ELECTRIC POWER RESEARCH INSTITUTE

Update on 52 Weldability

Influence of High Si-S Stainless Steels on the Solidification Cracking Susceptibility of High Chromium Nickel-Base Metals

Industry/U.S. NRC Materials Program Technical Information Exchange Meeting

Rockville, MD
Wednesday June 4, 2014

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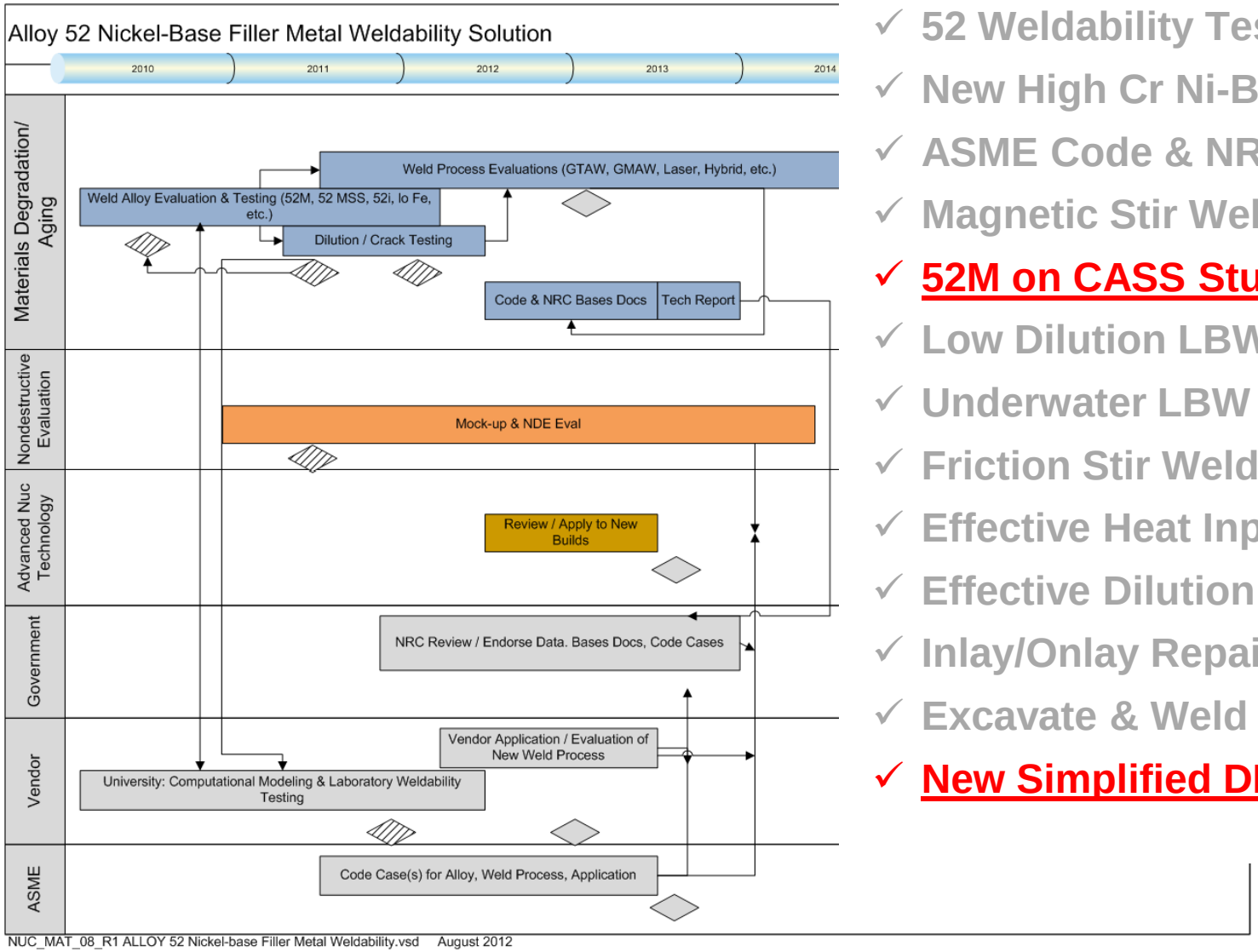
EPRI Welding & Repair Technology Center

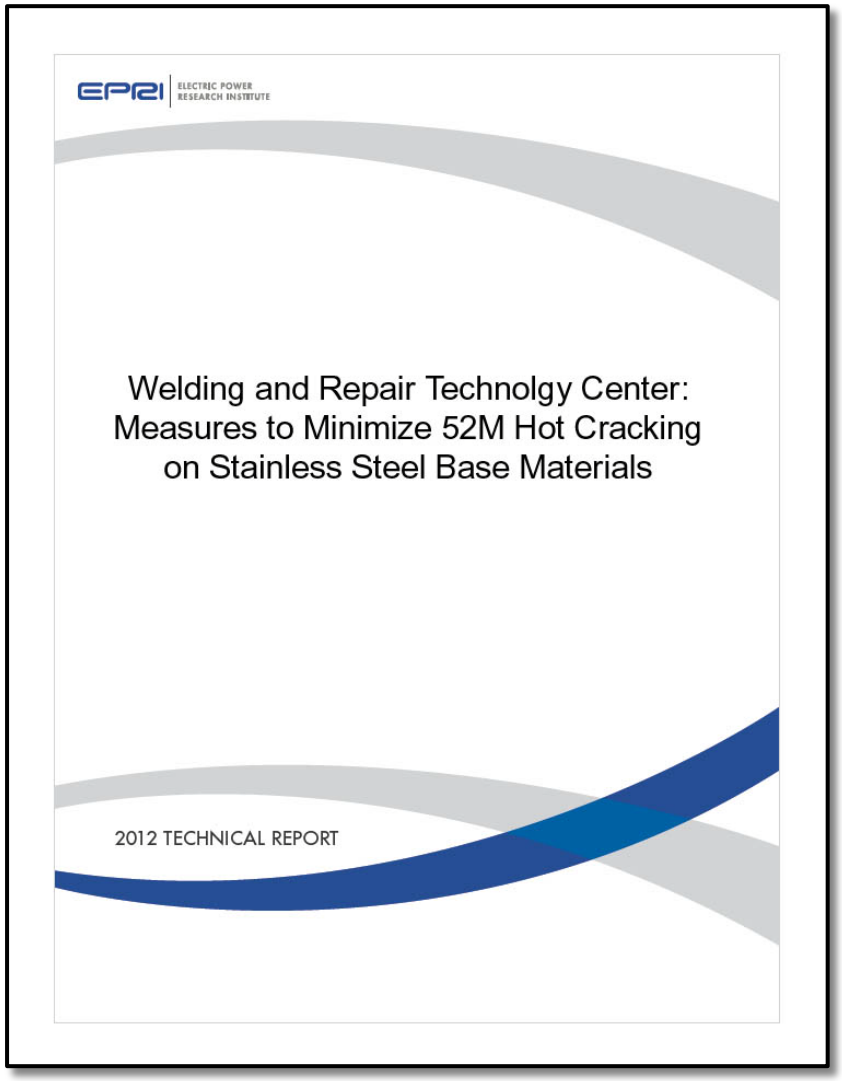
WRTC Roadmap: Alloy 52 Weldability Solution



- ✓ 52 Weldability Testing
- ✓ New High Cr Ni-Base Alloy
- ✓ ASME Code & NRC Support
- ✓ Magnetic Stir Welding
- ✓ **52M on CASS Studies**
- ✓ Low Dilution LBW
- ✓ Underwater LBW
- ✓ Friction Stir Welding
- ✓ Effective Heat Input Equation
- ✓ Effective Dilution Equation
- ✓ Inlay/Onlay Repair
- ✓ Excavate & Weld Repair
- ✓ **New Simplified DDC Test**

