ELECTRIC POWER RESEARCH INSTITUTE

Welding Issues:

Alloy 52 Weldability & Testing; Magnetic Stir Welding; Laser & Friction Stir Welding on Irradiated Material

NRC/Industry Technical Meeting

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EPRI Welding and Repair Technology Center
Charlotte, North Carolina, USA

Presentation Roadmap

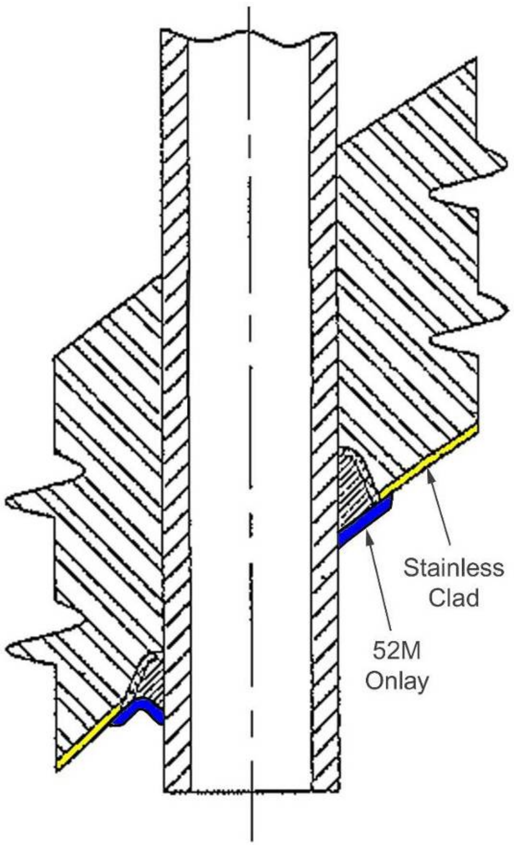
- **Alloy 52 / 52M Challenges**
- **Cracking Mechanisms**
- **Weldability Testing**
  - Description of Testing and Ranking of Filler Metals
  - Dilution Issues and Testing
  - High Chromium Nickel-Base Alloy Development
- **Magnetic Stir Welding**
- **Welding Irradiated Material**
  - Problem and Issue
  - Laser Welding
  - Friction Stir Welding

Filler Metal 52 & 52M Welding Challenges

- Alloy 52 / 52M weldability issues
  - Sluggish weld puddle
  - Heat-to-heat variations can cause significant difference in weldability
- Ti & Al oxide buildup
- Tendency for lack of bond and/or lack of fusion

- Susceptible to various types of weld metal cracking
  - ***Ductility-dip cracking (DDC)***
  - Liquation cracking
  - ***Solidification (hot) cracking***

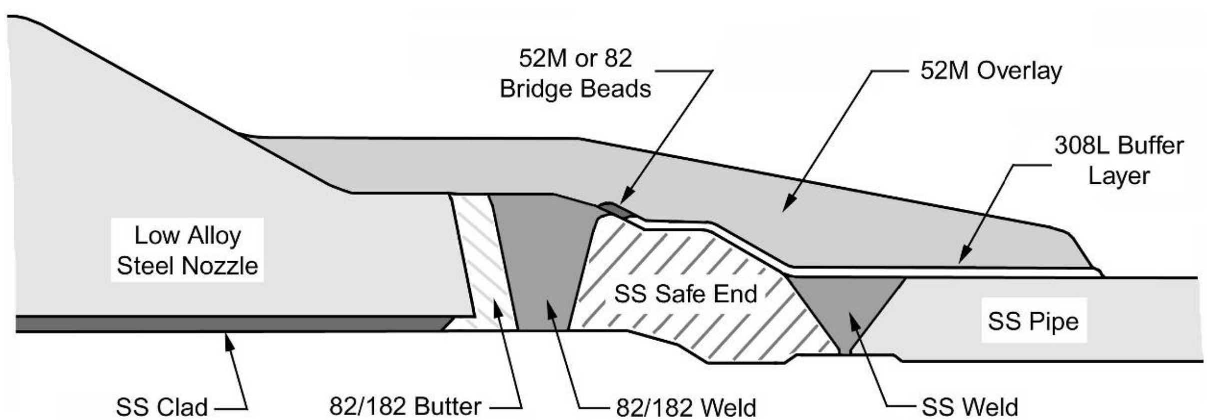
52 / 52M Must be Welded on Variety of Materials



CRDM Schematic with 52M Onlay

- 52 / 52M must weld successfully over a variety of materials
  - Low alloy steel, 82/182 weld metal, SS weld metal, 304 & 316 base metals, CF8A & CF8M cast materials, etc.

Schematic of 52M Structural Weld Overlay



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Cracking Mechanism No. 1

- **<u>Solidification Cracking (type of hot cracking)</u>**
  - Occurs in the weld fusion zone at the terminal stage of solidification in brittle temperature range (BTR)
  - Associated with liquid films along grain boundaries
  - Low melting constituents segregate to grain boundaries where they form liquid films that separate during thermal contraction of the weld
  - Controlled by volume fraction of low melting point liquid, grain boundary area, and wetting characteristics

Cracking Mechanism No. 2

- **Ductility-Dip Cracking (DDC)**
  - Occurs in weld metal HAZ during multi-pass welding
  - Associated with a sharp drop in ductility at temperatures slightly above the recrystallization temperature (~ ½ T_L to ¾ T_L range)
  - One theory suggests that DDC occurs during rapid grain growth in the ductility-dip temperature range (DTR) along migrated grain boundaries
  - Low impurity weld metals, such as filler metal 52, have low fraction of 2nd phase particles to control and obstruct grain growth

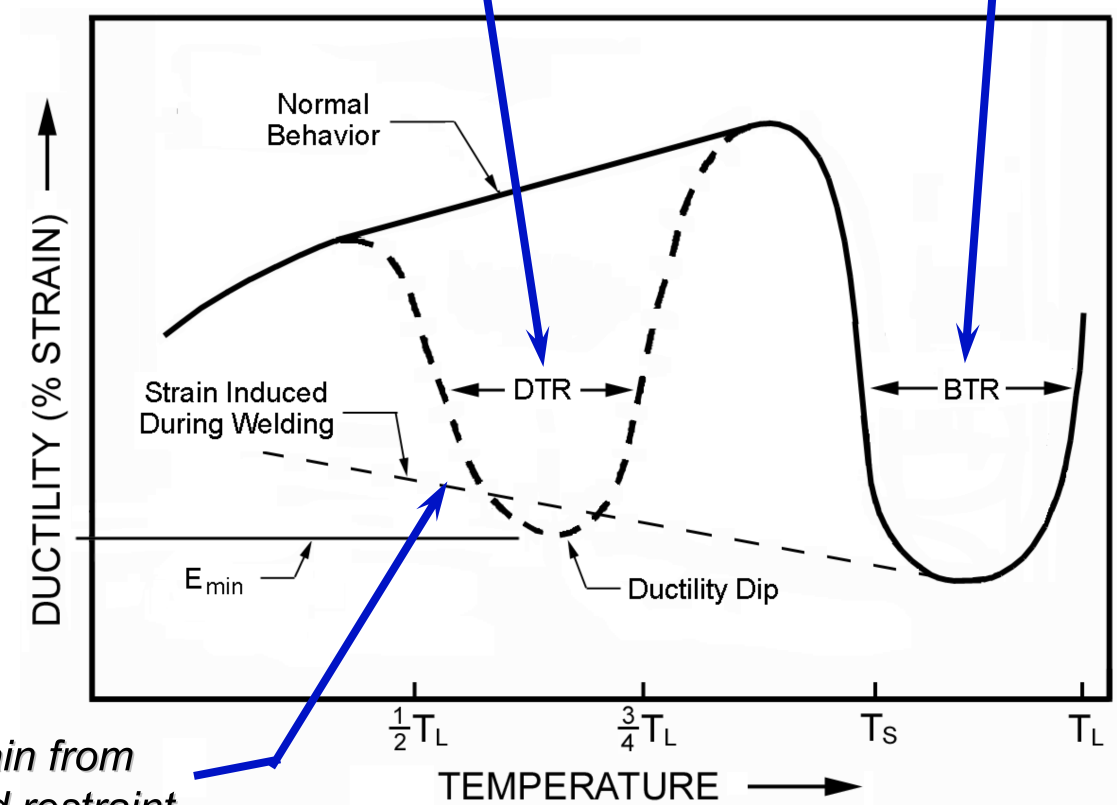
Ductility-Dip and Brittle Temperature Ranges

Ductility-dip Temperature Range (DTR)

range of ductility-dip envelope
(~ 10% to 15% strain)

Brittle Temperature Range (BTR)

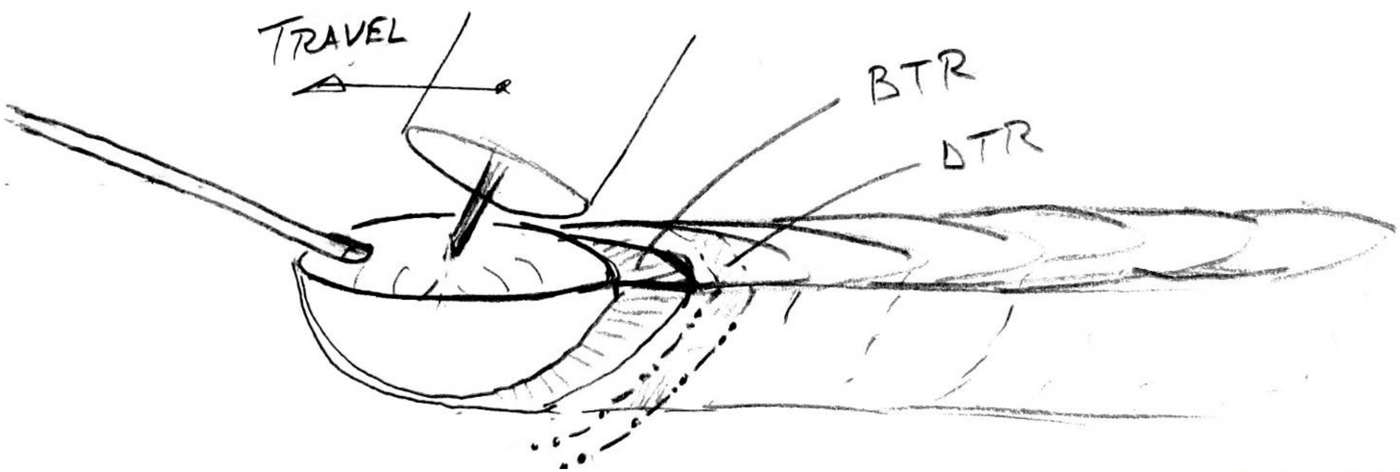
~ liquidus to terminal solidus range



applied strain from shrinkage and restraint

Solidification & Ductility-Dip Crack Locations

- **Solidification Cracks**
  - Initiate in the Brittle Temperature Range (BTR)
  - Typically surface connected and sometimes subsurface in weld fusion zone where shrinkage strain is high enough to cause rupture
- **Ductility-Dip Cracks (DDC)**
  - Initiate in the Ductility-dip Temperature Range (DTR)
  - Typically subsurface in reheated weld metal where strain is high enough to cause rupture

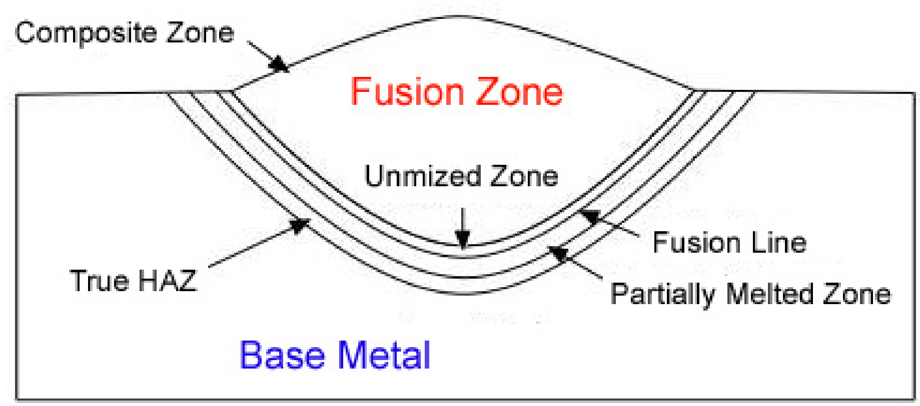


Weld Zone Definitions and Crack Locations

- **Heat Affected Zone** (HAZ) **includes:**
  - **Partially Melted Zone** (PMZ): *base metal* that only partially melts and re-solidifies during welding where temperature is between the liquidus T_L and terminal solidus T_{TS} temperatures
  - **True Heat Affected Zone** (T-HAZ): *base metal* or reheated *weld metal* where no melting occurs

- **Fusion Zone includes:**
  - **Composite Zone** (CZ): mixture of *base metal and weld filler metal*
  - **Un-mixed Zone** (UMZ): melted and re-solidified *base metal* that does not mix with the weld metal

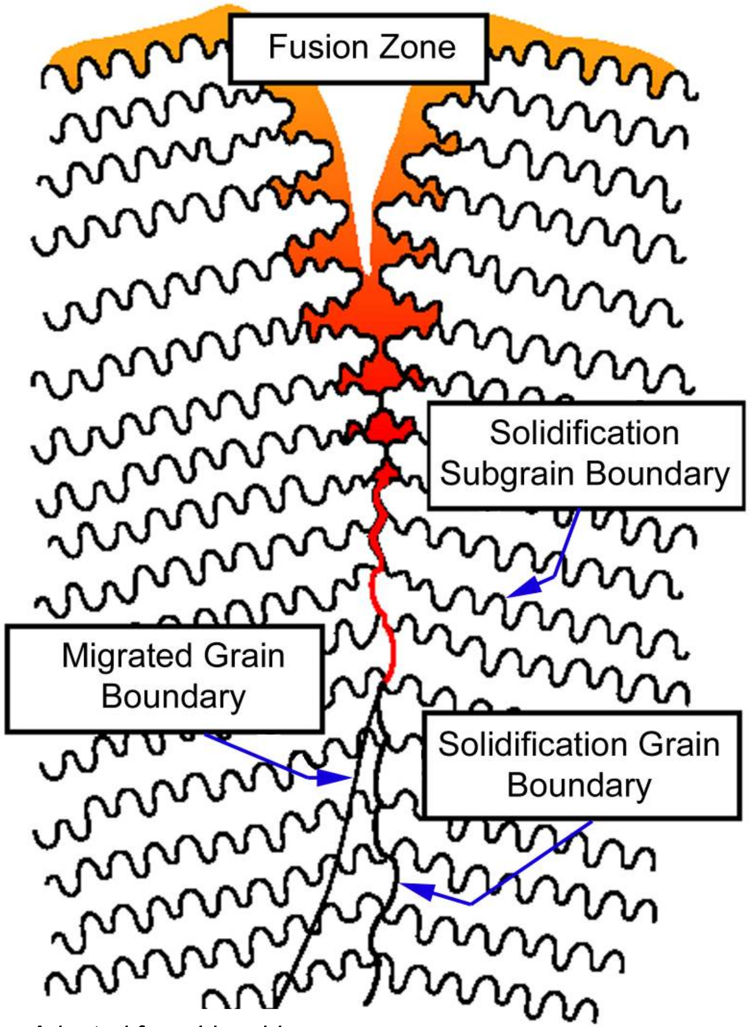
Solidification Cracks Occur in the Fusion Zone



DDC Occurs in the True HAZ

Liquation Cracks Occur in the PMZ

Solidification & Ductility-dip Crack Morphology

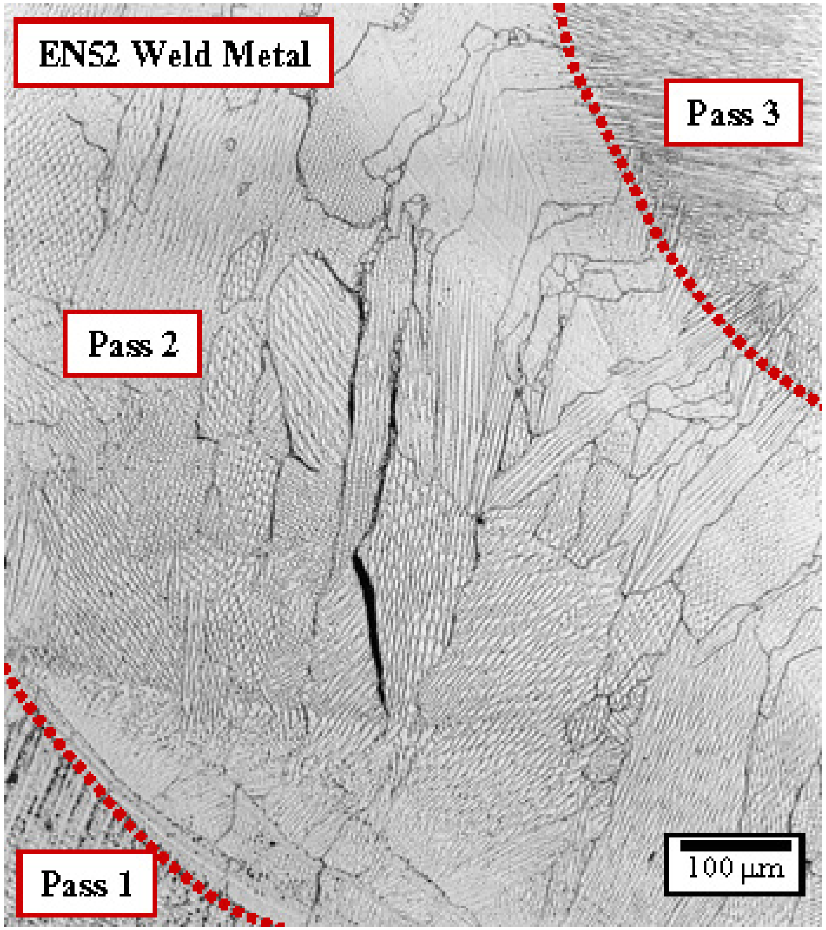


Adapted from Lippold

- **Solidification Grain Boundary** (SGB)
  - High composition gradient
  - High angle misorientation
- **Solidification Subgrain Boundary** (SSGB)
  - High composition gradient
  - Low angle misorientation
- **Migrated Grain Boundary** (MGB)
  - Local variation in composition
  - High angle misorientation

- **Solidification cracks occur in SGBs & SSGBs**
- **Ductility-dip cracks occur along MGBs**

Ductility-Dip Crack Location and Morphology



Courtesy Mark Cola

- Ductility-dip crack (DDC) in 2nd pass reheated in ductility-dip temperature range by 3rd weld pass
- DDC occurs along large and straight migrated grain boundaries
- Susceptible weld metals (i.e., 52 & 52M) have low impurities and few 2nd phases to pin migration (growth) of weld metal grains

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Filler Metals in EPRI Test Matrix

- Special Metals (21% Cr)
  - **82 (ERNiCr-3)** ** *special heat with high hot crack resistance*
- ThyssenKrupp (27% Cr)
  - **52i-A (ERNiCrFe-15)** * *small experimental melt*
  - **52i-B (ERNiCrFe-15)** ** *large production melt*
- Special Metals (30% Cr)
  - **52 (ERNiCrFe-7)** *not in test matrix*
  - **52M (ERNiCrFe-7A)** *
  - **52MSS-A & B (ERNiCrFe-13)** * *two small experimental melts*
  - **52MSS-C (ERNiCrFe-13)** * *large production melt*
  - **52MSS-D (ERNiCrFe-13)** ** *large production melt*
  - **52MSS-E low Fe (ERNiCrFe-13)** *** *small experimental melt*

