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Nutchanat Thongchuea, Eakkachai Warinsiriruk, Noppakorn Phuraya, and Paphon Sa-Ngasoongsong

Corrosion Behavior on Cerclage-Wire Joining Using Laser Welding

Nutchanat Thongchuea[1], Eakkachai Warinsiriruk[1, a)] Noppakorn Phuraya[1] and Paphon Sa-ngasoongsong[2]

[1]Department of Industrial Engineering, Faculty of Engineering, Mahidol University, Thailand
[2]Department of Orthopedics, Ramathibodi Hospital, Mahidol University, Thailand

[a)]Corresponding author: Eakkachai.war@mahidol.ac.th

Abstract. The aim of this study is to investigate the pitting corrosion behavior on cerclage wire under the effect of Nd:YAG laser welding. The application of a modern surgical procedure for the femoral treatment is a target for contribution. A stainless steel wire 316L according to ASTM F 138 (UNS S31673) with a diameter of 1.5 mm as a surgical implant of the orthopedic surgeon was used in this experiment. The charge voltage, multi – frequency, and width of the laser pulse are the studied variables. The corrosion testing was conducted by using electrochemical test in 9 g/L NaCl solution at 37±1ºC which was evaluated by potentiodynamic polarization. Effect of heat input was discussed on corrosion behavior. It was found that using the high value of the laser parameters, which have a high heat input delivered to a cerclage wire, resulted in increasing of corrosion current density i_{corr} and corrosion potential E_{corr}. The lowest heat input of 17.09 J/cm or the combination of the charge voltage of 80 volts, pulse– frequency of 6 Hz and the pulse width of 1.5 ms provided high efficiency pitting corrosion resistance in this study.

INTRODUCTION

Cerclage wire is commonly used for internal fixation in a femoral bone fracture which is one of the procedures in the surgical implant of orthopaedic surgeon. Consequently, surgically implanted materials must have acceptable corrosion resistant in the human body. Stainless steel 316L according to ASTM F 138 (UNS S31673) is an acceptable grade for surgical implants due to their high corrosion resistance, good mechanical and especially excellent biocompatible [1]. As for information, 316L has good corrosion resistance to chlorine-bearing solutions such as physiological saline in the human body [2].

Recently [3-4], it was reported that cerclage wire has a problem of loosening or de-twisting from a fatigue loading. Weak alignment of fixation plate on femoral bone has a negative recovery of the patient. Then, a new idea to fix that problem is applying a permanent locking joint by a welding process. Laser welding has been specified as discussed on the new surgical idea since as non-electric arc welding and a good controllable welding parameter with a high precision joining concept. Micro-joining by the laser beam is available for a small area of a flare joint on the cerclage-wire loop. However, the fusion welding process was concerned with a sensitization problem or pitting corrosion on stainless steel. An unqualified procedure which will be applied for the modern surgeon may seriously affect a harmful-material degradation inside a body. Therefore, the welded-laser joint should have a resistance of pitting corrosion similar to an original cerclage wire. The minimized heat input from an acceptable welding condition should be clarified for pitting-resistance parameter.

The objective in this research is an investigation of pitting-corrosion behavior under effect of laser welding parameters for making an anti-loosening joint of cerclage wire in a new orthopedic-surgical procedure. Calculated heat input from the laser-welding parameter was a selected variable for discussion to understand in the approach of the heat input effect.