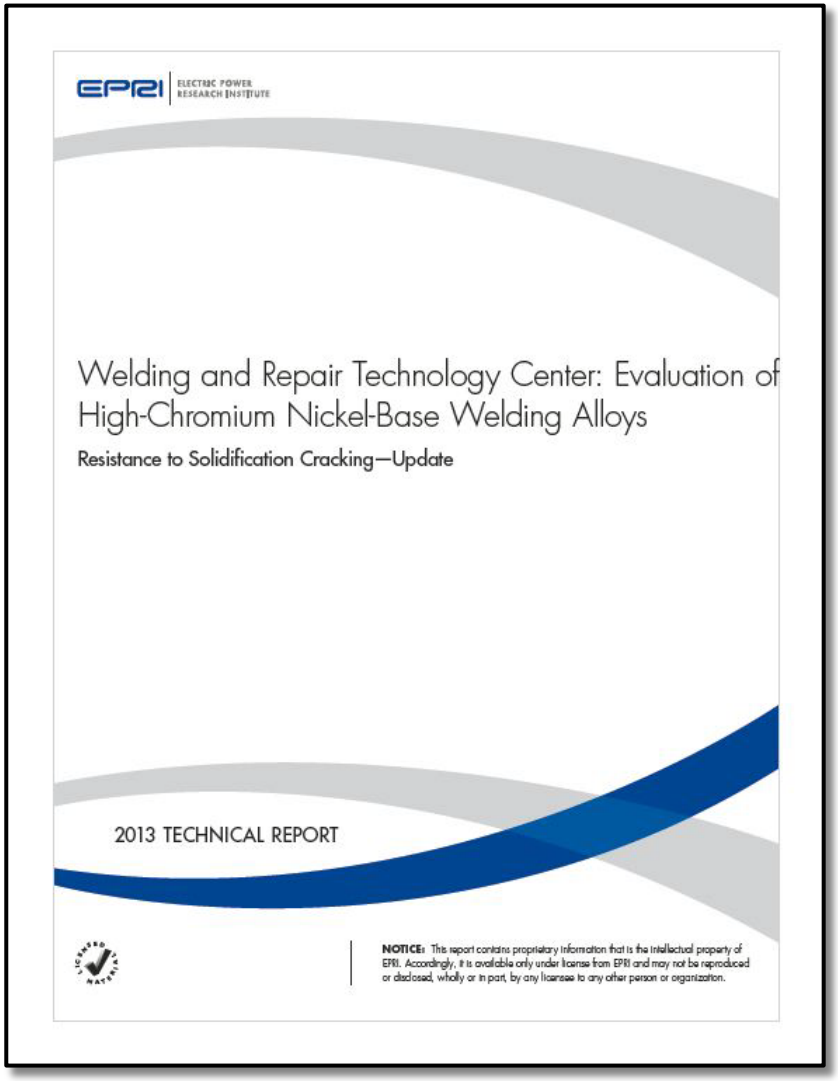
EPRI Report 1025167

- **Measures to Minimize 52M Hot Cracking on Stainless Steel Base Materials**
- **Publication Date: December 2012**
  - Background on hot cracking experience
  - Focus on 52M
  - Hot cracking testing approach and test results
  - Discussion with measures to minimize hot cracking
  - Dilution control & buffer layer options
  - Future work



EPRI Report 3002000641

- **Evaluation of High-Chromium Nickel-Base Welding Alloys**
- **Publication Date: August 2013**
  - Thermodynamic simulations
  - Single sensor differential thermal analysis
  - Transverse varestraint testing
  - Cast pin tear testing
  - Strain to fracture testing
- Ranks susceptibility of filler metals to ductility-dip cracking and solidification cracking
- Discusses cracking mechanisms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Welding and Repair Technology Center: Evaluation of High-Chromium Nickel-Base Welding Alloys

Resistance to Solidification Cracking—Update

2013 TECHNICAL REPORT

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52M Hot Cracking on Stainless Steel

Presentation Outline

- Background and Motivation
- Test Design and Approach
- Test Results and Observations
  - Hot Crack Ranking of Filler Metals Tested
  - Influence of Si and S on Hot Cracking
  - Influence of Si and S on Dilution and Bead Shape
  - Safe Dilution Threshold
  - Safe Si and S+P Limits
- Conclusions and Guidelines

Ductility-Dip and Solidification (Hot) Cracking

Ductility-dip Temperature Range (DTR)
ductility-dip ~ 10% to 15% strain
~ 950°C to 1150°C temperature range

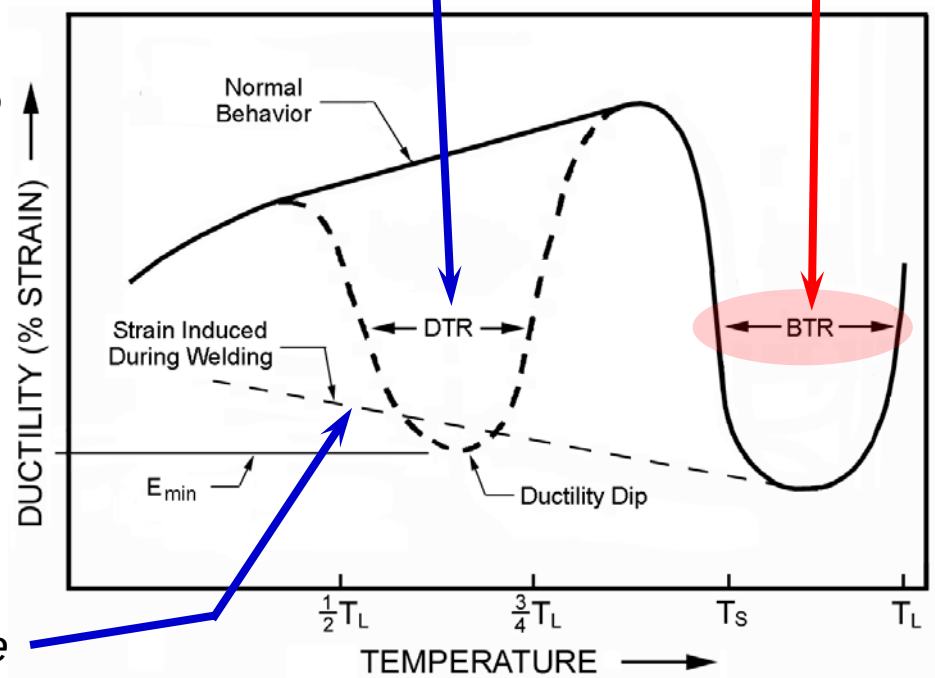
Brittle Temperature Range (BTR)
~ liquidus to terminal solidus

Ductility-dip Cracking

Solid state cracking mechanism that occurs in the ductility-dip temperature range (reheated weld metal)

