

# Current Status and Prospects of Underwater Welding Technology for Key Sensitive Equipment in Nuclear Power Plants

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**Abstract.** This paper analyzes the application status of underwater welding technology in nuclear power plant welding repair. Take the local dry-method underwater welding 304 austenitic stainless steel butt weld as an example. It points out the gap between the mechanical properties and corrosion resistance of underwater welded joints and the welded joints in the air. In order to adapt to the underwater welding environment with high radioactivity and high risk environment in the future, the development of local dry underwater welding automation system will be the key to underwater welding repair of key sensitive components of nuclear power plants in the future.

## 1. Introduction

The design life of a nuclear power plant is generally 30 to 40 years. According to the existing engineering practice experience, for nuclear power plants with a running time of more than 10 years, the workload of welding maintenance is quite large, which can be compared with the welding workload of nuclear power plant construction and installation[1]. For a variety of reasons, equipment and components in nuclear reactors operating in high-radioactivity, high-temperature environments will be partially damaged after long-term operation. In order to ensure the safe and stable operation of nuclear power plants, these equipment and components must be inspected, repaired and replaced to ensure their integrity.

At present, the underwater welding carried out in in-service nuclear reactors and spent fuel pools is mainly based on manual welding by welders, and the above areas are extremely radioactive, and manual welding in high-radiation environments adversely affects the welder's health. In addition, because the welder has greater psychological pressure during the operation, the welding quality cannot be guaranteed. Therefore, the search for feasible underwater automatic welding technology has become an urgent problem to be solved.

## 2. Application Status of Underwater Welding Technology in Nuclear Power Plants

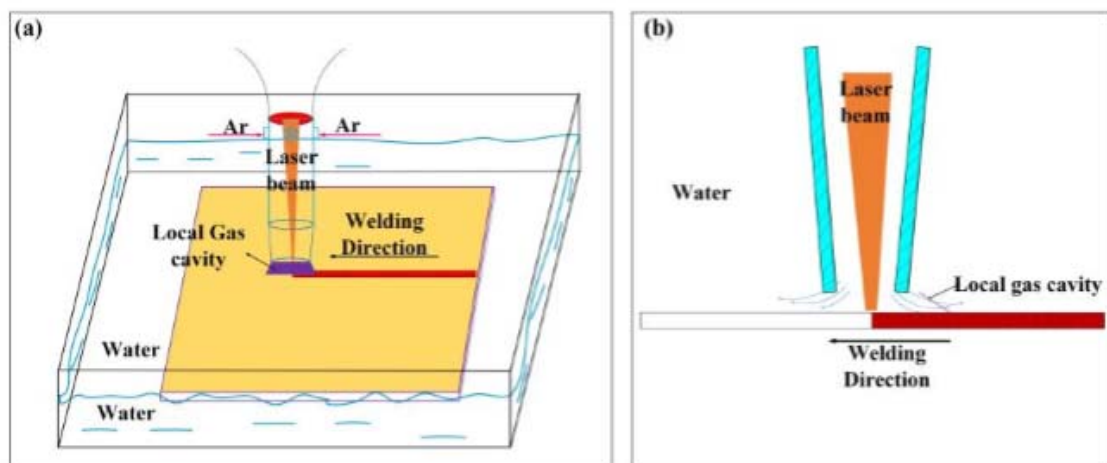
Underwater welding can be roughly divided into wet welding and dry welding from the working environment, wherein dry welding includes partial dry welding, high pressure dry welding, and atmospheric dry welding. Local dry underwater welding mainly includes underwater arc local dry welding and underwater laser local dry welding[2].

Underwater arc local dry welding, the area to be welded is separated from the water to create a smaller gas phase zone for welding. Compared with wet welding, the welding quality is easier to guarantee. Compared to dry welding, the cost is lower and more flexible. However, in practical applications, the following drawbacks also exist: Due to the use of arc technology and diver operation,



the arc will contract under high pressure[3], so the water depth has an important influence on the quality of the arc welding and the depth of the person's dive, and the remote operation is not high.

