Underwater hyperbaric dry welding of high strength steel arctic oil and gas pipelines

S Parshin¹, A Levchenko²

¹ Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia
² LLC “Regional North-West Interdisciplinary Certification Center”, St. Petersburg, Russia

parshin@spbstu.ru

Abstract. The paper describes the results of research about orbital hyperbaric FCA-welding of API X70 steel pipes with the use of gas-shielded flux cored wires with the flux of TiO₂-CaF₂ system with the higher content of fluorides in the flux core. As a result of the research, the dependences of the welding current, arc voltage, metallurgical features and mechanical properties depending the pressure in the hyperbaric chamber are determined. The use of gas-shielded flux cored wires of TiO₂-CaF₂ system within the gas pressure 0.1–0.6 MPa, for the orbital welding of API X70 steel provides the favourable microstructure of welded joint and mechanical properties of welds according to the Class A per ANSI/AWS D3.6M:2010.

1. Introduction

1.1. General information
The hyperbaric welding is widely used during installation and repair of underwater pipelines and high strength steel structures at various depths up to 2500 m [1]. For weld joints in hyperbaric welding, the requirements of mechanical properties for class A are established according to AWS D3.6M [2]. Mostly subsea pipelines are made using high-strength steels with strength class X60-X90, for welding of which special welding wires with Ni, Mo, Ti alloying with low hydrogen content and high oxygen content are used [3]. The main methods of hyperbaric welding is the use of gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) [4], [5], [6]. With increasing depth and with increasing pressure decreases arc stability, increase oxidation and hydrogenation of the weld, increases the probability of cold cracks, non-metallic inclusions and gas pores. To improve the quality of hyperbaric welding, flux-cored arc welding (FCAW) can be applied using flux-cored wires, which can improve the quality and properties of welded joints at high pressure [7], [8], [9].

1.2. Research aim
The research aim was the development of the technology for the underwater orbital hyperbaric FCA-welding of pipes made of API X70 strength class steel with the use of the gas-shielded flux cored wires with the flux of TiO₂-CaF₂ system with the higher content of fluorides in the mixture.

1.3. Key problems of hyperbaric welding
GTAW-welding at depths up to 180 m provides a good quality of welding high strength steels [10], [11]. However, with increasing pressure, the stability of the arc and the durability of the tungsten electrode decrease, and poor root penetration occurs [12], [13], especially at pressures at a depth of more than 500–750 m [1].

Increasing the pressure during GMA welding also reduces the arc stability and increases spattering. Therefore, flux-cored wires with the introduction of alkali and alkaline-earth metal salts and special welding
inverters are used for hyperbaric GMA welding [4], [14].

With elevating pressure increases the ionization energy of the gas, which causes the arc to increase the voltage, which increases the heat input welding, and may deteriorate the microstructure. In [15], [16], the process of surfacing API-X70 steel in Ar + He mixtures with various Ar and He ratios at 10 bar with HBQ Coreweld wire with a diameter of 1 mm was investigated. When helium is introduced into argon, the average arc voltage increases from 24 to 27 V with increasing helium in the mixture from 0 to 100%, and the welding current decreases from 225 A to 212 A. In [17], hyperbaric welding was performed in a chamber in a mixture of 84% Ar + 16% CO2 using SPG3S1 wire with a diameter of 1.2 mm at pressures up to 0.6 MPa. With increasing depth from 0 to 60 m, the arc voltage increased linearly from 18 to 30 V, and the strength of the welding current increased from 170 to 250 A.

The key factor in hyperbaric welding is the composition of the protective gaseous medium, which determines the thermophysical properties, ionization and stability of the welding arc, the formation, microstructure and mechanical properties of the weld. It is known that in hyperbaric welding, argon, helium and CO2 are used, which have a thermal conductivity at room temperature, respectively, W×m⁻¹×K⁻¹: 17.7×10⁻³; 151.3×10⁻³; 71×10⁻³ and at 6000 K, respectively: 0.17; 1.5; 0.05 [18]. The increase in plasma thermal conductivity in the center of the welding arc is associated with the evaporation of iron and an increase in the degree of plasma ionization, according to the Saha-Langmuir equation. With increasing pressure, the thermal conductivity of argon and CO2 decreases markedly, which affects the shape of metal penetration and the geometry of the weld [14, 19].

