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STUDY OF PROCESS STABILITY, ELECTRODE METAL TRANSFER, AND WELD FORMATION IN UNDERWATER MANUAL ARC WELDING

Introduction. *Underwater welding has become a specialized method for joining steel structures in submerged environments. However, the working conditions for a diver-welder remain extreme. Establishing optimal welding modes for producing high-quality welds is complicated by a range of process-specific factors. Furthermore, reliable organoleptic (visual and sensory) assessment of weld quality has remained difficult and requires objective instrumental support.*

Problem Statement. *Under operational conditions, welding current, arc voltage, and heat input exert a decisive influence on arc stability, weld bead formation, and contamination of the weld metal with non-metallic inclusions. An imbalance in these parameters leads to increased defect formation and deterioration of weld morphology.*

Purpose. *The purpose of this research is to investigate electrode metal transfer, weld formation, and the stability of the underwater wet manual metal arc (MMA) welding process, as well as to determine the minimum welding parameters required to ensure stable operation and acceptable weld quality.*

Materials and Methods. *The experiments have been carried out using a UPE-500 electrode melting unit, an NM-1000P specialized underwater welding power source, and auxiliary equipment designed for underwater operations. Welding current and arc voltage have been recorded using an oscilloscope*

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and PicoScope software, enabling acquisition and statistical processing of electrical signal data. Weld bead geometry has been evaluated using macrosections (templates) prepared, etched, and examined under optical microscopy at ×100 magnification.

***Results.** To ensure guaranteed technological stability under real welding conditions, a lower threshold with increased electrical parameters (200 A, 27 V) has been recommended. Adherence to the recommended welding parameters has improved weld bead formation, prevented seam "triangularity" characteristic of underwater wet welding, and resulted in an approximately twofold reduction in the weld metal contamination with non-metallic inclusions.*

***Conclusions.** The obtained results can be used for configuring underwater welding modes in challenging operating conditions.*

Keywords: underwater wet welding, electrode metal transfer, welding mode parameters, welding process oscillograms, "triangularity" of welds, stability of the welding process.

Welding is a metal joining process that plays a crucial role in shipbuilding, construction, power engineering, transportation, and many other industrial sectors. Under certain conditions, underwater welding is required. In recent years, underwater welding has been widely used for emergency ship repair, sealing hull breaches during underwater ship maintenance, servicing and repairing damaged underwater structures, and maintaining underwater pipelines in order to extend their service life [1]. Underwater welding is also applied in the maintenance of nuclear power equipment. Water acts as a moderator and coolant in nuclear reactors; therefore, underwater welding is required during reactor maintenance in order to prevent contamination by ionizing radiation [2]. Another important application of underwater welding is the fabrication and maintenance of offshore platform structures. Maintaining such structures in operational condition generally requires specialized underwater repair work. Although alternative methods can sometimes be employed, underwater welding is still considered one of the most effective techniques, primarily for economic reasons, despite the fact that it demands a very high level of professional skill and physical fitness from welders.

According to the welding principle, two main types of underwater welding are distinguished: dry underwater welding and wet underwater welding. Dry underwater welding is a method of underwater joining performed inside a welding chamber filled with gas. The chamber is used to eliminate the adverse effects of water and to ensure weld quality comparable to that achieved in air. Wet underwater welding is a process in which a special waterproof electrode is used, and welding is carried out directly in water; therefore, the arc is surrounded by an aqueous environment. Wet underwater welding is generally preferred because of several advantages, including simple equipment, easier mobilization of welding tools underwater, short preparation time, operational continuity, and low operating costs.

Several welding technologies are used for wet underwater welding, including manual metal arc welding, flux-cored arc welding, and submerged arc welding. The most widely used technique for underwater welding is manual metal arc (MMA) welding, as it is simple and inexpensive in terms of both equipment and operation. Electrodes for MMA welding can be classified according to the type of coating that provides different mechanical properties and low diffusible hydrogen content in the deposited metal [3]. Due to the hygroscopic nature of the electrode coating, electrodes still require special conditioning before use in order to prevent hydrogen diffusion into the weld metal.