Solidification Cracking

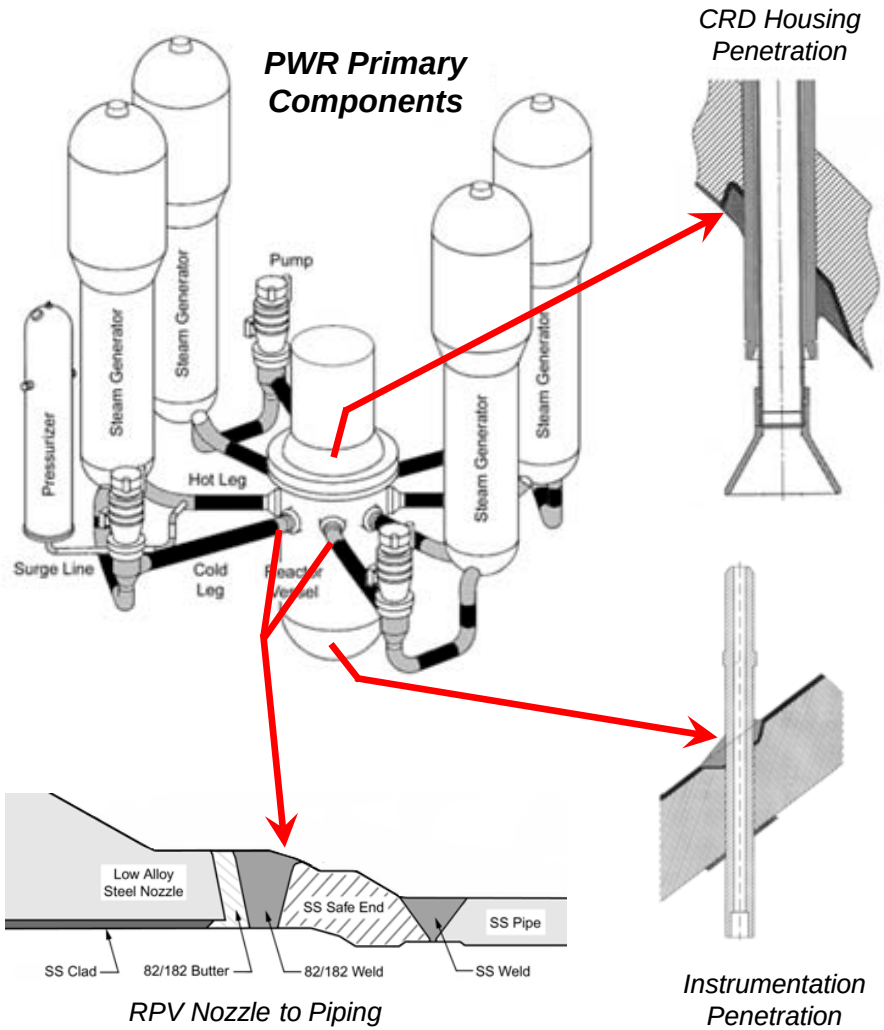
Liquation cracking mechanism that occurs during solidification in the brittle temperature range (mushy zone)



Strain applied Due to weld shrinkage & joint restraint

Nuclear Power Industry Issue

52/152 Hot Cracking on Stainless Steel



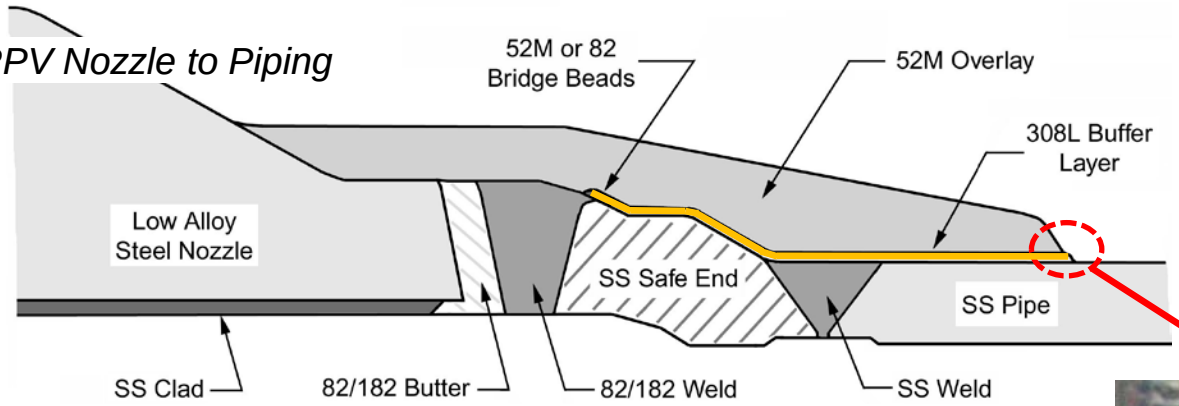
- 82/182 *(Ni-18Cr alloy)* was used extensively in PWR & BWR dissimilar metal welds
- 82/182 is degraded by <u>PWSCC and IGSCC</u>
- 52/152 *(Ni-30Cr alloy)* is resistant to SCC and is the weld metal of choice for repair, SCC mitigation, and new fabrication
- Experience and testing shows that Ni-30Cr weld metals are susceptible to solidification (hot) cracking when welding on some stainless steel materials

52M Hot Cracking

Weld Overlay Repair on Cast Stainless Steel Reactor Coolant Pipe

- Example of 52M hot cracks on CF8A with ER308L buffer layer
- Base metal is SA-351 CF8A (0.019% S, 0.032% P, 0.72% Si)

RPV Nozzle to Piping



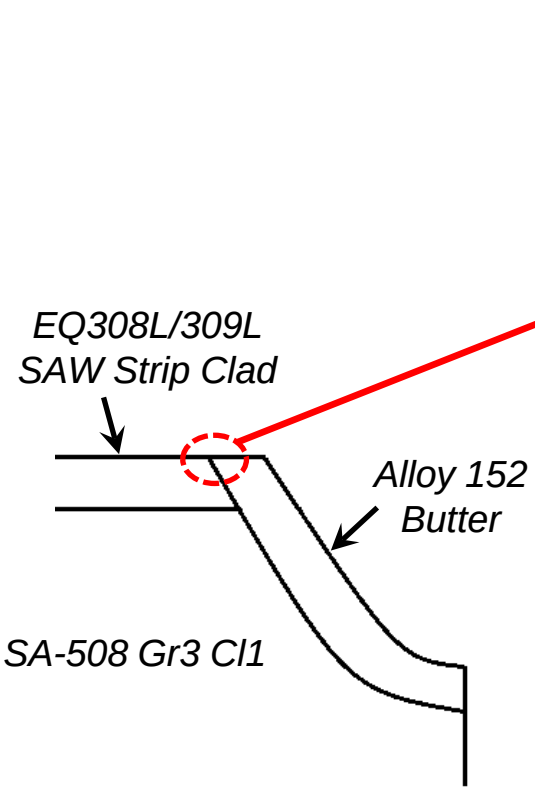
Hot cracks in 52M on CF8A material

Liquid penetrant indications in 52M over ER308L buffer

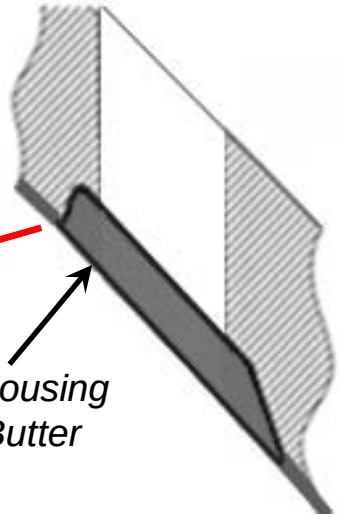
152 Hot Cracking

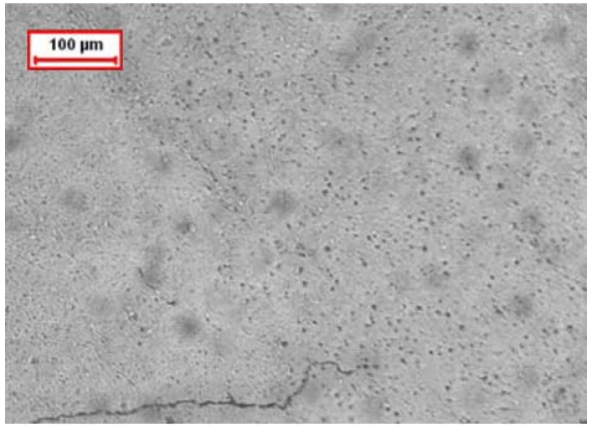
Buttering in J-groove Pocket on Reactor Vessel Head

