International Journal of Technical Research and Applications e-ISSN: 2320-8163,
www.ijtra.com Volume 3, Issue4 (July-August 2015), PP. 413-419

COMPARATIVE STUDY OF THE RESPONSE OF COMMERCIALLY AVAILABLE ELECTRODES TO UNDERWATER-WELDING AND AIR-WELDING

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Abstract— **The first ever underwater welding was carried out by British Admiralty- Dockyard for sealing leaking ship rivets below the water line. Underwater welding is an important tool for underwater fabrication work. In 1946, special waterproof electrodes were developed in Holland by 'Vander Willingen'In the past half century a great deal of research effort has been directed towards the development of underwater shielded metal arc wet welding process. Different investigators have reported results of their findings using different types of coated electrodes. The present work reports a systematic study of ten different varieties of commercially available electrodes regarding their response to underwater welding. These electrodes have been evaluated in stages on the basis of (1) arc stability (2) electrodes running characteristics through bead- on- plate and bead-in-groove trials and (3) controlled thermal severity tests. The electrodes successful in the final screening have been further tested for the mechanical properties of the joints they produced. Among the electrodes tested oxidizing iron-oxide electrodes showed better arc stability, produced smooth and regular beads, free from undercuts , no cracks in weld metal and heat affected zone (HAZ) were observed even in CTS tests, metal transfer was free from short circuits and mechanical properties were superior to the commonly used rutile iron-powder electrodes.**

Index Terms— **Wet welding, Shielded metal arc welding, underwater welding, open water welding, Arc welding ,underwater**

I. Introduction

Shielded metal arc welding is one of the oldest, simplest and most versatile processes of welding ferrous base metals in air. This process has found equally good importance in underwater welding. Underwater welding process could be broadly classified into two basic types: (1) Dry habitat welding and (2) Open water wet- welding. Because of high cost of dry habitat welding, the primary thrust on research and development has been with the" wet" welding process. Underwater welds are susceptible to defects like undercuts, hard and brittle HAZ, micro cracks due to hydrogen embrittlement, solidification cracking etc.Past few years have seen some development in wet underwater welding. Cochrane and Swetnam [4] have tested "ferrite" electrodes and "nickel" base electrodes on 0.15 C, 1.05 Mn steel and 0.14 C, 1.34 Mn steel plates. The results were reported to be favorably comparable to those typical of dry welds. Hydrogen embrittlement has been reported to remain a major problem. Szelagovski [5] has also made brief comments on dry, semi-wet and wet-welding under water in regard to factors influencing the process, surrounding medium, ambient pressure and shielding gas as they affect spattering. In the present investigation a systematic study has been carried out with a view to make specific recommendation regarding the electrode and welding parameters to be used to obtain high quality welds free from defects. The electrodes were water proofed by cellulosic lacquer paint which produced a gas trapping shroud around the arc [6].This shroud kept the water away from the arc and weld-pool region and reduced the cooling rate which in turn reduced the tendency to form undercuts.

A. Experimental set-up

The experimental set-up used in this investigation is shown in fig.1.Welding was carried out in a Perspex tank containing about 250 liter of continuously running fresh water mounted on a mechanized table . The test specimen was kept 200mm below the free surface of water. Instantaneous variations in voltage and current during welding were observed on oscilloscope and recorded on an ultraviolet light beam recorder. The welding power source was 400A rectifier with a maximum open circuit voltage of 80 V. The electrodes were held in a specially insulated electrode holder.

B. Results and discussion

A. Bead –on- plate welds-All the electrodes used were waterproofed by lacquer paint of 0.2 mm average coating thickness. Arc stability, metal transfer and weld characteristics were examined for 10 different types of electrodes. The results are shown in Table 1.Cellulosic electrodes (E-6010) give harsh digging arc which agitates molten weld pool and molten metal is forced upwards. As the arc moves along the weld seam, the molten metal come down and fills the weld cavity in air welding. But because of fast cooling rates in underwater welding the metal solidifies as mounds and deep undercuts are produced.