However, the wet underwater manual metal arc welding method also has a number of drawbacks that occur frequently and strongly depend both on the diver-welder's skills and on the selected welding parameters [4]. These drawbacks include instability of weld bead formation, reduced material ductility, increased hardness in the heat-affected zone (HAZ), and defects in the weld metal. This is associated with the adverse influence of the aquatic environment: an arc burning underwater is subjected to two types of constriction — due to the cooling effect of hydrogen and due to the hydrostatic pressure of the liquid column. The cooling action of water, elevated pressure, dissociation of water and its vapors, and the resulting gas formation lead to destabilization of the arc burning process. During underwater welding, the arc burns inside a gas bubble formed as a result of evaporation and decomposition of water, as well as the vapors and gases of the molten metal and welding consumable components. All of the above necessitates the use of higher power to sustain the arc discharge than is required for welding in air [5].

Consequently, welding current, arc voltage, and linear heat input exhibit specific effects on arc stability, penetration, heat dissipation, bead geometry, and the width of the critical zone during wet underwater welding [6, 7].

The purpose of this study has been to investigate electrode metal transfer, weld bead formation, and the stability of the wet underwater manual metal arc welding process, as well as to determine the minimum welding modes required to ensure process stability and high-quality weld formation.

The experiments have been conducted using a UPE-500 electrode melting unit that provides automatic recording, processing, and registration of the acquired data with simultaneous stabilization of welding parameters in automatic mode, thereby eliminating the influence of the human factor [8]. A similar methodology has been applied in the study by Moreno-Uribe [9]. In addition, a specialized NM-1000P power source for underwater welding and dedicated equipment enabling welding at a depth of 0.4 m have been used. Beads were deposited on 16-mm-thick SS400 steel plates using 4-mm-diameter rutile-coated electrodes specially designed for underwater welding of pearlitic steels and developed at the Paton Electric Welding Institute. Welding current and arc voltage were recorded using a *PicoScope* oscilloscope and *PicoScope* 7 software, which made it possible to acquire and mathematically process statistical data on the electrical parameters of the welding process.