Increasing the pressure reduces the cross section of the arc and reduces the stability of the arc [20]. Compression of the arc changes the gradient of the thermal field in the melting zone and in the heat-affected zone [21], [22], [23], [24], which, when welding X70 steel, changes the critical cooling rate and the level of residual stresses [25], [26]. The thermodeformation welding cycle changes the microstructure and mechanical properties of the weld [27], [28], [29].

1.4. Research methodology
The orbital FCA-welding of pipes with a diameter of 1420 mm with thickness of 21.3 mm made of API X70 steel was performed in the hyperbaric welding chamber with a volume of 19.25 m³ at a pressure of 0 to 0.6 MPa (0 to 6 bar), fig. 1.

![Figure 1. Automatic welding machine in a hyperbaric chamber during orbital FCA-welding of pipe with a diameter of 1420 mm with a thickness of 21.3 mm. View of root weld at a pressure of 0.2 MPa before and after slag removal](image)

The following mixtures are used as the shielded gas: 80 % Ar + 20 % CO2; 75 % Ar + 25 % CO2; the pressure of the gaseous medium in the chamber is changed with an interval of 0.1 MPa. For filling the groove we applied the welding rutile flux cored wire of Power Pipe 60R grade as per AWS ASME 5.29 E81T1-Ni1M-J H4 with a diameter of 1.2 mm with the chemical composition of weld metal as follows: C – 0.046; Mn – 1.483; Si – 0.468; Ni – 0.755; S – 0.012; P – 0.011. Chemical composition of welded API X70 steel is as follows: C – 0.1; Mn – 1.69; Si – 0.32; Ni – 0.2; S – 0.006; P – 0.0075.
Oscillography of welding current and voltage was performed by the digital oscilloscope with a frequency of 50 kHz. Cutting of samples and testing was performed according to ANSI/AWS D3.6M:2010. For mechanical testing we used the tensile testing machine Super L60, pendulum impact testing machine PH450, hardness tester EMCOTEST DuraScan-20; chemical composition was determined by the optical emission spectrometer Bruker Q4 TASMAN. The microstructure examination was performed using the microscope Zeiss Axiovert 200 MAT with automatic image analyzer Thixomet Pro. Micro-hardness was measured by micro-hardness tester Buehler Micromet 6040 comprising the complex Thixomet MHT.

2. Research results
Thermodynamic modeling using the Terra program of the Institute of High Temperatures of the Russian Academy of Sciences confirms that increasing the pressure to 0.6 MPa in plasma from 80% Ar + 20% CO\(_2\) in the presence of 10% iron vapor leads to a noticeable decrease in thermal conductivity and concentration of electrons in the center of the welding arc at a temperature of about 6500–7500 K. In this case, the introduction of a 10% mass fraction of CaF\(_2\) vapors into the plasma allows one to significantly increase the thermal conductivity and electron concentration in the center of the welding arc, fig. 2.

![Figure 2](image)

**Figure 2.** Change in total thermal conductivity and electron concentration (right) in an equilibrium plasma from a mixture of 80% Ar + 20% CO\(_2\) in the presence of 10% Fe: 1 - at a pressure of 0.1 MPa; 2 - at a pressure of 0.6 MPa; 3 - at a pressure of 0.1 MPa with 10% CaF\(_2\); 4 - at a pressure of 0.6 MPa with 10% CaF\(_2\).

Another important aspect is the deterioration of the metallurgical weldability of high-strength steel due to the high pressure and humidity in the hyperbaric chambers. With an increase CO\(_2\) concentration in protective gas, the carbon content in the weld may increase, which contributes to the unfavorable microstructure of upper bainite, which reduces the impact energy of the weld and resistance to cracks under the influence of hydrogen. An increase in the oxidizing potential of a gas mixture with the introduction of CO\(_2\) leads to a decrease Mn in the weld, which reduces the amount of acicular ferrite [30], [19].