Arc stability*:* Oscillografic records of voltage and current reveal that rutile (E -6012) and (E-6013) and rutile iron- powder (E-6014 and E-6024) electrodes showed good arc stability and smooth beads. Underwater welding arc was more stable in straight polarity welding than the corresponding arc in air welding. For super- heavy coated electrodes arc was more stable in reverse polarity welding than in straight polarity. These electrodes formed a stable cup (barrel) at the electrode tip during underwater welding. This barrel formation together with the shroud [6] formation by the waterproof coating provided some degree of mechanical protection to the weld-pool against water environment. The metal transfer from these electrodes was seen to be free from short circuits as revealed by their oscillographs fig .These electrodes gave smoother beads higher deposition rates and easier slag removal than the ordinary rutile electrodes. Thus they would save bottom time for welders. Low hydrogen basic electrodes (E-7018HJ, E-7016HJ) gave stable arc during underwater welding only when electrodes were dried before waterproofing. When these electrodes were waterproofed as delivered, the flux peeled off the core wire and did not burn during welding to provide the usual protective gas shield. The arc stability was poor. Iron- oxide electrodes E-6020 were found to give stable arc both in straight as well as in reverse polarity welding. The arc was more stable in water than in air in reverse polarity welding as seen in oscillographic records shown in Fig-2. In reverse polarity welding, the metal transfer appears to be free from short circuits.

Weld-bead appearance: Undercutting was a serious problem with cellulosic electrodes, specially when reverse polarity was used. This might be due to the localized heat generated by electrode sputtering action which develops gouge near the toe of the weld bead. This effect is further enhanced due to (1) the harsh digging action of cellulosic electrodes and (2) the high rate of cooling which constricts the underwater arc and increases the arc forces. Slight undercuts were presents in most of the electrodes tested except for 5 mm diameter rutile E-6013, in reverse polarity and 5mm diameter low hydrogen E-7018 and E-6016 in both polarities. With oxidizing iron- oxides E-6020 electrodes in 4 mm and 5 mm diameter sizes no undercuts were found in straight and reverse polarity welding conditions. These results are given in Table 1. In general the electrodes which gave comparatively smoother and more regular beads in air, gave smoother and more regular beads in water also.

Bead geometry: Weld bead cross-section profiles were studied for all electrodes. Weld penetration shape factor and percentage weld metal were determined for all the electrodes to compare their penetration shape characteristics. Table 1 shows the results of this study. Good overall results in respect of weld geometry were obtained with rutile and iron- oxides electrodes.Allthough rutile electrodes have shown better shape factor and percentage weld-metal values as compared to iron-oxides electrodes but their beads contained slight undercuts at higher currents which are very harmful. Beads obtained with iron- oxides electrodes were smooth and free from undercuts .Keeping these results in mind further studies were carried out on electrodes successful in the above screening.

Macro-structure study: The results of metallographic examination for cracking and weld-metal hardness for bead-on-plate welds are shown in table2, for selected electrodes and welding conditions used. In other electrodes cracks were found in weld-metal and not in the HAZ except in cellulosic electrodes where the cracks were observed in the HAZ as well. Most consistent results were obtained with E-6020 oxidizing iron-oxide electrodes where no cracks were observed in either polarity and in either 4mm or 5mm size.

Electrode size: It was difficult to strike and maintain an arc with 3.15 mm electrodes of all types. In most of the underwater welding situations thick plates are required to be welded for which 4mm electrodes are marginally good and 5 mm electrodes should be preferred to reduce the excessive number of weld-passes and the consequent risk of slag inclusion.

B. **Bead-in-groove welds-** The results of bead-in groove trials given in Table2 show the effect of welding procedure on weld-deposit cracking susceptibility for bead-in-groove welds. It can be seen that as the energy input to the weld was increased weld-metal and HAZ hardness reduced. Inspite of these manipulations basic electrodes showed cracks in weld-metal.

Controlled thermal severity (CTS) tests: The results of these tests are shown in Table2. These results indicate that in the case of E-6013 rutile, E-7024 rutile iron powder and E-6020 oxidizing iron-oxide coated electrodes no cracks were observed in the weld metal and HAZ under the high restraint conditions provided by these tests. In contrast the welds obtained with E-7018 basic electrodes contained slight cracks in the weld-metal and fine cracks in the HAZ. These results are in agreement with the results of “bead-on-plate “and “bead-in-groove “trials

Microstructure study: Non- equilibrium microstructures were obtained in underwater welding due to the fast cooling rates. Martensite and bainite were formed within the coarse grains observed adjacent to the fusion boundary in the HAZ region. Rutile, rutile iron-powder and iron-oxide electrodes gave welds free from micro cracks. Width of HAZ was smaller but the width of coarse grains within the HAZ was larger for underwater welds as compared to air welds. This was due to higher arc and metal temperature during underwater welding. Rutile, rutile iron-powder and iron-oxide electrodes gave welds free from micro cracks or other defects and were, therefore, chosen for further testing for the mechanical properties of the welds they produced.

Mechanical properties: The results of the tests for mechanical properties are given in Table3 through 5. Iron-oxide electrodes gave overall better results as compared to rutile and rutile iron-powder electrodes.

