Results Presentation

NSRP SP-7 Welding Panel Meeting

Provo, Utah, April 5, 2006

Evaluation of Variable Balance AC Submerged Arc Welding and Metal Cored Electrode Technology for Panel Welding

NSRP / ASE Project 2005-386

Results Presentation

PROJECT TEAM

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Results Presentation

- OUTLINE
  - Background
  - Objectives
  - VBAC
  - Task 1 – Summarize Current One-sided Welding (OSW) Practice for Submerged Arc Welding (SAW) of DH36, HSLA-65, and HSLA-100 Steels
  - Task 2 – Develop Metal Cored Electrode Chemistries for High Heat Input Welding of DH36, HSLA-65, and HSLA-100 Steels
  - Task 3 – Develop and Qualify Tandem Welding Procedures using Variable Balance AC (VBAC) SAW and Metal Cored Electrodes
  - Comparison of Results to Current Practice
  - Potential Consumable and Labor Cost Savings
  - Conclusions
  - Recommendations for Further Work
  - Questions?

Results Presentation

- **BACKGROUND**
  - High strength steels such as HSLA-65 and HSLA-100 were produced to optimize the weight of Naval platforms as well as reduce the steel and fabrication costs.
  - Distortion is one of the more major issues being addressed for thin plate (<3/8”). Foreseen cost savings have been offset by considerable rework / fit-up efforts.
  - Other Issues??? Productivity is limited when welding HSLA-100 due to a heat input restriction of 85kJ/in for ½” and greater thickness.
    - Restriction ensures that minimum specified weld metal yield strength (88 < 102ksi for under matching) is achieved when welding with MIL100S-1/S-2 type electrodes.
    - CG-HAZ impact properties can be problematic when welding HSLA-100 in the “lean” range of composition.
  - HSLA-65 CG-HAZ impact toughness requirements can be difficult to achieve consistently with high heat input procedures.

Results Presentation

- OBJECTIVES
  - Develop metal cored electrode chemistries that will retain minimum specified weld metal mechanical properties at high heat inputs.
    - Be used with off-the-shelf highly basic fluxes.
  - Develop highly productive tandem SAW procedures for panel welding using VBAC technology and metal cored electrodes.
    - Single pass OSW of ½” and 1” DH36
    - Single pass OSW of ½” and 1” HSLA-65
    - Multi-pass OSW of 1” HSLA-100
    - Two sided welding of ½” and 1” HSLA-100, 1 pass per side, with no back gouging
  - Determine if VBAC procedures will allow for the HSLA-100 heat input restriction to be expanded past 85kJ/in for higher productivity welding.

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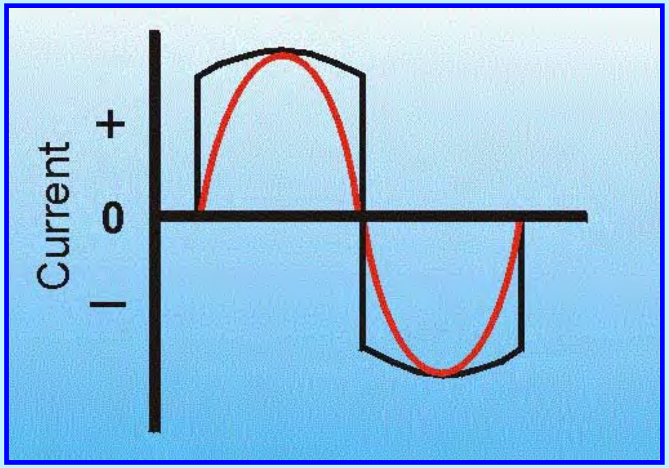
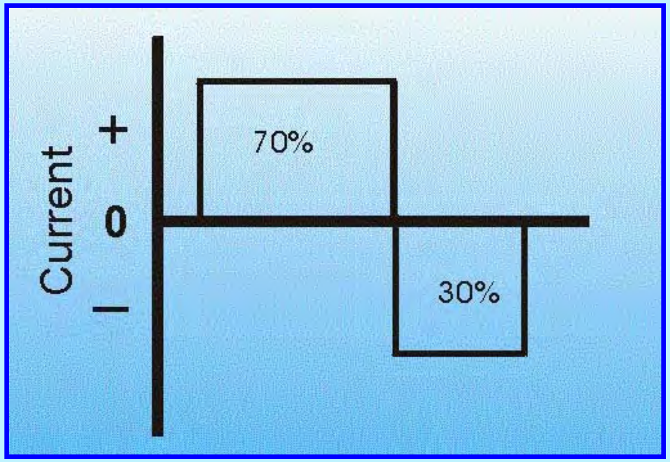
- **VBAC SAW**
  - Heat generated at the cathode (-)
  - DCEP greater portion of heat at work piece
    - Deep penetration
  - DCEN greater portion of heat at electrode
    - Enhanced weld deposition rates
  - Balanced AC provides characteristics between EP and EN polarity
  - Variable Balance AC
    - Control over EP / EN duration





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- **Task 1 – Summarize Current Practice for Panel Welding**
- **DH36 Welding at NGSS**
  - **Series Arc Sine Wave AC onto a Flux Copper Backing (FCB)**
  - **3/16” Lead and 1/8” Trail Lincoln L-61 Electrodes (AWS EM12K)**
  - **Lincoln 780 Flux for both backing and welding**

Plate Thickness	Joint Preparation Details			Pass (#)	WFS (ipm)	Amps (A)	Volts (V)	Travel Speed (ipm)	Heat Input (kJ/in)	“Arc Time” (min/ft of joint) *
	Included Angle	Root Face	Root Opening							
½”	Square Groove	N.A.	¼”	1	60 Series Arc	780	41	12	160	1
1”	Single-V 45°	¼”	5/32”	1	60 Series Arc	780	41	12	160	4.4
				2 to 5	N.A. Single Arc	650	32	14	89	

** Arc time per foot of joint doesn’t consider interpass operations*

Results Presentation

- **Task 1 – Summarize Current Practice for Panel Welding, cont.**
- **HSLA-65**
  - **Tandem Arc onto a Flux Copper Backing (FCB)**
  - **5/32” DC+ Lead and AC Trail, MIL-100S-1 w/ Lincoln MIL800-H flux (Nittetsu NSH-1R backing flux) – Spaced at 5.5”**

Plate Thickness	Joint Preparation Details			Pass (#)	WFS (ipm)	Amps (A)	Volts (V)	Travel Speed (ipm)	Total Heat Input (kJ/in)	“Arc Time” (min/ft of joint) *
	Included Angle	Root Face	Root Opening							
½”	Single-V 45°	3/32”	0”	1	N.A.	L-875	29	27.5	94.3	0.44
					N.A.	T-525	34			
1”	Single-V 45°	5/32”	0”	1	N.A.	L-1050	29	23.5	160.5	1.3
					N.A.	T-900	36			
				2	N.A.	825	34	15.5	108.6	