** Testing complete ** Testing in progress *** Testing planned*

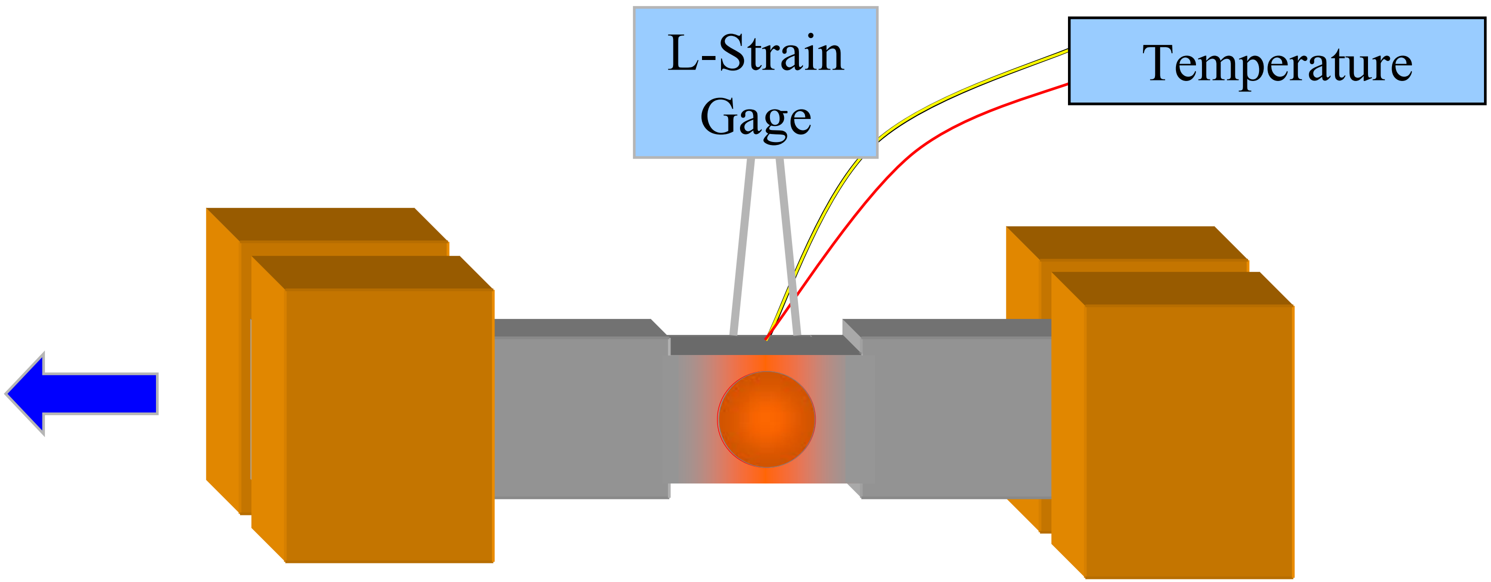
Table of Filler Metal Compositions

	52M	52MSS-A	52MSS-B	52MSS-C	52MSS-D	52i-A	52i-B	82	
	NX0T85TK	D5-8423	HV1224	NX77W3UK	NX79W1UK	HD52	187775	6359DR	
Al	0.09	0.07	0.24	0.13	0.12	0.06	0.45	-	Al
B	0.0004	-	-	0.001	-	0.0002	<0.0010	-	B
C	0.02	0.03	0.018	0.023	0.03	0.031	0.040	0.033	C
Co	0.011	<0.001	0.003	<0.01	0.014	-	<0.02	0.03	Co
Cr	30.11	29.92	29.20	29.49	29.46	26.88	26.98	21.35	Cr
Cu	0.03	0.06	0.055	0.05	0.04	-	0.01	0.01	Cu
Fe	8.87	8.31	8.63	8.79	8.91	3.00	2.55	0.53	Fe
Mn	0.72	0.19	0.70	0.31	0.31	3.19	3.04	2.90	Mn
Mo	0.05	3.83	3.68	3.51	3.20	-	0.003	-	Mo
Nb	0.87	2.57	2.4	2.51	2.40	2.65	2.58	2.43	Nb
Ni	59.21	54.67	54.67	52.36	56.20	63.84	63.88	74.55	Ni
P	0.002	<0.001	0.016	0.004	0.005	0.003	0.002	0.003	P
S	0.0005	0.001	0.0006	<0.0005	0.00015	0.0006	0.001	0.001	S
Si	0.11	0.12	0.15	0.11	0.11	0.15	0.05	0.16	Si
Ta	<0.01	0.017	0.013	0.01	<0.01	-	0.004	<0.01	Ta
Ti	0.16	0.19	0.21	0.18	0.18	0.19	0.37	0.33	Ti
Mg	-	-	-	-	-	0.0003	0.002	-	Mg

(1) Composition from Certified Material Test Reports

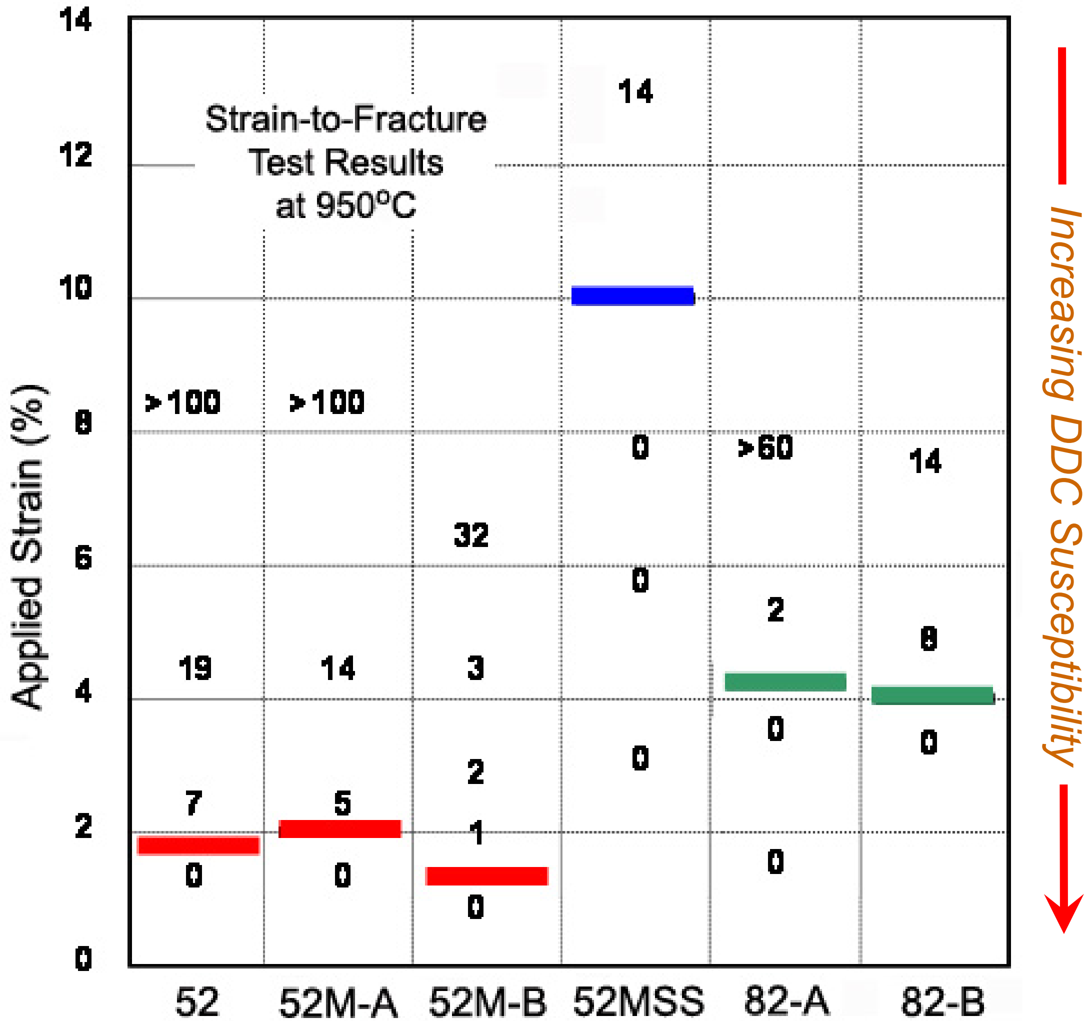
Strain-to-Fracture (STF) Test Description

- STF test measures susceptibility to ductility-dip cracking (DDC)
- Specimens are prepared with weld metal in the gage area with a polished spot weld to provide consistent weld grain structure
- Gleeble™ tester is used to apply controlled heating and strain loading



From John Lippold, OSU

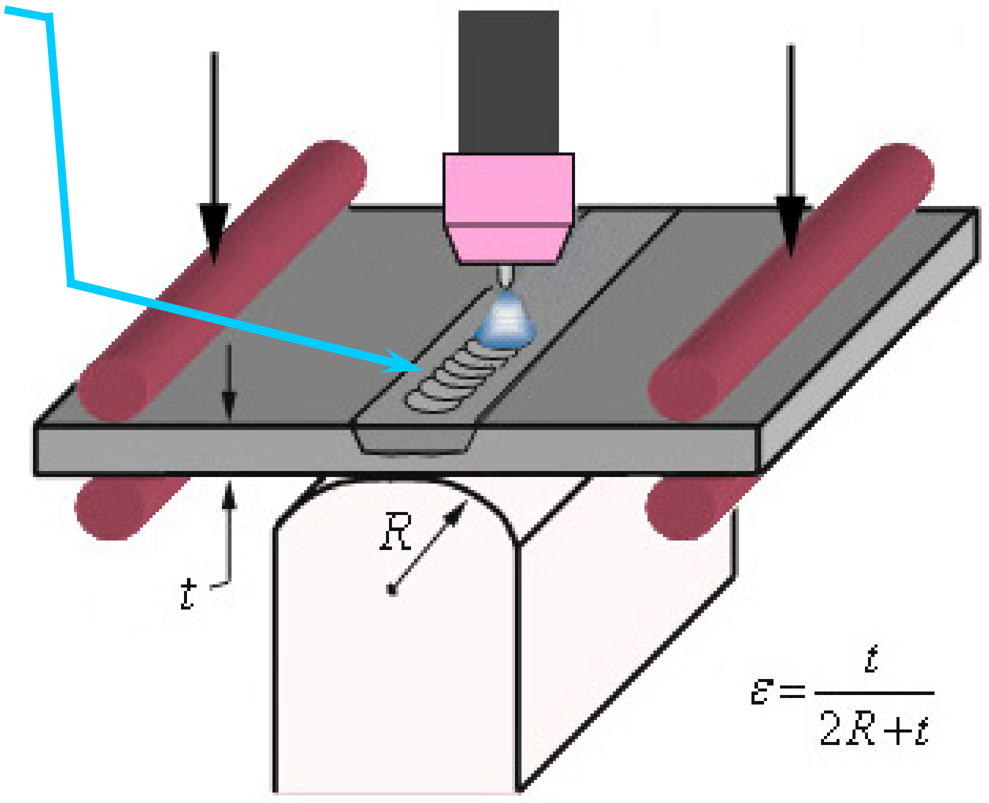
Strain-to-Fracture (STF) Data



- Ductility-dip cracking (DDC) is a solid state 'reheat' type cracking mechanism
- 52 & 52M both have low resistance to DDC
- 82 is considered acceptable based on experience
- 52MSS shows superior resistance to DDC
- Recent new heat of 52MSS is off the chart with threshold between 19% and 21% applied strain
- No STF testing with 52i

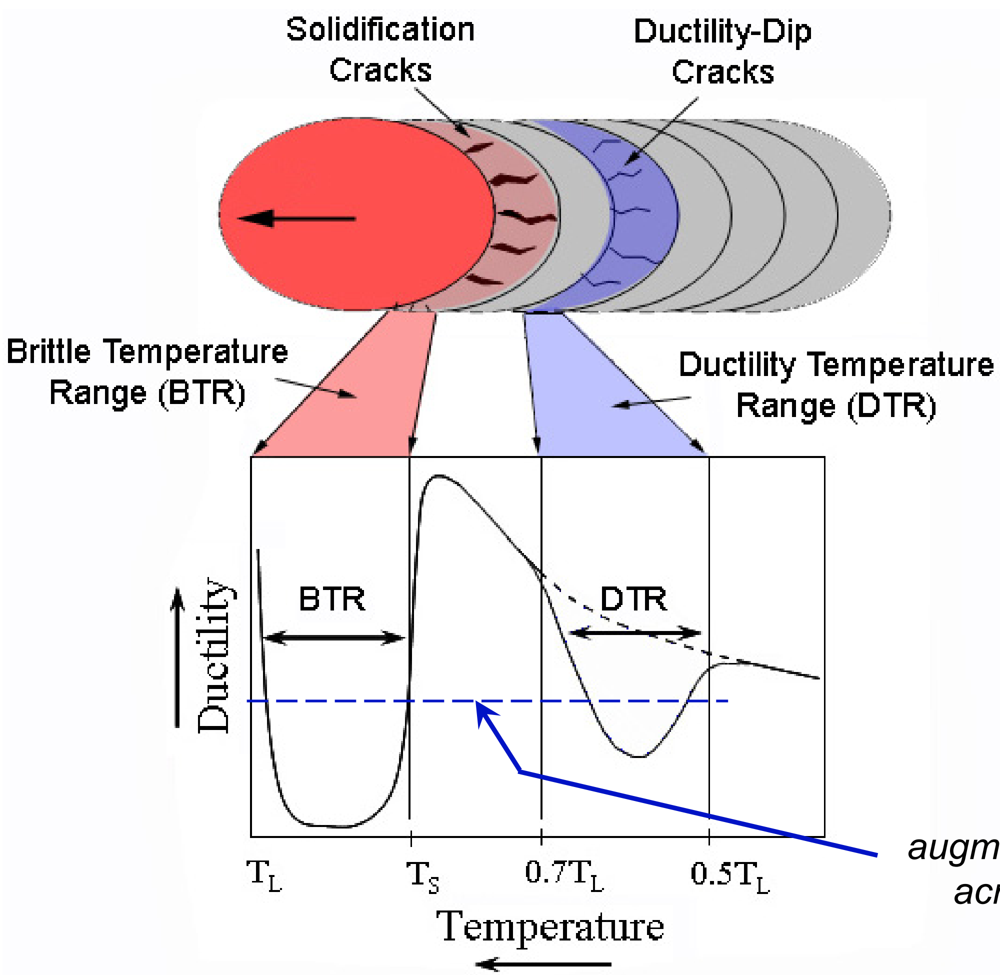
Transverse Varestraint Test Description

- Autogenous weld bead (no filler metal) over all weld metal specimen
- Specimen is bent during welding to apply an augmented strain on the plate surface during weld solidification
- Testing is performed over range of strain values *(radius of die block determines strain)*



$$\varepsilon = \frac{t}{2R+t}$$

Transverse Varestraint Weld Details



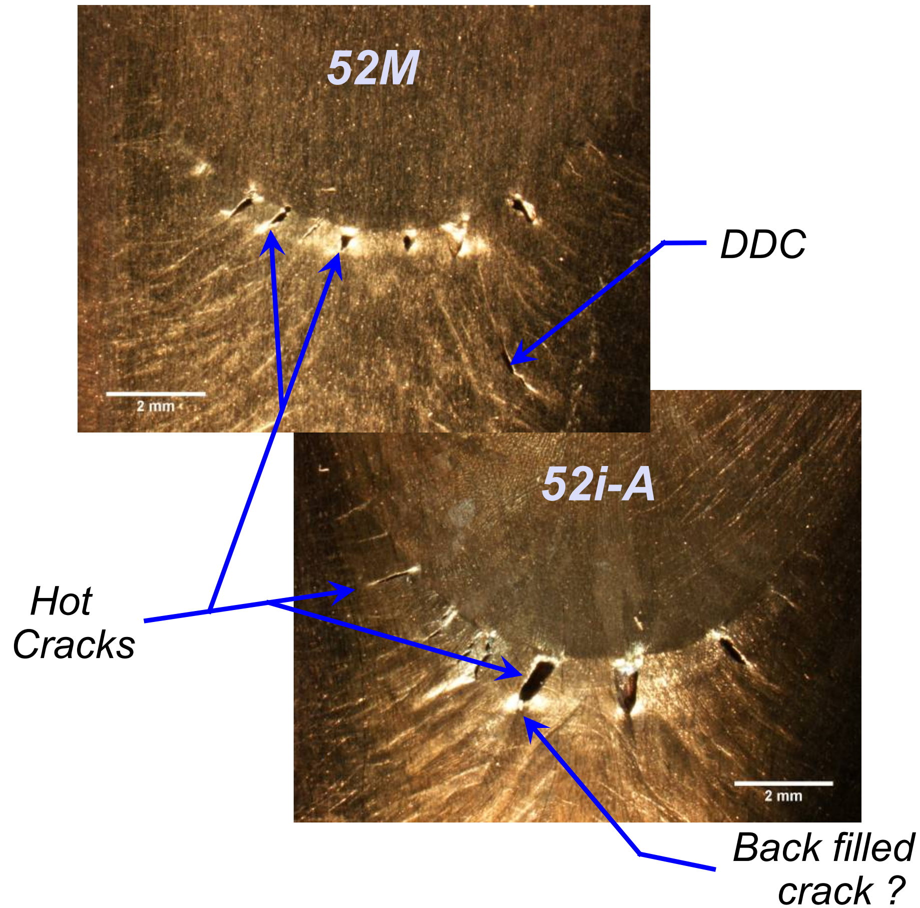
augmented strain is constant across BTR & DTR troughs

Test Parameters

Current, A	180
Voltage, V	10
Arc Length, in	0.08
Travel Speed, ipm	5.0
Augmented Strain Range, %	0.25 – 10.0
Ram Travel Speed, in/min	6.0
Pre-Bend Weld Length, in	1.5
Total Weld Length, in	2.0

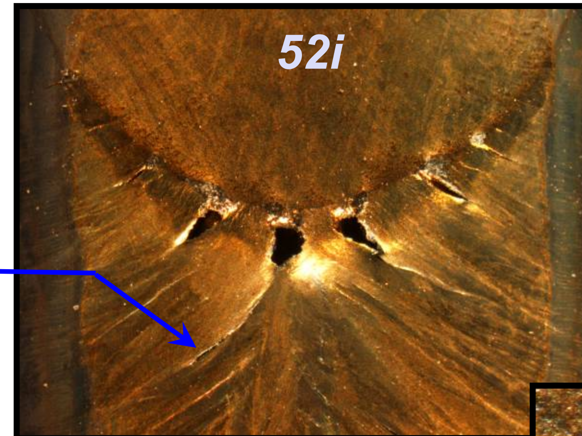
Evaluation of Transverse Varestraint Cracks

- Maximum crack length (MCL) is measured for each strain level tested
- Maximum crack distance (MCD) is longest crack measured at or above the saturation strain
- Above saturation strain threshold the MCL is essentially constant
- DDC can also be found by the transverse varestraint test

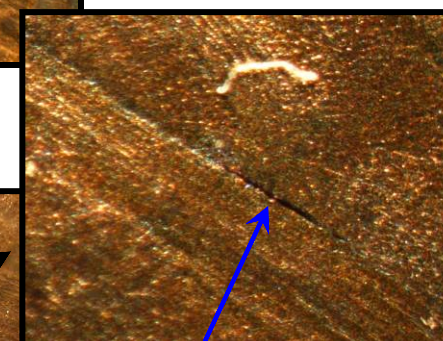


Varestraint Test Results (DDC Resistance)

- Solidification cracking occurs between T_{liq} and T_{sol}
- DDC occurs between ~$0.75T_{liq}$ and $0.5T_{liq}$
- DDC observed in 52M at 5% strain
- DDC observed in 82 at 7% strain
- DDC observed in 52i at 5% strain

