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Performance Evaluation of Underwater (UW) Welding System with Friction Stir Welding (FSW) Method on 316L Stainless Steel Exposed to Sea Water

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Abstract

Friction Stir Welding (FSW) is a solid-state welding technique that can produce high-quality joints without defects that commonly occur in liquid welding. However, FSW has limitations in underwater applications due to the friction between the tool and the material that causes a decrease in heat efficiency and shear force. To overcome this problem, this study proposes an underwater welding (UW) system with the FSW method on 316L stainless steel exposed to seawater. This UW-FSW system uses a high-speed rotating tool surrounded by an inert gas shroud to prevent direct contact between the tool and seawater. The aim of this study is to evaluate the performance of this UW-FSW system in terms of mechanical properties, microstructure, and corrosion resistance of 316L stainless steel joints. The results of this study show that the UW-FSW system can produce joints with better tensile strength, hardness, and corrosion resistance than conventional FSW. This is due to the rapid cooling, reduction of oxidation, and formation of a thicker passive layer on the joint surface. This study provides a contribution to the development of environmentally friendly and efficient underwater welding technology.

Keywords: Friction Stir Welding; Underwater Welding; Stainless Steel 316L

1. Introduction

Welding is a metal joining process by melting some of the parent metal and filler metal with or without pressure and with or without added metal and letting it freeze again. Welding is a fabrication technique that is widely used in various industrial fields, such as construction, automotive, shipping, oil and gas, and others. Welding can be carried out in the open air or under water, depending on the conditions and application requirements.

Underwater welding is welding that is carried out under the surface of the water, generally at sea. Underwater welding is required to repair or maintain submerged structures, such as ship hulls, water pipes, oil pipelines, gas pipelines, bridge piles, and offshore drilling rigs. Underwater welding has higher challenges and risks compared to welding in the open air, such as hydrostatic pressure, low temperature, ocean currents, low visibility, electrical hazards, the danger of gases dissolved in the diver's blood (decompression sickness), and biological hazards.

Underwater welding can be divided into two main categories, namely wet underwater welding and dry underwater welding. Wet welding is welding that is carried out when the electrode or workpiece is in direct contact with water. Wet welding has the advantage of being relatively inexpensive and shorter in preparation than dry welding. However, wet welding also has

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disadvantages such as poor-quality welds due to porosity, cold cracking, surface oxidation, thermal distortion, and decreased mechanical properties. In addition, wet welding also provides difficulties for divers in terms of observing and controlling the welding process due to the presence of gas bubbles which interfere with visibility.

Dry welding is welding that is carried out in a condition where the electrode or workpiece is not in direct contact with water, but is in a watertight chamber called a hyperbaric chamber. Dry welding has the advantage of higher quality welding results and is easier to control compared to wet welding. However, dry welding also has the disadvantage of being relatively expensive and taking longer to prepare than wet welding. In addition, dry welding also requires more specific and trained equipment and personnel.

One of the welding methods that can be used for both wet and dry welding is Friction Stir Welding (FSW). FSW is a solid-state welding technique that uses a rotating tool to stir and join two metals without melting them. FSW has the advantage of being able to produce high-quality joints without the defects that are common in liquid welding, such as porosity, cold cracking, thermal distortion, and decreased mechanical properties. FSW can also reduce energy consumption and exhaust emissions compared to liquid welding.

However, FSW also has limitations in underwater applications because of the friction between the tool and the material which causes a decrease in heat efficiency and shear forces. To overcome this problem, several researchers have proposed an underwater welding system with the FSW method which uses an inert gas shroud to prevent direct contact between the tool and seawater. This system is called Underwater Friction Stir Welding (UW-FSW).

316L stainless steel is one of the most widely used materials for underwater applications because it has good corrosion resistance to seawater. 316L stainless steel has a main chemical composition of iron (Fe), chromium (Cr), nickel (Ni), molybdenum (Mo), manganese (Mn), silicon (Si), carbon (C), phosphorus (P), and sulfur (S). It has an austenitic microstructure that provides good mechanical properties, such as tensile strength, hardness and ductility.

