Effect of Water Depth and Flow Velocity on Microstructure, Tensile Strength and Hardness in Underwater Wet Welding

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Abstract. Wet underwater welding is a welding process carried out under water. The depth and water flow velocity greatly affect the welding results. Thus, a further research needs to be done about the effect of the depth and water flow velocity of underwater wet welding. The research aimed to determine the effect of depth and velocity of water flow on underwater wet welding on physical and mechanical properties. The welding process is carried out by using SMAW method at a depth of 2.5 m and 5 m with variations in water flow velocity of 0, 1, and 2 m/s. Land welding is performed as a comparison. X-ray radiography, micro-structure, tensile strength, and Vickers hardness test were performed to determine the type of welding defects. Radiographic test results indicate an incomplete penetration defect (I), spatter (S), porosity (P), undercut (U), concavity (V), and irregular surface (Z). The results of the micro-structure test show that the grain size is fine and coarse as the depth and velocity of the water flow increase. Tensile strength and micro-hardness testing increase along with an increasing depth and velocity of water flow.

1. Introduction
Underwater welding is a welding process carried out under water. Based on the method, underwater welding can be divided into underwater wet welding and underwater dry welding method [1-3]. Underwater dry welding is a process of underwater welding in dry conditions. This welding is usually undertaken in the chamber [4-5].

Underwater wet welding is performed in the water environment where the welder, workpiece, and electrode are in direct contact with water [2-3]. Underwater welding is widely used in maintenance, offshore construction, platforms, and nuclear power plants [6-7]. This welding has many advantages, including that fact that it is simple and cheap [8]. However, underwater wet welding has a disadvantage as well, in which welding defects are easily occurred [6, 9-10].

Information about underwater wet welding research is still minimal. In previous research, underwater wet welding was carried out on a laboratory scale, where the depth was less than 1 meter without water flow [7, 11-12]; so, the previous research was considered unsuitable to represent the real situation. Therefore, further research was conducted to determine the effect of water flow velocity and depth of underwater wet welding on physical and mechanical properties. The objective of this study is to determine the effect of welding depth and water flow velocity on underwater wet welding towards its micro-structure, hardness and tensile strength.
2. Experimental Methods

In this research, a low carbon steel type SS400 was used as a base metal (BM). The dimension of the welding specimen is 100 x 400 x 4 mm, with a butt joint welding type. Welding specimen are shown in Figure 1.

![Figure 1. Welding specimen (in mm)](image)

The underwater wet welding process was carried out in Solo Techno Park (STP) by certified welder. The welder was also an instructor at that compound who already has welding experiences. The welding process used was Shielded Metal Arc Welding (SMAW) type DCRP, with a nominal current of 90A and electrode type of E6013 with a diameter of 4mm. Underwater wet welding was carried out at a depth of 2.5 m and 5 m using variations in water flow velocity of 0, 1, and 2 m/s, and land welding as a comparison. The water nozzle was placed with a distance of 15 cm from the welding metal and water spraying was arranged so that the flow velocity was constant. The difference in depth affects the temperature difference. At a depth of 2.5 m, it has a temperature of 25.5°C, and at depth of 5 m it is 24.5°C. Table 1 shows the variables of the research.

| Code | Depth of water (m) | Water flow velocity (m/s) | Temperature (°C) | Total |
|------|-------------------|---------------------------|------------------|-------|
| A    | 0                 | 0                         | 32               | 1     |
| B    | 2.5               | 0                         | 25.5             | 1     |
| C    | 2.5               | 1                         | 25.5             | 1     |
| D    | 2.5               | 2                         | 25.5             | 1     |
| E    | 5                 | 0                         | 24.5             | 1     |
| F    | 5                 | 1                         | 24.5             | 1     |
| G    | 5                 | 2                         | 24.5             | 1     |

Figure 2 shows the underwater wet welding process. Figure 2a is the process of welding without water flow, while 2b shows the welding process of variations in water flow velocity. After the welding process, radiographic X-ray, micro-structure, Vickers hardness and tensile testing were carried out. Tensile testing was carried out using UTM tools with the JIS Z 2201 standard test and micro-hardness testing using Highwood machine with 9.8 N and ASTM E384 standard.

![Figure 2. Welding process (a) without water flow, (b) with water flow.](image)
3. Result and discussion

3.1. Chemical composition
The material used in this research was low carbon steel SS400. Before welding, the material was tested to determine its composition. Table 2 shows the results of the chemical composition test.

| Chemical | Fe   | C    | Si   | Mn   | P    | Cr    | Cu   |
|----------|------|------|------|------|------|-------|------|
| (%)      | 96.4 | 0.0337 | 0.193 | 0.288 | 0.0018 | 0.0273 | 0.0136 |

3.2. X-Ray Radiographic
Welding defect examination was carried out using X-ray radiography. Figure 3 shows the results of X-ray radiographic testing conducted at PT. Robutech Surabaya.