The basic principle of underwater laser local dry welding is to pass high pressure gas into the glass hood, and drain the small area around the part to be welded to form a partial drying space to prevent water from contacting the surface of the workpiece to be welded. Form a good gas atmosphere. At the same time, the laser beam is transmitted to the vicinity of the component to be welded through the optical fiber. The laser beam passes through the local gas phase region and acts on the surface of the component to be welded. The workpiece to be welded absorbs the energy of the laser beam and melts, thereby achieving welding. The principle of the device is shown in Fig. 1[4].



**Figure 1.** Schematic diagram of partial dry underwater laser welding

Compared with the arc welding method, the laser beam of the laser welding can be transmitted over long distances through the optical fiber, and the control precision is high, and it is suitable for welding and repairing the position where the welding precision is high; Laser welding has a low heat input and a fast cooling rate, so the heat affected zone of the weld is small and the residual stress level is low; The laser welding system is easy to simplify and integrate, especially for equipment maintenance where the working position is small. The local dry underwater laser welding technology combines the advantages of local dry method and laser welding, and with the continuous development of welding automation and intelligence. This technology is increasingly becoming one of the preferred technologies for remote repair of nuclear power plants, especially in the maintenance of critical sensitive equipment for reactors[2].

In foreign countries, Hitachi developed a curtain laser torch in 2001 to achieve a stable underwater dry space. The U-shaped groove underwater laser downward and horizontal transverse welding test under the pressure of 0.3MPa was carried out by means of 4KW laser and filler wire. In 2004, Japan Ishikawa Chemical Co., Ltd. carried out remote-controlled underwater laser welding operations inside the radioactive container of a nuclear power plant. The underwater laser welding system developed by Toshiba Company formed a localized dry space of laser welding by argon gas drainage, successfully welded the flat test piece, and simulated the inner circumference of the round pipe to obtain a good all-position laser welding layer. In 2009, Westinghouse Electric Company and the American Electric Power Research Institute collaborated to use underwater laser welding technology to automatic welding repair of underwater simulated cracks[5].

In China, some researchers have used the method of wire-filled thermal welding to study the influencing factors of underwater laser welding quality under the protection of local dry cavity. It was found that the gas nozzle can be used to form a local dry space, and the parameters such as the nozzle structure and the gas flow rate can be adjusted to obtain a good underwater weld quality[5].

### 3. Local Dry Underwater Laser Welding Joint Performance

304 austenitic stainless steel is one of the main materials for nuclear power plant application. This paper takes 304 austenitic stainless steel as an example to explore the feasibility of local dry underwater laser welding. The 304 austenitic stainless steel has a thickness of 4 mm and the chemical composition of the material is shown in Table 1[4].

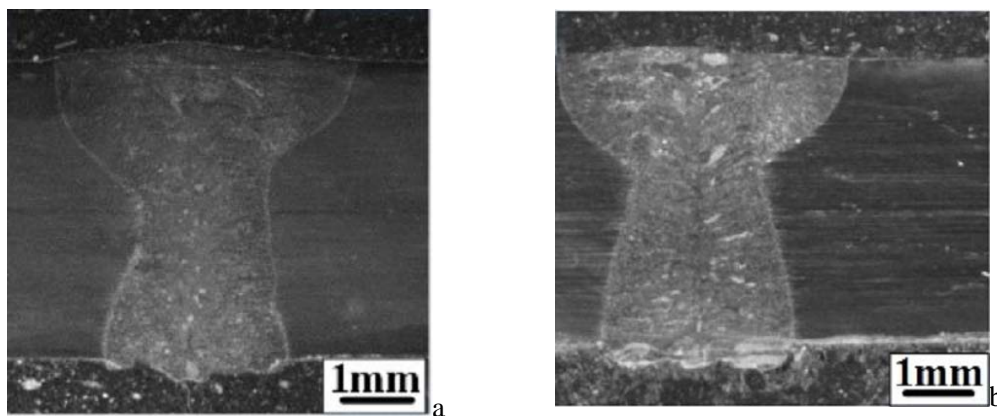
**Table 1.** Chemical composition of 304 (unit: mass percentage)

