Research Article

E. Surojo, J. Anindito, F. Paundra, A. R. Prabowo, E. P. Budiana, N. Muhayat, M. Badaruddin, and Triyono*

Effect of water flow and depth on fatigue crack growth rate of underwater wet welded low carbon steel SS400

https://doi.org/10.1515/eng-2021-0036
Received Jun 30, 2020; accepted Jan 03, 2021

Abstract: Underwater wet welding (UWW) is widely used in repair of offshore constructions and underwater pipelines by the shielded metal arc welding (SMAW) method. They are subjected the dynamic load due to sea water flow. In this condition, they can experience the fatigue failure. This study was aimed to determine the effect of water flow speed (0 m/s, 1 m/s, and 2 m/s) and water depth (2.5 m and 5 m) on the crack growth rate of underwater wet welded low carbon steel SS400. Underwater wet welding processes were conducted using E6013 electrode (RB26) with a diameter of 4 mm, type of negative electrode polarity and constant electric current and welding speed of 90 A and 1.5 mm/s respectively. In air welding process was also conducted for comparison. Compared to in air welded joint, underwater wet welded joints have more weld defects including porosity, incomplete penetration and irregular surface. Fatigue crack growth rate of underwater wet welded joints will decrease as water depth increases and water flow rate decreases. It is represented by Paris's constant, where specimens in air welding, 2.5 m and 5 m water depth have average Paris's constant of 8.16, 7.54 and 5.56 respectively. The increasing water depth will cause the formation of Acicular Ferrite structure which has high fatigue crack resistance. The higher the water flow rate, the higher the welding defects, thereby reducing the fatigue crack resistance.

Keywords: Underwater wet welding, low carbon steel SS400, water depth, water flow, fatigue crack growth rate

***Corresponding Author: Triyono:** Department of Mechanical Engineering, Universitas Sebelas Maret, Surakarta, Indonesia; Email: triyono74@staff.uns.ac.id

E. Surojo, J. Anindito, A. R. Prabowo, E. P. Budiana, N. Muhayat: Department of Mechanical Engineering, Universitas Sebelas Maret, Surakarta, Indonesia

F. Paundra: Department of Mechanical Engineering, Institut Teknologi Sumatera, Lampung, Indonesia

1 Introduction

Underwater welding is a welding process which is carried out in water [1]. This welding process has been widely applied for offshore constructions, underwater pipe joints and ship hulls welding [2, 3]. The advantages of this welding technique are that it is relatively inexpensive and the preparation required is much shorter than other joining techniques.

Based on the welding process, underwater welding can be divided into 2, namely underwater wet welding and underwater dry welding [4, 5]. Underwater dry welding is an underwater welding process which is conducted in a special chamber designed appropriate to shape and size of underwater construction. Underwater weld chamber serves as a protective room to avoid the adverse effects of water and ensure the underwater welding quality is equivalent to that of welding in air. Due to complex structure of underwater welding chamber, underwater dry welding is expensive [6]. Meanwhile, underwater wet welding is an underwater welding process which is carried out directly in water so the electrode and workpiece are in direct contact and surrounded by water [7, 8]. Underwater wet welding is widely applied in the underwater welding process because it is simple and cheap. On the other hand, underwater wet welding has a weakness, where the water depth of underwater wet welding greatly affects the stability of the arc and the molten metal transfer. The transfer of molten metal from the electrode to the weld metal will be hampered by water pressure so that it will facilitate the occurrence of welding defects [9, 10]. In addition, the underwater wet welding process is also prone to inclusions. Large amounts of inclusions in weld metal can increase the rate of fatigue cracks propagation [3].

M. Badaruddin: Department of Mechanical Engineering, Universitas Lampung, Bandar Lampung, Indonesia

Fatigue is a type of structural failure caused by dynamic loading [11, 12]. The mechanism of fatigue can be divided into 3 stages, namely crack initiation, crack propagation, and static fracture [13]. Fatigue failure of welded joint is greatly influenced by welding defects of weld metal, where the defect can not only be an initial crack but also accelerate the rate of crack propagation [4, 14].

Information about fatigue crack propagation in underwater wet welded joints related to the depth and speed of water flow is still very limited. There have been many previous studies on underwater wet welding, but it was carried out on a laboratory scale only, where the depth was less than 1 meter [15, 16]. Research on underwater wet welding in flow water conditions focused on the transfer of molten metal and arc stability only [7, 17]. Even though in its application, underwater wet welding is carried out at a water depth of more than 1 meter and a sea water wave causes water to flow around the welding environment. Yasinta *et al.* [18] and Paundra *et al.* [19] have conducted research on underwater wet welded joints with varying water depth and speed of water flow, but the characterization of underwater wet welded joints was still limited to physical properties and basic mechanical properties including hardness and tensile strength. Because underwater construction experiences dynamic loads caused by sea waves, it is very important to continue the research on the fatigue crack growth rate of underwater wet welded joints. This work aimed to investigate the effect of water flow and depth on the fatigue crack growth rate of underwater wet welded joint low carbon steel SS400.

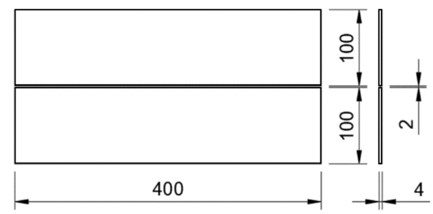


Figure 1: Dimension of test coupon (mm).

