

E.O.Paton Electric Welding Institute activity in the field of underwater welding and cutting

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Summary. Presents the results of E.O.Paton Electric Welding Institute developments on creating electrode materials, equipment and technology for wet underwater welding and cutting. The R&D efforts in this area include investigation of the effect of cooling rate, hydrogen saturation, hydrostatic pressure and other factors upon process of welding and quality of resulting joints, studies of weldability of steels, development of special welding consumables, methods and procedures, elaboration of the basic principles of mechanisation of the wet welding and cutting processes. The experience of wet underwater welding and cutting application is evidence of possibility to apply the methods, at least, for restoration of wharfs, platforms, pipelines, ships and other underwater constructions.

The electrodes and flux-cored wires can be used for:

- welding the mild steels and low alloyed high strength steels up to 40 mm in thickness with tensile strength of up to 600 MPa at the depths down to 30 m;
- welding high-alloy corrosion-resistant steels ANSI 304L, 308L, 347 AND 321 type;
- cutting of carbon and alloyed steels and non-ferrous alloys up to 40 mm in thickness at the depths down to 60 m.

Key words: underwater welding and cutting, flux-cored wire, low-alloyed steel, stainless steel, mechanical properties.



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INTRODUCTION

The world ocean is an inexhaustible source of mineral resources [1, 2]. Welding takes the important place in construction and repair of underwater structures. The volume of application for these purposes of wet welding, which is performed directly in water and excludes application of expensive caissons and chambers, recently has considerably extended [3, 4]. During the underwater welding the arc is burning in a gas bubble which is formed due to evaporation and decomposition of water, vapors and gases of molten metal and components of welding consumables. Water consists of 88,9% oxygen and 11,1% hydrogen. Reliable protection of molten metal, first of all from hydrogen and oxidizing effect of environment, is one of the main tasks in the development of consumables for welding steels under water. The second typical feature in underwater welding is the intensive cooling which should also be taken into account. It is possible to compensate the heat losses by optimum selection of slag-forming components. The problem of overcoming the difficulties associated with wet welding and its related applications such as the repair and maintenance of subsea structures and pipelines by arc welding, was solved by the introduction of semi-

automatic wet welding with self-shielding flux-cored wires developed at the E.O.Paton Electric Welding Institute (PWI) [5, 6].

THE GENERAL DIRECTIONS OF THE PWI ACTIVITY

Due to the increased volume of underwater constructions in the 60's and 70's encompassing a variety of applications, a quest for an economical and quality underwater welding began. Though both dry hyperbaric and wet welding techniques were introduced, the method of wet welding was adopted in the former USSR because of its inherent versatility, manoeuvrability, and relatively low cost. Most often the techniques and technologies associated with wet welding focus on the shielded metal-arc welding (SMAW) process using in many cases a proprietary waterproof coating developed by the manufacturer.

When assessing the performance requirements of wet welding to obtain quality joints the greatest difficulties to be overcome are due to the following circumstances:

- a high rate of cooling of welding joint causes the formation of quenching structures and brittle fracture of the joints
- large amount of hydrogen and oxygen drastically reduces the toughness and ductility of the welded joints and is dissolved in the welds
- a high skill of the diver-welder is required to obtain welds of satisfactory quality.

Therefore, taking into consideration the aforementioned, the application of the SMAW process to wet welding is limited by its inability to consistently produce quality welded joints by surface standards. Nevertheless, underwater welding directly in water (so-called wet welding) becomes an important technological method due to a number of its advantages as compared with dry welding.