C	Si	Mn	P	S	Cr	Ni	Cu	N	Fe
0.04	0.33	1.16	0.034	0.002	18.03	8.01	0.1023	0.0386	Bal.

The underwater laser welding parameters are shown in Table 2. For comparison, the welding parameters are shown in Table 2. The gas flow referred to herein is the gas flow rate at each inlet. The weld profiles after underwater welding and air welding are X-shaped, as shown in Figure 2.

**Table 2.** Underwater and in-air welding parameters

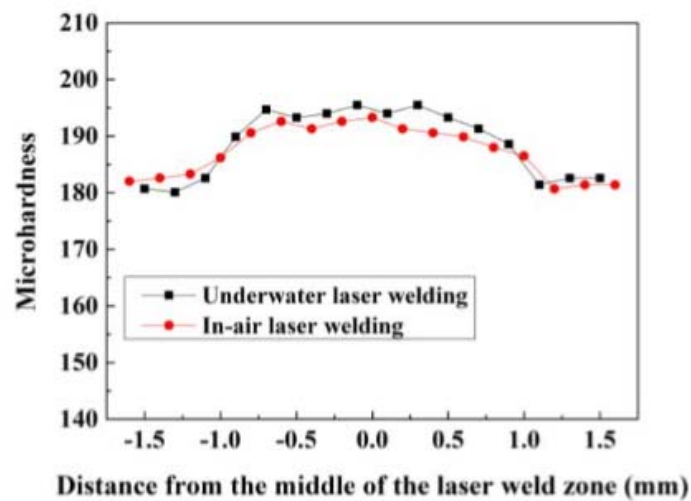
Welding method	Laser Power P (W)	Welding Speed v (mm/s)	Defocusing Dis-tance D (mm)	Gas Flow Rate F (L/min)
Underwater	1400	8	0	25
In-air	1100	8	0	15



**Figure 2.** Weld section, a-underwater welding, b-air welding

#### 3.1. Weld Hardness

Micro-hardness testing of underwater laser penetration welds and laser penetration welds in air, the hardness is located at the waist of the X-weld. The microhardness distribution is shown in Figure 3.



**Figure 3.** Weld microhardness distribution

The average microhardness of the base metal was 181 HV. The average microhardness of the underwater laser weld is 193 HV, and the average microhardness of the air laser weld is 190 HV. The microhardness of the underwater laser weld is slightly higher than the microhardness of the air laser weld. The main reasons are as follows: after the laser is attenuated by the aerosol with water vapor, the energy is irradiated to the plate member less than that of the air laser, and the cooling speed of the underwater welding is fast. The grain of the weld is fine, and the smaller the grain size, the greater the hardness value; In addition, the rapid cooling rate leads to the uncomplete transformation of ferrite into austenite structure. The residual ferrite content in the underwater laser weld increases, and a small amount of ferrite in the weld acts as a second phase strengthening effect on the weld.

