Service Life of Tungsten Electrodes in Hyperbaric Dry Underwater Welding

Service life diagrams were developed for two types of commonly used tungsten electrodes

BY H. OZDEN AND K. T. GURSEL

ABSTRACT. In hyperbaric dry underwater welding, the hyperbaric gas tungsten arc welding (GTAW) procedure offers many advantages. However, determination of the electrode service life is a substantial condition for good results in unmanned and computer-remote-controlled hyperbaric GTAW. Electrode service life is the time in which one electrode can be welded from a polished state to reaching a wear mark as an applied condition criterion under certain conditions. Extending electrode service life can drastically reduce the cost of the process; however, many influencing factors, as well as unpredictable occurrences during hyperbaric GTAW, make exact determination of the electrode service life more difficult. In this study, electrode service life was examined in the dependence on the electrode type, arc current, and arc power under different ambient pressure levels. For determining service life of the electrodes in hyperbaric GTAW, wear rate (percentage shortening of the electrode point due to wear) was considered as an evaluation criterion, because the wear rate contains all of the above-mentioned parameters and reflects all the effects of them.

For the delimitation of the service life tests, two kinds of tungsten electrodes [WL10 (with 1.0% LaO_2) and WT 20 (with 2.0% ThO_2)] were selected, which are the types predominantly preferred in practice. The results of this work indicate that the electrode service life heavily depends on the type of electrode under high ambient pressure. The WL10 electrode exhibits a longer arc-on time and a greater electrical load capacity and, therefore, a longer service life than the WT20 electrode. The compiled formulas for the computation of the electrode service life have an empirical form, which can be used for estimation as well as for comparison of the service life of electrodes in hyperbaric GTAW. The provided service life diagrams as a function of ambient pressure and arc power, in which the test results are represented, can be of great relevance for use both in onshore and offshore technology, especially in performing reproducible, high-quality welded underwater joints.

H. OZDEN and K. T. GURSEL are with the Mechanical Engineering Department, Faculty of Engineering, Ege University, Izmir, Turkey.

KEY WORDS

Service Life
Tungsten Electrode
Hyperbaric GTAW
Underwater Welding

Introduction

The intensified use of computers in welding makes it necessary to collaterally improve the pertinent peripheral devices and to adapt to the new requirements. For example, in fully mechanized hyperbaric GTAW, exact determination of the electrode service life as a function of the procedure and electrode parameters is very important, because service life has crucial effects on performing good, reproducible weld joints and the cost of the procedure, especially for underwater welding in deep water where remote control is necessary.

Barely any literature can be found dealing with the determination and calculation of electrode service life in hyperbaric GTAW. Some investigations on electrode service life in spot welding are available, but, in practice, these are hardly applicable to hyperbaric GTAW (Refs. 1–11). The aim of this study is to make a contribution regarding the questions about electrode service life in hyperbaric GTAW in both onshore and offshore conditions.

Problems in Determining Electrode Service Life

The electrode service life t_{El} is the time in which one electrode can be welded from a polished state to reaching a wear mark as an applied condition criterion under certain conditions. Apart from the service life, different condition sizes such as weld bead (crawler) length, joint surface, and joint volume can be consulted for evaluating the serviceability of an electrode. The electrode service life depends essentially on the following parameters (Refs. 1–11):

- Process variables (especially arc current, arc voltage)
- Inert gas type
- Electrode parameters (type, dimensions, tip included angle, diameter, and surface of the electrode)
- Cooling of the electrode (water cooled)
- Ignition parameters, ignition of the arc
- Environmental medium.

The numerous variables of influence and their mutual relations make an exact mathematical description of electrode service life more difficult. In addition, the missing guidelines for determining service life hinder the accurate definition of the problem. An exact experimental service life determination of the electrodes is connected with a high expenditure of material and time (Refs. 6, 7, 10). Hence, the main objective of the present study is to examine the service life of tungsten electrodes in the dependence on the electrode types, arc current, and arc power under different ambient pressures.

