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Study on the Welding Parameters of Steel Pipes for Higher Sulfide Stress Corrosion Cracking Resistance for Field Application

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The Sulfide Stress Corrosion Cracking (SSCC) resistance of structural steels is one of the critical concerns for the operators, material designers, and fabricators of oil-field equipment, especially treating sour gas (H2S) containing fluids. As far as its fabricators concerned, the systematic care of welding parameters should be taken to obtain comparable SSCC resistance of their weldment to that of its base material. In this respect, every different type of welding joint design for this use should be verified to be SSCC-proof with relevant test procedures. In this study, the welding parameters to secure a proper SSCC resistance of steel pipe's weldments were reviewed on the Welding Procedure Qualification Records (WPQR), which had been employed for actual fabrication of an offshore structure for oil and gas production. Based on this review, a guideline of welding parameters, such as, heat input, welding consumable for Y.S. 65 ksi class steel pipe material is proposed in terms of the NACE criteria for SSCC resistance.

Keywords : *Sulfide Stress Corrosion Cracking (SSCC), sour gas, welding process, heat input, consumable, steel pipe, WPQR, Y.S. 65 ksi*

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1. Introduction : SSCC and HIC of steel and their measures

The Sulfide Stress Corrosion Cracking (SSCC) is one of the hydrogen-related damages of metallic materials, which are exposed to aqueous hydrogen sulfide (H_2S) environment. Hydrogen atoms produced by the corrosion reaction of iron with H_2S ($Fe + H_2S \rightarrow FeS + 2H$), usually combine to form hydrogen gas molecules.[1] However, in the presence of sulfide, the hydrogen recombination reaction is retarded so that the hydrogen atoms diffuse into the steel rather than recombining on the steel surface. Hydrogen atoms that enter the steel can cause embrittlement and failure. SSCC occurs when additional stress (applied stress and/or residual stress) is working on steel, and propagates to the vertical direction to the axial stress.[2] On the other hand, Hydrogen Induced Cracking (HIC) occurs even under a condition without additional stress. The cracking may initiate at material's internal defects and propagate parallel to the plate surface and then, stepwise to the thickness direction with time.[3] Surface swelling due to occurrence of cracks on the surface or immediately beneath the surface is called blistering. The mechanism of hydrogen related damages such as SSCC and HIC is generally different from that of similar damage form of stress corrosion cracking (Table 1). The cathodic protection techniques, most widely used corrosion control method for offshore steel structures, may aggravate SSCC and other hydrogen related damages. Thus, material selection and proper welding design are the most effective measure against SSCC and HIC damages.

Steel pipe materials for offshore structures pipeline in sour service are generally required to conform to NACE standard material requirements, in which carbon and low

Table 1. Corrosion cracking damages of steel under H_2S environment

Damage Type	Stress	Environment	Damage Form
Stress Corrosion Cracking	Applied or residual stress	Specific corrosive	
Sulfide Stress Cracking	Applied or residual stress	Hydrogen	
Hydrogen Induced Cracking	No stress	Hydrogen	
Hydrogen Blistering	No stress	Hydrogen	

alloy steels should be maintained below 250 Hv (~22 HRC) hardness as well as should have less than 1% nickel.[1)] Wrought carbon and low alloy steels out of these requirements must meet the test criteria specified in additional NACE test standards.[4)-6)] However, even carbon and low alloy steels satisfying hardness and nickel content requirements may suffer SSCC and HIC damages occasionally due to existence of the microscopic, local area with excessive hardness.[7)] For this reason, actual application procedure for offshore pipeline materials in sour service, especially when welding work is involved, generally adopt NACE corrosion tests for all types of weldments, despite the base metals satisfy NACE material requirements.

