Selection of Cost Effective Plasma Cutting Process for Weld Integrity

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Outline

- Goal, Scope & Motivation
- Background
- Experimental Setup
- Results & Discussion
- Summary & Conclusion

Goal

- Effect of plasma cutting method on Stainless Steel and Aluminum weldability.

  – Intent: maximize the effect of surface contaminants caused by the cutting methods used on the subsequent autogenous weld properties.

- Selection of cost effective cutting process for welding applications.

Scope

- Limit the study to:
  - Stainless Steel: 304
    - Wide availability and use
  - Aluminum: 5052 H32
    - Weldable with GTAW in autogenous mode
    - Wide availability and use
  - Thickness: ¼" (5 – 6mm)
    - Near upper limit for autogenous mode
    - Weld repeatability
- Limit the cutting process to high quality cutting
  - Ar/H_2 (H35: 35%H_2 by volume) plasma and N_2 secondary
  - N_2 plasma and H_2O secondary
- Limit joining to an autogenous weld
- Gas/fluid quality:
  - Industrial grade N_2
  - Welding grade $Ar\text{-}H_2$
  - Tap water – untreated – (Lebanon, NH)

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Alternative Processes
Sheet Product Cutting

Water	High Quality High Precision Medium-High Reproducibility	Slow Speed Medium-High Capital Cost High Operating Cost	Gauge – 2”+ 1mm - 50mm
Oxyfuel	Low Quality Low Precision High Reproducibility	Slow Speed Low Capital Cost High Operating Cost	1.5”+ 30mm +
Plasma	Medium Quality Medium Precision Low Reproducibility	High Speed Medium Capital Cost Low Operating Cost	1/4” - 2” 5mm – 50mm
Laser	High Quality High Precision High Reproducibility	High Speed High Capital Cost Medium to high Operating Cost	Gauge - 1/2” 1mm – 12mm

Arrow indicate thicker material
Color intensity indicate optimum thickness range

Metal Cutting Methods Comparison

Speeds (m/min) (ipm) **Thickness SS**	Water Jet Pump (27kW)	Laser CO_2 laser (4 kW)	Plasma N_2/H_2O (14-16 kW)
6mm ~ ¼"	0.32 ~13	2.1 ~83	2.7 ~106
12mm ~1/2"	0.13 ~5	0.75 ~20	1.4 ~55

Plasma Cutting
H35 vs. N_2/H_2O

	H35	N_2/H_2O
Quality	High Precision: No Dross Sharp Edges Cut Angle < 2 Degrees	High Precision: No Dross Sharp Edges Cut Angle < 2 Degrees
Speed	100A / ¼" Thickness SS: 72 ipm (1.83 m/min) Al: 80 ipm (2.03 m/min)	100A / ¼" Thickness SS: 95 ipm (2.41 m/min) Al: 90 ipm (2.29 m/min)
Current Range Thickness Range	100A – 300A + ¼" +	30A – 300A + Gauge +

Cutting Cost
H35 vs. N_2/H_2O

- 100A SS Cutting

- Thickness: ¼” - ½” (6 – 12 mm)

- N_2/H_2O cost/ft of cut is 20% - 30% cheaper than H35
  - Higher cutting speeds: 15% - 30%
  - Cheaper gas: H35 is four times more expensive than N_2
  - Given the same consumable life and cost

Fume and NOx Emissions

- Fume emission:
  - Dry cutting :Semi-dry: Under water

    100 : 10 : 1

- NOx emission:
  - Dry cutting :Semi-dry: Under water

    4 : 2 : 1

Lillienberg et. al.

- H35 is a dry cutting process
- N_2/H_2O will fall bellow dry cutting
  - Possibly on the order on semi-dry cutting

Literature Overview

- Concentration of literature dealing with weldability of plasma air cutting on carbon steel [Frolov, Williamson, Kobeleva *et. al.,* Vasil'ev *et. al.*, Fujimura, *et. al.*, Haferkamp *et. al.*]
  - Particularly before oxygen cutting became economically viable.

- Metallurgical effects of plasma cutting of carbon steel, stainless steel and aluminum as well as effect on weldability [O'Brien *et. al.*, Levin *et. al.*, Bach *et. al.*, Skillingberg, Masiashvili *et. al.*, Hackett, Uchida *et. al.*]
  - Size of heat affected zone (perpendicular & parallel to cut face)
    - Due to thickness
    - Current level
    - Plasma gas composition
    - Material type, alloying and tempering
  - Micro-hardness

- Comparison with oxy-fuel cutting.

- Little available in terms of comparing weldability of SS /Al using H35 and N_2/H_2O
  - Significant improvements on cutting systems since inception.

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Experimental Setup
Plasma Cutting