- Example of hot cracks in 152 weld metal at interface between J-groove weld butter and SAW strip clad deposit
- SAW clad deposit is EQ308L *(0.012% S, 0.014% P, 0.96% Si)*



Liquid penetrant indications at 152 / EQ308L interface





Replication of hot crack

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- Conclusions and Recommendations

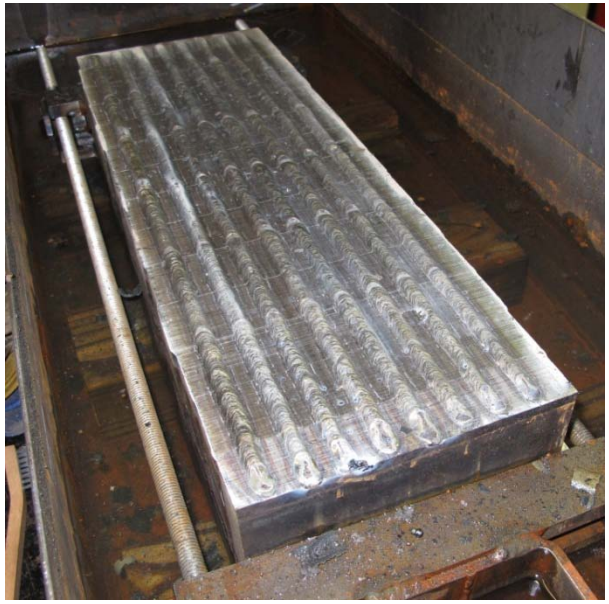
Focus and Goal of Testing

Industry Requested and Needed Simple Guidelines

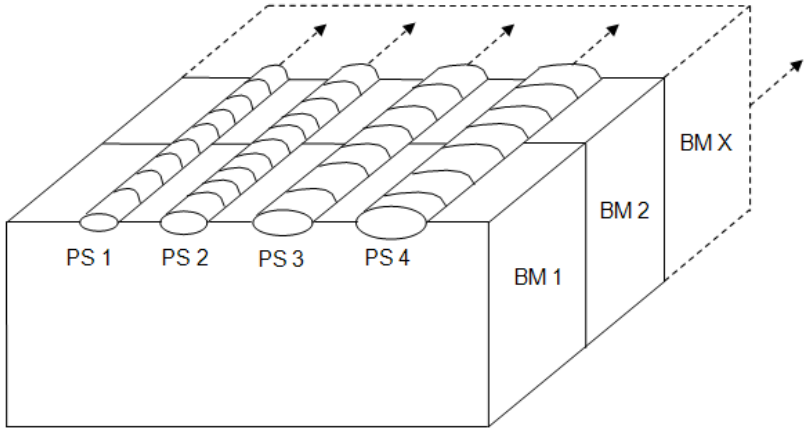
- Focus of the test program
  - Understand influence of austenitic stainless steel dilution on high chromium nickel-base (Ni-30Cr) filler metal hot cracking
  - What is a safe level of Ni-30Cr dilution with high Si-S stainless steels?
  - What is influence of Si and S on dilution?
  - What are safe S+P and Si thresholds for crack free welds?
  - What is the relative potency of Si and S on Ni-Cr30 hot cracking?
  - Is one variant of Ni-30Cr weld metal more resistant to hot cracking?
- Goal of the test program
  - Develop simple industry guidelines to manage Ni-30Cr hot cracking when welding on high Si-S austenitic stainless steels

Bead-on-plate Testing Approach

GTAW and SMAW on Two Sets of Base Materials



152-152M Beads on CASS Specimens



Bead-on-Plate Setup

CASS Specimen

Machine GTAW Setup

52M Beads on CASS Specimens

Base Metal Samples & Filler Metals Tested

Test Matrix Overview

- Cast SA-351 CF8A (Type 304) is base composition with min and max specified Si and S to simulate reactor coolant piping

Si & S wt% matrix compositions:

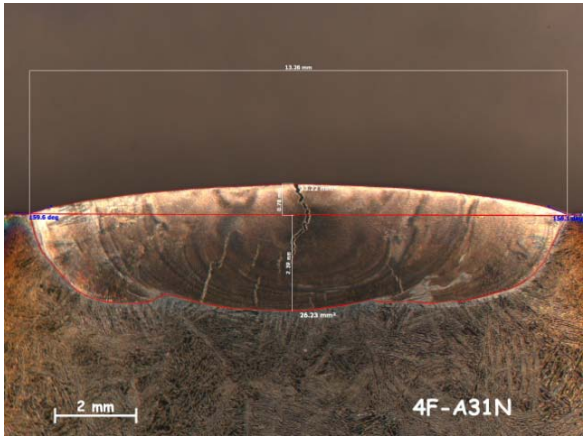
Silicon	Low	Med	High
	0.05	0.90	1.80
Sulfur	Low	Med	High
	0.001	0.020	0.040

- Weld metal matrix:
  - 82 (ERNiCr-3)
  - 52 (ERNiCrFe-7)
  - 52M (ERNiCrFe-7A)
  - 52MSS (ERNiCrFe-13)
  - 52i (ErNiCrFe-15)
  - 152 (ENiCrFe-7)
  - 152M (ENiCrFe-7
  - 622 (ERNiCrMo-10)
  - 625 (ERNiCrMo-3)

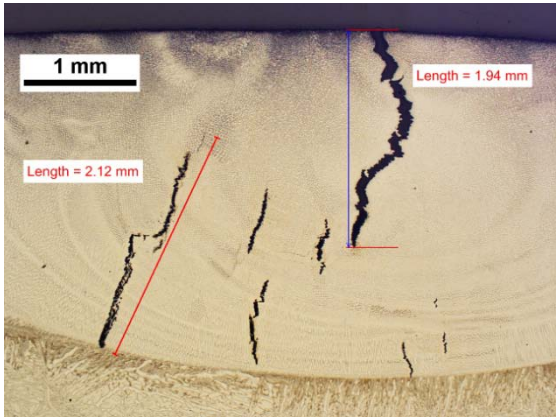
Hot Crack Characterization

Specified Methodology Used for All Specimens

- Measured and recorded the following:
  - ✓ Composite zone areas, toe angle(s), depth, width, and penetration
- Calculated dilution by area method
- Inspected for cracks at 50x
- Cracks graded as follows:
  - ✓ TNC – Total Number of Cracks > 0.2 mm
  - ✓ TCL – Total Crack Length (sum of all cracks)
  - ✓ MCL – Maximum Crack Length (single largest crack length)
  - ✓ Cracks within ≤ 0.2 mm proximity are counted and sized as one crack
  - ✓ Cracks categorization as:
    - – Surface Crack
    - – Midwall Crack
    - – Fusion Line Crack
    - – Evidence of backing filling was noted