** Arc time per foot of joint doesn’t consider interpass operations*

Results Presentation

- **Task 1 – Summarize Current Practice for Panel Welding, cont.**
- **HSLA-100**
  - **Single Arc DC+, 1/8" MIL-100S-1/S-2 w/ MIL-800H flux**
  - **Heat input restricted to 85 kJ/in**
  - **Back gouging to sound weld metal prior to completing second side**

Plate Thickness	Joint Preparation Details			Pass (#)	WFS (ipm)	Amps (A)	Volts (V)	Travel Speed (ipm)	Heat Input (kJ/in)	"Arc Time" (min/ft of joint) *
	Included Angle	Root Face	Root Opening							
½"	Square Groove	N.A.	N.A.	1	N.A.	650	30	14	83.5	1.7
				2	N.A.	650	30	14	83.5	
1"	Double-V 60°	5/16"	0"	1-4	N.A.	650	30	14	83.5	6.8
				5-8	N.A.	650	30	14	83.5	

**** Arc time per foot of joint doesn't include interpass operations***

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- **Task 2 – Metal Cored Electrode Development**
  - DH36 Targets – Modified AWS EC1 Classification
    - Min. 58ksi YS, 71 to 95ksi UTS, and 20% Elongation
    - Impacts of 20ft-lbs @ -20F
  - HSLA-65 Targets – MIL-100S-1C per MIL-E-23765/2E
    - Min. 65ksi YS, 20% Elongation
    - Impacts of 30 ft-lbs @ -20F
  - HSLA-100 Targets – MIL-100S-1C per MIL-E-23765/2E
    - 88 to < 102ksi YS (under matching applications) and 18% Elongation
    - Impacts of 35 ft-lbs at -60F

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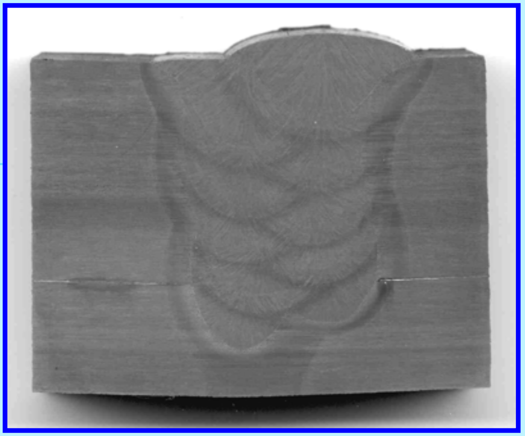

- **Task 2 – Metal Cored Electrode Development**
  - **Welding Parameters:**
    - Standard AWS A5.XX Test
    - 575A, 30V, 18 ipm TS, Heat Input 57.5 kJ/in
    - 2 passes per layer, 5 layers
    - Each test plate made from same 1” thick DH36, HSLA-65, and HSLA-100 base metal used for procedure qualifications
  - **Mechanical Testing**
    - All weld metal tensile and impact specimens extracted from the T/2 position along the weld centerline
  - **Deposited Chemical Analysis**
    - Sample extracted from fractured tensile specimens

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Specimen	Diameter (in.)	Area (in^2)	Yield Load (lbs)	Yield Strength (psi)	Minimum YS Requirement (psi)	Maximum Load (lbs)	Ultimate Tensile Strength (psi)	UTS Requirement (psi)	Elongation (%)	Elongation Requirement (%)
DH36-2 OK 10.62	.502	.198	17,958	**90,698**	**58,000**	19,850	100,253	71,000 to 95,000	**27**	**20**
HSLA-65-2 MIL800-H	.479	.180	18,000	**100,000**	**65,000**	20,790	115,500	NA	**21**	**20**
HSLA-100-3 MIL800-H	.502	.198	21,050	**106,312**	**88,000 to < 102,000**	24,110	121,767	NA	**20**	**18**

Specimen	Test Temperature (°F)	Energy (ft-lbs)	Average* (ft-lbs)	Requirement (ft-lbs)
DH36 (OK10.62 Flux)				
-1	-20	85	89	20
-2		87		
-3		95		
-4		94		
-5		74		
HSLA-65 (MIL800-H Flux)				
-1	-20	61	59	30
-2		58		
-3		58		
-4		62		
-5		54		
HSLA-100 (MIL800-H Flux)				
-1	-60	48	43	35
-2		43		
-3		38		
-4		43		
-5		43		

Results Presentation

- **Task 2 – Metal Cored Electrode Development**
  - **Electrode Formulations and Deposited Chemical Analysis**
    - **All weld metal chemical analysis sample extracted from reduced section of fractured tensile specimen**

	Compositions (%)																	
	C	Mn	Si	S	P	Ni	Cr	Mo	Al	B	Cu	Zr	Nb	Ti	V	N	O	Pcm
DH-36 Formulation	0.060	1.400	0.550	0.002	0.002	0.500	0.015	0.150	0.004	0.004	0.060	0.008	0.002	0.015	0.001			0.191
DH36 / OK 10.62	0.070	1.510	0.410	0.009	0.017	0.480	0.051	0.160	0.023	0.002	0.110	0.005	0.021	0.012	0.030	0.010	0.040	0.197
HSLA-65 Formulation	0.035	1.600	0.450	0.002	0.002	1.800	0.100	0.350	0.004	0.004	0.030	0.008	0.010	0.030	0.004			0.210
HSLA-65 / MIL800-H	0.060	1.680	0.360	0.008	0.015	1.750	0.120	0.360	0.024	0.001	0.089	0.005	0.025	0.010	0.045	0.010	0.037	0.231
HSLA-100 Formulation	0.050	1.750	0.450	0.002	0.002	2.300	0.175	0.450	0.007	0.004	0.030	0.008	0.010	0.030	0.007			0.252
HSLA-100 / MIL800-H	0.060	1.360	0.330	0.005	0.013	2.000	0.450	0.430	0.037	0.001	0.750	0.045	0.032	0.008	0.005	0.010	0.030	0.268

