Jan Hilkes, Jürgen Tuchtfeld

Underwater "Wet Welding & Cutting" with NAUTICA Stick Electrodes for Marine and Offshore Applications

Abstract: The basics of diving and working under water have been highlighted and explained as such, while these circumstances have also great influence on the welding behavior of the consumables applied. The challenge is in the execution of the welds and repairs. The paper covers the diving, welding and metallurgical aspects of underwater „wet" welding & cutting using covered electrodes based on industrial examples and applications for joining and repair welding. Shielded Metal Arc Welding (SMAW) and covered stick electrodes are a very versatile, flexible, simple and practical welding process, for this reason often used for underwater maintenance and repairs.

Keywords: underwater welding, underwater cutting, offshore, welding electrodes

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Introduction

A vast part of many Marine and Offshore constructions, such as the supporting structures of platforms and wind-towers, as well as pipelines, manifolds, jackets, corrosion preventing anodes, steel waterway & harbor constructions, sealing of bulkhead panels (sheet pile walls), locks, ship hull repairs and so on, are to a great extent underwater. Hence, it is obvious that welding and cutting activities for maintenance & repair are bound to take place underwater as well.

Shielded Metal Arc Welding (SMAW) and covered stick electrodes are a very versatile, flexible, simple and practical welding process, for this reason often used for underwater maintenance and repairs. It was used already over 80 years ago for sealing leaking rivets in riveted ship hulls. A covered stick electrode as the consumable and a power source is almost all that is required to be operational. Mind you, the power source has to be adapted and prepared for underwater welding to assure the safety aspects of such an underwater welding operation. The same set up can be used for underwater cutting as well. Since safety is the first priority, many safety measures have to be taken into consideration to ensure the entire operation is safe.

Since the underwater environment is always wet, and in north-west Europe also cold and dark as well, the working circumstances for the diver-welder are not ideal to say the least. Profound diving training and welder qualification is required to prepare for such a demanding job. The basics of diving and working under such circumstances will be highlighted and explained as such, while these circumstances have also great influence on the welding behavior of the consumables applied. The challenge is in the execution of the welds and repairs.

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Diving: "Working under pressure"

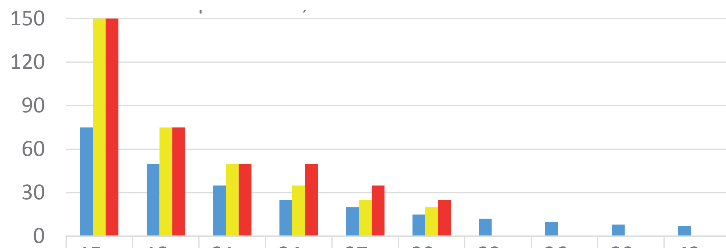
When a diver submerges, the body experiences the pressure of the surrounding water. Every 10 m is an additional bar in pressure. One bar of pressure equals a mass of one kg on a one cm^2 surface area! In consequence, the pressure on the diver´s body at 10 m is two bar, one from the ambient surface pressure plus one from the 10m water column. At 20 m, the pressure is three bar and so on. In order for the chest and lungs not to be compressed or squeezed, the diver has to inhale breathing air that has the same pressure as the surrounding water pressure; the pressure inside the lungs has to be equal to the external water pressure on the body to prevent any damage. The pressure of the breathing air is equalized by a regulator or demand valve with a mouthpiece, which the diver has in his mouth to breathe from. The regulator connects with a first-stage, which reduces the high initial pressure, to the air supply in form of an up to 15 or double 15- liter gas cylinder(s) that contains compressed breathing air. In this case, the compressed breathing air is just the natural air we all breathe on the surface, containing about 80% Nitrogen and 20% Oxygen. It is "only" the Oxygen we need to supply to our organs and the Nitrogen is the carrier gas. The pressure in such bottle is usually 200 to 250 bar at the start of a dive.

While diving and breathing compressed air, the Nitrogen (N_2-gas) is pressed into the blood and our blood streams through our veins. The amount of Nitrogen gas present in the blood depends on the pressure (depth) and the residence time at a certain depth. At 20 m, the partial pressure of Nitrogen gas (ppN_2) in the breathing air is 2.4 bar! When a diver ascends to return to the surface, the Nitrogen gas in the blood veins will form small gas bubbles that can become larger when the pressure is reduced (Boyle´s law: P x V = Constant) and those bubbles could block certain veins when no precautions would be taken. The first precaution is to restrict the depth and the residence time at certain depth in order to prevent having too much Nitrogen solved in our blood in the first place. Second important precaution is not to ascend faster than 10m/minute, in order to allow the Nitrogen gas in the blood to dissolve properly into more tiny bubbles without formation of too many, too large bubbles. A third important precaution is to make a safety stop at 3 or 5 m before surfacing. An additional effect of an increased amount of Nitrogen in the blood is that it can make feeling tired and euphoric while diving, called Nitrogen narcosis, which can lead to dangerous and unsafe situations.

Another solution to reduce the amount of Nitrogen pressed into the blood is to reduce the amount of Nitrogen in the breathing air. For this reason, mixed gases have been introduced in which Oxygen is added to the natural air, the so-called NITROX breathing gasses. These gasses have increased Oxygen content and depending on the Oxygen content referred to as EAN 32, EAN 36 etc. EAN in this case stands for Enriched Air Nitrogen and the number indicates the percentage of Oxygen. Since every advantage also has its disadvantage, in this case the increased Oxygen content becomes toxic over a partial pressure (ppO_2) of 1.6 bar. With 36% of Oxygen in the breathing air, the 1.6 bar partial pressure of Oxygen is reached at a depth of 34m, hence restricting the maximum diving depth.

In order to allow divers, sports divers as well as commercial/professional divers, to dive safely and to be able to practice the precaution of restricting the depth and residence time in a proper fashion, the so-called diving tables have been developed already back in 1937 by the U.S. Navy for compressed and as of 1962 for Nitrox gasses. Subsequently, sports-diving associations as CMAS, PADI etc, have adopted these tables for use by their member SCUBA divers (Fig. 1). Obviously, diving computers for recreational diving are also based on these tables. (SCUBA: Self Contained Underwater Breathing Apparatus).

