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Applied Research Laboratory
The Pennsylvania State University

Development and Implementation of Hybrid Welding for Shipyard Applications

Presented at the SP-7 Meeting

Presented by: Rich Martukanitz and Mike Ludwig

Co-Principal Investigator: Dr. S. M. Kelly

Team Members:
IMAST at ARL-Penn State
General Dynamics Bath Iron Works
Northrop Grumman Ship Systems
NSWCCD

March 6, 2008

Bath Iron Works
A GENERAL DYNAMICS COMPANY

NORTHROP GRUMMAN
Ship Systems

NAVSEA
CARDEROCK
Surface Warfare Center Division

PENNSTATE iMAST

Program Outline

Phase I

Define Applications and Preliminary Benefits

- Preliminary Process Development
- Initial Cost Benefit Analysis
- Define Applications
- Thin Steel Panel Structures

Phase II

Application Specific Process Development and Demonstration

- Define Weld Performance and Qualification Requirements (Begin/Refine Qualification Roadmap)
- Develop Process for Shipyard Demonstration
- Conduct Weld Performance Testing
- Conduct Shipyard Demonstration
- Complete Implementation Roadmap
- Demonstration Success ?
  - Yes: Phase III
  - No: Final Report

Refine Process Window and define additional testing

Phase III

Execution of Qualification Roadmap

- Specify (and build) system
- Conduct additional testing on remaining target materials and applications
- Qualification Testing
- Implementation Implementation Tracking

Phase II Metrics:

1) 50% reduction in distortion over conventional process
1) Shipyard acceptance
2) Pre-qualified to:
   TP-248
   MIL-STD-1689

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Hybrid Welding Demonstration at Bath Iron Works Harding's Facility

January 2008

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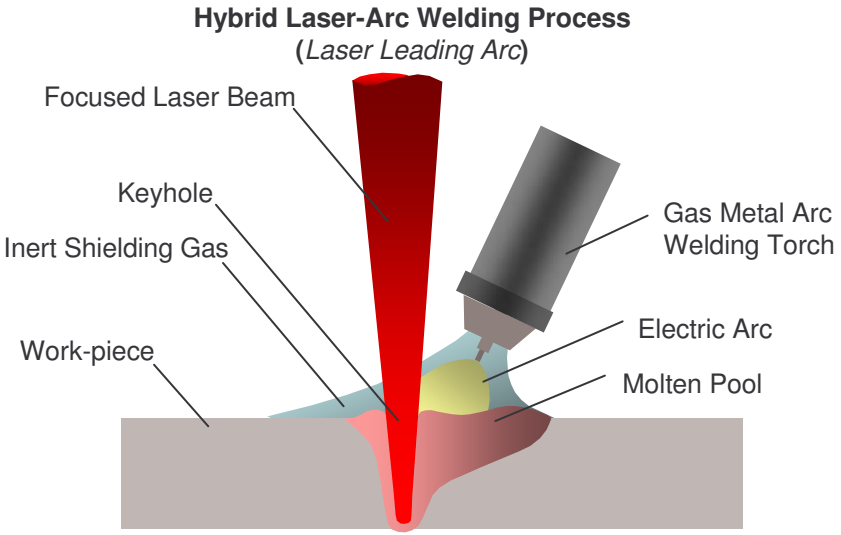
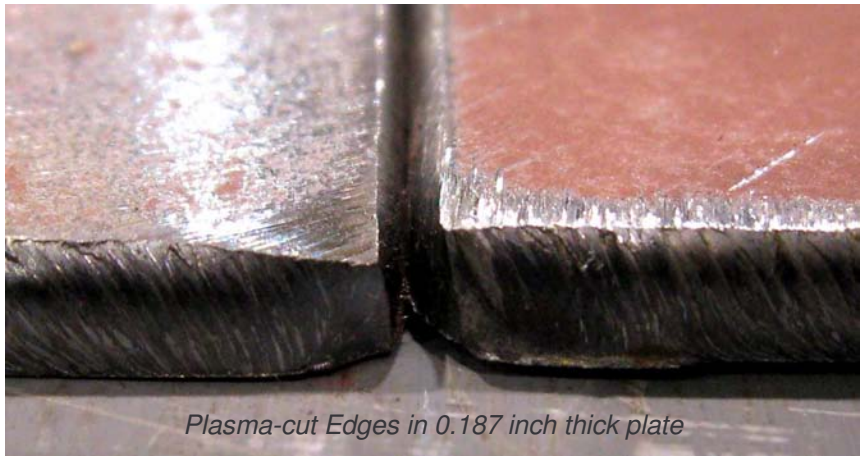
- Objective: Demonstrate the technical and economic feasibility of Hybrid Laser Arc Welding within the current shipyard production environment.
- Shipyard Production Environment Issues:
  - Plasma cut edges.
  - Typical shipyard fit-up.
  - Safety…locally enclose welding process.
  - Production-size components.
- Demo Operational Requirements:
  - Cannot interrupt production.
  - Cannot build a "room", must locally enclose welding process.
  - Provide own motion system (cannot use side beam or gantry).
- Weld Process Comparisons Made:
  - HLAW vs. GMAW.
  - HLAW vs. SAW.
  - Compare distortion and productiviy.
- Attendees:
  - Over 40 representatives from four U.S. shipyards, U.S. Navy, and industry attended.





Plasma-cut Edges in 0.187 inch thick plate

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Demonstration System, v1.0

Portable hybrid welding system required for demonstration at BIW Hardings facility

- Laser
  - 7kW IPG Photonics Yb-Fiber Laser
  - 300 um diameter fiber (Optoskand), 150 mm collimator (Precitec), 200 mm focal length (Trumpf)…optics not rated above ~4500 W.
- Arc Welding
  - Miller AutoAxcess 450, Pulse.
  - Abicor-Binzell Water Cooled Torch.
- Motion
  - Dual Bug-O Tractors (Master/Slave). Travel speeds up to 120 in/min.
  - **No Seam tracker.** Manual alignment of Bug-O track with joint.
- Enclosure
  - Laser safe window (O.D. 7) and arc welding curtain.
  - Dual wire brush skirt with silicone rubber insert.
  - Venting.
  - Additional silicone rubber drape.
  - No interruption in production, no laser safe room.
- Safety
  - Window interlock.
  - E-Stop.
  - Laser window and arc curtain.
  - Spectroscopy measurements completed at ARL-PSU.

HLAW demonstration system on demonstration panel

View inside welding enclosure. Laser window is open.

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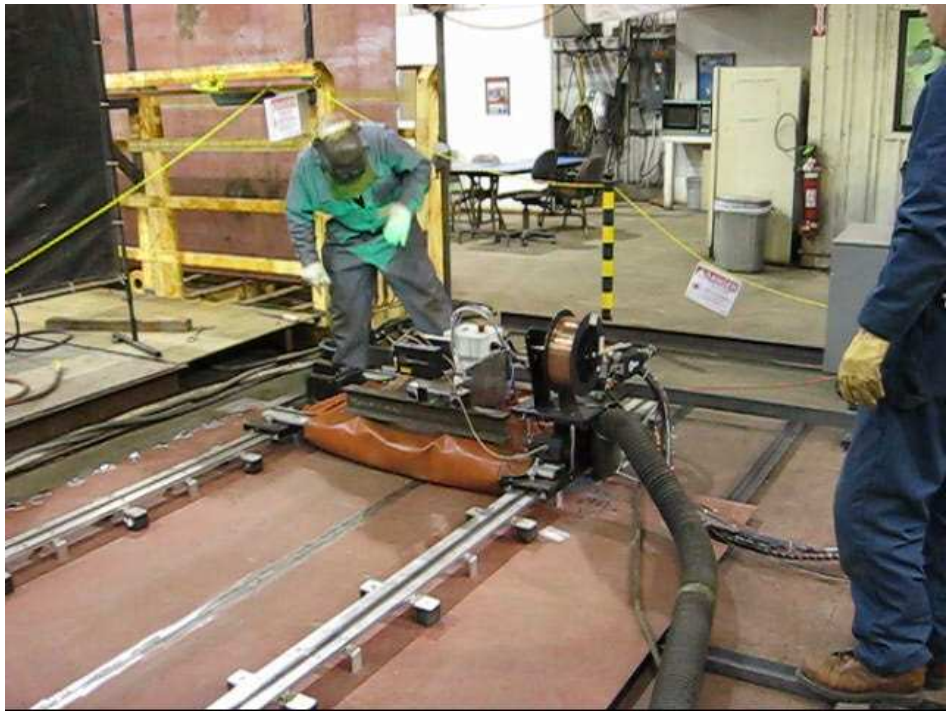
Safety

- 7kW Yb fiber laser is a Class 4 laser.
- Interlocked enclosure and welding system ensures no contact with direct beam.
- Exhaust vents below line of sight.
- Wire brush skirt limits diffuse reflection to large angles; hazard zone is within 15 ft.
- External silicone rubber drape provides additional protection.
- Spectroscopy measurements performed at Penn State to quantify light leakage.