In normal current load, the lifespan of an electrode can persist several days. However, the degradation of arc stability resulting from electrode wear can be corrected by adjusting the parameters such as increasing the arc current or decreasing the welding speed and the arc length. If the required joint quality cannot be ensured with the electrode under high ambient pressure due to the wear, it should be welded under lower ambient pressure. Further, the selection of the wear mark for a condition criterion is pressure dependent and can be different according to producible joint quality and welding type.

In determining the service life of electrodes, an accurate definition of their characteristics and features is necessary for the serviceability of the electrodes in certain weld joint quality. If strong shortening and rounding of the electrode point as well as wear debris at the electrode point occur, the electrode must be replaced. However, shortening of the electrode point due to electrode wear cannot be an exclusive criterion for determining service life. In addition, for preservation of permissible joint quality, the arising deformations and pollutions are also of importance. In the examples shown in Figs. 1 and 2, different wear features such as deformations at the electrode point are represented. After arc ignition, a ball forms at the electrode point. The formation of such a slight blunt end extends the service life of the electrode and enables stabilization of the arc-on time as shown in Fig. 2, Field III. The service life is also extended substantially with aftertreatment of the surfaces of the electrode points — Fig. 2, Field II. With increased pollutants and wear debris at the electrode point, the instability of the arc increases; this effect becomes drastic with increasing ambient pressure (Refs. 3–6, 10, 11). The wear debris descends in the course of time into the melting bath, and thus, weld joint quality is reduced. Furthermore, the gradual wear of the electrode point accelerates — Fig. 2, Field IV.

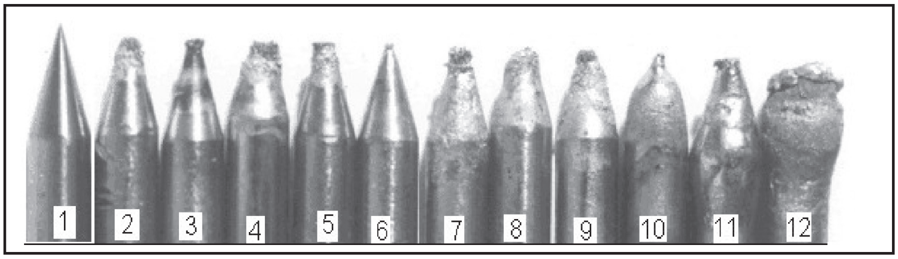

Fig. 1 — Electrode wear; 1 — before welding, 2–12 — after welding.

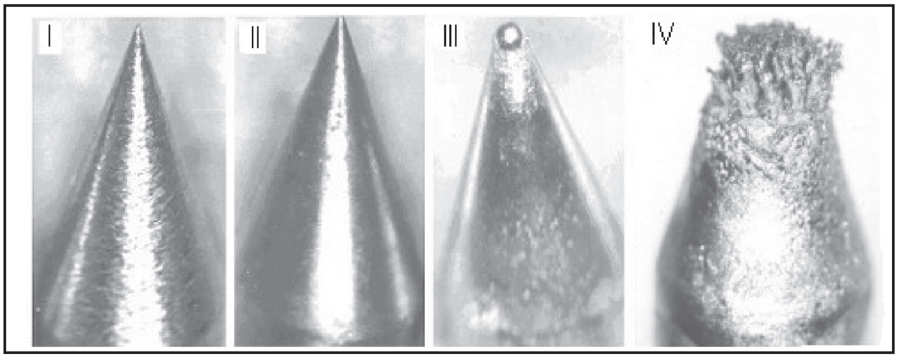

Fig. 2 — Electrode ends and point surfaces. I — Unpolished; II — polished; III — ball; IV — erosion at the electrode point.