82 Bead on A31N sample



25x Micrograph 82 on A31N sample

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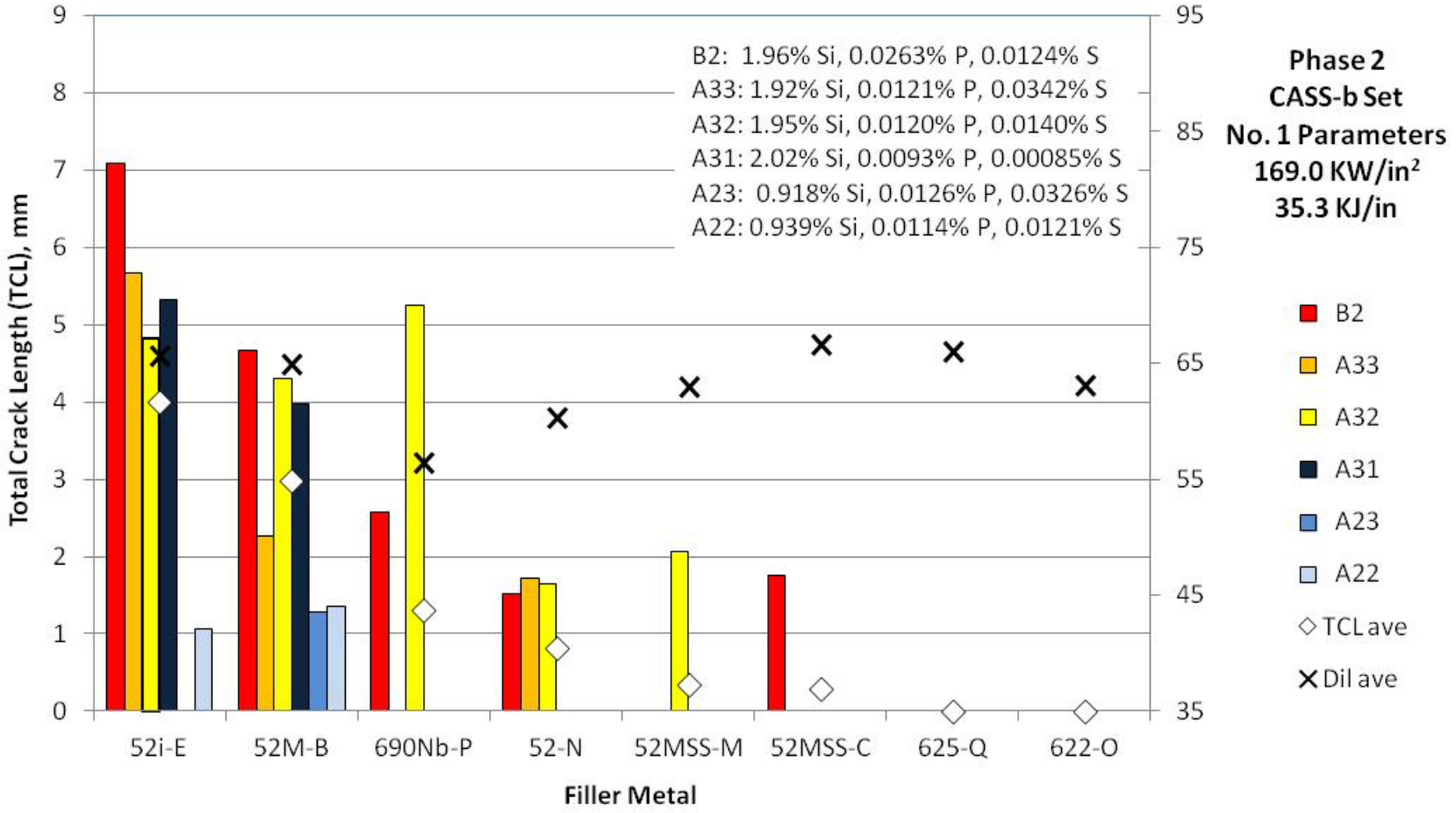
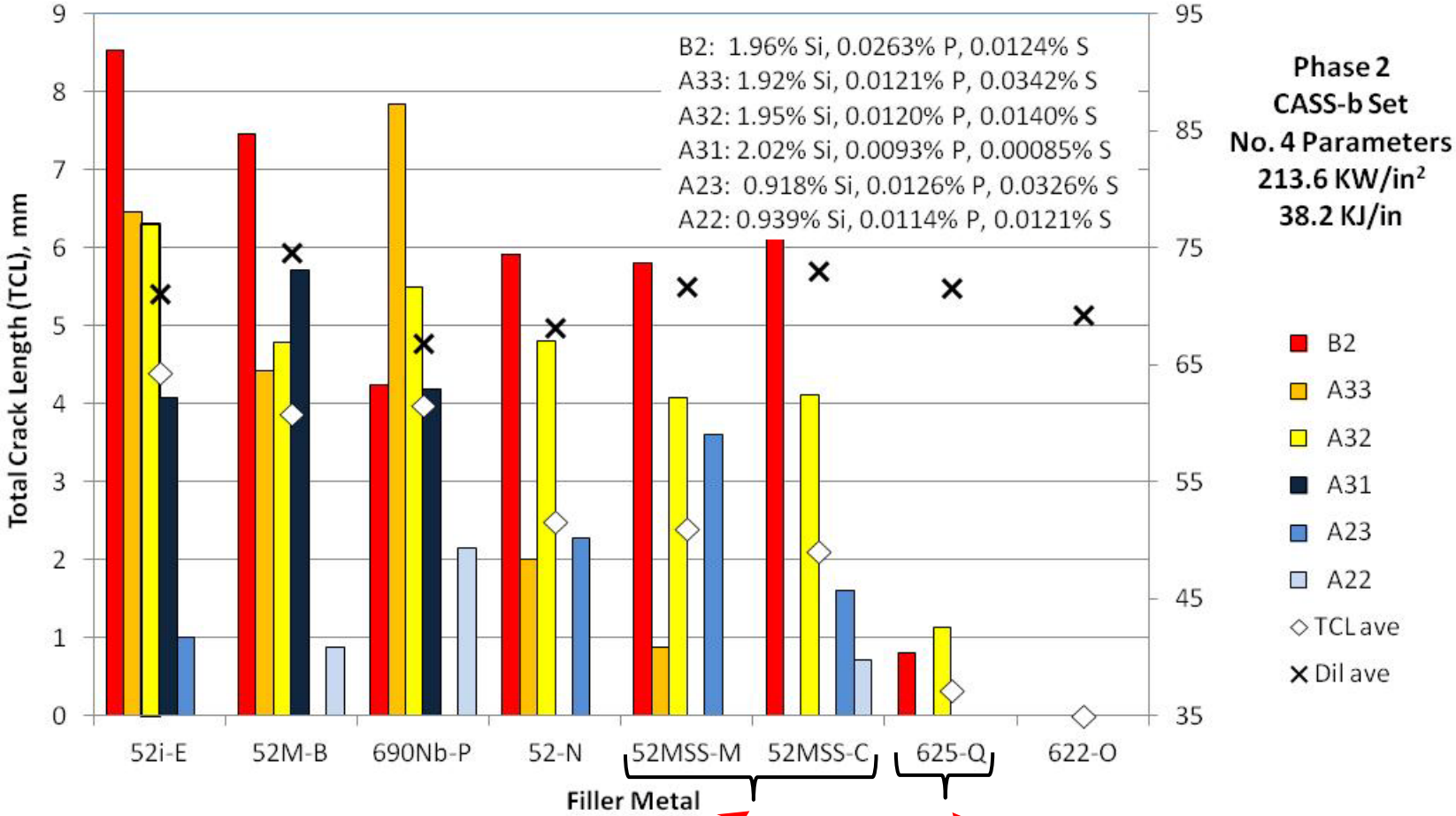
Hot Crack Response Comparison by Filler Metal