- Plasma Cutting Process
  - Mechanized dual gas system
  - Water cooled torch

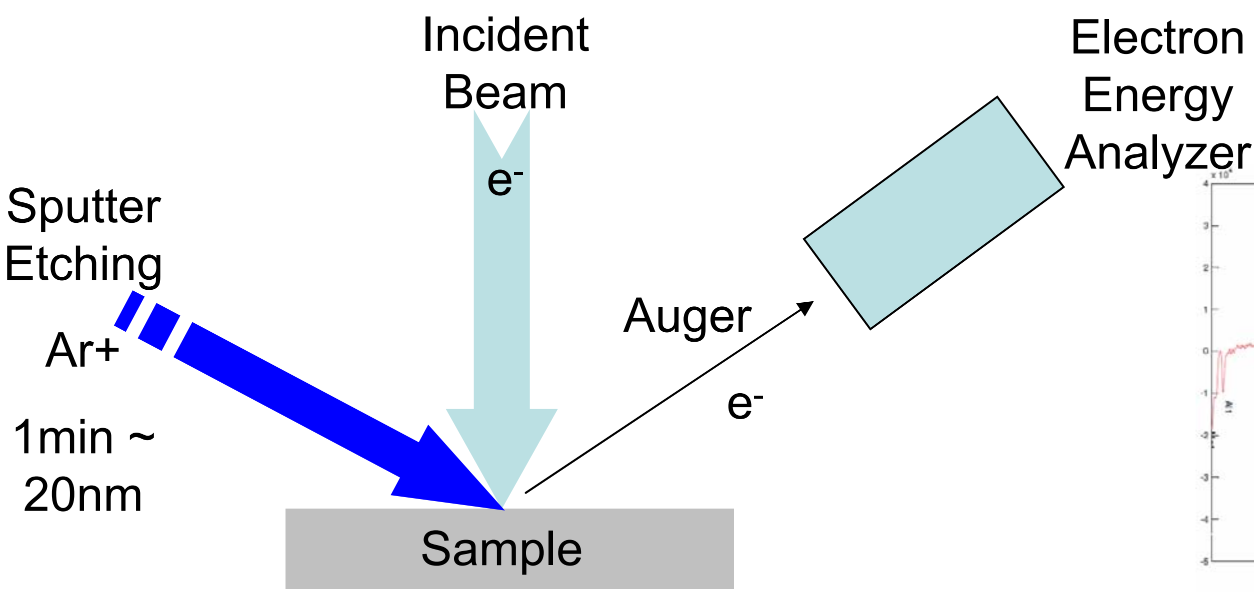
100A **S.S.** ***Al***	Plasma Flow [SLPM (SCFH)] Pressure [Bar (psig)]	Shield Flow [SLPM (SCFH)] Pressure [Bar (psig)]	Speed [m/min (IPM)]	Standoff [mm (in)]	Voltage [V]
H35/N2	Flow 20.1(42.6) Pressure 6.2 (90)	Flow 39(82.6) Pressure 8.3 (120)	1.83 (72) *2.03 (80)*	2.54 (0.100) *5.08 (0.200)*	158 *160*
N2/H2O	Flow 12.5 (26.5) Pressure 6.2 (90)	[SLPM / GPH] 0.44 / 7 Pressure 3.8 (55)	2.41 (95) *2.29 (90)*	2.54 (0.100) *3.81 (0.150)*	148 *160*

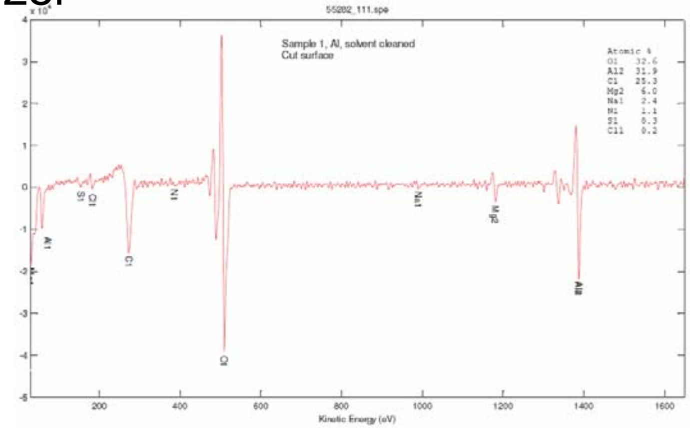
Cut Surface Elemental Analysis: Scanning Auger Microanalysis

- Goal: measure the content of atomic nitrogen in the cut face on Al and SS cut with N_2/H_2O and $H35/N_2$.
- Surface analysis technique that determines elemental composition and some chemistry of surfaces and interfaces.
- Sampling depth of 2-3nm with lateral resolution of 50 nm.
- SAM also shows the spatial distribution of elements on a surface (SAM element images) as well as elemental depth distributions from 1 to 2000 nm (when used in conjunction with ion-milling).
- Detection limit: all atomic elements (except hydrogen and helium) at concentrations greater than 0.1 atomic percent.

Cut Surface Elemental Analysis: Scanning Auger Microanalysis

- Principle Of Operation:
  - Sample scanned with focused electron beam
    - Auger electrons (low energy) emission.
  - Auger electron energies measured
    - Elemental surface analysis (top few monolayers).
  - Argon ion beam can be used to remove surface layers from the sample.





Experimental Setup
Stainless Steel Welding

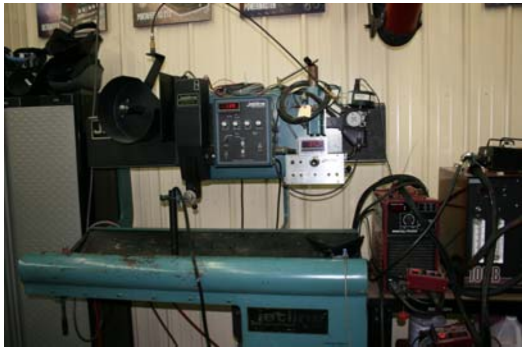
- Stainless Steel – 304
  - Common & readily available
  - Weldable with PAW from 1 side
  - Keyhole
- No filler material
  - Maximize the effects of surface contaminates in weld zone
- Automated seam welding table

Process	PAW – DC-
Current	175 – 180A
Plasma Gas	Ar 3 scfh (~1.4 SLPM)
Shield Gas	Ar/H_2 (95/5) 20 scfh (~9.5 SLPM)
Travel Speed	10 ipm (0.25 m/min)
Standoff	¼” (6 mm) Maximum electrode setback