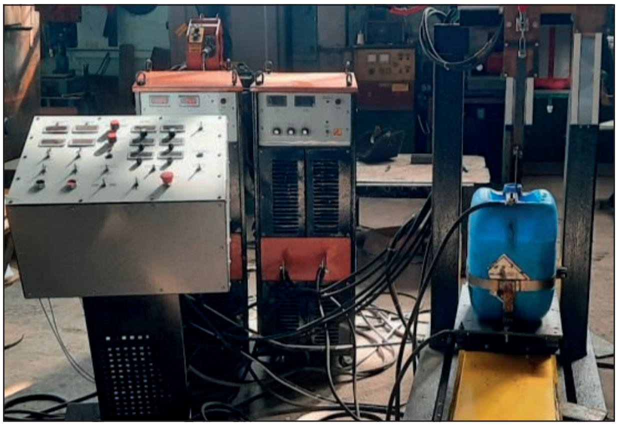


Fig. 1. General view of the experimental apparatus

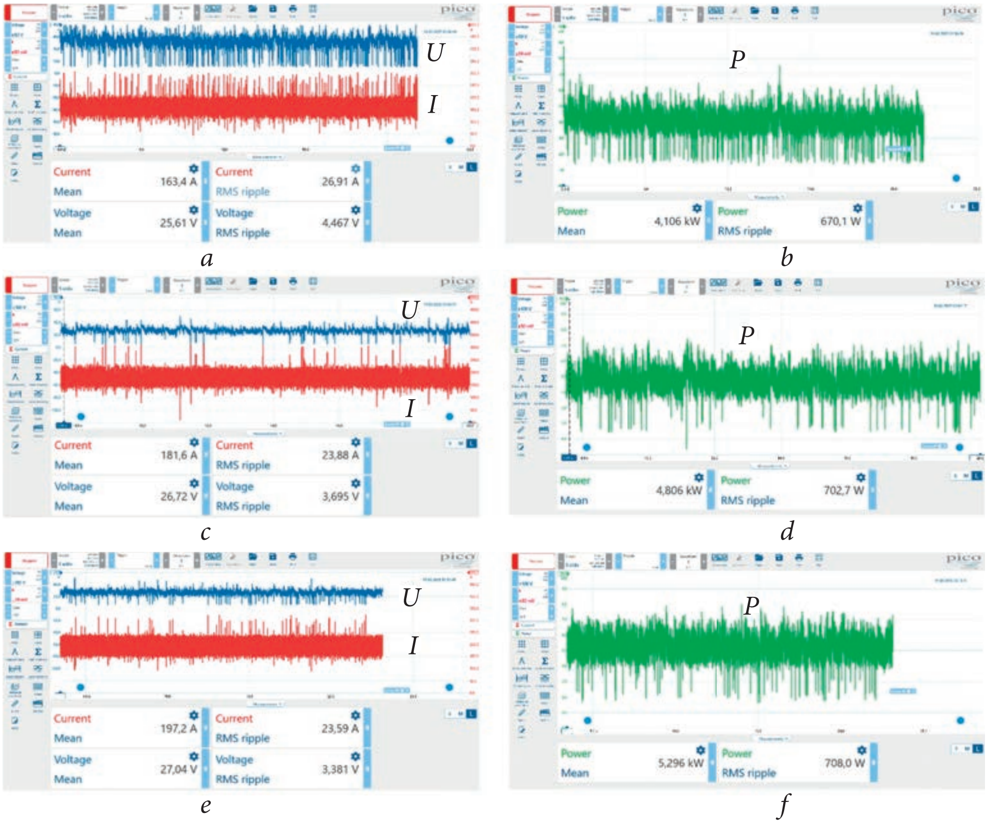
Considering the aforementioned need to increase power during wet underwater welding, the maximum welding mode recommended for rutile-coated electrodes when welding in air has been adopted as the minimum mode (Mode I). Accordingly, to study the regularities of weld bead formation, process stability, and the type of electrode metal transfer in accordance with ISO 4063:2009, the following welding modes have been selected: Mode I — 160 A, 25 V, 10 cm/min; Mode II — 180 A, 26.5 V, 10 cm/min; Mode III — 200 A, 27 V, 10 cm/min.

Oscillograms of welding current, voltage, and process power are presented in Fig. 2.

The calculated values of the process stability parameters — the coefficients of variation of current, voltage, and power, defined as the percentage ratio of RMS ripple to the mean value of the corresponding quantity — are presented in Table 1 and Fig. 3.

Table 1. **Coefficients of Variation of Welding Process Parameters**

Welding conditions	K_{VI}, %	K_{VU}, %	K_{VP}, %
Mode/option I	16.5	17.5	16.3
Mode/option II	13.1	13.8	14.6
Mode/option III	11.9	12.5	13.3



a:
Current Mean 163,4 A
Current RMS ripple 26,91 A
Voltage Mean 25,61 V
Voltage RMS ripple 4,467 V

b:
Power Mean 4,106 kW
Power RMS ripple 670,1 W

c:
Current Mean 181,6 A
Current RMS ripple 23,88 A
Voltage Mean 26,72 V
Voltage RMS ripple 3,695 V

d:
Power Mean 4,806 kW
Power RMS ripple 702,7 W

e:
Current Mean 197,2 A
Current RMS ripple 23,59 A
Voltage Mean 27,04 V
Voltage RMS ripple 3,381 V

f:
Power Mean 5,296 kW
Power RMS ripple 708,0 W

Fig. 2. Oscillograms of the welding process: *a*, *b* — Mode I; *c*, *d* — Mode II; *e*, *f* — Mode III; *a*, *c*, *e* — current (*I*) and voltage (*U*) oscillograms; *b*, *d*, *f* — arc power (*P*)