It was further observed that for each of these electrodes better results were obtained with lower heat input and more number of passes than for those with higher heat input and lesser number of passes. This was due to the heat treating effect of subsequent beads which relieved the stresses set-up due to fast cooling rates in underwater welding. Superiority of iron-oxide electrodes may be due to the presence of iron-oxide inclusions in the weld-metal deposited by these electrodes which acts as sinks for hydrogen and are believed to reduce the diffusible hydrogen content by oxidation of some hydrogen into steam. Stalker [7] carried out weld-metal analysis of oxidizing iron-oxide electrodes for air and underwater weld deposits and indicates that the underwater deposits contained virtually pure iron with traces of common alloying elements. Our results are in agreement with the findings of Stalker. This is further confirmed from the results of all weld-metal tensile tests given in Table 4, which shows low yield strength of weld deposits obtained with these electrodes. Thus the weld deposit yields and reduces the strain in the HAZ and thereby reduces the risk of cracking. Results of V-notch impact tests and transverse face-bend tests are shown in Tables 4 and 5. Impact strength of underwater welds is only 43 percent of the corresponding air welds for the E-6020 electrode. Face-bend tests indicate that both rutile and iron oxide electrodes show an initiation of 1.5 mm crack at a mean angle of bend of 55 to 56 degrees. It can therefore, be concluded that successful welds free from undercuts and cracks could be deposited in open water environments which had been the first stumbling block in underwater wet- welding. Further work is still needed to develop some heat treatment facility to improve the bending and impact characteristics of these welds.

Table 1
Results of bead –on-plate trials

S.No	**Electrode specification**	**Size mm**	**Arc stability**	**Weld nugget geometry**		**undercuts**		**macro cracks**	
				SF	**%WM SP-RP**	**SP**	**RP**	**WM**	**HAZ**
1	E-6010 cellulosic	3-4 5	P	-----	------	D	D	SE	SE
2	E-6012 rutile	3 4-5	F G	2.5 2.8	55-40 54 -51	SL SL	SL SL	SL NO	NO NO
3	E-6013 rutile	3 4-5	F G	3.6 3.8	60-65 50-50	SL SL	NO NO	SL NO	NO NO
4	E-7014 rutile iron powder(IP)	3 4-5	F G	3.0 3.5	60-50 60-50	SL SL	SL SL	SL SL	NO NO
5	E-7024 heavy coated IP	3 4-5	F G	4.2 4.8	50-50 50-50	NO NO	SL SL	MOD NO	NO NO
6	E-7018 low hydrogen	3 4-5	F G	3.3 3.1	50-50 50-50	NO NO	SL NO	SL SL	NO NO
7	E-7016H lowHyd.med heavy coated	3 4-5	F G	3.2 3.2	45-40 50-40	SL NO	SL NO	SL MOD	NO NO
8	E-7016HJ -do-IP	3 4-5	F G	3.5 3.8	50-40 52-45	SL NO	SL SL	MOD SL	NO NO
9	E-6027 Mineral IP	5	G	3.0	44 -40	SL	SL	SL	NO
10	E-6020 Oxidizing iron-oxide	4-5	G	5.5	54 -45	NO	NO	NO	NO

Table 2.
Weld metal hardness test results of bead-on-plate, bead-in-groove and cts tests, tests weld metal and haz cracking tendency in cts tests is also included.

Type, size and polarity	Arc energy KJ/mm	Bead –on-plate welds		Bead-in-groove welds			Controlled thermal severity results on 20mm plate			
		Weld metal hardness VHN		Avg. hardness of capping pass			cracking		Hardness VHN	
		Avg.	range	No. of passes	WM	HAZ	WM	HAZ	WM	HAZ
E-6013										
4mm SP	1.2	189	181-193	10	207	343	-----	-----	----	----
5mm SP	1.5	199	180-202	6	207	350	NIL	NIL	207	370
5mm RP	1.5	205	180-216	6	197	230	NIL	NIL	205	370
E-7024										
4mm SP	2.0	228	221-243	6	225	337	NIL	NIL	222	380
5mm RP	2.5	219	178-238	5	220	280	NIL	NIL	221	390
E-7018										
4mm RP	1.5	220	214-230	10	235	302	Slight	Fine	251	460
5mm RP	2.0	218	210-225	6	242	315		Fine	230	470
E-6020										
4mm SP	1.5	203	199-206	7	163	363	NIL	NIL	218	421
4mm RP	1.5	230	219-235	7	170	360	NIL	NIL	221	417
5mm SP	2.0	219	213-228	5	205	352	NIL	NIL	218	401
5mm RP	2.0	216	203-225	5	206	364	NIL	NIL	216	409

International Journal of Technical Research and Applications e-ISSN: 2320-8163,
www.ijtra.com Volume 3, Issue4 (July-August 2015), PP. 413-419

Table 3.
Tensile test results.

