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A Short Review on the Mechanical and Thermal Processes for Underwater Cutting of Metal Structures

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금속 구조물의 수중 절단을 위한 기계적 열적 공정의 특징 분석

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ABSTRACT

Underwater cutting has a different mechanism than dry cutting, and there are more restrictions than benefits. Due to these constraints, research and development of underwater cutting has been very limited. At present, reactor dismantling is emerging as an important task worldwide, and reactor pressure containers, a key part of the reactor, are decommissioned based on underwater cutting. Reactor pressure containers are high-level radioactive waste, which is one of the main goals of today, such as to bridge the gap between environmental, safety, and cutting performance; hence, a process suitable for cutting should be applied. Therefore, many studies are being conducted on underwater cutting in connection with the dismantling of nuclear reactors in various areas in order to find appropriate processes. This paper first introduces the core technology of underwater cutting processes and discusses various processes. The emphasis is then placed on the adequacy of the reactor dismantling application. More specifically, we examine the suitability for the mechanical and thermal cutting processes, respectively, to find a solution suitable for dismantling a reactor. We discuss how each solution can sufficiently perform the specified functions at each stage of reactor dismantling and suggest that these processes can perform all of the work of underwater cutting.

Key Words : Underwater Cutting(수중 절단), Reactor Dismantling(원자로 해체), Radioactive Waste Management(방사성폐기물 관리), Metal Cutting(금속 절단)

1. Introduction

The underwater cutting process is required to manufacture or dismantle metal structures in various fields, such as offshore plants, ships, and reactors. Unlike dry cutting, there are many additional characteristics to consider when performing underwater cutting. The benefits of underwater cutting include reduced dust, a reduced radiation effect, lower reaction force, reduced waste gas, and reduced aerosols. By contrast, factors that hinder

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cutting include water viscosity resistance, electrical conduction, water turbulence, light scattering, and bubble generation. When cutting radioactive wastes, additional secondary by-products can be generated, such as large amounts of wastewater, aerosols, fumes, and waste gases contaminated with radioactivity. Therefore, for the efficient performance of the underwater cutting process, the above-mentioned characteristics must be considered [1-11]. In this study, underwater cutting processes developed recently are largely classified into mechanical and thermal cutting to describe their characteristics and analyze various factors to be considered in the actual process. In addition, guidelines for the development direction of the underwater cutting process are presented.

2. Mechanical Cutting Method

The process of cutting using physical force without heating was classified as mechanical cutting. This method has the advantage that cutting is possible without a phase change of the target material, but there is a design difficulty because a large reaction force is applied. Furthermore, the working space has a limitation, and the amount of radioactive aerosols generated when cutting a radioactive material using a mechanical cutting tool is approximately 10 times larger than that of the thermal cutting process[2].

2.1 Abrasive Waterjet

The waterjet process was originally developed for cutting rubber but is now applicable to almost any material and has high precision. Cold working prevents the deformation of materials caused by heat and the cutting of heat-sensitive materials and the heat treatment of high-carbon and high-alloy steels. It is environmentally friendly because slag and debris are not generated to avoid aerosols and no oil or gas is required during processing. Furthermore, non-contact cutting allows a variety of shapes to be cut. However, one disadvantage of the waterjet process is that the efficiency decreases rapidly as a large amount of secondary waste is generated and the water depth increases. When applied to the dismantling of a nuclear reactor, it has the advantage of avoiding water shielding against radiation and aerosol generation but is not favorable for wastewater treatment because a large amount of water is generated as secondary waste.

In a study on the application of the waterjet process to dismantling nuclear reactors, for the treatment of secondary wastes (a problem of the waterjet process), Brandauer developed a waste separation device that separates iron particles from wastes and proposed a waste reduction method using this device[12].

Tezuka investigated a waterjet process for application to the first Fukushima nuclear power plant. The waterjet process could cut approximately 270-mm-thick base metal in air, but the cuttable thickness in water decreased to approximately 220 mm, which was 80% of the cutting performance in air. Based on this, Tezuka derived the relationship between the cuttable thickness and the distance of the abrasive feed line affecting the cutting performance of the waterjet process. Because the decrease in cutting performance was due to the resistance of the water, the abrasive waterjet (AWJ) flow system was optimized by changing the nozzle type, and the performance improved[13].