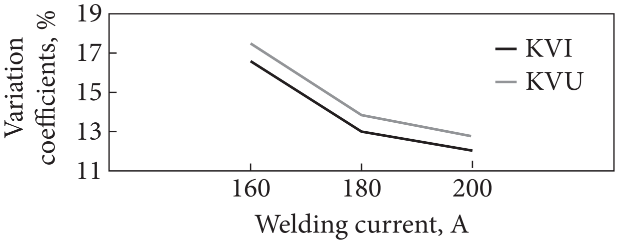
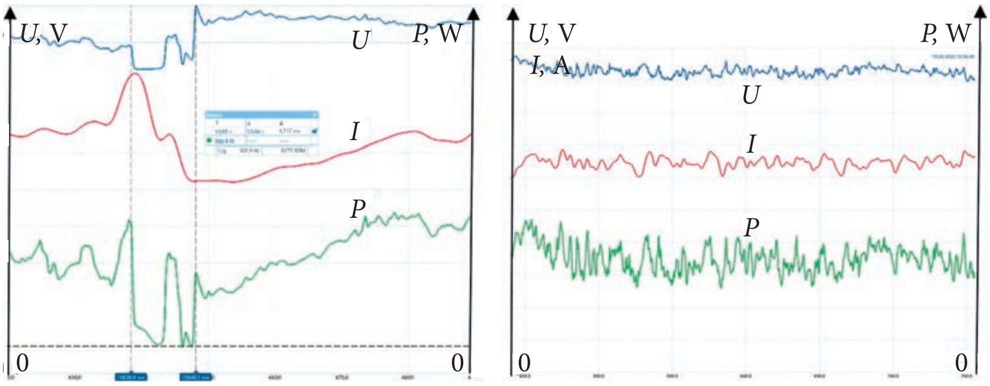


Fig. 3. Coefficients of variation as a function of welding current

The increased ripple of the parameters in Mode I (Fig. 1, *a*, *b*), which is visually observed in the oscillograms, is fully confirmed by the obtained values of the process stability parameters, namely the coefficients of variation of the welding regime. The well-known trend is preserved: as the welding parameters increase, the coefficients of variation decrease and the process stability improves.

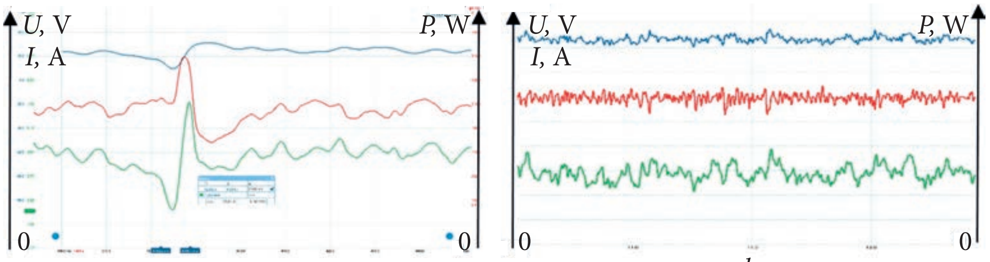
Although the coefficients of variation for all three modes do not exceed the threshold value of 20% considered acceptable for a stable process [10], a detailed analysis of the oscillograms has revealed fundamental differences for Mode I. From the standpoint of electrode metal transfer, Mode I is characterized by continuous changes in the transfer mode. The predominant mechanism is short-circuiting transfer of type D (Fig. 4, *a*); however, the process periodically and briefly transitions to droplet transfer of type G (Fig. 4, *b*), according to ISO 4063:2009. Such uncontrolled changes in the mode of metal transfer do not satisfy the criterion of process stability.

For Modes II and III, droplet transfer (type G) predominates (Fig. 5, *b*), with only occasional process disturbances in the form of short-circuiting transfer (type D) (Fig. 5, *a*).



a *b*

Fig. 4. Oscillograms of electrode metal transfer in Mode I: *a* — type D; *b* — type S



a *b*

Fig. 5. Oscillograms of electrode metal transfer in Mode III: *a* — type D; *b* — type G

Thus, the process stability in Mode I cannot be considered satisfactory, despite acceptable values of the variation coefficients. An analysis of the differences in the variation coefficients (Table 1 and Fig. 3) confirms this conclusion: for the same increment in welding current, the difference in variation coefficients between Modes I and II is much greater than that between Modes II and III.