2. Review on welding design parameters for actual fabrication

In this study, welding design parameters for an offshore project are reviewed, where three types of Y.S. 65 ksi grade carbon steel pipe materials were used for the sealine and riser pipeline, as summarized in Table 2. The welding design for the offshore structure pipeline basically includes welding method and welding position, according to its application and work stage (Table 3). In this step, welding speed, defect probability, and back-bead formation are the critical factors for its design considerations (Table 4). For example, the process which is capable of providing high welding speed should be adopted for the continuous sealine pipe welding, in which the reduction of total working time is beneficial due to the high barge rental fee. On the other hand, the highly productive welding process yielding high deposit rate would be preferred for the welding fabricators. As a result, a semi-auto welding (Flux Cored Arc Welding, FCAW) process is preferred for its higher productivity to manual welding (Shielded Metal Arc Welding, SMAW) process. Gas tungsten arc welding (GTAW) process is also used in combination with SMAW or FCAW to provide better back-bead formation at the root pass. The welding consumables and welding condition, then, are to be determined considering its mechanical properties as well as welding position and acceptance criteria for SSCC resistance of weldments as shown in Table 5. The final welding design for the sealine and riser pipeline of the concerned project are summarized for every welding application types and weld joints as shown in Table 6.

Table 2. Chemical composition and mechanical properties of base metals

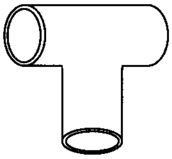
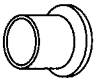
Material Type	**Pipe** *API 5L X65* 	**Tee** *WPHY-65* 	**Flange** *ASTM A694 F65* 
Chemical, wt.%			
C	max. 0.15	max. 0.17	max. 0.265
Ni	max. 0.30	max. 0.6	-
Si	max. 0.50	max. 0.4	0.1~0.4
Mn	max. 1.30	max. 1.3	max. 1.44
P	max. 0.025	max. 0.02	max. 0.030
S	max. 0.008	max. 0.01	max. 0.030
Ceq	max. 0.39	max. 0.43	-
Mechanical			
YS, ksi	min. 65	min. 65	min. 65
TS, ksi	77~100	min. 77	min. 77
EL, %	min. 23.5	min. 20	min. 20
Hardness, Hv	max. 248	-	-
E, Joule Each	min. 39	-	-
E, Joule Avg.	min. 52	-	-

Table 3. Summary of welding process application

Welding Process		Work Stage Condition	Application
Method	Position		
SMAW	2G	Installation on board	Riser
	5G-up	Fabrication in shipyard	Riser & Repair
	5G-down	Installation on barge	Sealine
GTAW+ FCAW	5G-up	Fabrication in shipyard	Riser
GTAW+ SMAW	5G-up	Fabrication in shipyard	Riser

Table 4. Technical considerations of welding process

Welding Process		Speed	Deposit Rate	Backbead	Defect
Method	Position				
SMAW	2G	MEDIUM	MEDIUM	FAIR	LOW
	5G-up	LOW	HIGH	FAIR	LOW
	5G-down	HIGH	LOW	FAIR	MEDIUM
GTAW+ FCAW	5G-up	MEDIUM	LOW	GOOD	LOW
GTAW+ SMAW	5G-up	LOW	LOW	GOOD	LOW

Table 5. Welding consumable's grade

Welding Process			Consumable						
Method	Position	Pass	AWS grade	Comp.(wt.%)		Mechanical Properties			
				C	Ni	YS, ksi	TS, ksi	EL.%	Impact, J
SMAW	2G	All	E8016-G	0.058	0.84	69	82	26.2	176 @-20℃
	5G-up								
	5G-down	Root	E7010-P1	0.14	-	61	72	22.0	70 @ 20℃
		Others	E8010-P1	0.15	0.82	70	80	22	110 @ 20℃
GTAW + FCAW	5G-up	Root	ER70S-G	0.08	-	72	87	28.4	178 @-29℃
		Others	E81T2Ni1	0.04	0.96	84	92	27	33 @-30℃
GTAW + SMAW	5G-up	Root	ER70S-G	0.08	-	72	87	28.4	178 @-29℃
		Others	E8016-G	0.058	0.84	69	82	26.2	176 @-20℃