10ft panel HLAW weld at BIW on 17 Jan 2008

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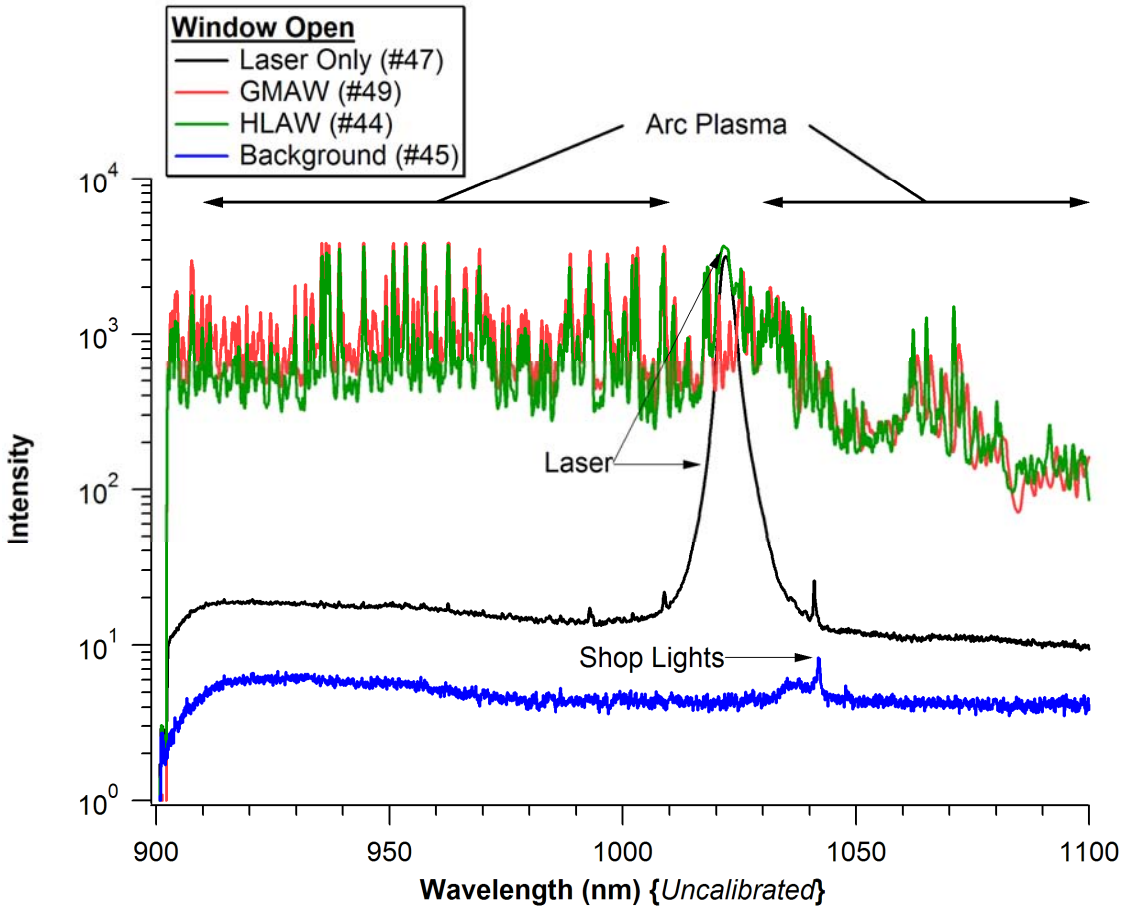
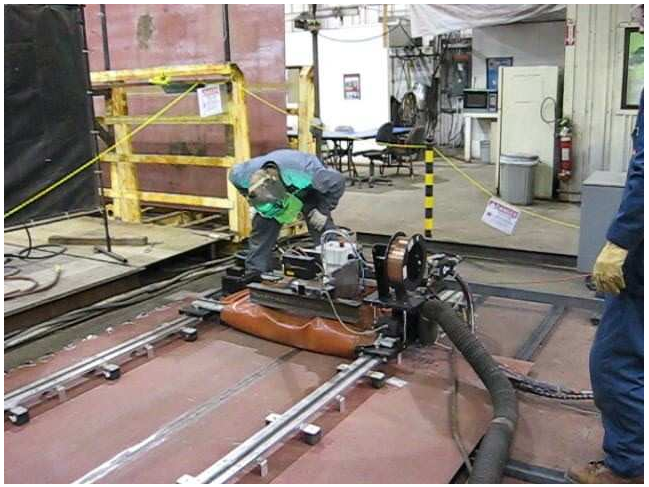
Safety, Spectroscopy Results



- Intensity of arc and laser emission are comparable.

Hybrid vs. Single Sided GMAW

- Material: AB/DH36
- Welded Plate Size: 96x120x0.188 inches.
- Plasma Cut Edge, Square Butt
- Wire: 0.045 inch 70S-6
- 3 Test Panels
  - TP-1 and TP-2 Hybrid welded on 1/16/08 and 1/17/08.
  - TP-3 GMA welded on 1/28/08.
  - All panels measured before and after for distortion.
- Notable differences
  - Seam Welder:
    - Restraint and water cooled copper backing.
    - Req'd root opening: 1/16 in.
    - GMAW-Spray
  - Hybrid:
    - No restraint, or active clamping.
    - Fit-up Gap ranged from 0 to < 0.030 in.
    - GMAW-Pulse



HLAW, welding TP-2 on 17 January 2008. Note arc weld curtain lifted.

Harding's BIW GMAW Seam Welder, welding TP-3 on 28 January 2008.

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Process Comparison: Hybrid vs. Single Sided GMAW

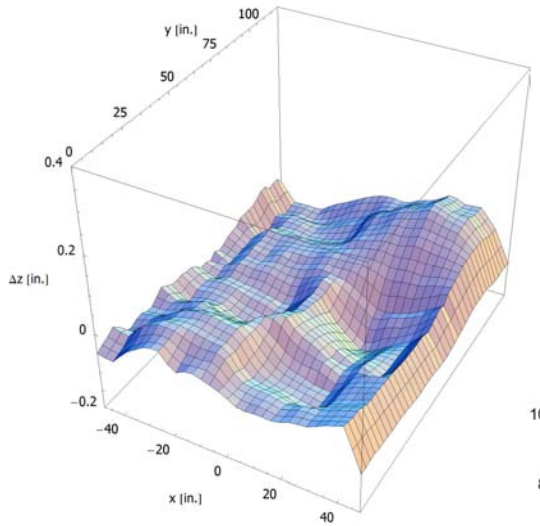
Quantity	HLAW	GMAW	GMAW is…
Productivity (time to weld 10 ft plate)	1.9 min	5.0 min	…is 2.6 times slower,
Heat Input (kJ/in)	8.6 kJ/in	24 kJ/in	…adds 2.8 times more heat,
Weld Metal Deposited (lb/ft)	0.0054 lb/ft	0.0915 lb/ft	…uses 17 times more weld metal,
Shield Gas Consumption (SCFH)	95	50	…uses 0.5 times the shielding gas,

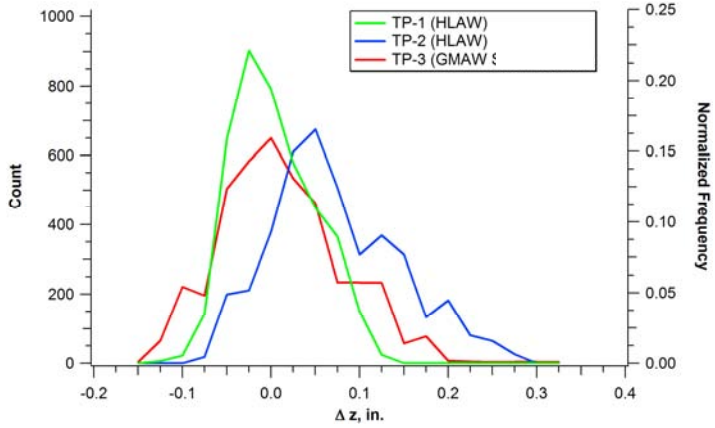
…than a hybrid laser arc welding process.

HLAW would offer productivity improvements over a single sided GMAW process with chill bar.