The subject tables indicate the max. residence time at a certain depth for which no decompression stop is required, the so-called "Zero-Deco Diving Times". When exceeding these times, additional stops at a certain depth are required in order to "decompress", i.e. to dissolve all of the excess of Nitrogen gas in the blood that is tolerable at ambient pressure, so, on the surface. This can add up pretty fast in time and even impose stops at multiple levels where air supply has to be readily available. For safety reasons, most sports divers remain within the Zero-Deco Diving Times to prevent any dangerous situations and hazardous circumstances. Main rule is to "Plan the dive and Dive the Plan". It has to be stressed again, that even when the Zero-Deco Diving Times have not been exceeded, a safety stop at 3 to 5 m is always recommended and required by reputable diving organizations and diving schools. In addition to the Zero-Deco Diving Times, these tables are extended with subsequent information tables for multiple dives within a certain time after previous dives. The tables indicate the remaining maximum depth and residence time based on the duration of the surface interval between subsequent dives. Diving computers have this as a standard option available and they can be used easily for multiple dives, as long as everybody keeps using their own and same diving computer. The diving computer also indicates the depth and the time of the safety stop. To indicate the Zero-Deco Diving Times as described above, Figure 1 illustrates the differences in the maximum bottom times for standard Compressed Air, EAN 32 and EAN 36 (Combined diving tables from and used by the U.S. Navy, NOB, CMAS, PADI, SSI & SUUNTO diving computers) [1, 2 and 3]. It is clearly visible that the diving times without Decompression requirements are reducing rapidly with increased depths for all breathing air mixtures. With Compressed Air, only 7 minutes maximum bottom time is available before entering into a Deco situation. It also shows that with EAN breathing air mixtures the residence time increases substantially compared to diving with standard Compressed Air. Nevertheless, with Enriched Air Nitrogen, the depth is restricted to max. 30 m, for reasons as explained before. It shall be noted that these tables are initially meant for sports divers that are trained and healthy, for diving without extreme circumstances as cold or high altitudes such as mountain lakes and for when no hard labor involved! When the dives are not leisure or only for fun but becoming commercial and professional hard work and difficult low visibility and cold circumstances, the effect of "Working under Pressure" drastically changes and other precautions and safety measures will have to be taken. The maximum residence times and maximum depths as indicated in the standard diving tables have to be adapted for the more severe environment and working circumstances. The Dutch Navy uses the Canadian DCIEM (Defence and Civil Institute of Environmental Medicine) diving tables that go to 72 m of water depth. These tables



	15m	18m	21m	24m	27m	30m	33m	36m	39m	42m
Compressed Air	75	50	35	25	20	15	12	10	8	7
EAN 32	150	75	50	35	25	20	0	0	0	0
EAN 36	150	75	50	50	35	25	0	0	0	0

Compressed Air EAN 32 EAN 36

Fig. 1. Zero-Deco Diving Times (min) vs Depth (m) for Compressed Air, EAN 32 & 36

include decompression stops in the water but also in combination with stops in a recompression tank onboard the support vessel. For example, a dive with standard compressed air to 54 m and a diving time of 30 minutes generates a deco-schedule of 85 minutes with multiple stops from 18 m to 3 m water depth, the last stop at 3 m being 50'. A combined deco-schedule of 78 minutes would include 20' for multiple stops in the water from 18 m to 9 m, a 4' surface interval to transfer from the water into the recompression tank and a further 47' of decompression at a pressure equivalent to 12 m water depth with oxygen treatment [4]. To optimize the diver´s comfort, dry-suits with wool jumpsuits underneath are used that have a better insulation than thick neoprene wet-suits. Also full-face masks or helmets with communication systems included are used, as shown in Figure 2. (Courtesy of the Royal Dutch Navy – Diving Group).

The above provides some background as to what a diver-welder has to deal with in addition to being a welder when he has to perform and execute welds under certain extreme and difficult circumstances.

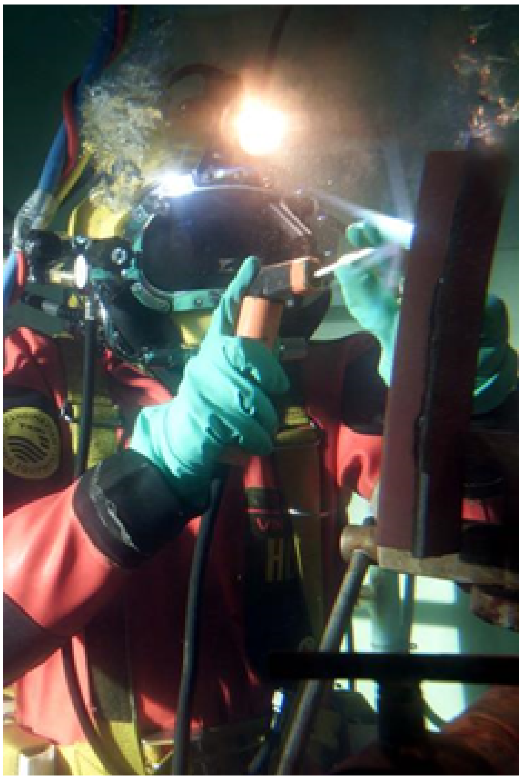


Fig. 2. Underwater welding equipment

Underwater Welding & Cutting

Underwater, welding can take place under two distinct circumstances or conditions. The first option is one which is directly in the water with "wet" diver-welders, who dive with compressed air or an enriched air mixture, with which the depth and residence time is restricted to about 30m and 42m of water depth respectively with corresponding diving times of maximum 25 and 7 minutes for standard non-deco dives. The consequences for deeper and/or longer dives has been described in the previous chapter. The advantage of such wet-welding operations is that they are very flexible and mobile, also ideal for short repairs and welding jobs in a larger area, in docks, waterways, floodgates, locks, anchor lines, ship repairs etc. The set-up is also relatively quick and practical, from either a shore or a boat. Obviously, the underwater work has to be properly scheduled and planned in detail. Welding with coated stick electrodes is often applied for underwater welding but other welding processes such as GMAW, FCAW and GTAW can be applied when using special welding guns with special nozzles to keep the surrounding water away from the arc. The weld quality is acceptable and very suited for maintenance and repair welding and for multi-pass fillet welds.