In a study on the application of the AWJ process in the sea, Sun designed an AWJ process applicable to large-tonnage lifting equipment. Sun used the kinematic and kinetic solutions of the cutting path to analyze the movement control, thereby laying the foundation for ultra-high-pressure abrasive jet technology[14].

2.2 Grinding

The characteristics of underwater grinding are not significantly different from those of the abovementioned mechanical underwater cutting. This process also causes water drag, and when excessive force is applied to the grinder, the grinder stops; if the applied force is insufficient, the grinder pops up. Therefore, maintaining optimum torque and speed is critically important.

Thuot developed a process model based on the material removal rate (MRR) considering the energy loss due to the water drag during underwater grinding, as shown in Fig. 1. He investigated a technique for covering a grinding wheel with an air injector to enhance the efficiency of the underwater process. The power loss decreased by up to 80%, and it was found that at a low speed, the developed wet grinding process had a higher MRR than the dry grinding process[15].

In a study on process conditions, Kim mathematically modeled and experimented on a hydraulic motor and cylinder for rock-grinding work using an underwater construction robot, as shown in Fig. 2. He demonstrated that hydraulic motor speed control for rock grinding requires compensation for the changing volume of the motor chamber, and the hydraulic cylinder force control only depends on the flow. Based on this, Kim proposed an active control technique for maintaining the optimal torque and speed[16].

In a study on the application of underwater grinding in deep sea, Guo developed a deep-sea pipeline repair machine (DPRM) and applied a rotation-compatible mechanism to solve the problem of existing equipment (exceeding the cutting dimensions when a corrosion-resistant coating of the pipeline is ground). A steel-wire brush was proposed as an appropriate grinding tool. To determine the suitability of the steel-wire brush, an underwater grinding model was established based on boundary layer theory, and the relationships among the grinding drag torque, grinding tool radius, rotation speed, and positive pressure were modeled. It was verified through experiments that the steel-wire brush was the best choice[17].

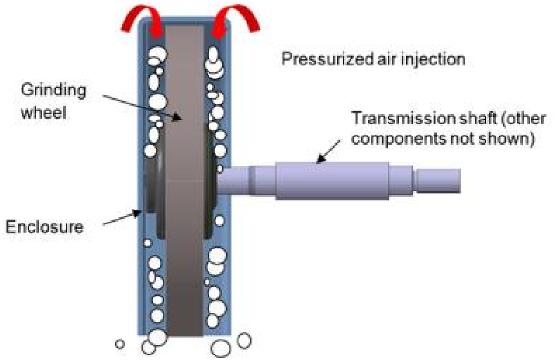

Fig. 1 Schematic of air injector set-up[15]

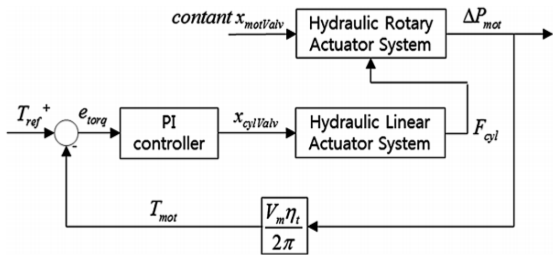

Fig. 2 Block diagram of the active control algorithm for maintaining the optimal torque in rock grinding[16]

Mendez combined grinding and underwater welding to repair local cracks at the T-welding connection of a deep-sea pipeline, as shown in Fig. 3. It was demonstrated that this combination could restore the mechanical properties of damaged structures but had the shortcoming that the Charpy energy value was much lower than that before the damage[18].

2.3 Diamond Wire Cutting

Diamond wire cutting is a combined process of sawing and grinding using an iron rope composed of diamond elements. It has relatively low noise and vibration and no limitation in the cutting depth and material of the object. However, it is difficult to apply diamond wire cutting to precise cutting and it generates a large amount of secondary wastes.