As noted earlier, arc power is a key parameter in underwater wet welding, as it counteracts the constricting effect of water and ensures the formation and maintenance of a gas bubble of sufficient volume. Analysis of the power oscillograms shows that during short-circuiting the power decreases as follows: for Mode I (Fig. 4, *a*), to 1 kW (more than 70%) for a duration of 10 ms; for Mode II (Fig. 5, *a*), to 2 kW (less than 60%) for a duration of 6 ms. Since short-circuiting transfer is the predominant metal transfer mode in Mode I, such power losses are expected to adversely affect bead formation and weld pool shielding, which has been confirmed by metallographic examinations (Fig. 6).

Examination of the plate after surfacing has shown a practically complete absence of slag crust on the bead surface when the recommended welding modes are applied. The bead formed in Mode I has a triangular shape (Fig. 6, *a*) that is undesirable both from the viewpoint of microstructural formation and in terms of stress concentration in welded joints. In addition, contamination of the weld metal with non-metallic inclusions is observed (Fig. 6, *b*). Similar defects, typical of low welding modes, have been reported previously [6, 10]. Thus, metallographic investigations confirm the technological instability of the welding process in Mode I.

The increased welding modes II and III, for which a continuous and stable process has been ensured according to oscillogram analysis, provide a significant improvement in weld bead formation

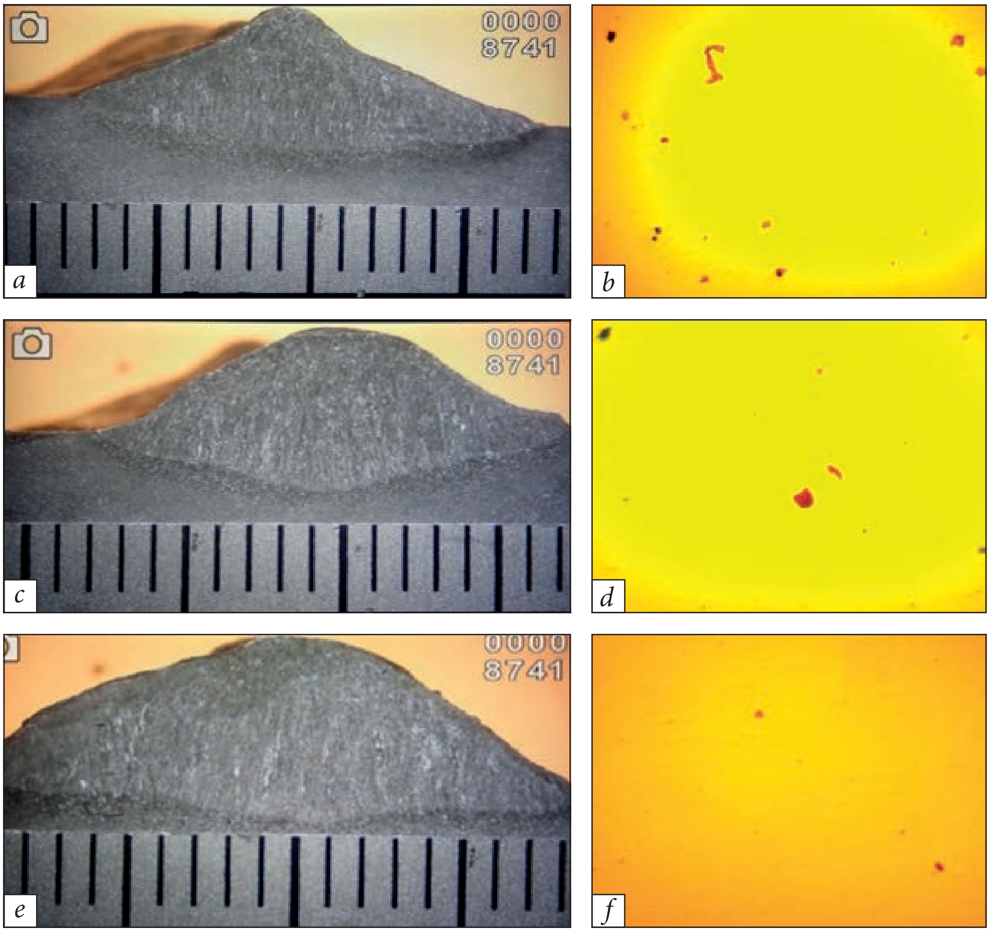


Fig. 6. Microstructure (×30) and non-metallic inclusions (×100) in the deposited metal: *a, b* — Mode I; *c, d* — Mode II; *e, f* — Mode III

(Fig. 6, *c—f*) and ensure technological stability of the process, which is also consistent with the data reported in [6].