The general directions of the PWI activity in the field of underwater wet welding and cutting are as follows:

- R&D on wet semi-automatic arc welding with the self-shielded flux-cored wire
- R&D on wet manual arc welding
- R&D on wet semi-automatic cutting without additional supply of oxygen
- R&D on arc cutting with stick electrodes

- Creation of the unique equipment (semi-automatic machine) for wet underwater arc welding

- Working out and introduction of wet arc welding and cutting technologies

The fundamental researches of PWI in the field of wet arc underwater welding are as follows:

- * Peculiarities of arc burning in fresh water and water of different salinity
- * Conditions for ensuring the stable arcing under different hydrostatic pressures
- * Composition of waste gases and their interaction with molten metal in the vapour-gas bubble atmosphere
- * Peculiarities of transfer of the alloying elements from the electrode to the weld metal
- * Effect of alloying upon the structure and properties of the weld metal
- * Conditions for elimination of porosity and non-metallic inclusions in weld metal
- * Effect of hydrostatic pressure and welding parameters upon the level of mechanical properties of welded joints
- * Quality of the cut and economical indices of mechanized underwater arc cutting of steels and non-ferrous metals
- * Structural steels weld ability including peculiarities of formation of the welded joint microstructure and properties, mechanism of formation and precautions for avoidance of heat-affected zone cracking
- * Structural strength of welded joints and considerations for their fitness-in-service
- * Technical requirements to unique equipment for wet welding and cutting including power sources and feeding devices.

WET SEMI-AUTOMATIC UNDERWATER WELDING

The idea of developing the basic technology of wet welding using self-shielded flux-cored wire was based on the evident advantages of such an approach. The nature of the flux-cored wire is such that its chemical composition can be varied over wide ranges. This offered us a possibility of having tight and strong welds without any additional gas or flux shielding of metal. The reliable shielding

could be provided by the wire itself, i.e., by the proper selection of its chemical composition. We believed that the problem of hydrogenation of the weld metal and the heat-affected zone, as well as the consequences of this phenomenon, which were already well-known, could be solved if not completely then at least partially, through a special design of the flux-cored wire. Whereas an electrode coating is in a direct contact with water and, hence, is moistened, the core of the flux-cored wire is protected by a sheath. It is an advantage of this wire with regard to one of the sources of hydrogen saturation. Then, development of the self-shielding wire meant elimination of extra devices which made the torch heavier and the work of a welding diver more difficult and eventually greatly simplified the basic operations. Handling the above problem on the basis of using the flux-cored wire provided a combination of maneuverability and versatility of manual welding and the advantages characteristic of the semi-automatic welding. It was evident that with this method we could solve the problem of continuity of welding operations, provide a fundamental increase in the productivity of labor of a welding diver and reduce the time of a stay of a human being under the water. Additionally, it was known that the semi-automatic welding could be mastered under conventional conditions much quicker than the manual welding. This advantage must also manifest itself under the underwater welding conditions. Therefore, the above idea accounted also for human factor. This could simplify choosing and training of people for performing the underwater welding.

At the first stages of developing the semi-automatic wet flux-cored arc welding (FCAW) it was applied to structures of mild steels with yield point up to 280 MPa. Further research and development permitted the field of the method application to be widened. By now the satisfactory quality of wet welded joints is also ensured when welding the low-alloy structural steels with yield and tensile strength of up to 350 MPa and 500 MPa respectively and with the carbon equivalent value up to 0,35 [7]. The welded joint mechanical properties are presented in Table 1. Analysis of these data shows

that even with slight alloying the weld metal has the sufficiently high level of strength, ductility, and Charpy toughness. The appearance of the samples after the tests is shown in the Fig.1.



a



b

Fig.1. The appearance of the samples after the bend (a) and tensile (b) tests of the welding joints of low alloyed steel

The use of this flux-cored wire in transition to modern low alloyed high strength steels yields unsatisfactory results. The main cause is formation of cold cracks in the heat-affected zone [8]. This problem can be solved through using electrode materials providing formation of the austenitic structure of the weld metal [9] and, therefore, decreasing the amount of hydrogen diffusing into the HAZ. For these purposes, for welding at depths of up to 30 m, electrodes and flux-cored wire were developed. It is very important that mechanical properties of the deposited metal are in good agreement with mechanical properties of the base metal (Table 2), which is required to maintain operating reliability of a welded joint. The bend angle in this case was 180°. Macrosections and appearance of the samples after the tests are shown in the Fig.2.