Thermodynamic modeling shows that increasing the pressure to 0.6 MPa causes a decrease in the concentration of atomic oxygen, probably due to an increase in the dissociation energy of CO\(_2\) molecules. However, the oxidizing ability of the gas mixture increases due to the intensification of reactions of Fe with CO\(_2\): an increase in pressure to 0.6 MPa in plasma from 80% Ar + 20% CO\(_2\) in the presence of 10% iron vapor leads to an increase in the concentration of iron oxide in plasma, especially on boundary welding arc at a temperature of about 4000-5000 K. Introduction to the plasma 10% mass fraction of vapors of CaF\(_2\) can significantly reduce the oxidizing ability of the gas mixture, fig. 3.
Figure 3. Changes in the concentration of atomic oxygen and iron oxide FeO (right) in an equilibrium plasma of 80% Ar + 20% CO$_2$ in the presence of 10% Fe: 1 - at a pressure of 0.1 MPa; 2 - at a pressure of 0.6 MPa; 3 - at a pressure of 0.1 MPa with 10% CaF$_2$; 4 - at a pressure of 0.6 MPa with 10% CaF$_2$.

With increasing pressure, the concentration of oxygen and nitrogen in the weld increases, which deteriorates the impact energy and crack resistance. In [31], the ESAB HBQ Coreweld flux cored wire with a diameter of 1.0 mm and Inconel 625 solid wire with a diameter of 0.9 mm at a pressure of 12–35 bar in the chamber were used for hyperbaric welding of API X65 steel. A high content of oxygen and nitrogen in the welds was noted, respectively: with ESAB HBQ Coreweld wire - 520–580; 80–160 ppm, with Inconel 625 wire - 220–230; 180–200 ppm. In [32], the process of hyperbaric welding of API 5L X65 steel with AWS A-5.29 / E80TS-G flux-cored wire with a diameter of 1.2 and the C-Mn and C-Mn + 1% Ni alloying systems was investigated. With increasing pressure from 11 to 71 bar in a mixture of He and CO$_2$, the nitrogen content increased from 90 to 980 ppm and oxygen from 540 to 885 ppm, and the carbon content decreased from 0.036 to 0.032%, manganese from 1.54 to 0.99% and silicon from 0.46 to 0.25%.

On the other hand, an increase of pressure intensifies oxidation in low-active mixtures, for example, 93% Ar + 5% CO$_2$ + 2% O$_2$ at a pressure of 10 bar, which is considered favorable for the formation of non-metallic inclusions for nucleation of acicular ferrite and an increase of impact energy of bainitic steels [33], [34]. API-X70 hyperbaric welding of steel with HBQ wire at a pressure of 10 bar showed a significant effect of the gas mixture of argon, helium and CO$_2$ on the porosity, the formation of acicular ferrite and the mechanical properties of weld joints [8].

In general, this underlines the relevance of further research to establish the effect of nitrogen, hydrogen and oxygen concentrations on impact energy and cracking in hyperbaric welding of bainitic steels.

Oscillography of welding currents and voltages during automatic orbital welding with rate of 12–12.6 m/h with wire feed speed of 7–7.3 m/min has showed that when welding with flux-cored wire of Power Pipe 60R grade with a diameter of 1.2 mm in a mixture of 20% CO$_2$ the drop transfer is carried out by small drops with short circuits. When welding in the chamber at the gas pressure of 0.2 MPa in a mixture of 20% CO$_2$, deviation of the arc voltage from the arithmetic mean value reaches ±9 V, and of welding current is up to ±110 A, fig. 4. In case of increasing the pressure, parameters of the welding process and drop transfer are worse: the deviation of the arc voltage from the arithmetic mean value reaches ±10 V; frequency of low-frequency voltage ripple is reduced by 30–40 Hz; the duration of ripples and pauses between ripples increases. The increase in pressure leads to the increase in the average value of the arc voltage and the welding current, i.e. the arc column under the influence of pressure is compressed.
According to the results of the samples mechanical testing within the studied range of the environment pressure, the significant influence on the strength has not been detected; the coupons strength reached 610-620 MPa, the static bending angle is over 121 degrees. The slight increase in strength was detected at the pressure of 0.6 MPa. Study of Charpy impact energy carried out in the gas mixtures with different CO\textsuperscript{2} content has showed that due to increase in the gas mixture of CO\textsuperscript{2} from 20 % to 25 % the average value of the impact energy decreases: in the weld from 130,6 J/cm\textsuperscript{2} to 75,8 J/cm\textsuperscript{2}, on the weld boundary along fusion zone from 269,3 J/cm\textsuperscript{2} to 221 J/cm\textsuperscript{2}. In case of the increase of gas pressure the linear decrease in the average value of impact energy occurs: at the pressure of 0.2 MPa, the value KCV\textsubscript{20} at the weld decreases from 130,6 J/cm\textsuperscript{2} up to 120,6 J/cm\textsuperscript{2}, on the weld boundary KCV\textsubscript{20} reduces from 269,3 J/cm\textsuperscript{2} to 163,6 J/cm\textsuperscript{2}. In general, at the pressure of 0.6 MPa the average value KCV\textsubscript{20} at the weld decreases from 130,6 J/cm\textsuperscript{2} up to 72 J/cm\textsuperscript{2}, on the weld boundary KCV\textsubscript{20} reduces from 269,3 J/cm\textsuperscript{2} up to 120 J/cm\textsuperscript{2}, fig. 5.

