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# Analysis of the Application of Laser Welding Technology on Maintenance of the Underwater Components of Nuclear Power Station

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**Abstract.** This paper put its eyes on the PWR's underwater components which have the risk of early failure after long-term inservice because the material tends to deteriorate and embrittle due to irradiation and other factors, and should be maintenanced. In this paper, we contrastively analyse two main technologies used as underwater welding, named underwater wet laser welding and underwater local dry laser welding. It is difficult to obtain high quality weld seam by underwater wet laser welding for the reason of some disadvantages on laser beam underwater, such as water attenuation, bubble reflection and so on. On constract, underwater local dry laser-welding can obtain high quality weld-joints, and becomes the current hotshot. But, there are still some problems to be settled, such as the way to obtain stable underwater chamber and the protection of back of full penetration weld. Analysis of the retrieva of underwater laser welding on Web Science, we can find that underwater laser welding technology has step out laboratory to engineering application and the in-depth theoretical research is also actively carried out on the fields of picosecond, femtosecond laser.

## 1. Introduction

Because nuclear power has the both advantages of stable power supply and non-fossil fuel power (Ref.1), it is an indispensable way to replace the fossil power generation in China. As can be seen in Figure 1, the numbers of nuclear power station in China has entered a rapid development period since 2009, and the steps of annual growth becomes faster and faster. By the end of 2018, the installed capacity of nuclear power generation had already reached 295 billion kWh in China, which increased 18.9% more than that of previous year( Ref.2). Although China has the largest number and capacity of nuclear power including the inserve units and the under-construction units in the world, the proportion of nuclear power generation in the whole Chinese power generation is only 3.8% according to the 2017 year statistics of China which is far lower than that in the United States, France and Russia (Ref.3). So, the nuclear power construction is still rapidly developing in China. At the same time, the safety of nuclear power generation has attracted more and more public attention, and has become one of the key influnce on the development of nuclear power (Ref.4). Both the "neighborhood avoidance phenomenon"(Ref.5) and the "anti-neighborhood avoidance phenomenon"(Ref.6-7) are two completely opposite attitudes towards the nearby nuclear power facilities, which are due to the counterbalance of the economic benefits brought by nuclear power equipment and the security risks caused by nuclear power equipment. Therefore, it is significantly important for enhancing the experiencement of nuclear power profits, improving the confidence of nuclear power, and reducing anxious feeling of nuclear power risk to ensure the nuclear equipment safties and prevent the nuclear accidents (Ref.8-9).

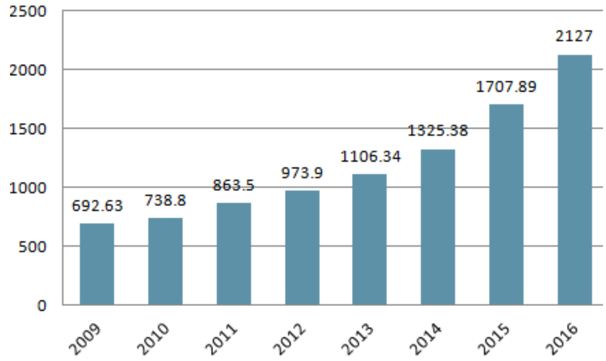


**Figure 1.** Statistics of Chinese nuclear power output from 2009 to 2017.2

The core structures of reactor pressure vessel are one of the most sensitive underwater equipment of pressurized water reactor nuclear power plant (Abb. PWR). The technology of maintaining these components is of great significance for PWR to win the safety awareness and support of public. So, this paper analyses the prospect of application an advanced technology which name is underwater laser welding on the maintenance of PWR's underwater components.

## 2. Maintenance Characteristics of PWR's Underwater Components

Boron-containing water is used as coolant and moderator in the primary loop system, spent fuel pool and auxiliary system of PWR nuclear power plant. As the results of irradiation, the materials of the components, such as core structures of reactor pressure vessel and fuel assemblies and so on, would easily come into intergranular stress corrosion cracking at the reason of hardening, swelling, and grain boundary Cr dilution due to dislocation rings and vacancies occurred in materials (Reference10) on the one hand; on the other hand, irradiation can also decompose water into H2O2 and O2, which increase the water electrode potential and promote stress corrosion cracking. The failure of connecting bolts between fencing plate and forming plate has been found on CP0 of French power plant (Reference 11). Therefore, the underwater components will cause to early failure leading by the material degradation under high temperature, high pressure and high irradiation environment of nuclear power plants.