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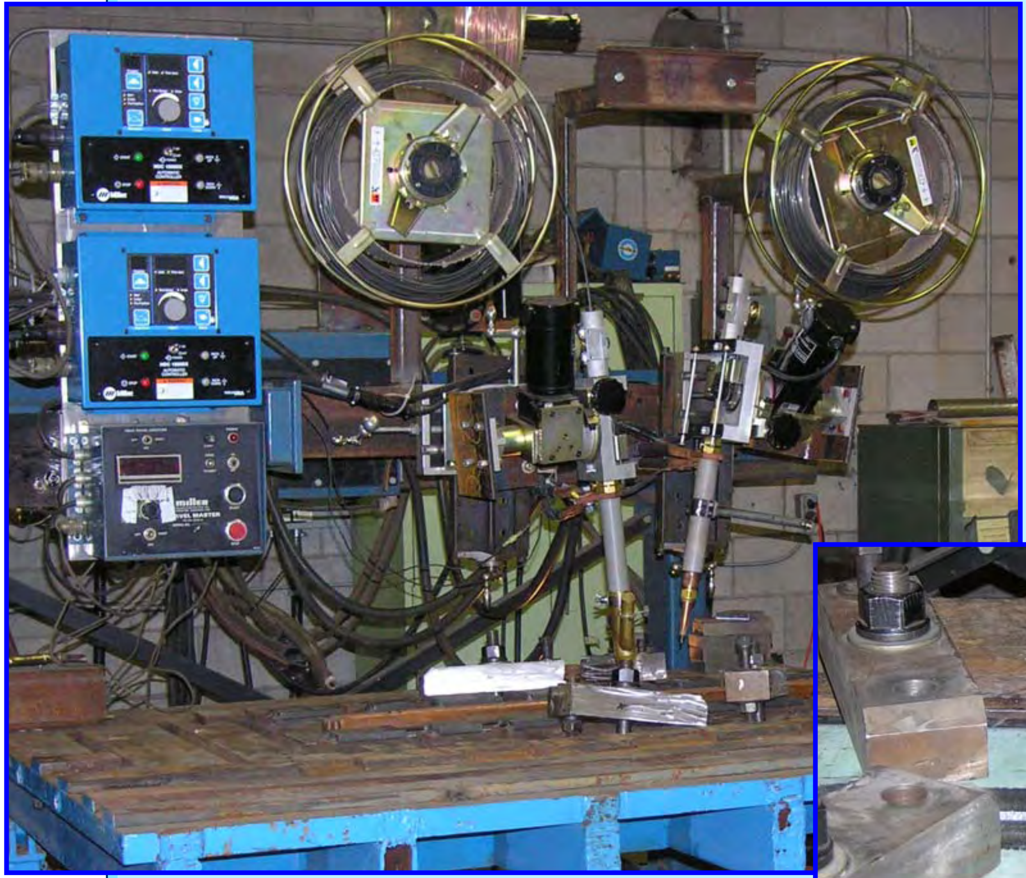
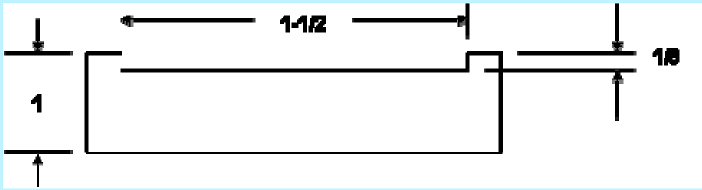
- **Task 3 – Procedure Development**
  - **DH36 and HSLA-65 Tandem Set-up**

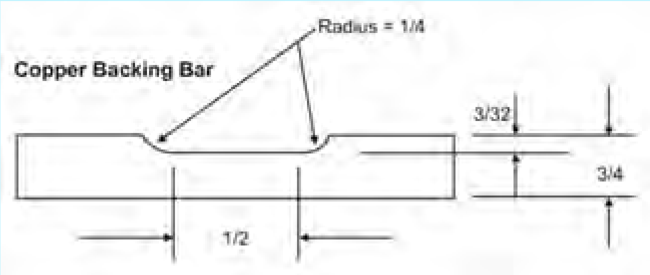


Results Presentation

- **Task 3 – Procedure Development**
  - Inconsistent results with existing FCB configuration
  - Root bead shape and height (for a given procedure) a function of flux particle size and distribution as well as consistency of flux compression between copper bar and back of plate along the length of the weld
    - Same procedure varies from one plate to the next (inconsistent root bead height and widths, undercutting, etc)
    - Excessive melt through (increased root bead height) resulted in loss of cap.



Original Design



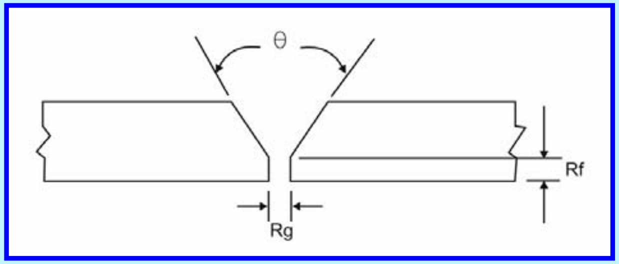
Modified Design

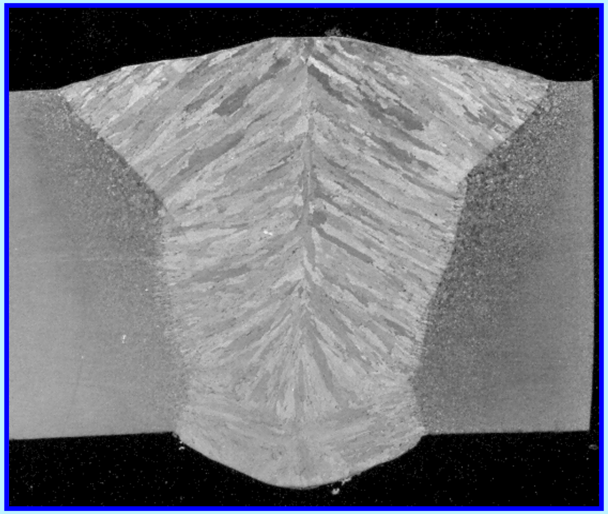
  - Small groove design provides improved local flux compression and weld bead support

Results Presentation

- **Task 3 – Procedure Development - ½” DH36 Steel**
  - **Lead 1/8” and Trail 5/32”**

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	Single-V ϴ = 30°, Rf = 1/8", Rg = 3/32"	
Electrode Spacing	5 1/4"	
Flux	ESAB OK 10.62	
Welding Parameters		
	Lead Electrode	**Trailing Electrode**
Amperage (A)	800	700
Voltage (V)	37.5	37.5
WFS (ipm)	200	100
Travel Speed (ipm)	**30**	
Benchark Travel Speed (ipm)	**12**	
Travel Angle (°)	15 drag	5 push
CTWD (in)	3/4	1 3/4
Heat Input (kJ/in)	**112.5 (combined)**	
Benchmark Heat Input (kJ/in)	**160 (combined)**	