The results of hardness measurements in two cross-sections showed that in case of increase in the gas mixture of CO\textsuperscript{2} from 20 % to 25 % there is a decrease in the average hardness of the weld by 1 % from 190 HV\textsubscript{10} to 188 HV\textsubscript{10}, within heat-affected zone by 3,3 % from 212 HV\textsubscript{10} to 205 HV\textsubscript{10}. In case of the increase in the gas pressure, the linear increase of the average hardness value occurs: at the pressure of 0.2 MPa HV\textsubscript{10} on the weld it increases from 190 to 215 HV\textsubscript{10}, within heat-affected zone from 212 HV\textsubscript{10} to 223 HV\textsubscript{10}. In general, at the pressure of 0.6 MPa the average value HV\textsubscript{10} on the weld increases from 190 to 236 HV\textsubscript{10}, within heat-affected zone from 212 HV\textsubscript{10} to 231 HV\textsubscript{10}, fig. 5.

The results of weld samples chemical analysis performed in mixtures of gases with different CO\textsuperscript{2} content showed that in case of increase in the gas mixture of CO\textsuperscript{2} from 20 % to 25 % the noticeable reduction of alloying elements occurs: the average content of carbon in the three zones of the weld is decreased from 0,08 % C up to 0,069 % C; silicon from 0,517 % Si up to 0,472 % Si; manganese from 1,57 % Mn to 1,5 % Mn; nickel from 0,854 % Ni to 0,8 % Ni. In this case, the content of alloying elements in the cross section is uneven: the content of elements decreases in the direction from the root of the weld to the top of the weld.
When welding in a hyperbaric chamber in a mixture of 80 % Ar+20 % \( \text{CO}_2 \) with increasing the environment pressure from 0 to 0,6 MPa, there is further reduction in the average content of carbon, manganese, silicon and nickel. The degree of decrease in the concentration of alloying elements when increasing the pressure of the environment is in accordance with the increase in the degree of affinity of elements to oxygen in the range: \( \text{Ni} \rightarrow \text{Si} \rightarrow \text{Mn} \rightarrow \text{C} \).

The content of nitrogen and oxygen in the weld metal was determined with the gas analyzer ELTRA ON900 by means of the method of reductive melting in the environment of ultra-pure helium. To do this, from the root zone and weld reinforcement we cut samples measuring 7×1×2 mm. The samples were cut by the precision machine Buehler Isomet 4000, equipped with the titanium cutting discs with diamond coating.

The results of gas analysis of weld samples performed in mixtures of gases with different \( \text{CO}_2 \) content showed that in case of increase in the gas mixture of \( \text{CO}_2 \) from 20 % to 25 % there is increase of the average integral oxygen content in the root of the weld by 13,4 % from 432 ppm to 490 ppm, however, nitrogen content is reduced by 19,2 % from 78 ppm to 63 ppm. In the top of the weld in case of increase in gas mixture of \( \text{CO}_2 \) from 20 % to 25 %, there is decrease of the average integral oxygen content by 10.2 % from 467 ppm to 419 ppm, however, nitrogen content increased by 13,4 % from 67 ppm to 76 ppm. This data indicates the inverse dependence between the content of oxygen and nitrogen in the weld.