In addition to the characteristics of high irradiation, the underwater components maintenance of nuclear power plants also has the characteristics of high quality requirements, small operating space and high cleanliness requirements. The traditional underwater arc welding technology, such as MIG/MAG and TIG welding technology, has a large space demands for complex operation of equipment. It is also difficult to avoid the generation of impurity particles such as welding slag during operation Moreover, the welding quality is hard to guarantee the weld quality to reach the qurequirements of nuclear power plants due to the negative influence of water cooling. In 1983, at the International Conference on the Application of Lasers and Optical Devices, Sepold and Teske proposed underwater laser welding technology and verified its feasibility by surfacing on the underwater carbon steel plate. From that time, a lot of researches have been carried out on underwater laser welding in developed countries. Among them, the United States and Japan are in the leading position, and have reached the practical stage of engineering maintenance. In recent years, underwater laser welding technology being used to the nuclear components maintenance become hotspot and tendency in this field (Reference13-15).

## 3. Analysis of the Underwater Laser Welding Characteristics

The laser is released in the duration of the transition to higher level when the electron absorbs energy and the drop back to lower level after the electron releases photons. Laser has the characteristics of high energy density, good monochrome, high brightness and good directivity, and is widely used in medical, national defense, communications, industry and other fields. At present, solid state lasers (such as Na: YAG lasers), gas lasers (such as CO2 lasers) and semiconductor lasers are the main lasers used for metal cutting and welding.

The weld-purpose laser can be divided into continuous or pulsed laser beams. Corresponding welding principles can also be divided into conduction and keyhole deep penetration. At present, laser welding generally refers to pulse laser beam keyhole deep penetration welding, which has the characteristics of fast welding speed, deep penetration/wide penetration.

### *3.1. Characteristics of Laser Transmission in Liquid Medium*

Laser transfers in both air and water in the form of plasma shock wave. Because the density of water is higher and the compressibility ratio is smaller than air, it is easier to observe the plasma and shock wave formed by laser transmission in water medium. Figure 2 (Reference16) displays the asymmetric laser plasma and ellipsoidal shock wave surface. We can see that the asymmetry of plasma and shock wave surface increases further following with the increase of pulse width.

There are two main mechanisms in the theory of laser underwater plasma formation, namely avalanche ionization mechanism and multiphoton ionization mechanism (Reference17-18). Free electrons collide with atoms or molecules in a strong magnetic field to absorb energy. When the inverse bremsstrahlung effect results in more than ionization energy, a new electron will be generated. When this process occurs in tandem, avalanche ionization will be formed.

In reference 19, an analytical expression of laser breakdown threshold in pure water is derived from the evolution of free electron density equation. Compared with the experimental data, it is found that avalanche ionization is dominant in nanosecond laser in water and is in good agreement with the calculated results, while multiphoton ionization is dominant in femtosecond laser, which is quite different from the calculated data (Reference19). Therefore, avalanche ionization is the main mode of laser propagation in water.

The plasma threshold formed by laser breakdown of water is closely related to the characteristics of liquid and laser. The higher the initial electron density in water is, the lower the plasma breakdown threshold is. In PWR nuclear power plants, water solution containing large amounts of initial electrons, which are not only boric acid and other substances used as moderator but also the H + and OH- particles after waterare irradiated (Reference20). So, the initial electron density in water medium is very high, which can conducive to the formation of plasma.

Ref.21 studies the experiment of laser plasma shock wave in liquid, and establishes an equivalent rotating ellipsoid wavefront propagation model of attenuated laser plasma shock wave in liquid. The results show that the power density of laser pulse and the transmission velocity of acoustic wave in medium have great influence on the initial maximum Mach number of attenuated shock wave front, which is the main factor affecting the attenuation of laser shock wave in liquid (Reference21).

From the above analysis, it can be concluded that the shape of plasma and shock wave surface formed by laser transmission under water has an important influence on the attenuation of laser beam.