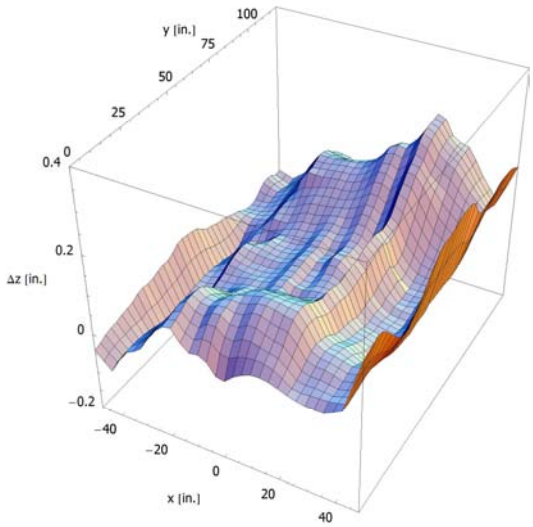
Distortion Comparison: Hybrid and GMAW

HLAW #1

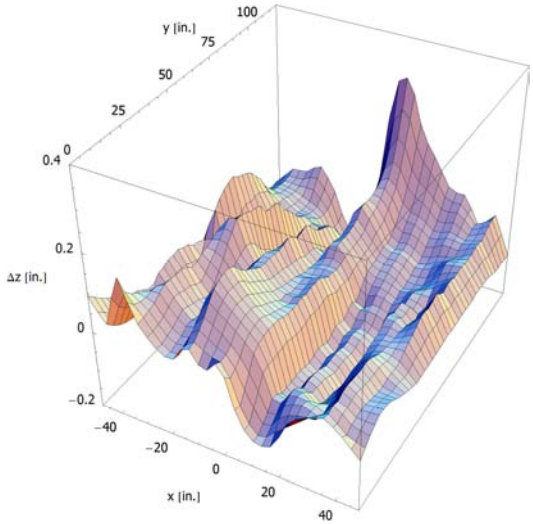




HLAW #2



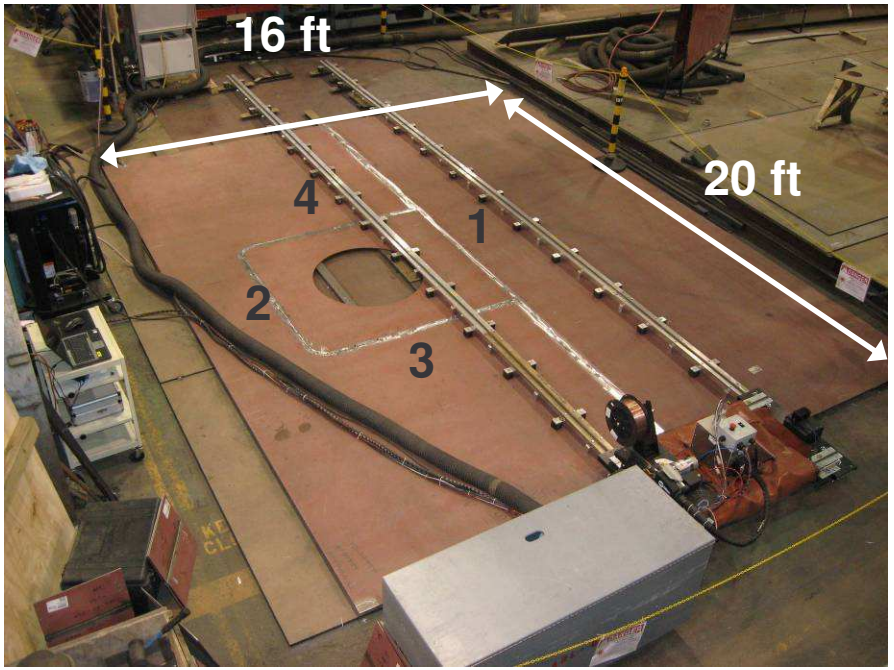
GMAW



- Change in plate shape comparable for all three panels despite 2.8 times more heat in the GMA weld.
- Equivalent distortion attributed to water cooled copper chill bar and clamping of plate at the seam welder station.

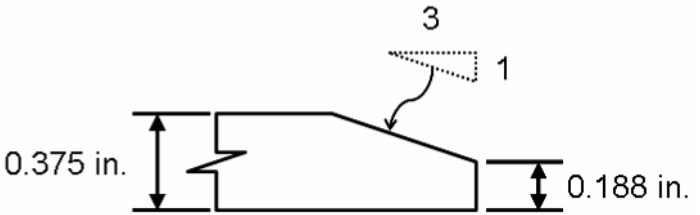
Production Scale Demonstration Panels Welded at BIW

- Material
  - 0.188 in thick panel with 0.375 inch thick insert.
  - AB/DH36
  - Consumable:
    - HLAW: 0.045 in. ER70S-6
    - SAW: 0.125in MIL-EM21K/761 Flux
- Preparation
  - Typical for conventional process.
  - Grinding of edges, tack welding.
- Welding
  - Demo Panel 1: Hybrid Laser Arc Welding (1-side). 1/23/08
  - Demo Panel 2: Submerged Arc Welding (2-side). 1/30/08. (Tractor)
  - No clamping or restraint.
  - Insert radii not welded on either panel.



DP-1 at BIW Harding's prior to welding

Sequence	Type	Length	Gap Range	
			Hybrid	SAW
1	Butt/Insert	20 ft	0 to 0.030	0 to 0.030
2	Insert	5.5 ft	0.030 to 0.083	0 to 0.040
3	Insert	5.75 ft	0 to 0.030	0 to 0.020
4	Insert	5.75 ft	0 to 0.030	0 to 0.050



Insert Detail

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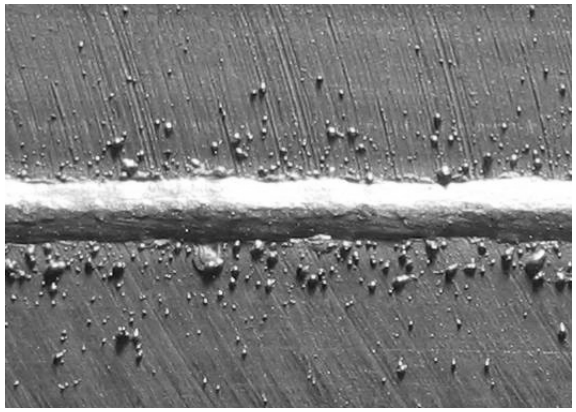
Hybrid Weld Results

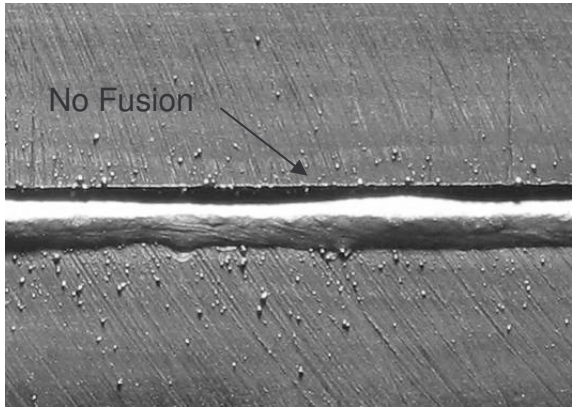
Demonstration Panel (DP-1), 23 January 2008

- Visual Inspection
  - Acceptable: 56% (19.6 ft)
  - Unacceptable: 44% (15.4 ft)
    - Lack of Fusion (20%)
    - Lack of Penetration (15%)
    - Lack of Fill/ Over-penetration (9%)
- Ultrasonic Inspection
  - 75% of welds inspected.
  - Revealed above defects.
  - Random porosity. RT being conducted in these locations.
- **<u>All</u> unacceptable defects could be corrected with seam tracking:**
  - Accurate alignment of process with joint.
  - Determine appropriate fill.
  - Seam tracking not feasible with budget and time constraints.

Photos of Weld Root



Acceptable



Unacceptable (lack of fusion to one side due to misalignment of laser)

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Successful hybrid welds made at the shipyard and in the lab.

