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Effect of welding parameters on weld bead shape for welds done underwater

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Abstract: The desire to model a control system so as to optimize the welding process parameters and the effect of the environment during underwater wet welding makes it necessary to study the effects of these parameters as it affects the weld bead geometry of welds achieved in underwater welding. The objective of this paper is to analyze how welding arc current, voltage, speed, and the effect of the water environment affect the weld bead geometry such as bead width, penetration, and reinforcement height. Comparing the differences of the effects of welding input parameters for air and wet welding as it affects the welding output quality parameter is the method employed in this research paper. The result of this study will give a better understanding of applying control mechanism in predicting the quality of a weld during underwater welding. A clearer insight of the weldability of structural steels for offshore applications as it relates to underwater welding, having a full knowledge of the nonlinear multivariable parameters is indicative of better control methods.

Keywords: Bead Geometry, Process Parameter, Water Depth, Water Temperature, Underwater Welding

1. Introduction

Underwater welding is used for repair welding of ships and other offshore engineering structures. The quality of welds achieved from underwater wet welding faces some quality challenges because of the rapid cooling of the weld by the water surrounding the weld zone. There is reduction in ductility and tensile strength of 50% and 20% respectively of the heat affected zone (HAZ) of welds in underwater welding as compared to air welding [1]. The bead geometry of an underwater weld is important in determining the mechanical properties of a weld joint [2].This paper gives a background for the design of an artificial neural network control of the welding process parameters as it affects the weld bead geometry. The optimization of the welding parameters (Fig. 1) which are nonlinear multivariable inputs will be discussed in the subsequent paper by the author. The water temperature and water depth are not welding process parameters but parameter of the water environment that affects the welding quality of underwater wet welding. The illustration of the weld bead geometry (Fig. 2) parameters, where *W* is the weld bead width (mm), *R* is the height of reinforcement (mm), and *P* is height of penetration (mm). WPSF (penetration shape factor) = *W/P*, WRFF (reinforcement form factor) = *W/R*. The strength of a weld is influenced by the composition of the metal, distortion and also the weld bead shape. The desired weld bead shape is dependent on the heat energy which is supplied by the arc to the base metal per unit length of weld, welding speed, joint preparation and the water environment in the case of wet welding [3, 4].

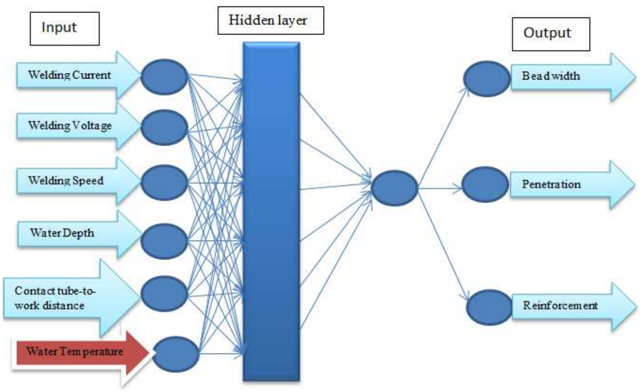


Fig. 1. *Welding input vs output parameters.*

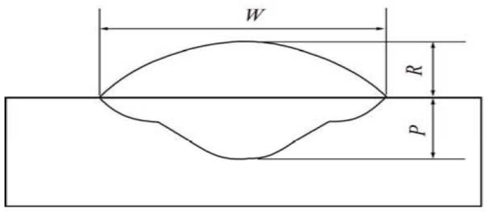


Fig. 2. *Weld bead geometry of underwater wet FCAW [2].*

2. Underwater Welding Processes

2.1. Shielded Metal Arc Welding (SMAW)

Shielded metal arc welding process is one of the most widely used welding processes. The process employs the heat of the arc to melt the base metal and the tip of the consumable covered electrode, and the flux covering the electrode melts during the welding. The melted flux forms gas and slag which act as a shield to the arc and molten weld pool (fig 3). The flux adds deoxidizes, scavengers and alloying elements to the weld metal. The welding current for SMAW can either be alternating current (AC) or direct current (DC) depending on the electrode used. Underwater SMAW uses a DCEN polarity. The use of DC is common in SMAW because of fewer arc outages, less spatter, easier arc starting, less sticking, and better control in out-of-position welds. Underwater welding electrodes are usually water proofed, and the flux creates bubbles during the welding process and displaces water from the welding arc and weld pool area. The welding speed and voltage have to be properly adjusted to create a stable bubble formation by the flux, because the gas bubble makes welding possible underwater. Underwater SMAW process uses two basic techniques known as the self-consuming techniques and the manipulative or weave technique. In the self-consuming technique, the electrode is dragged across the workpiece and pressure is applied by the welder. The manipulative technique, the arc is held as in surface welding and little or no pressure is required on the electrode. The manipulative technique requires more skills than the self-consuming technique [5, 6].