Radiographic test results indicate the presence of various types of welding defects. The types of defects include incomplete penetration (I) that occurs in all welded joints, spatter (S), porosity (P), undercut (U), concavity (V), and irregular surface (Z).
The results of land welding and underwater wet welding show incomplete penetration defects. Incomplete penetration (I) is the lack of penetration in the welding area. This greatly affects the results of welding because it can reduce its mechanical strength. This defect occurs because the welding current is too small, and the electrode distance is too far apart. Spatter defects are welding sparks; this happens because the electrode and base metal are too far apart. The results of the test show that there is more spatter in land welding than in underwater wet welding.

Underwater wet welding is susceptible to porosity. Porosity is a small hole in the weld metal. Porosity in underwater wet welding occurs due to hydrogen inclusion. Hydrogen inclusion is caused by direct contact between water and electricity arcs at high temperatures forming gas particles. Rapid freezing will cause gas particles to be trapped in the metal, which results in porosity[13,14].

Undercut and concavity are conditions where the surface of the weld metal is lower than the base metal, which occurs in underwater wet welding due to lack of filler metal. They are shown in Figure 3 (b, c, d, f, and g), and concavity are presented in Figure 3 (c, d, f, and g). The most common undercut and concavity defects occur at a flow velocity of 2 m/s. The undercut is more common in welding with water flow. The undercut is a groove between weld metal and base metal that is not filled with welded molten metal due to high heat of the welded molten metal. This occurs as a result of an increased welding heat dissipation caused by high-water flow velocity, which results in a decrease of arc temperature and arc shrinkage [15]. High water flow velocity (2 m/s) results in many irregular surface defects. Irregular surface defects are shown in Figure 3 (d and g), which are weld surface conditions that contain notches or abrupt changes in thickness or appearance, in convex and concave surfaces. These conditions occur with variations in size that are too high. Irregular surface occurs due to poor welding arc stability with fluctuations in amperage and volts as water flow velocity increases. The irregular surface also occurs due to the process of liquid metal arc transfer, which is not good due to high water flow and protective bubbles that are less stable.

3.3. Microstructure
Figure 4 (a) is a base metal microstructure of SS400 material. In the picture, it can be observed that the morphology of base metal microstructures are ferrite and pearlite. The ferrite structure has a low hardness and ductile strength, while the pearlite structure has a stronger and harder tensile strength and more brittle than ferrite [16, 17]. Figure 4 (b-h) shows the weld metal area of the welding results with variations in depth and water flow velocity. Weld metal consists of four types of mixed ferrite; grain boundary ferrite (GBF), ferrite with the second phase (FSP), acicular ferrite (AF) and polygonal ferrite (PF). Underwater wet welding with a higher flow of water causes a higher cooling rate[18]. Uneven cooling rates and lower ambient temperatures cause the micro-structure of weld metal regions to be non-uniform and contain less PF. Increased welding heat input results in increasing grain size with a reduced relative amount of FSP and AF and increased GBF and PF. The width of GBF and FSP also increases with the increase in welding heat input. Increased welding heat input means reduced cooling rate during the welding process. FSP has properties with low impact values and low elongation percentage values. AF has high tensile strength and hardness properties and a good impact value compared to PF and GBF.

Figure 4 (b) shows the weld metal area of land welding results containing PF, FSP, and GBF. FSP and GBF have the biggest size compared to welding in water caused by slow cooling speeds. Microstructure has a lot of PF but there is no AF. Weld metal welding in water with a depth of 2.5 m without flow shows a smaller structure of GBF and FSP as seen in Figure 4 (c) than welding on land and the presence of AF structures started to emerge. Increasing the velocity of water flow up to 1 m/s in welding with a depth of 2.5 m results in the smaller and flatter GBF and FSP structures shown in Figure 4 (d). Many AF structures emerge with a reduced PF structure. The flow velocity of 2 m/s at a depth of 2.5 m causes the GBF structure does not appear but the AF structure becomes more numerous and the PF structure also multiplies.

Underwater wet welding at 5 m depth has a slightly different micro-structure than that of welding at 2.5 m depth. The results of welding without flow when compared to that of 2.5 m depth have a
smaller and flatter GBF and FSP micro-structure. A depth of 5 m with a flow velocity of 1 m/s results in FSP and AF which are denser than 2.5 depth. The microstructure of the flow velocity of 2 m/s at a depth of 5 m contains more FSP and AF compared to that of in a depth of 2.5 m and in a depth of 5 m with a flow velocity of 1 m/s or without flow. The amount of PF decreases due to insufficient time to develop. The presence of AF and FSP are the main factors in weld metal areas which have high tensile strength. The more AF structures the weld metal will produce higher tensile strength values[17, 19]. Thus, based on observations of micro-structure, welding with a depth of 5 m and a flow velocity of 2 m/s produces a high tensile strength.

Figure 4. Microstructure of base metal and weld metal.

Figure 5 shows a HAZ area consisting of ferrite and pearlite. The increasing depth and velocity of water flow results in small and smooth micro-structures. The fine grains are found in underwater wet welding with a depth of 5 m and a water flow velocity of 2 m/s as in Fig 5 (g). The base metal has a larger grain size compared to the HAZ area performed on land welding. Based on Figure 5 (a and b) the grain size on land welding has a much rougher size than underwater wet welding. An increase in water flow velocity causes an increase in the cooling rate and a reduction in welding heat input. The cooling rate is very fast as a grain growth and causes grain size to be finer and coarser than welding on land.