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EXPERIMENT PROCEDURE

Material Preparation and Laser Parameters

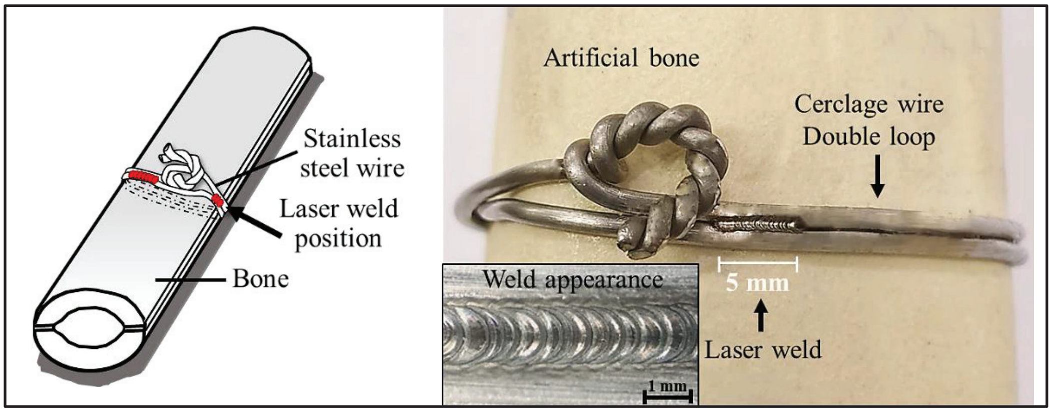
Stainless steel wire 316L (Synthes GmbH, Solothurn, Switzerland) according to ASTM F 138 with a diameter of 1.5 millimeters was used as a base metal, which contains the chemical composition as shown in Table 1. The experiment was performed on laser welding machine AHL – Laser (model XBW- 400) setup with a laser medium of Nd:YAG , a wavelength of 1064 nm. The laser beam was delivered by a fiber-optic line and was set in a defocus distance of 56 mm to obtain a beam spot-size of 1.76 millimeters. During welding, argon gas was used at a flow rate of 10 L/min for shielding welding area to prevent oxidation. The charge voltage (volt), pulse – frequency (Hz), and pulse duration (ms) or industrial technique called pulse width are the main laser variables for the study. It was noted that [5] the range of welding variables for this study have been already optimized on an acceptable sound weld and mechanical property. Then, high and low levels were selected from the boundary of the qualified process window. The design of the experiment is shown in Table 2. In this study, the cerclage configuration with a double-loop method was designed for a flare welding and corrosion testing as shown in Fig. 1 (a). Weld length 5 millimeters was controlled for all specimen for corrosion testing. The specimens were mounted in cold-curing epoxy resin which all of the samples were cut out after laser welded on the wire and only welded surface – exposed which was controlled at 0.8×5 mm^2 on the solution during testing as shown in Fig. 1 (b).

TABLE 1. Chemical composition of stainless steel wire 316L (Synthes GmbH, Solothurn, Switzerland) as measured by a spectrometer.

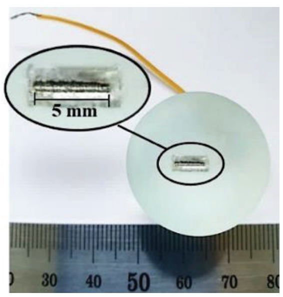
316LSS	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	Fe	Ca	V
wt%	0.030	1.690	0.410	0.010	0.551	18.000	13.000	2.650	0.064	63.350	0.180	0.065

TABLE 2. Laser parameters used for the experiments

Parameters	Level	
Charge voltage (Volt)	80	100
Pulse width (ms)	1.5	3
Pulse – frequency (Hz)	6	9
Ar gas shielding (L/min)	10	
Defocused length (mm)	56	
Beam diameter (mm)	1.76	
Length of welding (mm)	5	
Nominal current (Amp)	30	
Welding travel speed (cm/sec)	1.264	



(a) – Cerclage wire double loop



(b) – cold-curing epoxy resin for the pitting corrosion testing

FIGURE 1. Methodology of (a) the laser welding on cerclage-wire and (b) preparation of the pitting corrosion specimen.

In addition, the influence of laser parameters on corrosion occurrence will be explained by the heat which calculated as a function of heat input in Equations 1 and 2.

$$\text{Power (Watt,J/s)} = \text{Voltage (Volt)} \times \text{Current (Amp)} \tag{1}$$

$$\text{Heat input (J/cm)} = \frac{\text{Power (J/s)} \times \text{Pulse width (ms)} \times \text{Pulse-frequency (Hz)}}{\text{Welding travel speed (cm/s)}} \tag{2}$$

Solution Preparation

This study was conducted in a saline solution, which consists of 9 g/L sodium chloride (NaCl) [6] in distilled water at 37$\pm$1ºC. This solution is a physiological solution that has a concentration the same as the human blood plasma.

Potentiodynamic Polarization Measurement

The corrosion testing was carried out by using an electrochemical test which uses three – electrode system. Stainless steel wire 316L as the working electrode (WE), platinum as the counter electrode (CE) and saturated calomel electrode (SCE) as the reference electrode (RE). The circuit of the electrochemical cell for corrosion test as shown in Fig. 2. This experiment used potentiostat (Digi-ivy; DY 2300 Series) for corrosion test and hotplate digital for controlling the test solution temperature within 37±1ºC. The exposed time during corrosion testing is 5 minutes.