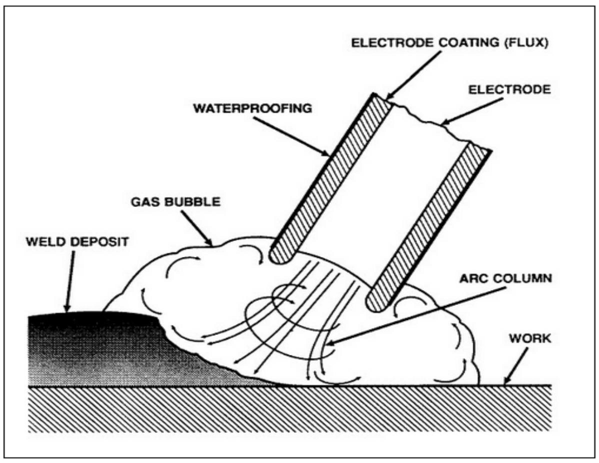


Fig. 3. *Schematic illustration of SMAW process [5].*

2.2. Flux Cored Arc Welding (FCAW)

FCAW uses heat generated by a DC electric arc to join the metal in the joint area. This welding process utilizes a continuously fed consumable welding wire that consists of a metal sheath which is composed of flux and alloying elements (Fig. 4). The flux formed is used to stabilize the welding arc, formation of slag, and produces shielding gas which protects the molten metal transfer and weld puddle as in SMAW process. The shielding in FCAW is achieved either by an additional gas shield supplied from an external source, or by the decomposition of the fluxing agent within the wire also known as self-shielding.The need for automation, out of position welding proficiency, high deposition rate and self-shielding capability has led to the development of underwater FCAW welding process [7]. FCAW technique using rutile type wire has a potential for high deposition rate and can be adapted to automated equipment [8]. The FCAW is suitable for underwater wet welding because of its self-shielding possibilities, ease of automation and out of position welding efficiency.