Experimental Setup
Aluminum Welding

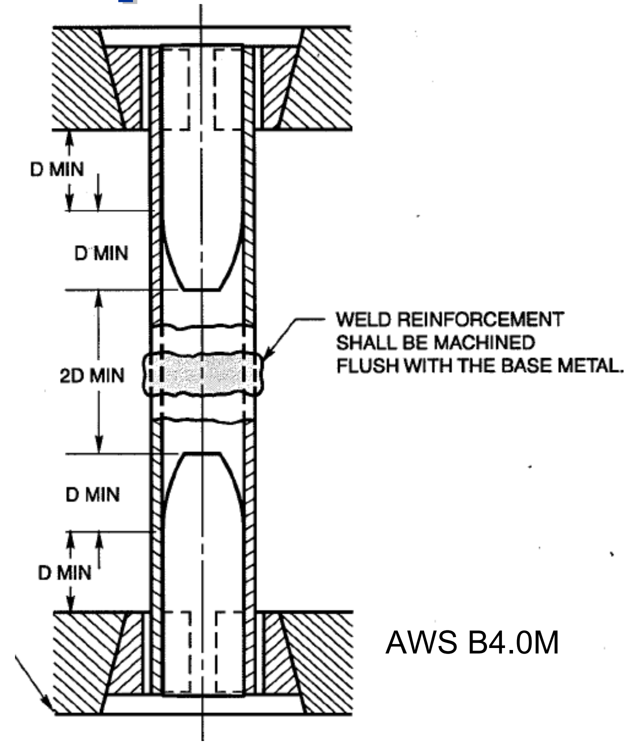
- Aluminum: 5052 - H32
  - Common & readily available
  - Weldable with GTAW
  - Two sided weld
- No filler material
  - Maximize the effects of surface contaminates in weld zone
- Automated seam welding table

Process	GTAW – AC pulse
Current	350A, 250A back side 50% background current, 40 pps
Shield Gas	75% He / 25% Ar 20 scfh (~9.5 SLPM)
Travel Speed	11 ipm (0.28 m/min)
Standoff	1/8” (~3 mm)

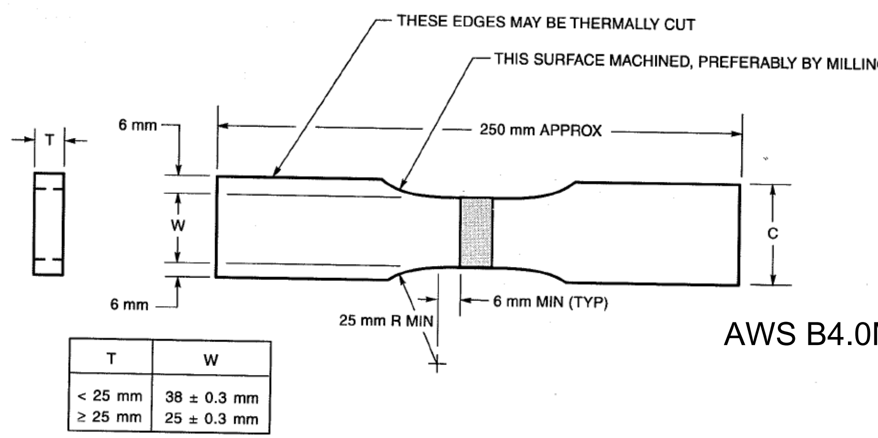


Experimental Setup
Tensile Pull

- Following Standard:
  - AWS B4.0M: Standard Methods for Mechanical Testing of Welds
  - AWS D1.6: Structural Welding Code - Stainless Steel
  - AWS D1.2: Structural Welding Code - Aluminum
- Instrument
  - Tensile testing unite: Sawyer Mfg. Company, Model 273-25
- Number of Samples:
  - SS & Al
    - 12 H35/N_2
    - 12 N_2/H_2O
    - 2 sheared surface weld