### 3.2. Tensile Test

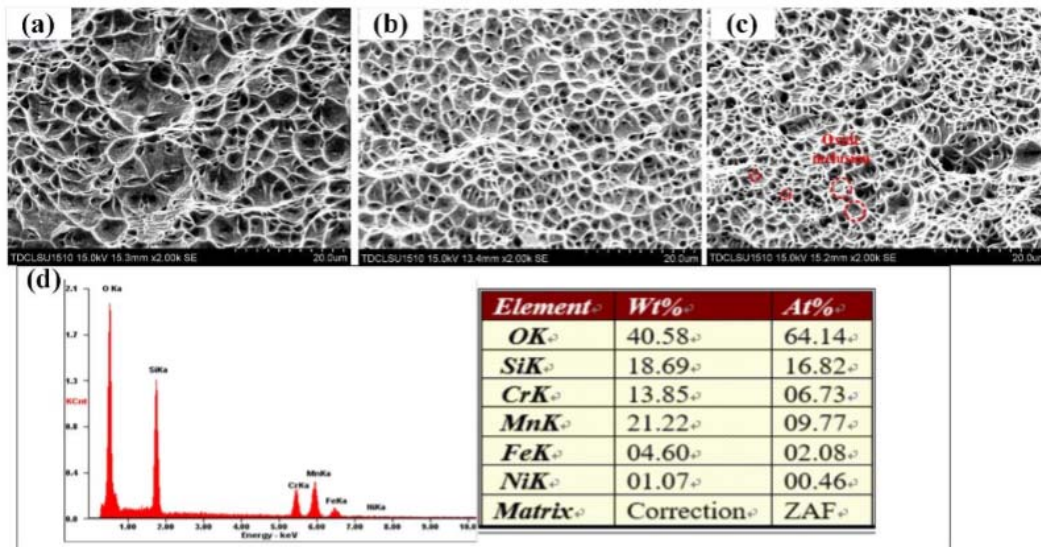
The transverse tensile test was carried out on the underwater weld and the air laser weld. The test results showed that the test pieces were broken at the weld. The specific results are shown in Table 3. The data listed in the table are the average of the three samples.

**Table 3.** Transverse tensile mechanical properties

Sample	Tensile strength (MPa)	Elongation (%)
Base metal	626	53.4
Air laser welding	613	43.3
Underwater laser welding	559	38.3

The tensile strength and elongation of underwater laser welds are reduced compared with air laser welds, which are 91.2% and 88.5% in air, respectively. This is because in the case of water immersion on the back side of the weld, the bottom weld metal is poorly formed, the alloying elements are oxidized, and at the same time, metallurgical pores are generated in the underwater laser weld, which provides a possibility for crack initiation during the stretching process.

Figure 4 shows the fracture scan of the base material, the laser weld under air, and the underwater laser weld.

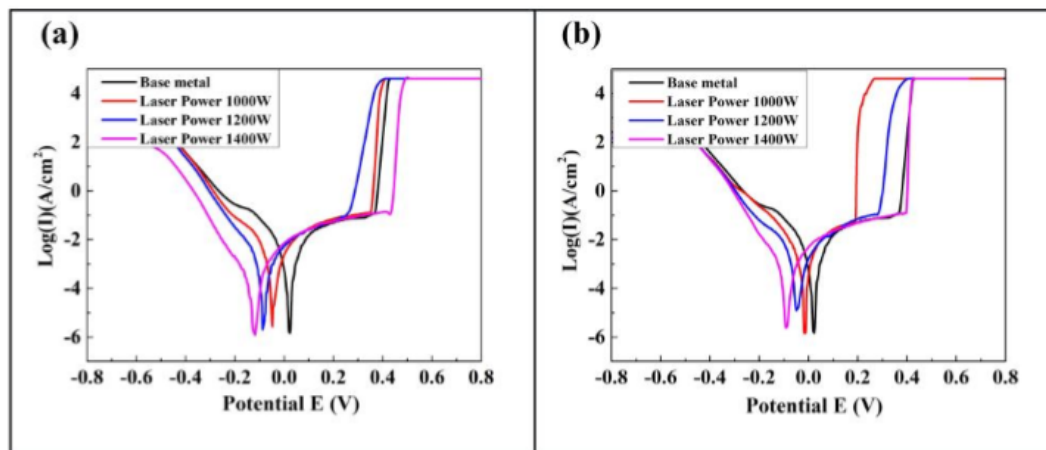


**Figure 4.** Typical fracture morphology: (a) base metal; (b) weld under air medium; (c) weld under water medium; (d) scanning of inclusions in underwater welds