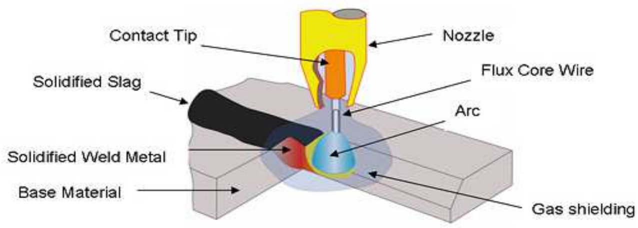


Fig. 4. *Schematic illustration of FCAW process [9].*

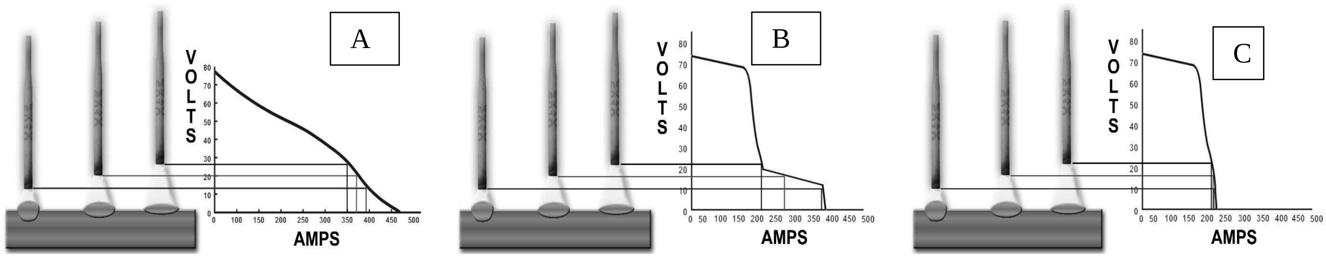
3. Welding Inputs

3.1. Welding Current

Welding current is an important parameter which affects the weld bead shape. The current controls deposition rate because it controls the melting rate of the electrode. The amount of melted base metal, the HAZ, depth of penetration is controlled by the welding current. An increase in welding current increases penetration and reinforcement. A low welding current will lead to unstable arc, low penetration and overlapping. Changing the polarity from direct current electrode posistive (DCEP) to direct current electrode negative (DCEN) affects the amount of heat generated at the electrode and workpiece which affects the metal deposition rate, weld bead geometry and mechanical properties of the weld metal. The positive electrode generates two third of the total heat, while the negative electrode generates one third of the total heat. The DCEN polarity produces higher deposition rate and reinforcement than the DCEP polarity in submerged arc welding. The level of hydrogen absorption in underwater wet welding which results in porosity can be minimized by using low current DCEP or a high current DCEN [3, 10, 11].

3.2. Welding Voltage

The length of the arc between the electrode and molten weld metal determines the variation of the welding voltage. An increase in the arc length increases the voltage. The voltage determines the shape of the weld bead cross section and external appearance. Increasing the voltage at a constant current will result in a flatter, wider, and reduced penetration, which also leads to reduced porosity caused by rust on steels. Increase in arc voltage results to an increase in the size of droplets and thereby reduce the number of droplets. Increase in voltage enhances flux consumption, but a further increase in voltage will increase the possibility of breaking the arc and hinder normal welding process. Increase in arc voltage beyond the optimum value leads to an increase in loss of alloying elements which affects the metallurgical and mechanical properties of the weld metal. Arc voltage beyond the optimum value produces a wide bead shape that is susceptible to cracking, increase undercut and difficulty of slag removal. Lowering the arc voltage results in stiffer arc that improves penetration. Excessively lowering of the arc voltage results in a narrow bead and difficulty of slag removal along the bead edges. A decrease in the welding voltage will decrease the diffusible hydrogen content during underwater welding. In many of the MILLER electric power sources, the constant current output are equipped with a feature called Arc Force, Dig or Arc Control, and Hot Start. In electric arc welding process, as the arc length increases, the voltage increases. The load voltage of a constant current welding machine is controlled by controlling the arc length. However these power sources does not work well for TIG welding process because it is better if the current does not change as the arc length changes in TIG welding. Power sources that have Arc Force (fig. 5B) allow the operator to change the shape of the volt/amp curve to meet the requirement of the operation being performed. Power sources with no Arc Force (fig. 5C) gives a more vertical shape of the volt/amp curve meaning that the current will not change much as the arc length is changed [10, 12-15].



Traditional welding power source Arc Force added to the circuit No Arc Force

Fig. 5. *Electric arc welding power sources [14].*

3.3. Welding Speed

The linear rate at which the arc is moved along the weld joint influences the heat input per unit length of the weld. An increase in the welding speed will decrease the heat input and less filler metal is applied per unit length of the weld, which will result in less weld reinforcement and a smaller weld bead. The welding speed is the most influencing factor on weld penetration than other parameters except welding current. Excessive welding speed may result in porosity, undercutting, arc blow, uneven bead shape, cracking and increased slag inclusion in the weld metal. Higher welding speed results in less HAZ and finer grains. A relatively slow welding speed gives room for gases to escape from the molten metal, thereby reducing porosity. The bead width at any current is inversely proportional to the welding speed. A fast welding speed with low DCEN or high DCEP can minimize the level of porosity in wet welding [10, 11, 16].

3.4. Contact tube-to-Work Distance

Experimental evidence indicate that weld bead geometry is influenced by the change of the contact tube-to-work distance (CTWD) (Fig. 6) during welding. The CTWD influences the formation of the weld pool and the resulting weld shape by changing the arc length and welding current. the arc length which is related to the welding voltage and CTWD are closely related to the weld bead geometry. The convection in the weld pool affects the weld pool geometry. An increase in arc length due to an increase in CTWD increases the bead width because of the widened arc area at the surface of the weld. Increase in arc length reduces the reinforcement height because the same volume of filler metal is used [17].