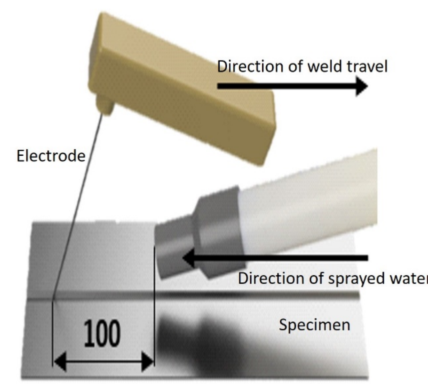


Figure 2: Welding scheme (mm).

2 Methodology

Low carbon steel SS400 with dimensions of 400 mm × 100 mm × 4 mm was used as test coupon and shown in Figure 1. Its chemical composition based on the spectrometer test is shown in Table 1.

Underwater wet welding was carried out using Shielded Metal Arc Welding (SMAW) machine of KOBEWEL KA 602 in water reservoir with length, width and depth were 15 m, 15 m and 10 m respectively. Normal, non-treatment water with temperature of 27°C and degree of acidity (pH) of about 7.0 was used. E6013 (RB26) rutile electrode with a diameter of 4 mm, thin wax coated was used. SMAW was operated manually in negative electrode polarity with average welding speed and welding current of 1.5 mm/s and 90 A respectively. During welding processes, water was sprayed with distance of 10 cm and opposite to welding direction to make variation of water flow speed of 0 m/s, 1 m/s, and 2 m/s as shown in Figure 2. Underwater wet welding processes were performed in two levels of water depth, 2.5 m and 5 m. In air welding process was also conducted for comparison.

Radiographic test was used to see the defects of welded joint. After radiographic checking, the welded joints were tested for fatigue crack growth rate. It used the MTS Landmark 100 kN with a stress ratio (R) of 0.1, a frequency of 10 Hz and a stress level of 30%. The test specimens were made according to the ASTM E647 standard with a notch length and angle of 8 mm and 30° respectively as shown in Figure 3. The crack propagation was observed using a portable digital microscope at 100× magnification as shown in Figure 4. The seven points incremental method (ASTM

Table 1: Chemical composition of SS400.

Element	Fe	C	Si	Mn	P	Cr	S	Cu
%	96.4	0.0337	0.193	0.288	0.0018	0.0273	0.005	0.0136

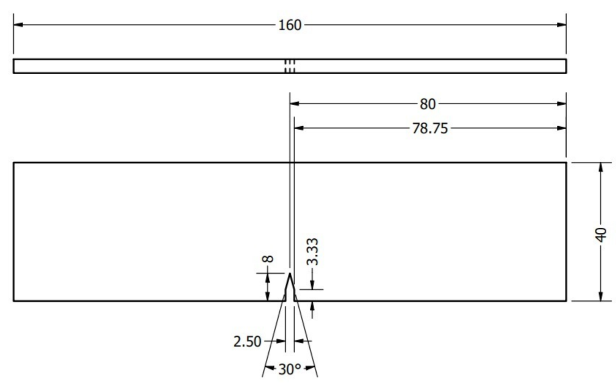


Figure 3: Dimension of fatigue crack growth rate specimen (mm).

E647) was used to calculate the fatigue crack growth rate and then present it in a da/ N versus ΔK diagram.

3 Results and Discussion

Based on the radiographic test as seen in Figure 5, there are various kinds of defects in the welded joints, especially un-

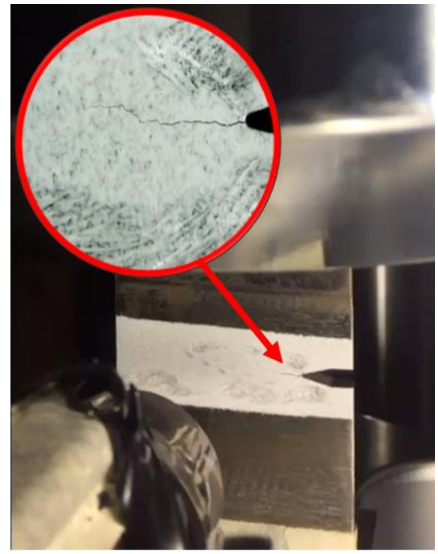


Figure 4: Crack investigation during fatigue crack growth rate test.

derwater wet welded joints including incomplete penetration (I) that occurs in all welded joints, spatter (S), porosity (P), undercut (U), concavity (V), and irregular surface (Z). Incomplete penetration is the lack of molten metal penetra-

Table 2: List of welding defects based on the radiographic test.

Specimen	Defect type	Number	Max. size (mm)
On land	Incomplete Penetration (I)	1	400 mm
	Spatter (S)	79	3.93 mm
UWW 2.5 m, 0 m/s	Incomplete Penetration (I)	1	400 mm
	Spatter (S)	5	3.7 mm
	Undercut (U)	5	20.4 mm
UWW 2.5 m, 1 m/s	Incomplete Penetration (I)	1	400 mm
	Undercut (U)	8	27.8 mm
UWW 2.5 m, 2 m/s	Incomplete Penetration (I)	1	400 mm
	Undercut (U)	7	51.3 mm
	Porosity (P)	12	485.02 µm
	Concavity (V)	4	5.4 mm
	Irregular Surface (Z)	8	51 mm
UWW 5 m, 0 m/s	Incomplete Penetration (I)	1	400 mm
	Porosity (P)	89	0.5 mm
UWW 5 m, 1 m/s	Incomplete Penetration (I)	1	400 mm
	Undercut (U)	8	21 mm
	Porosity (P)	12	0.6 mm
	Concavity (V)	2	10.5 mm
UWW 5 m, 2 m/s	Incomplete Penetration (I)	1	400 mm
	Undercut (U)	9	24 mm
	Porosity (P)	14	1310 µm
	Concavity (V)	2	7.2 mm
	Irregular Surface (Z)	8	53.5 mm

