WET UNDERWATER WELDING OF LOW-ALLOY STEELS OF INCREASED STRENGTH

S.Yu. MAKSIMOV and **I.V. LYAKHOVAYA**
E.O. Paton Electric Welding Institute, NASU
11 Bozhenko Str., 03680, Kiev, Ukraine. E-mail: office@paton.kiev.ua

Conditions of welding directly in water environment limit greatly the feasibility of producing quality welded joints of low-alloy steels of increased strength. This is due to the fact that mechanical properties of weld metal are inferior to properties of base metal, and the initiation of cold cracks in the heat-affected zone (HAZ) is possible. Investigation of weld metal structure showed that depending on degree of alloying the weld areas, adjacent to the fusion line, can have different structures of transient compositions. The obtained results allowed working out requirements to the deposited metal composition to prevent the formation in HAZ of a brittle interlayer with an increased hardness, which is a place of initiation of cold cracks. Welded joints of steel 17G1S of 14 and 40 mm thickness, made under water using developed electrodes with rods of high-alloy steel, provide weld metal mechanical properties, corresponding to the requirements of class A of Specification AWS/ANSI D3.6 on underwater welding, and also resistance of welded joint against crack formation. Electrodes can be used in repair and construction of special-purpose metal structures, made of low-alloy steels of increased strength of up to 40 mm thickness. 8 Ref., 6 Figures, 1 Table.

Keywords: *wet underwater welding, low-alloy steels of increased strength, weld, structure, chemical composition, cracks, mechanical properties*

Wet welding is very attractive due to efficiency and simplicity in fulfillment [1, 2]. However, it encounters significant difficulties of a metallurgical nature. The hydrogen-oxygen atmosphere of a vapor-gas bubble contributes to oxidation of alloying elements and saturation of weld pool metal with hydrogen, and the accelerated cooling by surrounding water leads to its fixation in weld metal and formation of hardening structures in HAZ metal [3]. As a result, a risk of formation of cold cracks is greatly increased, in particular in welding of increased strength low-alloy steels of 17G1S or X60 type. The problem can be solved by applying electrode materials, providing the formation of austenitic structure of weld metal and, thus, decreasing the amount of hydrogen, diffusing into HAZ [4].

The preliminary experiments on welding with a flux-cored wire, having a sheath of nickel strip, confirmed, on the one hand, the feasibility of producing of quality welded joint on X60 type low-alloy steel of increased strength (without cracks in HAZ metal), and, on the other hand, revealed the difficulty in guaranteeing the required level of mechanical properties of weld metal. A large amount of hydrogen increases the weld metal resistance to plastic deformation and decreases the limiting characteristics of its ductility. Such result is correlated with a known susceptibility of nickel to hydrogen embrittlement [6]. This phenomenon becomes more noticeable in the presence of oxygen as an impurity and increased rate of cooling [6] that is typical of the underwater welding conditions. In the author's opinion the presence of oxygen in nickel facilitates the intergranular fracture which occurs in this case at lower concentrations of hydrogen, as the hydrogen pressure is added by pressure of water vapors, forming in reduction of nickel oxides. Cracks, initiating along the grain boundaries, lead to fracture of specimens at tensile tests even at a negligible deformation.

Coming from the above-mentioned, the results of study of hydrogen brittleness of nickel alloys with iron and chromium represent interest. Authors of work [6] found that hydrogen brittleness of nickel alloys with iron and chromium is decreased with increase in content of the latter. They consider that this nature of effect of chemical composition is due to the change of electron state of alloys. Therefore, in our opinion, the application of electrode materials for underwater welding, providing the weld metal on the base of Fe–Ni–Cr alloying, can be rather successful. However, in one's time the electrodes with a core of stainless steel [7] were recognized as not promising because of a risk of crack formation in weld metal near the fusion line that was explained by dilution of electrode metal with base metal. Nevertheless, the authors of work [8] inform about the development of electrodes with a rod of Sv-