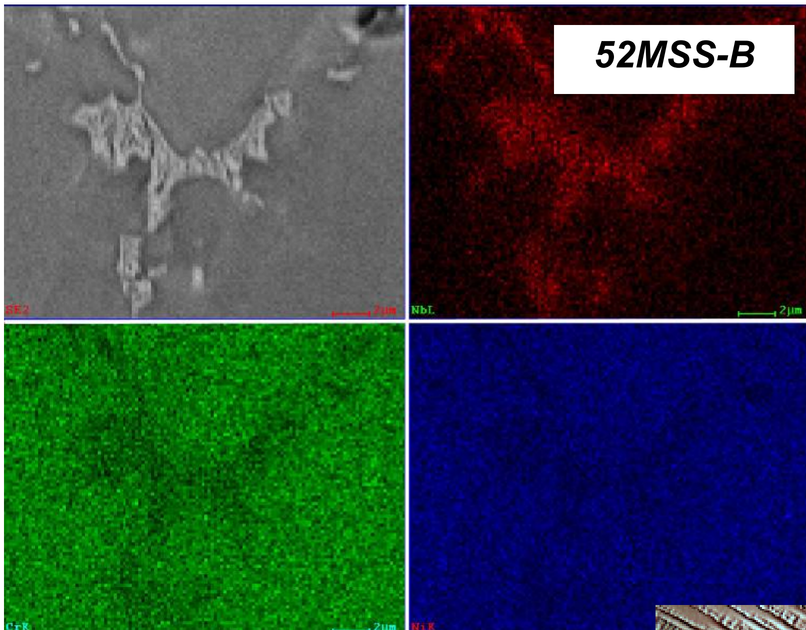


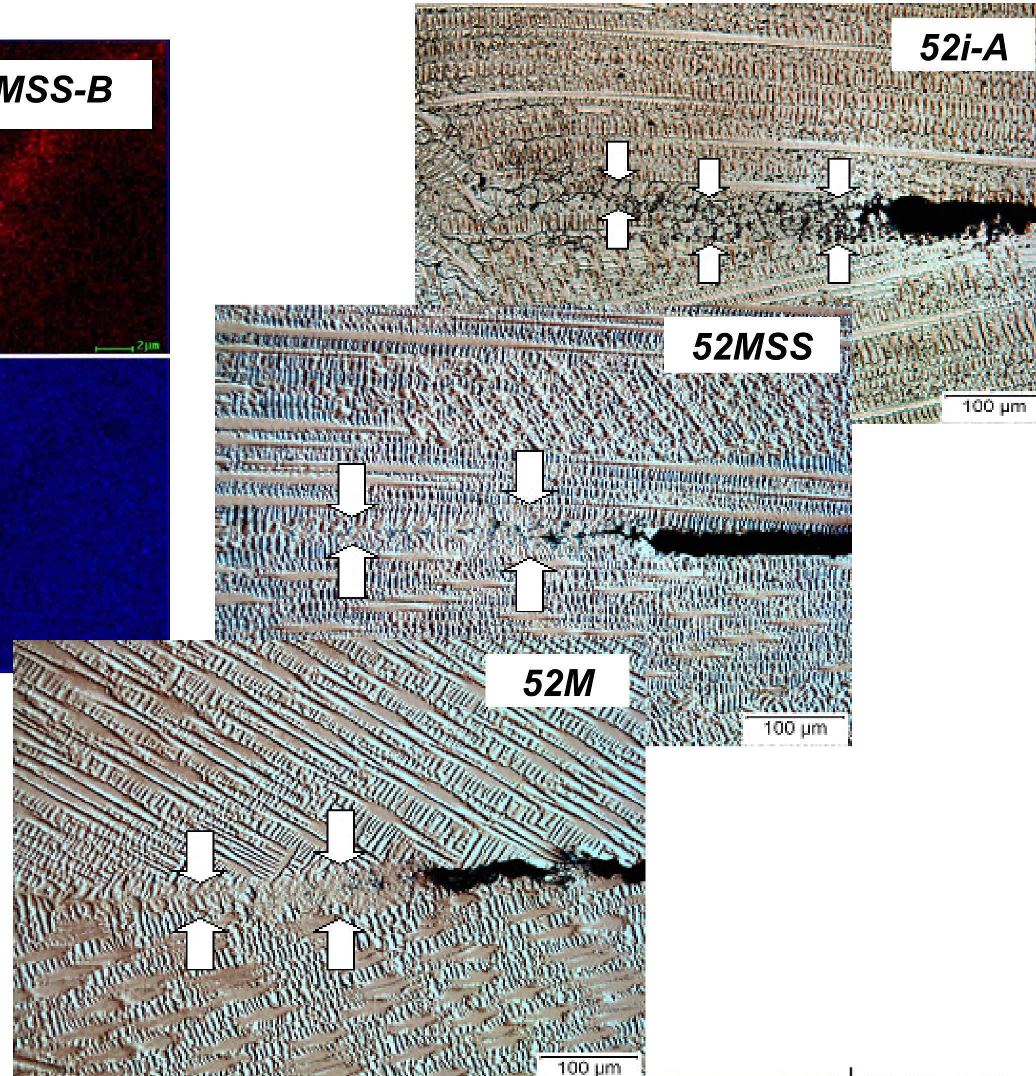
52i at 5% strain (10x)



82 at 7% strain (10x)

Backfilling in Transverse Varestraint Cracks

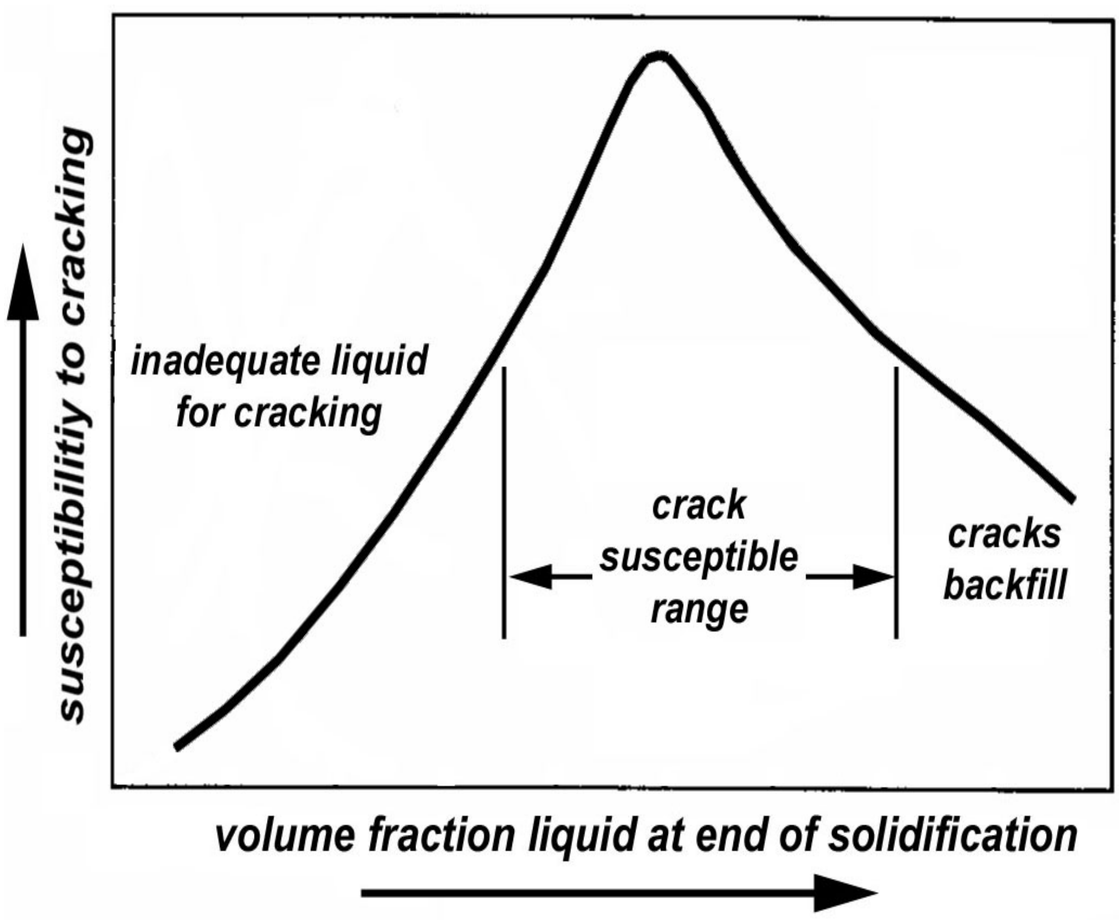




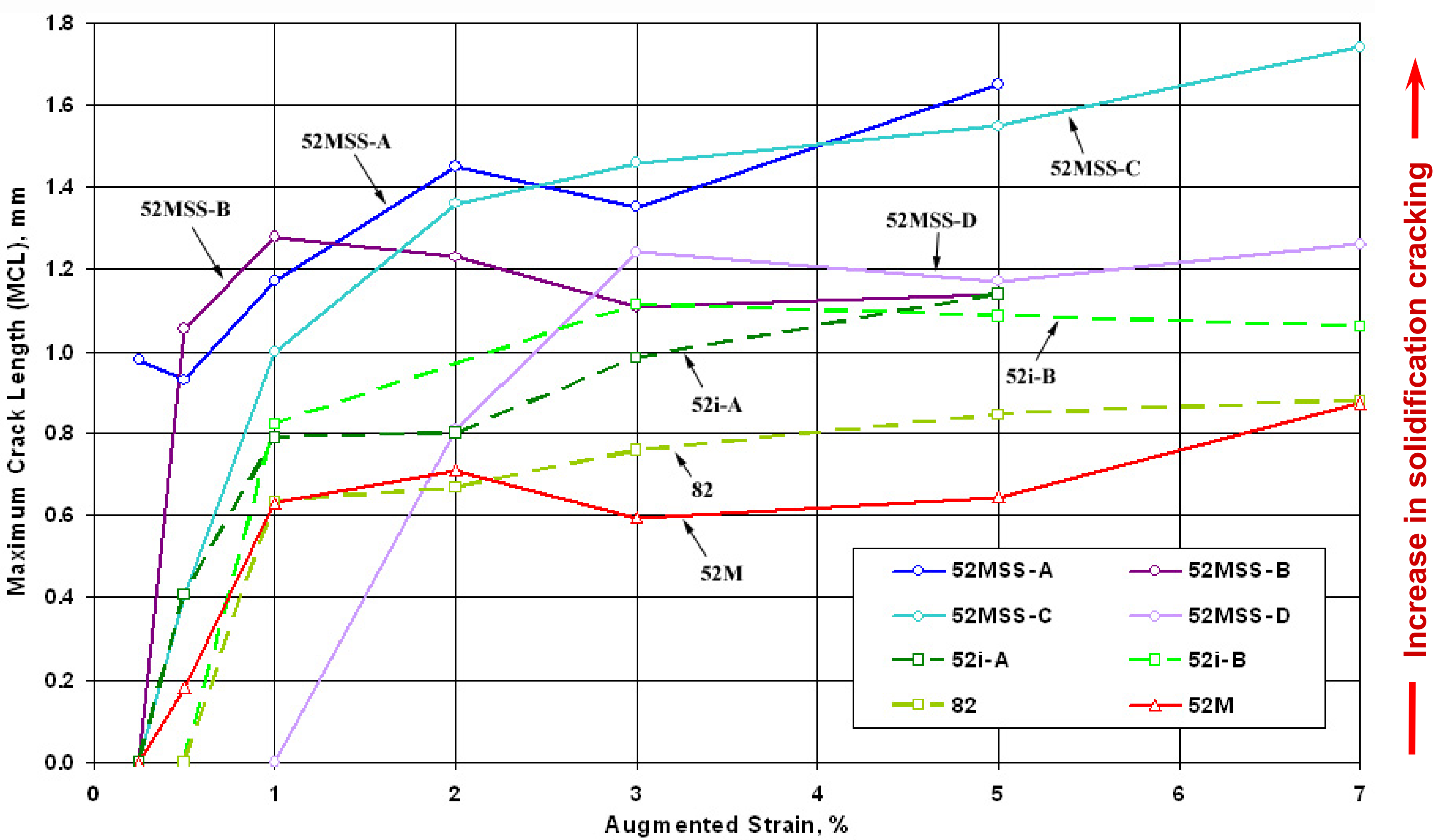
- Evidence of backfilling (crack healing) in 52i-A, 52MSS, and 52M
- EDS analyses shows NbC eutectic and Laves in solidification boundaries

Crack Healing by Backfill Mechanism

- Wide solidification temperature range indicates higher volume fraction liquid at end of solidification
- 52i has widest solidification range but is less susceptible to cracking
- Reduced susceptibility to cracking is likely due to adequate volume fraction of liquid to cause crack 'healing' (back filling)



Maximum Crack Length vs Augmented Strain



Cast Pin Tear Test (CPTT) Description

- CPTT evaluates solidification crack susceptibility
- Alloy charge is cast into a 3/8" diameter mold
- Charge may be adjusted for weld metal dilution
- Longitudinal tensile strain occurs in pin as it solidifies and cools
- Strain increases as pin length increases

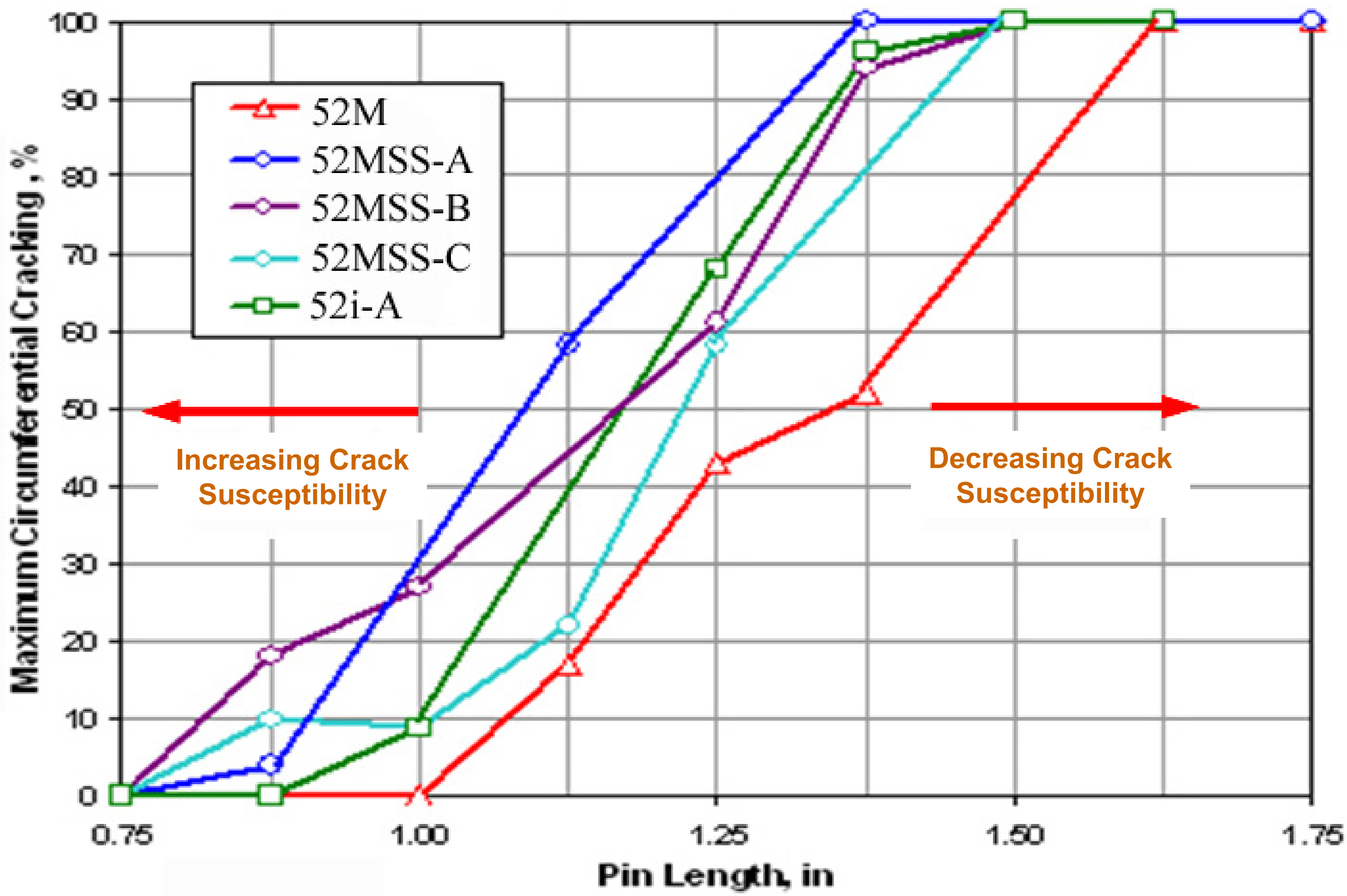
OSU cast pin tear test apparatus

Set of buttons is prepared for each heat

Button is melted by electric arc and cast into pin mold

3/8" diameter pins are cast from 3/8" to 2-1/8" gauge length in 1/8" increments. Head and foot of pin restrain gauge length during cooling

Max Circumferential Cracking (MCC) vs Pin Length



Comparison of Filler Metal Cracking Susceptibility

- Cast pin tear test results (solidification cracking at 40% MCC)

  52MSS-A > 52MSS-B > 52i-A > 52MSS-C > 52M

- Transverse varestraint results (solidification cracking in 2% - 5% stain range)

  52MSS-A > 52MSS-C > 52MSS-B > 52MSS-D > 52i-B > 52i-A > 82 > 52M

  ← *Increase in Solidification Cracking* —

- Transverse varestraint results (DDC)

  52i-A > 52M > 82 > 52MSS (no DCC observed in 52MSS)

- Strain-to-fracture test results (DDC)

  52 = 52M > 82 > 52MSS (no STF test data for 52i)

  ← *Increase in Ductility-dip Cracking (DDC)* —

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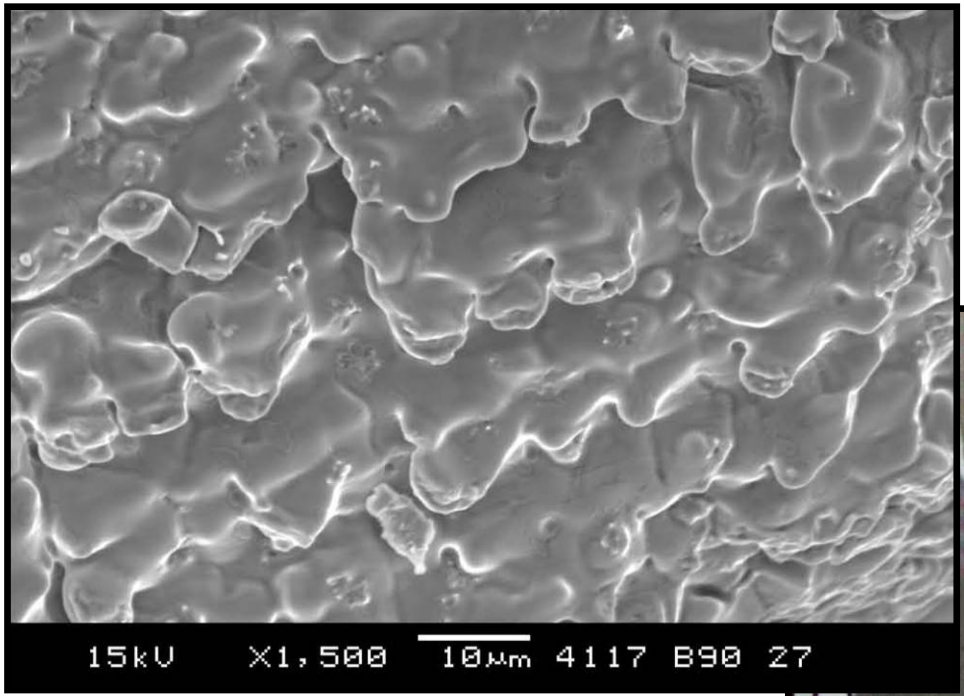
Dilution Testing Objectives

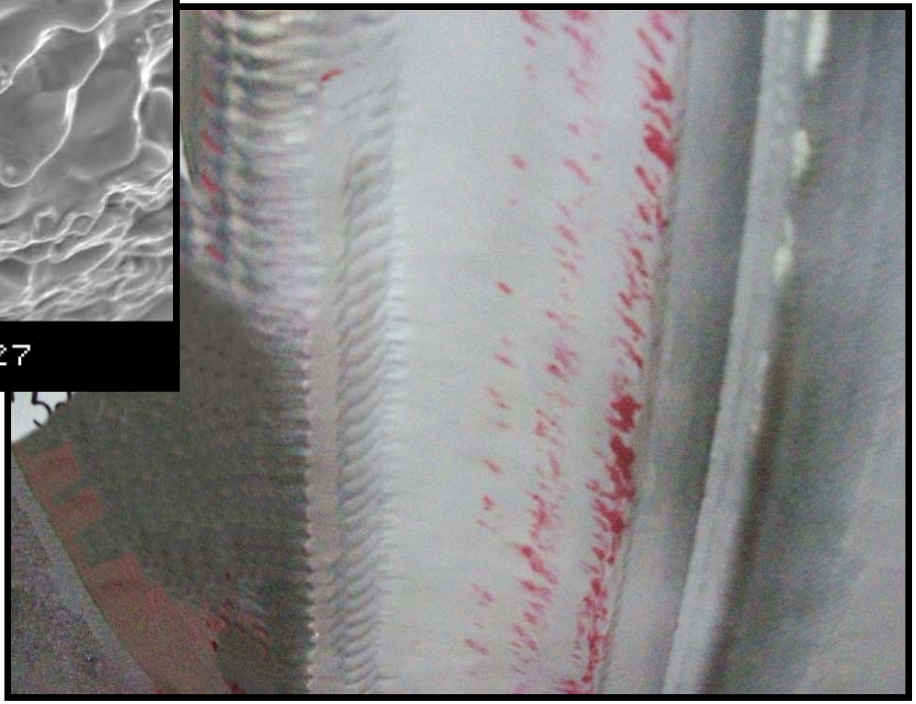
- Investigate and quantify influence of dissimilar metal dilution on heats and classifications of 52M
  - Determine level of dilution with stainless steel that causes solidification cracking
    - *Testing to date shows 52M diluted with ~35% Fe increases susceptibility to hot cracking*
  - Establish S & P and Si threshold(s) that promote solidification cracking
  - Investigate influence of S + Si on dilution and potential for increasing risk for solidification cracking
  - Optimize Cast Pin Tear apparatus to improve resolution and sensitivity for dilution effects on solidification cracking