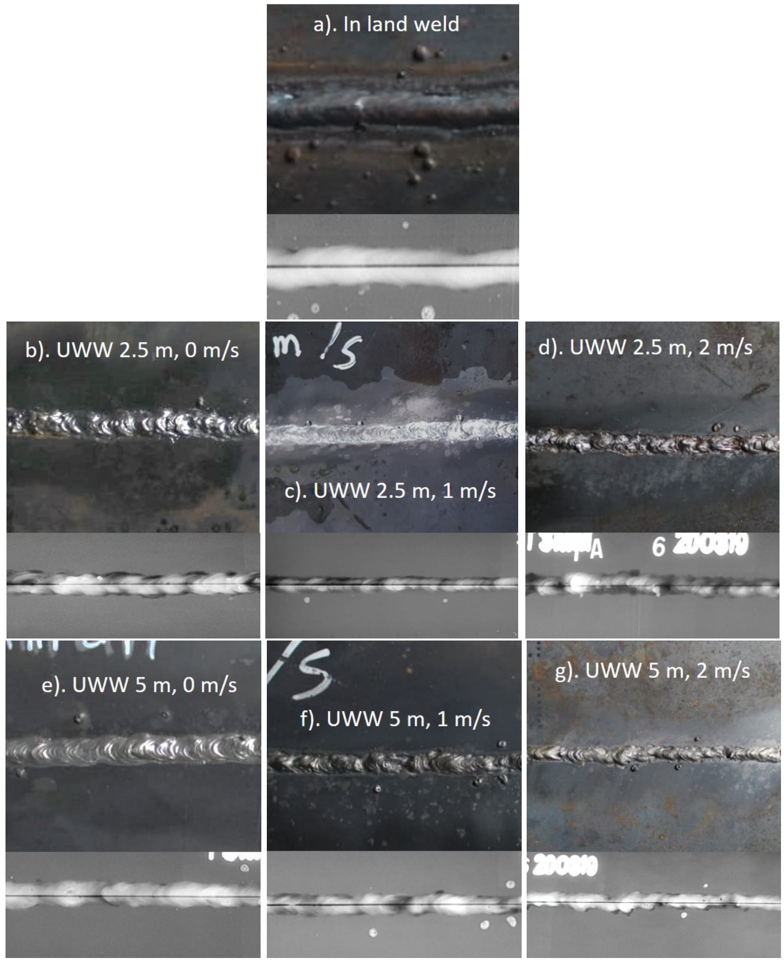


Figure 5: Welded joint appearance and radiographic test result.

tion that occurs due to poor welding techniques, especially low value of heat input. Spatter defects often occur in in air welding caused by the molten metal temperature is too high. The largest number and size of defects is resumed in Table 2.

Weld metal of underwater wet welding has a lot of porosities due to hydrogen presence arising from direct contact with water. Water around the weld arc have high temperature and will dissociate into hydrogen and oxygen gas [20]. Hydrogen and oxygen gases don't get to the specimen surface and were trapped in the weld metal due to rapid solidification [10]. Table 2 shows that the number of porosities in the underwater wet weld metal increases as increasing of water depth and water pressure.

Undercut is more common in underwater wet welding in flow water. Water flow increases welding heat dissipation which decreases arc temperature and arc shrinkage [7]. Underwater wet welding in high water flow velocity (2 m/s) can make many irregular surfaces of weld bead. Weld bead becomes too wide or too narrow and bead surface becomes too convex or too concave. Irregular surface occurs due to poor welding arc stability and unfavorable transfer process of molten metal from electrode to weld pool because of water flow presence [21–23].

Macro and micro structures of underwater wet welded joints related to water depth and flow have been discussed in our previous papers [18, 19]. There are differences in weld penetration depth and porosity due to differences in water depth and water flow speed of underwater wet welding. When water flow speed increases, porosity will increase. Underwater wet welding at 2 m/s water flow indicated the presence of large porosity in the weld metal. Porosity is caused by trapped gas in weld metal. It will increase as increasing cooling rate of welding process [24, 25]. The heat of underwater welding process will experience a forced convection heat transfer so there are a lot of heat lost in underwater welding. The amount of heat lost is directly proportional to the water flow speed [26]. Due to the heat lost, cooling rate of underwater wet welding process is higher than that of in air welding process. Very high cooling rate makes the weld metal solidify rapidly and leads the gas in the molten metal is trapped [21, 27]. Welding process with high heat input will reduce the cooling rate and solidification time of the weld metal for longer time so it gives opportunity the gas in the molten metal to come out [28]. Świerczyńska *et al.* [29] stated that water is one of the main sources of hydrogen gas. Diffusible hydrogen content in weld metal depends on the hydrostatic pressure of water [30]. Due to high hydrostatic pressure of underwater wet welding in deep water, the welding shielding gas rise more quickly to the water surface and make the protection of the weld metal decrease [2, 4]. Lack of arc welding protection from bubbles increases the porosity [20]. Figure 6 shows the scheme of the porosity formation in underwater wet welding due to high hydrostatic pressure.

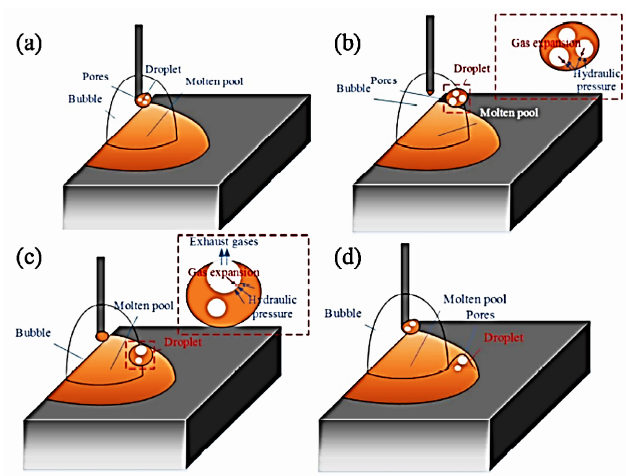


Figure 6: Schematic force analysis of porosity gas expansion during droplet transitions [20].