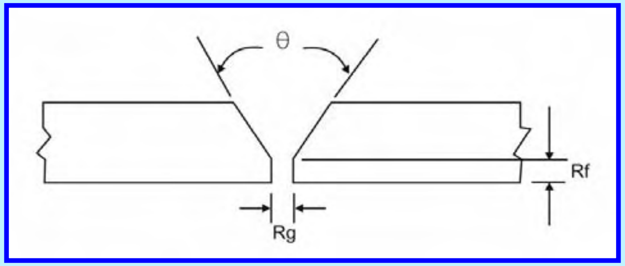


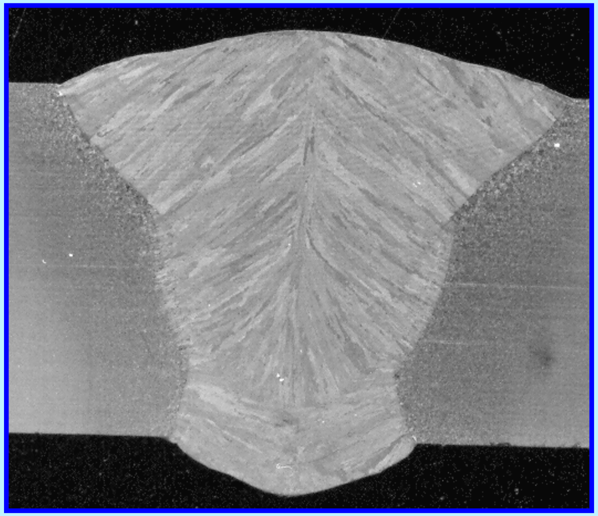


Results Presentation

- **Task 3 – Procedure Development - ½" HSLA-65**
  - **Lead 1/8" and Trail 5/32"**

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	Single-V ϴ = 30°, Rf = 1/8", Rg = 3/32"	
Electrode Spacing	5 ¼"	
Flux	Lincoln MIL800-H	
Welding Parameters		
	Lead Electrode	Trailing Electrode
Amperage (A)	800	700
Voltage (V)	37.5	37.5
WFS (ipm)	200	100
Travel Speed (ipm)	30	
Benchark Travel Speed (ipm)	27.5	
Travel Angle (°)	15 drag	5 push
CTWD (in)	3/4	1 3/4
Heat Input (kJ/in)	112.5 (combined)	
Benchmark Heat Input (kJ/in)	94.3 (combined)	

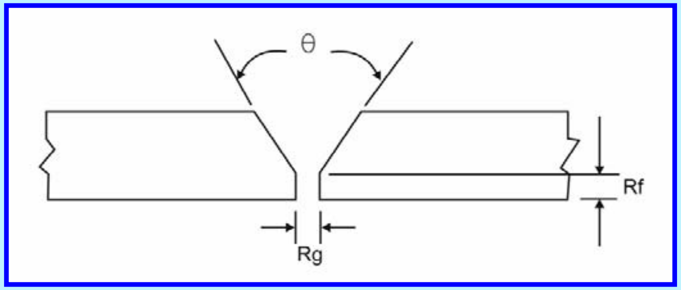


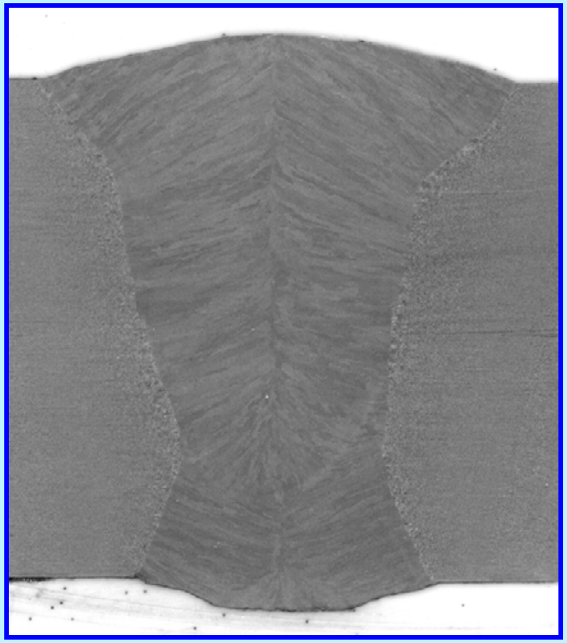


Results Presentation

- **Task 3 – Procedure Development – 1" DH36 Steel**
  - **5/32" Lead and Trail**

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	ϴ=30° Included Angle Rg = 3/32" Rf = 3/16"	
Electrode Spacing	4"	
Flux	ESAB OK 10.62	
Tandem Welding Parameters		
	Lead Electrode	**Trailing Electrode**
Amperage (A)	1150	980
Voltage (V)	32.5	36.5
WFS (ipm)	225	175
Travel Speed (ipm)	**20.5 - 1 pass only**	
Benchmark Travel Speed (ipm)	**12 for1st pass, and 14 for 2nd, 3rd, 4th, and 5th passes**	
Travel Angle (°)	15 drag	0
CTWD (in)	1/2	1 3/4
Heat Input (kJ/mm)	**214.1 (combined)**	
Benchmark Heat Input (kJ/in)	**160.5 for 1st pass and 89 for 2nd, 3rd, 4th, and 5th passes**	

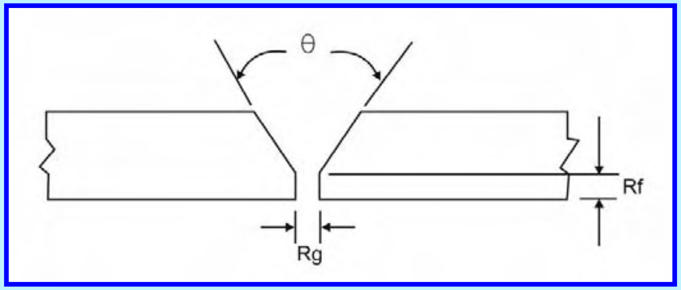




Results Presentation

- **Task 3 – Procedure Development – 1" HSLA-65 Steel**
  - **5/32" Lead and Trail**

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	ϴ=30° Included Angle Rg = 3/32" Rf = 3/16"	
Electrode Spacing	4"	
Flux	Lincoln MIL800-H	
Tandem Welding Parameters		
	Lead Electrode	Trailing Electrode
Amperage (A)	1180	950
Voltage (V)	32.5	36.5
WFS (ipm)	225	175
Travel Speed (ipm)	20.5 - 1 pass only	
Benchmark Travel Speed (ipm)	23.5 for 1st pass and 15.5 for 2nd pass	
Travel Angle (°)	15 drag	0
CTWD (in)	1/2	1 3/4
Heat Input (kJ/mm)	214.1 (combined)	
Benchmark Heat Input (kJ/in)	160.5 for 1st pass and 108.6 2nd pass	