Result of Excessive Dilution by Cast Stainless Steel



Test Mockup (below) - 52M pad on ER308L buffer layer

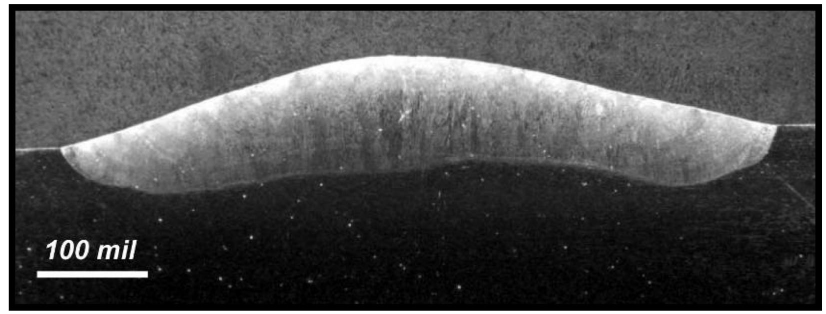
Base metal is SA-351 CF8A 0.019% S, 0.032% P, 0.72% Si



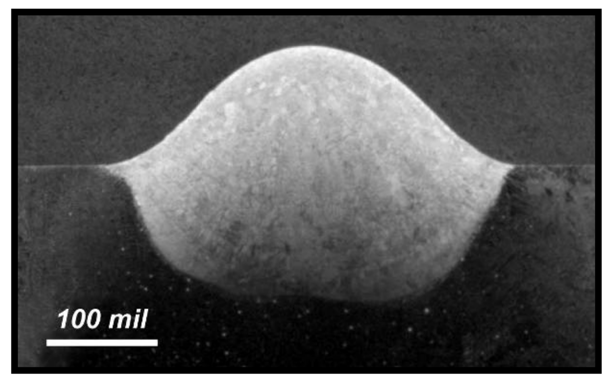
- *SEM of hot crack (above) in boat sample removed from 52M overlay*
- *52M layer (right) shows multiple liquid penetrant crack indications*

Influence of CASS Piping on 52M Weld Bead Shape

- Influence of CASS trace elements on weldability:
  - Weld bead shape and penetration
  - Susceptibility to hot cracking
- Industry needs to:
  - Understand how CASS influences 52M welding
  - Identify deleterious trace elements in CASS
  - Define threshold values to protect against hot cracking



Weld Shape on 304L Plate

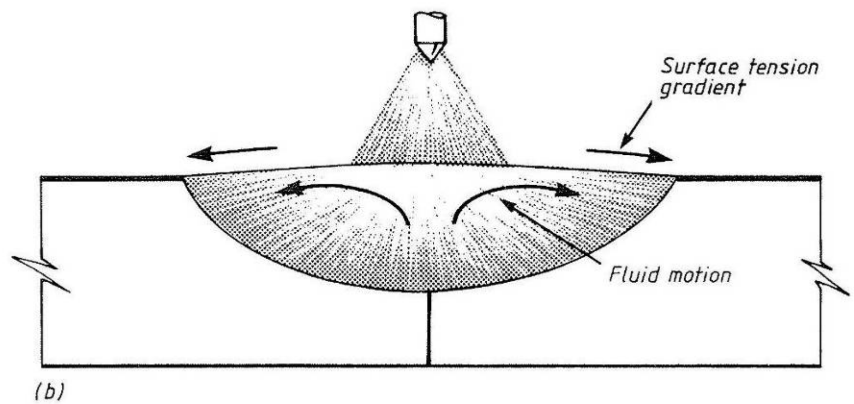


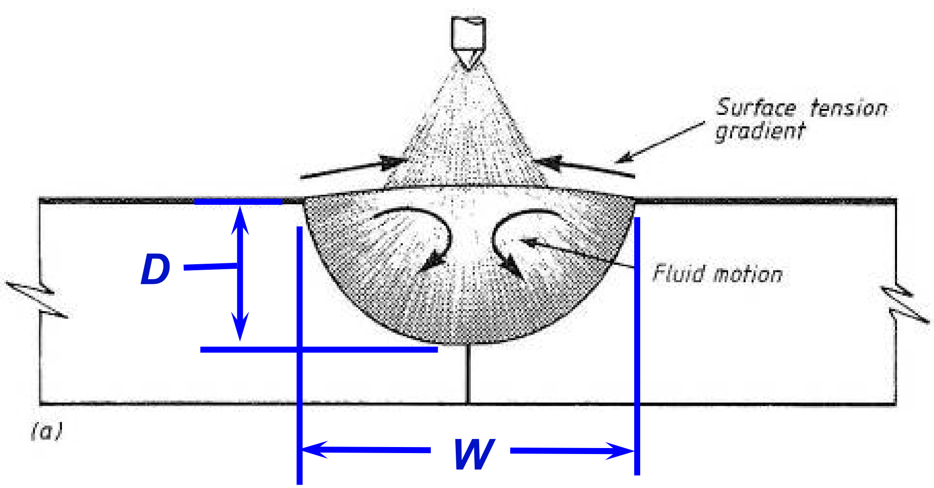
Weld Shape on CF8A (CASS) Pipe

Effect of Sulfur and Silicon on Austenitic Welds

- Sulfur influences the weld pool surface tension gradient in austenitic welds
- Surface tension gradient drives molten metal flow (Marangoni flow)
- Silicon addition decreases viscosity which enhances flow

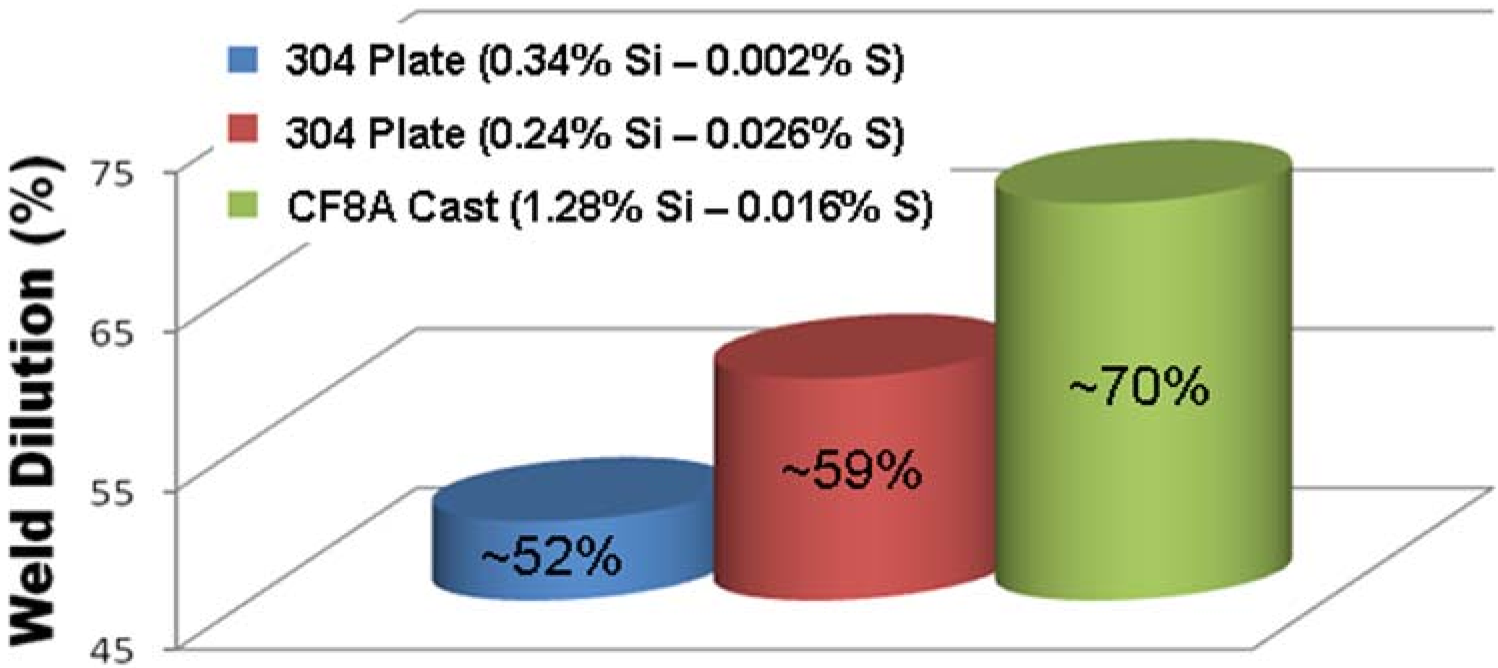
From Tinkler – London Conf Nov 1983





- Shallow & wide bead < 0.008% sulfur
- Deep & narrow bead > 0.015% sulfur
- High sulfur is known to cause hot cracking

Influence of S & Si Composition on Dilution



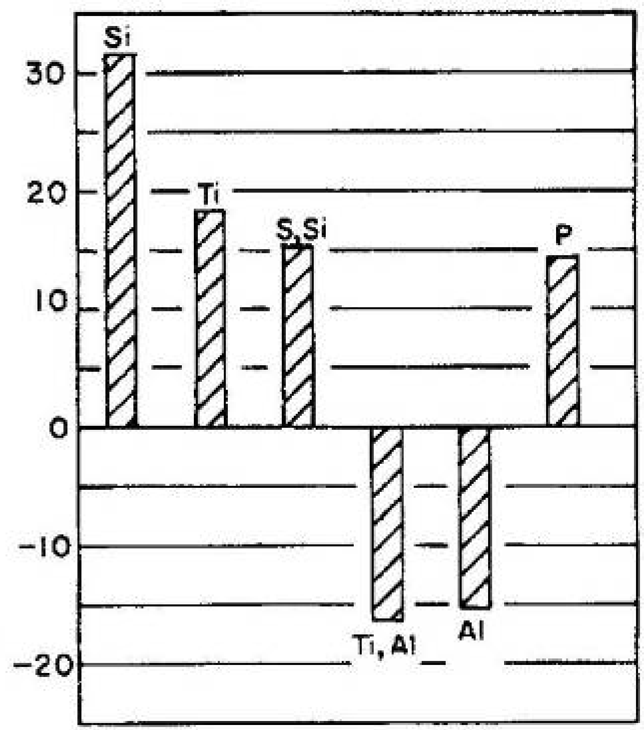
Single bead dilution ranged from 52% to 70% for low to high S & Si

Minor Element Influence on Inconel 600

- Si, S-Si, and P increased weld cross-sectional area
  - Area increase corresponds to increase in dilution
- Si decreases viscosity and S increases penetration

Cross-Sectional Area

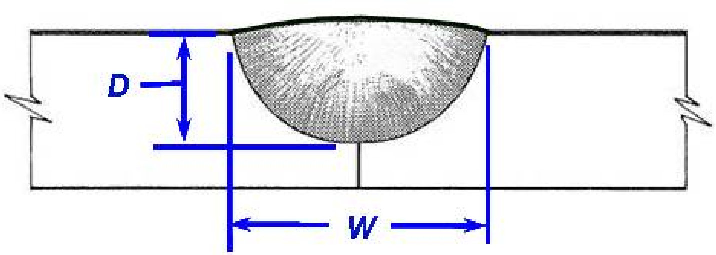
Treatment combination	Effect	Best value
Si	31.3	17.3
Ti	18.1	37.9
S-Si	17.7	35.0
Ti-Al	−16.2	6.4
Al	−15.4	4.4
P	14.1	17.7
Mean	—	27

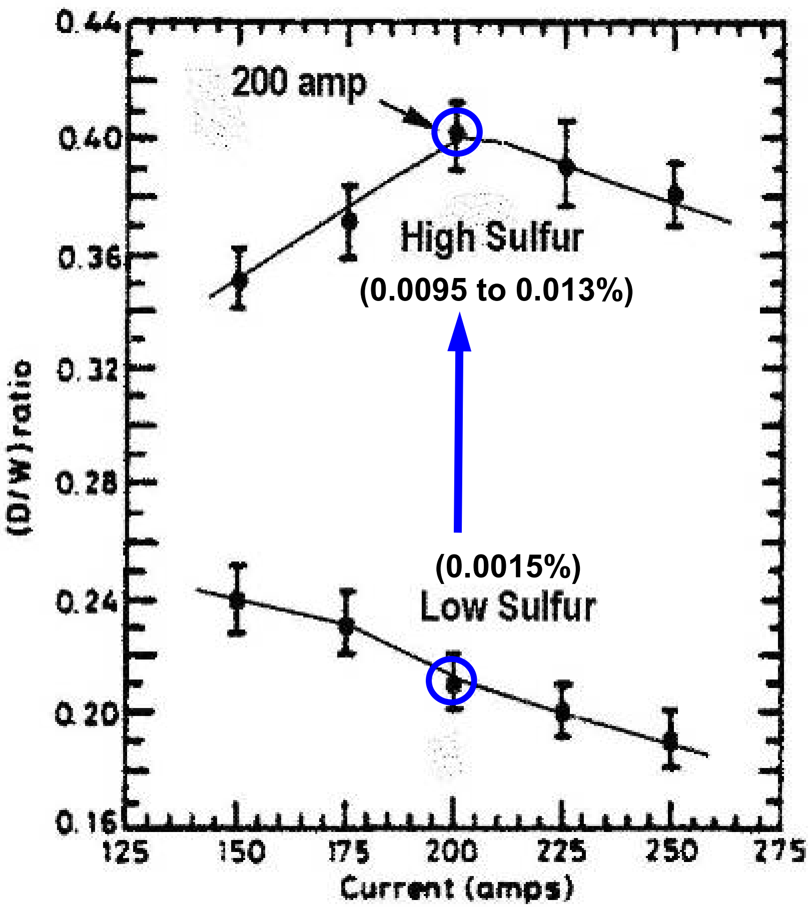


From Savage – WJ April 1977

Influence of Current and Sulfur on D/W

- Influence of current on austenitic stainless steels (304L & 316L) with
  - Low 0.0015%S
  - High 0.0095 to 0.013%S
- Low S – D/W ratio decreases as current increases
- High S – D/W ratio is higher and peaks at 200 amps



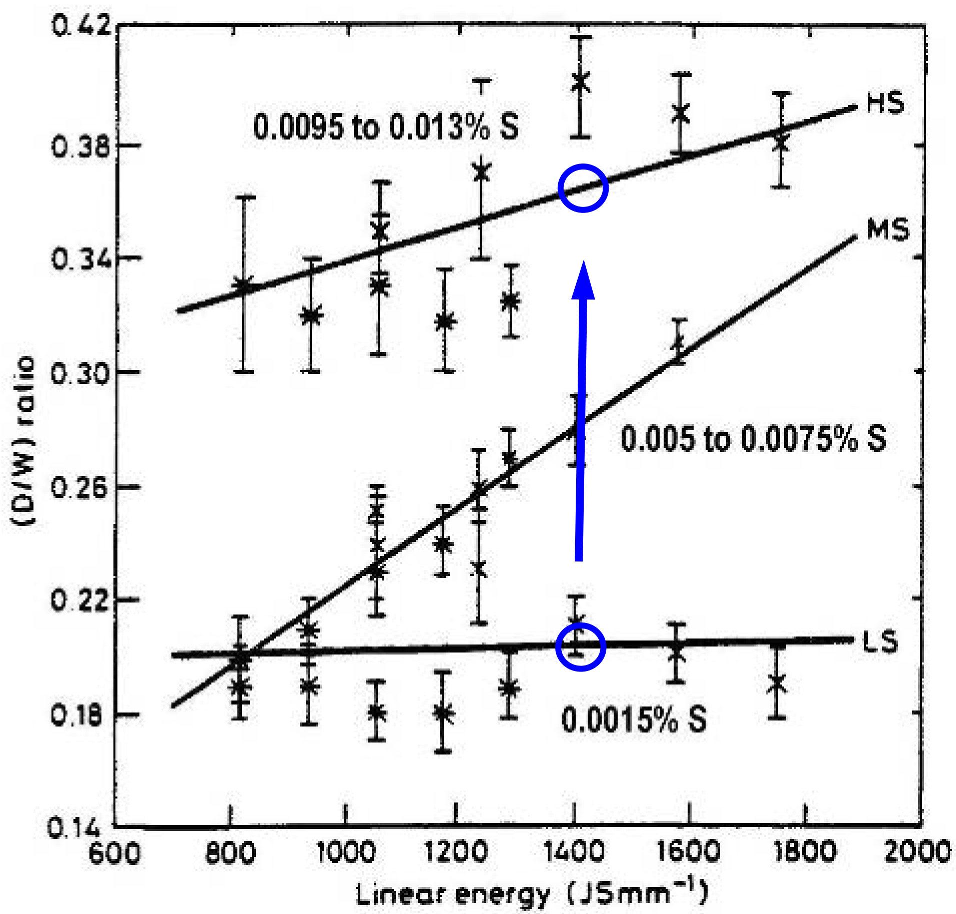


From Shirali – WJ July 1993

Influence of Sulfur and Heat Input on D/W

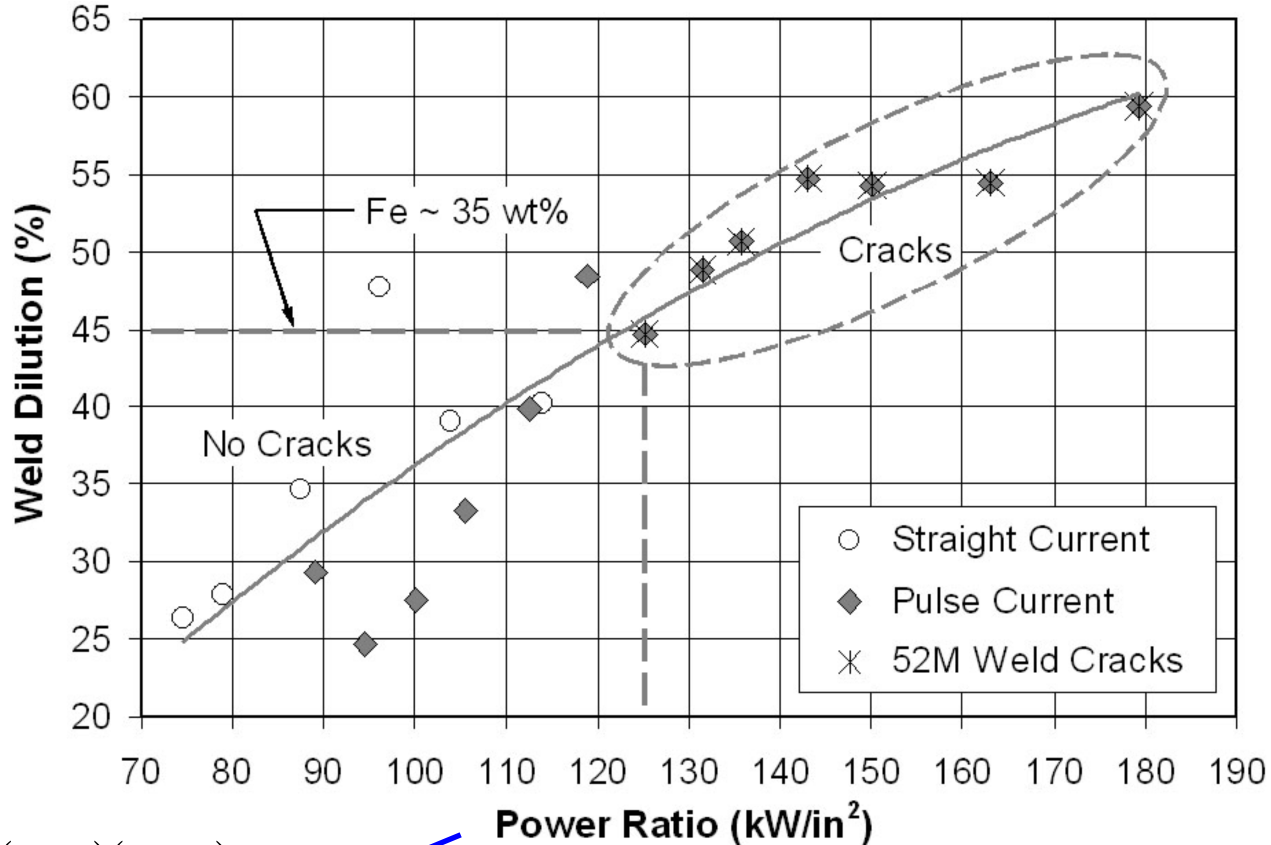
- Influence of heat input on austenitic stainless steels (304L & 316L) with low – med – high sulfur content
- Depth-to-width (D/W) ratio varies with heat input depending on sulfur content
- Heat input has little influence on D/W on low sulfur (≤ 0.0015%)
- Heat input has strong influence on D/W on med sulfur (0.005 to 0.0075%) and high sulfur (0.0095 to 0.013%)