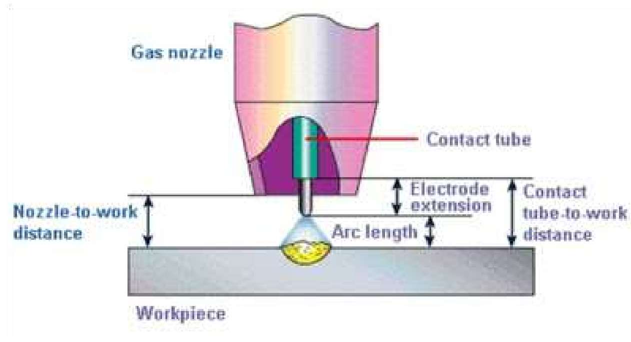


Fig. 6. *Contact tube-to-work distance [18].*

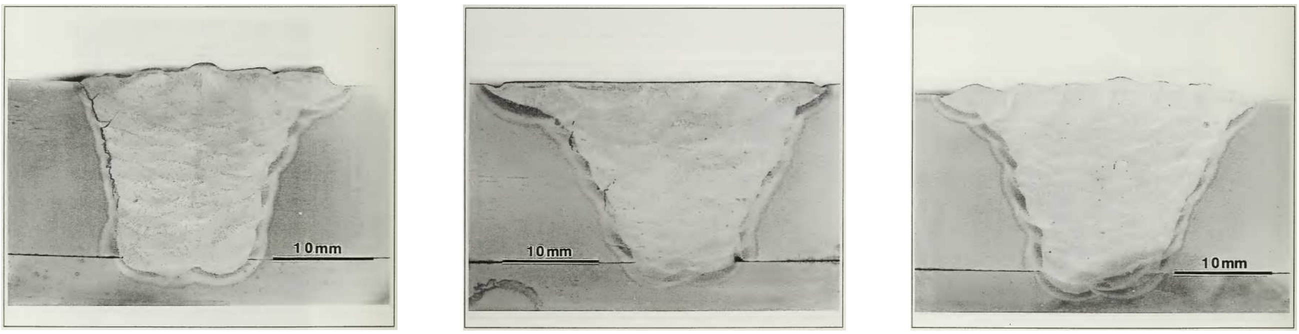
4. Environmental Parameters

4.1. Water Depth

Increased water depth constricts the welding arc resulting in an increased weld penetration on higher rate of filler metal transfer. The arc constriction results in an increased voltage and current as the water depth increases [19]. Weld metal oxygen, carbon, manganese, and silicon are fairly constant at water depth of 50 m to 100 m. oxygen content controls weld metal manganese and silicon content. At depth greater than 50 m, the diameter of the arc column decreases with increasing pressure (depth). Water reaction becomes increasingly important at depth greater than 50 m. The operating process parameter space decreases with increasing depth because high ionization potential for hydrogen makes it difficult to sustain the welding arc [11].

4.2. Water Temperature

The presence of water and the type of water surrounding the weld metal affects the welding process and the resulting temperatures. This effect is due to the greater convective heat transfer coefficient of water as compared to air which results in the rapid cooling in underwater welding [20]. At higher water temperature, for higher oxygen content, the diffusible hydrogen contents are likely to be less thereby, lowering the tendency of hydrogen assisted cracking. When welding at lower water temperature, there are few inclusions resulting in higher diffusible hydrogen level in the coarsed grain heat affected zone which leads to greater cracking tendency. The weldment sample (fig. 6) at 2.8^0C has cracking over two thirds of the weld height. The macrograph shows that the cracking progressed along the HAZ and a bit into the weld metal. At 10^0C the weldment has two cracks on the left hand edge, and the crack starts from the HAZ and unto the weld metal. The macrograph shows that the cracking is perpendicular to the direction of maximum tensile stress as a result of the cooling. The sample test conducted at the highest water temperature of 31^0C shows the highest volume fraction of inclusions of slag and oxide. This resulted in highest porosity level. Again, because of the higher oxygen content leading to lesser diffusible hydrogen content at higher temperature, thereby, resulting in a lower cracking tendency [19]. Underwater weld pool shape differs from air welds because of the heat transfer conditions caused by the cooling effect of the water and the presence of steam bubble [8].