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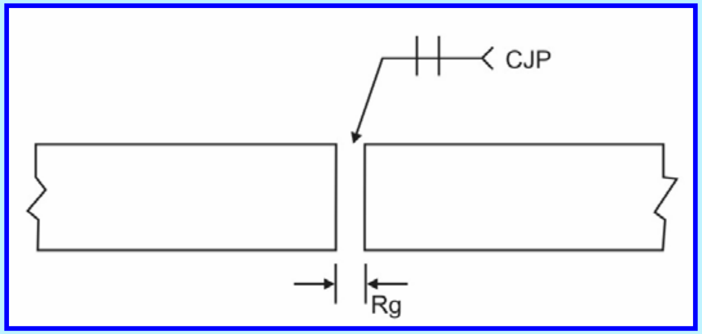
- Task 3 – Procedure Development – HSLA-100
  - 5/32” Lead and Trail
  - Min 60°F Preheat and Max 300°F Interpass Temperatures

Results Presentation

- **Task 3 – Procedure Development – HSLA-100**
- **½" Thickness – Two Sided Weld, One Pass Per Side, No Back Gouging**

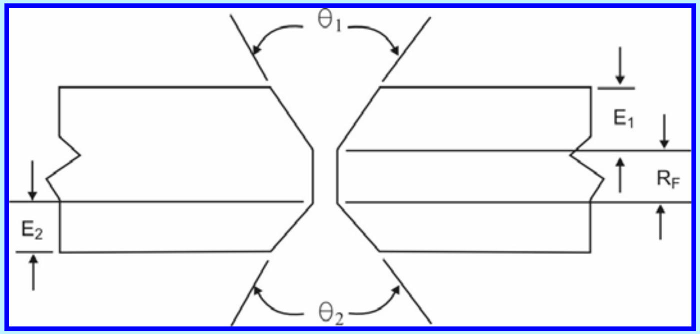
Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	Square Groove, Rg = 0	
Electrode Spacing	7/8"	
Travel Angle (°)	0 Lead	15 push Trail
CTWD (in)	3/4 Lead	1 3/4 Trail
Flux	Lincoln MIL800-H	
Welding Parameters		
	Lead Electrode	**Trailing Electrode**
Side 1		
Amperage (A)	950	600
Voltage (V)	30	35
WFS (ipm)	150	100
Travel Speed (ipm)	**45 for 1st Pass**	
Side 2		
Amperage (A)	950	600
Voltage (V)	30	35
WFS (ipm)	150	100
Travel Speed (ipm)	**45 for 2nd Pass**	
Benchark Travel Speeds	**14 for 1st and 2nd Pass**	
Heat Input (kJ/in)	**66 (combined) for each pass**	
Benchmark Heat Input (kJ/in)	**83.5**	

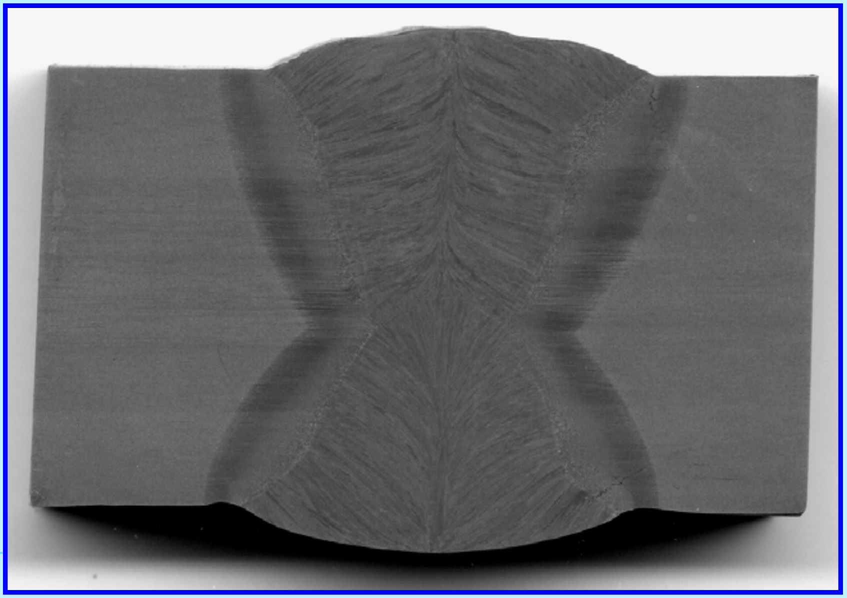


Results Presentation

- **Task 3 – Procedure Development – HSLA-100**
- **1" Thickness – Two Sided Weld, One Pass Per Side, No Back Gouging – 66/34 Balance**

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	Θ1=70° Included Angle, Θ2=90° Included Angle, Rg = 0, Rf = 5/16, E1=7/16, E2=1/4	
Electrode Spacing	7/8"	
Travel Angle (°)	0 Lead	15 push Trail
CTWD (in)	1 1/4 Lead	1 1/2 Trail
Flux	Lincoln MIL800-H	
Welding Parameters		
	Lead Electrode	**Trailing Electrode**
Side 1		
Amperage (A)	1000	850
Voltage (V)	32.5	36
WFS (ipm)	175	195
Travel Speed (ipm)	**38 for 1st Pass**	
Side 2		
Amperage (A)	950	725
Voltage (V)	32.5	35
WFS (ipm)	160	160
Travel Speed (ipm)	**45 for 2nd Pass**	
Benchark Travel Speeds	**14 for 8 passes (4 per side)**	
Heat Input (kJ/in)	**99.6 (combined) for 1st Pass and 75 kJ/in for 2nd Pass**	
Benchmark Heat Input (kJ/in)	**83.5 each pass**	