Table 6. Welding design for field fabrication of offshore structure

No	WPQ Section	Welding Process	Base Material	Filler Material (AWS class)	Corr. Test	
					HIC	SSCC
1	Sealine pipe to pipe	SMAW (5G-down)	X65+X65	Root: E7010-P1 Others: E8010-P1	○	○
2	Riser tie-in pipe-to-pipe	SMAW (2G)	X65+X65	E8016-G	○	○
3	Riser fabrication/ Dogleg pipe-to-pipe	GTAW+FCAW (5G-up)	X65+X65	GT: ER70S-G FC: E80T1Ni1	○	○
4	Riser fabrication tee to flange	GTAW+SMAW (5G-up)	WPHY65 +A694 F65	GT: ER70S-G SM: E8016-G	○	○
5	Riser fabrication bend to elbow	GTAW+SMAW (5G-up)	X65+WPHY65	GT: ER70S-G SM: E8016-G	○	○
6	Riser fabrication pipe-to-pipe	SMAW(5G-up)	X65+X65	E8016-G	○	○
7	Cap repair	SMAW(5G-up)	X65+X65	E8016-G	-	-
8	Partial repair	SMAW(5G-up)	X65+X65	E8016-G	-	-
9	Full repair deck line	SMAW(5G-up)	X65+X65	E8016-G	○	○
10	Fillet	SMAW(5F-up)	X65+5LB	E8016-G	-	-

○: Corrosion test required, - : Corrosion test not required

3. Experimentals

To clarify the effect of welding design on the SSCC resistance, the welding condition is reviewed based on the nickel content in welding deposit, macroscopic hardness level, and SSCC and HIC test result. The nickel content was analyzed in samples extracted respectively from cap and root weld areas as shown in Fig. 1 and Table 7, and weldment hardness was measured along with the 1mm sub-surface line respectively from inner and outer surface of pipe as shown in the Fig. 1. The hardness data were averaged respectively for weld, HAZ, and base material as summarized in Table 7. On the other hand, SSCC and HIC test were conducted in accordance with NACE TM-0177 and NACE TM-0284, respectively. As for the corrosion condition, H_2S (purity of 99.98%) gas was initially supplied for 20 minutes at a rate of 200 ml/min in a Solution A type for saturation, then the H2S gas was contiunously supplied to keep bubbling in the NaOH solution bottle connected to the satureted gas outlet. SSCC

Table 7. Summary of welding parameters and corrosion test results

No	WPQ Section	Pass	Heat Input, (kJ/cm)	Interpass Temp., (℃)	Ni Content in Weld, (wt.%)	Hardness (Hv, 5kg)			Corrosion Test Result	
						Weld	HAZ	Base	HIC	SSCC
1	Sealine pipe-to-pipe	Root	6.2~10.4	38~50	0.38	190	195	200	○	○
		Cap	12.7~20.1	81~169	0.65	218	214	200	○	○
2	Riser tie-in pipe-to-pipe	Root	8.5~21.5	127~140	0.70	196	210	200	○	○
		Cap	11.2~21.8	104~135	0.80	208	214	200	○	○
3	Riser fabrication pipe-to-pipe	Root	10.0~12.1	107~109	0.02	188	199	208	○	○
		Cap	14.2~19.3	117~146	0.93	235	212	208	×	×
4	Riser fabrication tee-to-flange	Root	12.9~13.8	105~133	0.63	215	218	178	○	○
		Cap	19.2~54.8	105~134	0.74	216	214	178	○	○
5	Riser fabrication bend-to-elbow	Root	13.3~18.2	105~120	0.60	205	201	172	○	○
		Cap	18.0~54.0	106~132	0.75	219	200	172	○	○
6	Riser fabrication pipe-to-pipe	Root	24.9~27.1	132~135	0.73	207	198	214	○	○
		Cap	18.8~25.6	103~132	0.75	214	206	214	○	○
9	Full repair deck line	Root	32.5	117	-	179	194	198	○	○
		Cap	25.3~36.3	107~152	-	201	207	198	○	○