The fatigue crack growth rate test is performed to measure the relationship between the crack length and the cycles number. Due to the dynamic load, the rate of the crack length addition is affected by the load. The greater the load used, the faster the crack length addition. The fatigue crack growth rate data tests were the crack length and loading cycle number which were then plotted. Figures 7 is the illustration of the relationship between crack length (a) and the number of cycles (N) of the underwater wet welded joint in water depth of 2.5 m and 5 m respectively. In air welded specimens experienced a fatigue cycles number of 179,680 and a maximum crack length of 10.69 mm. All of underwater wet welding specimens have almost similar maximum crack length but varying fatigue cycles number. Fatigue cycles number is affected by crack tip condition during preparing notch using EDM (Electrical Discharge Machining). Initial crack on the notch tip is significantly affected by notch tip condition. When the initial crack appears, crack then will propagate and finally specimen will fail.

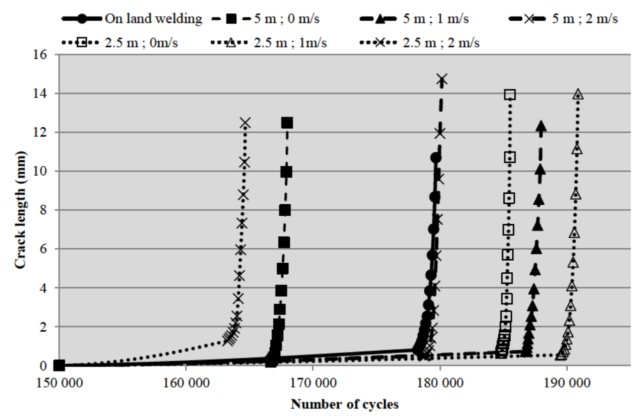


Figure 7: Relationship between crack length (a) and the number of cycles (N) of the underwater wet welded joint.

Data of crack length and number of cycles were used to determine the crack growth rate (da/dN) and stress intensity factor (ΔK) using the incremental polynomial method based on the ASTM E647 standard. The calculated values of da/dN and ΔK were then plotted in logarithmic curves so that the material constant (C) and the exponential constant (m) were obtained. The exponential constant (m) represents the slope of the curve and is known as Paris constant. In general, the curve part which is considered for the m calculation is a linear part which has a regular crack propagation rate. The Paris constant is the value which is used to characterize the fatigue crack growth rate where it illustrates how fast the crack is propagating. The greater the Paris constant (m), the faster the crack propagation [31].

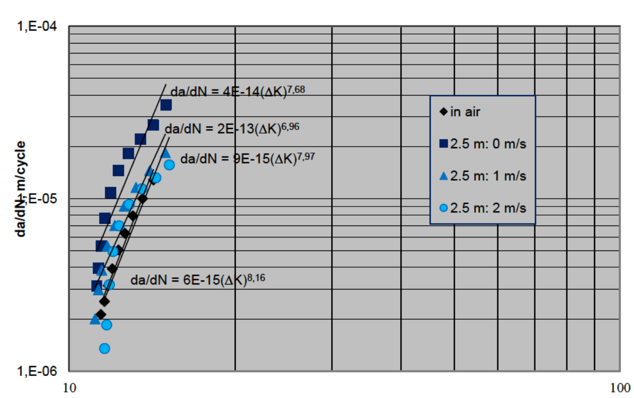


Figure 8: da/dN - ΔK diagram for underwater wet welding in water depth of 2.5 m.

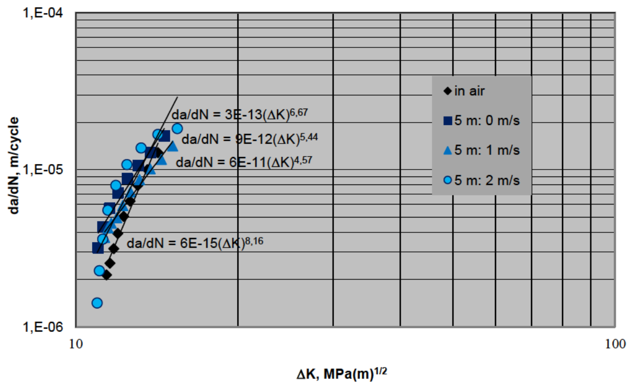


Figure 9: da/dN - ΔK diagram for underwater wet welding in water depth of 5 m.

Table 3: Paris constant (m) and material constant (C)

No.	Spcimen	Material constant (C)	Paris constant (m)
1.	In air (A)	6×10^{-15}	8.16
2.	2.5 m; 0 m/s (B)	4×10^{-14}	7.68
3.	2.5 m; 1 m/s (C)	2×10^{-13}	6.96
4.	2.5 m; 2 m/s (D)	9×10^{-15}	7.97
5.	5 m; 0 m/s (E)	9×10^{-12}	5.44
6.	5 m;1 m/s (F)	6×10^{-11}	4.57
7.	5 m; 2 m/s (G)	3×10^{-13}	6.67

Figure 8 and 9 show the relationship between the fatigue crack growth rate (da/dN) and the stress intensity factor (ΔK) for in air welding and underwater wet welding in water depth 2.5 m and 5 m respectively. It is known that in air welding specimen has Paris constant (m) of 8.16 and material constant (C) of 6×10^{-15}. Paris constants (m) and material constants (C) for all fatigue crack growth rate test specimens are presented in Table 3.