For studies on the application of diamond wire cutting to offshore plants, Molfino selected bead widths of 6mm and 10mm as experimental conditions, as shown in Fig. 4, and checked cutting characteristics according to bead width, as shown in Fig. 5. The optimal bead width was selected according to the cut surface in this process[19]. Furthermore, Yongrui researched the diamond wire saw for subsea oil pipe cutting. It was concluded that cutting parameters including the wire speed, feed rate, and cutting pressure had significant effects on the cutting efficiency, and the optimal values of the cutting parameters were derived to increase the cutting efficiency[20]. Furthermore, the equation of the parallel load mechanism was derived through the kinematic analysis of the underwater diamond wire saw and modal analysis was performed using ANSYS. An analytical motion equation for expressing the mechanism to strengthen the lever force was established, and guidelines were provided for the location and cutting of non-loaded ropes[21]. Pangerc examined the noise generated when an oil gas platform was cut by underwater diamond wire cutting. The radiant sound was experimentally measured at a depth of 10m, but it was difficult to measure due to background noise. At 4–15 dB, the higher the frequency, the more the noise increased. This data was used to explain the radiation noise generated in the diamond wire-cutting process that can be used in the public domain[22]. Knecht researched the wear behavior of diamond wires by selecting the speed, pressure, cutting angle, shape of the cutting area, processing material, and distortion as variables and proposed the cutting time prediction and wire replacement cycle[23]. Further, Gentes investigated the cutting process of a contaminated nuclear reactor using a diamond wire. The automated remote process was researched by

Fig. 4 Narrow (left) and standard (right) diamond beads[19]

considering economic benefits and workers' health. For the effective underwater decomposition of the components of the contaminated power plant with the minimum labor, a new measuring instrument that can monitor the remote cutting process and examine the wear situation was developed[24].

3. Thermal Cutting Method

Thermal cutting methods are mostly applied to metals. The thermal cutting process has the advantage of a small reaction due to a lack of direct contact between the tool and workpiece and easy application to thick materials. Moreover, the system for remote operation is simple. Cutting work using heat is carried out by melting or burning the material using a high energy density in the machined area. This generates some aerosol particles, dust, and gas and requires appropriate measures, such as an inhalation device with a filter system, to protect workers and prevent the diffusion of pollutants. Even though underwater cutting decreases the generation of particles by at least three times compared with cutting in air, the particles in water obstruct transparency and make visual inspection difficult. Therefore, underwater thermal cutting requires an appropriate filter system to collect the generated byproducts and keep the water clean[2].

3.1 Plasma Arc Cutting

The plasma arc cutting (PAC) process uses the electric energy generated by arc discharge. Fig. 6 shows a schematic of the PAC process. Most metals can be cut by PAC, including those that cannot be cut by gas cutting, such as aluminum, aluminum alloy, stainless steel, mild steel, and low-carbon steel. PAC has a much higher cutting speed than oxygen cutting. However, it is difficult to cut thick materials with this method because the thermal energy is supplied from the top of the material and the supply energy is limited. Furthermore, secondary waste collection is required because the nitrogen and oxygen in the air that were dragged into the plasma airflow react to form nitrogen oxides. Another disadvantage of underwater cutting is that the efficiency decreases as the depth increases.

Regarding studies related to nuclear reactor dismantling, Shoji developed underwater plasma jet cutting technology for dismantling nuclear power plants. This process can be performed in a very small space inside a reactor and can cut 42-mm steel and 50-mm ceramic in water[25].

Tezuka performed the PAC process in dry and wet conditions to develop core thermal cutting technology for application to the inside of the first Fukushima nuclear power plant. He found that when cutting stainless steel at 600A in water, the efficiency dropped by half compared with the dry condition[13].

Wang conducted experiments to examine the cutting phenomena that are changed when oxygen and air are used as plasma gas and shield gas in the underwater PAC process, as shown in Fig. 7. As the oxygen content decreased, the cuff shape and the smoothness of the cut surface improved, but as the heat-affected zone became larger, the adhesive residues and the cutting hardness increased. Furthermore, PAC in water could obtain a better cut surface and higher surface hardness than those in air[26].