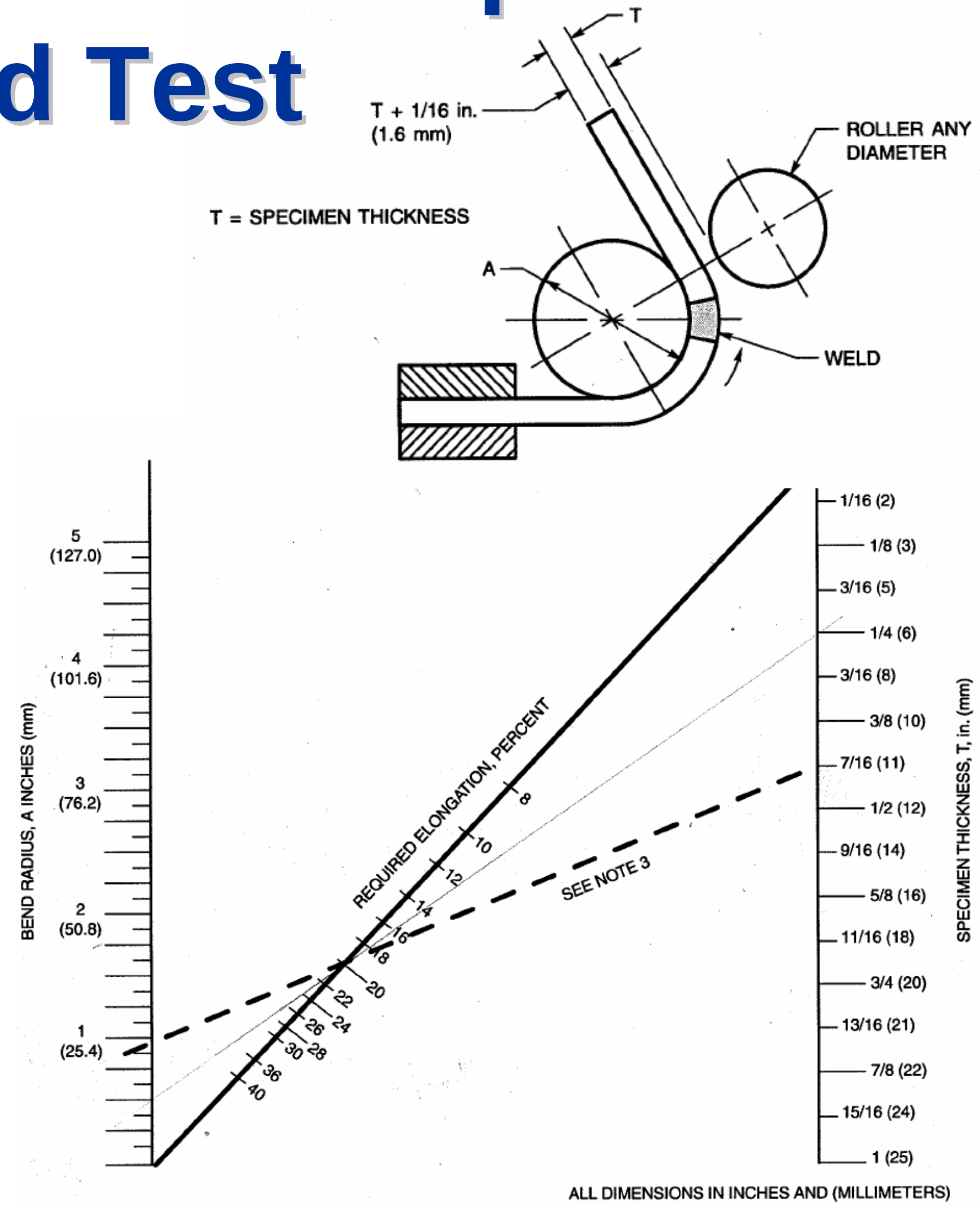
AWS B4.0M



AWS B4.0M

Experimental Setup
Bend Test

- Following Standard:
  - AWS B4.0 Standard methods for mechanical testing of welds
  - AWS D1.6 Structural welding code stainless steel
  - AWS D1.2 Structural welding code aluminum
- Mandrel 1/2” radius for 1/4 “ thick samples with 20% elongation
- Three top bends & three bottom bends for:
    - $H35/N_2$ and N_2/H_2O
    - Al & SS
  - Sheared surface weld: 1 top bend and 1 bottom bend.



Experimental Setup
Material Characterization

- Micrographs of as cut material and welded material
  - Sectioning and mounting in epoxy
  - Polishing (metallographic finish)
  - micrograph imaging
- Knoop microhardness test (100g for Al, 300g for SS)
  - As cut samples
  - Base metal, heat affected zone (HAZ) and weld
  - Knoop hardness number (KHN):

KHN = F/A = P/CL2

F = applied load (kgf)

A = un-recovered projected area in mm²

  - Precision of measurements: 1 hardness unit.

Work Performed by New Hampshire Materials Laboratory, Somersworth, NH

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Experimental Results
Nitrogen Content of Cut Faces

Results are in atomic %

Cleaning (Solvent)			
	Base Material	**N_2/H_2O**	**$H35/N_2$**
SS	**-**	**2.3** (O, C, N, Fe)	**0.6** (C, O, Fe, N)
Al	**-**	**0.4** (C, N, O, Al)	**0.8** (C, O, Mg, Al, N)