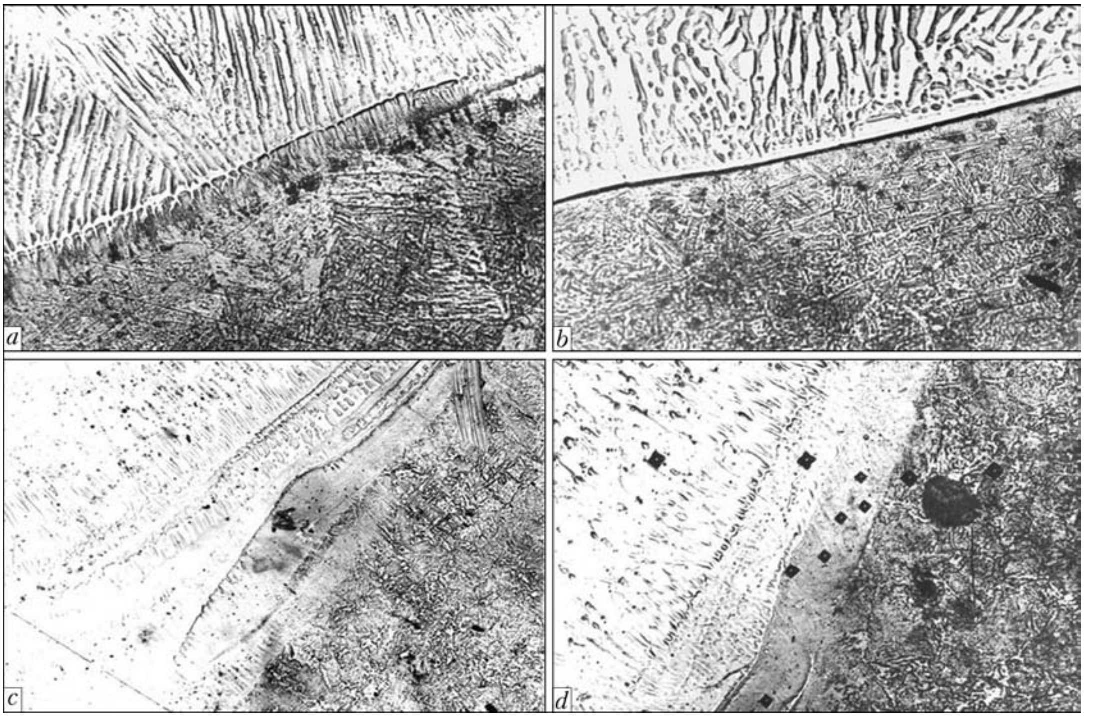

Figure 1. Microstructures (×650) of fusion zone areas with a feathery structure (*a*), with distinctly expressed fusion line (*b*), with flowing-in of base metal (*c*) and with a parallel boundary (*d*)

10Kh16N25AM6 wire for underwater welding of high-strength steels, providing the quality welded joints with high mechanical properties and resistance against cold crack formation.

The aim of the present work was to study the structure, chemical composition and mechanical properties of welded joints of steel 17G1S of 14 and 40 mm thickness, made under water using electrodes with a rod of high-alloy steel, and to select the weld metal composition providing its mechanical properties at the level of base metal properties and welded joint resistance against the crack formation.

Taking into account the possible dilution of weld metal with base metal at the level of 40 %, the wires with chromium equivalent $Cr_{eq} \cong 21$–33 % and nickel equivalent $Ni_{eq} \cong 19$–32 % were selected as electrode rods for the preliminary experiments. Experimental electrodes of 4 mm diameter with rutile-fluorite coating were manufactured from these rods. Welding of butt specimens was made by a diver-welder in the laboratory basin at 1 m depth using the following conditions: I_w = 140–160 A, U_a = 26–28 V, direct current of reversed polarity. As a base metal the plates of 14 and 40 mm thickness of 17G1S type steel were used (wt.%: 0.18 C, 0.36 Si, 1.67 Mn).

It was found by the spectral analysis that the value Cr_{eq} in root welds was changed in the ranges of 12.0–15.5 %, and Ni_{eq} — 10.8–22.7 %. According to obtained compositions, metal of all the welds in the Schaeffler's structural diagram is highly-alloyed Cr–Ni austenite. However, the weld areas, adjacent to fusion line, represent a system of structures of transient compositions. Among them, austenite-martensite and martensite interlayers are of interest and hazard due to their increased hardness and brittleness and possibility of initiation of cracks in them during welding or under the service conditions. Width and length of these interlayers, as well as values of their hardness depend, on the one hand, on the degree of alloying of weld metals (margin of austenite content), and, on the other hand, on the degree of base metal penetration, i.e. on change of weld composition in dilution of base (pearlitic) and deposited (austenitic) metal.