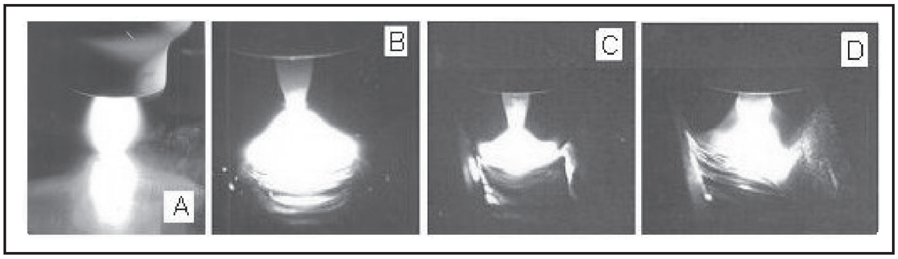

Fig. 3 — Close-up view of the arc and the electrode during welding. A — Shortly after arc ignition; B — during buildup welding; C — passes with filler metal; D — electrode point burned strongly during filler pass.

Service Life Criteria

For determining service life of tungsten electrodes in underwater welding, the following evaluation criteria are used:

- Wear rate VR in % (percentage shortening of the electrode point due to wear),
- Rounding diameters of the electrode end in mm,
- Increased instability of the welding arc in %,
- Increased arc voltage in %,
- Uniform weld bead formation,
- Modification of the shape of the core arc (as seen in Fig. 3),
- Electrode temperature in °C.

Electrode wear influences arc instability and the rise of the arc voltage more effectively when the ambient pressure increases (Refs. 1–11). The occurring voltage fluctuations as well as the arc diversions in frequency and height can be consulted as criteria for the service life determination of the electrodes. These service life criteria can be an advantage in fully automated hyperbaric GTAW, in which the electrode change can take place automatically after reaching these service life criteria with or without inquiries. Figure 4 schematically represents the types of wear. From this, the percentage wear rate can be calculated as follows:

$$VR_1 = 100\frac{VT}{SL} \quad (1)$$

$$VR_2 = 100\frac{VD}{d_{El}} = 100\frac{VD}{2SL}\cot\frac{\beta}{2} \quad (2)$$

where VR_1 is the wear rate of the electrode in % under consideration of electrode point length, VR_2 is the wear rate in % under consideration of the electrode point diameter, VT is shortening of the electrode point in mm, VD is the wear diameter (i.e., final state of the electrode point diameter in mm), SL is the electrode point length in mm before welding, d_{El} is the electrode diameter in mm, and β is the tip included angle in degrees — Fig. 4.

The temperature in the electrode point depends on the type, the dimensions, and the cooling of the electrode when welding parameters are held constant. With longer arc-on time or higher current rate, the sustainable heat capacity can be exceeded due to the Joule's resistance heating according to Equation 3.

$$Q = UIt = I^2Rt = \frac{U^2t}{R} \quad (3)$$

where Q is arc energy in J = W·s, U is arc voltage in V, I is arc current in A, R is electrical resistance of the electrode in ohms, and t is the duration of the current flow in seconds.

Apart from the current heating the electrode, thermal conduction from the arc to the electrode and the radiant heat of the arc contribute to its heating. Ac-