Table 1. Welded joint mechanical properties

Steel	Tensile Strength, MPa	Yield Strength, MPa	Impact Energy, J (-20°C)	Bend angle, degrees
St3	420...450	320...340	35...45	180
09G2	430...460	330...350	40...50	180
A36 (USA)	420...460	320...350	40...50	180

Note: 1. All samples were tested according with ANSI/AWS D3.6
2. Bend angle values have been determined at root and face bend testing

Table 2. Mechanical properties of the weld metal (ANSI/AWS D3.6)

Welding method	$\sigma_{0,2}$, MPa	σ_B , MPa	δ , %	ψ , %	KCV ^{-20°C} , J/sm
manual	≥ 410	≥ 600	≥ 30	≥ 40	≥ 110
semi-automatic	≥ 350	≥ 550	≥ 30	≥ 64	—
API 5L X60	≥ 415	≥ 520	≥ 19	—	—

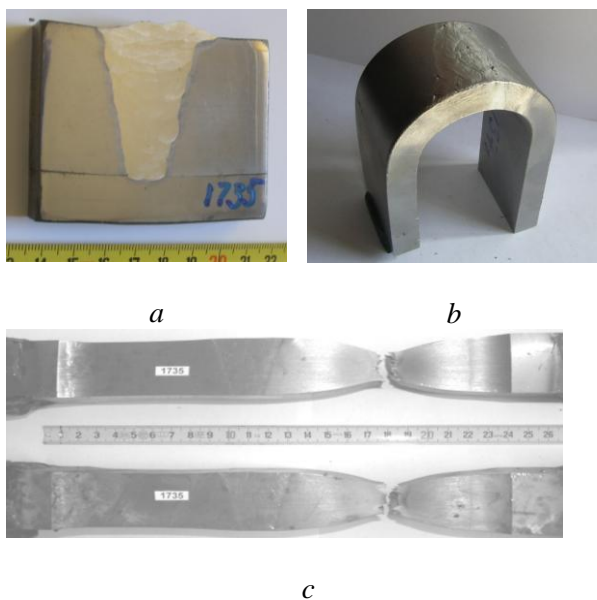


Fig.2. Macrosections (a) and appearance of the samples after the bend (b) and tensile (c) tests of the 40 mm thick welding joints of low alloyed high strength steel

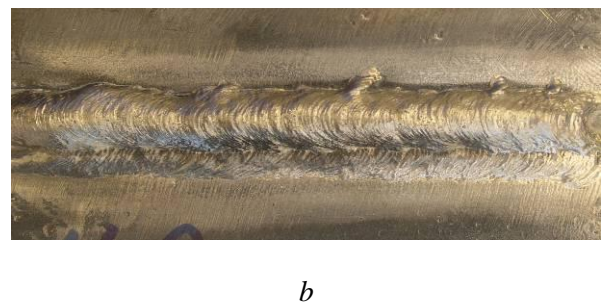
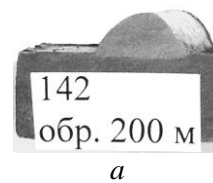


Fig.3. Macrosections (a) and the appearance of the butt joint (b), depth 200 m



Fig.4. Formation of metal of multilayer weld

For welding at great depths, a flux-cored wire with a nickel shell was developed. Bead on plate macrosections and the appearance of the butt joint are shown in Fig.3.

WELDING OF STAINLESS STEELS UNDER WATER

Repair of elements of nuclear power plants constructions is attended with the risk of radioactive irradiation of personnel. The use of water as a physical barrier against a radiation allows to increase possible time of performing of works. It does perspective development of materials for the wet underwater welding of stainless steels. Evident is the expediency of mechanization and automation of the process to minimize the human labor near the radiation source Based on long-term experience of application of the mechanized flux-cored wire welding in the E.O.Paton Electric Welding Institute a selfshealing flux-cored wire is worked out for wet welding of stainless steels [10]. It allows to perform welding of butt, fillet and overlapped joints in flat and vertical positions of high-alloy corrosion-resistant steels type of AISI 304L, 308L, 347 and 321. Fig.4 shows the appearance of a filling layers of 12 mm thick steel 12Cr18Ni10Ti welded joint, made under water using 1,6 mm diameter flux-cored wire [11].