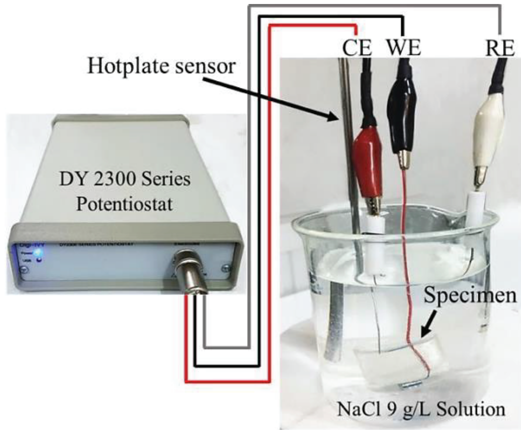


FIGURE 2. A circuit of an electrochemical cell for corrosion test

RESULTS AND DISCUSSION

Surface Observation after Corrosion Test

As-weld surface and the corroded surface of the welding area in different laser parameters are shown in Fig. 3. Calculated heat input from each welding conditions was arranged from low-to-high level to simply understand their effect. For as-weld visual inspection, all of the weld results are free-oxidation, small and perfect sound appearance. As for the result, corroded surface and pitting could be visually observed. It was able observed that the high heat-input condition had occurred corrosion than the low heat-input condition severely. In addition, increasing the set value of the charge voltage and the pulse width causes a larger ripple of the weld bead width which is more corrosion attack. The energy input of 17.09 J/cm is parameter set of 80 volt, 1.5 ms and 6 Hz. We note that when the laser parameter used was lower than 80 volt, the shape of the weld joint become non-uniform, resulting in a low joint strength. Therefore, in this case, the lower laser energy from the setup parameter is an insufficient energy for producing a completed fusion weld.

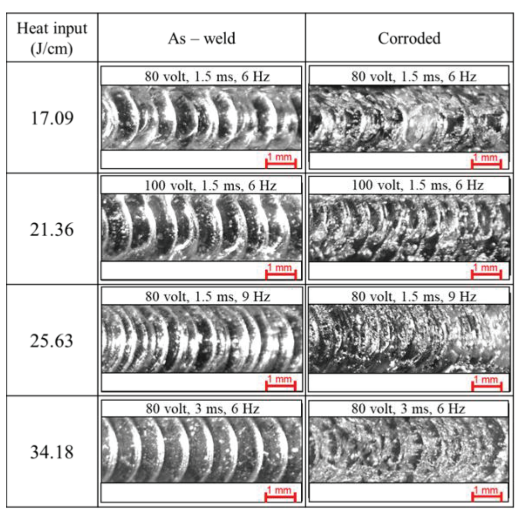


FIGURE 3. Surface observation between before (as-weld) and after (corroded) test

Results of Potentiodynamic Polarization Curves

Figure 4 shows the polarization curves of stainless-steel wire 316L (Base metal) in saline solution with concentration 9 g/L which are defined through Tafel extrapolation. The pitting potential (E_{pit}) of stainless steel 316L is 0.474 V or 474 mV and corrosion potential (E_{corr}) is -567 mV which indicates pitting potential and corrosion potential region on polarization curves including current density (I_{corr}) is 0.979 µA/cm^2. (Note: pH before test 7.347 and after test 6.926). Normally, the value of pitting potential (E_{pit}) is used for evaluating the resistance of pitting corrosion [7]. High E_{pit} value is the meaning of a good pitting resistance while low E_{pit} is susceptible to pitting corrosion.

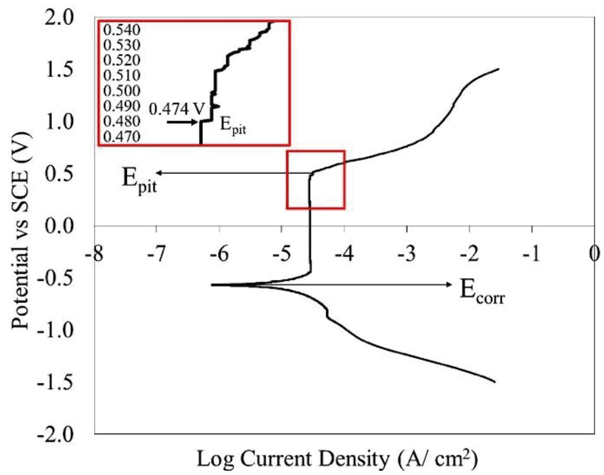


FIGURE 4. Polarization curves of stainless-steel wire 316L in 9 g/L NaCl solution.