Welded at 2.8^0C water temperature and 6.7 m water depth

Welded at 10^0C water temperature and 5.5 m water depth

Welded at 31^0C water temperature and 7.3 m water depth

Fig. 7. *Macrophotograph of different weld samples [19].*

5. Welding Outputs

5.1. Bead Width

The bead width of a weld is the maximum width of weld metal deposited. This influences the flux consumption rate. The bead width is in direct proportion to the arc current, welding voltage and diameter of the electrode. It is inversely proportional to the welding speed [21, 22].

5.2. Penetration

Penetration is the maximum distance between the top of the base plate and depth of fusion. Penetration is influenced by welding current, welding speed, polarity, electrode stick out, basicity index and physical properties of the flux. Penetration is directly proportional to welding current and inversely proportional to welding speed and diameter of electrode. Increase in thermal conductivity of the weld metal decreases penetration. Deepest penetration is achieved with DCEP polarity than DCEN polarity. A stable arc increases penetration because the arc wander is minimized which allows more efficient heat transfer [19, 20].

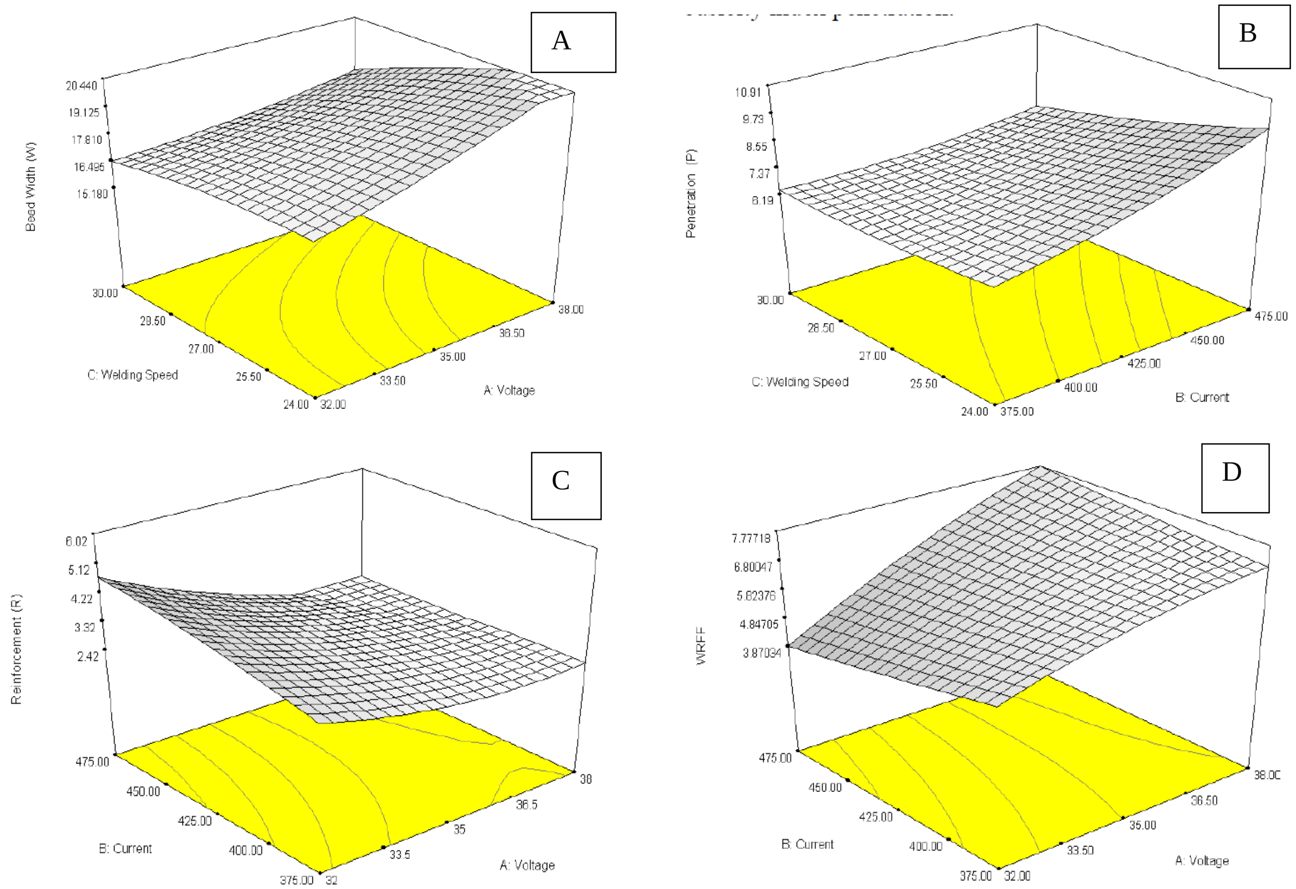
5.3. Reinforcement

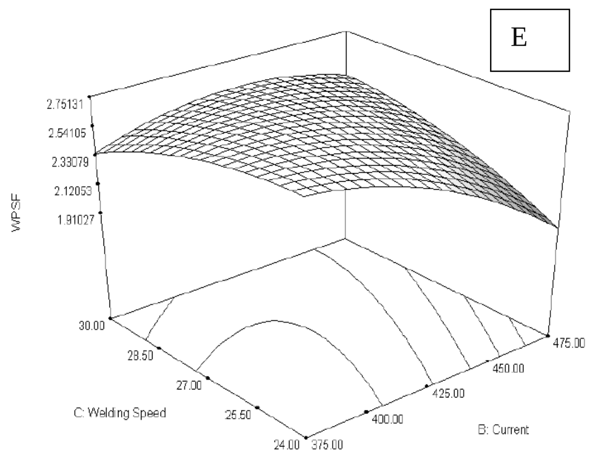