In case of increasing the pressure up to 0.2 MPa, there is the rise of integrated oxygen content \([O]\) by 26.1 % from 432 ppm to 545 ppm in the root of the weld and by 8.3 % from 467 ppm to 506 ppm in the top weld. With increasing the pressure up to 0.6 MPa the average content \([O]\) is increased by 67 %, fig. 8. The average nitrogen content in root of the weld and top of the weld in case of increasing the pressure up to 0.6 MPa increases by 53-64 %, fig. 6.

**Figure 6.** The change in the integral oxygen content \([O]\) and nitrogen \([N]\) depending on the pressure in the welding chamber: 1 – root of the weld; 2 – top of the weld

Analysis of metal microstructure of the weld various sections and the heat affected zone of welded joints performed at higher pressure showed that the microstructure of the weld is favorable and has the high resistance to cold cracking. However, with increasing the environment pressure, in the presence of oxygen and while filling the weld is observed a tendency to grain growth and deterioration of the microstructure, fig. 7.
3. Conclusions
Hyperbaric FCA-welding of pipes made of API X70 steel using fluoride flux cored wires with a gas pressure in the hyperbaric chamber up to 0.6 MPa showed that the properties of weld joints correspond to class A according to ANSI/AWS D3.6M: 2010.

However, as the pressure increases to 0.6 MPa, the stability of the welding arc decreases and the thermophysical properties of the welding arc change due to an increase in thermal conductivity and electron concentration in the center of the welding arc at temperatures of 6500-7500 K, depending on the content of iron vapor and CaF₂.

The increase of pressure during welding of X70 steel is accompanied by an increase of the arc power and the oxidizing ability of the gas mixture, which leads to reduction of C, Mn, Si, Ni alloying elements, to an increase of the total content of oxygen and nitrogen in the weld, to a deterioration of the microstructure and impact energy. For hyperbaric welding of bainitic steel X70, it is necessary to use special wires with a high content of deoxidizers and fluorides for the metallurgical treatment of the weld pool and the regulation of the microstructure of the weld.

Acknowledgements
The work was performed during the project ‘Energy-efficient systems based on renewable energy for Arctic conditions’ (EFREA), KS1054, South-East Finland-Russia CBC Programme 2014-2020.

References
[1] Richardson I M, Nixon J H, Nosal P, Hart P, Billingham J 2000 Hyperbaric GMA welding to 2500 m water depth International Conference ETC/OMAE
[2] ANSI/AWS D3.6M:2017: Underwater welding code. American Welding Society, Miami, USA
[3] Akselsen O M, Aune R, Fostervoll H and Harsvoer A S 2006 Dry hyperbaric welding of subsea pipelines in the North Sea Weld. J. 85(6) 52-55
[4] Richardson I M, Nixon J H 1997 Deepwater hyperbaric welding – initial process evaluation ISOPE 493
[5] Woodward N 2006 Developments in diverless subsea welding Welding Journal 85(10) 25-39
[6] Apeland K E, Berge J O, Verley R, Armstrong M, Woodward N 2006 Deepwater remote welding technology for pipeline repair and hot-tapping Offshore 66(52)
[7] Woodward N, Fostervoll H, Akselsen O M, Ahlen C H, Berge J O, Armstrong M 2008 Evaluation of welding procedures and consumables for hyperbaric GMAW for diverless retrofit tee hot-tap applications International Journal of Offshore and Polar Engineering 18 149
[8] Azar A S, Lange H I, Ostby E, Akselsen O M 2012 Effect of hyperbaric gas composition on mechanical properties of the weldmetal Materials Science and Engineering A 556 465-472
[9] Akselsen O M, Fostervoll H, Harsvoer A S M and Aune R 2006 Weld metal mechanical properties in hyperbaric GTAW of X70 pipeline International Journal of Offshore and Polar Engineering 16(3) 233-240
[10] Richardson I M 1991 Properties of the constricted gas tungsten (plasma) welding arc at elevated pressures: Ph.D. Thesis Cranfield Institute of Technology
[11] Sakakibara J and Hamasaki M 1983 Study on underwater dry hyperbaric TIG welding, part I: effect of ambient pressure on electrode erosion and arc characteristics J. High Temp. 9(1) 27-31
[12] Nixon J H, Allum C J, Lowes J M 1982 Underwater welding – a review Conference Internationale – Penetration Sous-Marine 147
[13] Allum C J 1982 Characteristics and structure of high pressure (1-42 bars) gas tungsten arcs. vol. Ph.D Thesis Cranfield Institute of Technology p 1063
[14] Azar A S, Woodward N, Fostervoll H, Akselsen O M 2012 Statistical analysis of the arc behavior in dry hyperbaric GMA welding from 1 to 250 bar. Journal of Materials Processing Technology 212 211-219
[15] Rao Z H, Hu J, Liao S M and Tsai H L 2010 Modeling of the transport phenomena in GMAW using argon-helium mixtures. Part I. The arc. *Int. J. Heat Mass Transf.* **53**(25-26) 5707-5721