Results of polarization curves were shown as a pair of high and low value for charge voltage (volt), pulse width (ms) and pulse – frequency (Hz) in Fig. 5a, 5b and 5c, respectively. The polarization curve of the base metal was also compared in all figures to indicate the effect of welding parameter.

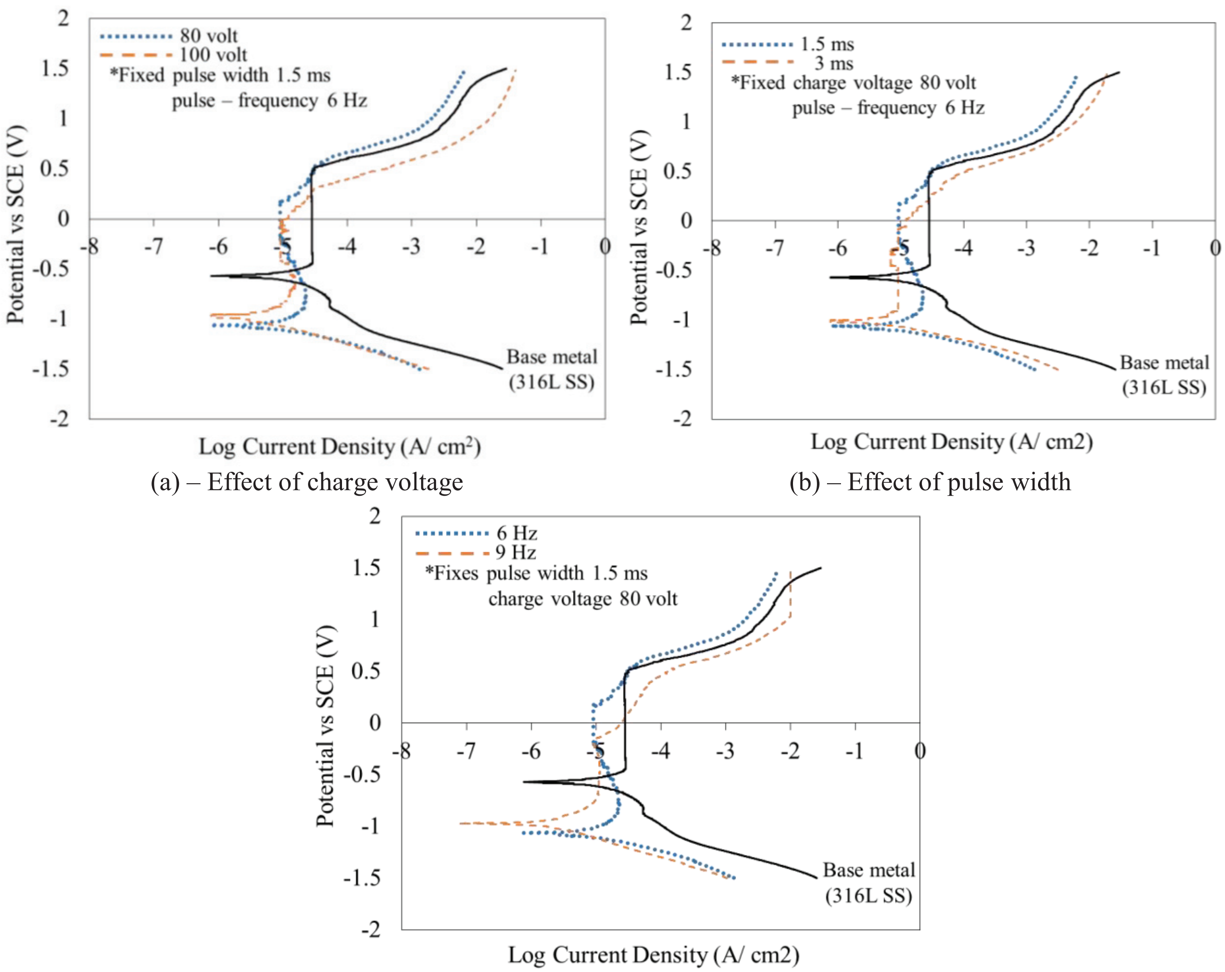
As shown in Fig. 5a, the charge voltage of 80 volts shows the E_{pit} value of + 167 mV while welded by charge voltage of 100 volts shows the E_{pit} of -73 mV. The negative notation of E_{pit} is indicated that welding by high laser power is susceptible to pitting corrosion. Meanwhile, 80 volts of the charge voltage has a good pitting resistance.