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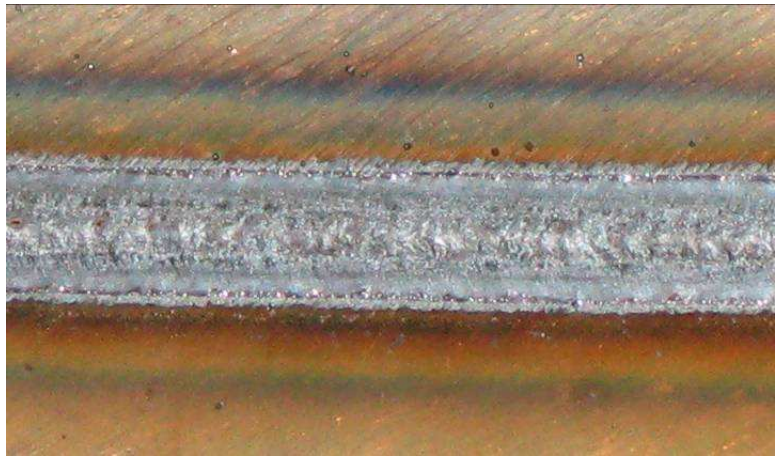
- Unprepared plasma cut edge plates:
  - Passed RT inspection – no systematic defects
  - No-gap plasma cut joints could tolerate a ~1.2mm offset from joint centerline.
- Gap tolerance experiments:
  - Conditions for 0.063 inch gap were determined…limited material and time available to optimize.
- Two 10 ft test panels successfully welded at BIW:
  - Test Panel 1: First 2 feet: correctable gas shielding issues; remaining 8 feet acceptable.
  - Test Panel 2: 95% of weld acceptable; root lack of fusion last 6 inches due to misalignment.

Hybrid Test Panel 2 Photos



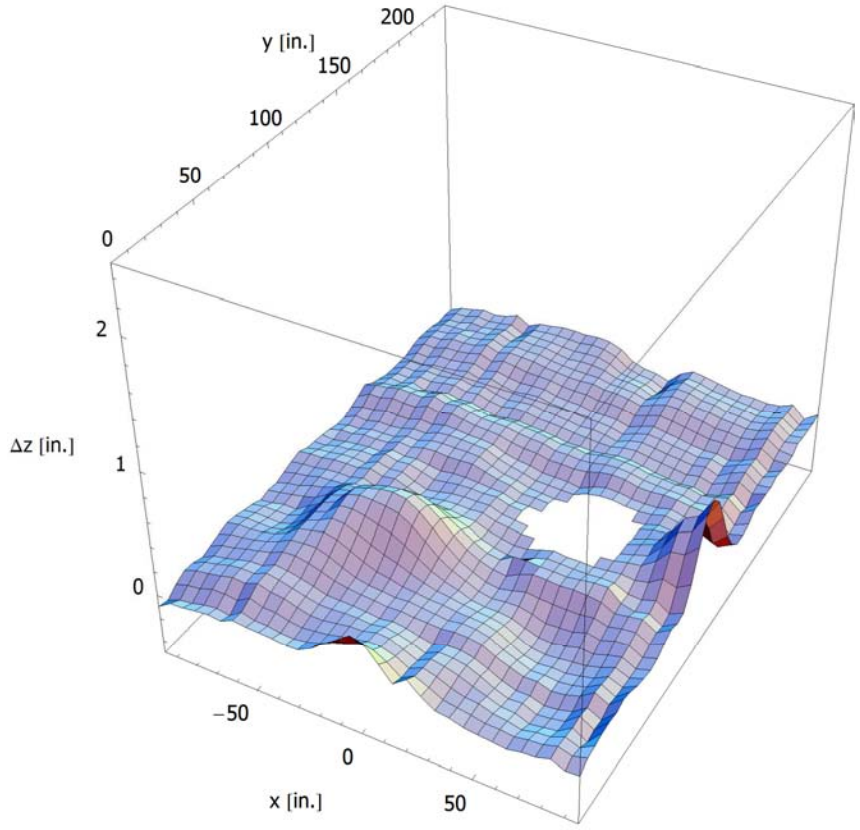
Crown

Root

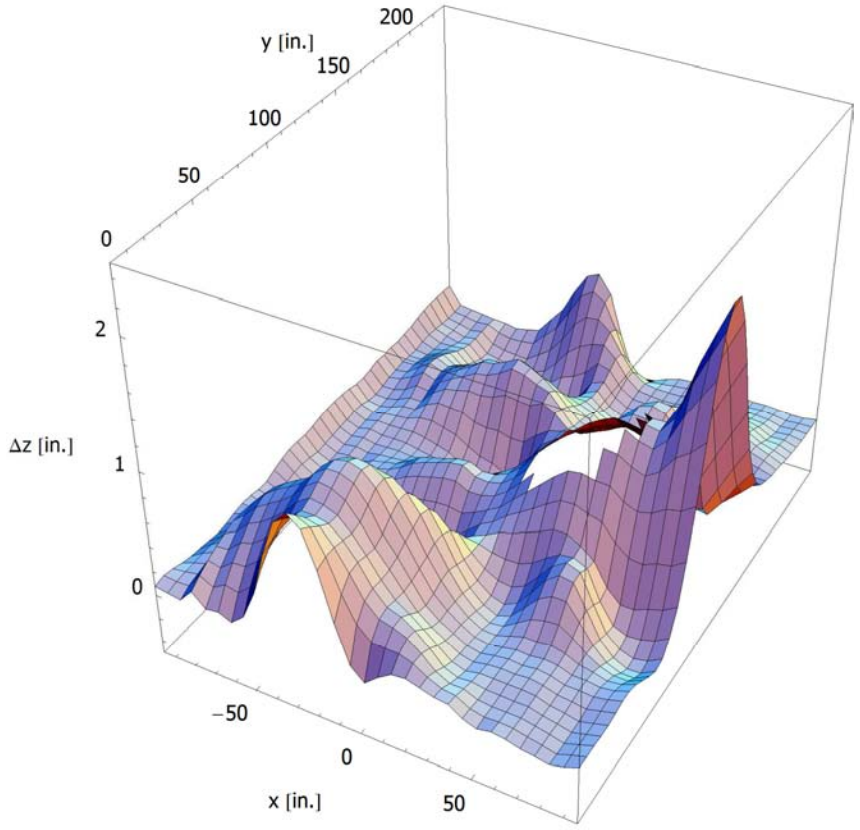
Can a hybrid process reduce welding distortion?

Change in Panel Shapes ($\Delta z = z_{after} - z_{before}$)