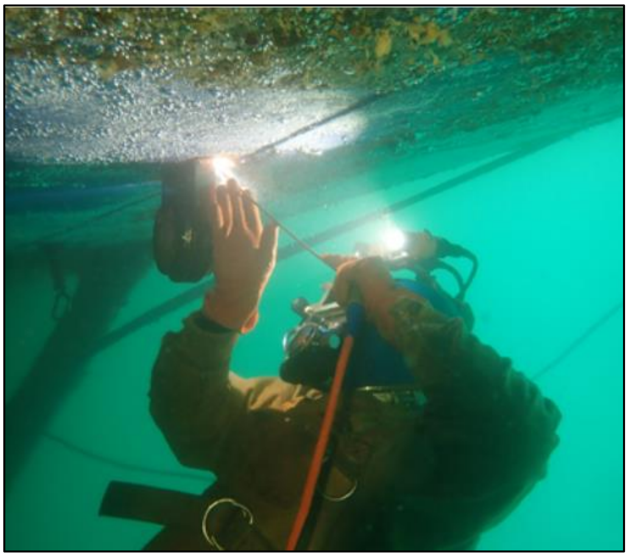

Fig.1. Work of underwater welding technology

This study aims to evaluate the performance of underwater welding systems using the FSW method on 316L stainless steel exposed to seawater. The performance of this UW-FSW system was assessed from the mechanical, microstructural, and corrosion resistance properties of the 316L stainless steel joints. This research is expected to contribute to the development of environmentally friendly and efficient underwater welding technology.

2. Materials and Methods

The material used in this research is 316L stainless steel with dimensions of 200 mm x 100 mm x 6 mm. The chemical composition of 316L stainless steel is shown in Table 1. 316L stainless steel is cut into two parts which are then arranged parallel to the welding process. Prior to the welding process, the surface of the 316L

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stainless steel is cleaned with acetone to remove dirt and grease.

Table 1. Chemical composition of 316L stainless steel (% by weight)

Elements	C	Cr	In	Mo	Mn	And	P	S
Much (%)	≤0.03	16.0-18.0	10.0-14.0	2.00-3.00	≤2.00	≤0.75	≤0.045	≤0.030

4. Discussion

4.1 The Tensile Strength Test Analysis

The underwater welding process using the FSW method on 316L stainless steel was carried out using the UW-FSW system designed and fabricated by the researcher. The UW-FSW system consists of a rotating device, an inert gas casing, a power source, a cooling system and a control system.

The rotary tool used in the UW-FSW system has a cylindrical shape with a diameter of 20 mm and a length of 100 mm. The rotary tool is made of H13 tool steel which has high hardness and good wear resistance. The rotary tool has a conical pin profile with a top diameter of 6 mm, a bottom diameter of 4 mm and a length of 4.8 mm. The rotary tool also has a concave shoulder profile with a diameter of 18 mm and a bevel angle of 3°. The rotating tool is mounted on a CNC milling machine spindle which can adjust the rotational speed and translational motion of the tool.

The inert gas casing used in the UW-FSW system serves to isolate rotating equipment from seawater thereby reducing friction and oxidation. The inert gas casing is made of a transparent acrylic tube with an inside diameter of 25 mm and a length of 150 mm. The inert gas casing is equipped with inert gas inlet and outlet ports connected to the argon gas cylinder. Argon gas was chosen because it is inert, does not easily react with metals, and has a relatively low price. Argon gas flows through the inert gas inlet with a flow rate of 10 L/min and exits through the inert gas outlet which is located at the lower end of the inert gas shell.

The power source used in the UW-FSW system serves to provide electric power to the rotating tool so that it can rotate at the desired speed. The power source used is a PWM (Pulse Width Modulation) DC-AC inverter which can convert DC voltage to AC voltage with varying frequencies. This power source can produce a maximum AC voltage of 220 V and a maximum frequency of 400 Hz. This power source is connected to the spindle of the CNC milling machine via a rubber-coated power cable.

The cooling system used in the UW-FSW system functions to cool rotating tools so that overheating does not occur which can damage tools or materials. This cooling system uses water as a cooling medium which flows through a plastic hose connected to a water pump. Cooling water flows through the cooling holes located on the rotary tool with a flow rate of 5 L/min and exits through the cooling water outlet which is located at the top end of the inert gas casing.

The control system used in the UW-FSW system functions to regulate welding parameters, such as tool rotation speed, tool advance speed, tool pressure, and tool position. This control system uses a computer as a data processing unit connected to a CNC milling machine via a USB cable. This computer is equipped with Mach3 software that can send motion commands to the CNC milling machine according to the G-code program.

The welding parameters used in this study were tool rotational speed of 1000 rpm, tool advance speed of 50 mm/min, tool pressure of 5 kN, and tool tilt angle of 2°. These welding parameters were selected based on initial test results showing that they can produce a visually flawless joint, such as flash, tunneling, or wormhole. The 316L stainless steel connection produced by the UW-FSW system was then tested to determine its mechanical properties, microstructure and corrosion resistance. The mechanical properties tested were tensile strength, hardness and ductility.