From Shirali – WJ July 1993



Solidification Cracking by Dilution with Stainless Steel

- 52M solidification cracking on 304L plate (not high S material)
- Solidification cracking occurs at high dilution
- Studies show 52M diluted with > 35% Fe is susceptible to solidification cracking

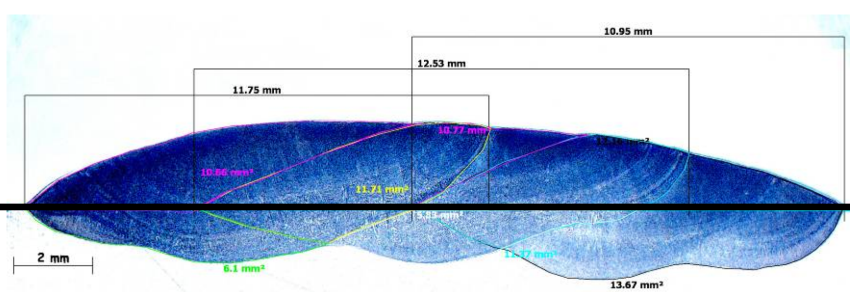


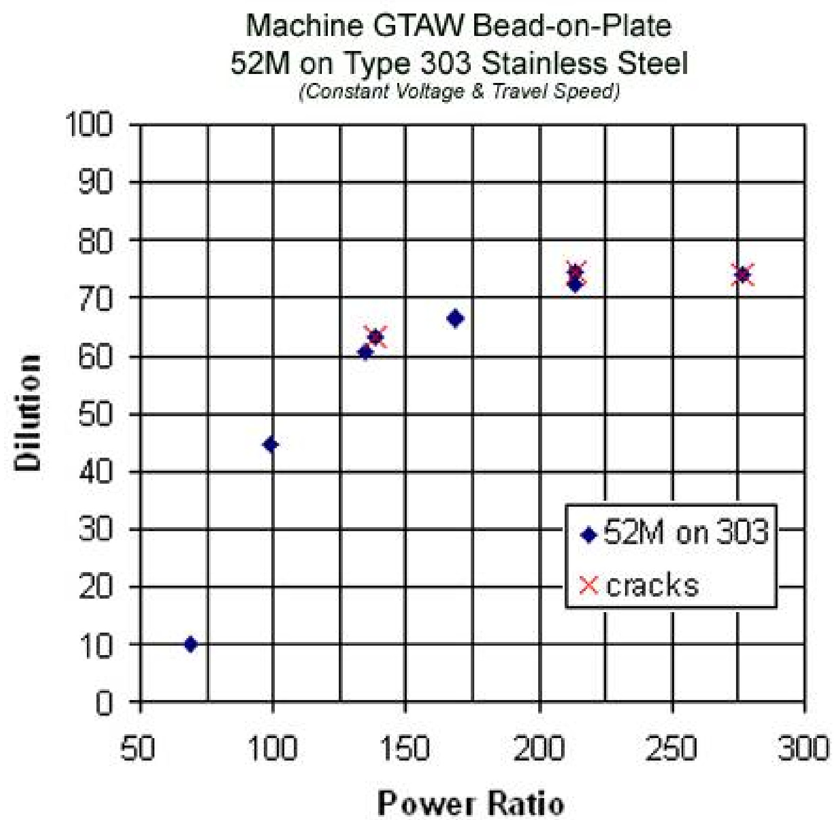
$$\frac{Power}{Weld\ Deposit\ Area} = \frac{(volt)(amp)}{\left(\frac{WFS}{TS}\right)(A_{wire})}$$

EPRI ELECTRIC POWER RESEARCH INSTITUTE
Welding and Repair Technology Center

Bead on Plate – 52M on Type 303 Plate

- 52M bead on Type 303 plate testing
  - Measure dilution by cross section
  - Calculate composition from dilution
- Hot cracking occurred at 60% dilution
  - Expected extensive hot cracking – only found small cracks in cross section
  - Type 303 plate has 0.21% S
  - Hot cracking occurred in 60% to 80% dilution range
    - S - 0.132% to 0.156%
    - Si - 0.35% to 0.39%
    - Mn - 1.35% to 1.45%





Why wasn't cracking more severe?

Crack healing by backfilling?

Or due to high Mn?

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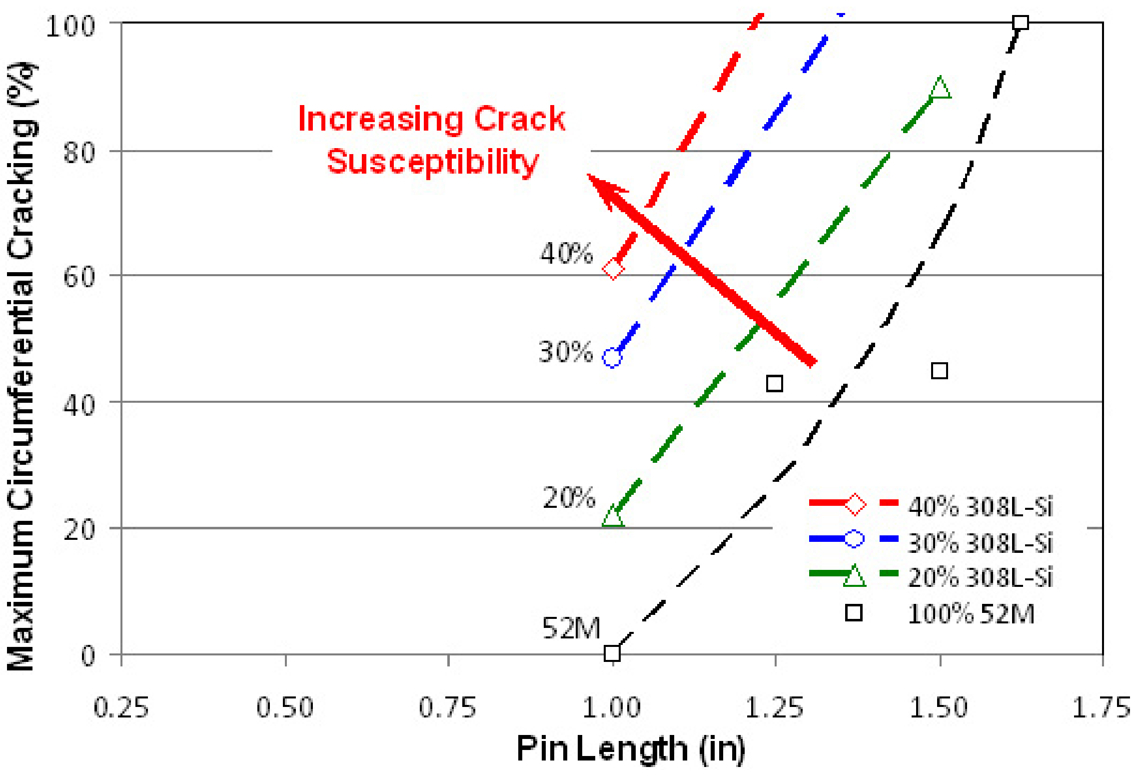
Bead on Plate – 52M on 303 Plate Clad with ER308L-Si

- Added ER308L-Si cladding to Type 303 plate to increase Si level
  - 52M hot cracking occurred in all but extremely low dilution levels (~10% dilution)
  - Demonstrates synergy of S + Si and potential benefit of Mn in 52M filler wire
- Work in progress and all results are not yet analyzed

52M Dilution by 308L-Si *(Preliminary CPTT Data)*

	Cr	Ni	Fe	Mn	Si	Nb	Al	Ti	Mo	C	S	P
52M	30.1	59.2	8.9	0.72	0.11	0.87	0.09	0.16	0.05	0.020	0.0005	0.002
308L-Si	20.0	10.1	66.8	1.89	0.82	---	---	---	0.13	0.023	0.0118	0.0274
20%	28.1	49.4	20.5	0.95	0.25	0.70	0.07	0.13	0.07	0.021	0.003	0.007
30%	27.1	44.5	26.3	1.07	0.32	0.61	0.06	0.11	0.07	0.021	0.004	0.010
40%	26.1	39.6	32.1	1.19	0.39	0.52	0.05	0.10	0.08	0.021	0.005	0.012



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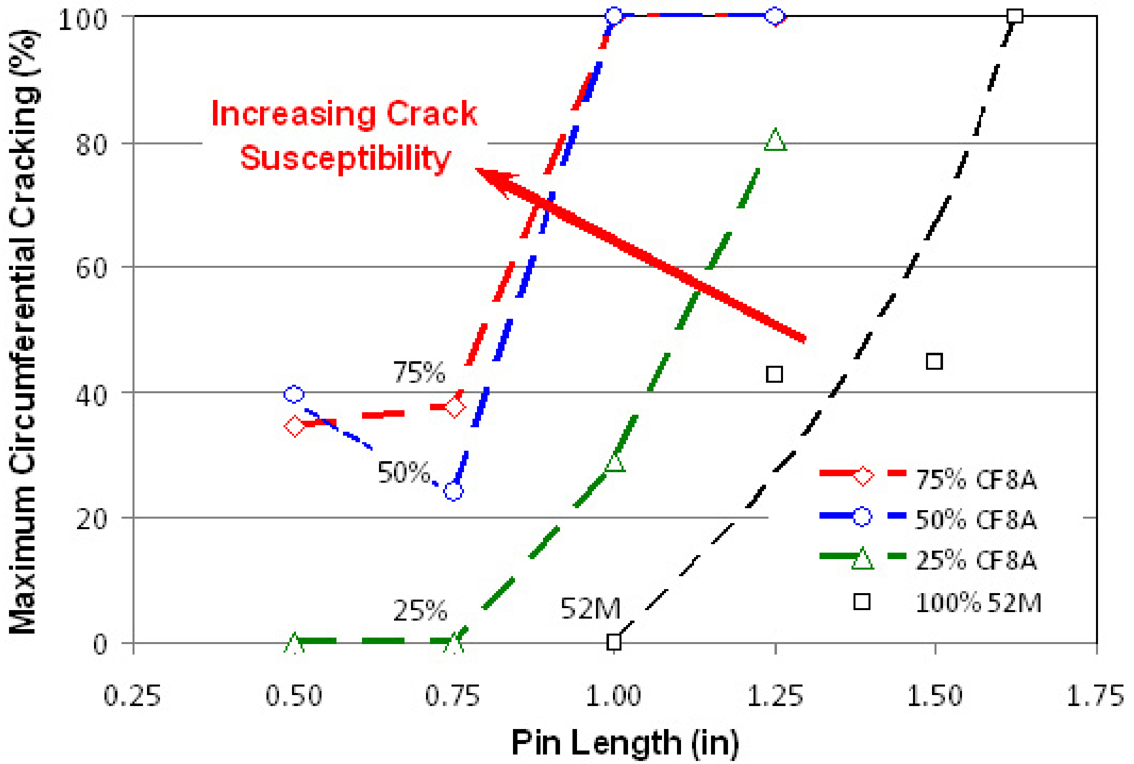
52M Dilution by CF8A *(Preliminary CPTT Data)*

	Cr	Ni	Fe	Mn	Si	Nb	Al	Ti	Mo	C	S	P
52M	29.75	58.93	8.75	0.74	0.11	0.93	0.13	0.19	0.08	0.020	< 0.001	< 0.01
CF8A	20.9	8.4	70.6	0.59	0.92	---	---	---	0.05	0.04	0.015	0.020
25%	27.5	46.3	24.2	0.70	0.31	0.70	0.10	0.14	0.07	0.025	0.005	0.0125
50%	25.3	33.7	39.7	0.67	0.52	0.47	0.07	0.10	0.07	0.03	0.008	0.015
75%	23.1	21.0	55.1	0.63	0.72	0.23	0.03	0.05	0.06	0.035	0.012	0.0175



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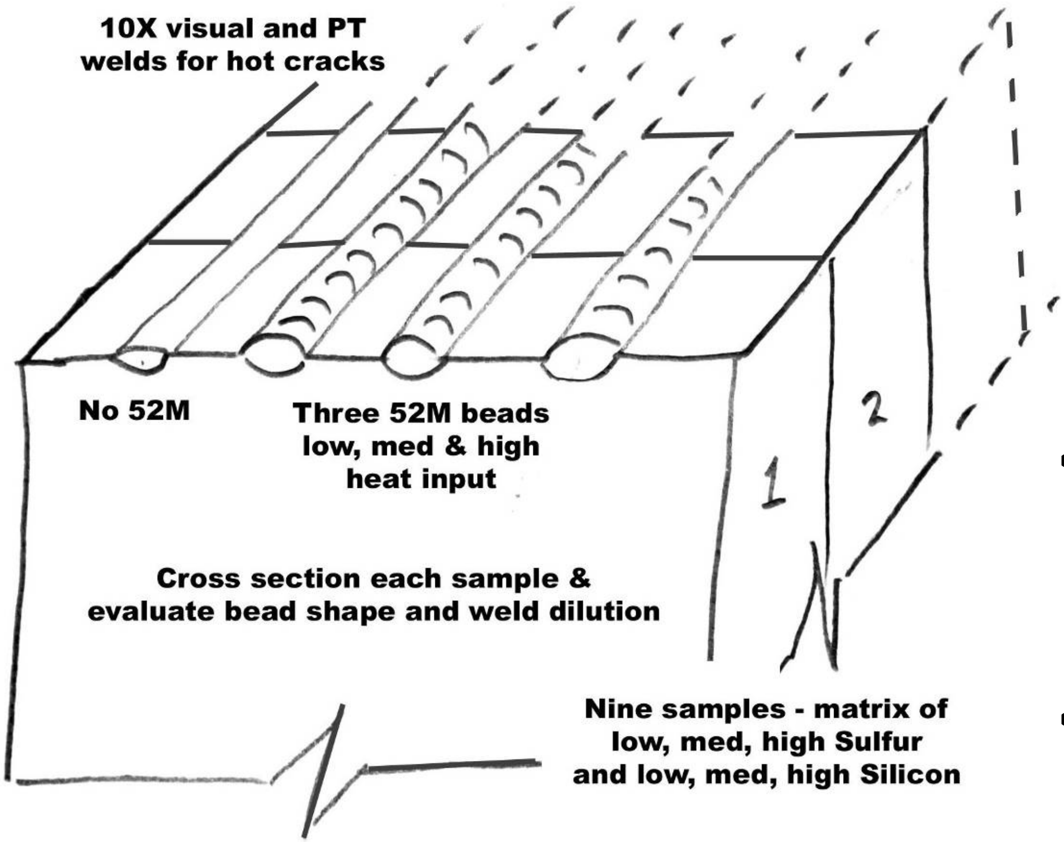
Bead-on-Plate Tests on Controlled Composition Plates



- Testing on 9 controlled composition CASS samples

  (based on domestic PWR survey)
  - Sample matrix:

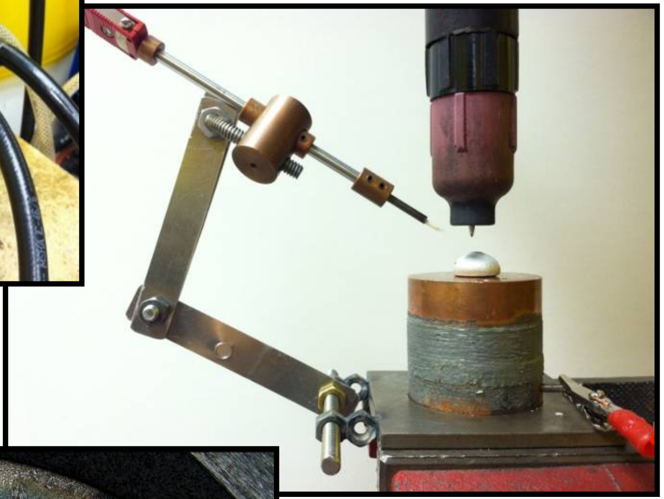
    Sulfur Low - Med - High

    0.001 - 0.020 - 0.040

    Silicon Low - Med - High

    0.05 - 0.90 - 1.80
- Determine hot cracking thresholds for different heats and specifications of high Cr nickel-base filler metals
- Evaluate synergy of S & Si on weld bead shape and dilution

Button Melting Testing – Effects of Dilution on 52M



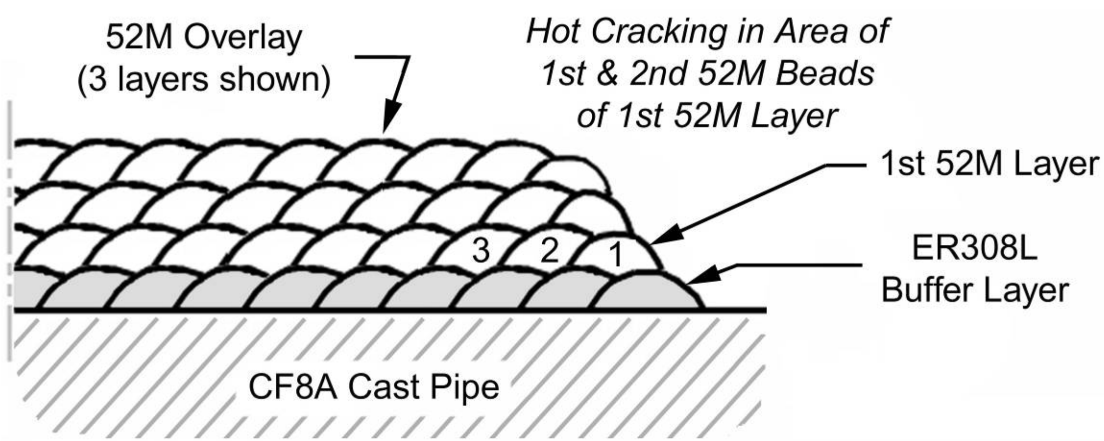
- Controlled 52M dilution compositions made by casting buttons
- Buttons are partially re-melted by GTAW
- Cooling curve is measured by plunging a Type-C thermal couple into the weld metal
- Solidification temperature range and eutectic start are measured by SS DTA technique
- Solidification grain boundaries are evaluated by SEM to determine low melting point constituents that coat the solidification grain boundary and cause hot cracking

52M Hot Cracking Controls

- Reduce susceptibility to hot cracking by controlling dilution:
  - Decrease power ratio (heat input)
    - Lowers S & P in diluted 52M weld metal
    - Lowers Fe in diluted 52M weld metal
  - Optimize and manage weld process parameters
  - Optimize and manage bead placement
  - Install hot crack resistant buffer layer
    - ER308L, ER309L, or crack resistant Alloy 82 buffer (barrier) layer
    - Improved buffer layer option may be low Fe 52MSS (ERNiCrFe-13)
      - High 30% Cr for PWSCC resistance
      - 52MSS is essentially immune to DDC

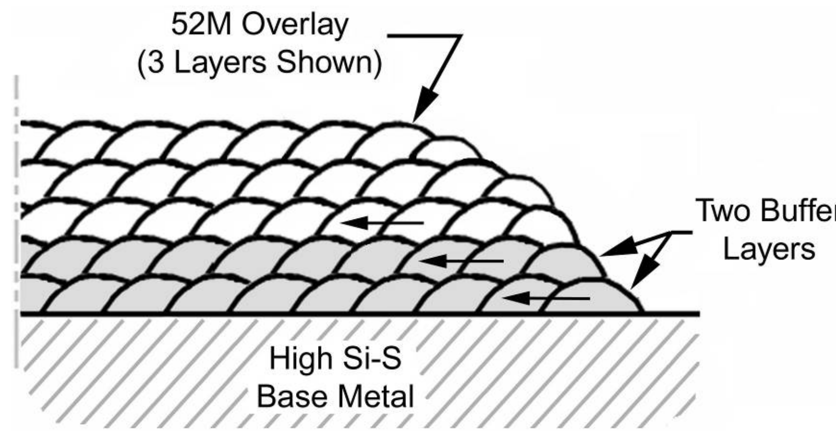
Dilution Control by Buffer Layer

- Dilution of 52M with deleterious base metal is typical cause of hot cracking
  – ER308L layer installed to ‘buffer’ 52M from base metal (lowers dilution)
- Hot cracking may still occur in 1st 52M beads over buffer layer