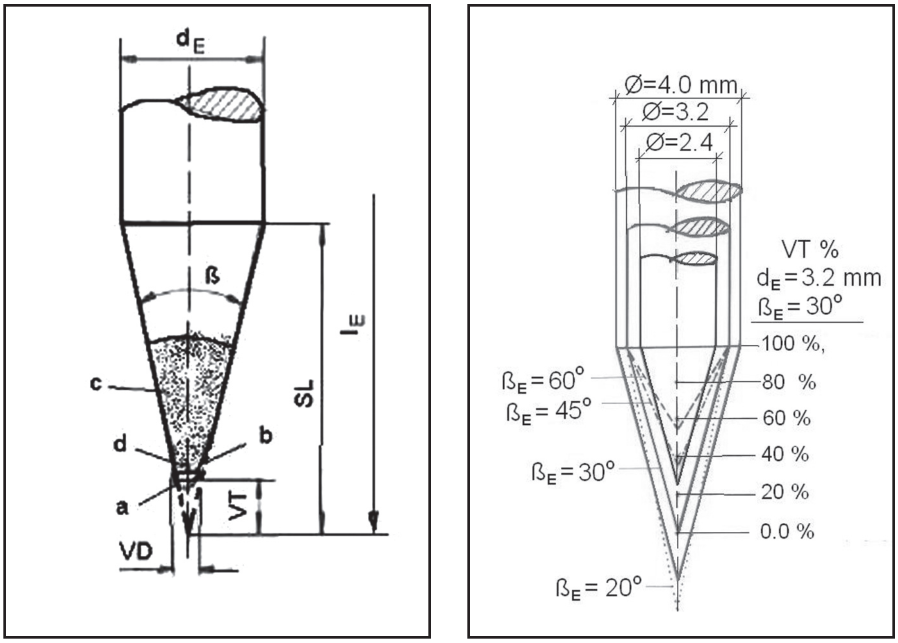

Fig. 4 — Wear dimensions at the electrode point.

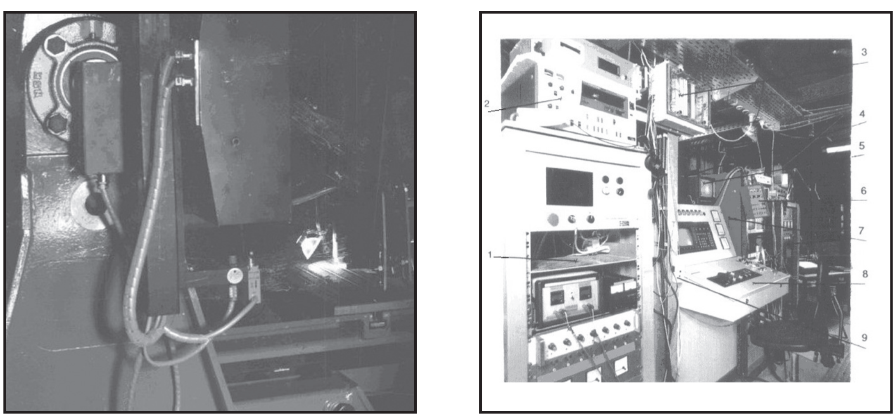

Fig. 5 — Computer numerically remote-controlled GTAW device of the hyperbaric pressure chamber.

cording to an equation for the heat development in the electrode, the current heat increases with cubic power of time. Equation 4 after Aman (Ref. 1) can be used to qualitatively compare the GTAW electrodes

$$Q_1 = 0.24\frac{I^2 L_0}{q t_0}\left[0.53t^3 - \frac{0.39}{t_0}t^3 - 0.1t_0 t\right]\left[cal\right] \quad (4)$$

where Q_1 is the theoretical amount of heat without losses, which is developed in the electrode within the time interval between the beginning t_0 and end of welding t; I is the arc current, and q is the electrode cross section.

Equation 5 gives the temperature rise ΔT in °C in the electrode as a function of specific heat c, density s, and electrical conductivity σ during the entire welding time t as follows:

$$\Delta T = \frac{QI\sigma}{cs}\frac{I^2}{q^2}t \quad \left[°C\right] \quad (5)$$

Long arc-on time and high current load can lead to a fast destruction of the electrode point and, thus, to instabilities in the arc and weld joint errors. Therefore, it is possible that the electrode temperature can be regarded as a condition criterion.

Selection of the condition criterion depends especially on the test conditions. The choice of a wear mark on electrodes in different pressure levels resulted in difficulties, because a "new" wear mark in each test should be determined depending upon ambient pressure. For the following tests, percentage shortening of the electrode point was selected as a main condition criterion because the wear rate contains all the parameters mentioned in the previous sections and reflects all the effects of them.

Tests for Determining Electrode Service Life

Both long-term and short-term tests for determining electrode service life can be performed. In long-term tests, service life values can be determined more precisely than in short-term tests. Because of the high expenditure of materials and time, short-term service life tests were used for this study. In these tests, sufficiently exact reference values could also be obtained. Depending upon the test aim, service life tests with current load or wear were executed. In the test with current load, the electrode was loaded in a certain time period with different amperages. The rising electrode wear was determined for comparison and extrapolated for longer periods of operation. In the service life test according to wear, the time period in which a respective wear criterion limit applied under certain welding conditions was achieved was measured. In order to shorten the test duration, one operates with higher amperages and standard welding values.