When charge voltage was fixed at 80 voltage, for results in Fig. 5b, results of E_{pit} value under the effect of pulse width value between 1.5 and 3 ms are +167 and -162 mV, respectively. It was a reversal effect when the pulse width was set two times. Longer laser irradiation time provided more substantial heat input and resulted in the severe occurrence of pitting corrosion.

For discuss the effect of pulse-frequency, the charge voltage of 80 volts and a pulse width of 1.5 ms were fixed from a good E_{pit} value as mentioned. Fig. 5c shown results of pulse-frequency of 6 and 9 Hz which having results of E_{pit} value are +167 and -156 mV, respectively. It was indicated that high number of laser-energy pulse exposed to stainless steel negatively affects corrosion resistance.

When E_{corr} and I_{corr} values were set the statement for corrosion resistance property that briefly discussed that the high negative value of E_{corr} result is low corrosion resistance and high positive value of I_{corr} result is low corrosion resistance. It indicates that increasing of I_{corr} represents the degradation of the corrosion resistance. From the results have been shown in Fig. 5a, 5b and 5c that most of the conditions of high variable level showed high negative E_{corr} and high positive I_{corr} values. On the other hand, acceptable weld quality which welded by low energy levels has better corrosion resistance.

For the selected parameter for a cerclage-wire joining that the charge voltage of 80 volts, pulse width of 1.5 ms and pulse – frequency 6 Hz is the best corrosion-resistance performance.



(a) – Effect of charge voltage

(b) – Effect of pulse width

(C) – Effect of pulse-frequency

FIGURE 5. Polarization curves under the effect of laser-welding parameters

Effect of Welding Heat Input on E_{corr}, I_{corr} and E_{pit}

The effects of heat input of laser welding on cerclage wire were also discussed. Fig. 6a, 6b and 6c are the results of corrosion potential (E_{corr}), current density (I_{corr}) and pitting potential (E_{pit}). The polarization curves were plotted as a function of calculated heat input. As shown in Fig. 6a, increase in the heat input results in the decrease of E_{corr} and/or lose the property of corrosion resistance in a cerclage wire. For I_{corr} (Fig. 6b), increase in the heat input results in the increase of I_{corr}. I_{corr} is a multiple factor which is usually used for calculation of the corrosion rate (mm/year) of bulk [9]. High value of I_{corr} of the high heat input condition has a poor corrosion resistance. Welded specimens obtained from the heat input over 25 J/cm have gradually increased the I_{corr} or they have high risk of a weld-joint failure on the cerclage wire. Regrading pitting potential (E_{pit}) under effect of heat input as shown Fig. 6c, increasing the high heat input conditions have significantly decrease the E_{pit}. Base on corrosion principle, if E_{pit} value has a high value (especially positive value), that part has an ability to resist the passive film breakdown or it has a high-localized corrosion resistance. On the other hands, when the parts have a low E_{pit} (especially the negative value), it is susceptible to passive film breakdown and localized attack corrosion could occur severely.

To identify the optimal condition of heat input content, it can be seen that only one condition of 17.06 J/cm is a good corrosion resistance such as having E_{pit} is + 167 mV. And the optimal heat input condition is set parameter of the charge voltage of 80 volts, a pulse width of 1.5 ms and pulse – frequency 6 Hz.