HLAW



SAW



z-scale factor is 320 times x-scale

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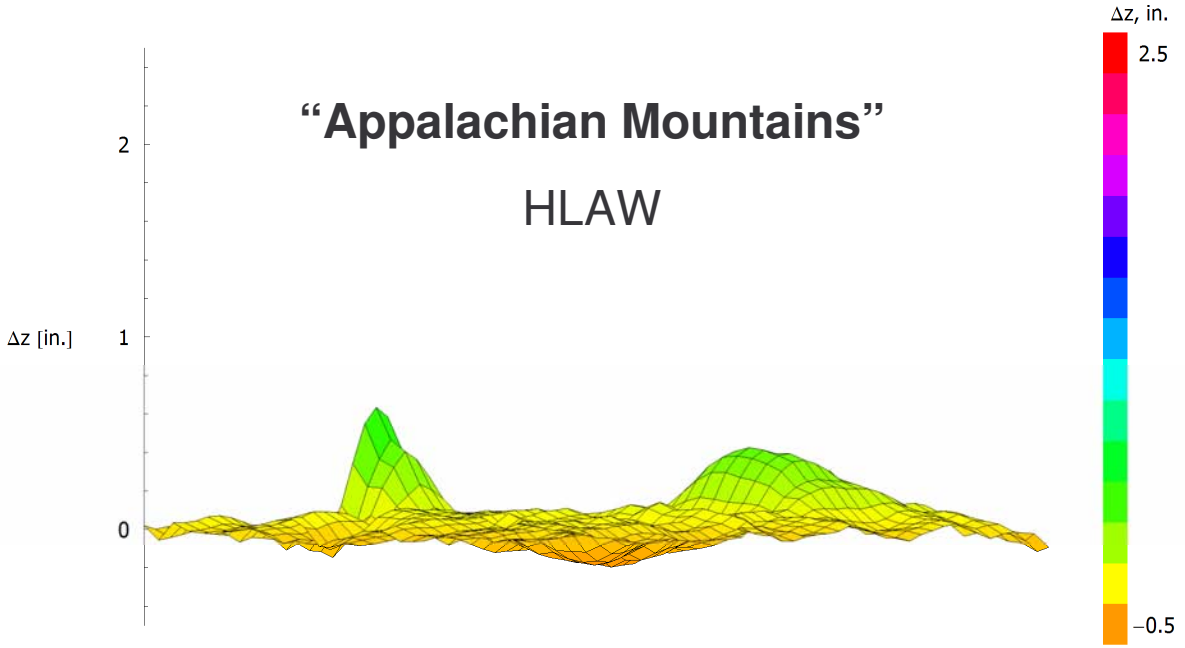
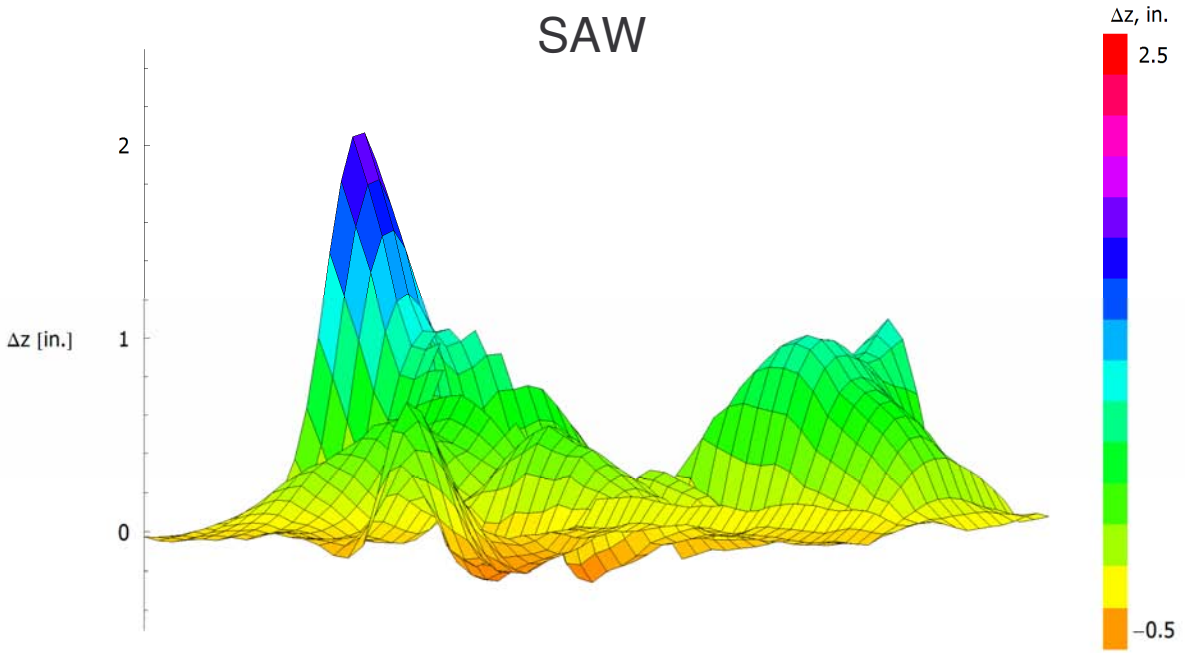
“Appalachian Mountains”

HLAW



“Rocky Mountains”

SAW



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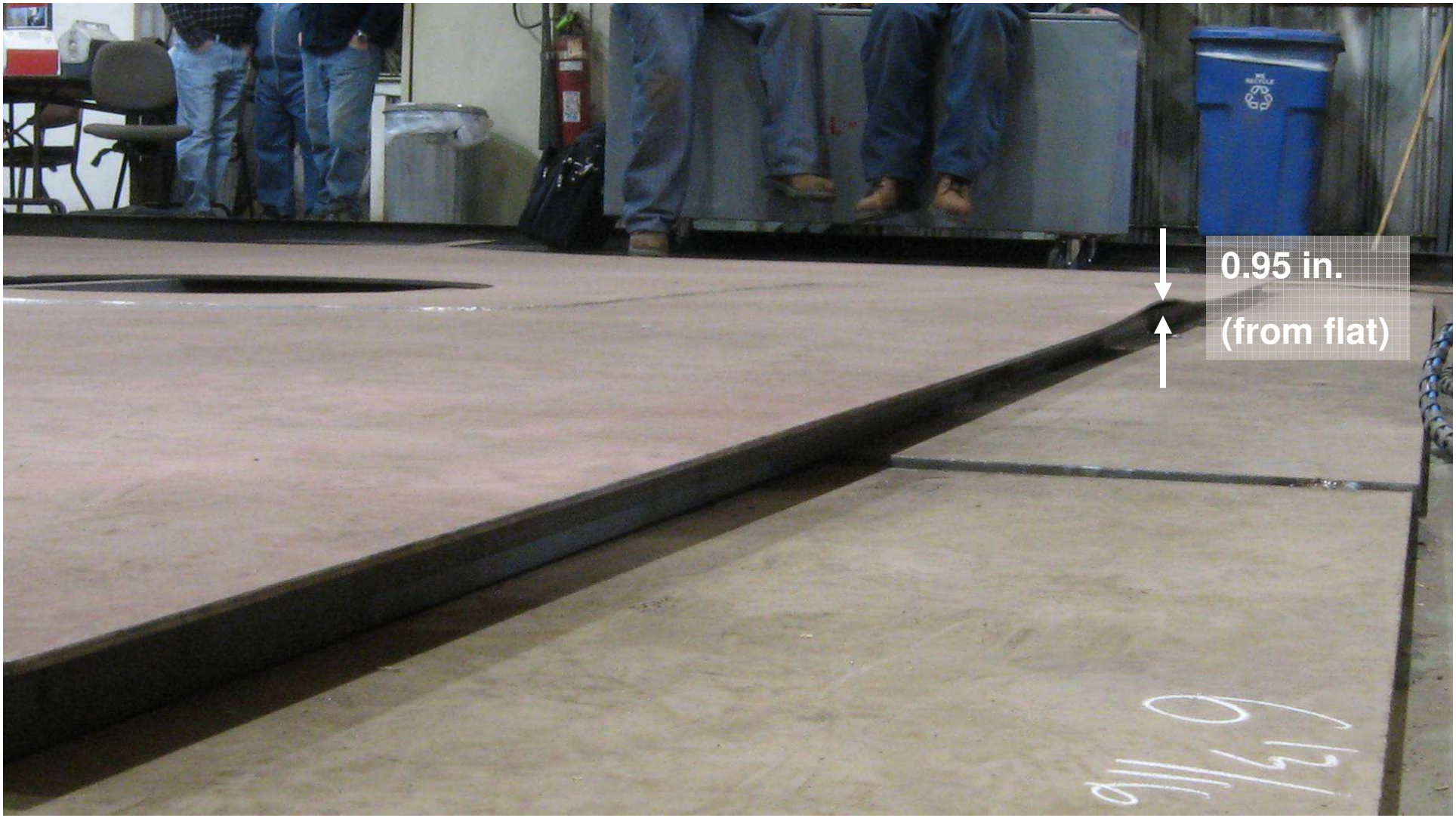
HLAW Panel

Distortion on Insert Side



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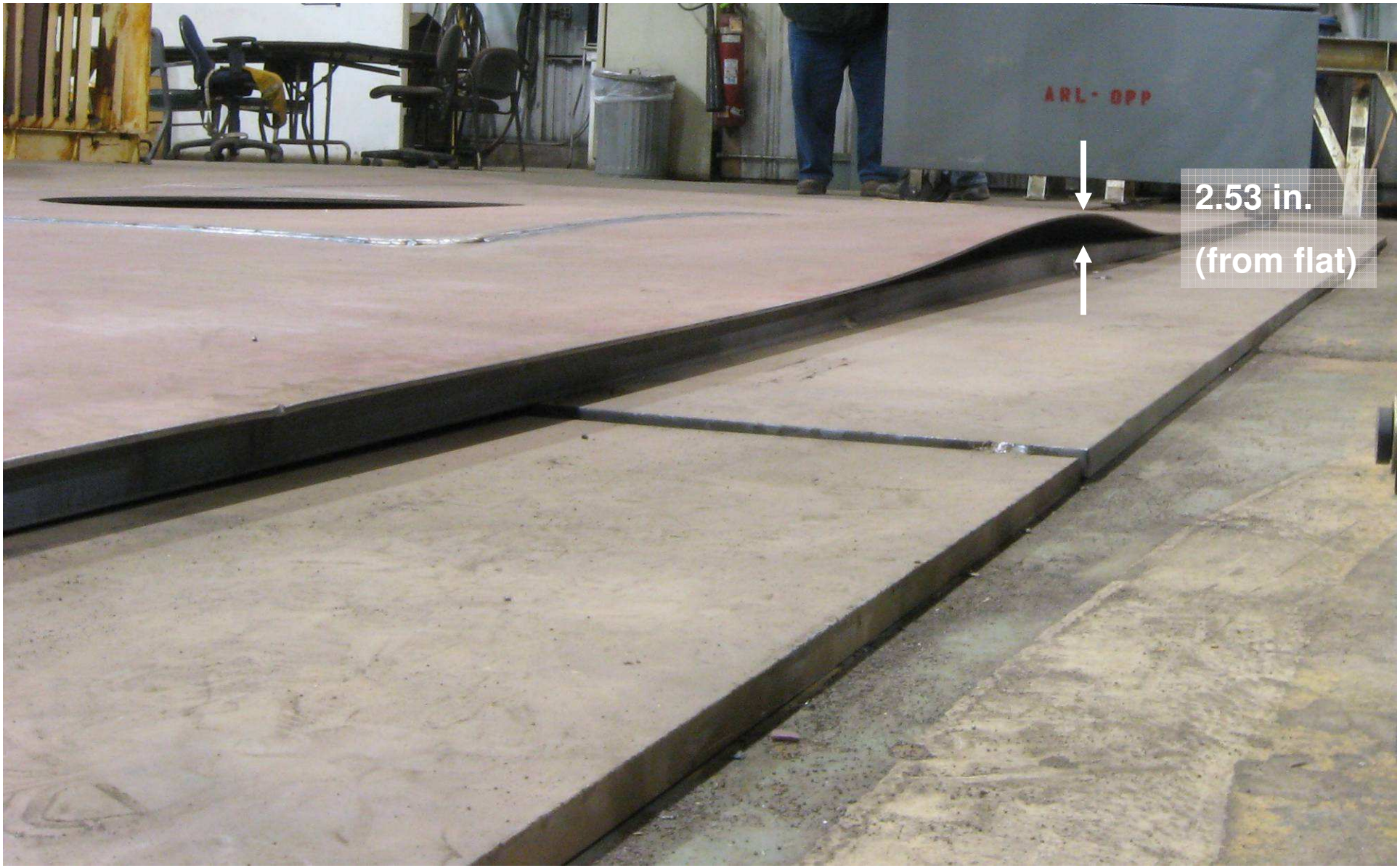
SAW Panel