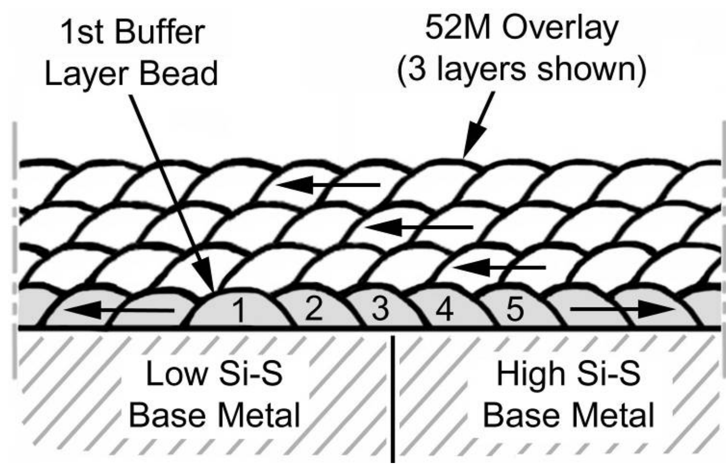


Dilution Control by Bead Placement

- Other options:
  - Two buffer layers *(doesn't solve high Fe problem)*

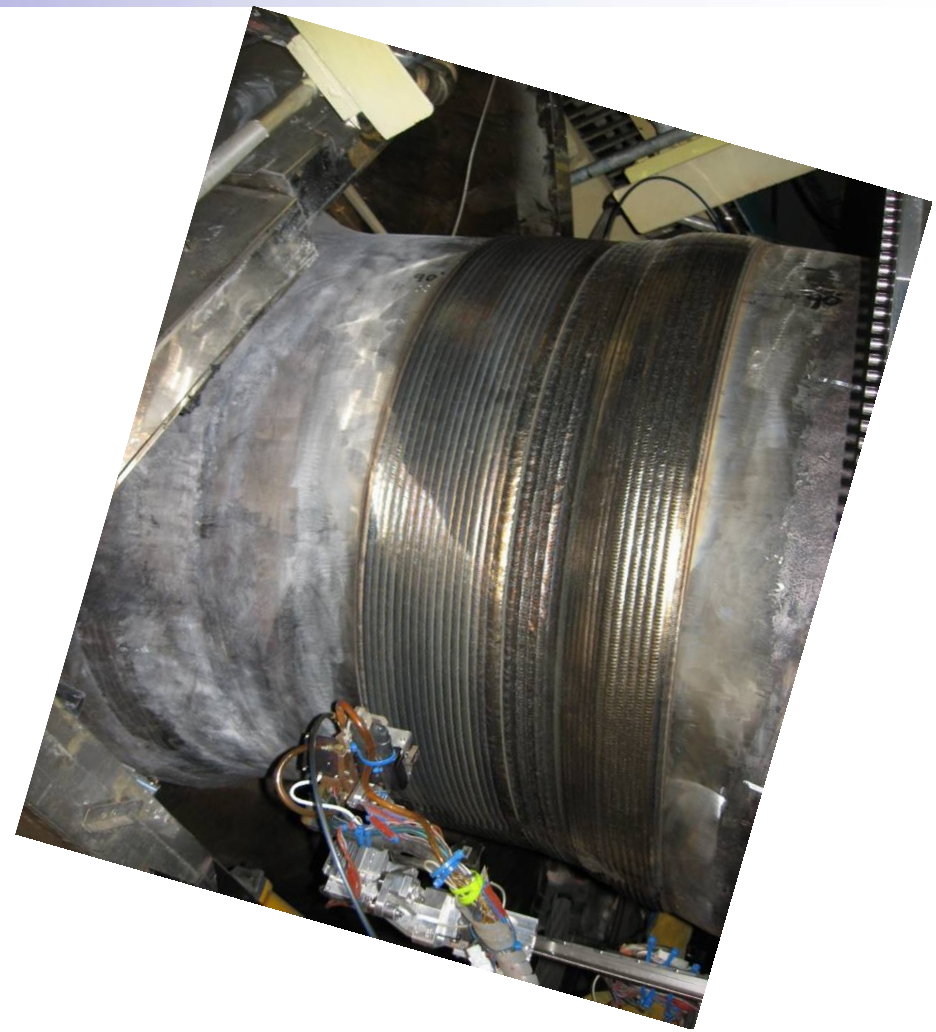


  - Bead placement to minimize dilution with deleterious base material



Successful 52M WOLs by Careful Control of Dilution

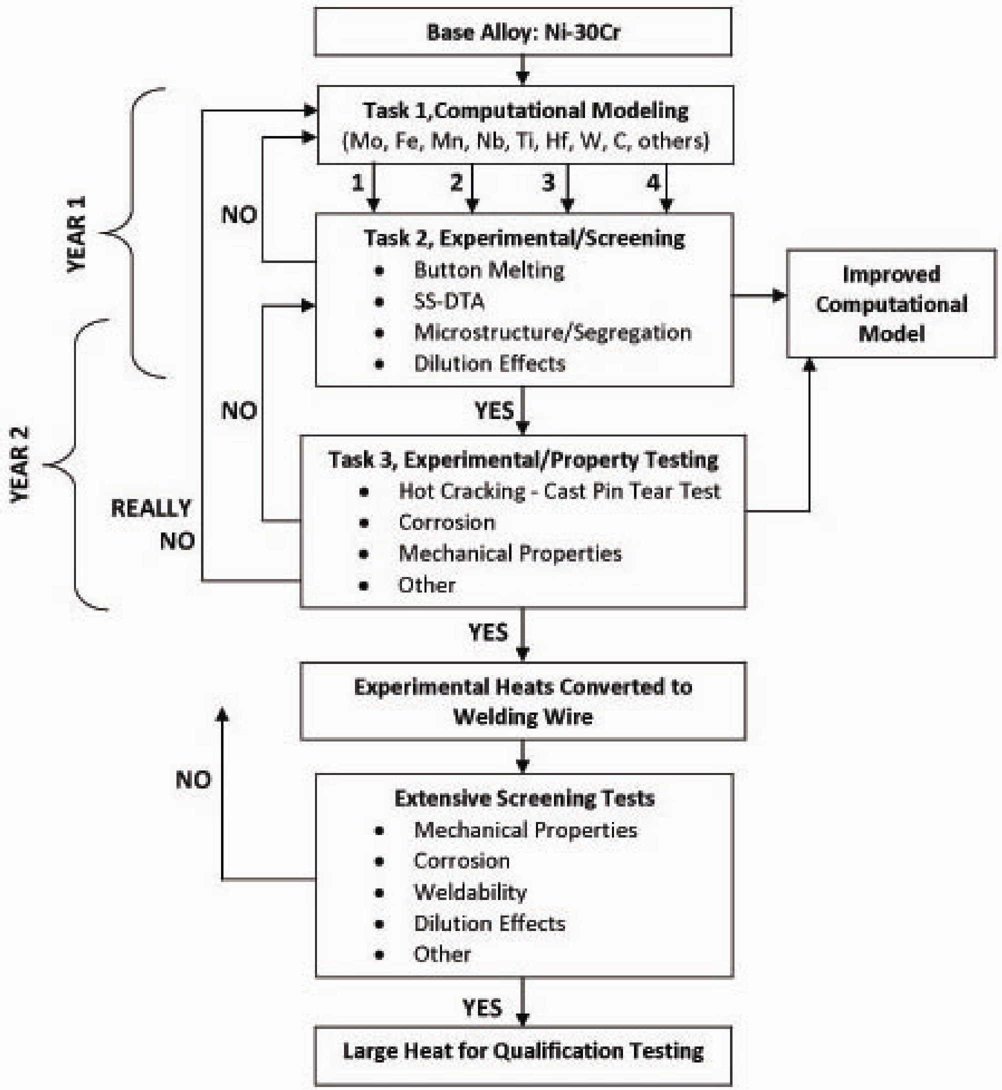
- Successful OWOL application on 4 RCP discharge nozzles
- Successful SWOL application on 4 RCP suction nozzles plus 5 other nozzles
- Rework was required to achieve acceptable quality on some WOLs
- Significant mock up testing was done to define parameters and techniques needed for successful welding



Presentation Roadmap

- **Alloy 52 / 52M Challenges**
- **Cracking Mechanisms**
- **Weldability Testing**
  - Description of Testing and Ranking of Filler Metals
  - Dilution Issues and Testing
  - High Chromium Nickel-Base Alloy Development
- **Magnetic Stir Welding**
- **Welding Irradiated Material**
  - Problem and Issue
  - Laser Welding
  - Friction Stir Welding

Development of a New High Cr Filler Metal



- EPRI project to develop a new filler metal was kicked off in fall of 2010
- Base composition is 30% Cr nickel-base
- Initial computational modeling at OSU to study solidification behavior and 2nd phases at the end of solidification is nearly complete
- Initial button melting experiments at OSU are in process
- New CPTT with induction melting capability and optimized mold design is nearly complete

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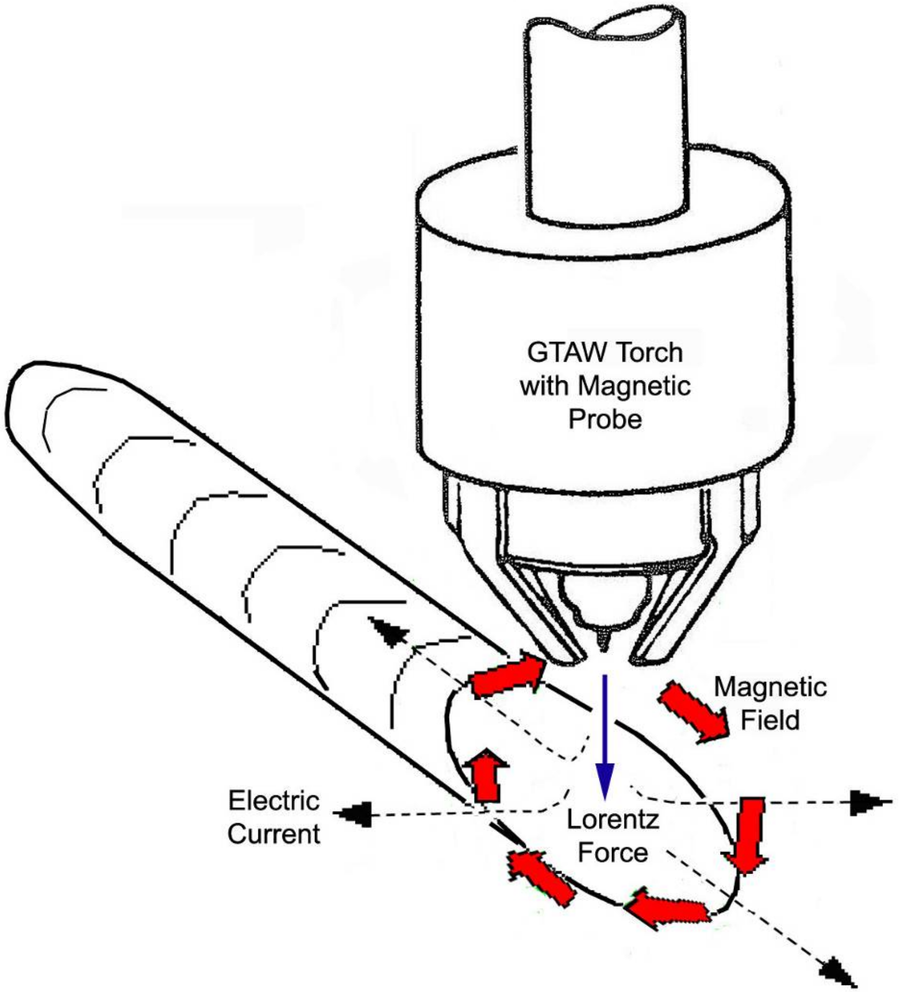
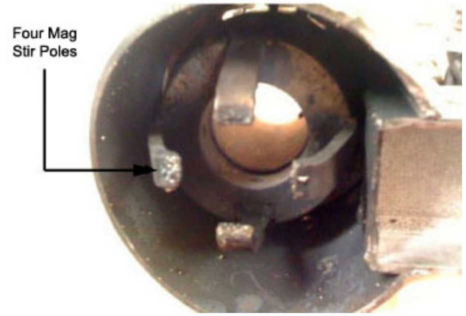
Magnetic Stir Welding (GTAW)

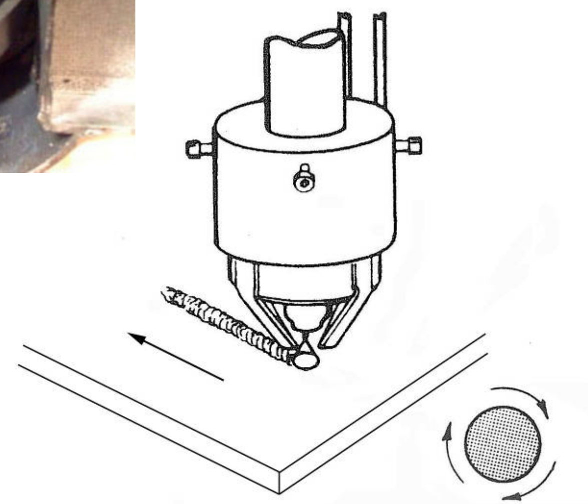
- **Magnetic field induced to deflect and stir the arc**
  - Circular pattern used for this study
  - Stirring breaks up solidification pattern and produces a smaller grain size
  - Smaller weld metal grains are more conducive UT examination (lower attenuation)
  - Smaller grains also improve resistance to solidification cracking

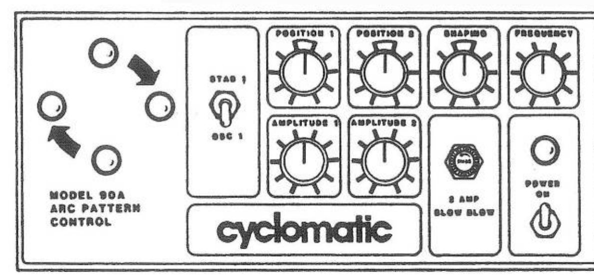


Magnetic Stirring Equipment and Settings

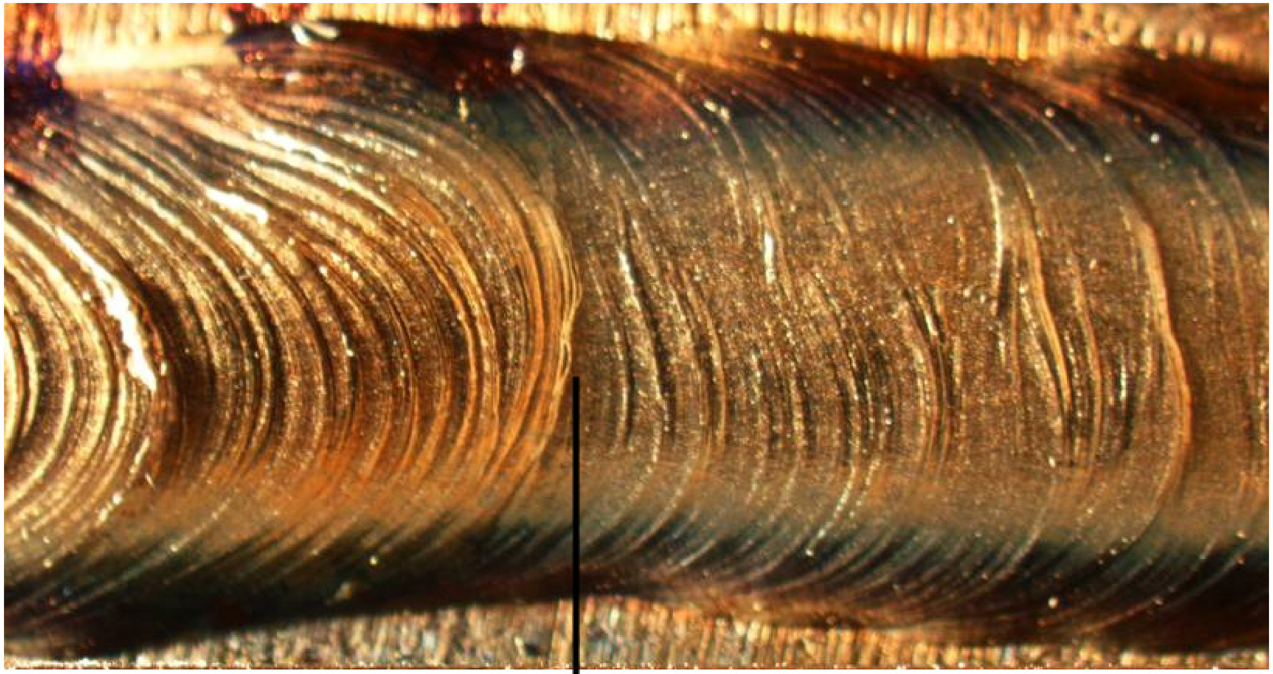
- **Cyclomatic Model 90A used for feasibility testing**
  - Stirring set to circular arc stirring pattern
  - Testing included autogenous beads and 52M weld pads
  - Standard GTAW torch







Magnetic Stir GTAW Bead

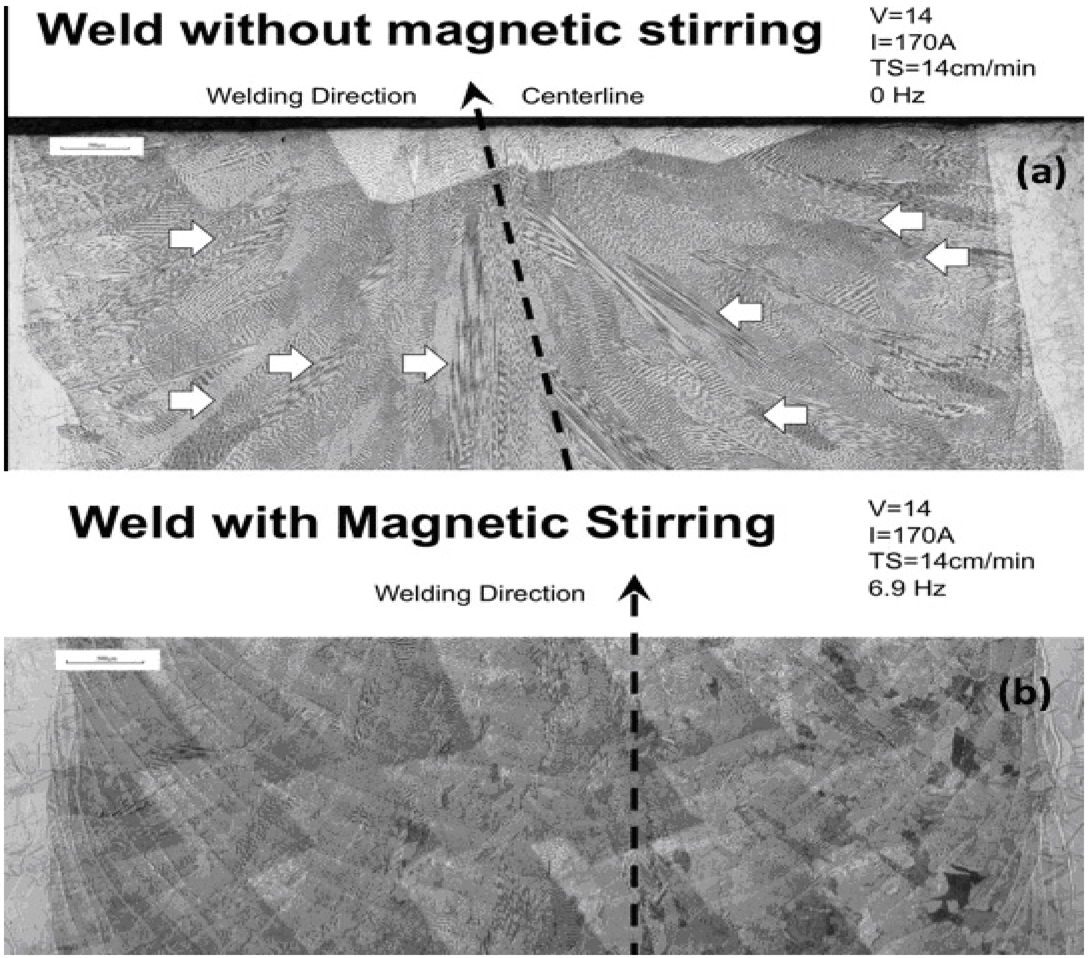


Magnetic Stirring
(7 Hz)

No Magnetic Stirring

- 170 to 190 amp, 11 volt, 4 to 5.5 ipm travel, 40 to 50 ipm, 7 Hz stir frequency
- 0.035” 52M filler metal on Alloy 690 plate