The reinforcement influences the strength of the weld and wire feed rate. Increasing the wire rate increases the reinforcement irrespective of welding current and polarity. Reinforcement is inversely proportional to welding voltage, welding speed and diameter of electrode. A bigger reinforcement is achieved with DCEN polarity than with DCEP polarity [21, 22].

6. Discussion

Weld joint is considered to be sound and economical if it has a maximum penetration, minimum bead width, reinforcement and dilution [23]. The relationship between speed, voltage, current, bead width, WRFF, and WPSF (Fig. 8) is explained for air welding in the figure below.

Howerever, underwater wet welding show some differences as compared to air welding. Water depth has a great influence on bead geometry when compared to other welding parameters when welding at a water depth less than 10 m. Welding carried out at a water depth greater than 10 m and changing the welding speed highly influence the bead geometry than other welding parameters [2].





A: Effect of voltage and speed on bead width

B: Effect of current and speed on penetration

C: Effect of voltage and current on reinforcement

D: Effect of voltage and current on WRRF

E: Effect of current and speed on WPSF

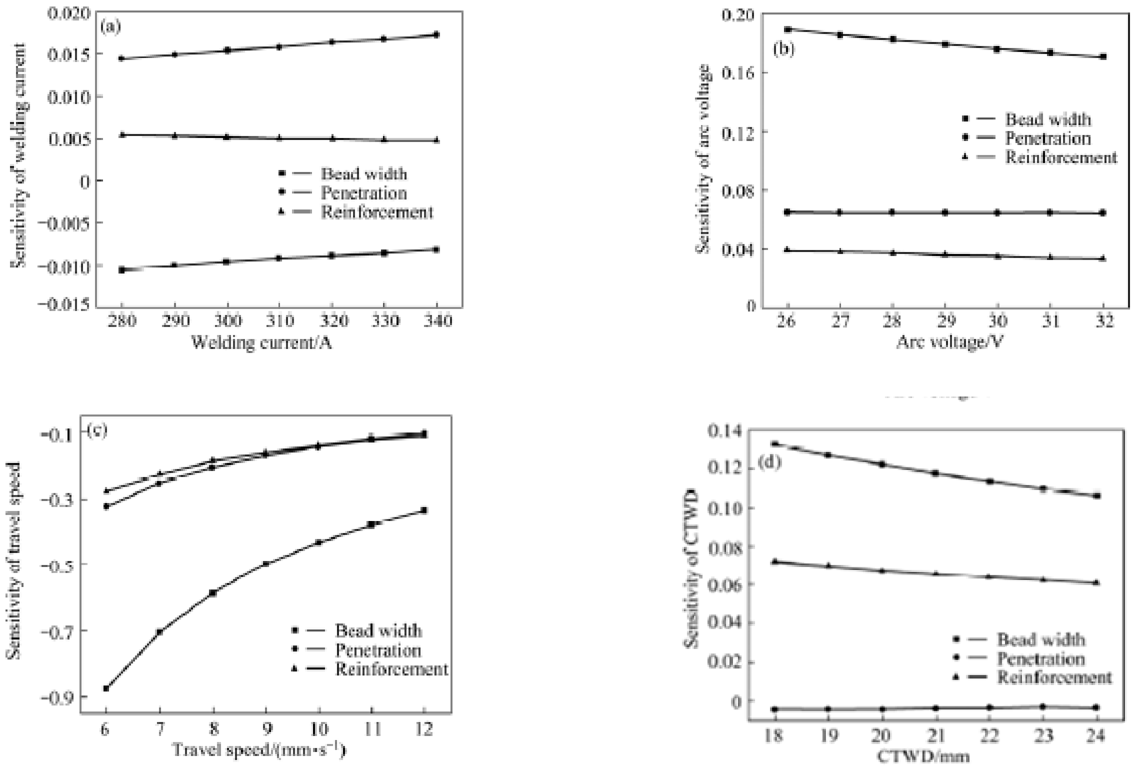
Fig. 8. *Effect of various welding parameters on weld bead geometry for air welding [4].*