The second option is "dry" hyperbaric welding with an underwater habitat (cofferdam) built around the parts or the structure that needs to be welded or welded upon. In this situation, the water is pressed out with air to create a relatively "dry" environment. This means the humidity in the habitat is relatively high but there is no surrounding water in contact with the work-piece or the welding consumables and the electrical arc. Hyperbaric welding is used for deep to very deep waters at great depths of up to hundreds of meters. The hyperbaric welders are so-called "saturation divers" who remain up to weeks at the specific depth or under the specific high (water) pressure. This means that they live in huge pressurized tanks as living quarters to sleep, eat and rest. Saturation here means that the blood of the welders saturates with the breathing gas mixture. As described before, Oxygen becomes toxic over a partial pressure of 1,6 bar so the breathing gas mixture can only contain a small amount of Oxygen. Since Nitrogen causes side effects as Nitrogen narcosis, which starts with compressed air already between 10 and 30 m of water depth, other gasses have to be used that do not cause such type of side effects or become toxic. The inert gas Helium suits well to be the carrier gas and with small amounts of Oxygen, this is used as breathing gas for hyperbaric saturation divers. Since the blood of such divers is completely saturated, it takes an extremely long time to decompress, up to many days depending on the maximum depth and dissolve all the excess gasses into the blood sufficiently not to suffer any remaining effects that can result from the tiny bubbles formed during the decompression stages.

This set up is much more complicated and requires a huge organization in order to run an operation safely and effectively. The planning and scheduling is much more complicated as well, not to speak about the weather condition on open sea! It is much less flexible due to the required controls to keep the divers safe and it is very expensive. However, for welding and repairs on sub-sea pipelines, tie-inns manifolds, wellheads and so on at up to about 300m, there are no real alternatives except robots and other remotely operated vehicles (ROV´s). The dry hyperbaric environment makes it possible to apply welding processes such as FCAW, GMAW in addition to SMAW and even GTAW to produce high X- ray quality welded joints, as for example subsea pipelines [5]. In this paper, we keep it wet and concentrate on welding with Covered Stick Electrodes!

Underwater "wet" welding with covered stick electrodes

Shielded Metal Arc welding (SMAW) with covered stick electrodes is a very versatile, simple, flexible and practical welding process, for which reason it is often used for underwater maintenance and repairs. It is suitable for welding in all positions. A covered stick electrode as the consumable and a "DC power source" is all that is required to be operational. Mind you, the "DC power source" has to be adapted and prepared for underwater welding to assure the safety aspects of such an underwater welding operation. In addition, many other precautions have to be taken regarding the suits and gear for the diver-welder.

The DC power source can be a type DC-generator, Transformer or Inverter, as long as the device is constructed and approved to use for underwater welding operations. According the German Guideline BGV D1:2001, this shall be indicated with an "S" on the machine, for power sources that are used under increased electrical danger. Amongst other safety features, such a power source is adapted to have a low Open Circuit Voltage (OCV) when there is no welding taking place, according the standards < 65 V, but machines exist that have an OCV of as low as 15 V. To guarantee the safety of the welders, it has to be clear that the functionality of Voltage Reduction Device (VRD) in welding machines for underwater welding is always safeguarded [5]. Still, standard DC inverter machines are used that have an electrical VRD build in, to assure an OCV of zero while being turned on. The machine is in fact in a "stand-by" mode. When the welder touches the work-piece, the RDV activates and the OCV increases to enable the welder to strike an arc and to start welding. The welder can use a remote control unit to set the welding current or via the welding operator onboard the support vessel. When the welder stops welding, the machine automatically falls back in the safe "stand-by" mode and the OCV goes to back to zero [6]. In this case, the machine is adapted for underwater welding applications, whereas a standard version would have an OCV of 42 V, which is the safe OCV for welding in workshops under a dry indoor environment according the present standards.

The modern welding machines can have additional options as Hot Start, Arc Force and remote control functions to make the welding easier to execute and to provide better penetration and protection of the welding arc during welding. Specialist welding power source producers are marketing special underwater welding machines for underwater welding companies to meet their demands.

When the suitable welding source has been determined, the connections of the work piece and the electrode holder cable are as follows. From the welding machine, one cables connects to the electrode holder and one cable to the work clamp, as show in Figure 3. The electrode cable connects to the negative terminal (straight polarity). When connecting the electrode cable to the positive terminal, electrolysis can occur which could deteriorate the metallic parts in the electrode holder! Hence, the work clamp cable connects to the positive terminal. The stick electrodes can usually be welded with DC+ or DC- and many procedures are welded DC+ as well, so when having a problem losing the electrode holder, DC- could be a possible solution. Precautions have to be taken to prevent mixing up the cables with positive and negative polarity when preparing the welding operation. A fully insulated electrode holder is used to prevent any current passing through the hand of the welder- diver, as current always follows the way of least resistance! To ensure the electrical safety of the operation, the welder has to be completely insulated from all electrical circuits; the welder should wear watertight rubber or rubberized canvas gloves, all the metallic parts inside the helmet shall be completely electrically insulated as well and possibly a dry-suit should be used to complete the overall electrical insulation. During lowering the electrode holder to the diver, when changing the electrodes, during any break and in any case of possible danger, the power shall be off with a zero OCV.

To start the welding operation safely, the cables for electrode and work have to be connected with the power source and the power supply has to be turned on. A device used to connect and disconnect both the electrode cable and the work-piece cable at the same time is the double pole-single throw "knife switch"; the moving parts of this device have the shape of a knife, hence, the name (Fig. 3) [7].