[16] Rao Z H, Hu J, Liao S M and Tsai H L 2010 Modeling of the transport phenomena in GMAW using argon-helium mixtures. Part II. The metal. *Int. J. Heat Mass Transf.* **53**(25-26) 5722-5732

[17] Skorupa A, Bal M, Maslowski A 1996 The strength of joints welded by a hyperbaric underwater method *Welding International* **10**(9) 683-688

[18] Grekov L I, Moskvin Yu V, Romanichev V S 1964 *The basic properties of gases at high temperatures* Moskow: Mashinostroenie p 40

[19] Woodward N, Fostervoll H, Akselsen O M 2009 The effects on process performance of reducing the pressure from 36 to 1 bar in hyperbaric MIG welding *Proceedings of the ASME 28th International Conference on Ocean, Offshore and Artic Engineering OMAE*

[20] Matsunawa A, Nishiguchi K 1979 Arc characteristics in high pressure argon atmosphere *International Conference of Arc Physics and Weld Pool Behaviour* 123-133

[21] Ozden H 2008 *Underwater welding in hyperbaric conditions* Sea Technol **49**(6) 52-54

[22] Khairetdinov A E, Mazel A G, Golovin S V 1981 Technological characteristics of the welding arc in the hyperbaric chamber *Welding production* **6** 11-13

[23] Mazzaferro J A E and Machado I G 2009 Study of arc stability in underwater shielded metal arc welding at shallow depths. *Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci.* **223**(3) 699-709

[24] Woodward N, Knagenhelm H O, Berge J O, Verley R, Armstrong M 2007 Hyperbaric GMA welding for contingency repair using a fillet welded sleeve at 1000 m water depth *Proceedings of the International Offshore and Polar Engineering Conference* 3403

[25] Rykalin N N 1951 *Calculations of thermal processes during welding* (Moskow: Mashgiz) p 296

[26] Karkhin V A 2019 Thermal processes in welding *Springer* p 478

[27] Onsoien M I, M’Hamdi M, Mo A 2009 A CCT diagram for an offshore pipeline steel of X70 type *The Welding Journal* **88**(1) 1s-6s

[28] Usani Unoh Ofem 2013 Laser assisted arc welding process for dry hyperbaric deep water application *Cranfield University* 285

[29] Praunseis Z 1999 The influence of microstructure on fracture toughness of undermatched weld metal *Kovove Materialy Met. Mater.* **37**(4) 266-279

[30] Evans G M 1980 Effect of manganese on the microstructure and properties of all-weld-metal deposits *Welding Journal* **69**(3) 67-75

[31] Akselsen O M, Fostervoll H, Ahlen C H 2008 Hyperbaric gas metal arc welding of API X65 pipeline steel at 12, 25 and 35 bar. *18th Int Offshore and Polar Eng. Conf. ISOPE* 246-253

[32] Santos J F, Szelagowski P, Schafstall H-G 1993 Hyperbaric welding by the FCAW process *Welding International* **7**(3) 200-205

[33] Abson D J 1987 *Non-metallic inclusions in ferritic steel weld metals. A review.* IIW doc IX-1486-87

[34] Christian J W 2002 The theory of transformations in metals and alloys (Part I + II) *Elsevier Science* p 1200