Reduced section transverse tensile test results						All weld metal tensile tests				
Electrode tested	Medium & polarity	Yield stress N/mm2	Ult. Tensile strength UTS N/mm2	Location of fracture BP WM	Flaws if any on fractured section	Yield stress N/mm2	UTS N/mm2	Elongation %	Reduction in area %	Fracture location
E-6013	Air SP	260.7	412.8	All Nil	Nil	408	486	24.8	65.5	Within gauge length all cases
	Air RP	255.9	393.0	All Nil	Nil	---	---	---	---	
	Water SP	253.5	413.7	All Nil	Nil	391	443	7.3	9.9	
	WaterRP	257.7	401.6	All Nil	Nil	414	476	10.2	12.0	Do
E-7024	Air SP	265.4	419.0	All Nil	Nil	444	518	27.0	62.5	
	Air RP	258.1	403.3	All Nil	Nil	---	---	---	---	Do
	Water SP	289.8	415.5	All Nil	Nil	442	585	9.7	16.0	Do
	WaterRP	292.0	416.3	All Nil	Nil	---	---	---	---	Do
E-6020	Air SP	264.2	415.8	All Nil	Nil	402	475	27	65.0	Do
	Air RP	250.8	408.2	All Nil	Nil	---	---	---	---	
	Water SP	279.6	405.2	All Nil	Nil	318	456	9.6	17.5	
	WaterRP	289.2	412.0	All Nil	Nil	313	444	10.4	17.0	

Table 4.
Charpy v- notch impact test results for iron-oxide electrode e- 6020, 5mm dia.testing temp.:27, polarity: straight welding arc energy input: 1.5 kj/mm

medium	**Energy absorbed**	**Lateral contraction mm**	**Shear %**	**defects**
Air Water	118.0 51.5	1.1 1.0	100 56.6	Nil Nil
1. Measured at root of the notch. 2. Ratio of fibrous area to the total area.				

Table 5.
RESULTS OF TRANSVERSE FACE-BEND TESTS USING 4T FORMER.

Electrode	Medium	Polarity	Energy input KJ/mm	Mean angle of bend to initiate 1.5 mm crack	Type and location of flaws
E-6013 5mm dia	Air Water Water	SP SP RP	1.5 1.5 1.5	180. 55. 56.	Nil Nil Nil
E-6020 5mm dia	Air Water Water	SP SP RP	1.5 1.5 1.5	180. 55. 56.	Nil Nil Nil

Indications

BP =base plate
SF =shape factor
IP=iron powder
C.T.S =controlled thermal severity
SP =straight polarity
P= poor
D =deep
U.T.S = ultimate tensile stress
RP= reverse polarity
F =fair
VHN =vickers hardness number
SE= severe
G =good
VG =very good
SL= slight
HAZ =heat affected zone
WM =weld metal