Distortion on Insert Side



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Quantification of Distortion Data

Do the panels meet fairness requirements?
(MIL-STD-1689)

Percentage of As-Welded Panel Meeting MIL-STD-1689 Fairness Req's.

Structure	HLAW	SAW
Primary	96 %	75 %
Secondary	99 %	83 %
Other	100 %	89 %

Prior to welding, 98 % of both the HLAW and SAW panels met primary structure flatness requirements.

21% less rework required for HLAW to meet MIL-STD-1689 Requirements for Primary Structure after butt-welding.

How much distortion was reduced?

Statistics from demonstration panels (Δz)

	HLAW	SAW	Factor
RMS Average	0.101 in.	0.396 in.	3.9x
Range (Max-Min)	0.874 in.	2.383 in.	2.7x

HLAW reduces distortion by at least a factor of 4 over SAW.

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Process Comparison: Hybrid and SAW

Quantity	HLAW	SAW	BIW SAW Process…
Productivity (time to weld demo panel)	6.9min	28.1 min	…is 4.0 times slower,
Total Heat Input (kJ/in)	10 kJ/in	40 kJ/in	…adds 3.9 times more heat,
Weld Metal Deposited (lb/ft)	0.029 lb/ft	0.180 lb/ft	…uses 6.2 times more weld metal,

…than a hybrid laser arc welding process.

HLAW would offer significant productivity and distortion rework improvements at a primary fabrication facility or panel line.

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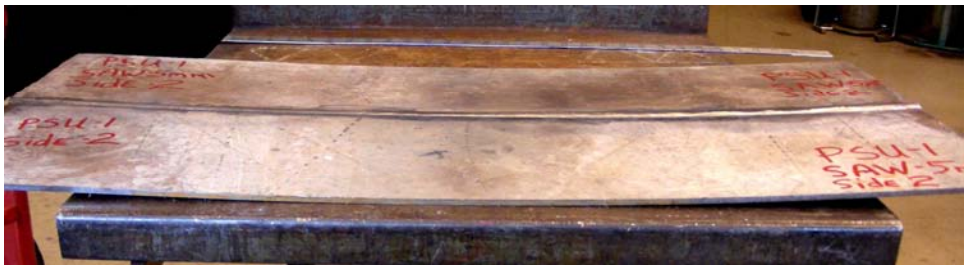
Can hybrid welding produce qualifiable welds?

- Benchmark comparison between HLAW and SAW:
  - 5mm thick AB/DH36
  - 70ksi filler
- Inspection
  - VT and RT per MIL-STD-2035, Class I.
- Destructive Testing
  - Long'l & Trans. Face and Root Bends
  - Transverse Tension
  - Weld Metal Charpy
  - Weld Metal Tension
  - Hardness & Macro

Hybrid Laser Arc Weld

Submerged Arc Weld - NGSS



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Can hybrid welding produce qualifiable welds?

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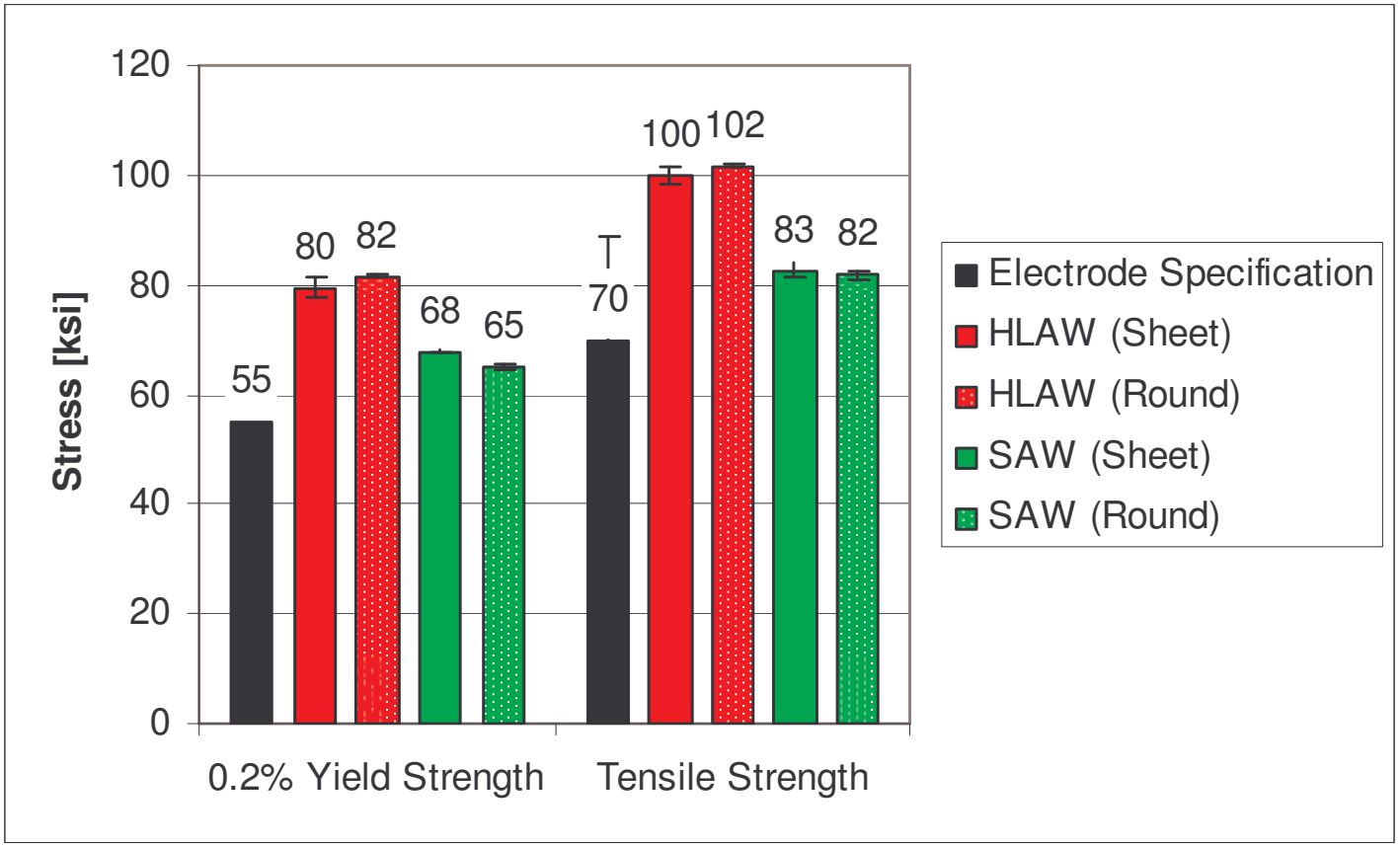

HLAW Sub-size All Weld Metal Specimens exhibit sufficient yield and tensile strength.