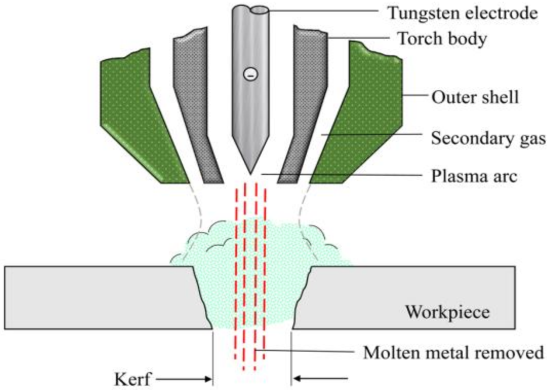

Fig. 6 Schematic diagram of plasma arc cutting

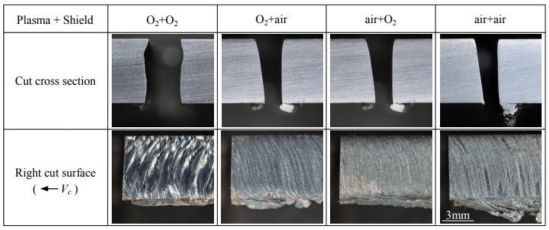

Fig. 7 Photographs of underwater plasma kerf shape and cut surface[26]

3.2 Laser Cutting

Laser cutting is a relatively new process, and the actual application of laser cutting to nuclear reactor dismantling has not been reported yet, but active research on laser applications to underwater cutting is underway. Most studies focus on underwater cutting for nuclear reactor dismantling, and the thickness of the base metal, comparison between wet and dry conditions, development of a hybrid process, and application of the Nd:YAG laser have been studied.

In a study on the application of laser cutting to nuclear reactor dismantling, Soejima designed a laser-cutting system composed of an articulated robot and a laser-cutting head and verified the stability and applicability of the system[27].

Khan mentioned the cutting speed, lightweight cutting head, flexibility, low reaction, and easy automation as the advantages of using a laser in nuclear reactor dismantling. He adjusted the laser beam focus and nozzle tip pressure in water and found that the cutting performance of the laser in water was similar to that in air. Furthermore, he confirmed that the extent of dross sticking was similar between the laser-cutting processes in water and in air. This minimized the discharge of radioactive materials[28].

Tamura conducted a study on the cutting of carbon steel and stainless steel sheets with a thickness of more than 100mm using a 30-kW fiber-optic laser to find the cutting conditions for nuclear decommissioning. When the distance between the nozzle tip of the laser head and the sample surface was maintained at 5 mm, the cuff expanded as the sheet thickness increased. As the distance between the nozzle tip and the sample surface naturally increased, beam separation occurred and the beam size increased, which enabled the cutting of a thick plate. Therefore, he suggested that a sufficient cuff is required to facilitate the melt flow for very thick plates[29].

Shin cut stainless steel and carbon steel plates of up to 100mm in thickness with a laser output of 6 kW, lower than the generally known cutting performance, for application to nuclear power plants[30].

For a study on the laser cutting of Inconel 625, which is applied to the outer walls of reactor pressure vessels (RPVs), as shown in Fig. 8, Roy investigated the reaction sensitivity of Inconel 625 in water with the variables of the lamp current, pulse frequency, duty cycle, cutting speed, and water column height. He suggested the optimal conditions for central composite design (CCD) based on the response surface methodology (RSM) and verified its fitness through ANOVA[31].