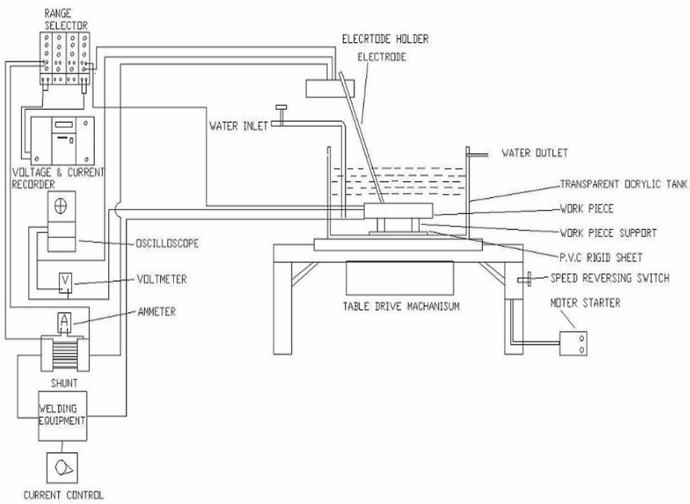

Fig-1 Schematic Arrangement Of The Test Set-Up

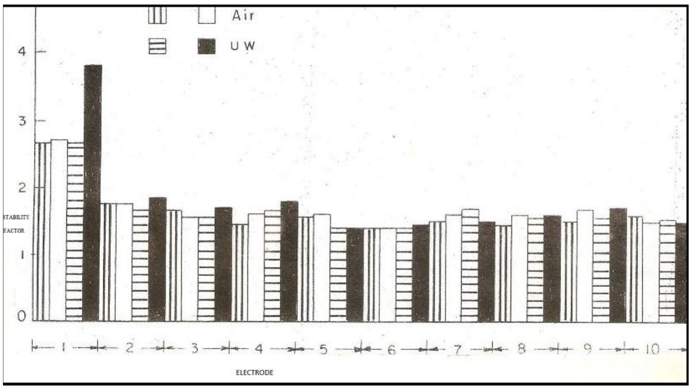

Fig-2

Response of different Electrodes During Air/Underwater Welding .

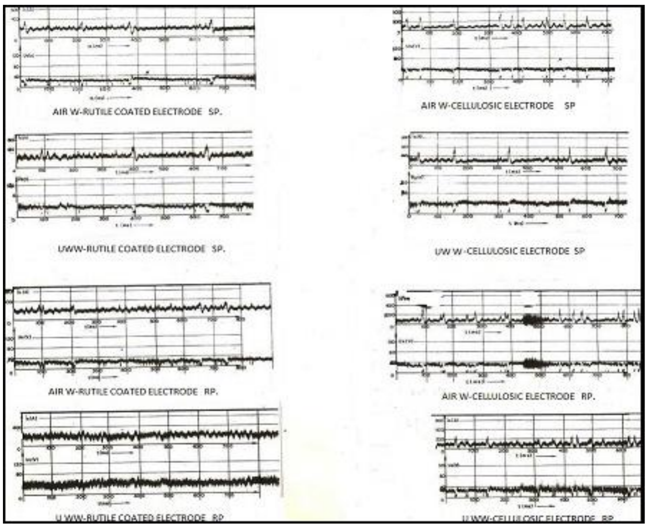

Fig-3

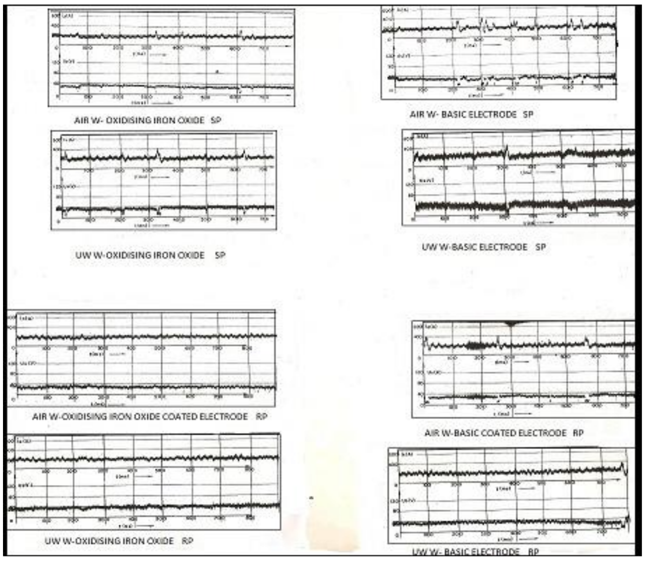

Fig-4

Oscillograms Of Current And Voltage For Iron-Oxide Electrodes During Air/Underwater Welding Using (A) Straight Polarity, (B) Reverse Polarity

1. Conclusions

The following major conclusions could be drawn from the above investigation.

1. Cellulosic electrodes gave unstable harsh digging arc which gave rise to deep undercuts and rough beads. This electrode is, therefore, unsuitable for underwater welding.
2. Rutile and rutile iron-powder electrodes gave stable arc, smooth and regular beads with from undercuts and good bead geometry. Weld deposits were free from cracks in weld metal and HAZ even in CTS tests. These electrodes were, however, inferior to iron-oxide electrodes.
3. Cellulosic electrodes gave unstable harsh digging arc, deep undercuts and rough beads(unsuitable for underwater welding)
4. Basic and basic iron-powder electrodes revealed cracks in WM and in HAZ in CTS tests.

5. Rutile and rutile iron- powder electrodes produce underwater welds with occasional occurrence of cracks and slag inclusion in weld -metal.
6. Iron-oxide electrodes showed good arc stability smooth and regular beads free from undercuts. CTS test revealed no cracks in WM and HAZ .metal transfer was free from short circuits and mechanical properties were superior to rutile or rutile iron-powder electrodes.
7. Optimum welding parameters for 5mm iron-oxide electrodes were: 25-26V, 200-210A, DCRP welding at 3.5mm/s welding speed.

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