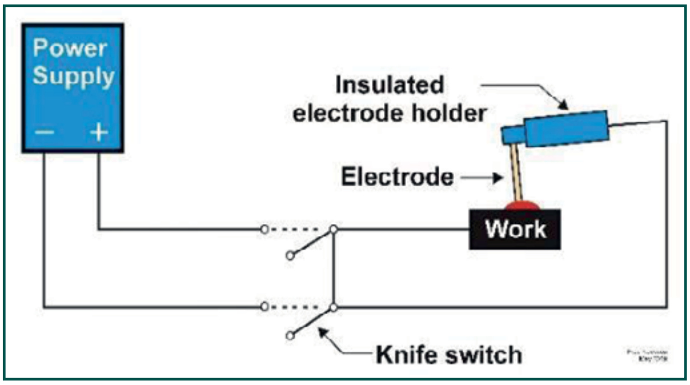


Fig. 3. The welding circuit for underwater MMA welding

This safety switch is only to be operated, to switch on or to switch off the welding current, upon the specific and direct request from the diver-welder in the water below.

An overview of the basic set-up for an underwater welding operation is illustrated in Figure 4. The overview shows the support vessel with the necessary equipment; the DC- welding power source, the work piece cables, the bulk bottle with compressed air or mixed gas for the welder to breathe and the audio- video communication system to connect the welder with the Dive Master/Operator on the vessel. The video connections makes it possible to follow the welding processes and the work underwater for guidance and/or for documentation of the welding actions. The Knife Switch connects the work piece and electrode cable with the welding machine above. Below the surface in the water, the welder wears a full dry-suit with diving helmet, has a safety bottle with breathing air on the back and a fully insulated electrode holder in the hand. The air hose, the communication & light cables and the depth tube all have a different color and combine into

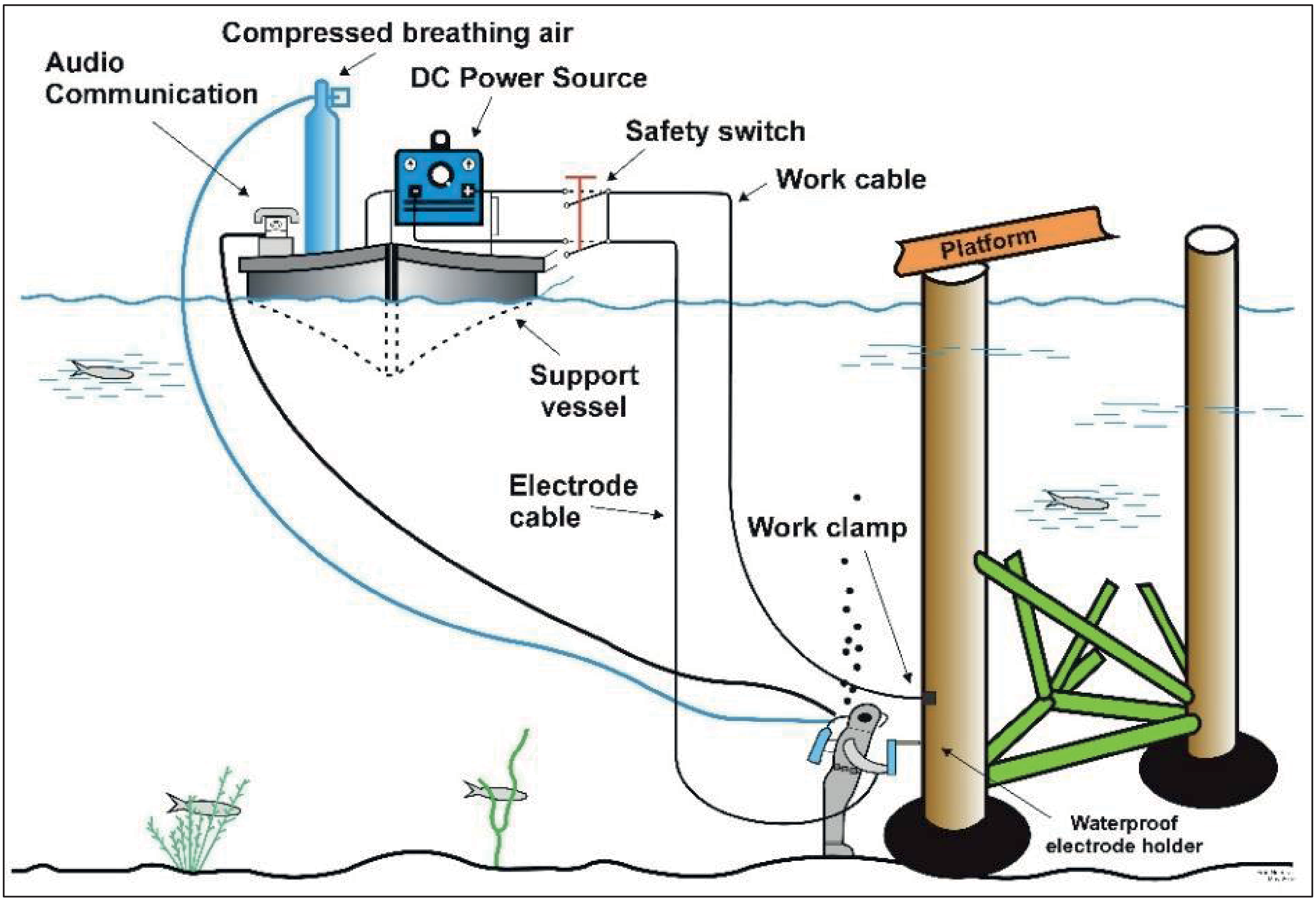


Fig. 4. Basic set-up for underwater welding operation

a so-called "umbilical" that connects the diver with the equipment on board the vessel. Figure 5 shows all these details of the diver entering the water. (Courtesy of the Royal Dutch Navy - Diving Group).