Naturally, stable maintenance of the gas bubble depends on both arc power and welding speed, which together determine the linear heat input, a parameter more familiar to welding personnel than arc power alone. For Modes II and III, the linear heat input calculated using Eq. (1) in Clause 4 of ISO/TR 18491:2015(E) is 2.9 kJ/mm and 3.19 kJ/mm, respectively. It should be noted that the present study has been performed with automatic stabilization of arc length (arc voltage) and welding speed, which allows these parameters to be controlled much more accurately than in manual operation. Therefore, as a technological recommendation for the minimum mode of underwater manual metal arc welding using rutile-coated electrodes, Mode III should be specified, as it can ensure technological stability under real welding conditions.

CONCLUSIONS

1. It has been established that analysis of the coefficients of variation of welding mode parameters alone may be insufficient for assessing the technological stability of the welding process; detailed

analysis of process oscillograms and metallographic examinations are also required.

2. The lower boundary of technological modes that ensure process stability under automatic stabilization of welding parameters has been determined as 180 A and 26.5 V. However, to achieve guaranteed technological stability under real welding conditions, a higher lower-limit mode of 200 A and 27 V has been recommended.

3. Adherence to the recommended welding parameters has been shown to prevent the formation of triangular weld beads during underwater wet welding and to significantly reduce contamination of the weld metal with non-metallic inclusions.

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ДОСЛІДЖЕННЯ СТАБІЛЬНОСТІ ПРОЦЕСУПЕРЕНОСУ ЕЛЕКТРОДНОГО МЕТАЛУ ТА ФОРМОУТВОРЕННЯ ШВІВ ПРИ ПІДВОДНОМУ РУЧНОМУ ДУГОВОМУ ЗВАРЮВАННІ

Вступ. Підводне зварювання — це унікальний спосіб з’єднання металів під водою, але умови роботи водолаза-зварювальника надважкі, а налаштування оптимального для якості шва режиму зварювання ускладнено низкою специфічних чинників процесу. Окрім цього не кожен фахівець може оцінити якість зварювання органолептично.

Проблематика. За умов роботи зварювальний струм, напруга та погонна енергія мають особливості впливу на стабільність дуги, формування і забрудненість металу зварного шва неметалевими включеннями. Порушення балансу параметрів режиму зварювання може привести до збільшення кількості дефектів шва та погіршенню його формоутворення.

Мета. Дослідження переносу електродного металу, формоутворення швів, стабільності процесу підводного мокрого ручного дугового зварювання та визначення мінімальних зварювальних режимів, необхідних для забезпечення стабільності процесу та якості шва.

Матеріали й методи. Дослідження проведено за допомогою установки плавлення електроду типу УПЕ 500, з використанням спеціалізованого джерела живлення для підводного зварювання НМ 1000П та спеціального обладнання, що забезпечує можливість зварювання під водою. Фіксування показників зварювального струму та напруги на дузі виконано за допомогою осцилографа та програмного забезпечення *PicoScope*, що дозволило отримати й математично обробити статистичні дані про електричні параметри процесу зварювання. Форми швів оцінено за допомогою темплетів, їх підготовки, протравлювання та подальшому дослідженні (×100).

Результати. Для досягнення гарантованої технологічної стабільності в реальних умовах зварювання рекомендовано нижню межу з більш високими показниками (200 А, 27 В), а дотримання рекомендованих параметрів режиму зварювання дозволяє покращити якість формування швів, уникнути «трикутності» швів при підводному мокрому зварюванні та зменшити забрудненість металу шва неметалевими включеннями приблизно вдвічі.

Висновки. Результати досліджень можуть бути використані при налаштуванні режимів підводного зварювання у складних умовах.

Ключові слова: підводне мокре зварювання, перенос електродного металу, параметри режиму зварювання, осцилограми процесу зварювання, «трикутність» зварних швів, стабільність процесу зварювання.