○: Cracking, ×: No cracking

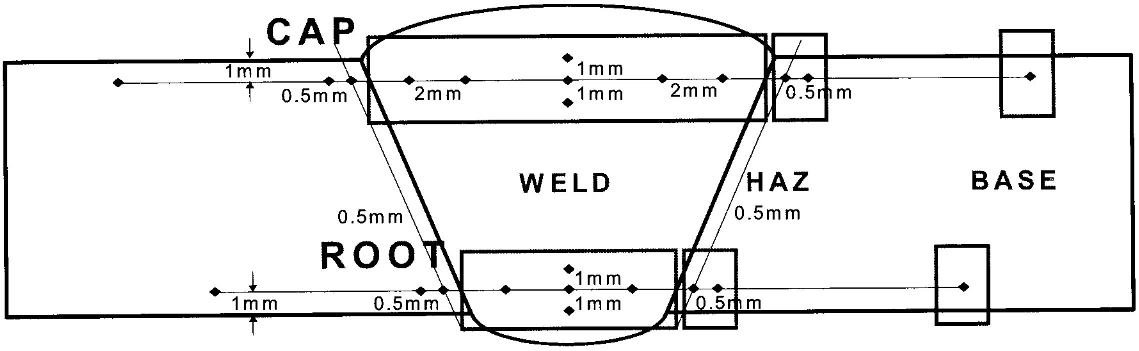


Fig. 1. Sampling locations for hardness measurement.

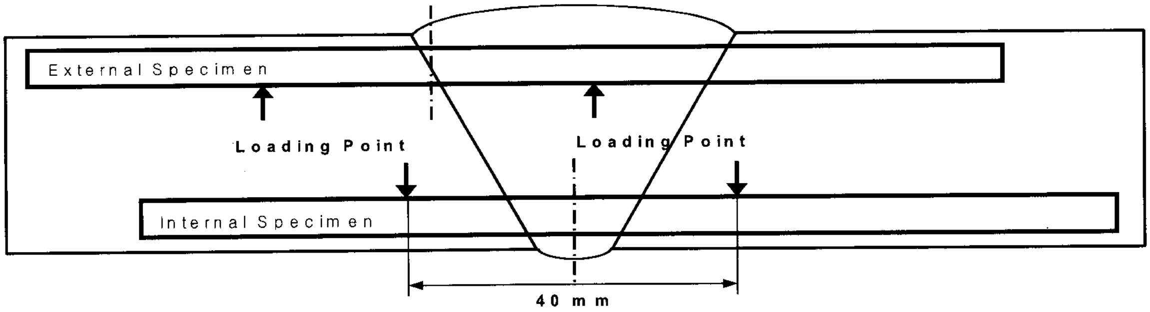


Fig. 2. SSCC test coupons sampled from weldments

resistance was evaluated by using a four point bending method in a load control mode with the rectangular specimens extracted from the weldments, as shown in Fig. 2 and Fig. 3, and test duration was 720 hours. The dis-

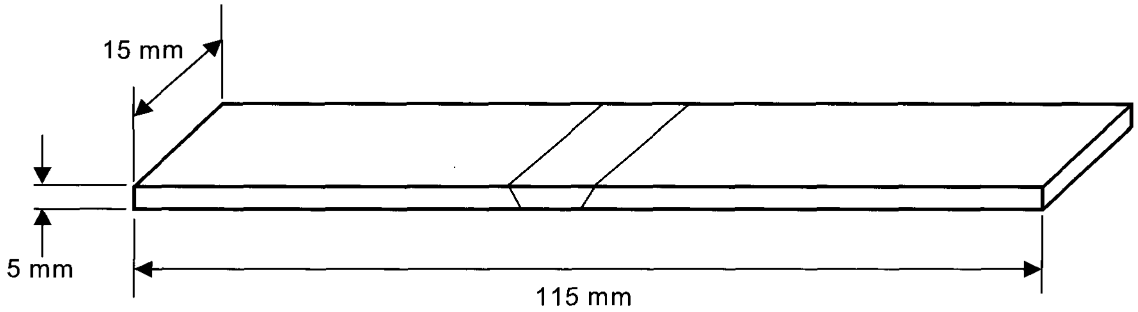


Fig. 3. HIC test coupons sampled from weldments

Table 8. Guideline for Welding parameters for proper SSCC resistance of Y.S. 65 ksi Gr. steel pipe material