Fig. 5. Underwater welding equipment

Although the breathing air for the welder below is supplied from the bulk unit or directly from the compressor on the vessel (Surface Supplied Equipment - SSE), the diver also needs to carry a small bottle on the back as a safety precaution in case the supply from above may oppose a problem or fail to supply breathing air. As mentioned before, the support vessel can also carry a recompression tank for safety and for carrying out complex and deep diving operations. To accommodate the welder while carrying out the underwater activities, a kind of scaffolding can be built, in form of a platform that is attached with cables and magnets to the hull of a ship or a structure as a jacket leg. In this way, the welder can stay in position more easily and comfortably to perform the demanding tasks. The full organization of such an operation can become complex, since everything has to come together in one smooth and safe combination of events and in a team with different disciplines.

The communication between the Diver-Welder in the water and the Dive Master/Welding Operator on the surface has to be spotless since lives can are at stake. Lots of training, profound knowledge, experience and trust has to be an intrinsic element of the cooperation within the whole team. The diver- welder has to be an excellent professional and commercial diver, as opposed to a sports diver, knowing all the ins and outs of safe diving and in addition be an expert welder to execute welds under extreme, often dark and cold, circumstances. When welding under water with stick electrodes, due to the gas that develops in the arc and the heat that makes the water boil, the welder cannot really see the actual weld pool and slag as he would under dry circumstances. This implies the welder has to have an incredible skill and feeling to produce a suitable and solid weld. The welding training therefor requires a lot of practice and qualification welding with subsequent maintenance of the qualifications by repeating the performance regularly.

This implies that profound training and exercise is required to be able to fulfill the requirements of such demanding job. Many national and international Underwater Welding & Training Facilities have been established to provide organized training and practice as well as for qualification of diver-welders and welding procedures under international standards. As for example, ISO 15618-1:2016, Qualification testing of welders for underwater welding - Part 1: Hyperbaric wet welding and ISO 15618-2:2002, Qualification testing of welders for underwater welding - Part 2: Diver-welders and welding operators for hyperbaric dry welding. Internationally, also the AWS D3.6M:2017, Underwater Welding Code can be used.

However, being underwater, the stick electrodes are exposed to one: a wet or very high humidity environment, the water/seawater and two: to an increased pressure caused by the water pressure, whereas every ten meter of water depth equals one Bar of pressure. This means that consumables need to be developed and designed especially to meet the necessary welding, chemical and mechanical requirements under these extreme circumstances of humidity and pressure. The following chapters will elaborate on these subjects.

Welding metallurgy and stick electrode coating development

When welding underwater with covered stick electrodes, three main phenomena play an eminent role in the chemical composition and the mechanical properties of the resulting weld:

- Due to the surrounding water that dissociates in the electrical arc, the hydrogen content and the oxygen content in the arc and weldmetal increase to relatively high levels. The amount of dissociated water is proportional to the water depth, hence, also the amount of hydrogen and oxygen in the arc and subsequently in the weld metal.
- Due to the water pressure, the metallurgical processes in the electrical arc are influenced and cause a change in chemical composition, caused and enhanced by the higher oxygen content.
- Due to the surrounding water, the cooling rate is always 3-dimentional and the t8/5 time is short, whilst pre-heating is usually not always easy or practical to carry out in practice, so the hardness of the weldmetal and adjacent base material increases.

Hydrogen Content

Due to the dissociation of the surrounding water, the hydrogen content in the deposited weldmetal increases and can be up to 70 ml/100g (H_{DM}). This means that the initial H_{DM} of the “dry” electrode of 5-12 ml/100g is not too significant any more. The high hydrogen levels can lead to porosity in the weld as well as to hydrogen induced cracking in both weldmetal and heat-affected-zone (HAZ). The amount of dissociated water increases with increasing pressure, which is proportional to the water depth. To reduce the amount of weldmetal hydrogen, thin layers are necessary to allow the hydrogen to escape. Thin layers can be obtained when welding stringer beads in the vertical down position (PG) using 3,2mm diameter stick electrodes. A smaller diameter electrode would produce a too thin a weld bead to withstand the stresses and would crack, whereas larger diameter electrodes would produce too much weldmetal to handle and a too heavy a bead thickness to enjoy the reheating effect in the previous layer [5]. Therefore, in any case, multi-pass welding will give an extra hydrogen reduction and reheating effect in the previous layer(s).

Metallurgical processes and Oxygen

Due to dissociation of the surrounding water in the electrical welding arc, the oxygen level in the arc and the liquid weldmetal increases. In ferritic (mild steel) materials, the oxygen will oxidize elements as Mn to form MnO, hence reducing the level of Mn, which is needed to generate a microstructure that provides good mechanical properties as yield strength (YS) and ultimate tensile strength (UTS) of the solidified weld metal. In addition, the Si is oxidized to SiO_2, hence reducing the effect of Si, which leads to less nice executive welding characteristics and lower wetting action of the weldmetal. The amount of loss of Mn and Si increases with increasing water depth, i.e. hydrostatic pressure. Back in 1987, Ibarra et al. published the relation between the reduction of Mn and Si content, and the water depth [8]. Figure 6 shows the results of their work and it indicates that already at 10 m water depth (2 bar pressure), both Mn and Si content is reduced by 50%. They also report that the carbon level can increase slightly with increasing pressure until about 50m of water depth. This effect is apparently associated with the carbon monoxide (CO) that is present in the welding arc coming from carbonates in the electrode covering. The increase can be up to 0.08% at 50 m, after that it remains constant.

The effect of a reduced Mn content in ferritic welding consumables and base materials is a reduction of the amount of acicular ferrite (AF) and fine-grained ferrite (FG), formed during solidification; this reduces the YS and UTS. It only provides a reasonable impact toughness at 0 to -20°C and a good elongation, as published by G. Evans [9].