Phase 2 CF8A CASS-b Set (169.0 KW/in²)



Hot Crack Response Comparison by Filler Metal

Phase 2 CF8A CASS-b Set (213.6 KW/in²)

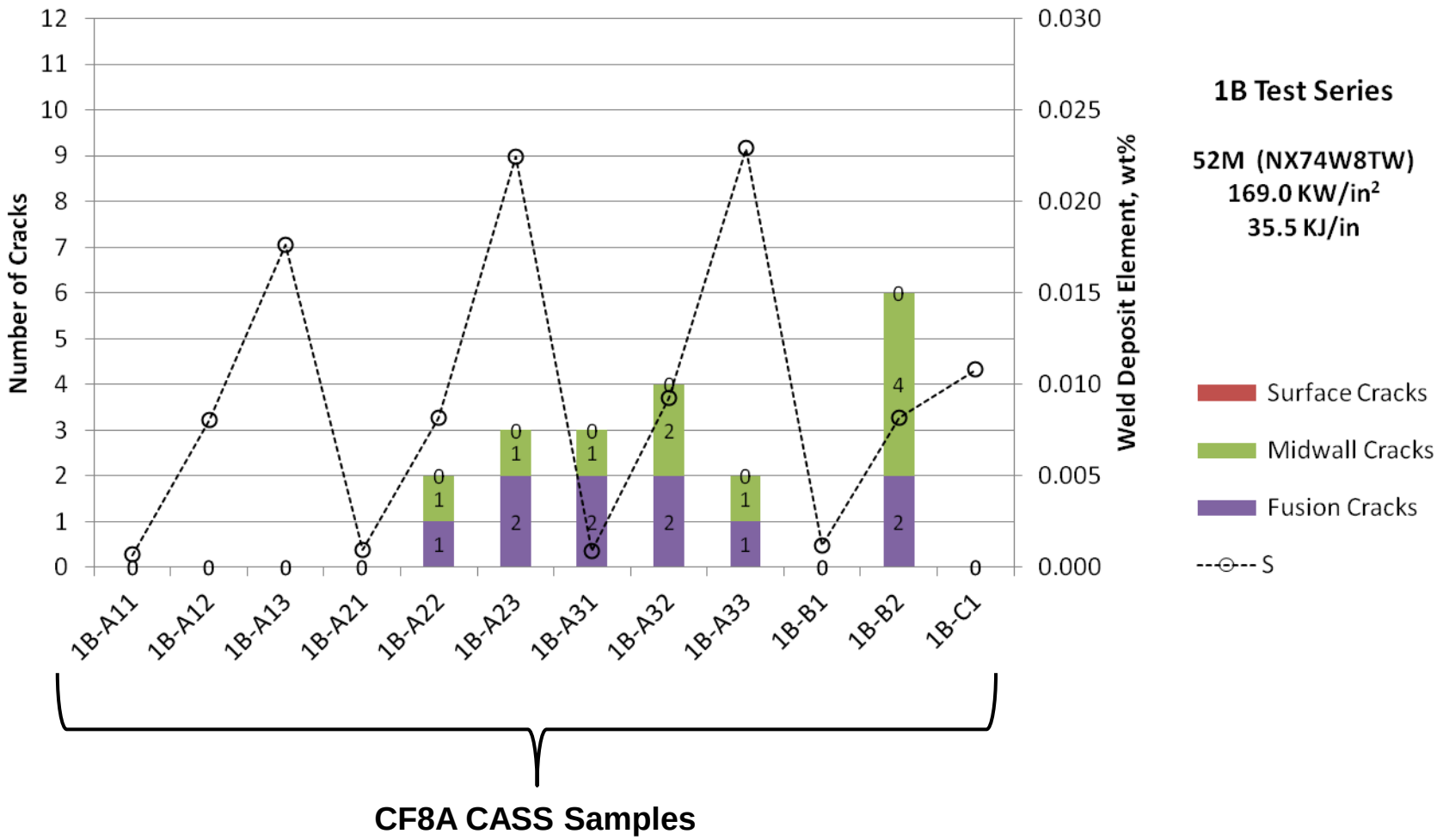


Limited Backfilling Observed at Crack Tips in 52MSS

All Cracks Healed by Backfilling in 625

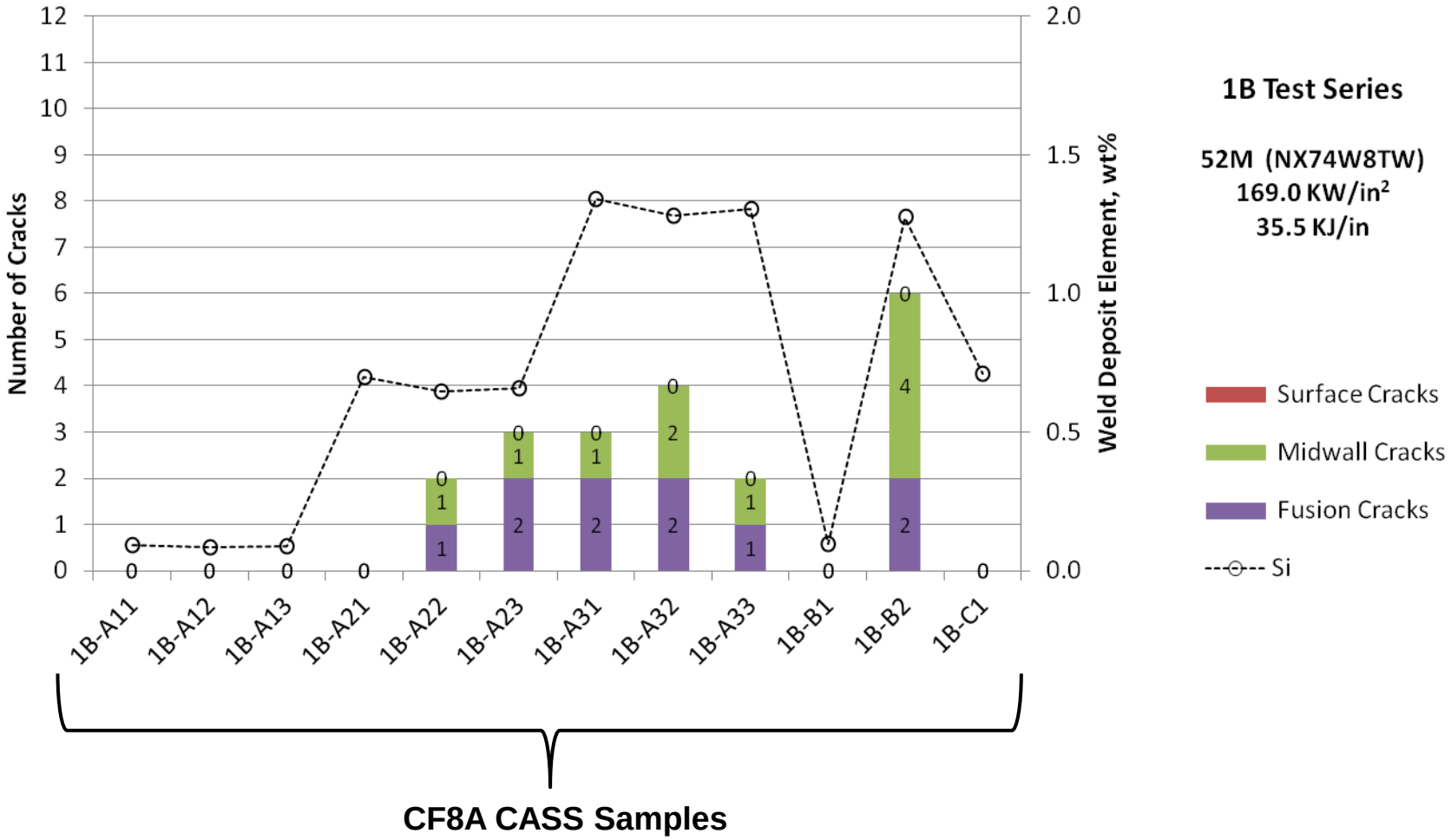
Crack Susceptibility Plot with Sulfur (S)