Mechanical properties of weld metal meet to the requirements, specified to the welds, performed on air. Results of testing specimens, cut out from the butt joint, are given in Table 3.

Table 3. Mechanical properties of weld metal at 20°C test temperature

$\sigma_{0.2}$, MPa	σ_{ult} , MPa	δ , %	ψ , %	KCV, J/cm^2	Bend angle, $R = t$
≥ 350	≥ 620	≥ 26	≥ 29	≥ 90	68...103

Application of the flux-cored wire opens the prospect of automation of welding process and exception participating of diver-welder in works in extra hazardous conditions.

WET SEMI-AUTOMATIC UNDERWATER CUTTING

One of the actual tasks, determining the development of underwater technique, is improvement of existing underwater cutting methods, creation of new electrode materials and of highly efficient process of cutting metals and non-metals. Arc cutting methods have a key position in these attempts. They are based mainly on application of stick electrodes with oxygen supplied to arcing zone. The heat of both the electric arc and exothermic reactions of base metal and metal electrode in the oxygen environment is used for heating metal being cut. Essential disadvantages of such a technique are high oxygen consumption (0,2...0,35 m³ per running meter of a cut) and the necessity of frequent changes of electrodes. Besides, application of this method for cutting non-ferrous metals and high-alloy steels is practically impossible.

To eliminate the above-mentioned disadvantages of the known cutting methods, to increase the process capacity, and to improve diver's labour conditions, the fundamental researches on metallurgical peculiarities of underwater cutting have been performed at the E.O.Paton Electric Welding Institute, including study the physical characteristics of arcing under water down to depth of 60 m [12].

Absence of additional oxygen supply into the arc zone and the continuity of cutting performance are important feature of the technique. The high cutting through capability and arc burning stability are achieved at the expense of the flux-cored wire composition. Gas- and oxygen forming components, besides their action as liquid metal oxidisers and vapour-gas bubble creators, form the plasma jet. The latter exerts active gas-dynamic pressure on the liquid metal, thus accelerating the burning through of the base metal.

Flux-cored wires for underwater cutting meet a number of technical requirements which determine the possibility and expediency of their application for steel of different thickness in the wide range of operation depths. The main requirement of the metallurgical nature is intensive oxidizing of molten

metal in the cut cavity. The technological requirements include the stable arcing and quality formation of the cut edges. The components of the flux-cored wire charge are strong oxidiser, gas-forming and arc stabilising compounds.

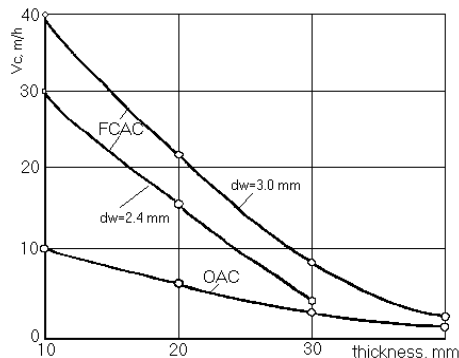


Fig 5. Relationship between underwater cutting speed and thickness of sheet being cut (St3) in FCAC ($V_{wf}=350$ m/h) and OAC

The wires of a small diameter (2,0...2,4 mm) are preferable for semi-automatic FCAC, because they allow a light-weight holder to be used which is more convenient for underwater application.

When 2,0...2,4 mm dia. wires are used, up to 30 mm thick low-carbon steels can be cut by FCAC; however, the said wires are more reasonable to be used for underwater cutting the 15...20 mm thick metals at cutting speed not less than 10...15 m/h (Fig.5) [13]. Some data in respect to process parameters are given in Table 4.

The arc cutting process with flux-cored wire exceeds the best procedure of manual oxy-arc cutting by tubular electrodes in terms to productivity. The speed of cutting low-carbon and low-alloy steels is practically similar.