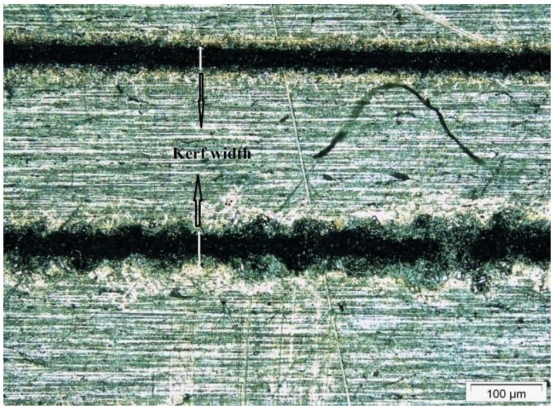

Fig. 8 Schematic diagram of submerged laser beam machine[31]

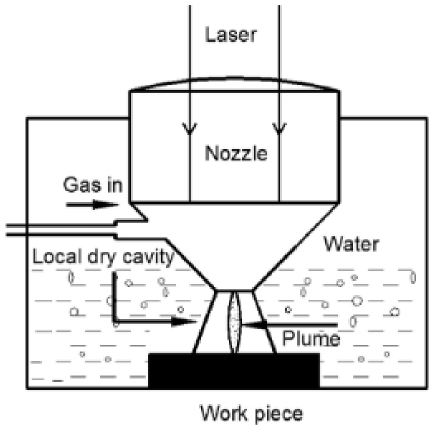

Fig. 9 Schematic diagram of local dry cavity[32]

Choubey investigated Nd:YAG laser cutting in air and water for Inconel 625 for the application of the laser process in radioactive and underwater environments, as shown in Fig. 9. He tested the cutting speed while changing the pulse duration, spot overlap, and subsidiary gas pressure and found that the cutting speed increased[32].

For studies on the underwater laser process, Krstulovic compared the laser aluminum drilling process between air and water conditions. He suggested that it was more efficient to perform the process in water, found that the optimal water thickness

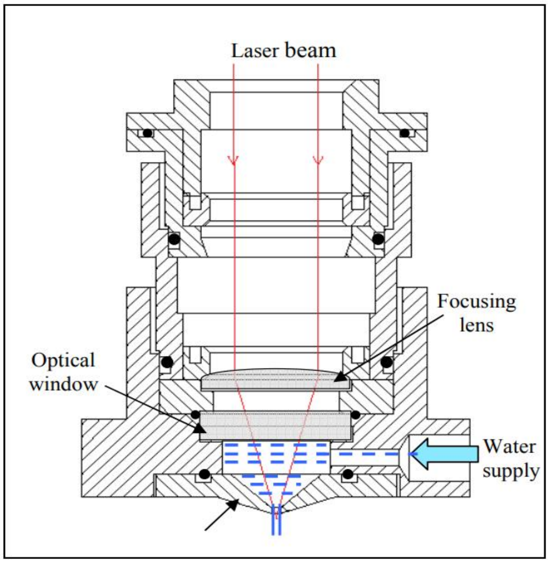

Fig. 10 Schematic of the cutting nozzle and transmission of laser beam through water[36, 37]

was 3mm, and reported that the crater volume increased by 28 times and the crater depth increased by 18 times[33].

Leschke proposed an underwater laser-cutting process for process integrity, maintenance, and replacement. The important parameters included the nozzle gap, focus location, and cutting gas pressure[34].

Acherjee reported that laser-based micro-channeling is emerging as the most widely used process for the fabrication of polymer-based micro fluid devices. The underwater laser process created cleaner and finer structures than the process in the air by minimizing the adverse effects of the heat-affected zone and others[35].

Finally, studies have proposed hybrid processes by adding the waterjet process to the laser process. Mullick proposed a new underwater laser-cutting process by adding the waterjet process to the laser process, as shown in Fig. 10. He suggested that this complex process ultimately decreased contamination by reducing air bubbles, water turbulence, aerosols, and waste gas. Furthermore, when pulse-mode cutting was performed using this complex process, the laser scattering loss decreased significantly. The cutting quality was optimized using the Box–Behnken method (RSM). Furthermore, the loss mechanism and shear force were formulated by considering the interaction between the laser process and water, and the output parameter was predicted. The results showed that scattering in water vapor caused approximately 4–50% of the laser loss, and it was predicted that the loss would be low if the laser power was high and the water jet velocity was low[36, 37].

3.3 Electric Discharge Machining

Electric discharge machining (EDM) is a process of cutting by melting or sublimating the work material by inducing a high voltage and low current from the electrode (mainly copper) to the cutting object, thus generating sparks. The advantage of this process is that the cut surface is relatively fine and accurate, but the disadvantage is slow cutting speed.