GTAW – 52M-B on CASS-b material set



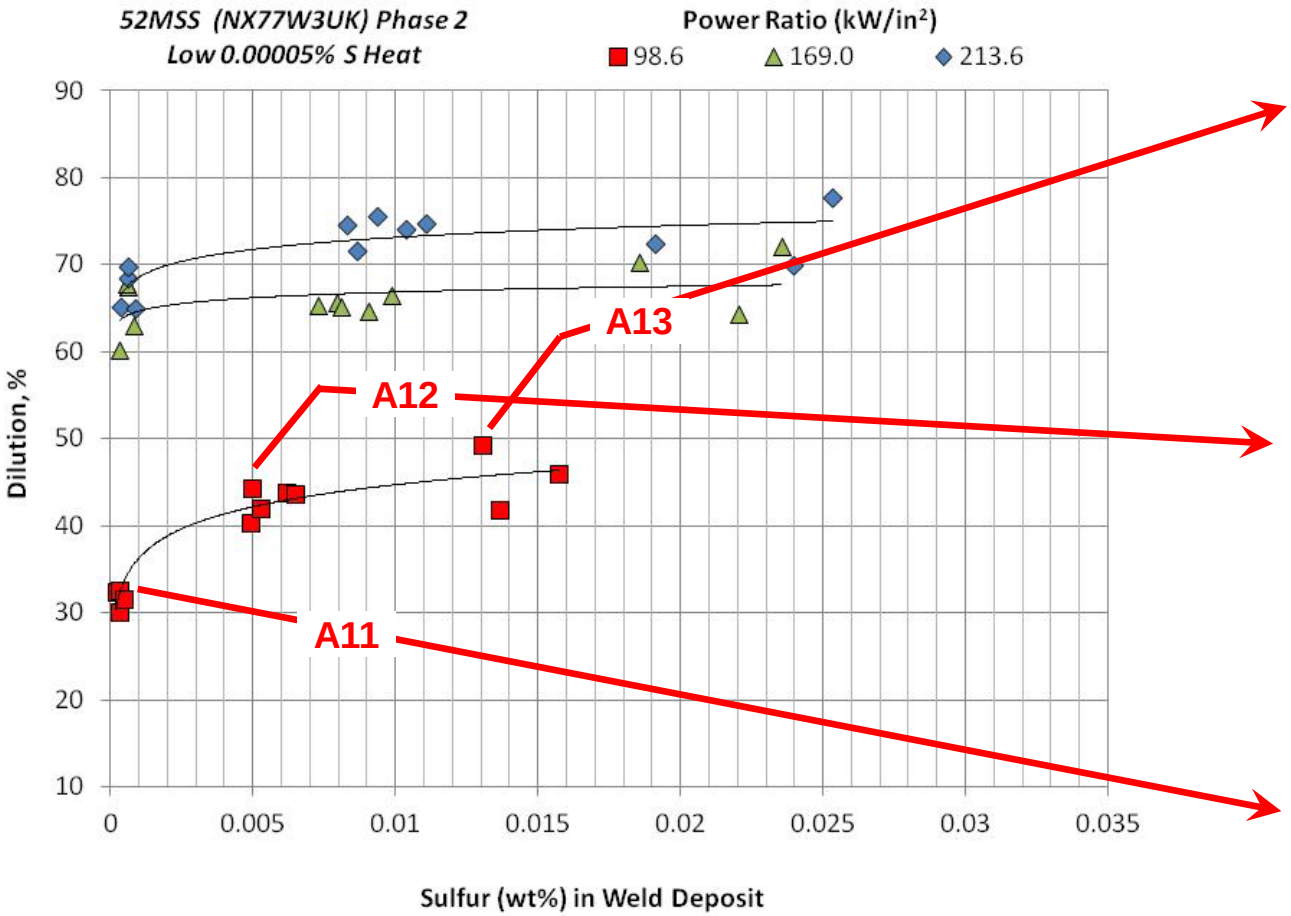
Crack Susceptibility Plot with Silicon (Si)