The metallographic examinations revealed the variety of structures of a narrow zone of weld metal, adjacent to fusion line. Conditionally it is possible to distinguish four types of structures:

- so-called feathery structure, formed by weld metal, flowed-in between the fused grains of the base metal (Figure 1, *a*);
- regions with distinctly expressed fusion line. They are typical by the transition zone absence. Weld metal structure is radically differed from that of base metal (Figure 1, *b*);
- so-called flows-in («tongues») (Figure 1, *c*) of base non-fused metal, flowed into the weld and often characterized also by the increased hardness. The appearance of these structures is due to stirring of base metal under the direct influence by the welding arc. The less stable the welding condition, the larger fraction of these inclusions can be;

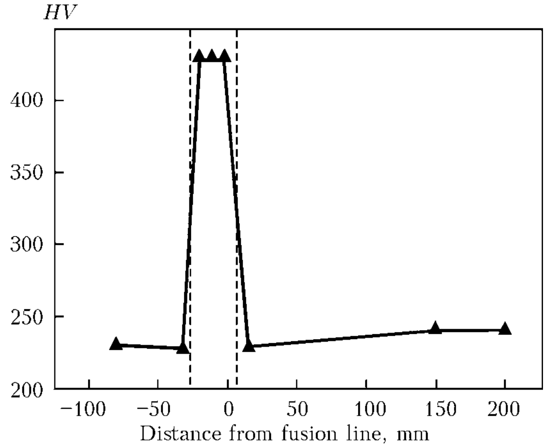

Figure 2. Distribution of microhardness in the presence of martensitic interlayer

- structure with the presence of so-called parallel boundary on the weld metal side (Figure 1, *d*) when a thin interlayer of increased hardness is arranged between the base and weld metal. Approximate diagram of distribution of microhardness in the presence of such interlayer is given in Figure 2.

Relations between the chemical composition of weld metal, weld arrangement in multilayer joint and structure type were not found. The most hazardous is the structure with a parallel boundary, in which the cold crack formation is possible at high hardness. This is typical of root welds. In final welds the hardness of these structures is significantly lower even at smaller amount of alloying elements.

To define by numerical method the conditions of prevention of brittle interlayer formation in weld metal, the effect of alloying degree per a fraction of forming martensite was investigated. For this purpose, the weld metal alloying with nickel in the ranges of 12–25 % and chromium in the range of 11–15 % was imitated. Results of

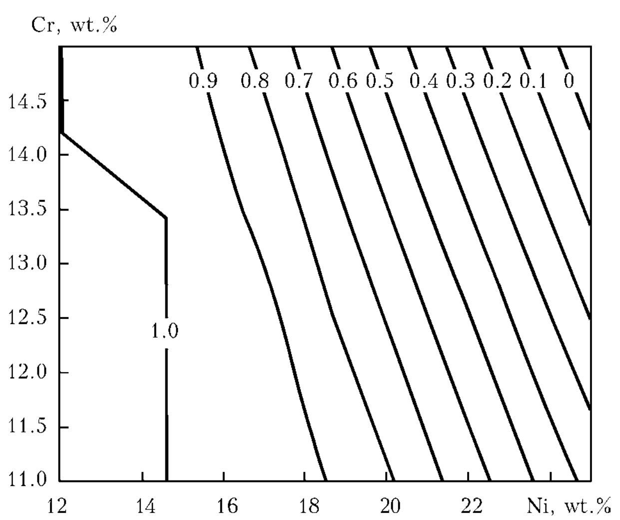

Figure 3. Effect of alloying of austenitic weld metal on martensite fraction in interlayer

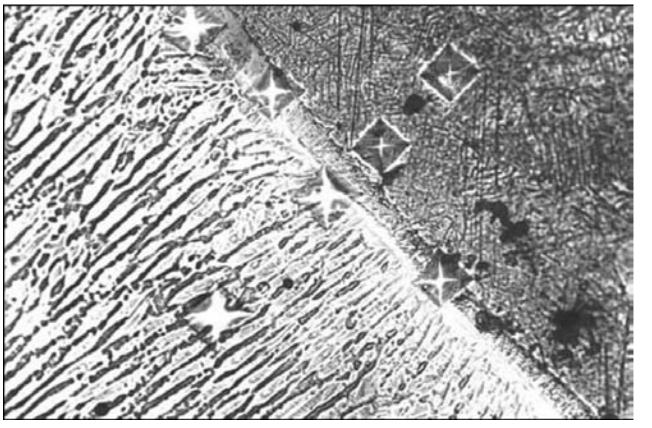

Figure 4. Parallel boundary with interlayer of low hardness (×650)

calculations (Figure 3) showed that to minimize a fraction of martensite, which is formed in weld metal interlayer near the fusion line during underwater welding, the nickel and chromium equivalents of the latter should lie above the line in state diagram, parallel to the line dividing the regions with austenitic and austenitic-martensitic structure, and passing through a point with coordinates $Ni_{eq} = 24.2$ % and $Cr_{eq} = 14.3$ %. Under these conditions the interlayer hardness is at the level of hardness of the surrounding metal (Figure 4).