The mechanical properties of metals are influenced by micro-structure. The grain size of the weld metal will change according to the cooling rate. An increase in cooling rate will result in fine and coarse grain sizes. The small grain size causes increased tensile strength and hardness[20]. Based on the results of the micro-structure, the welding depth of up to 5 m has a greater effect on changes in the micro-structure compared to that of the influence of flow rates up to 2 m/s. Welding protective
bubbles which rise more quickly to the surface result in more frequent metal contact with water which increased the cooling rate.

![Micrographs of HAZ microstructure](image)

(a) HAZ land welding  
(b) HAZ 2.5 m; 0 m/s  
(c) HAZ 2.5 m; 1 m/s  
(d) HAZ 2.5 m; 2 m/s  
(e) HAZ 5 m; 0 m/s  
(f) 5 m; 1 m/s  
(g) HAZ 5 m; 2 m/s

**Figure 5.** HAZ microstructure.

3.4. Micro-Vickers

Micro-Vickers testing was conducted at three different points, namely weld metal, HAZ and base metal. Figures 6 (a and b) show the results of the micro-Vickers test. The lowest value of hardness is found in welding performed on land with the highest hardness value in the weld metal region of 131.4 HV, HAZ area 139.5 HV, and base metal 108 HV; whereas the highest hardness is observed in underwater wet welding with a depth of 5 m at 2 m/s of water flow velocity, with the highest hardness in the weld metal area of 188.8 HV, HAZ area 233.7 HV, and base metal 110.7 HV. Underwater wet welding with the lowest hardness is found in welding with a depth of 2.5 m without water flow. The highest hardness value in the weld metal area is 141.7 HV, HAZ 157 HV area, and base metal 109.6 HV.

Increasing the welding depth from 2.5 m depth to 5 m significantly affects the hardness, as presented in Figures 6. The depth of welding has a greater effect than the increase in water flow velocity on the hardness value in the weld metal and HAZ area. The HAZ area of welding with a depth of 2.5 m at a flow velocity of 2 m/s has the highest hardness of 170.6 HV, while the highest hardness at a depth of 5 m with a flow of 2 m/s is 233.7 HV.

The increase in hardness of the weld joint along with an increase in water depth and speed of water flow is caused by an increase in the cooling rate or due to reduced heat input. This happens because of weld metal and base metal came into direct contact with water and forced convection occurs due to
Increasing the welding depth causes the protective bubbles to rise to the surface so that the weld joint is exposed to water directly more frequently. Increased cooling rate or reduced heat input will cause the increasing of AF and FSP growth. Increased AF and FSP contribute to an increase in the hardness of underwater wet welding joints. Reduction of heat input due to rapid cooling produces small and smooth grains that will increase hardness and strength in the HAZ.

3.5. Tensile Strength

Tensile testing was carried out to determine the tensile strength of the welded joint. Figure 7 shows the results of the weld joint tensile test. The graph shows that the value of tensile strength in land welding is below the average of the one in underwater wet welding. This happens because the welding of the land has a deeper but less penetration than that of the underwater wet welding.

The tensile strength value of underwater wet welding increases with the addition of variations in depth and water flow velocity. The smallest tensile strength occurs at a depth of 2.5 m without flow, with a tensile strength of 206 N/mm². The highest tensile strength value was obtained at a depth of 5 m with a variation of flow velocity of 1 m/s, which is 230.52 N/mm². Increased tensile strength in underwater wet welding is due to the increasing number of ferrite with the second phase (FSP) and acicular ferrite (AF) structures. Ferrite with the second phase (FSP) and acicular ferrite (AF) structures are formed due to very fast cooling [19]. Another factor influencing the increase in tensile strength is grain size. In underwater wet welding, the cooling speed increases with the addition of depth and water flow velocity. An increase in cooling speed will result in finer grain sizes.
4. Conclusions

X-ray radiographic test results showed a defect in the welding joints. The defects include incomplete penetration (I) occurred at all welded joints, spatter (S), porosity (P), undercut (U), concavity (V), and irregular surface (Z). Porosity increased with increasing depth and velocity of water flow. Microstructure investigation showed that increasing the depth and flow velocity of water increased the formation of AF and FSP structures. On the other hand, the rapid cooling rate performed the stunted grain growth which results in a fine and coarse grain size. The micro-hardness of the underwater wet weld joint increased as increase of water depth and flow velocity. The welding depth of 5 m with a flow velocity of 2 m/s has the highest Vickers hardness in the weld metal and HAZ, in which the highest hardness weld metal and HAZ area were 188.8 and 233.7 HV respectively. Tensile strength of the underwater wet welding joint increased due to water depth and water flow velocity. The lowest tensile strength was 206.13 N/mm² and obtained by specimens welded at a water depth of 2.5 m without flow while the highest tensile strength was 230.52 N/mm² and obtained by specimens welded at a water depth of 5 m with a flow velocity of 1 m/s.

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