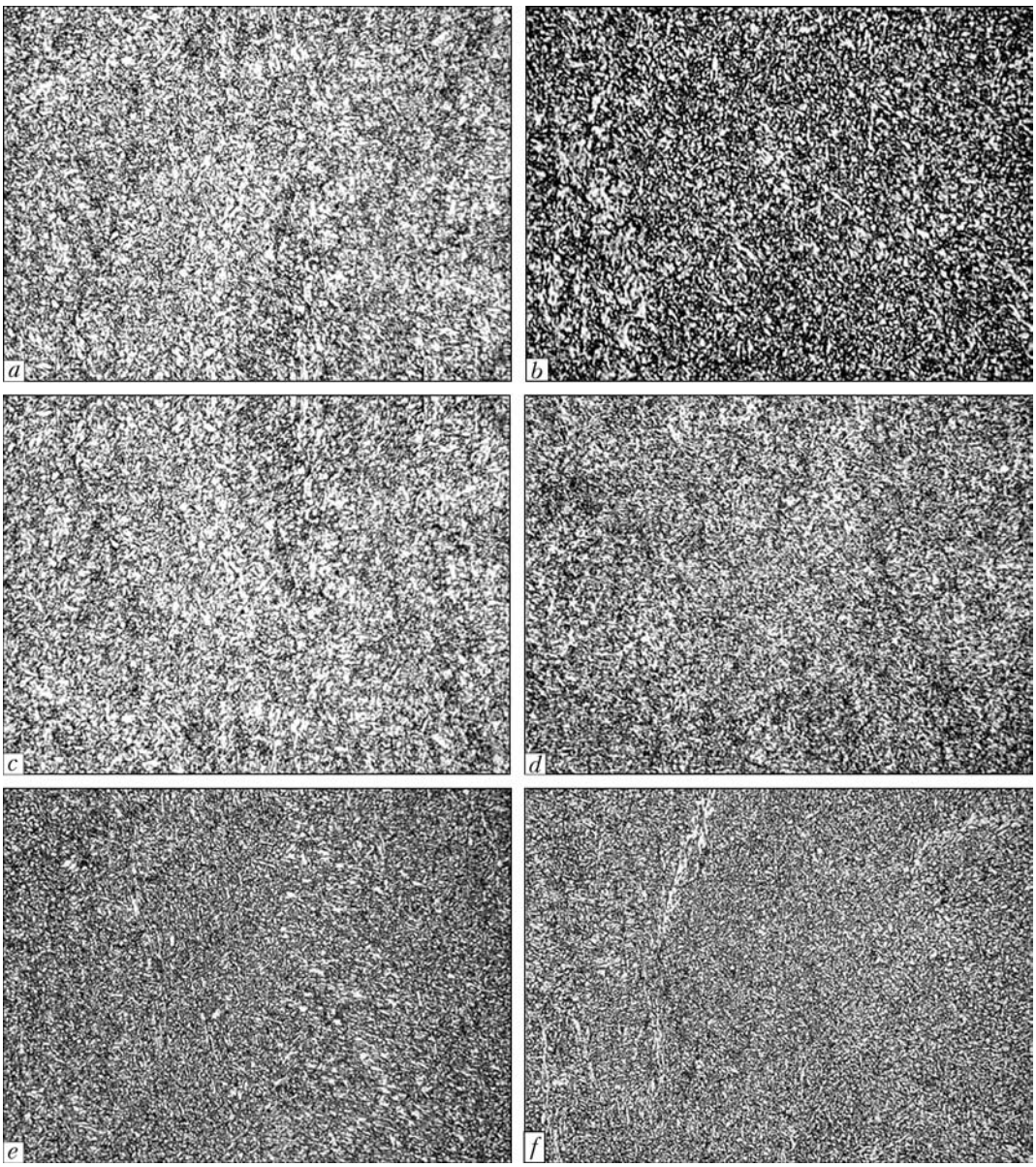

Figure 4. Microstructures (×500) of metal of multilayer welds made with experimental electrodes: *a* — IP 1; *b* — IP 6; *c* — IP 7; *d* — IP 11; *e* — IP 12; *f* — IP 16

The effect of yttrium on the metal structure and content of non-metallic inclusions was investigated on samples of the ten-layer welds made under the following conditions: I_w = 160–165 A (direct current of reverse polarity), U_a = 24–26 V, v_w = 8–9 m/h, experimental electrodes.

Microstructures of the multilayer weld metals were examined with microscope «Neophot-32». Photos of the microstructures shown in Figure 4 were obtained with camera «Olympus».