As confirmed and published by Duo Liu et al. [10], to improve the mechanical properties, additions of Titanium and Boron in the welding consumable as used for welding HSLA steels can be an option. With B as the grain-refining element and Ti as the element to catch the oxygen in order to protect the B, with increased weldmetal oxygen content when welding underwater, the amounts of these elements in the welding consumable for underwater welding will have to be different from those used for standard "dry welding" circumstances. As the de-oxidant, Ti will reduce the oxygen level in the weld and as such lower the amount of porosity and reduce the burning loss of Mn and Si etc.

In the same paper, the effect of Mo is described in detail for various weldmetal compositions. Mo is known to suppress the formation of pro-eutectic ferrite (PF), it promotes fine-grained microstructure and it stabilizes the

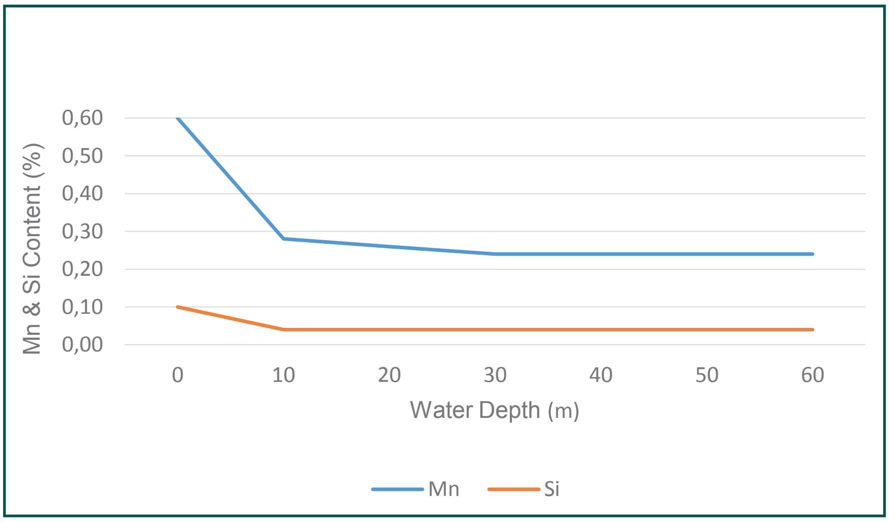


Fig. 6. Wet underwater weld metal Mn and Si content (%) as a function of Depht (m)

carbides, hence, improving the strength and toughness properties of the weldmetal. Since Mo is not prone to being oxidized, it can be used as a stable element against Mn.

In austenitic materials, the level of elements as Cr and Ni is also reduced with increasing water depth, i.e. static water pressure. This means the loss of corrosion resistance may occur when no measures are anticipated when developing the welding consumables.

Cooling Rate

When welding a work piece completely submerged in water, the cooling rate is rather 3-dimensional and thus fast. This is the nightmare of any welding engineer, since pre-heating is virtually impossible. However, gas or induction pre-heating systems exist and are in use for welding hot-taps underwater. The fast cooling leads to short $t_{8/5}$ times: the time a weldmetal and HAZ are cooling down continuously from 800 to below 500°C. The final microstructure is mainly formed in this temperature range. This means that there is less time to form the desired ferritic (AF) microstructure with acceptable mechanical properties. Instead, also, bainite and martensite are formed, that do not have good toughness properties but show higher hardness, which can lead to hydrogen induced cracking or even cold cracking. With increasing depth, the effect of having less ductile ferrite increases until about 50 m of water depth, below that, the microstructure remains relatively constant, as described for underwater welding of offshore installations by Jushua E. Omajena et al., [11].

The amount of ferrite, bainite and martensite formed, depends also on the chemical composition. The higher the Carbon Equivalent (CE) the more bainite and martensite forms, and the higher the hardness will be. One of many formulas to calculate the CE is:

$$CE = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15 \ [wt\%].$$

This means all these elements contribute to the factor that indicates the hardenability and the desire to generate a martensitic microstructure.

In general, materials with a carbon equivalent of less than 0.37% are regarded as completely weldable without any specific precautions as pre-heating or the use of basic coated electrodes etc. under standard ambient conditions, even up to 15 mm thickness. However, due to the rapid cooling with underwater welding, this changes and precautions have to be taken; the execution of the welds has to be reviewed. It is recommended to use base materials with a C content of less than 0.15%. In addition, the welding consumables have to be adapted, even when the carbon equivalent of mild steel consumables is relatively low, about 0.20 to 0.30%. As mentioned before, the Carbon content can increase with increasing pressure, i.e. water depth, depending on the amount of available Carbonates in the electrode covering.

The crack susceptible microstructure with high hardness, combined with the elevated hydrogen content and the presence of welding stresses situation in the welded joint, can lead to hydrogen induced cracking. In order to prevent this type of cracking, one of the three components has to be eliminated or the combination of the three reduced to a minimum. A practical but partial solution that can help reducing the risk of this type of cracking is the Temper-bead method. This implies for multi-pass welds, that the subsequent pass reheats the previous pass with HAZ and "tempers" the microstructure in the bead due to grain-refinement, which improves mechanical properties as toughness and reduces the hardness of the weldmetal and HAZ. To have the optimal effect of the method, the weld beads shall be not too thick so the ideal electrode diameter is again 3,2 mm. The larger diameter electrodes would produce too thick beads to have sufficient tempering effect throughout the bead by the subsequent weld-pass.

Stick electrode coating development

All the phenomena and influences that occur and play a role during underwater welding and cutting, as described before, have been evaluated and considered in the design and development of coated stick electrodes. This also implies that the electrodes have to be specifically designed for certain water-depth range in order to meet the desired results and mechanical properties at a specific water-depth. The main constituents of the coating of a stick electrode for welding unalloyed materials are discussed in the following paragraphs. The core wire is usually an unalloyed high purity mild steel.