From Fig. 4, it can be seen that the fracture of base metal, air laser welding seam and underwater laser welding seam are dimple-like, both of them are ductile fracture. The base material fracture has a large and deep dimple shape, and the weld fracture in the air presents a relatively uniform equiaxed dimple shape. The underwater weld fracture has dimples of different sizes and the overall size is small. As shown in Fig. 4 (d), there are obvious inclusions in the dimples of underwater welds, but not in figs. 4 (a) and (b). The main oxide inclusions of Si, Mn and Cr are determined by EDS. These inclusions are related to the back seam immersion during underwater welding. Oxygen element enters the weld and oxidizes the alloy element to form oxide inclusion, which makes the performance of the weld worse. In addition, the existence of pore can also be seen on the fracture surface of underwater weld. The pore of underwater laser welding reduces the effective bearing area of the weld and reduces its carrying capacity.

### 3.3. Corrosion Resistance of Underwater Laser Weld

Figure 5 shows the Tafel electrochemical polarization curves of underwater laser welding and air laser welding welds.

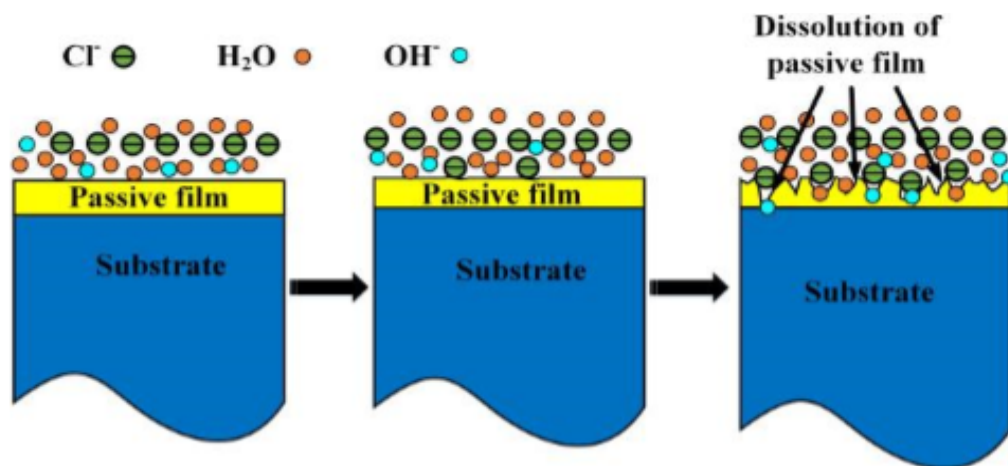


**Figure 5.** Tafel electrochemical polarization curve: (a) underwater laser weld; (b) in-air laser weld



In order to ensure the reliability of the test data, underwater welding samples and air welding samples of 1000W and 1200W laser power welding were added. The corrosion potential of underwater laser weld is -0.049 V, -0.087 V, -0.118 V when the laser power is 1000 W, 1200 W and 1400 W. The corrosion potential of laser weld in air is -0.015 V, -0.05 V, -0.092 V when laser power is 1000 W, 1200 W and 1400 W. The corrosion potential of the base metal is 0.023 V. It can be seen that the corrosion potential of the weld structure is lower than that of the base metal, indicating that the corrosion resistance of the weld is lower than that of the base metal. Under the same laser power, the corrosion potential of underwater laser welding is lower than that of air laser welding, and the corrosion resistance of underwater laser welding is lower than that of air laser welding. In addition, with the increase of laser power, the corrosion potential of underwater and air laser welds decreases, that is, with the increase of heat input, the corrosion resistance of welds decreases.