Welding Process		Heat Input, (kJ/cm)	Interpass (Temp., ℃)	Ni Content, (wt.%)	Avg. Hardness (Hv, 5kg)
Method	Position				
SMAW	2G	8.5~21.8	104~140	<0.80	<210
	5G-up	18.8~36.3	103~152	<0.75	<214
	5G-down	6.2~20.1	38~169	<0.65	<218
GTAW+FCAW	Unapplicable				
GTAW+SMAW	5G-up	12.9~54.8	105~134	<0.75	<219

placement was applied in the form of tensional stress for 80% of yield strength of each weldment. After SSCC test, the probable micro-cracks were examined by a magnetic particle inspection method for all specimens. HIC resistance was evaluated with crack sensitivity, crack length, crack thickness ratio of tested specimens.

3. Results and discussion

Corrosion test results for each welding application with various welding conditions based on NACE's material acceptance criteria, and guidelines for welding parameters for proper SSCC resistance were summarized in Table 7 and Table 8, respectively. The SMA weldments for Y.S. 65 ksi grade steel pipe material met the NACE material criteria of Ni content (less than 0.8 wt%) as well as hardness (less than 220 Hv), and provided satisfactory SSCC and HIC resistance in a wide range of heat input and interpass temperature for all welding positions as well as combination process with GTAW. In contrast, all samples extracted from the cap weld pass area of semi-auto welding process (FCAW) failed after SSCC and HIC test (Fig. 4 and Fig. 5). As shown in the Table 7, the hardness and Ni content of the weld by FACW process was relatively higher than those of SMAW process, but still satisfied NACE material criteria.

To confirm the SSCC resistance of the FCA weldment, additional weld coupons were prepared with the same base material and two kinds of welding consumables with the variation of interpass temperature as shown in Table 9, and then were subjected to HIC test for 72 hours. The new welding consumable for FCAW process was selected for its lower nitrogen content and carbon equivalent than

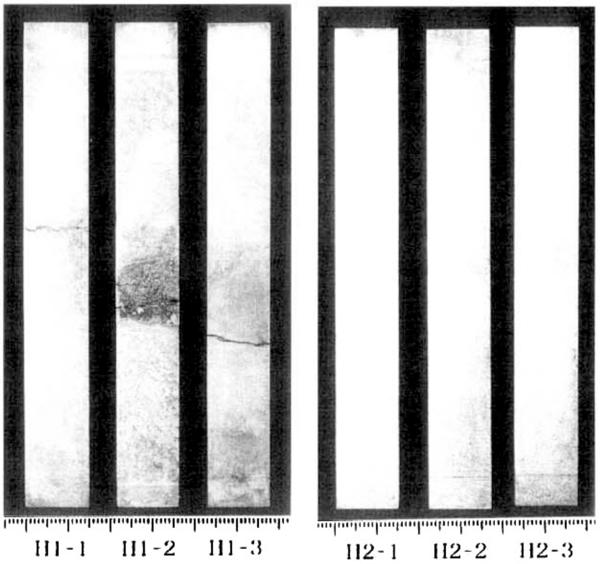


Fig. 4. Face view of sulfide cracking of FCA weldment after SSCC Test (Left: cap pass Area - crack, right: root pass area - no crack)