The test facilities consisted of a hyperbaric welding chamber, energy and gas supply system, and testing devices for welding, control, and monitoring as well as documentation. A pressure chamber with a volume of 10 m^3, a swivel-mounted and CNC remote-controlled welding device, a water cooler, and smoke filter made up the hyperbaric welding chamber — Fig. 5. In the tests, the buildup and joint welding were accomplished with V joint preparation for all welding positions in different water depths. Basic material S235JR (EN 10025) steel with a thickness of 15 mm was used. In direct current operation, the arc current was increased gradually from 50 to 300 A. Argon with a 4.6 grade and a mixture of argon and helium as shielding gas, as well as a "tri mix" (He, CO_2, and N_2) mixture as chamber gas were used. The GTAW machine with water cooling used in the test had a ceramic 10-mm-diameter inert gas nozzle. For the investigations, GTAW electrodes WT 20 and WL 10 with tip included angles of 30, 45, and 60 deg (EN 26848) and with diameters of 3.2 and 4.0 mm were selected — Fig. 4. The electrodes were abraded mechanically and accurately polished with a diamond disk. The contact ignition of the electrodes, which had proved more favorable than high-frequency ignition in hyperbaric GTAW conditions, took place alterna-

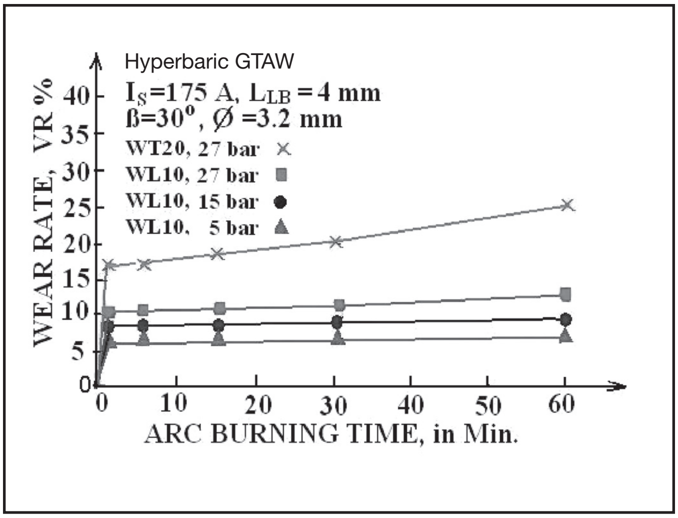

Fig. 6 — Percentage of wear rate as a function of arc-on time and ambient pressure at the electrode point.

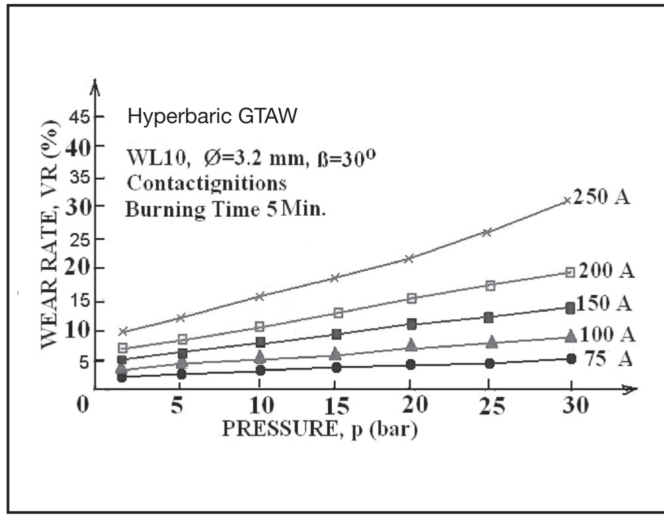

Fig. 7 — Wear rate as a function of the ambient pressure and arc current.

tively on a Cu sheet metal or on the workpiece with an arc length of 4 mm that was kept constant by an arc voltage control device — Fig. 3A. The prepared CNC program prevented excessive mechanical or electrical loading and, thus, possible damage to the electrode points during the ignition process.