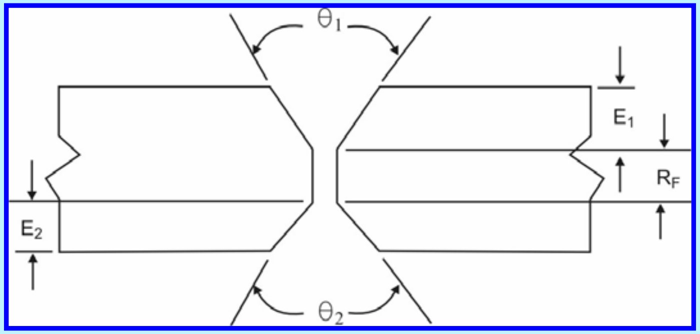


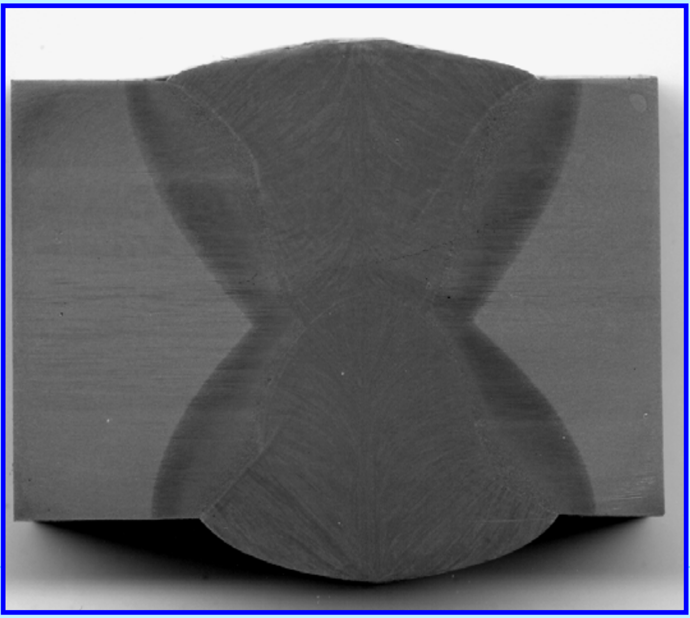


Results Presentation

- **Task 3 – Procedure Development – HSLA-100**
- **1" Thickness – Two Sided Weld, One Pass Per Side, No Back Gouging – 34/66 Balance**

Mode	Constant Voltage	
Balance (EP/EN)	34/66	
Joint Preparation	ϴ1=70° Included Angle, ϴ2=90° Included Angle, Rg = 0, Rf = 5/16, E1=7/16, E2=1/4	
Electrode Spacing	7/8"	
Travel Angle (°)	0 Lead	15 push Trail
CTWD (in)	1 1/4 Lead	1 1/2 Trail
Flux	Lincoln MIL800-H	
Welding Parameters		
	Lead Electrode	**Trailing Electrode**
Side 1		
Amperage (A)	1000	680
Voltage (V)	32.5	36
WFS (ipm)	200	200
Travel Speed (ipm)	**38 for 1st Pass**	
Side 2		
Amperage (A)	1050	800
Voltage (V)	32.5	36
WFS (ipm)	200	200
Travel Speed (ipm)	**45 for 2nd Pass**	
Benchark Travel Speeds	**14 for 8 passes (4 per side)**	
Heat Input (kJ/in)	**90 (combined) for 1st Pass and 83.9 kJ/in for 2nd Pass**	
Benchmark Heat Input (kJ/in)	**83.5 each pass**	

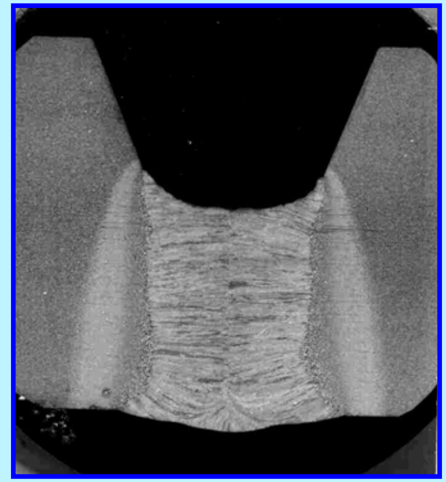


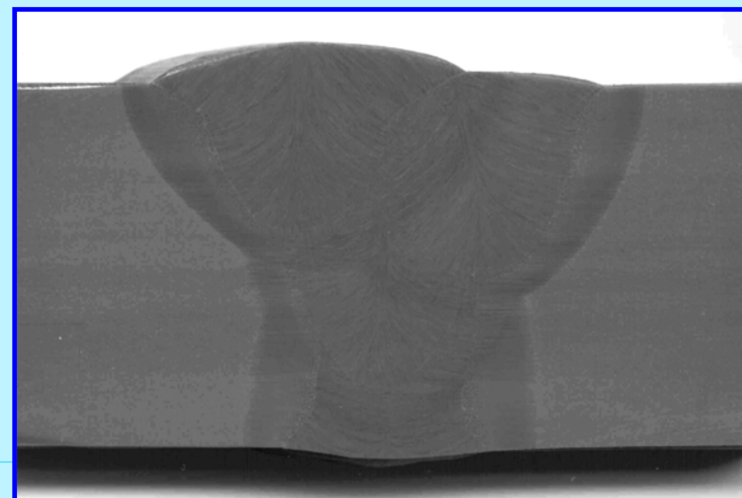


Results Presentation

- **Task 3 – Procedure Development – HSLA-100**
- **1" Thickness – Tandem Multi-pass OSW onto a FCB – 4 Passes**

Mode	Constant Voltage	
Balance (EP/EN)	66/34	
Joint Preparation	ϴ=45° Included Angle Rg = 1/8 Rf = 5/32	
Electrode Spacing	7/8"	
Travel Angle (°)	0 Lead	15 push Trail
CTWD (in)	1 1/4 Lead	1 1/4 Trail
Flux	Lincoln MIL800-H	
Tandem Welding Parameters		
	Lead Electrode	Trailing Electrode
Pass 1		
Amperage (A)	800	660
Voltage (V)	33	34
WFS (ipm)	145	145
Travel Speed (ipm)	35	
Pass 2		
Amperage (A)	860	680
Voltage (V)	33	34
WFS (ipm)	145	145
Travel Speed (ipm)	40	
Pass 3		
Amperage (A)	900	680
Voltage (V)	32.5	35
WFS (ipm)	145	145
Travel Speed (ipm)	45	
Pass 4		
Amperage (A)	920	700
Voltage (V)	32.5	35
WFS (ipm)	145	145
Travel Speed (ipm)	45	
Benchark Travel Speeds	Unknown for OSW'ing	
Heat Input (kJ/in)	83.8 1st Pass, 77.3 for 2nd, 70.7 for 3rd, and 72.6 for 4th	
Benchmark Heat Input (kJ/in)	Unknown for OSW'ing	





Results Presentation

- **Task 3 – Procedure Qualification Test Matrix**
  - All plates radiographed at 90° and +/-20° to surface
- **½” Plates**
  - 2 Cross Weld Tensiles
  - 1 Macro / Micro / Hardness
  - 4 Side Bends
  - Charpy V-notch Impact @ T/2
    - 5 Weld Centerline, 5 Fusion Line, 5 Fusion Line + 1mm, and 5 Fusion Line + 3mm
- **1” Plates**
  - 2 Cross Weld Tensiles
  - 1 All Weld Metal Tensile (centered at ¼” below Side #1 surface)
  - 1 Macro / Micro / Hardness
  - 4 Side Bends
  - Charpy V-notch Impact @ 1/16” from Side #1 surface
    - 5 Weld Centerline, 5 Fusion Line, 5 Fusion Line + 1mm, and 5 Fusion Line + 3mm