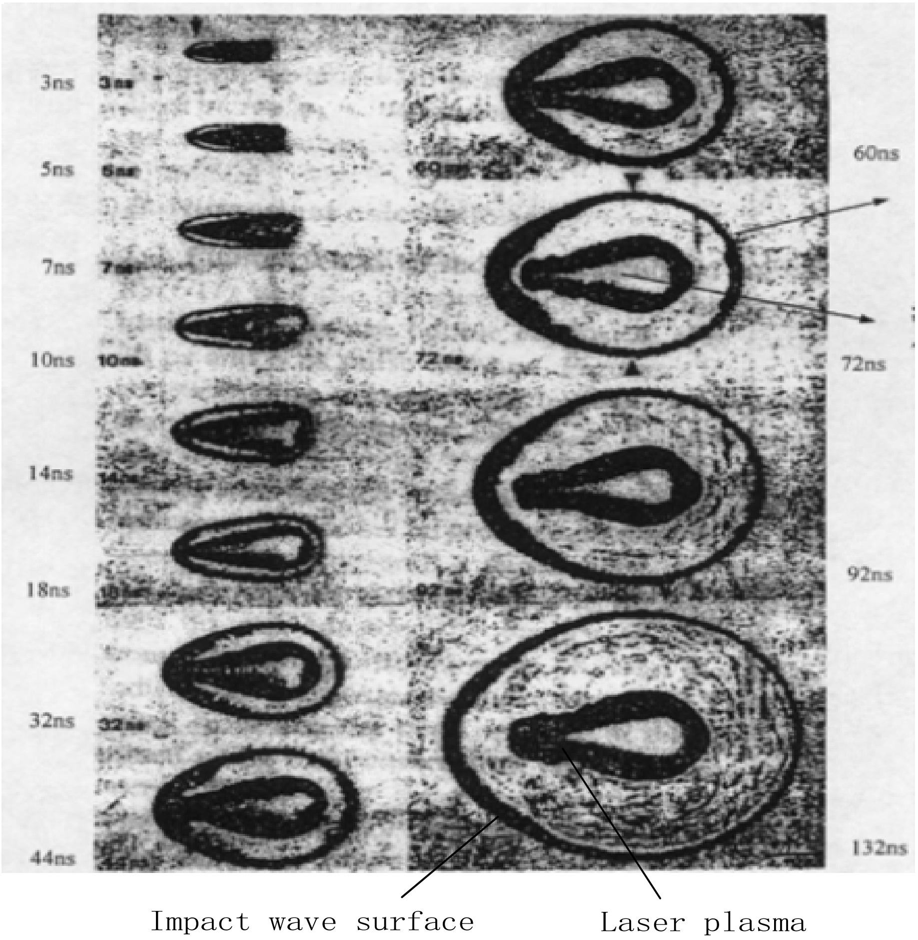


**Figure 2.** Diagrams of serial lasers underwater (Reference16)

### *3.2. Analysis of Underwater Laser Welding Technology*

Underwater laser welding can be divided into underwater wet method and underwater partial dry method. Underwater wet laser-welding has not only the superiority of simple equipment and flexible operation, but also the inferior of weld defects tendency, such as shallow penetration and gas holes on the surface of weld seam. Underwater partial dry laser-welding can get higher quality welds which benefits from the local chamber, but is also limited to be only used in large operation environment by the complex equipment.

#### *3.2.1. Underwater wet laser-welding*

The underwater wet laser welding means the laser beam passes through the water directly, and lights on the surface of workpiece. The process can be divided into three stages: laser transmit during the water medium; explosive boiling occures near the workpiece surface (Reference22); laser passes through a small local chamber builded by vapour from the surface water film caused by the high temperature weld-pool (Reference23). The duration is displayed in Figure 3.

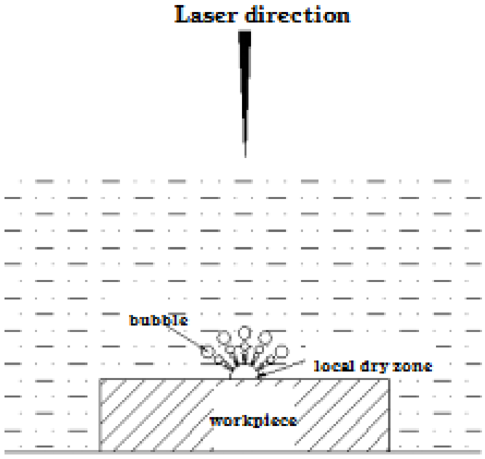


**Figure 3.** Illustration of the underwater wet laser welding

*3.2.2. Underwater local dry laser-welding*

Underwater local dry laser-welding is to transmit laser beam to the workpieces in a local dry chamber builded by some high pressure gas to discharge water, as shown in Figure 4.

There are three key problems to be solved for underwater local dry laser-welding: (1) scattering and absorption effect on laser beam from the aeroso in chamber; (2) disturbance of laser beam caused by protective airflow; (3) influence of water medium on the quality of back weld.