So first, to deal with the surrounding water and the pressure, the electrode coating has to be designed to generate a sufficiently powerful gas-shield around the electrical arc to keep the surrounding water away from the electrical arc as much as possible and to ensure sufficient positive penetration of the welds produced. This means sufficient CO_2-gas forming elements as Calcium Carbonate ($CaCO_3$) and other Carbonates have to be present in the coating. The Calcium Carbonate also stabilizes the electrical arc. In addition, cellulose produces CO_2 and used as well, for the same reason as it is used in pipe- welding electrodes. Since the Carbonates can cause an increase in weldmetal Carbon content, the total amount of Carbonates in the coating is restricted and has to be in balance with the other constituents in the electrode covering. To increase the power of the arc, the electrical arc should be relatively small in diameter and convergent. Also for this reason, an electrode diameter of 3.2 mm is an advantage. In addition, the welding current for underwater welding is about 20% higher as used on the surface, which also increases the arc force [5, 6, and 7]. The higher current also gives a higher Heat Input, which has a positive effect on the cooling rate and resulting microstructure. All depends obviously also on the coating thickness since the more coating, the more energy is required to "melt off" the coating constituents and less energy is left to contribute to the Heat Input as used for lower cooling rate.

Titanium-dioxide (Rutile or TiO_2) in the coating stabilizes the arc and produces a slag covering that easily detaches, it also contributes to a smooth weld bead surface. The amount of Rutile can be up to 50% or more. This electrode type is referred to as "Rutile Electrode". Due to the easy ignition and weld- ability of rutile electrodes, contact welding is possible which is required for underwater welding since the welding arc is hardly visible due to the bubbles generated. Rutile also reduces the amount of weldmetal hydrogen.

Silicates stabilize the arc whereas other silicates are slag formers and fluxing agents to improve wetting characteristics of the liquid weldmetal. Liquid Silicate binders are used to turn the dry mineral mix into a paste for extrusion of the electrodes in the production process of the stick electrodes. It is important that in the end, the electrode coating is strong and shows good adhesion with the core wire. Silicates can also reduce the oxygen content in the weldmetal.

Ferro-Manganese (FeMn) is used to compensate the burn-off loss or increase the Mn content and both Fe and Mn deoxidize the weldmetal, reducing the oxygen content thereof. Ferro-Silicon is added to compensate for the burn-off loss of Si and to deoxidize the weldmetal.

When Molybdenum is part of the desired weldmetal chemical composition to optimize the mechanical properties, it is usually added through the coating using Ferro-Molybdenum (FeMo). This is the easiest way when using an unalloyed core wire. The effect of Mo has been described previously. To enhance the arc force more, a certain amount of Iron-Oxide (Fe_2O_3) can be used. This means that the arc can withstand higher surrounding water pressure, i.e. be used at greater water depths. Stick electrodes types with a very high amount of Iron-Oxide are referred to as "Acid Electrode". Usually the coating is a mixture of Rutile and Acid in order to use the benefits from both types.

The effect that the Iron-Oxide burns-off so easily and creates such a powerful welding arc is used in coated stick electrodes for cutting. In this case, a large portion of the coating is Iron-Oxide which together with an Aluminum compound burns-off almost all coating constituents and the core wire, that no deposit is created. Only a very powerful and hot arc to melt the base material and blow it away while cutting the plate.

The electrodes for underwater welding have to show a very good weldability in fresh water since the weldability will always be better in salt water. This is due to the ionization of the salt, which improves the ignition properties of the electrodes. For this reason, electrodes that are qualified and classified for fresh water, also qualify and classify for salt water, the other way around is not accepted. In DIN 2302-2018-03, the designations "fr" for fresh water and "sa" for salt water are used.

When developing the optimal coating by using all possible ingredients, the electrode shall also be suited to perform in various welding positions. To be able to generate relatively thin weld beads, the vertical down (PG), overhead (PD) and down-hand (PB) positions are used with stringer bead technique.

Fig. 8. Electrode cans

To achieve very good mechanical properties when welding under ambient conditions, electrodes with a "basic" coating are used. However, when the amount of so-called basic constituents as Calcium Carbonate ($CaCO_3$) and Calcium Fluoride (CaF_2) is too high, the executive weldability is too difficult for use in "wet" underwater welding. In addition, the increase in Carbon content at deeper depths would cause unfavorable effects as described before. For this reason, these "Basic Electrodes" are not popular for underwater applications.

Waterproofing of the coated stick electrodes

When the coated stick electrode is ready, it subsequently has to be protected against the underwater environment, which is the water itself, and the water pressure (depth). This means that a protective waterproofing needs to be applied that meets certain requirements such as: non-conducting, non- hygroscopic, impervious, not water solvable, clear, melt or burn away gradually during welding, seal tight to the electrode coating to prevent water coming in between the sealing and the electrode coating. It should also not have a negative influence on the welding behavior and be strong enough and resistant to impact or damage by the water pressure.

In the early days, the electrodes were dipped in molten paraffin that protected the electrode well but was very soft and prone to be damaged. Later, a type of alkyd resin varnish was used which provided a strong and extremely tight waterproof coating that meets the requirements. The varnish can also be sprayed on but it is difficult to arrive at an even distribution of a solid and closed varnish coating around the electrode, which negatively affects the weldability. The latest development is a special PE shrink wrap, however the implementation is not yet finished. Depending on the production methods, the optimal solution shall be determined.

After the protective coating has been applied, the electrodes shall be properly packed in hermetically sealed metal cans or vacuum packaging in order to guarantee the optimal condition after transport and storage before the electrodes are being used on the job. The electrode cans are shown in Figure 8.

Stick electrodes for "wet" underwater welding

In line with all the above, voestalpine Böhler Welding has developed four different types of coated stick electrodes over the years for underwater welding and cutting that all have a solid Alkyd resin varnish protective coating which meet all the desired technical requirements. A short description of these consumables is given below, the typical chemical composition and mechanical properties are listed in Table 1. Additional information regarding applications and usage is available in form of Product Data Sheets. As indicated and explained before, the optimal electrode diameter is 3,2 mm. All electrodes can be welded DC+ and DC-, however DC- is recommended. The standard packaging are metal cans.