Results Presentation

- **Task 3 – Procedure Qualification Test Results**
- **½" Plates**

Procedure	Cross Weld Tensile Test: Requirement (ksi)	Result (ksi)	Base Metal UTS (ksi)	Joint Efficiency	Charpy V-notch Impacts: Requirement	Location	AVG Energy (ft-lbs)	Side Bends
DH36 OSW	71	80.7	80.1	101%	20 ft-lbs @ -20F	CL	111	Acceptable
		80.5	80.1	100%	17 ft-lbs @ -4F	FL	62	
						FL+1	60	
						FL+3	106	
HSLA-65 OSW	NA	82.1	80	103%	30 ft-lbs @ -20F	CL	100	Acceptable
		81.5	80	102%		FL	59	
						FL+1	58	
						FL+3	227	
HSLA-100 1 Pass Per Side	NA	122.1	119.7	102%	60 ft-lbs @ 0F	CL	77	Acceptable
		119.9	119.7	100%		FL	78	
						FL+1	60	
						FL+3	118	
					35 ft-lbs @ -60F	CL	54	
						FL	47	
						FL+1	34	
						FL+3	32	

Heat Input 66 kJ/in

Results Presentation

- **Task 3 – Procedure Qualification Test Results - 1" Plates**

Procedure	Cross Weld Tensile Test				All Weld Metal Tensile Test			Charpy V-notch Impacts			Side Bends
	Requirement (ksi)	Result (ksi)	Base Metal UTS (ksi)	Joint Efficiency	Yield Strength (ksi)	UTS (ksi)	Elongation (%)	Requirement	Location	AVG Energy (ft-lbs)	
DH36 OSW	71 to 95	87.4	77.8	112%	83.2	110.5	27.7	20 ft-lbs @ -20F	CL	75	Acceptable
		86.9	77.8	112%				17 ft-lbs @ -4F	FL	26	
					Requirement Yield Strength 58ksi, UTS 71 to 95ksi, and Elongation 20%				FL+1	21	
									FL+3	50	
HSLA-65 OSW	NA	81.2	78	104%	84.8	100.1	24.7	30 ft-lbs @ -20F	CL	91	Acceptable
		80.7	78	103%					FL	37	
					Requirement Yield Strength 65ksi and Elongation 20%				FL+1	44	
									FL+3	71	
HSLA-100 1 pass per side 66/34	NA	117.1	117.4	100%	94.8	116	21.8	60 ft-lbs @ 0F	CL	81	Acceptable
		118.5	117.4	101%					FL	59	
					Requirement Yield Strength 88 < 102ksi and Elongation 18%				FL+1	79	
									FL+3	173	
								35 ft-lbs @ -60F	CL	48	
									FL	37	
									FL+1	67	
									FL+3	118	
HSLA-100 1 pass per side 34/66	NA				98	119	21.3	60 ft-lbs @ 0F	CL	74	Acceptable
									FL	81	
					Requirement Yield Strength 88 < 102ksi and Elongation 18%				FL+1	Not Tested	
									FL+3		
								35 ft-lbs @ -60F	CL	42	
									FL	46	
									FL+1	64	
									FL+3	Not Tested	
HSLA-100 4 pass OSW	NA				89.8	123	20.4	60 ft-lbs @ 0F	CL	77	Acceptable
									FL	68	
					Requirement Yield Strength 88 < 102ksi and Elongation 18%				FL+1	Not Tested	
									FL+3		
								35 ft-lbs @ -60F	CL	43	
									FL	52	
									FL+1	73	
									FL+3	Not Tested	

99.6 kJ/in (HSLA-100 1 pass per side 66/34)

90 kJ/in (HSLA-100 1 pass per side 34/66)

Porosity Visible on Fracture Surface of Tensile Specimen (HSLA-100 4 pass OSW, Yield Strength 89.8)

Results Presentation

- **Task 3 – Procedure Qualification Test Results**
- **Hardness - Average HV_5**

Procedure	Thickness	Average Hardness (HV5)			
		Location			
		CL	FL	HAZ	BM
DH36	1/2"	210	187	165	154
	1"	226	214	185	166
HSLA-65	1/2"	227	198	180	168
	1"	228	204	172	164
HSLA-100 (66/34)	1/2"	261	246	239	256
	1"	254	272	251	259
HSLA-100 (34/66)	1"	266	289	275	280
HSLA-100 OSW - 4 Pass	1"	286	280	252	284

Results Presentation

- **Productivity Comparison with Current Practice**

	Procedure	Thickness (in)	Side	Pass (#)	Travel Speed (ipm)	Total Arc Time per ft of Joint (min)	Productivity Improvement Over Benchmarks (%)
Benchmarks	DH36 - Series AC	0.5	1	1	12	1.00	
		1	1	1	12	4.40	
				2 to 5	14		
	HSLA-65 - Tandem Arc	0.5	1	1	27.5	0.44	
		1	1	1	23.5	1.30	
				2	15.5		
	HSLA-100 - Single Arc	0.5	1	1	14	1.70	
			2	2	14		
		1	1	1 to 4	14	6.80	
			2	5 to 8	14		
VBAC Procedures	DH36 - Tandem OSW	0.5	1	1	30	0.40	250%
		1	1	1	20.5	0.59	746%
	HSLA-65 - Tandem OSW	0.5	1	1	30	0.40	10%
		1	1	1	20.5	0.59	245%
	HSLA-100 - Tandem 64/36 (EP/EN) - 2 passes	0.5	1	1	45	0.53	321%
			2	2	45		
		1	1	1	38	0.58	1172%
			2	2	45		
	HSLA-100 - Tandem 34/66 (EP/EN) - 2 Passes	1	1	1	38	0.58	1172%
			2	2	45		
	HSLA-100 - Tandem 64/36 (EP/EN) OSW - 4 Passes	1	1	1	35	1.18	576%
				2	38		
				3 to 4	45		

Results Presentation

- **Productivity Comparison – Deposition Rates**
  - **DH36 and HSLA-65 Procedures**
    - **75 lbs/hr (112.5 kJ/in) – (½" Thickness)**
    - **112 lbs/hr (214.1 kJ/in) – (1" Thickness)**
  - **HSLA-100 Steel Procedures**
    - **81 lbs/hr (66 kJ/in) – (½" thickness)**
    - **66/34 = 104 lbs/hr 1st pass (99.6 kJ/in), and, 89 lbs / hr 2nd pass (75 kJ/in) - (1" Thickness)**
    - **34/66 = 112 lbs/hr for 1st (90kJ/in) and 2nd (83 kJ/in) - (1" Thickness)**
    - **OSW = 81 lbs/hr for each of the 4 passes (70 to 83.9 kJ/in) - (1" Thickness)**