Based on the data in Table 3, it is seen that material constant (C) is varying and there is no certain correlation trend between C and welding condition. Material constant (C) is parameter which illustrates the material resistance to initial crack formation. Since the notch of all fatigue test specimens were deliberately machined, the condition of the notch tip greatly influenced the initial crack formation during cyclic loading. Shortly after the actual crack is formed, it will propagate according to the conditions of each material. This crack propagation is represented by the value of the Paris constant (m). Based on the Paris constant in Table 3, it can be seen that the crack propagation rate of on land welded joint generally is higher than all of underwater wet welded joints. It means that the crack in on land weld metals will propagate faster than in underwater wet weld metals. Based on our previous research [19, 32], the main microstructure of underwater wet weld metal was acicular ferrite which had small grain and good toughness. It will resist the movement of propagation crack. Conversely, weld metal of in air welding had coarse grain boundary ferrite and polygonal ferrite in which cracks can propagate easily.

In case of underwater wet welding, the fatigue crack growth rate decreases as increasing the water depth due to the increased cooling rate during the welding process. Muhayat *et al.* (2020) presented the continuous cooling transformation (CCT) diagram of low carbon steel and showed that thermal cycle of underwater wet welding in water depth of 5 m and 10 m will pass through the acicular ferrite region for more time and allow more opportunities for acicular ferrite to be formed [32]. Gao *et al.* [16] and Barbosa *et al.* [33] stated that the acicular ferrite (AF) structure contributes to the resistance of the fatigue crack propagation and increases the tensile strength of underwater welded joints. In addition, the acicular ferrite (AF) can also function as an interlocking structure that can inhibit the propagation of cracks.

Beside the water depth, water flow also affects the cooling rate of welding process. Therefore, underwater wet welding in flowing water with flow speed of 1 m/s has more acicular ferrite structure than that in without flow water. Consequently, weld metal of underwater wet welding in flowing water of 1 m/s has higher tensile strength and resistance of the fatigue crack propagation than that in without flow. It is evidenced by the Paris constant (m) whereas weld metal of underwater wet welding in flowing water of 1 m/s has lower Paris constant (m) than that in without flow both in water depth of 2.5 m and 5 m. However, if velocity of flowing water is increased, turbulence flow will occur around the weld arc so it will disturb the stability of weld arc, consequently increase weld defects. It is proven by radiographic test which showed that underwater wet weld metal in water flow of 2 m/s has more weld defects in the form of undercuts and porosity. According to Ottersboc *et al.* [34], undercut defects reduce the strength of a material, while Fomin *et al.* [35] and Arias [36] stated that porosity can accelerate the propagation of fatigue cracks. Another factor that affects the increase of the fatigue cracks growth rate is an inclusion in underwater wet welding.

The failure of the fatigue specimen is caused by repeated loading. The failure mechanism in fatigue testing can be divided into three stages, namely the crack initiation, the crack propagation and the final fracture. Fractographic observations were carried out in the fatigue crack propagation area. The propagation of fatigue cracks is initiated with the opening of the cracks because of shift in the crystal field due to increasing stress concentration. Furthermore,

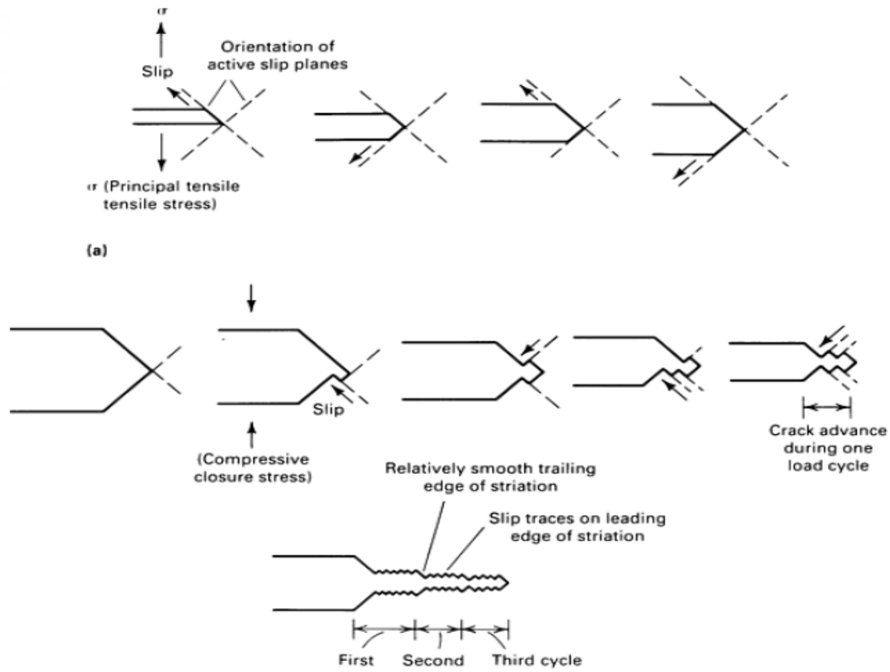


Figure 10: Failure mechanism in fatigue testing [37].

when there is an increase load, the tip of the crack will blunt and then become sharp again when fatigue load decreases. Figure 10 shows the mechanism of fatigue crack propagation.