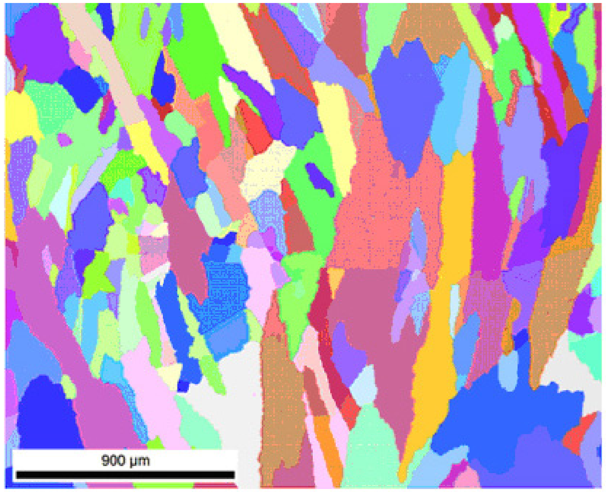
Grain Size and Orientation with Mag Stir



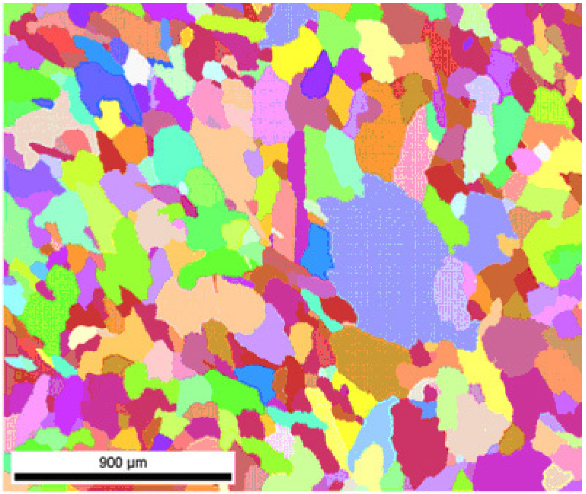
- Magnetic arc stirring breaks up long columnar grains
- 6.9 Hz circular stirring at 14 cm/min travel speed are most effective
- Reversal in weld metal solidification direction is what breaks up the weld metal grain growth

Results - Electron Back Scattered Diffraction

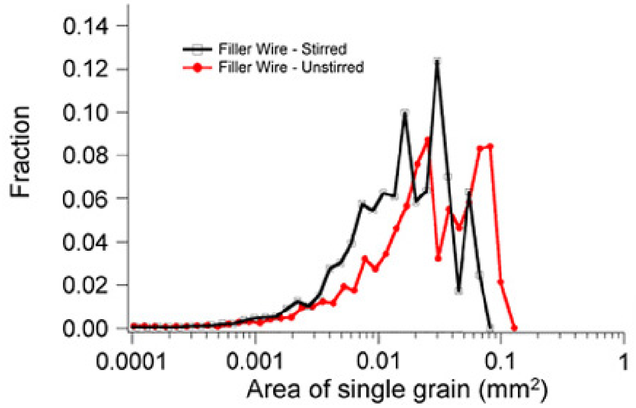
- Electron Back Scattered Diffraction
  - Method to look at grain size
  - Significant reduction in grain size with 6.9 Hz circular magnetic stirring



Unstirred (0 Hz)

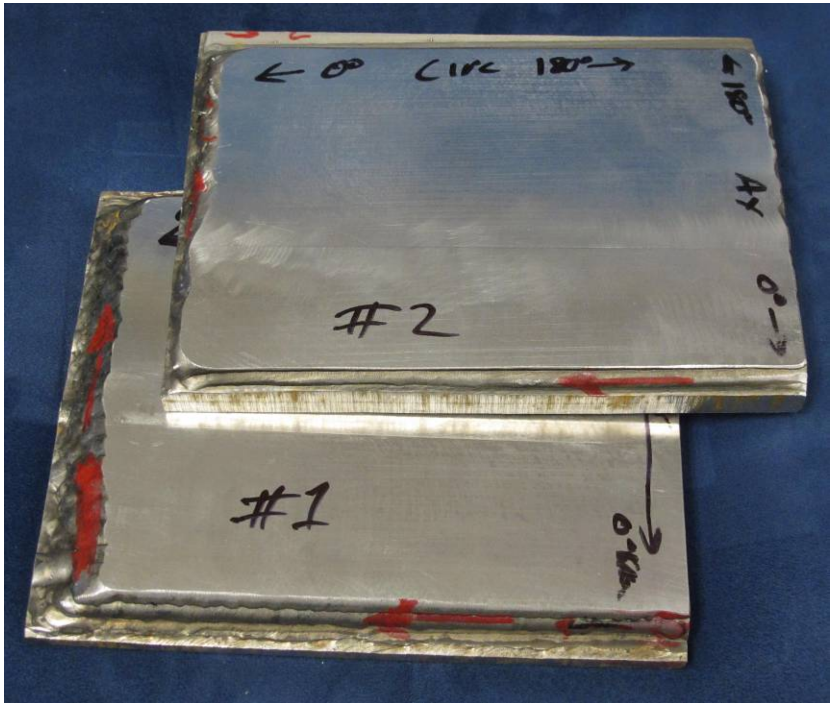


Stirred 6.9 Hz



Specimens for Ultrasonic Examination

- Two weld 52M pads on 690 plate
  - #1 non-pulse GTAW parameters
  - #2 with optimized magnetic stirring



- Weld pads prepared for UT examination
  - Machined flush with ~3/8” 52M thickness
  - Circ & axial EDM notches machined on plate back surface to 52M fusion line depth

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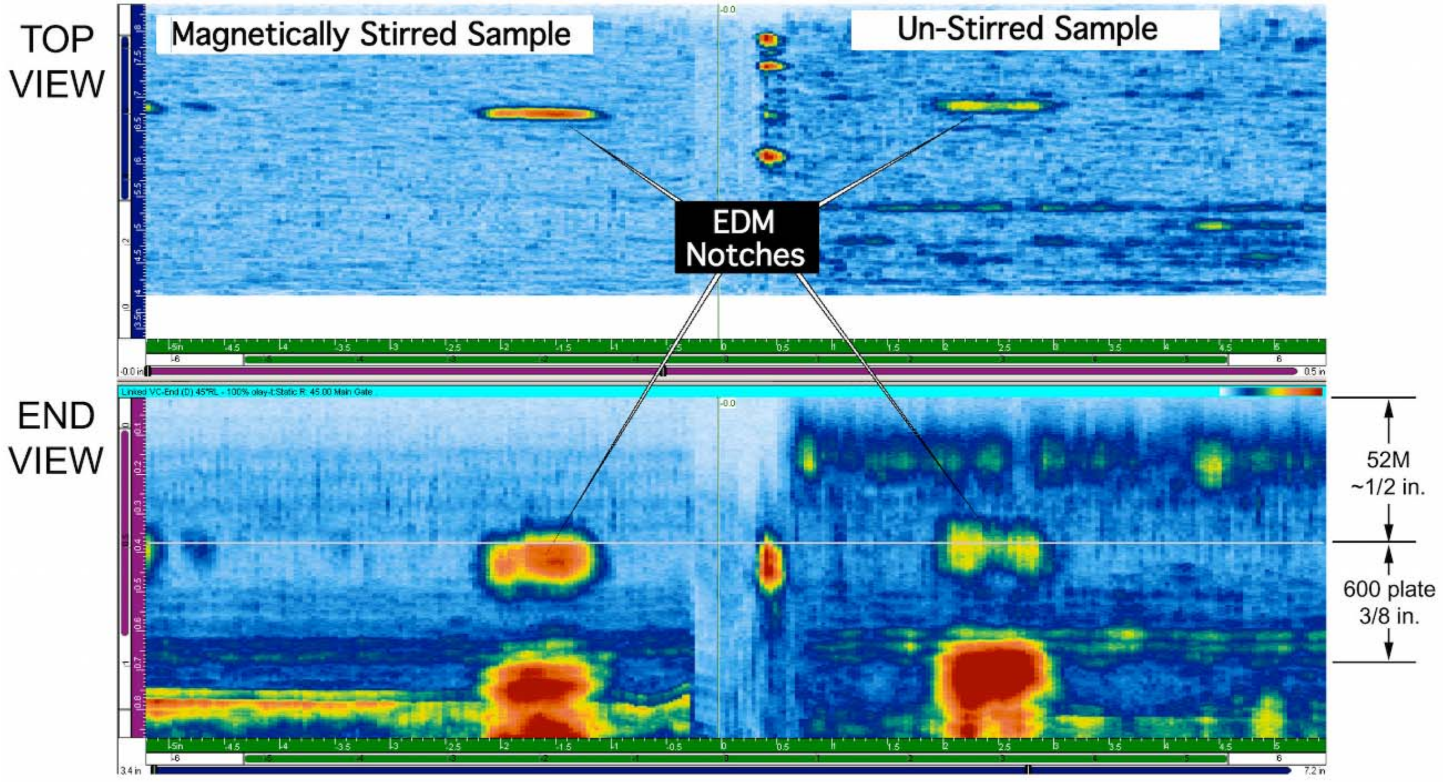
Improved Ultrasonic Response



- 45° RL Axial Scan
  - 13:1 to 20:1 *(+ & - scan direction)* signal-to-noise ratio with stirring
  - 5:1 & 8:1 *(+ & - scan direction)* signal-to-noise ratio without stirring

Improved Resistance to Solidification Cracking

- 52M weld pad on Type 303 plate clad with ER308L-Si weld metal
- Surface micrographs with & without magnetic arc stirring

- Standard GTAW without stirring
  - 11.5 Volt
  - 240 Amp
  - 4 ipm travel speed
  - 58 ipm wire feed speed (0.045” dia.)
- GTAW with magnetic stirring
  - Parameters same as above with 7Hz stirring

Magnetic Stir GTAW – Future Work & Potential

- Testing indicates that GTAW with optimized magnetic stirring:
  - Interrupts the solidification pattern at the weld puddle fusion line
  - Breaks up large columnar grains typical of nickel-base welds
  - Ultrasonic examination response is improved by smaller grains (lower sound attenuation with smaller grains)
- Preliminary testing shows GTAW with magnetic arc stirring:
  - Improves resistance to solidification cracking
  - Can GTAW pulse parameters (or GTAW waveform controls) be used to duplicate the magnetic stirring effect?
    - Preliminary studies with pulse parameters and variable polarity are in process

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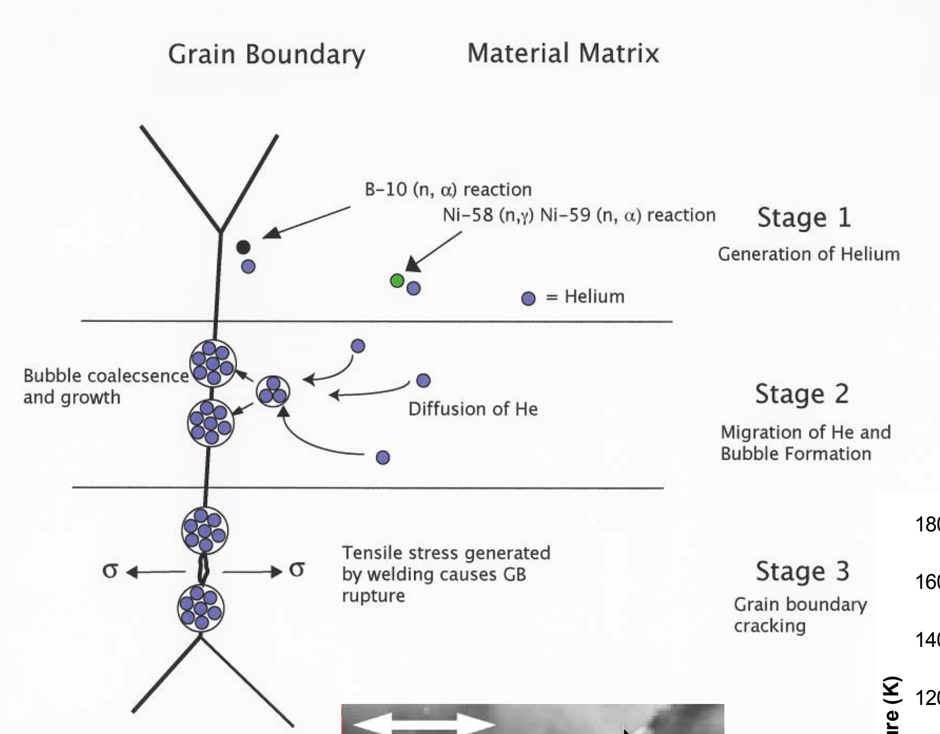
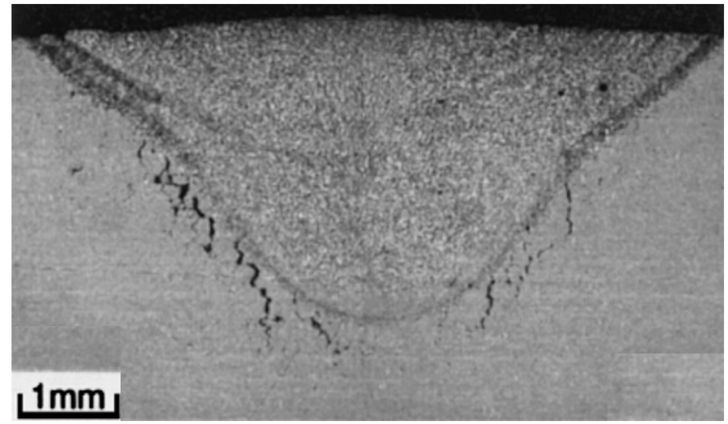
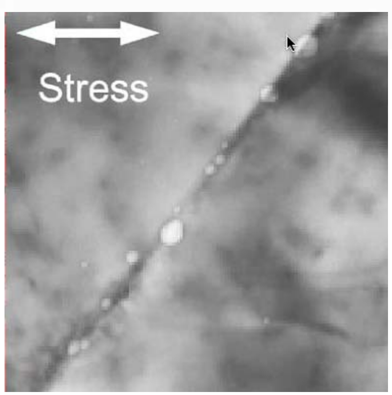
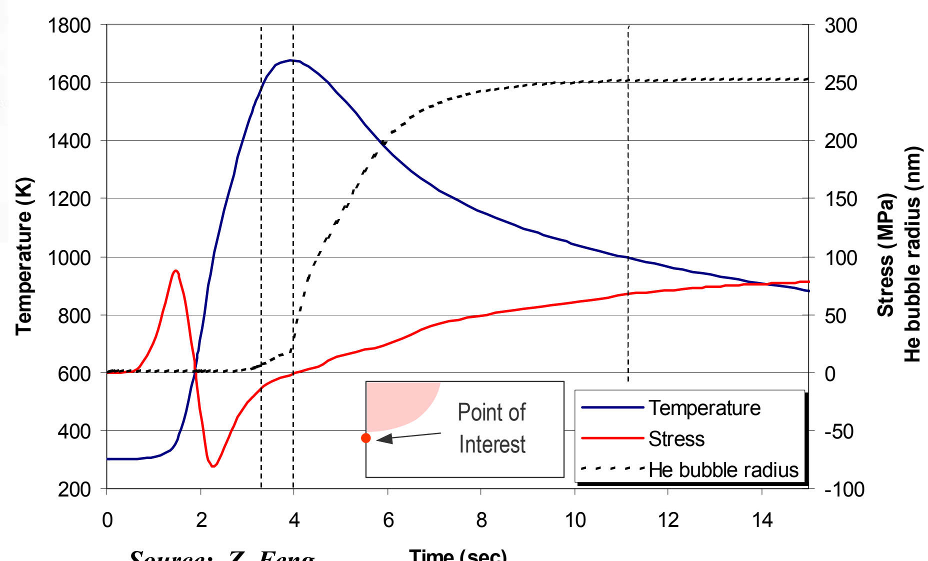
Cracking Mechanism of Irradiated Materials





Asano et al. J. Nucl. Mat. 264 (1999)1-9





Source: Z. Feng

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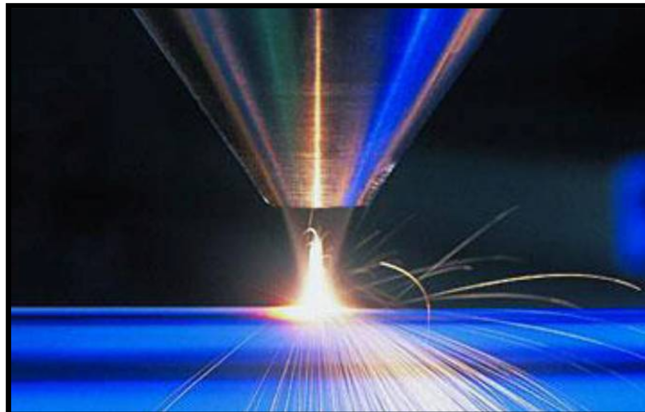
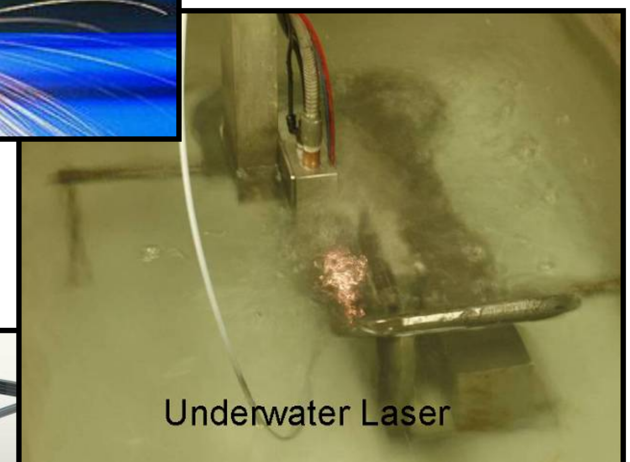
Laser Welding - Project Objectives and Scope

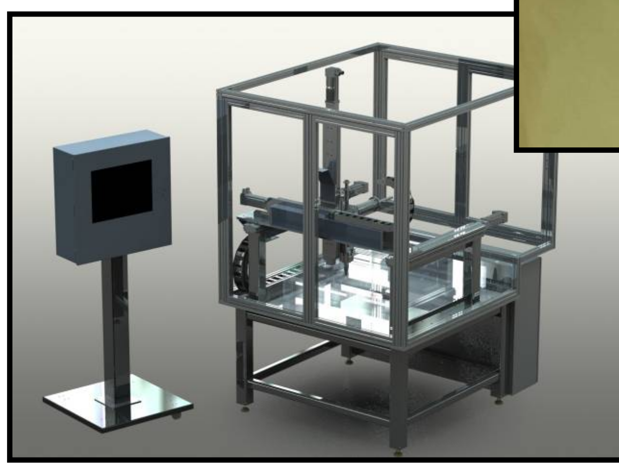
- Laser Beam Welding
  - Develop field deployable laser welding techniques for the repair or replacement of irradiated reactor materials
  - Install IPG fiber-laser and robotic manipulator
  - Develop low heat input laser beam welding parameters
  - Develop methodology for application of different weld types on irradiated material
    - WOL
    - Groove weld
    - Fillet weld
  - Develop BWRVIP guideline for laser beam welding

WRTC Fiber Laser Welding System

- **WRTC Laser Welding Equipment**
  - **Fiber optic IPG Photonics system**
  - **Nominal 2000 watts**
  - **Laser Mechanisms weld head (three focal lengths - 150mm, 200mm, & 250mm)**
  - **Four axis (x, y, z, angular tilt) positioner designed and fabricated by Dynamic Design Solutions**