Test Results and Discussion

A significant characteristic of electrode wear arises in the beginning of the test with the ignition process. After a few seconds, the wear process stabilizes and, then, a continuous wear that is dependent on the welding conditions arises. During the ignition process, about two-thirds of the entire point shortening of the electrode takes place. Figure 6 shows the time dependence of the wear rate percentage (VR) on the arc duration t_{Br} in GTAW under hyperbaric conditions. The measured values of the wear are approximately on a straight line in low ambient pressure. With rising ambient pressure, the gradient of the curves increases due to faster chemical destruction of electrodes caused by high temperatures.

The selection of the straight line of the wear mark VT20 (shortening of the electrode point around 20%) as condition criterion refers to previous test results (Ref. 10). Up to this wear mark, a reproducible joint quality is ensured. The intersection points of the straight lines of the wear as condition criterion are at approximately 10 min for WT 20, and at approximately 35 min for WL 10 in the ambient pressure of 30 bars.

The important test parameters are to be determined from the corresponding figures. Figure 7 gives the wear rate (used as a condition criterion) as a function of the ambient pressure with different current loads of 75, 100, 150, 200, and 250 A. Herein, the gradient of the curves rises also with increasing amperage. In normal atmospheric conditions, the difference is slight, about 5% up to 10 bars. However, the difference rises up to 20% in high ambient pressure of 30 bars. The investigations indicate that the instability of the arc increases with increasing ambient pressure at the same wear. Hence, for the selection of the service life mark, the arc stability and the weld joint formation are consulted as auxiliary criteria. The gradient of the curve of service life criterion decreases with rising ambient pressure. According to this characteristic, by a reduction of the amperage from 200 to 100 A, the intersection of the curves for wear and service life is raised from an ambient pressure of 25 bars up to 100 bars as seen in Figs. 8 and 9, respectively. Figure 8 shows percentage electrode wear rate VR represented double-logarithmically as a function of the arc power in different pressure phases. The most important test parameters are to be taken from the same figure. With rising arc power that depends on arc current and ambient pressure, the wear rate increases due to overheating electrode points. The average values are approximately on the straight lines of Equation 6:

$$C_{VT} = P_{LB} VT^{-\left(1/k\right)};\ \left(k = \tan\alpha\right) \qquad (6)$$

In Equation 6, C_{VT} and k are constants to be determined from the tests. Figure 9 indicates another service life diagram. Herein the service life of the WT 20 electrode is represented as a function of the arc power in hyperbaric GTAW on a double-logarithmic diagram. The values are on approached straight lines of Equation 7.

$$t = KP^{-m} = K\left(UI\right)^{-m} \qquad (7)$$

$$m = \tan\alpha = \frac{\log t_D - \log t}{\log P - \log P_D} \qquad (8)$$

$$m \log \frac{P}{P_D} = \log \frac{t_D}{t} \qquad (9)$$

$$\left(\frac{P}{P_D}\right)^m = \frac{t_D}{t} \qquad (10)$$

$$t = \frac{t_D P_D^m}{P^m} \qquad (11)$$

$$t = \frac{K}{P^m} \qquad (12)$$

The constant m is also called the Woehler curve exponent, and one receives the constant K from Equation 13, which denotes the gradient of the life curve as given in Fig. 9, as follows:

$$K = t_D P_D^m \qquad (13)$$

These constants can be determined from the test results as follows:

$$m = \frac{\sum \log P_i \sum \log t_j - n \sum \log t_j \log P_i}{n \sum \left(\log P_i\right)^2 - \left[\sum \log P_i\right]^2} \qquad (14)$$