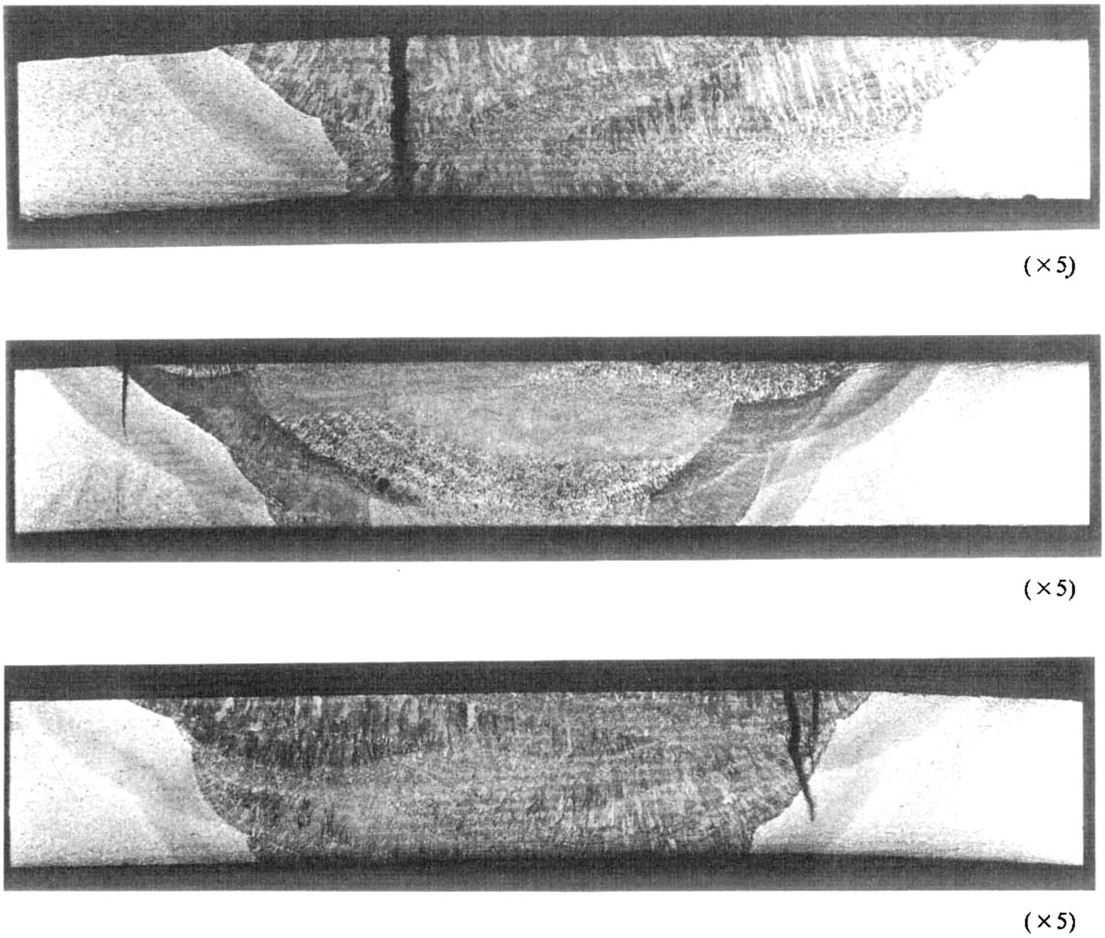


Fig. 5. Cross sectional view of sulfide cracking of FCA weldment after SSCC Test (Specimens from cap pass area)

Table 9. Test conditions for the weldment samples by FCAW process

Consumable	ID	Interpass Temp. (℃)	Chemical (wt%)		
			C	Ni	Ceq
Original	O-A	100~150	0.05	0.93	0.41
	O-B	150~250			
New	M-A	100~150	0.06	0.87	0.35
	M-B	150~250			

Table 10. Hardness of weld and HIC test results for FCA weldment coupons

Consumable	ID	Hardness, Hv, 5kg	Crack Length, mm			
			1	2	3	Avg.
Original	O-A	233, 267, 253, 292, 271 **Avg. 263**	2.5	4.0	0.0	2.2
	O-B	251, 241, 242, 245, 241 **Avg. 244**	2.5	2.5	0.0	1.7
New	M-A	227, 220, 190, 216, 230 **Avg. 217**	0.0	0.0	0.0	0.0
	M-B	190, 202, 211, 194, 210 **Avg. 202**	0.0	0.0	0.0	0.0