Microstructures of the samples from the upper layer of the deposited metal are approximately identical. They are of the bainitic type with fine precipitates of polygonal ferrite along the cast crystalline grain boundaries. Heat treated regions of the samples have structure of the mostly bainitic type without polygonal ferrite.

The fine-grained structure of all the samples is caused by alloying the weld metal with chromium, nickel and aluminium [13], and decrease in its dispersion degree is determined by adding yttrium.

It was established that adding FeY and AlNiY to the electrode coverings leads to decrease in the volume content of non-metallic inclusions. Chemical compositions of non-metallic inclusions in metal of the weld samples with the maximal yttrium content are given in Table 7. Inclusions are mostly silicon and manganese oxides with a low content of sulphur. The aluminium and titanium content was increased, and yttrium was detected in some inclusions at the highest FeY + AMP content of the electrode coverings.

Table 7. Chemical composition (wt.%) of non-metallic inclusions

Electrode index	O	Si	Mn	Al	Ti	S	Y
IP 6	38	13.6	43	0.5	2.8	2.1	–
IP 11	38	13.2	39	3.7	4.0	2.1	–

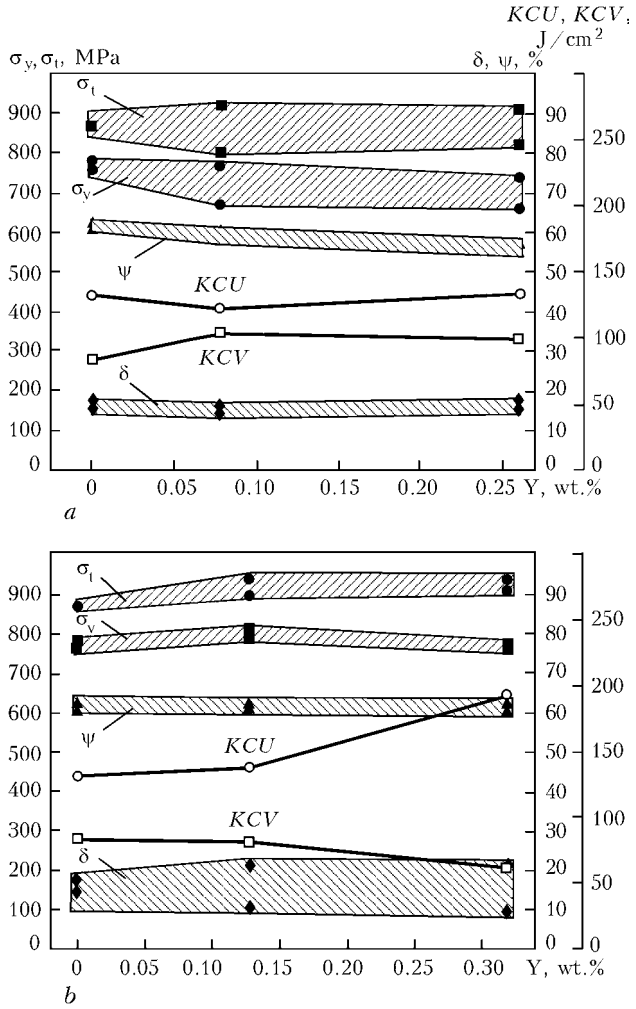

Figure 5. Effect of yttrium on mechanical properties of weld metal: *a* — electrodes with FeY in their coverings (series IP 1– IP 6); *b* — electrodes with AlNiY in their coverings (series IP 7– IP 11)

Bead on plate (steel VST3sp (killed) acc. to GOST 9466–750) welding was carried out under the following conditions to determine the effect of yttrium on mechanical properties of the deposited metal: I_w = = 160–165 A (direct current of reverse polarity), U_a = = 24–26 V, v_w = 8 m/h. Results of the mechanical tests conducted at 20 °C are shown in Figure 5.

The high values of strength and ductility of the deposited metal are preserved at 20 °C owing to alloying (see Tables 3 and 4) and fine-grained structure.

CONCLUSIONS

1. Welding with flux-cored wires in argon atmosphere provides a marked transfer of yttrium into the deposited metal and its interaction with hydrogen.

2. Thermal desorption analysis revealed formation of residual hydrogen with a maximal removal temperature of 340–350 °C at Y ≥ 0.013 %.

3. Welding with basic electrodes containing up to 0.35 wt.% Y in their coverings failed to provide the yttrium content of the deposited metal necessary for redistribution of hydrogen because of a high oxidation potential of the coverings.

4. Adding yttrium leads to decrease in the dispersion degree of structure of the deposited metal and volume content of non-metallic inclusions. Strength and ductility of the deposited metal remain at a constant level.

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