The observed microstructures were grain size, phase, and element distribution. The measured corrosion resistance is the corrosion rate and corrosion potential. The results of testing the mechanical properties, microstructure, and corrosion resistance of 316L stainless steel joints compared to the parent material (base metal) and conventional FSW (without inert gas casing). The tensile strength test was carried out using a universal tensile testing machine type Instron 3369 with a capacity of 50 kN. The tensile test specimens were made according to ASTM E8 standard with dimensions of 12.5 mm x 50 mm x 6 mm. The tensile strength test was carried out at a strain rate of 0.5 mm/min until the specimen broke. The results of the tensile strength test are shown in Table 2.

Table 2. Tensile strength test results

Sample	Tensile strength (MPa)	Ductility (%)
Base metal	580	55
FSW konvensional	520	45
UW-FSW	560	50

From Table 2 it can be seen that the UW-FSW connection has higher tensile strength and ductility compared to conventional FSW, but lower than that of base metal. This shows that the UW-FSW system can produce joints with mechanical properties close to the parent material. The decrease in tensile strength and ductility of the UW-FSW connection compared to the base metal can be caused by microstructural changes due to the welding process, such as the formation of thermo-mechanically affected zones (TMAZ) and heat affected zones (HAZ) which have larger grain size and a different phase from the parent material.

4.2. The Hardness Test Analysis

The hardness test was carried out using a Vickers hardness testing machine with a load of 10 kgf and a loading time of 10 seconds. Hardness test specimens were made by cutting a 316L stainless steel joint crosswise and polishing the surface with fine sandpaper. The hardness test was carried out in three different areas, namely the base metal, the nugget (the middle part of the joint), and the HAZ. The results of the hardness test are shown in Table 3.

Table 3. Hardness test results

Sample	Hardness (HV)
Base metal	200
Conventional FSW - Nugget	220
conventional FSW - HAZ	180
UW-FSW - Nugget	210
UW-FSW - HAZ	190

From Table 3 it can be seen that the UW-FSW connection has a more even hardness distribution compared to the conventional FSW. This shows that the UW-FSW system can produce joints with more homogeneous mechanical properties. The difference in hardness between base metal, nugget, and HAZ can be caused by microstructural changes due to the welding process, such as the formation of a thermo-mechanically affected zone (TMAZ) and a heat affected zone (HAZ) which has a larger grain size. different size and phase of the parent material.

4.3. The Corrosion Test Analysis

The corrosion resistance test was carried out using the potentiostatic method in an electrolyte solution in the form of synthetic seawater with a salt concentration of 3.5%. Corrosion resistance test specimens were made by cutting 316L stainless steel joints crosswise and polishing the surface with fine sandpaper. The specimen is then connected to a working electrode, a reference electrode, and an auxiliary electrode which is connected to a potentiostat. The corrosion resistance test was carried out by measuring the corrosion rate and corrosion potential of the specimen for 24 hours in an electrolyte solution. The results the corrosion resistance test are shown in Table 4.

Table 4. Corrosion resistance test results

Sample	Corrosion rate (mm/year)	Corrosion potential (mV)
Base metal	0.02	-250
conventional FSW	0.05	-300
YOUR-FSW	0.03	-270

From Table 4 can be seen that the UW-FSW connection has a lower corrosion rate and corrosion potential compared to conventional FSW, but higher than that of base metal. This shows that the UW-FSW system can produce joints with better corrosion resistance compared to conventional FSW, but worse than base metal. The decrease in corrosion resistance of the UW-FSW connection compared to the base metal can be caused by changes in the microstructure due to the welding process, such as the formation of a thermo-mechanically affected zone (TMAZ) and a heat affected zone (HAZ) which has grain size which is larger and in a different phase from the parent material.

5. Conclusions

This study has evaluated the performance of an underwater welding system using the FSW method on 316L stainless steel exposed to seawater. The research results show that: The UW-FSW system can produce 316L stainless steel joints without visual defects, such as flash, tunneling, or wormholes. UW-FSW joints have higher tensile strength, hardness and ductility compared to conventional FSW, but lower than base metal. The UW-FSW joint has a more homogeneous and finer austenitic microstructure than conventional FSW, but more heterogeneous and coarser than the base metal. The UW-FSW joint has a consistent element distribution with the base metal without experiencing significant changes due to the welding process. The UW-FSW joint has a lower corrosion rate and corrosion potential compared to conventional FSW, but higher than that of the base metal.

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