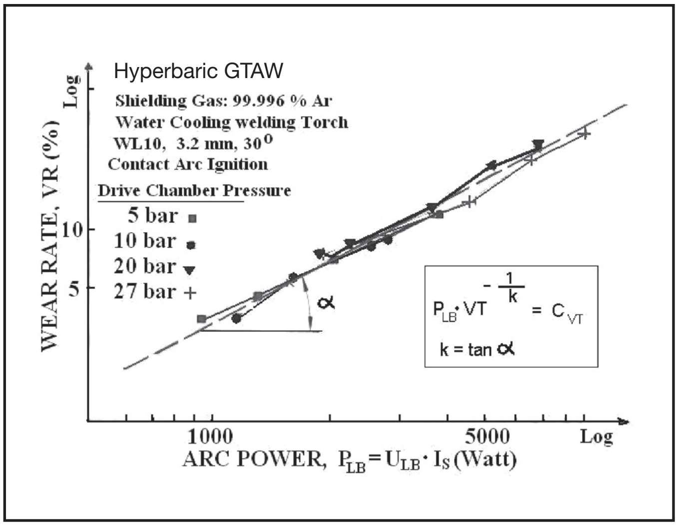

Fig. 8 — Wear rate as a function of arc power and ambient pressure.

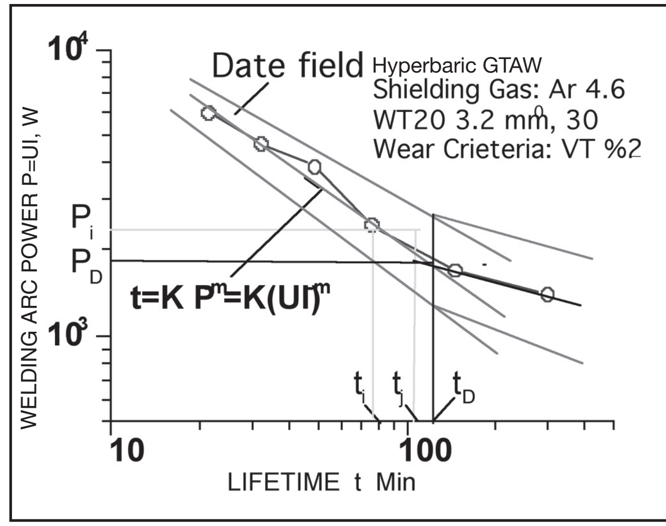

Fig. 9 — Service life of the tungsten electrode under hyperbaric welding conditions.

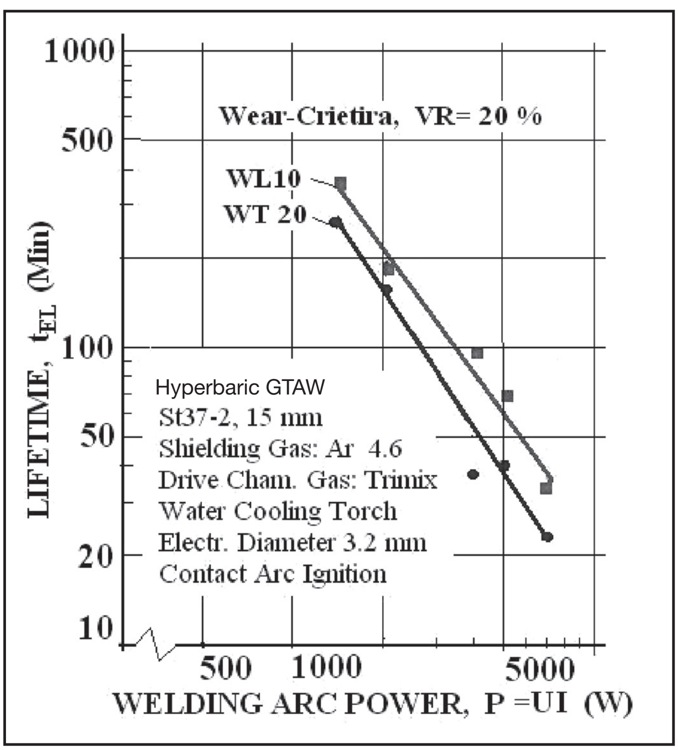

Fig. 10 — Lifetime straight lines of WL 10 and WT 20 electrode S235JR.

$$\log K = \frac{\sum\left(\log P_i\right)^2 \sum \log t_j - \sum \log t_i \sum \log t_j \log P_i}{n\sum\left(\log P_i\right)^2 - \left[\sum \log P_i\right]^2} \tag{15}$$

where P is arc power in watts, t_{El} is electrode service life in minutes, m is the tangent of the inclination angle α of the service life lines, and K is the value of the abscissa on the time axis for t_{El}.