Figure 11 shows the fatigue fracture surface of in air welded joint. Fatigue fracture is characterized by microscopic striation. The distance of striation indicates the crack propagation rate. The longer distance of striation, the faster crack propagation and vice versa [33, 38]. Figure 12 and 13 are the fatigue fracture surface of underwater welded joint in water depth of 2.5 and 5 m respectively. The surfaces fracture of fatigue crack growth rate test supported the data of Paris constant, where the surface fracture of in air welded joint specimen had coarse striation while that of underwater wet weld specimens had fine striation. The coarse striation represents the high crack growth rate while the fine striation represents the low crack growth rate. The figures also show that inclusion appeared in underwater wet welding with flowing water of 2 m/s both in water depth of 2.5 and 5 m. Inclusion is oxides and other non-metallic objects that are trapped in the weld metal [23, 37, 39]. During the underwater wet welding process, the spherical inclusions are pushed into the molten metal by the water flow and then trapped due to very high cooling rate of weld metal. Inclusion has a negative impact on weld metal, because it can reduce fatigue strength due to micro void (air bubbles) on the edges of the inclusion [14, 37]. During the fatigue test, the stress will concentrate on the micro void around the inclusion so the crack will initiate. It will continue to propagate, then merge with other cracks to make macrocrack and finally make specimen fail [14, 23]. This mechanism is illustrated in Figure 14.

During taking data analysis of underwater wet welded joint test, it is found that there was interesting relationship between tensile strength and fatigue crack growth rate. By taking the tensile test of underwater welded joints [19], the relationship between tensile strength and fatigue crack growth rate represented by Paris constant can be illustrated in Figure 15. It shows that there is a proportional relationship between tensile strength and fatigue crack growth rate. Sample with low tensile strength has high Paris constant and vice versa. Material with low tensile strength means it has low grain bonding force so crack will propagate easily when it has initial crack.

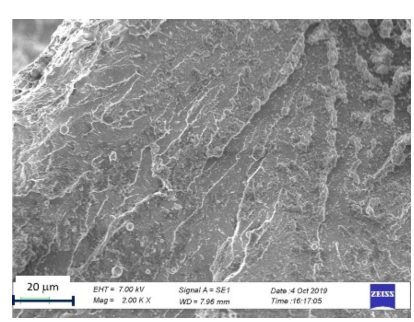
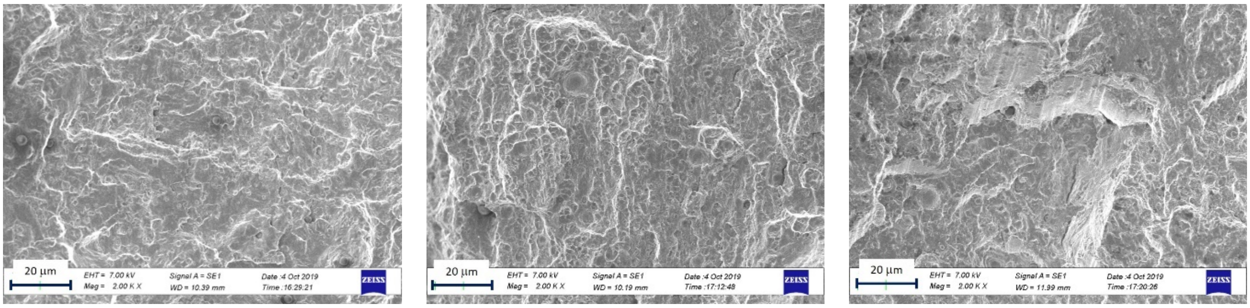
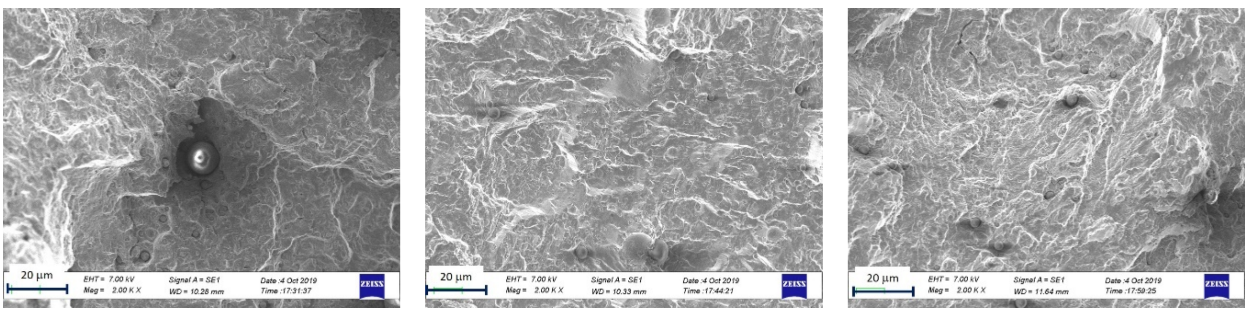


Figure 11: Fatigue fracture surface of on land weld.



(a) 0 m/s **(b)** 1 m/s **(c)** 2 m/s

Figure 12: Fatigue fracture surface of underwater wet welding in water depth of 2.5 m.



(a) 0 m/s **(b)** 1 m/s **(c)** 2 m/s

Figure 13: Fatigue fracture surface of underwater wet welding in water depth of 5 m.

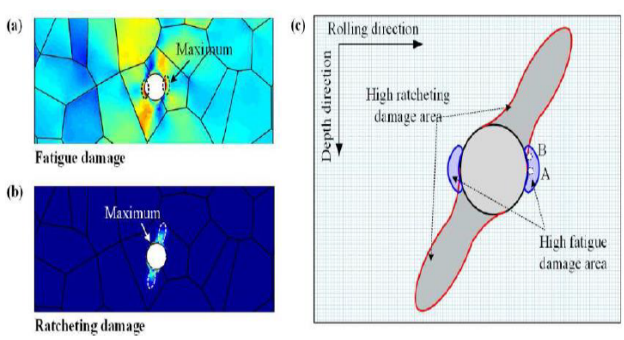


Figure 14: Mechanism of crack propagation around the inclusion [23].