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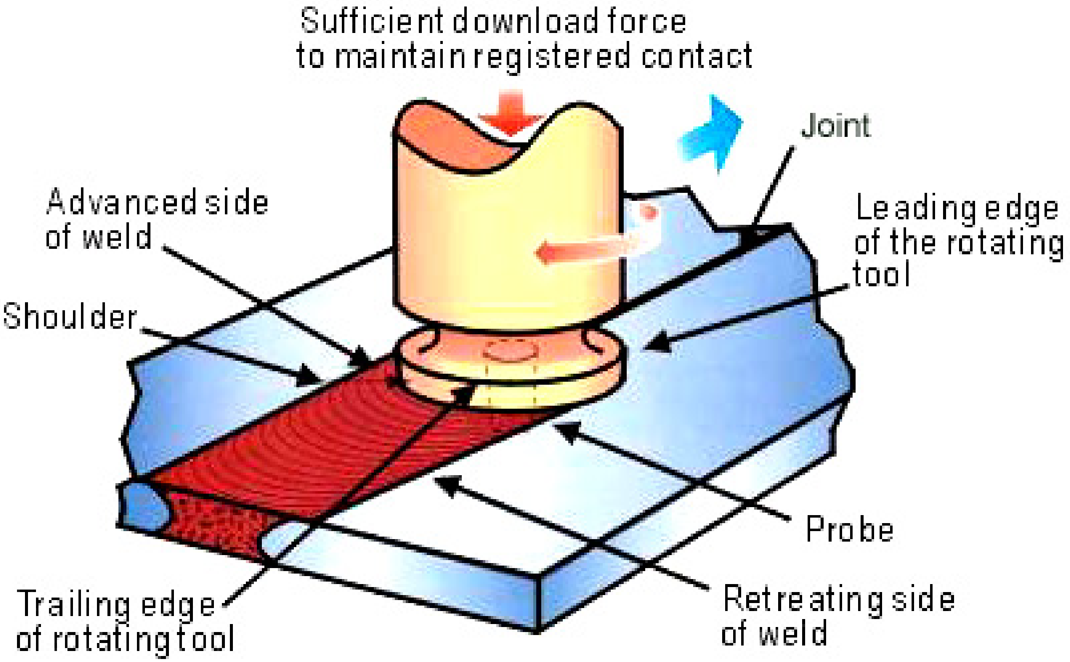
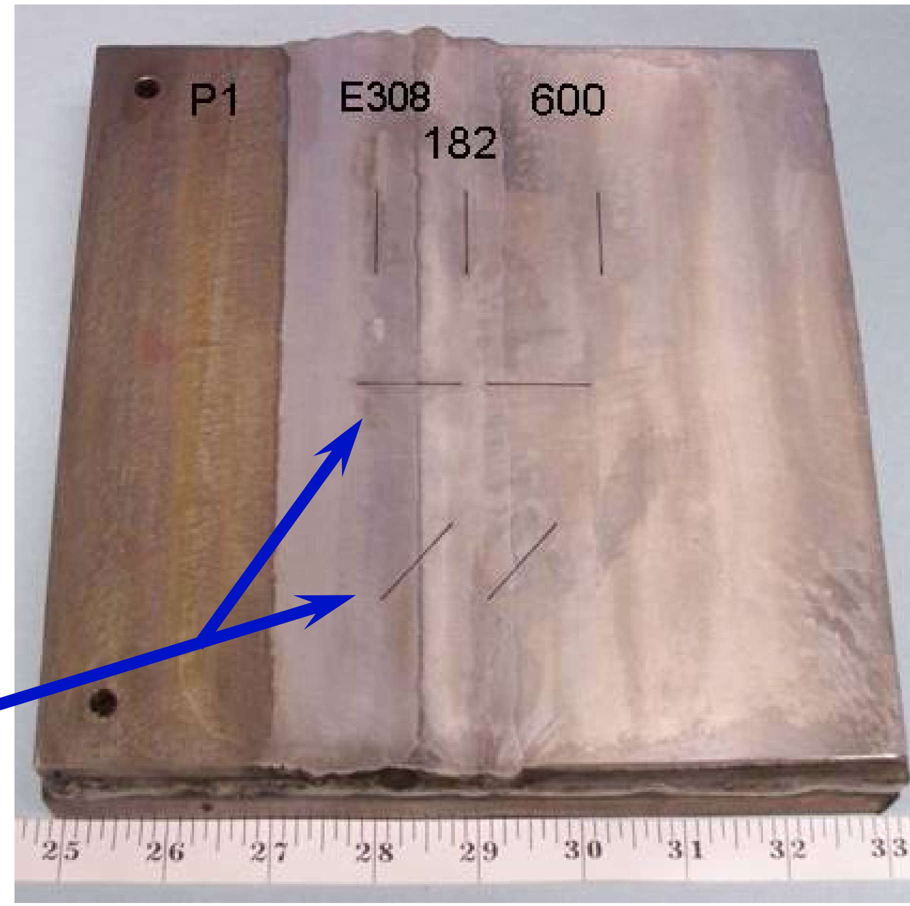
Friction Stir Welding - Objectives and Scope

- Friction Stir Welding (FSW)
  - Assess underwater FSW welding process to seal IGSCC or other cracks in reactor internal components
- Develop FSW technology for reactor internal repairs
  - Installation of buffer pad (plate) to irradiated components
  - Seal IGSCC or other crack-like defects
  - Weld repairs on range of carbon steels, stainless steels, and nickel-base alloys

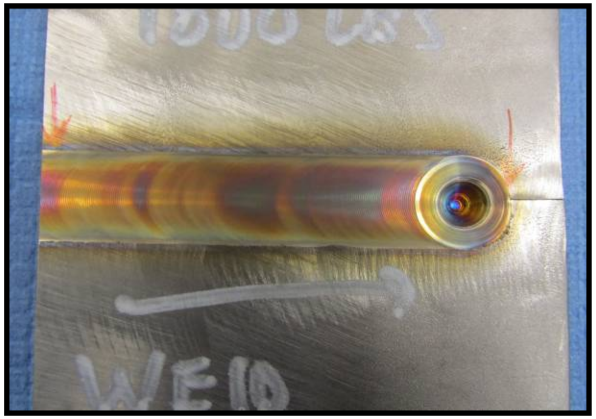


Dissimilar Material Crack Sealing Test Plate

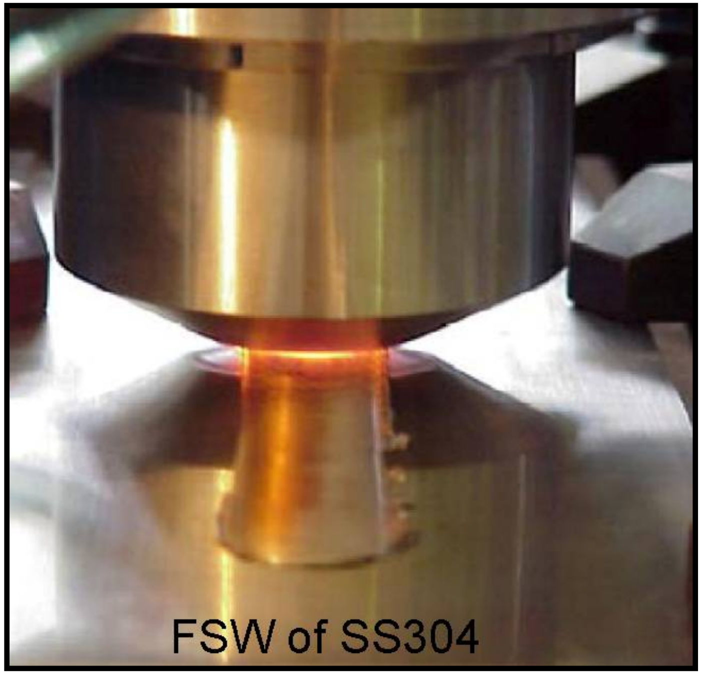
- Assess FSW crack sealing capability and welding on:
  - Wrought Type 304 plate
  - ER308L weld metal
  - Alloy 600 base metal
  - Alloy 182 weld metal
- Dissimilar metal weld test plate
- EDM notches simulate cracks along various orientations

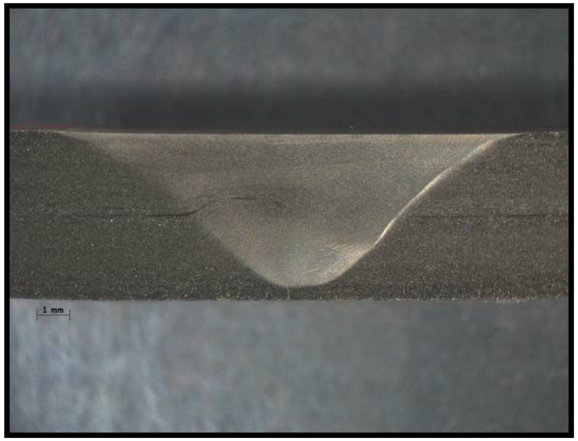


Example of FSW on Type 304 SS



Squared Groove Butt Weld on ¼ thick 304SS Plate





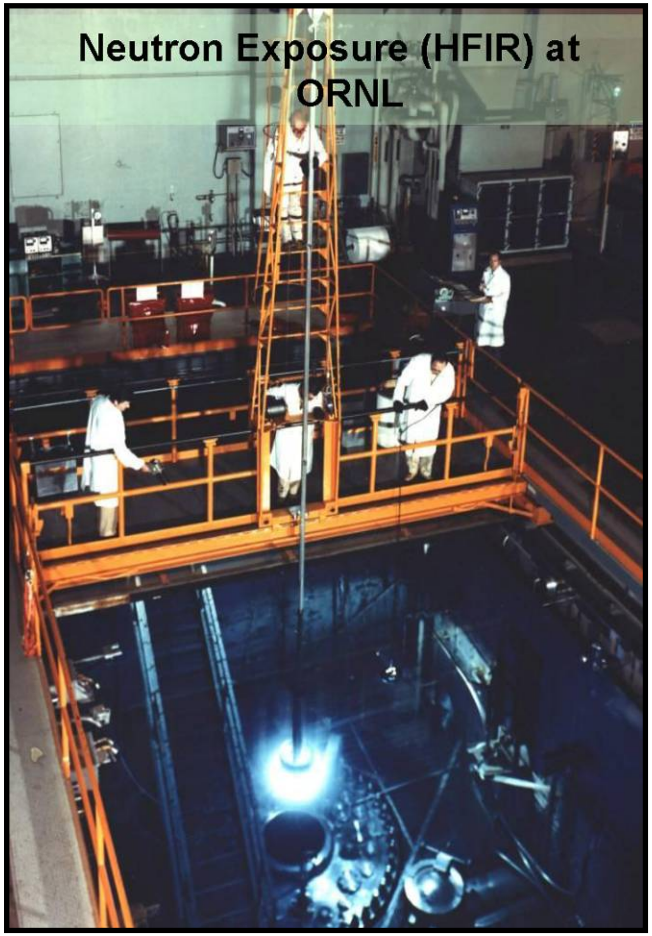
Cross Section of Butt Weld

LTO/LWRS Project Objectives and Scope

- Develop advanced welding technology required for reactor repair and upgrade to support reactor life extension beyond 60 years with an integrated approach between Industry EPRI/LTO and the DOE/LWRS -ORNL
  - Development of advanced welding technologies to weld highly irradiated material
  - Development modeling simulation to guide processes development and predictive application on irradiated materials
- Development of welding hot cell to deploy advance welding and coating processes
- Material degradation assessment development
  - Advanced weld simulation tool for lifetime prediction and weld performance assessment (future years)

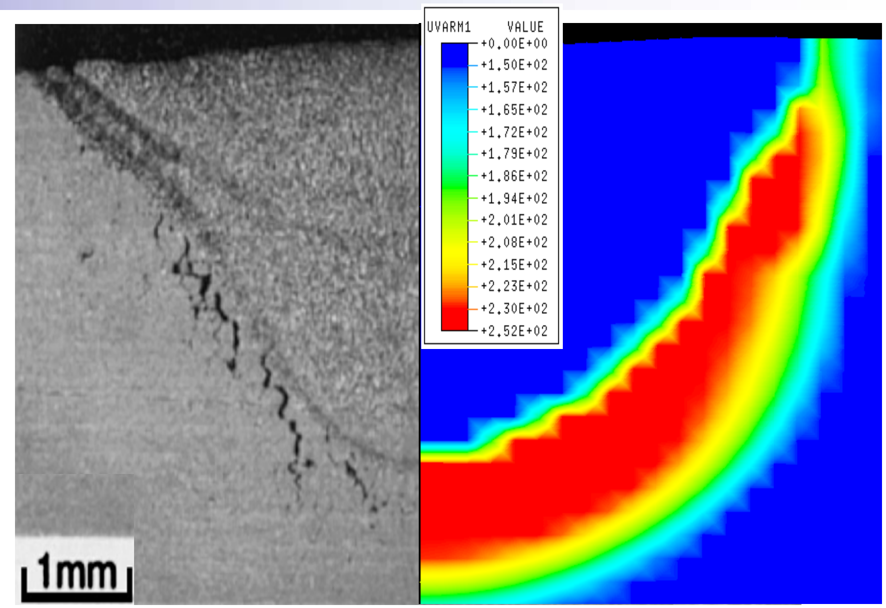
LTO/LWRS Project Task 1 (2010/11)

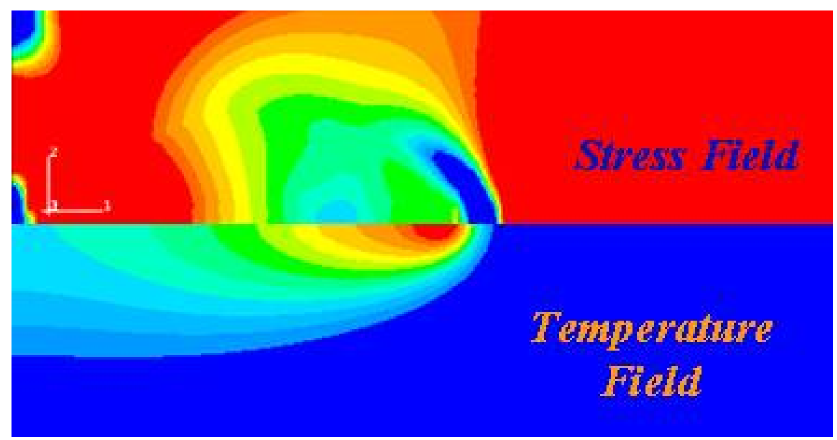
- Fabricate irradiated sample set for welding experiments
  - Type 304, Type 316, and Wrought 182
  - Determine initial boron concentration to achieve desired helium level using HFIR irradiation details
    - Flux, energy spectrum, etc……
    - Target boron levels for 50, 60 & 70 year reactor internal life
  - Determine the steel making practice samples
    - Powdered metallurgy
    - Conversional steel making practice (VIM)
    - Hot working
  - Detail calculations for HFIR exposure and sample holder design



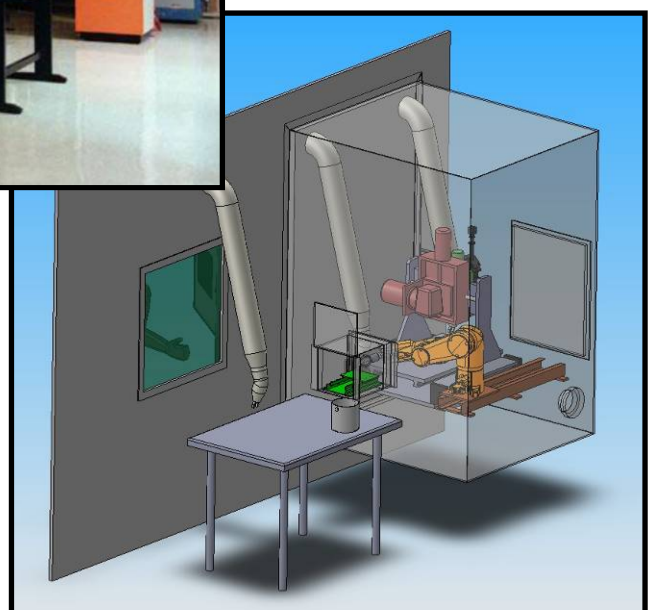
LTO/LWRS Project Task 2 (2010/11)

- Survey hybrid welding processes
- Develop computational model for hybrid processes
- Develop hybrid laser weld process model to optimize the weldability of irradiated material
  - Model based on welding process development
- Develop experiment methodology for direct measurement of transient high-temperature and stress history during welding





LTO/LWRS Project Task 3 (2010/11/12)

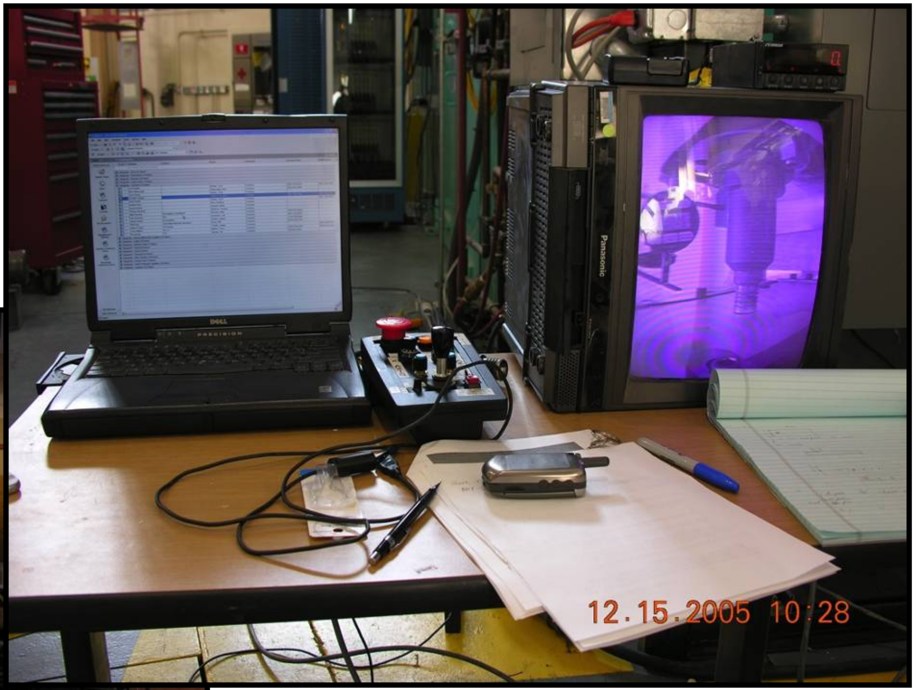


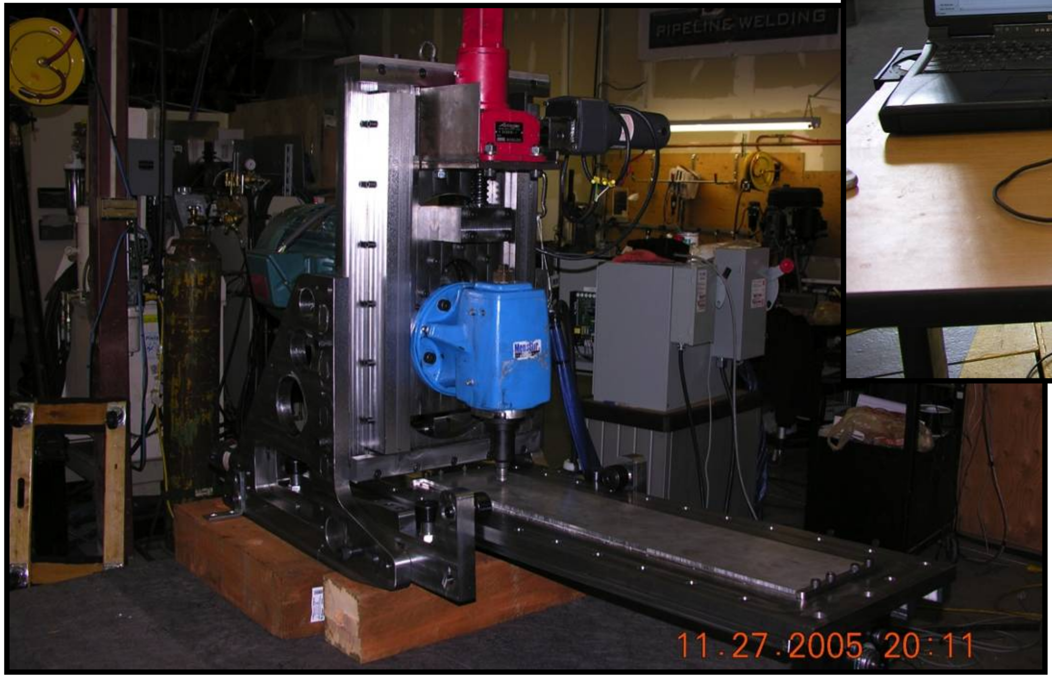
- **EPRI is collaborating with DOE to design and develop a New welding hot cell at ORNL**

- **Welding Capabilities**
  - Conventional and hybrid laser
  - Friction stir
  - Ultrasonic
  - Powder coating
  - Cold spray

LTO/LWRS Project Task 3 (2010/11) Cont.

Motion control platform centered around FSW system

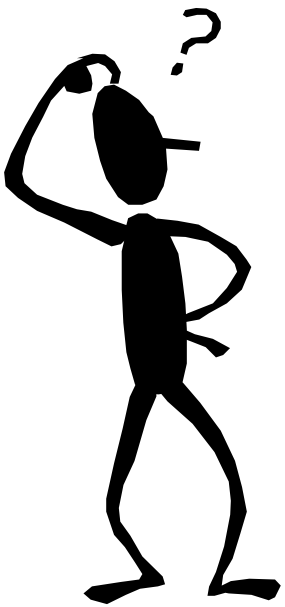




LTO/LWRS Project Task 4 (2010/11)

- Advance modeling of hybrid welding process and optimization of stress state for welding irradiated materials
- Installation of laser welding cell at EPRI Charlotte facility
  - New fiber laser welding (2kW) system
  - Procurement of secondary heat sources
  - Procurement and installation of manipulator
- Welding experiments with real time stress measurement
  - Provide feedback for calibration of hybrid welding model

Thank You – Questions or Comments?



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