Huang introduced underwater EDM technology, nuclear power plant research, and the structures and designs of mechanical and electric systems. Underwater EDM technology is mainly used in hole machining, plate cutting, and surface cutting, and its advantages are precision and high quality[38].

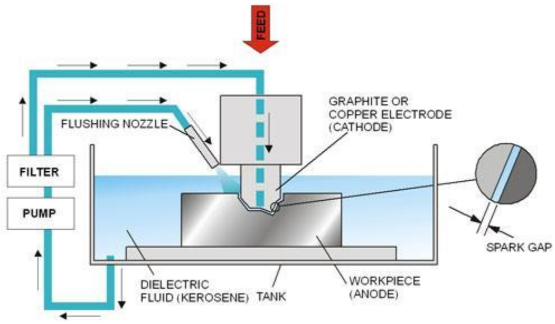

Fig. 11 Principle of electric discharge machining for underwater process

Table 1 Comparison between processes

Type	Mechanical Segmenting Tool			Thermal Segmenting Tool			
Process	AWJ	Grinding	DWC	PAC	LC	EDM	CAMC
In atmosphere use	Very well applicable	Very well applicable	Very well applicable	Very well applicable	Very well applicable	Not applicable	Not applicable
Underwater use	Applicable	Applicable	Applicable	Applicable	Applicable	Very well applicable	Very well applicable
Cutting of stainless steel	Applicable	Applicable	Applicable	Very well applicable	Applicable	Very well applicable	Very well applicable
Cutting of non-metal materials	Very well applicable	Not applicable	Applicable	Not applicable	Applicable	Not applicable	Not applicable
Material thickness	Low	Low	Middle	Middle	Low	Low	High
Complicated structures	Limited applicable	Not applicable	Limited applicable	Applicable	Applicable	Limited applicable	Very well applicable
Cutting speed by of higher material thickness	Average	Slow	Average	Fast	Slow	Slow	Average
Manipulator or guiding system	Middle requirements	Lower requirements	Higher requirements	Middle requirements	Middle requirements	Higher requirements	Middle requirements
Acquisition costs	High	Low	High	High	High	High	Middle
Costs of expendable items	High	Low	Middle	Low	Low	High	Low
Water pollution	High	High	Middle	Middle	Low	High	High
Required space for equipment	Low	Middle	High	Middle	Low	Middle	Low
the influence of water depth	High	High	High	High	High	High	Low
Remote control	High	Low	Low	High	High	Middle	High
Development	Middle	High	High	High	Low	High	Low
Reaction forces	Low	High	High	Low	Low	Low	Low

Zhang suggested that the development of air bubbles caused by electric discharge in EDM occurs in a very short time and a very small space, so observation and theoretical analysis were both difficult. Consequently, he performed 3D simulation of the air-bubble evolution process and researched the effects of the electrode and distance. The shorter the distance to the electrode, the larger the pressure and the faster the expansion speed of air bubbles became, resulting in a larger force applied to the electrode and workpiece[39].

3.4 Contact Arc Metal Cutting

Contact arc metal cutting (CAMC) is an electric process that acts at a very low voltage (<60V) and a high current (500–2000A) using metals and graphite as the electrode, as shown in Fig. 12. This is based on the irregular arc effect (short circuits) that occurs when an electrode contacts the workpiece. This arc is very hot and can melt all metals, and the molten metal does not attach to the workpiece through rinsing. This process has the advantages of low electrode consumption, no limitation in material size, and the ability to cut complex shapes with various thicknesses and multiple materials at once with a high cutting speed. Furthermore, relatively simple designs are possible because it is not affected by water turbulence, viscous resistance, light scattering, and air bubbles, and there is no reaction on the electrode. However, it also has disadvantages, such as the manual replacement of the consumed electrode and the generation of secondary wastes.

Bach developed a new cutting technique called CAMX processes for the underwater cutting of metal structures. CAMC has no limitation in the complex structures of the workpiece and is not influenced by undercuts and cavities. Furthermore, CAMG is a linear cutting process with a very high cutting speed, and CAMD can drill any geometric holes[40].