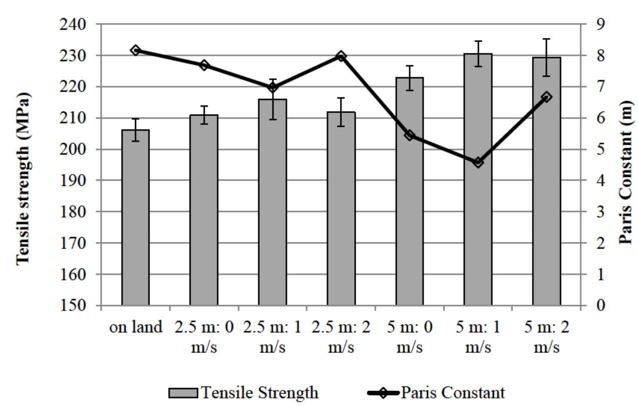


Figure 15: Relationship between tensile strength and Paris constant.

4 Conclusions

The conclusions obtained from this study are as follows:

1. There were many kinds of underwater wet welding defects such as incomplete penetration (I), spatter (S), porosity (P), undercut (U), concavity (V), and irregular surface (Z) defects.
2. Fatigue crack growth rate of on land welded joint is higher than that of underwater wet welded joint.
3. Fatigue crack growth rate of underwater wet weld decreased as increasing water depth due to the formation of acicular ferrite structure.
4. Fatigue crack growth rate of underwater wet weld decrease as increasing velocity of flowing water due to the defects.

Acknowledgement: Authors would like to thank a lot to University of Sebelas Maret, Surakarta, Indonesia for providing many facilities and financially supporting through Mandatory Research 2020 grant with Contract No. 452/UN27.21/PN/2020.

References

[1] Sun, Q.J., Cheng, W.Q., Liu, Y.B., Wang, J.F., Cai, C.W., Feng, J.C. (2016) Microstructure and mechanical properties of ultrasonic assisted underwater wet welding joints, *Mater. Des.*, 103, 63-70.

[2] Chen, H., Guo, N., Huang, L., Zhang, X., Feng, J., Wang, G. (2019) Effects of arc bubble behaviors and characteristics on droplet transfer in underwater wet welding using in-situ imaging method, *Mater. Des.*, 170, 107696.

[3] Wang, J., Sun, Q., Pan, Z., Yang, J., Feng, J. (2019) Effects of welding speed on bubble dynamics and process stability in mechanical constraint-assisted underwater wet welding of steel sheets, *J. Mater. Process. Technol.*, 264, 389-401.

[4] Guo, N., Du, Y., Feng, J., Guo, W., Deng, Z. (2015) Study of underwater wet welding stability using an X-raytransmission method. *J. Mater. Process. Technol.*, 225, 133-138.

[5] Fydrych, D., Świerczyńska, A., Rogalski, G., Łabanowski, J. (2016) Temper Bead Welding of S420G2+M Steel in Water Environment, *Adv. Mater. Sci.*, 16: 4, https://doi.org/10.1515/adms-2016-0018

[6] Tomków, J., Fydrych, D., Rogalski G. (2020) Dissimilar underwater wet welding of HSLA steels, Int. J. Adv. Manuf. Technol., 109:717–725, https://doi.org/10.1007/s00170-020-05617-y

[7] Chen, H., Guo, N., Shi, X., Du, Y., Feng, J., Wang, G. (2018) Effect of water flow on the arc stability and metal transfer inunderwater flux-cored wet welding, *J. Manuf. Process.*, 31, 103 – 115.

[8] Zhang, Y., Jia, C., Zhao, B., Hu, J., Wu, C. (2016) Heat input and metal transfer influences on the weld geometry and microstructure during underwater wet FCAW, *J. Mater. Process. Technol.*, 238, 373 – 382.

[9] Guo, N., Xu, C., Guo, W., Feng, J. (2015) Characterization of spatter in underwater wet welding by X-ray transmission method, *Mater. Des.*, 85, 156-161.

[10] Johnson (1997) The effect of water temperature on underbead cracking of underwater wet weldments, Naval Posgraduate School, Monterey, Calofornia.

[11] Matien, Y.A., Triyono, Muhayat, N., Saputro, Y.C.N. (2019) Effect of water depth on the microstructure and tensile strength of the 5 G position underwater wet welded low carbon steel, *AIP Conference Proceedings*, 2097, 030044.

[12] Bandgar, S., Gupta, C., Rao, G., Malik, P., Singh, R.N., Sridhar, K. (2019) Fatigue Crack Growth Rate Behaviour of HSLA Steel at Varying Load Amplitudes, *Structural Integrity*, 14, 330–336.

[13] Li, Z., Zhoua, S., Yang, C., Yonga, Q. (2019) High/very high cycle fatigue behaviors of medium carbon pearlitic wheel steels and the effects of microstructure and non-metallic inclusions, *Mater. Sci. Eng. A*, 764, 138208.

[14] Gu, C., Lian, J., Bao, Y., Xie, Q., Münstermann, S. (2019) Microstructure-based fatigue modelling with residual stresses: Prediction of the fatigue life for various inclusion sizes. *Int. J. Fatigue*, 129, 105158.

[15] Li, H., Liu, D., Yan, Y., Guo, Liu, Y., Feng, J. (2018) Effects of heat input on arc stability and weld quality in underwaterwet flux-cored arc welding of E40 steel, *J. Manuf. Process.*, 31, 833-843.

[16] Guo, N., Xing, X., Zhao, H., Tang, C., Feng, J., Deng, Z. (2016) Effect of water depth on weld quality and welding process in underwater fiber laser welding. *Mater. Des.*, 115, 112 – 115.