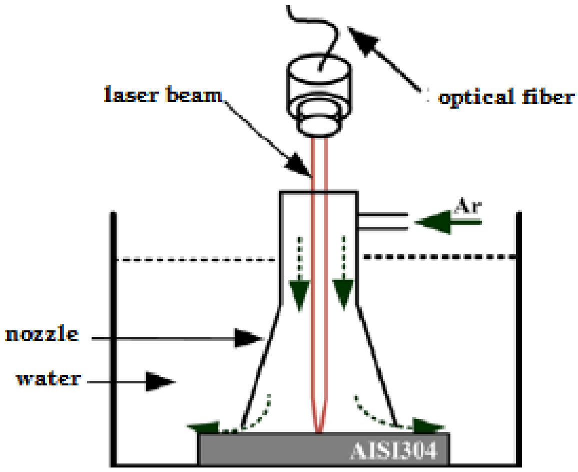


**Figure 4.** Illustration of the underwater local-dry laser welding

*3.2.3. Contrastive analysis of underwater laser welding technology*

*1)Analysis of underwater wet laser-welding*

Firstly, the laser beam is attenuated during the transmission in the forms of plasma ionization and shock wave through water, and the mechanism have been described in the previous section. Subsequently, the beam encounters a large number of bubbles generated by the boiling phenomenon on the surface of the workpiece. These bubbles will reflect and refract the laser beam, that will affect the shape of the spot irregularity and the expansion of the spot (Reference 23). At the same time, the liquid surface disturbance driven by bubbles will cause beam reflection. When the dip angle of the interface exceeds 30 degrees, the laser beam will be reflected enough to greatly reduce the laser quality (Reference24). Finally, after reaching the local chamber, the process is similar to that of the local dry chamber, but the beam intensity will be further attenuated due to the reflection, refraction and absorption of the aerosol in the chamber.

In addition to the above attenuation of laser beam, the water around the weld-pool will not only cool the molten metal rapidly, but also decompose into hydrogen and oxygen when the water is heated to enough temperature. The result of rapidly cooling of the weld-pool will cause the hardness increasing of the weld and heat affected zone, and lead to develop hardened microstructure in some cases. The hydrogen and oxygen will cause defects such as gas holes, oxidation and poor appearance on the weld surface, and increase the content of H and O in the weld metal (Reference 24-25).

*2)Underwater local dry laser-welding*

The aerosols in local chamber will scatter and absorb laser beams, then attenuate the beam intensity. The attenuation can be expressed by Bill's law, see Formula 1. The scattering effects of aerosols on beams can be described as two types of Raleigh scattering and Mie scattering. Raleigh scattering is suitable for aerosols whose size is smaller than the beam wavelength, see Formula 2. Mie scattering is suitable for aerosols whose size is idential or greater than the wavelength, see Formula 3. The two scattering modes are related to the laser wavelength and the number of aerosols, i. e. the dryness in the air chamber.

$$\mathrm{I} = \mathrm{I}_0 e^{-\mu(\lambda) l} \tag{1}$$

In the formula: $I/I_0$ is the transmittance. $\mu(\lambda)$ is the absorption coefficient related to wavelength lambda. L is the optical path.

$$\gamma_{\mathrm{p}}(\lambda) = \frac{8\pi^3 (n^2 - 1)^2}{3N\lambda^4} \times \frac{6 + 3\delta}{6 - 7\delta} \tag{2}$$

In the formula, $\gamma_p(\lambda)$ is the scattering coefficient. $\lambda$ is the laser wavelength. N is the number of particles. n is the refractive index of particles. $\delta$ is the radius tolerance of particles.

$$\mathrm{I}(\theta) = \frac{\lambda^2}{4\pi^2 \gamma^2} (i_2 \sin^2 \psi + i_2 \cos^2 \psi) I_0 \tag{3}$$

In the formula, $\lambda$ is the wavelength of laser. $\gamma$ is the scattering coefficient. N is the number of particles. n is the refractive index of particles. $\Psi$ is the angle between the vibration surface of incident light and the scattering surface. $\theta$ is the scattering angle.

Protecting gas flow rate has a great influence on the local chamber stability. If the flow rate of protective gas is small, water would enter into the protective zone and be turned into a large amount of vapor aerosol by the weld-pool. The number of aerosols scattering the laser beam increase to enough amount to make it is impossible to form stable metal plumes in severe cases (Reference 26). If the protective effect is poor, the elongation and section shrinkage of the weld metal would decrease greatly because of the oxygen content increases in the weld (Reference 27).

As respect to the full-penetration weld, the back weld quality is hard to guaranteed because of the lack of effective protection, which would cause defects as poor formation of welds, large numbers of metallurgical cavities and so on. Reference 26 has developed a flux for underwater backside protection (Reference 26), and achieves good results. This testifies that the use of welding protector is one of the effective ways to solve the back seam protection of underwater full-penetration laser welding. It is noteworthy that the flux on the back will produce particles such as slag. As reason of the strictly requirement of cleanliness in the reactor pressure vessel, it is necessary to evaluate the influence of these particles in PWR.