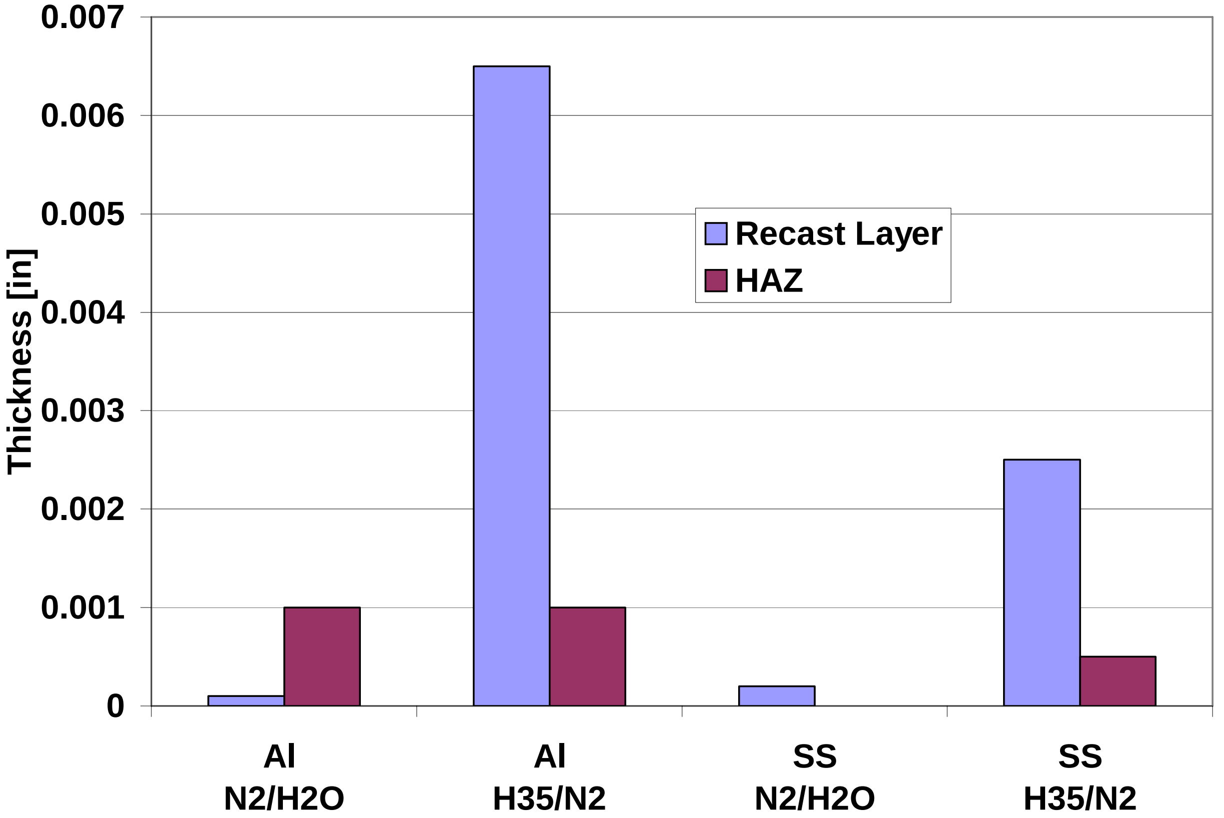
Cleaning and Ion Sputtering (1 min ~ 20 nm)			
	Base material	**N_2/H_2O**	**$H35/N_2$**
SS	**0.5** (C, O, Fe, N)	**1.5** (O,Fe, C, N)	**0.6** (O,Fe, C, N)
Al	**0.2 (5 min)** (Al, C, O, Mg)	**< 0.1** (Al, O,C, Mg, N)	**1.1** (Al, O,C, Mg, N)

- Nitrogen content is low overall
  - SS: nitrogen content is higher with N_2/H_2O
  - Al: nitrogen content is higher with $H35/N_2$
- Even after ion sputtering the surface is still strongly oxidized on all surfaces
- Post cut contamination dominates the cut surface chemistry

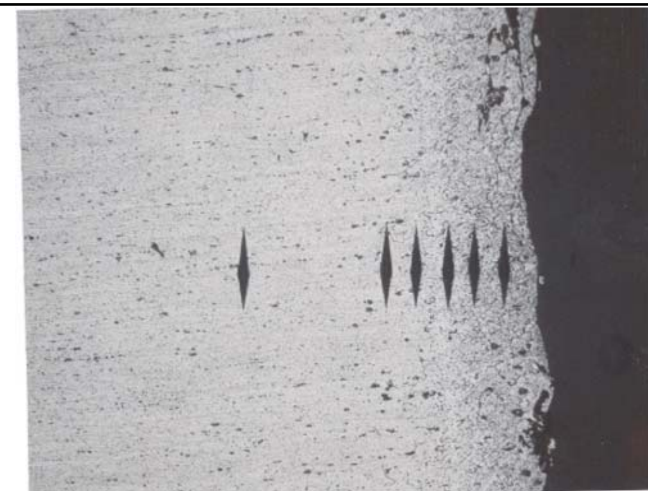
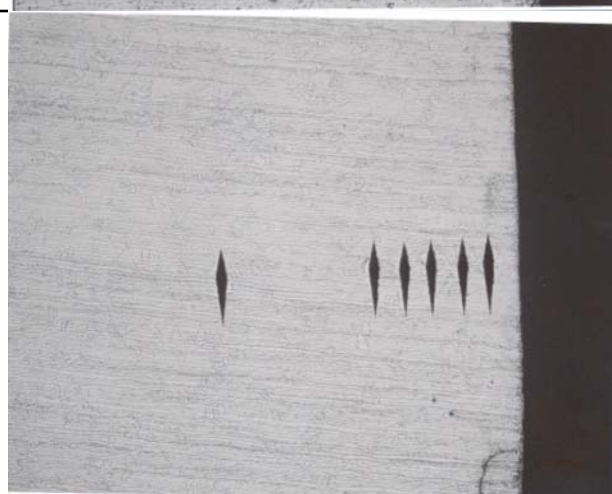
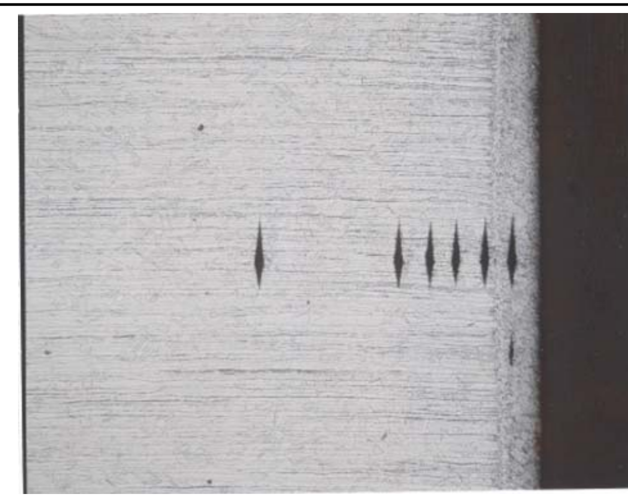
Work Performed by Analytical Answer Inc., Woburn, MA