[17] Xu, C., Guo, N., Zhang, X., Jiang, H., Chen, H., Feng, J. (2019) In situ X-ray imaging of melt pool dynamics in underwater arc welding, *Mater. Des.*, 179, 107899.

[18] Yasinta, S., Triyono, Muhayat, N., Saputro, Y.C.N. (2020) Effect of water depth and water flow on the physics and mechanic properties of the underwater wet welded low carbon steel with post weld heat treatment, AIP Conference Proceedings, 2217, 030093

[19] Paundra, F., Anindito, J., Muhayat, N., Saputro, Y.C.N., Triyono, (2020) Effect of water depth and flow velocity on microstructure, tensile strength and hardness in underwater wet welding, IOP Conf. Series: Mater. Sci. Eng., 833(1), 012084.

[20] Chen, H., Guo, N., Shi, X., Du, Y., Feng, J., Wang, G. (2018) Effect of hydrostatic pressure on protective bubble characteristic and weld quality in underwater flux cored wire wet welding, *J. Mater. Process. Technol.*, 259: 2, 159–168.

[21] Liu, X., Wang, G., Shi, Y., Zhong, J. (2007) Finite element simulation of three-dimensional temperature field in underwater welding, *Int. J. Adv. Manuf. Technol*, 16, 59-65.

[22] Li, H. L., Liu, D., Yan, Y. T., Guo, N., Feng, J. C. (2016) Microstructural characteristics and mechanical properties of underwater wet flux cored wire welded 316l stainless steel joints, *J. Mater. Process. Technol.*, 238, 423–430.

[23] Wang J., Sun Q., Ma J., Teng J., Jin P., Feng J. (2019) Investigation of acoustic radiator affecting bubble acoustic interaction in ultrasonic wave assisted uww at shallow water, *J. Manuf. Process.*, 37, 563-577.

[24] Surojo, E. Wicaksana, N. I., Saputro, Y.C.N., Budiana, E.P., Muhayat, N., Triyono, Prabowo, A.R. (2020) Effect of welding parameter on the corrosion rate of underwater wet welded SS400 low carbon steel, *Applied Sciences*, 10: 17.

[25] Di, X., Ji, S., Cheng, F., Wang, D., Cao, J. (2015) Effect of cooling rate on microstructure, inclusions and mechanical properties of weld metal in simulated local dry underwater welding, *Mater. Des.*, 88, 505-513.

[26] Incropera, F. P., Dewitt, D. P., Bergman, T. L., Lavine, A. S. (2011) Fundamentals of heat and mass transfer, 7th ed. New York: John Wiley and Sons.

[27] Fydrych, D., Świerczyńska, A., Rogalski, G. (2015) Effect of underwater wet welding conditions on the diffusible hydrogen content in deposited metal, *La Metallurgia Italiana*, 107: 11-12, 47–52.

[28] Shi, Y., Hu, Y., Yi, Y., Lin, S., Li, Z. (2017) Porosity and microstructure of underwater wet fcaw of duplex stainless steel, *Metallogr. Microstruct. Anal.*, 6: 5, 383–389.

[29] Świerczyńska, A., Fydrych, D., Rogalski, G. (2017) Diffusible hydrogen management in underwater wet self-shielded flux cored arc welding, *Int. J. Hydrogen Energy*, 42: 38, 24532-24540.

[30] Klett, J., Linowitzki, V.H., Grünzel, O., Schmidt, E., Maier, H. J., Hassel, T. (2020) Effect of the water depth on the hydrogen content in SMAW wet welded joints, *Applied Sciences*. 2, 1269 https://doi.org/10.1007/s42452-020-3066-8

[31] Yu, S., Yan, J., Li, H., Ding, R., Lall, A., Rabiei, A., Bowen, P. (2020) Fatigue crack growth resistance of the austeniticstainless steel Alloy 709 at elevated temperatures, *J. Mater. Res. Technol.*, 9, 12955-12969, https://doi.org/10.1016/j.jmrt.2020.09.050

[32] Muhayat, N., Matien, Y.A., Sukanto, H., Saputro, Y.C.N., Triyono (2020) Fatigue life of underwater wet welded low carbon steel

SS400, *Heliyon*, 6: 2.
[33] Barbosa, L.H.S., Modenesi, P.J., Godefroi, L.B., Arias, A.R. (2019) Fatigue crack growth rates on the weld metal of high heat input submerged arc welding. *Int. J. Fatigue*, 119, 43-51.
[34] Ottersbock, M.J., Leitner, M., Stoschka, M., Maurer, W. (2016) Effect of weld defects on the fatigue strength of ultra high-strength steels. *Procedia Engineering*, 160, 214-222.
[35] Fomin, F., Kashaev, N. (2017) Influence of porosity on the hight cycle fatigue behaviour of laser beam welded Ti-6Al-4V butt joint. *Procedia Structural Integrity*, 7, 415-422.
[36] Arias, A. R., Bracarense, A., Q. (2017) Fatigue Crack Growth Assessment in Underwater Wet Welds, *Welding J.*, 96, 287-294.
[37] Gao, G., Xu, Q., Guo, H., Gui, X., Zhang, B., Bai, B. (2019) Effect of inclusion and microstructure on the very high cycle fatigue behaviors of high strength bainite/martensite multiphase steels. *Mater. Sci. Eng. A*. 739, 404-414.
[38] Gao, W., Wang, D., Cheng, F., Deng, C., Liu, Y., Xu, W. (2015) Enhancement of the fatigue strength of underwater wet welds by grinding and ultrasonic impact treatment. *J. Mater. Process. Technol.* 223, 305-312. https://doi.org/10.1016/j.jmatprotec.2015.04.013
[39] Luiz, A. (2018) Non-metallic inclusions in steels-origin and control, *J. Mater. Res. Technol.* 7: 3, 283-299.