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Can hybrid welding produce qualifiable welds?

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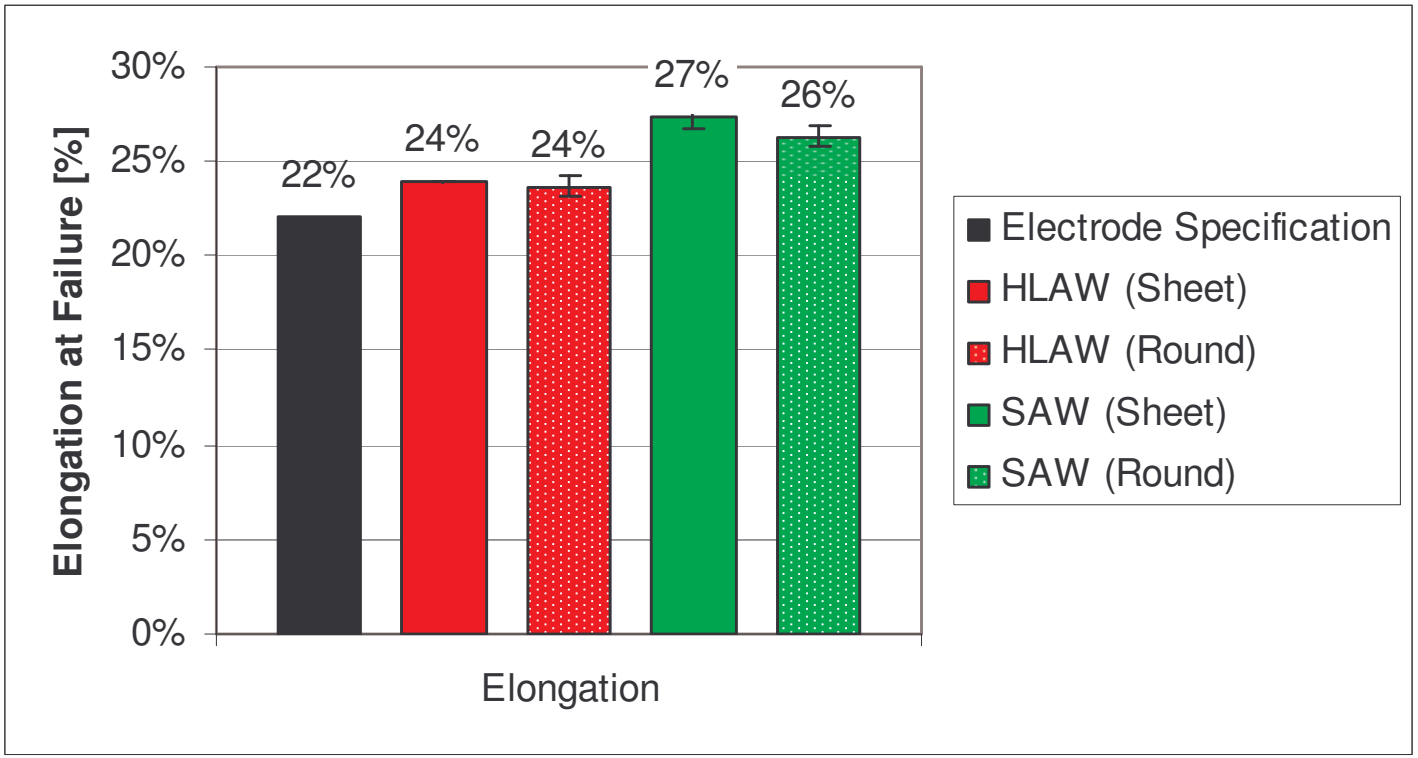

HLAW Sub-size All Weld Metal Specimens exhibit sufficient elongation.

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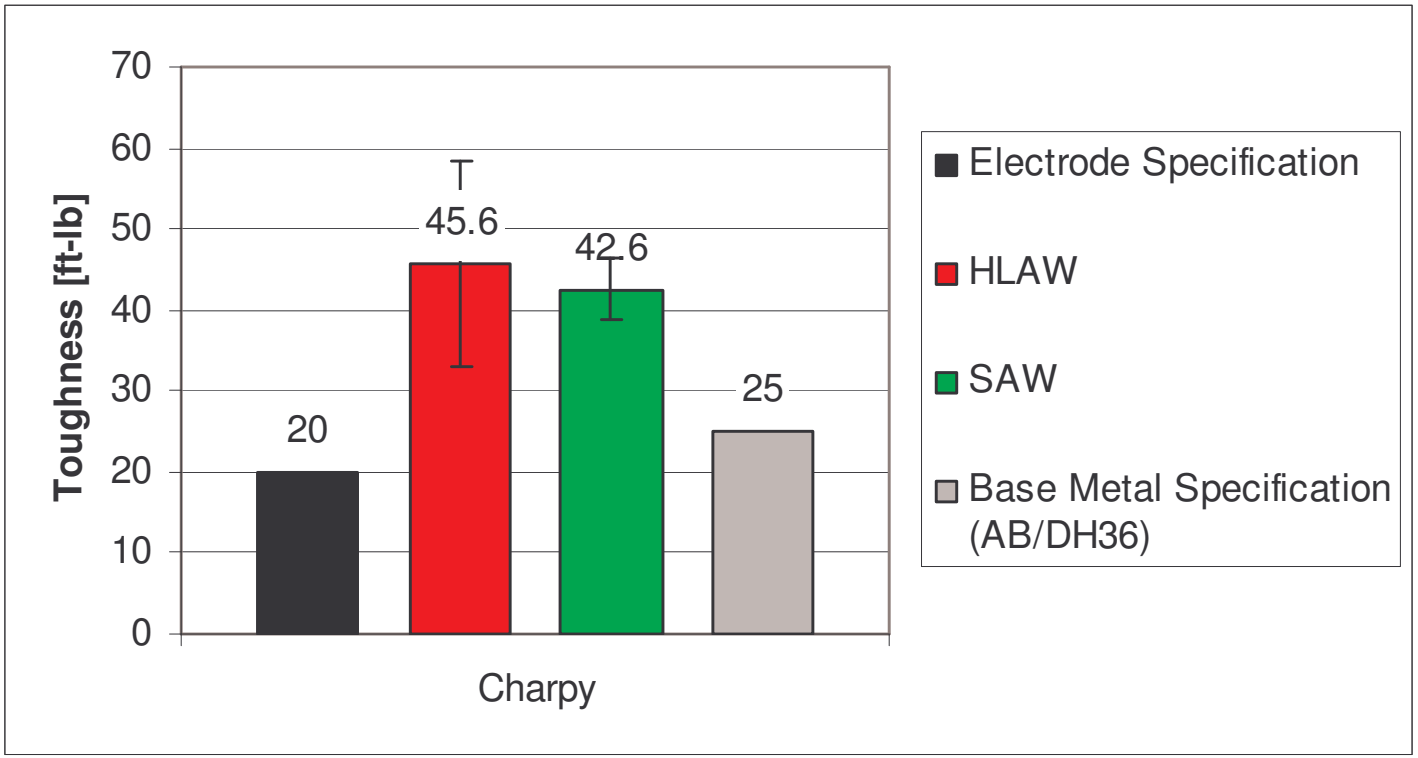
Can hybrid welding produce qualifiable welds?



** Specification is for a full size 10x10mm specimen. HLAW and SAW are for subsize 4 x 10mm specimens. Correcting for sample size would decrease specifications by a factor of 0.6.*

HLAW Sub-size All Weld Metal Charpy specimens exhibit sufficient toughness (@-20F).