Experimental Results
Effect of Cut Gases on Cut Surface

- Al
  - H35 shows larger recast layer
  - Comparable HAZ
- SS
  - H35 shows larger recast layer and HAZ
- Layer thickness is less than 0.010" (0.25mm) on all cut surfaces



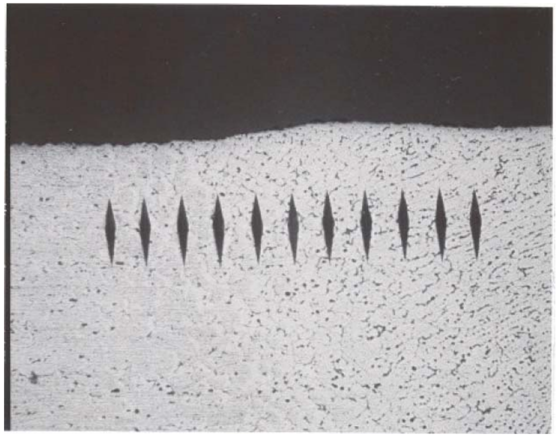
Experimental Results
As Cut Samples – Al/SS Micrographs

	N_2/H_2O	H35
Al		
SS		

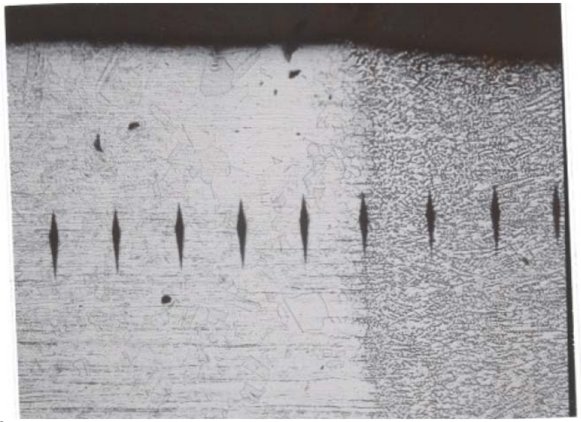
Experimental Results
Welded Samples

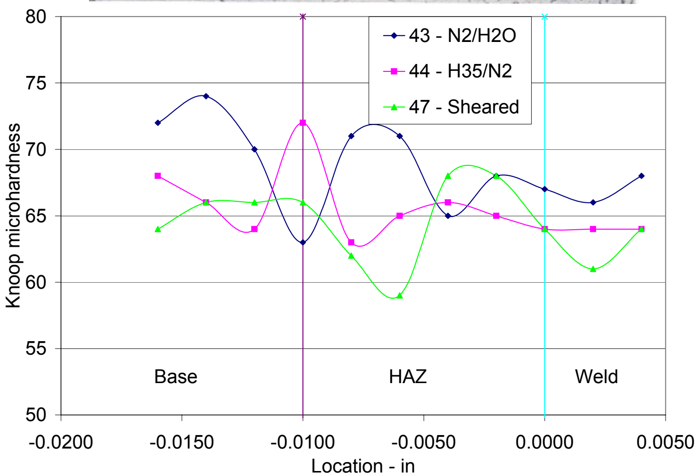
- No difference shown by Knoop hardness test between the welds of the three different cut processes