Jeong performed technical comparisons of the gas emissions, cutting power, handling requirements, and design approach for the PAC, CAMC, and abrasive water suspension jet processes based on previous works applicable to cutting for nuclear reactor dismantling. Through this comparison, the limitations of each process were verified[41].

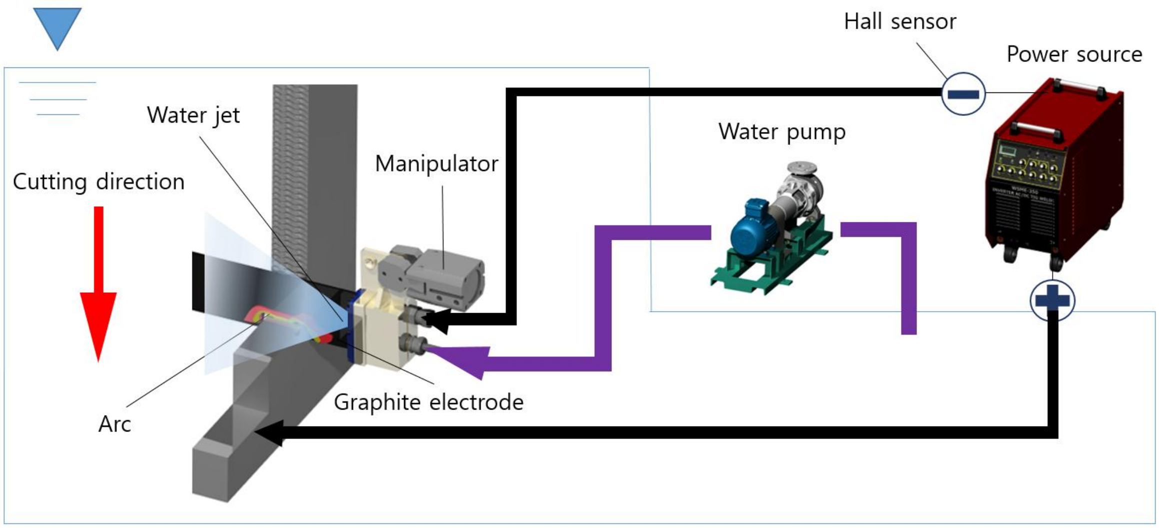

Fig. 12 Principle of contact arc metal cutting

Villoria introduced a process performed by the CIEMAT in the decommissioned frame of a research reactor. He evaluated various metal-cutting techniques, including PAC, CAMC, and saw cutting, by applying them to aluminum and stainless steel and presented the performance, advantages, and problems of each method[42].

Prechtl described the problems of PAC in RPV cutting and explained the CAMC process developed to solve this problem[43].

Mun conducted a study on the prediction of electrode consumption by monitoring voltage and current in real time to prevent electrode waste while minimizing the electrode consumption of the CAMC process, as shown in Fig. 12, and demonstrated that the electrode replacement cycle can be predicted.

4. Summary and Prospects

This paper introduced various underwater cutting processes and studies with new directions to develop them and examined the applicability of these processes to nuclear reactor dismantling. The results are outlined in Table 1. With the rising demand for nuclear reactor dismantling, research and development for various cutting processes for underwater cutting applications have been conducted.

At present, we cannot conclude which process is the best for underwater cutting; however, as mentioned above, every underwater cutting process has advantages and disadvantages. Therefore, an appropriate process should be applied according to the application.

Furthermore, underwater cutting has wide-ranging possibilities for development, because it can be applied not only to nuclear reactor dismantling, but also to various dismantling industries including offshore plants and sunken ships. New combinations of processes such as the plasma jet process and the waterjet + laser process, or new original processes, can be applied through continuous research and development of processes related to underwater cutting. Due to the nature of underwater cutting, a large amount of wastewater is generated as secondary waste. Hence, research focused on the reduction of secondary waste will be advantageous in terms of cost and environment. Furthermore, studies on the problems of underwater cutting should also be conducted, such as light scattering, water turbulence, bubble generation, and aerosol use.

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