The inclination of the straight lines depends on the electrode parameters, especially the chemical composition and the geometrical dimensions of the electrode. For selection of the GTAW electrodes and for the estimation of their service life, consideration of the arc power as a variable is of great relevance.

The determined values exhibit a longer service life and a higher electrical load capacity for the WL 10 electrode than for the WT 20, as shown in Fig. 10. This is explained by the fact that the alloy components of the WL 10 containing lanthanum oxide constituents possess higher wear resistances at higher temperatures. That means that the decomposition and the demolition of the thorium oxides, of which the WT 20 consists, are faster and their oxidation resistances are smaller at higher temperatures than those of lanthanum oxides.

In the tests performed, the influences of the following parameters on electrode service life were not considered: cooling water, type of current, inert gas, medium, and tip included angle of the electrodes. Effective cooling and high surface quality of electrodes can reduce electrode wear and extend the service life.

For accurate life expectancy of the tungsten electrodes, data from the experimental realizations are missing. At present, a solution of regression analysis would not be meaningful because of the missing knowledge, since many influences cannot be included yet. By the diagrams prepared with the test results, one can determine the ignition duration of the electrodes by means of the selected arc current and arc voltage. In Fig. 9, service life lines of the tungsten electrode represented as a function of the arc power with an instance of P_D = 1800 W point out an infinite arc-on time. Figure 10 shows the service lives of the examined electrodes. So, with these diagrams given, missing data and experiences can be bridged over.

The question is whether the expenditure for an exact determination of the electrode service life is precious. For remote-controlled, unmanned hyperbaric GTAW, its exact determination would be of great importance in onshore and offshore technology.

Discussion and Conclusions

Correct electrode selection and extending the service life of electrodes can substantially increase the efficiency of the procedure. For these reasons, in this study, the influences of the electrodes and the adjusting parameters such as the arc current and ambient pressure on the electrode service life were examined. Further, the other examined influences of the electrode parameters on the welding process — arc stability, ignition readiness, weld joint geometry, and electrode wear— were analyzed and will be published at a later time. Moreover, for determining and computing the service life of tungsten electrodes, wear criteria were compiled by means of the tests that were carried out. The choice of a wear mark on electrodes in different pressure levels resulted in difficulties, because a "new" wear mark in each test should be determined depending upon pressure levels. Already small wear leads to large arc fluctuations under high ambient pressure. For the delimitation of the service life tests, two kinds of electrodes (WL10 and WT 20), which are predominantly preferred in practice, were selected. The present study produced the following results:

- The provided service life diagrams of WL 10 and WT 20 electrodes as a function of ambient pressure and arc power are of great importance for practice in hyperbaric GTAW procedure.
- The determined values exhibited longer arc-on time and higher electrical load capacity and, thus, better performance for the WL 10 electrode than for the WT 20 electrode. This is of great importance for remote-controlled, unmanned underwater welding.
- By the diagrams prepared with the test results, one can determine the ignition duration of the electrodes by means of the selected arc current and arc voltage.
- The investigations showed that the contact ignition of the arc marginally depends on the type and tip included angle of the electrodes.
- The ignition current and affected period proved to be pressure-dependent.

The many influencing factors as well as unpredictable occurrences during hyperbaric GTAW make it more difficult to obtain an exact and generally accepted determination of the service life of the electrodes. The service life diagrams provided herein apply only under the test conditions given. The compiled formulas for computation of electrode service life have an empirical form, which can be used for estimation as well as for the comparison of their service life in hyperbaric dry GTAW. Further, an automated electrode change after a defined service life, such as with an automatic change of cutting tools during rotation or boring, is of great advantage in hyperbaric GTAW.

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550 NW LeJeune Road
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