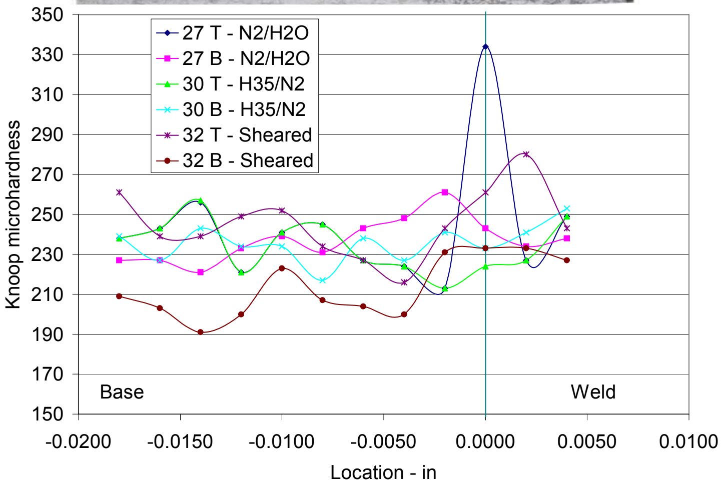
Al



SS

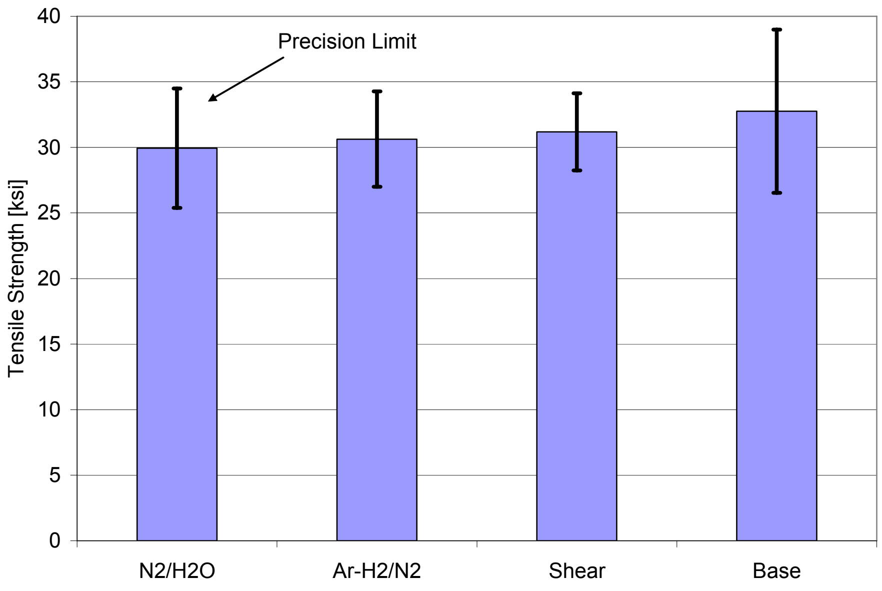


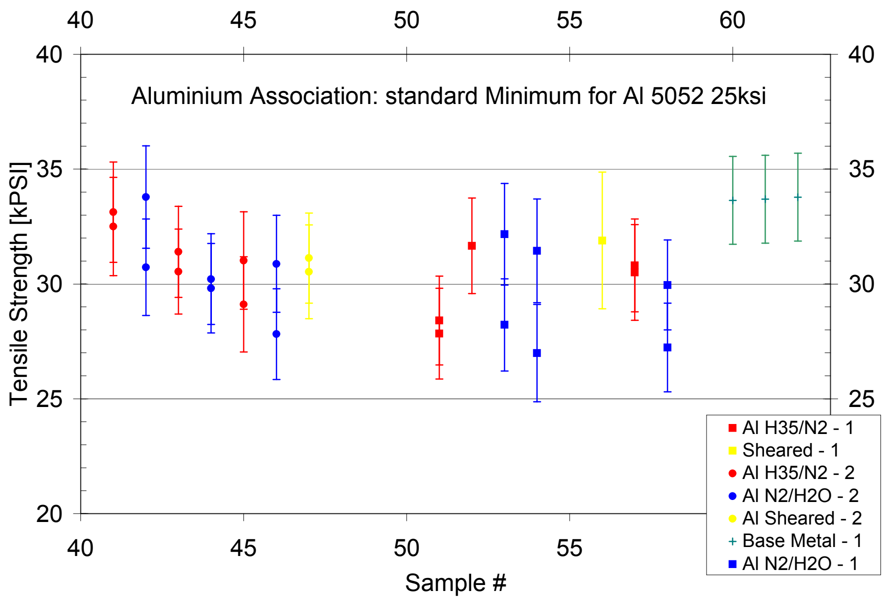




Results: Tensile Strength Al

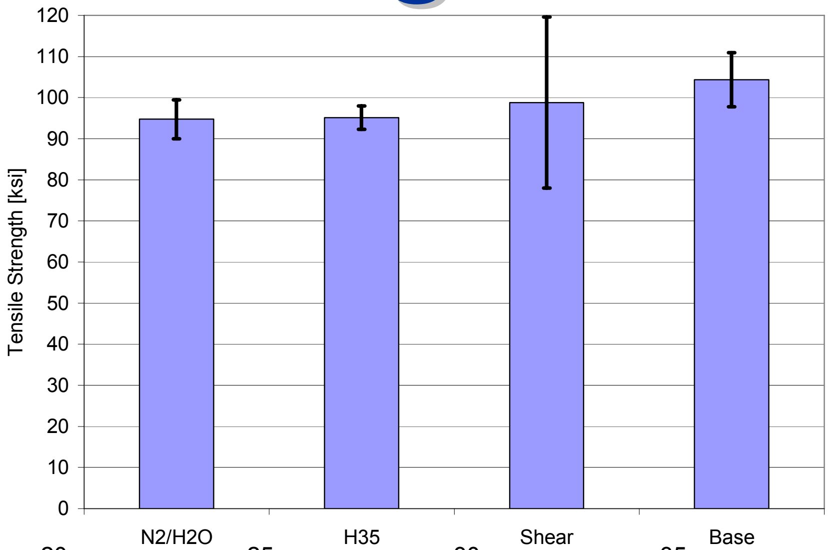
- Statistically indistinguishable tensile strengths between H35/N_2 and N_2/H_2O
- Tensile results are higher than minimum specified
  - Aluminum Association: 25ksi

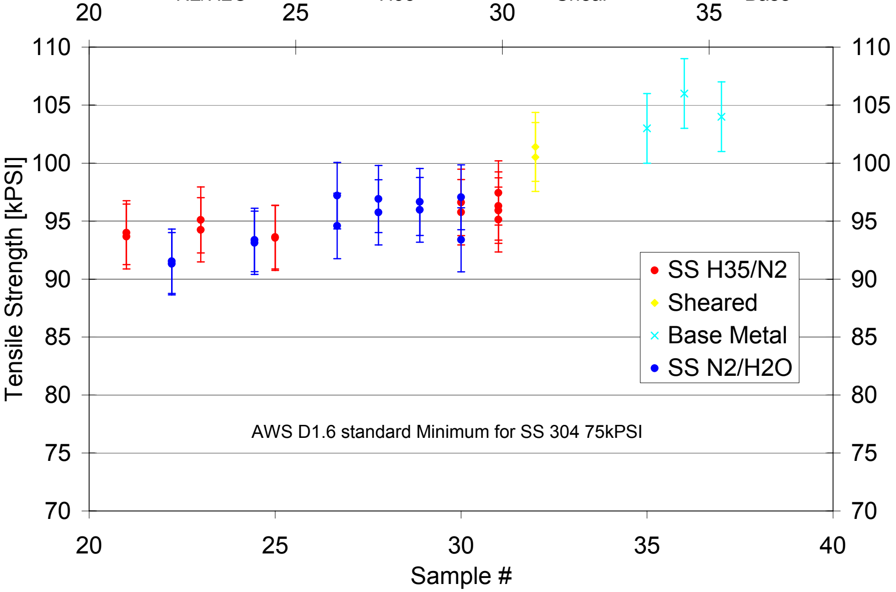




Results: Tensile Strength SS

- Statistically indistinguishable tensile strengths between H35/N_2 and N_2/H_2O.
- Slightly higher values of base material
- Tensile results are higher than minimum specified
  - AWS D1.6: 75ksi.