those of original one. The HIC test result, as summarized in Table 10, showed that the weldments with original welding consumable were found to have discernible crack regardless of the interpass temperature. In contrast, no crack was observed in the weldment with new welding consumable. The samples, prepared with original consumable at 150-250℃ of interpass temperature range, failed even though they had exhibited lower hardness than the NACE criteria. The weldment with new consumable showed lower hardness and provided proper HIC resistance, whereas, the FCAW process proved to be not suitable for this offshore project, due to the low impact toughness of its weld metal. It has been well known that the cored flux material in FCAW consumable wire has a certain amount of oxide to enhance weld slag formation and workability, which may reduce the impact toughness of the FCA weldment. For this reason, FCAW consumable retains relatively higher Ni content than the consumable for other welding process does.

This result clearly reconfirmed the previous reported study by D. D. Vitale that the materials can still suffer SSCC and HIC damages even though they satisfy NACE criteria of max. Ni content and max. macro hardness level if the weld's microscopic hardness exceeded the max. hardness (250 Hv).[6] Based on the present study. it is suggested that for a weldment to have proper SSCC resistance, the macroscopic, average hardness level should be controlled less than 220 Hv for the weldments reviewed in this study, which is much lower than the NACE recommended value of 250 Hv (Fig. 6).

As far as Ni content of the steel concerned, there has been a controversy regarding its effect on SSCC resistance, since many investigators consider that Ni has an adverse effect, particularly when its content exceeds 1%. Ni is known to increase the rate of corrosion and modify the type of sulfide film formation to more unstable one, thereby reducing the cracking resistance.[8] In contrast, some investigators showed that Ni has no adverse effect on cracking resistance, provided it does not lead to the formation of untempered martensite.[9] Based on this argument, high Ni content of FACW consumable, which is necessary for better impact toughness could facilitate generation of unwanted untempered martensite phase in its weldment, causing higher hardness and ultimately lower SSCC resistance. Thus, despite of better workability and productivity inherited in the FCAW prosess, the high risk of SSCC damage of FCA weldment made this process unapplicable to the steel pipe welding for offshore structure in sour service.

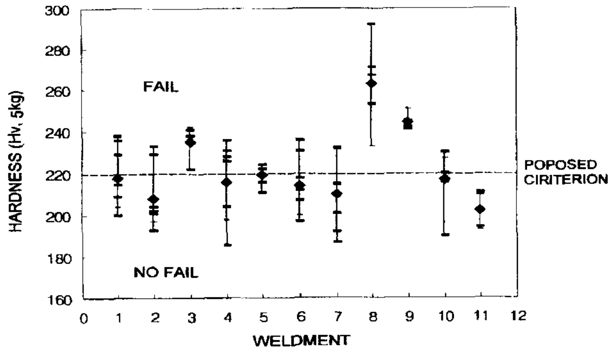


Fig. 6. Averaged macroscopic hardness of Y.S. 65 ksi steel pipe weld for their SSCC Resistance (1: SM-5G-D, 2: SM-2G, 3: GT+FC-5G-U, 4: GT+SM-5G-U, 5: GT+SM-5G-U, 6: SM-5G-U, 7: SM-5G-U, 8: FC Original Wire-1, 9: FC Original Wire-2, 10: FC New Wire-1, 11: FC New Wire-2)

4. Conclusions

1) For Y.S. 65 ksi grade steel pipe welding of offshore structures in sour service, SMAW process for all types of welding position may offer a wide range of heat input and interpass temperature, meeting the NACE material criteria and showing proper SSCC resistance. Besides that, combination process with GTAW process for root pass was found to be introduced successfully with same SSCC resistance. The FCAW process, however, may not be applied to the steel pipe welding of offshore structures in sour service due to its inevitably high Ni content in consumable material and resultant high hardness of its weldment.

2) For proper SSCC resistance, the macroscopic averaged hardness level should be controlled less than 220 Hv, which is much lower than the NACE recommended value of 250 Hv The fact that the materials can suffer SSCC and HIC damages even though they satisfy NACE criteria of Ni content and hardness level due to its microscopically excessive hardened area was reconfirmed actually for steel pipe weldment in this study.

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