Results Presentation

- **Cost Analysis**
  - Metal cored $/lb cost approximately the same as an EM12K solid wire, and, 30% less than an alloyed solid wire
  - Assumed $55/hr labor rate
  - Cost reductions are for arc time only, and do not include further savings that can be achieved by elimination of interpass operations (chipping slag, back gouging, realignment of electrodes, etc) typical for the benchmark procedures

	Procedure	Thickness (in)	Side	Pass (#)	Weld Weight per Foot (lbs)	Electrode Cost ($/lb)	Electrode Cost per Foot ($)	Travel Speed (ipm)	Total Arc Time per ft (min)	Labor Cost ($/hr)	Labor Cost per Foot ($)	Total Electrode and Labor Cost per Foot ($)	Potential Cost Reduction
Benchmarks	DH36 - Series AC	0.5	1	1	0.43	1.75	0.75	12	1.00	55	0.92	1.67	
		1	1	1	1.6	1.75	2.80	12	4.40	55	4.03	6.83	
				2 to 5				14					
	HSLA-65 - Tandem Arc	0.5	1	1	0.62	3.5	2.17	27.5	0.44	55	0.40	2.57	
		1	1	1	1.6	3.5	5.60	23.5	1.30	55	1.19	6.79	
				2				15.5					
	HSLA-100 - Single Arc	0.5	1	1	0.43	3.5	1.51	14	1.70	55	1.56	3.06	
			2	2				14					
		1	1	1 to 4	0.95	3.5	3.33	14	6.80	55	6.23	9.56	
			2	5 to 8				14					
VBAC Procedures	DH36 - Tandem	0.5	1	1	0.5	1.75	0.875	30	0.40	55	0.37	1.24	-26%
		1	1	1	1.09	1.75	1.9075	20.5	0.59	55	0.54	2.45	-64%
	HSLA-65 - Tandem	0.5	1	1	0.5	3.1	1.55	30	0.40	55	0.37	1.92	-26%
		1	1	1	1.09	3.1	3.379	20.5	0.59	55	0.54	3.92	-42%
	HSLA-100 - Tandem 64/36 (EP/EN)	0.5	1	1	0.72	3.1	2.232	45	0.53	55	0.49	2.72	-11%
			2	2				45					
		1	1	1	0.94	3.1	2.914	38	0.58	55	0.53	3.45	-64%
			2	2				45					
	HSLA-100 - Tandem 34/66 (EP/EN)	1	1	1	1.09	3.1	3.379	38	0.58	55	0.53	3.91	-59%
			2	2				45					
	HSLA-100 - Tandem OSW - 4 Pass	1	1	1	1.59	3.1	4.929	35	1.18	55	1.08	6.01	-37%
				2				38					
				3 to 4				45					

Results Presentation

- **Conclusions**
  - **Highly productive VBAC tandem procedures have been developed for single pass OSW of ½” and 1” thick DH36 and HSLA-65 steels.**
    - **All procedures demonstrated a minimum of 100% joint efficiency and met all weld metal and HAZ requirements.**
    - **Productivity improvements (arc time per foot of completed joint) as high as 750% were demonstrated over benchmark procedures for current panel line welding practice**
    - **Weld metal deposition rates as high as 112 lbs / hr were achieved.**
    - **The calculated cost per foot of completed joint (electrode and labor costs) demonstrated reductions as much as 64% compared to benchmark procedures that use solid wire electrodes**

Results Presentation

- **Conclusions, cont.**
  - Highly productive VBAC tandem procedures have been developed for two sided welding (1 pass per side) with no back gouging of ½" and 1" thick HSLA-100 steels.
    - All procedures demonstrated a minimum of 100% joint efficiency and met all weld metal requirements, even for heat inputs as high as 99.6 kJ/in.
    - HAZ impact properties for the ½" thickness marginally failed the HAZ FL+1 and FL+3 requirements of 35ft-lbs @ -60F, despite the welding heat input (66kJ/in) being well below the 85kJ/in restriction
    - Productivity improvements (arc time per foot of completed joint) as high as 1172% were demonstrated over benchmark procedures for current panel line welding practice
    - Weld metal deposition rates as high as 112 lbs / hr were achieved. Switching from 66/34 (EP/EN) to 34/66 (EP/EN) balance setting demonstrated a 15% improvement in deposition rate for the same welding conditions
    - The calculated cost per foot of completed joint (electrode and labor costs) demonstrated reductions as much as 64% compared to benchmark two sided procedures that use solid wire electrodes
    - Further cost reductions can be demonstrated by considering the elimination of interpass welding operations such as back gouging, chipping and cleaning slag, realignment of electrodes, etc.

Results Presentation

- **Conclusions, cont.**
  - **Highly productive VBAC tandem procedures have been developed for multi-pass OSW of 1" thick HSLA-100 steel onto a FCB.**
    - **All procedures demonstrated a minimum of 100% joint efficiency and met all weld metal and HAZ requirements.**
    - **Productivity improvements (arc time per foot of completed joint) as high as 576% were demonstrated over benchmark procedures for current panel line welding practice**
    - **Weld metal deposition rates as high as 81 lbs / hr were achieved.**
    - **The calculated cost per foot of completed joint (electrode and labor costs) demonstrated reductions as much as 37% compared to two sided benchmark procedures that use solid wire electrodes**
    - **Further cost reductions can be demonstrated by considering the elimination of interpass welding operations such as back gouging, chipping and cleaning slag, realignment of electrodes, etc.**

Results Presentation

- **Recommendations for Further Work**
  - **Evaluate Range of HSLA-100 Compositions (Lean and Rich) for 1” Thickness**
  - **Evaluate 2” Thick HSLA-100**
    - **Compare productivity of Tandem VBAC to other practices, “*can even higher heat inputs be adopted for 2 inch thickness due to the greater heat sink capacity?*”**
      - **Lower Preheat and Interpass Temperatures?**
      - **Improved Weld Metal and HAZ Properties?**
    - **Qualification for Aircraft Carriers (Explosion Bulge and Dynamic Tear Testing)**
  - **Production Trials and Demonstrations**

Results Presentation

QUESTIONS?

High Speed Submerged Arc Fillet Welding – Follow-on Project

- **Twin Wire and Twin-Wire Tandem Configuration (4mm to 10mm fillet welds)**
  - **Higher Deposition Rates and Productivity Compared to Single Wire**
  - **Lead and Trail Twin-Wire Torch Work Angles and Stand-off Control Fillet Weld Leg Size, in Conjunction with Travel and Wire Feed Speeds**
    - **Allow for large weld sizes to be deposited in a single run at higher speeds compared to single wire multi-pass or a single twin-wire torch**