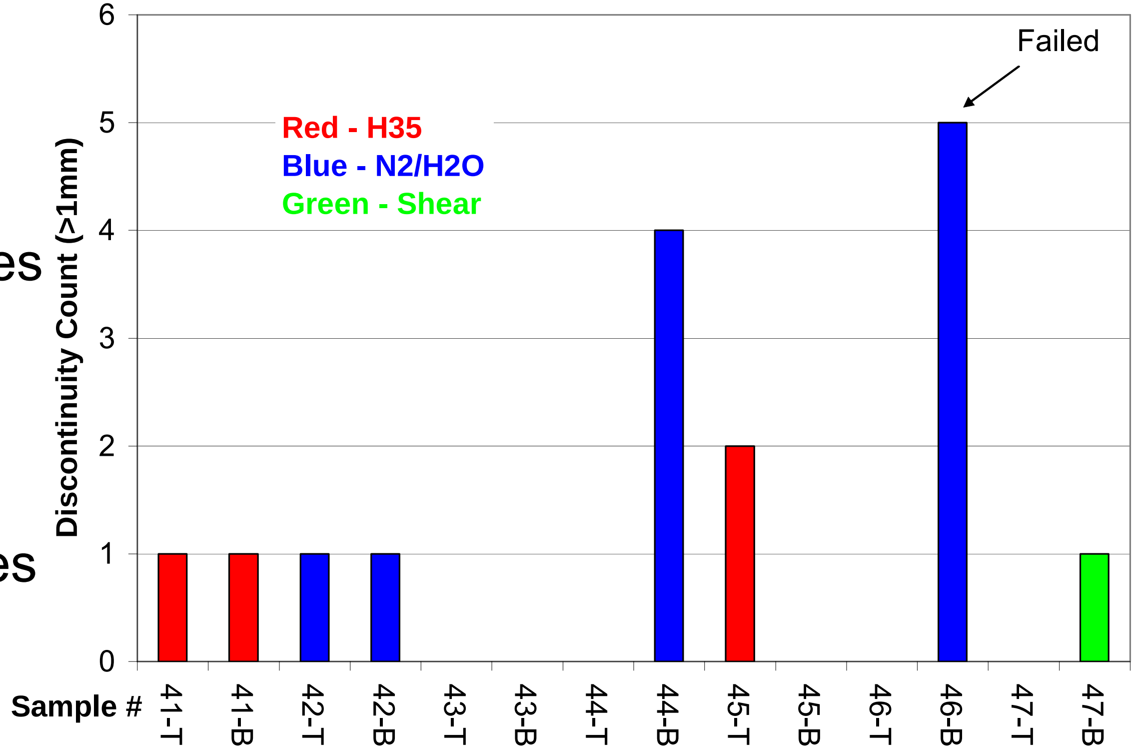
Experimental Results
Bend Tests: SS

- Acceptance Criteria: AWS D1.6 & D1.2
  - Measured all observable discontinuities on convex surface
    - 1mm (1/32”) and above
  - Classified measurements for failure criteria
    - Fail if corner crack
    - Fail if any discontinuity ≥ 3mm (1/8”)
    - Fail if sum of discontinuities under 3mm ≥ 10mm (3/8”)

- Stainless Steel
  - No corner cracks
  - No discontinuities observed
- No observable effect of cutting process on bend test

Experimental Results
Bend Tests: Al

- Aluminum
  - No corner cracks
  - Failure of one sample from one side
    - N_2/H_2O welded cut
- Appearance of discontinuities not exclusive to a particular cut process
- No correlation between top bend / bottom bend and appearance of discontinuities



- Note:
  - No cleaning was performed prior to welding on any cut surface

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Summary

	N_2/H_2O	$H35/N_2$
	As Cut	
HAZ	Comparable or Slightly Smaller	Comparable or Slightly Larger
Recast Layer	Slightly Smaller	Slightly Larger
Atomic Nitrogen Content on Cut Face	Comparable	Comparable
	Welded	
Tensile Strength	Comparable Mechanical Cut Welded Samples	Comparable Mechanical Cut Welded Samples
Bend Test	1 of 6 Failed	0 of 6 Failed

Conclusion

- Weld integrity is maintained regardless of cutting process: sheared, N_2/H2O plasma cut, H35/N_2 plasma cut.
    - No added alloying element in the weld to compensate for the loss of alloys in the base metal due to the welding operation

- Pre weld preparation should be required on any cut surface per welding standards

- N_2/H_2O cutting process is recommended:
    - No compromise on weldability
    - High definition cut quality
    - Larger thickness range and parameter windows
    - Lower fume and NOx emissions
    - Lower cost

Limitations and Future Study

- Material thickness for as cut characterization and welding study
  - May require use of filler material
- Surface contamination due to environment
- Other cutting gas mixtures
  - Air/Air
  - N_2/N_2
  - N_2-H_2/N_2
  - Other
- N_2/H_2O & H35/N_2 Fume and NOx generation as a function of thickness and current

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