Coming from the set requirements to the chemical composition, the electrodes with rods of wire Sv-10Kh16N25AM6 and additional alloying by coating were developed. To determine the

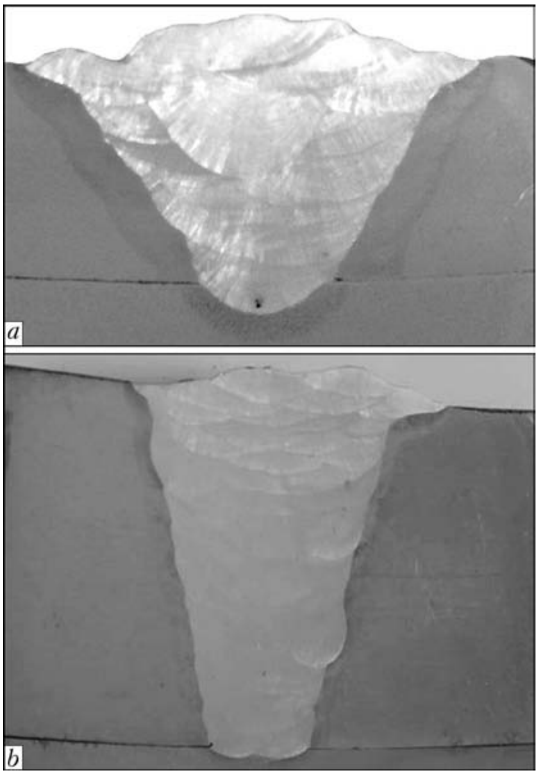

Figure 5. Macrosections of welded joints of 14 (*a*) and 40 mm (*b*) thickness

Mechanical properties of weld metal and base metal

Material	$\sigma_{0.2}$, MPa	σ_{ult}, MPa	δ, %	ψ, %	KCV_{-20}, J/cm^2	Bending angle, deg, $R = 2t$
Weld, 14 mm	≥410	≥620	≥32	≥38	≥108	180
Weld, 40 mm	≥460	≥600	≥29	≥47	≥105	180
Steel 17G1S	340	510	23	–	–	–

mechanical properties, the butt specimens of 14 and 40 mm thickness with V-shaped grooving were welded. Tests were conducted in accordance with requirements of class A of Specification AWS/ANSI D3.6 on underwater welding. The obtained results are presented in Table. Macrosections, cut out from welded specimens, are given in Figure 5.

Metallographic examinations of macrosections of Tekken sample, made by the developed electrodes, showed the absence of cracks in welded joint (Figure 6).

Thus, the application of developed electrodes with Cr–Ni–Mn system of alloying guarantees producing of underwater welded joints of increased strength low-alloy steels without cracks in HAZ metal and with mechanical properties meeting the requirements of class A of Specification AWS/ANSI D3.6 on underwater welding.

In conclusion, as a result of carried out investigations it was found during wet underwater welding of low-alloy steels of increased strength that:

- brittle interlayers of increased hardness (up to 4500 MPa), susceptible to cold cracking are formed near the fusion line on the side of weld metal as a result of dilution with base metal;
- to prevent crack formation the required and sufficient range of alloying by chromium together with nickel should be determined by the following values: Cr_{eq} = 17.5–23 %, Ni_{eq} = 18–28 %;
- mechanical properties of welded joints of 14 and 40 mm thickness, made by the developed electrodes, meet the requirements of class A of Specification AWS/ANSI D3.6 on underwater welding.

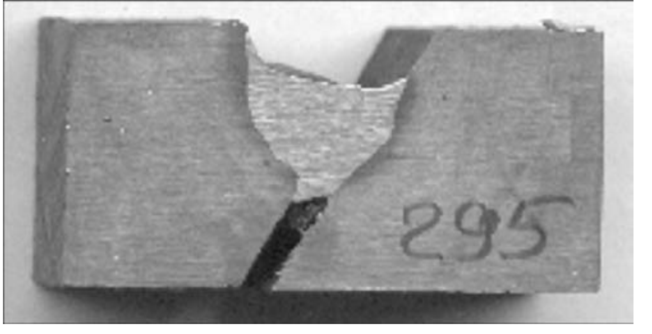

Figure 6. Macrosection of technological sample Tekken

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