Austenitic steels can be cut by 10...15% faster, this being explained by the higher concentration of the cutting jet heat energy due to the lower thermal conductivity of the metal. The speed of cutting aluminum is 1.5...2 times as high as that of cutting low-carbon steel of the same thickness, this being related mainly to the great differences in the melting points. At the same time, the speed of cutting copper

is by 2...3 times lower, though the difference in the melting points is effective as well. In the latter case, the great effect is produced by the high thermal conductivity of copper.

Table 4. Typical process parameters of underwater flux-cored arc cutting of carbon steels

H, msw	δ , mm	dw, mm	Ic, A	Ua, V	Vc, m/h
10	10	2,0	470	40	20,0
		2,4	620	45	25,0
	20	2,0	460	45	8,0
		2,4	600	50	15,0
20	10	2,0	450	42	18,0
		2,4	610	47	23,0
	20	2,0	440	47	6,0
		2,4	580	52	13,0
30	10	2,0	440	44	16,0
		2,4	570	49	20,0
	20	2,0	420	49	4,0
		2,4	560	54	10,0

The E.O.Paton Electric Welding Institute widely uses the new cutting technology in practice [11]. A number of unique operations are performed in salvaging of ships, repair of oil and gas pipelines, restoration of bridges, clearing of river-beds, repair of sea moorages and so on.

PECULIARITIES OF THE SEMI-AUTOMATIC WELDING AND CUTTING EQUIPMENT

To realize the processes of welding and cutting by using the flux-cored wires, the E.O.Paton Electric Welding Institute has developed a series of semi-automatic machines of a unique design [14]. The control cabinet and power source are on the surface. Submersible block is filled with water to balance the hydrostatic pressure and can operate at the depths down to 500 m. If necessary, the diver can open the cover of container "in situ", replace the empty reel and install new one with wire. The multi-year service confirmed the reliability and serviceability of the suggested conception.

At present this direction is successfully developed using both a previous experience, and

also new technological solutions and updated element base. The E.O.Paton Electric Welding Institute has designed and tested under the real conditions the new high-efficient model of the semi-automatic machine for underwater welding and cutting [13].

The new semi-automatic machine provides:

- stability of flux-cored wire feeding at varying of conditions of works fulfillment (depth, water salinity, manipulation of holder by a diver-welder) and condition parameters
- reliability of service: safety of hardware and possibility of a quick change of units and elements, coming out of order (maintainability)
- convenience of service in setting-up and keeping the condition parameters
- feasibility of operation using any type of welding current source
- integral protection of supply system from the effect of water medium of different origin at action of high pressures.

EXPERIENCE OF APPLICATION

The important feature of wet semi-automatic technology is its many years successful application. The first experimental tests on real objects were made at the end of 70-s. By now serious experience has been accumulated in repair of gas- and oil pipelines and ships afloat.

Pipelines. Since 1970 more than 80 gas-, oil-, and water pipelines across the water obstacle were restored using the FCAW system, Fig.6. In the most difficult cases the defective site of pipe was excluded with help semi-automatic cutting by flux-cored wire. The samples simulating repair of typical defects are shown in Fig.7 [15].

The experience of E.O.Paton EWI and CIS-companies which use the FCA welding techniques relates to restoration of river pipeline passages at the depths down to 20 m [16]. The maximum diameter of repaired pipes was 1020 mm, the inner operating pressure being up to 5 MPa. Usually, the duration of restoration including removing of faulty area, mechanical treatment, adjustment of patch, welding and quality inspection, was 4...10 days.

Ship afloat. For the first time the semi-

automatic flux-cored arc welding was applied in salvaging the motor ship "Mozdok" sunk in the Odessa port [17]. The mentioned ship got a 7×14 m breach as a result of collision and submer-creating hazards for normal navigation in this region.



Fig.6. Wet semi-automatic welding of pipeline



Fig.7. The samples simulating repair of the typical defects of pipelines after testing under inner pressure of 5 MPa

The ship salvaging was performed by the combined methods: using lifting pontoons and creating the positive floatability of the hull by pumping polystyrene into the holds. It was necessary to ensure complete tightness of the brought-in patch and of the ship cargo hold covers to prevent the leakage of polystyrene pumped into the holds. The semi-automatic underwater welding allowed to perform a large volume of welding jobs in a short time. The vertical overlap welds, 30...12 m deep, and the welds in the vertical and flat position 12 m

deep, were made in two passes. The total length of welds was 230 m, Fig.8. There were no problems of polystyrene leakage after a through sealing, and the ship was lifted by the time fixed.