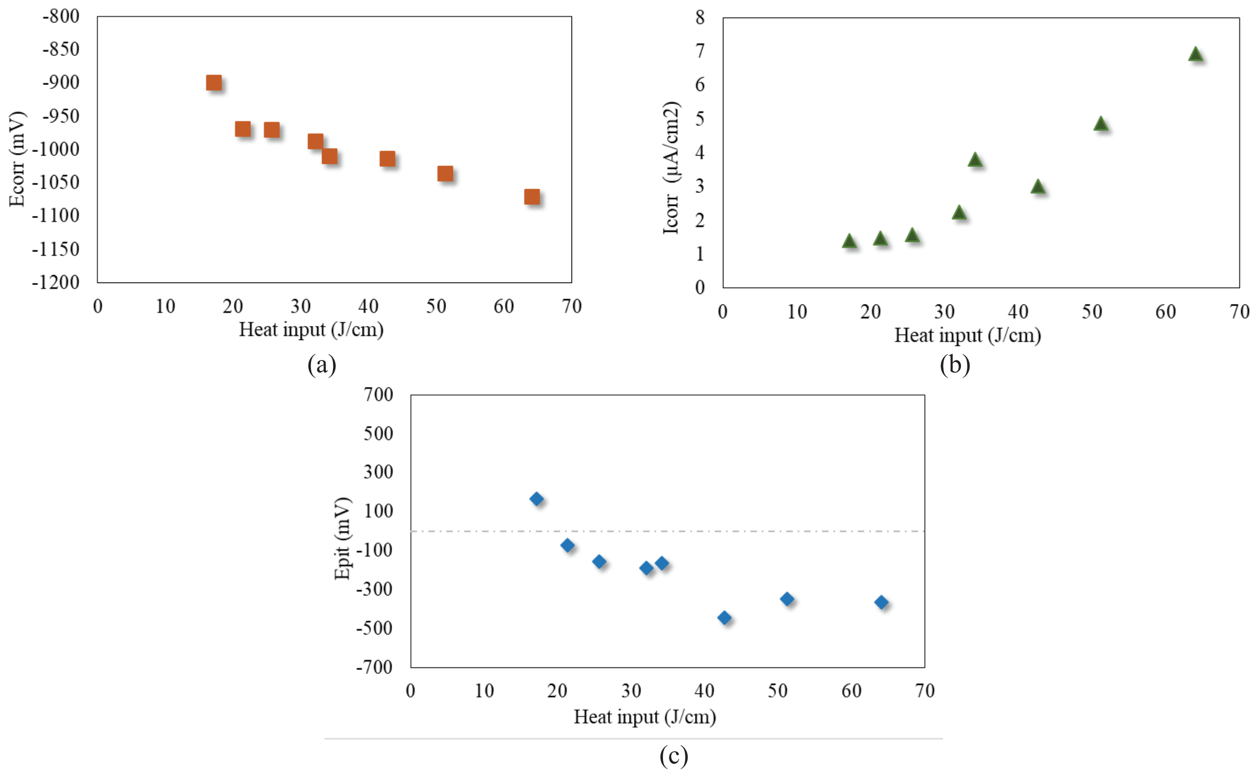


FIGURE 6. Effect of heat input on (a) corrosion potential (E_{corr}), (b) current density (I_{corr}) and (c) pitting potential (E_{pit})

It was observed that a low heat-input joining process by laser weld was achieved on the cerclage wire. The proposed process could be continuously developed in term of the demonstration of surgery in the body. And then the biocompatible evaluation will be performed to reach in a main target of the modern femoral surgery. Moreover, this case study is a preliminary study to show that laser welding on surgical stainless steel 316L is possible. This novel approach of using laser welding for the fixation of metal wire during femoral bone fracture surgery has a greater advantage over the conventional twisting method. The welding can be done on a wire as small as 1.5 mm in diameter.

CONCLUSION

The corrosion behavior of cerclage-wire welded joint from laser welding was studied. Charge voltage (volt), pulse width (ms) and pulse – frequency (Hz) were studied parameters. It cloud be concluded that:

1. The results of the as-weld surface from corrosion test, the high heat-input condition was susceptible to the occurrence of corrosion attack.
2. The set value at the high level of the laser parameters significantly affected the increasing high negative value of E_{corr} and I_{corr} and decreasing the positive value of E_{pit}. It was evaluated that the performance of pitting corrosion resistance was reduced by the high heat-input welding.
3. The target of good corrosion performance of the cerclage-wire weld has been successfully performed by the low heat-input laser welding. Sound weld with free-from oxidation was able obtained by heat input of 17.06 J/cm. The optimized laser parameter is the charge voltage of 80 volts, a pulse width of 1.5 ms and pulse – frequency of 6 Hz.

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