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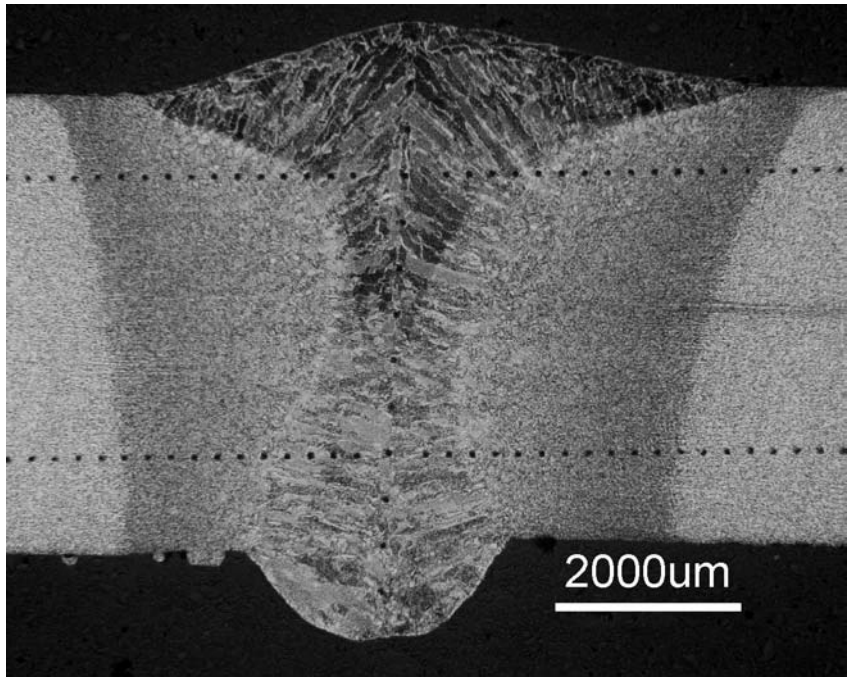
Can hybrid welding produce qualifiable welds?

- **Passed** VT and RT per MIL-STD-2035 Class I.
  - No systematic porosity.
  - Both machined butts and plasma-cut edges passed.
- **Passed** Transverse and Longitudinal Bends…at 22% elongation.
- **Passed** Transverse tensile…samples failed in base metal.
- **Sufficient** weld metal strength and toughness…compared to electrode specification.
- HLAW Weld Metal Hardness 20% Harder than baseplate.



HLAW Macrograph

Yes. Properties of HLAW welded plate meet or exceed required specifications.

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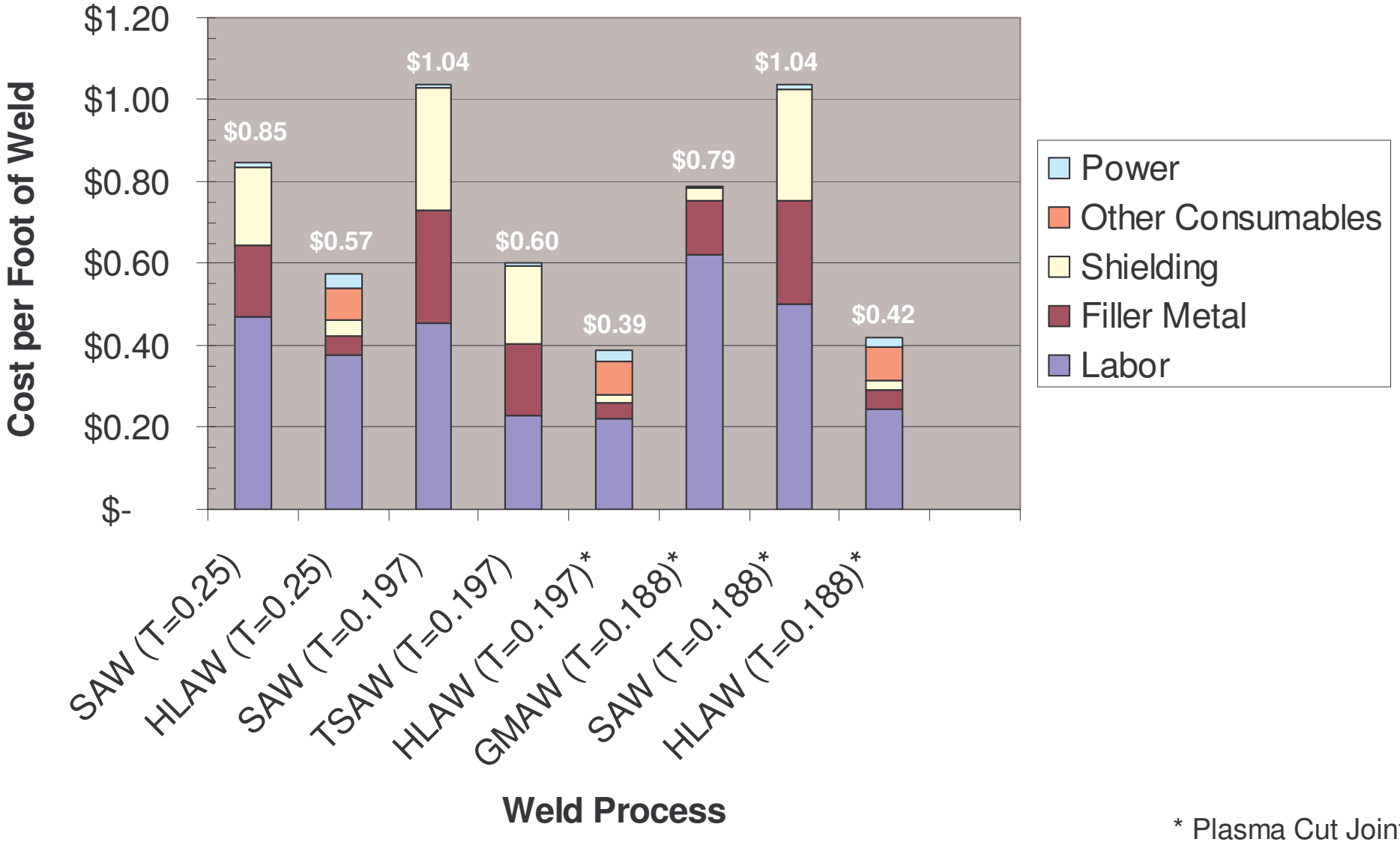
Cost Comparison



* Plasma Cut Joint

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DDG-1000 Cost Benefit Analysis

Distortion Costs		
Total Distortion Cost per LPD-17	$13,100k	
Panel Butt-Welding Distortion Cost (15%)	$1,965k	
Percentage of butt welds less than 10mm	57%	
Cost of butt and insert welding distortion on LPD-17	$1,117K	
Estimated cost of butt and insert welding distortion in DDG-1000	$1,508K	
Distortion Cost and Savings	**HLAW**	**SAW**
Reduction in Distortion achieved by HLAW over SAW at BIW demonstration. (Factor = SAW Distortion / HLAW Distortion)	3.9	1
Actual Cost of Distortion per DDG-1000	$385K	$1,503K
Distortion Savings per DDG-1000	$1,118K	$0
Process Cost		
Welding Cost/foot	$0.41/foot	$1.04/foot
Estimated welded feet of butt weld less than 10mm per DDG-1000	19,923 ft.	
Processing Cost/ship	$8k	$21k
Total Butt Welding Costs per DDG-1000	**$394K**	**$1,524K**
Acquisition Cost for HLAW		
Minimum welding system acquisition cost	$979k	
Time Share for Butt Welding (50% of laser, chiller, switch costs)	50%	
Acquisition Cost	$483k	
Projected Savings for HLAW		
10 year savings (1/2 ship year, discounted at 5%/year)	$4,364k	
ROI = Discounted savings / Acquisition Costs	9.0	

Assumptions for conservative estimate

- Only butt and insert welds considered. Including stiffeners would increase savings.
- DDG-1000 has 1.35 times as many units as LPD-17. Costs for DDG-1000 are extrapolated using this factor.
- Reduction in distortion by HLAW over SAW at BIW demonstration. (Factor = SAW Distortion / HLAW Distortion).
- Acquisition Cost
  - 50% time share on laser. Remaining 50% would come from cutting and or stiffener applications.
  - Does not include motion device or integration.

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Steps to Implementation

1. Produce qualifiable welds? **YES**
2. Be a cost effective alternative for increasing affordability? **YES**
   - Acquisition costs of a shared laser system could be recovered after building 1 DDG-1000.
   - HLAW Processing costs are less than GMAW and SAW due to reduction in filler metal.
3. Be applied in the current shipyard production environment? **YES,**
   - "Potential for implementation, just need to work out the bugs." (M. Ludwig, BIW).
4. Reduce welding distortion? **YES**
   - Distortion can be reduced by a factor of 4 using a hybrid welding process. This has been shown on multiple occasions by ARL through direct comparisons with conventional arc welding processes.

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Summary

- HLAW vs. GMAW
  - HLAW is $0.37 per foot cheaper than SAW.
    - Reduced labor and welding consumable costs.
  - HLAW (unrestrained, no heat sink) results in equivalent distortion as GMAW (restrained, with copper backing).
- HLAW vs. SAW
  - HLAW is $0.62 per foot cheaper than SAW.
  - Distortion from HLAW is at least 4x less than conventional SAW.
- The cost savings from a hybrid butt welding process for a surface combatant is estimated at $1,130K per hull.
- A hybrid laser arc welding system can safely and effectively operate in the current shipyard production environment.