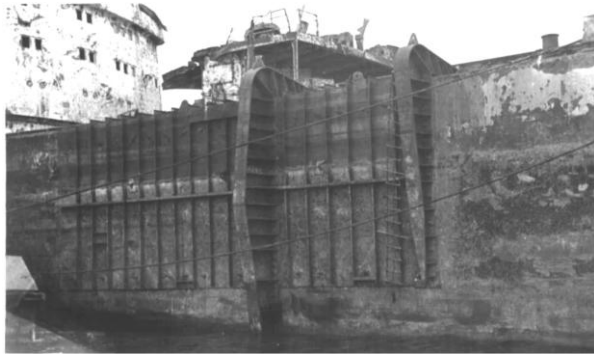


Fig.8. The path (7×14 m) welded with semi-automatic welding

Since that time more than 200 ship-repairing and ship-rising works were carried out on the base of FCA welding technology. The accumulated experience of practical application of FCA welding technique shows the possibility and expediency of its utilization in the next cases:

- repair of ship hulls with navigation and corrosion damages
- hermetization of ship hulls before transportation to place of ship liquidation
- hermetization of Kingston's shafts for repair and substitution of fittings
- installation of protective casing around screw propeller
- substitution of protectors
- restoration of rudders
- repair of floating docks and moorages
- ship rising.

CONCLUSIONS

1. At the E.O.Paton Electric Welding Institute the two unique methods for performance of underwater work have been created: wet semi-automatic welding and wet semi-automatic cutting. Both of them are based on using special flux-cored wires permitting the process to be performed directly in water.

2. The reached level of weld metal mechanical properties is believed to be sufficient for satisfactory performance of repair and maintenance work on underwater structures made from mild and low-alloyed high strength steels.

3. The semi-automatic underwater welding application in emergency cases and in case of emergency repair in distant industrial regions gives such important advantages as mobility and a possibility of a fast mobilization of the equipment, high speed of the operation performance due to a high efficiency of the process, moderate expenses for the welding performance and very high economic efficiency.

4. The underwater flux-cored wire semi-automatic arc cutting is widely used in restoration of underwater steel structures and salvaging operations. The method features the absence of any additional supply of oxygen to the arcing zone and is intended for cutting of carbon and high-alloyed steels, non-ferrous metals and alloys up to 40 mm thick at the operation depths up to 60 m, both in fresh and sea water.

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Разработки Института электросварки имени Е.О.Патона в области сварки и резки под водой

Сергей Максимов

Аннотация. Представлены результаты разработок ИЭС имени Е.О.Патона по созданию электродных материалов, оборудования и технологии мокрой подводной сварки и резки. Научные исследования в этой области включают изучение влияния скорости охлаждения, насыщения водородом, гидростатического давления и других факторов на процесс сварки и качество получаемых соединений, изучение свариваемости сталей, разработку специальных сварочных материалов, методов и технологий, развитие основных принципов механизации процессов мокрой сварки и резки. Опыт применения мокрой подводной сварки и резки наглядно свидетельствует о применимости этих технологий по крайней мере к восстановлению причалов, платформ, трубопроводов, судов и других подводных конструкций.

Электроды и порошковые проволоки могут быть использованы для:

- сварки малоуглеродистых сталей и низколегированных сталей повышенной прочности толщиной до 40 мм с пределом прочности до 600 МПа на глубинах до 30 м

- сварки высоколегированных коррозионно-стойких сталей типа ANSI 304L, 308L, 347 AND 321

- резки углеродистых и легированных сталей цветных сплавов толщиной до 40 мм на глубинах до 60 м.

Ключевые слова: подводная сварка и резка, порошковая проволока, низкоуглеродистая сталь, нержавеющая сталь, механические свойства.