Reference 28 carried out the underwater laser-welding of Q235 steel, obtained well shaped weld, and observed the ferrite, acicular lower bainite and widmanstatten with large morphological differences in the weld and heat affected zone after metallography on the seam, which is caused by rapid cooling of surrounding water (Reference 28). Reference 25 and 29 both carried out the underwater local dry laser welding of 304 stainless steel, and obtained high quality welds with clear and uniform weld ripple and good penetration (Reference 25,29).

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Based on the above comparative analysis, the underwater local dry laser-welding technology can obtain high quality weld-joints, but its operation space is limited because of the complex equipment. The underwater wet laser-welding technology still has long way to solve the problem of laser attenuation in water medium, which is not mature at present.

## 4. Tendency Analysis of Underwater Laser Welding Technology

Web of Science is a WEB-based product developed by ISI Company in the United States, including three citation libraries (SCI, SSCI and A&HCI) and two chemical databases (CCR, IC), covering 22,000 + journals, 3,100 million patents, 60,000 conference records, 5500 professional websites, 5,000 academic monographs and 2 million chemical structures. This paper uses underwater laser welding as a guide word to search on Web of Science. The results show that there are 303 records, the top ten of which are listed in Table 1.

**Table 1.** Statistics on research direction

| Number | Contents | Records | %/303 |
|---|---|---|---|
| 1 | ENGINEERING | 271 | 89.44% |
| 2 | MATERIALS SCIENCE | 172 | 56.77% |
| 3 | INSTRUMENTS INSTRUMENTATION | 128 | 42.24% |
| 4 | METALLURGICAL ENGINEERING | 105 | 34.65% |
| 5 | OPTICS | 86 | 28.38% |
| 6 | CHEMISTRY | 80 | 26.40% |
| 7 | PHYSICS | 69 | 22.77% |
| 8 | COMPUTER SCIENCE | 39 | 12.87% |
| 9 | BUSINESS ECONOMICS | 33 | 10.89% |
| 10 | MATHEMATICS | 30 | 9.90% |

The following conclusions can be drawn from the data in the above table:

- Underwater laser welding technology is developing continuously to the level of Engineering application. This can be confirmed by the high proportion of engineering and equipment research in total records, which is 89.44% and 42.24% respectively. It is noteworthy that the records of economic analysis of underwater laser welding have 10.89% proportion, which means that the underwater laser-welding technology has been developed from experiment to application.
- Material R&D and welding metallurgy have high accounted for 56.77% and 34.65% in the whole records respectively, which means they are one of the current research hotspots. When the underwater laser welding technology is applied in different fields and different components, the material and requirements of welding quality for maintenance are different. Then, the high proportion of these two indexes also indicates that the technology has aimed at being applied in muti-fields..
- Five of the top ten items are related to theory basic research, they are optics, chemistry, physics, computer science and mathematics. While the proportion of engineering applications is in the dominant position, there is still such a high proportion of basic research. This indicates that the research of underwater laser welding technology is developing forwards to deeper stage. Because the water medium has a great attenuation of long-pulse-width lasers (Reference 19), the application of underwater laser technology is likely to be oriented to the study of ultra-short lasers, such as picoseconds, femtoseconds, etc. (Reference 31-32).

Based on the above analysis, underwater laser welding technology has developed to a relatively mature stage, and its related research directions are focus on engineering application, instrumentation, welding metallurgy, material science and economic analysis. At the same time, deeper theoretical research is also actively carried out, and the main research directions are optics, chemistry, physics, computer science and mathematics.

## 5. Conclusions

The PWR's underwater components have early failure risk in the influence of operational environment. Laser welding technology has the characteristics of deep penetration, high quality and pollution-free, which meet the requirements of PWR's underwater parts maintenance.

- Local dry underwater laser-welding can obtain high quality weld-joints, but there are two problems to be dealed: one is that the facilities of local chamber may limit its application in shallow spaces; the other is that although the problem of back weld could be solved by means of welding flux, but the slag formed may be the risk of nuclear power plants.
- The research of underwater wet laser-welding has enabled people to have a deep understanding of the characteristics of laser transmission in water. However, due to the attenuation of the laser-beam in water, it is impossible to obtain high quality weld-joints. So, the engineering application has not been realized at present.
- According to the results of retrieving the subject of underwater laser welding research on Web of Science, we can find that underwater laser welding technology has developed from experiment to engineering application, and the research of related technology has become a hotspots at this stage. At the same time, the direction of further theoretical research is probably about ultra-short pulse width laser, such as picosecond and femtosecond laser.

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