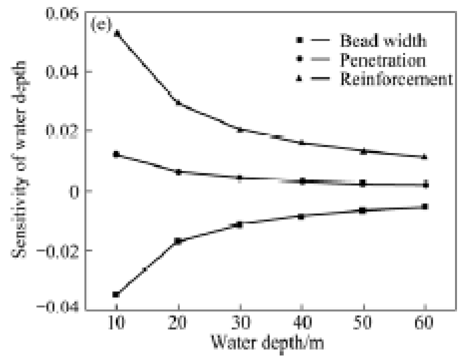
For all (Fig. 8A) values of speed an increase in voltage increases W. The bead width increases from 17.40 to 21.07 mm and from 16.49 to 17.75 mm with an increase in welding voltage from 32 to 38 volts, at welding speed of 24 and 30 m/hr respectively. This implies that voltage has a positive effect while welding speed has a negative effect on weld bead width [4].

The metal penetration (Fig.8B) increases with an increase in welding current for all values of welding speed. The metal penetration increases from 6.63 to 9.67 mm, and from 6.38 to 7.12 mm when welding current increased at welding speed of 24 and 30 m/hr respectively. Current has a positive effect on penetration while speed has a negative effect on penetration [4].

From (Fig. 8C), reinforcement decreases with increase in voltage with an increase in current from 375 to 475 amperes [4].

WRFF (Fig.8D) increases for all values of current when the voltage is increased from 32 to 38 volts. Voltage has a positive effect on WRFF while current has a negative effect. Weld bead width increases with an increase in voltage but almost remain constant with change of current, while reinforcement decreases with increasing voltage and increase with increase in current [4]. The effect of current and speed on WPSF is shown in Fig. 8E.





a. Sensitivity of welding current

b. Sensitivity of welding voltage

c. Sensitivity of welding speed

d. Sensitivity of welding CTWD

e. Sensitivity of water depth

Fig. 9. *Sensitivity of various welding parameters (welding current, speed, voltage) and water depth on weld bead geometry in underwater wet welding [2].*

7. Conclusions

The major challenge facing underwater welding is the fast cooling rate of the base metal by the surrounding water. This leads to the formation of microstructures that are susceptible to cracking. The effect of water depth and the cooling rate of the weld metal from the water temperature influence the effect of welding current, welding speed, and voltage on the weld bead geometry during underwater welding. It is evident that a proper adjustment of welding process parameter to minimize hydrogen pick up and alter the influence of the water environment can yield a sound weld in underwater welding as compared to air welding. The weld bead shape of a welded joint determines the mechanical properties of the joint. DCEN polarity is the most suitable power source for underwater wet welding. Arc stability increases penetration because of the reduction of arc wander and efficient heat transfer. Increase in water depth or pressure decreases bead width, but increases penetration, and reinforcement. Increase in voltage will increase bead width, penetration, and reinforcement. Welding current has greater influence on penetration than on bead width and reinforcement. Porosity in underwater welding can be minimized by the use of low current DCEP or high current DCEN. Voltage increase beyond the optimal value will result in the loss of alloying elements.

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