The reasons for the above phenomena are related to the process of electrochemical corrosion and the microstructure of the matrix. Pitting corrosion is the main corrosion form of austenitic stainless steel and its weld under electrochemical corrosion[6]. Under the action of Cr element in austenitic stainless steel and weld, a passivation film will be formed on the surface of metal, which can effectively block the metal matrix from the medium. Once the passivation film is destroyed or weak, the metal matrix contacts with the medium, and corrosion will occur, especially the corrosive ion ( $\text{Cl}^-$ ) will accelerate the corrosion process. There are three main effects of  $\text{Cl}^-$  on passivation film in  $\text{Cl}^-$  medium, namely adsorption, penetration and local passivation film destruction.  $\text{Cl}^-$  and hydroxyl groups compete to adsorb on the surface of passive film. While  $\text{Cl}^-$  and dissolved metal cations combine to form soluble chloride, which have low lattice binding energy, low activation energy for migration, and accelerate the passivation film. Dissolved,  $\text{Cl}^-$  is further adsorbed on the surface of weak areas, causing increased corrosion [7,8]. When the electric field at the interface between solution and film is very strong,  $\text{Cl}^-$  adsorbed on the passive film will soak and pollute the passive film, and enter into the metal matrix to dissolve the metal. This  $\text{Cl}^-$ -contaminated passivation film is more conductive than the original passivation film, speeding up the transport speed and transfer speed of the particles. The metal ions continuously diffuse from the interface between the metal and the passivation film to the interface between the passivation film and the solution, which may cause vacancies on the interface between the passivation film and the metal. When the size of the vacancy reaches a certain level, the passivation film will be cracked. When the passivation film is damaged locally,  $\text{Cl}^-$  causes the dissolution rate of the exposed matrix metal to be greater than that of its re-passivation, which leads to the corrosion of the matrix. Summarize the process of electrochemical corrosion of the matrix containing  $\text{Cl}^-$  media as shown in Figure 6.



**Figure 6.** Schematic of matrix electrochemical corrosion in  $\text{Cl}^-$  medium

In summary, after analyzing the hardness, tensile strength, elongation, fracture scanning electron microscopy and corrosion resistance of the local dry underwater laser welded joints, it is found that the

performance of underwater laser welded joints is still far from that of air welded joints. Mainly due to the water immersion in the back weld, oxygen enters the weld and oxidizes the alloying elements to form oxide inclusions, which deteriorates the mechanical properties and corrosion resistance of the weld. Zunyue Huang[4] of Tianjin University and others used the method of applying activator on the back to prevent the back seam from being immersed in water, and the effect was good.

#### **4. Development Trend of Underwater Welding Automatic Welding Technology in Nuclear Power Station**

At present, the local dry-based underwater welding technology is one of the main methods for underwater welding of nuclear reactors and spent fuel pool components. However, this method still has the limitations of necessary welder diving repair. Therefore, the development of high-radiation working environment welding robots for nuclear reactors and spent fuel pools, using robots instead of manual operations in high-risk areas, is the future development trend of underwater welding technology.

The Key Laboratory of Underwater Robotics of Harbin Engineering University has developed a six-degree-of-freedom isomorphic master-slave underwater manipulator for underwater operation of nuclear power plant reactors and spent fuel pools[9]. Furthermore, through the hydrodynamic modeling of the underwater manipulator, a set of master-slave nonlinear fuzzy PID closed-loop control scheme was designed according to the working environment conditions, and the reliability of the control system was verified by setting up the experimental platform. This research provides a new idea and possibility for the next step to realize the local dry underwater welding robot.

#### **5. Conclusion**

At present, although there are still many problems in the performance of underwater welded joints, with the accumulation of underwater welding experience and the systematic cooperation of various scientific research institutions[10], the quality of joints will eventually break through. On this basis, the development of local dry underwater welding automation system will be the key to underwater welding repair of key sensitive components of nuclear power plants in the future.

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