- **UTP Nautica 20** is an electrode for fillet welding of unalloyed and fine-grained structural steel to a water depth of 20 m. It has GL and LR approval and is suitable for welding positions PB, PD and PG. The recommended welding current for the 3,2mm diameter electrode is 140 to 180 A.
- **UTP Nautica 100** is an electrode for fillet welding of unalloyed and fine-grained structural steel to a water depth of 100 m. It is suitable for welding positions PB, PD and PG. The recommended welding current is 150 to 200 A.
- **UTP Nautica CUT** is an electrode for underwater cutting. The strong gas jet blows the molten metal away and leaves a perfect clean cut surface. With a current of about 240 A, a primed 10mm mild steel plate is easily be cut or pierced. Vertical down and horizontal electrode movement can be used.
- **UTP Thermanautica** is an electrode with a duplex stainless steel composition and can be used for welding dissimilar joints and stainless to stainless joints. The composition has a high resistance to seawater corrosion. The recommended welding current for the 3,2mm electrode is 110 to 160 A.

Underwater Wet Welding & Cutting with stick electrodes - Applications

Applications for underwater wet welding & cutting are numerous when realizing how much steel material is used in and around water. Whether platforms or wind-towers in the sea that all have corrosion preventing anodes welded upon, whether corrugated bulkhead panels (sheet pile walls) in waterways that are sealed with welds to make them watertight, whether steel harbor constructions, as water locks and sluice gates, need welding repair and whether navy or commercial ships and submarine hulls need welding patches or repairs.

All these welds have in common is that the majority are fillet welds and the water depths of down to about 20 m. For ship repairs, it makes a huge difference when a welding repair can be carried out while in the water as opposed to a very expensive dry dock solution. For all

Table 1. Overview UTP NAUTICA Stick Electrodes & Typical Weldmetal Properties

Product Name	**DIN 2302:2018-03**	C	Si	Mn	Mo	Cr	Ni	YS	UTS	CVN
		%						MPa		J @ 0°C
UTP Nautica 20	E42 0 Z R 2 20 fr	0,1	0,3	0,55	0,5	-	-	420	500	38
UTP Nautica 100	E42 0 Z RA 2 100 fr	0,1	0,65	0,95	-	-	-	440	550	35
UTP Nautica Cut	n.a.	n.a.	-	-	-	-	-			
UTP Thermonautica	n.a.	<0,04	0,9	0,9	3,2	22,2	9,5	600	750	45

these applications, wet welding with stick electrodes is very suitable. Also underwater cutting of small parts or for making a hole, stick electrodes are much more economical as opposed to complicated underwater oxygen arc cutting. Since all these applications fall under certain regulations and approvals as GL or LR etc, the welding procedures and qualifications as well as the welder qualifications have to be carried out in accordance and under the supervision of theses Approval Institutes to comply with the regulations.

The Dutch Navy [6] qualified the Nautica 20 under LR for welding patches or lap-plates onto naval ship hulls, in case the material thickness has reduced due to corrosion or other damage. In order to qualify the "wet" welding procedures (WPQ) and the welders (WQ), fillet welds have been executed in plates of 10 mm thickness with Nautica 20. This took place in an indoor diving tank filled with 3%-salt water to simulate marine seawater conditions, as shown in Figure 9. (Courtesy of the Royal Dutch Navy – Diving Group). Part of the qualification welds were fillet welds that were produced in double lap-plates, prepared with on one side, full fillet welds made in the workshop. The other side was welded in the tank with a 3,2 mm electrode at about 150A in the vertical down position (PG). The test weld was a smaller size in order to test if the specimen would break in the weld or in the base material that was to be tested.

Figure 10 shows the double lap-plates with one side welded in the shop (left) and the other side welded underwater (right) show that the specimen all broke in the base material or on the side of the workshop welds. The result of the multi-pass fillet weld in vertical down position is shown in Figure 11. The bead appearance is very good, especially considering the lack of visibility for the welder. The cross-section of this weld in Figure 12, shows a positive penetration, which is one of the qualification requirements. This a proven by means of a break test that shows the amount of positive penetration per length of weld.

Fig. 9. Qualification of electrodes

To maintain the qualification, the welders have to requalify every three months to stay qualified for certified underwater welding onto naval vessels.

As practice makes perfect, training sessions in open water are organized for the entire underwater diving and welding team of the Dutch Navy. Figure 13 shows a diver-welder with insulating rubber gloves and getting ready, standing behind an underwater workbench with clamping device on a platform that can be lowered

Fig. 10. Double lap-plates with one side welded in the shop (left) and the other side welded underwater (right)

Fig. 11. The result of the multi-pass fillet weld in vertical down position

Fig. 12. The cross-section of this weld

into the water for practicing purposes.

These welders have also performed underwater cutting with Nautica Cut stick electrodes. Using 240 A, a 10 mm plate could easily be cut

Fig. 13. Diver-welder with insulating rubber gloves

up in many parts. The cutting length is up to 200mm with one electrode. The electrode size is 3,2 mm diameter and 450 mm long. The length of 450 mm makes it possible to distinguish between the repair electrodes Nautica 20 since they are 350 mm. The welder can easily carry both types to be prepared for all applications under water. To witness an actual underwater welding operation of the Dutch Navy Diving Group was an incredible experience and provided a good insight in underwater welding and cutting in practice.

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Standards & Guidelines

- BGV D1:2001: "Welding, Cutting and allied Processes", German Safety Guideline, Previously VBG 15. MMBG (Machinenbau- und Metall Berufsgenossenschaft)
- ISO 15618-1:2016: "Qualification testing of welders for underwater welding" - Part 1: Hyperbaric wet welding"
- ISO 15618-2:2002: "Qualification testing of welders for underwater welding" - Part 2: Diver-welders and welding operators for hyperbaric dry welding"
- DIN 2302:2018-03: "Welding consumables - Covered electrodes for manual metal arc welding of non-alloy and fine grain steels in a wet hyperbaric environment - Classification"
- AWS D3.6M:2017: "Underwater Welding Code - Specification for Underwater Welding and other Weld-related Activities"

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