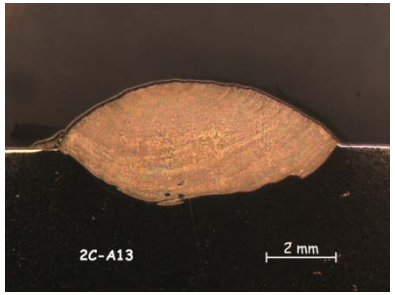
GTAW – 52M-B on CASS-b material set



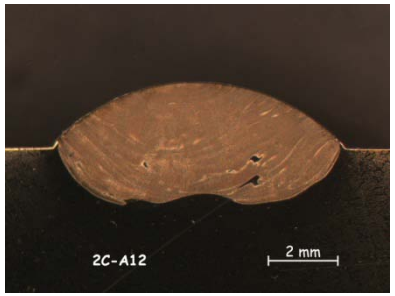
Influence of S on Low Si Samples

FM 52MSS-C with Ultra Low 0.00005% S





0.09 Si - 0.0130 S

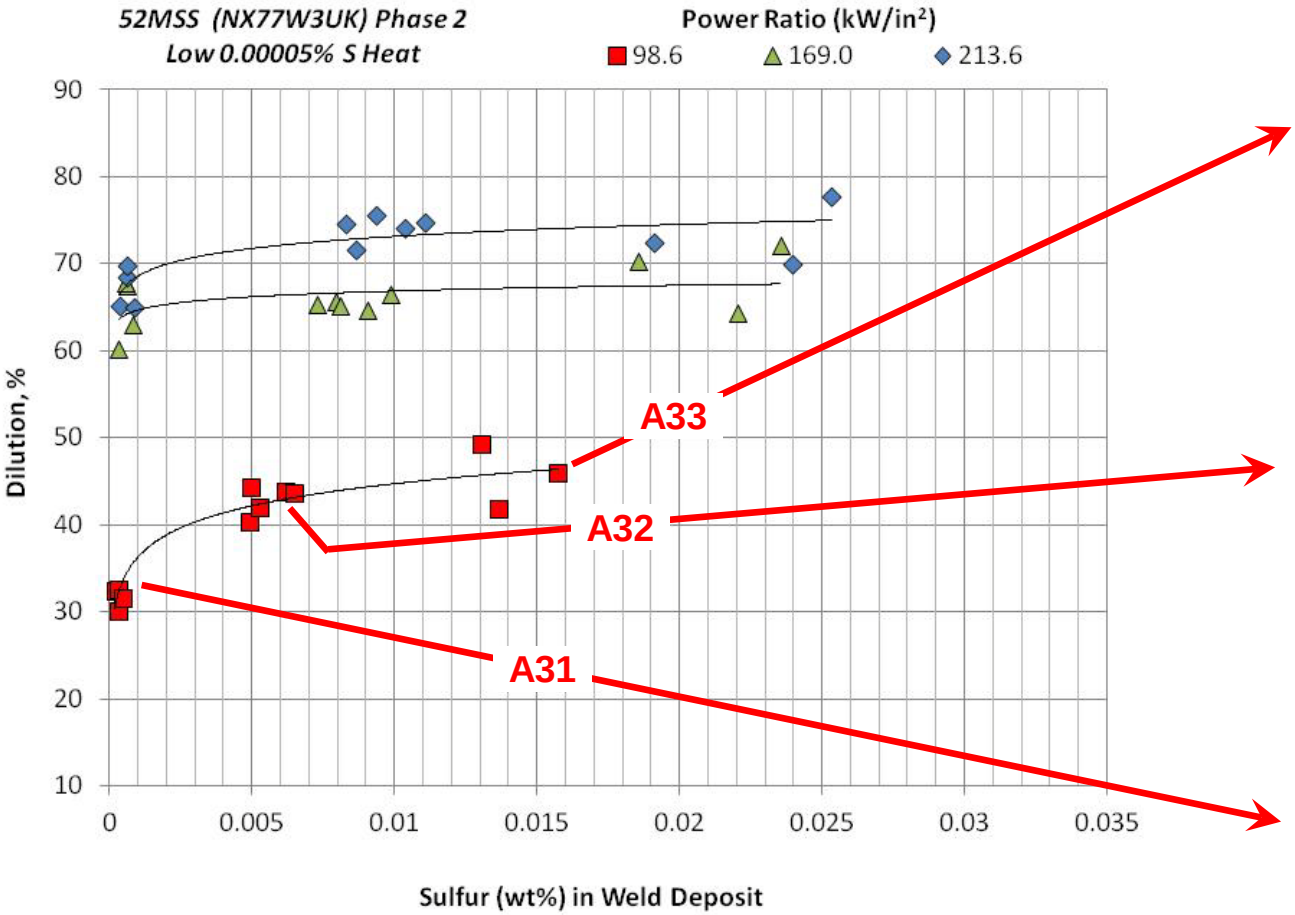


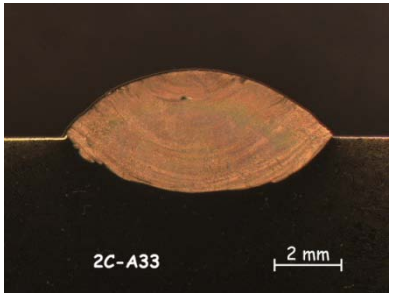
0.09 Si - 0.0050 S

0.10 Si - 0.0002 S

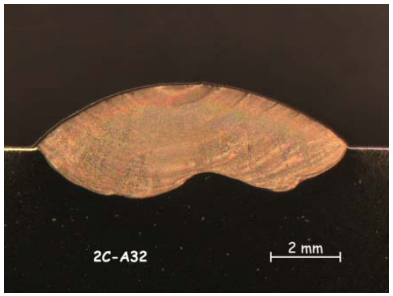
Influence of S on High Si Samples

FM 52MSS-C with Ultra Low 0.00005% S

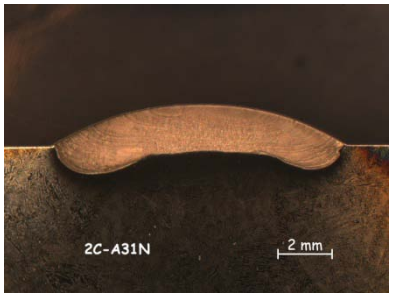




0.94 Si - 0.0157 S



0.91 Si - 0.0062 S



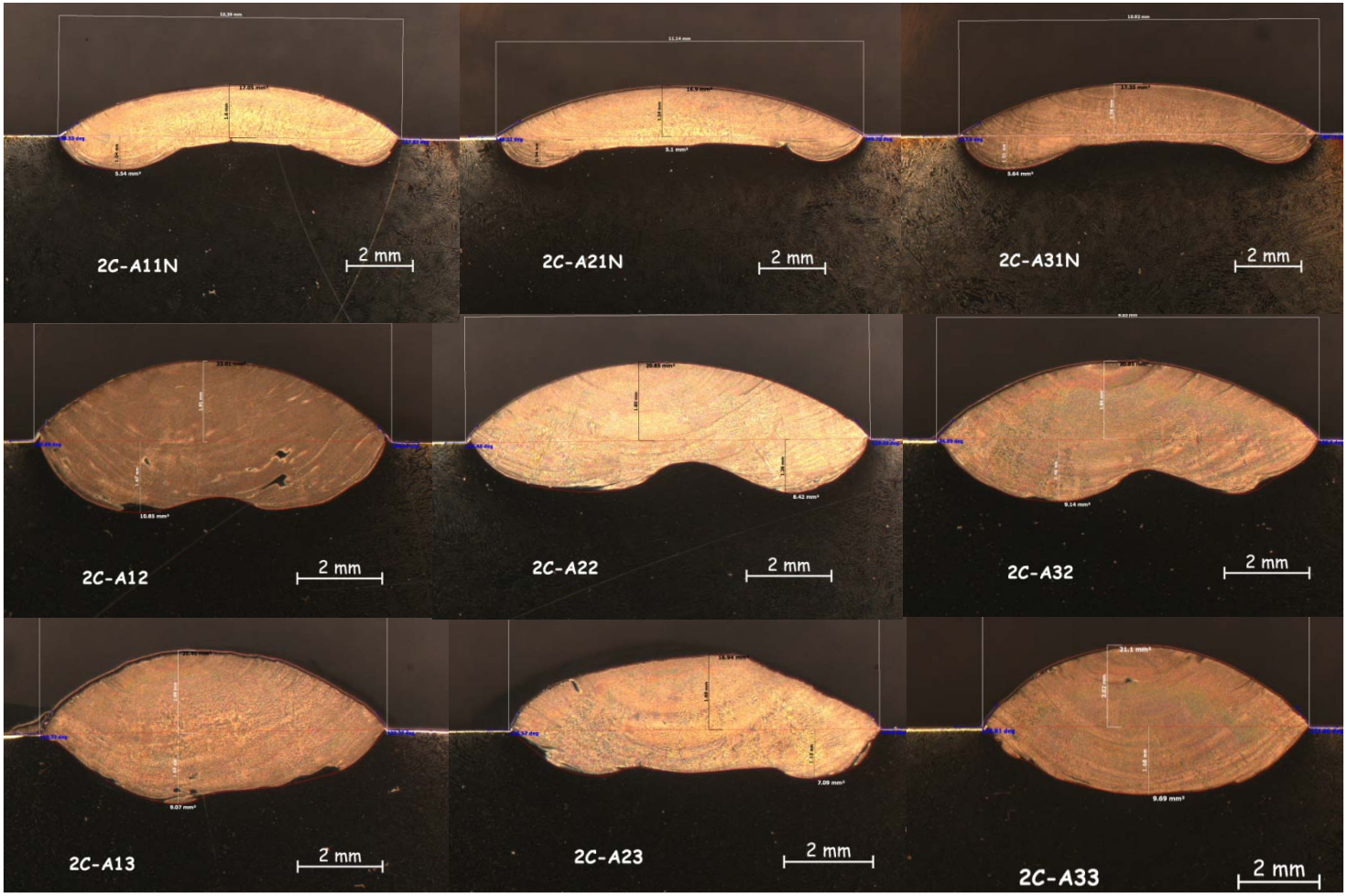
0.73 Si - 0.0003 S

Influence of Si and S on Bead Shape

52MSS-C (0.00005% S Wire with Power Ratio 98.6 kW/in²)

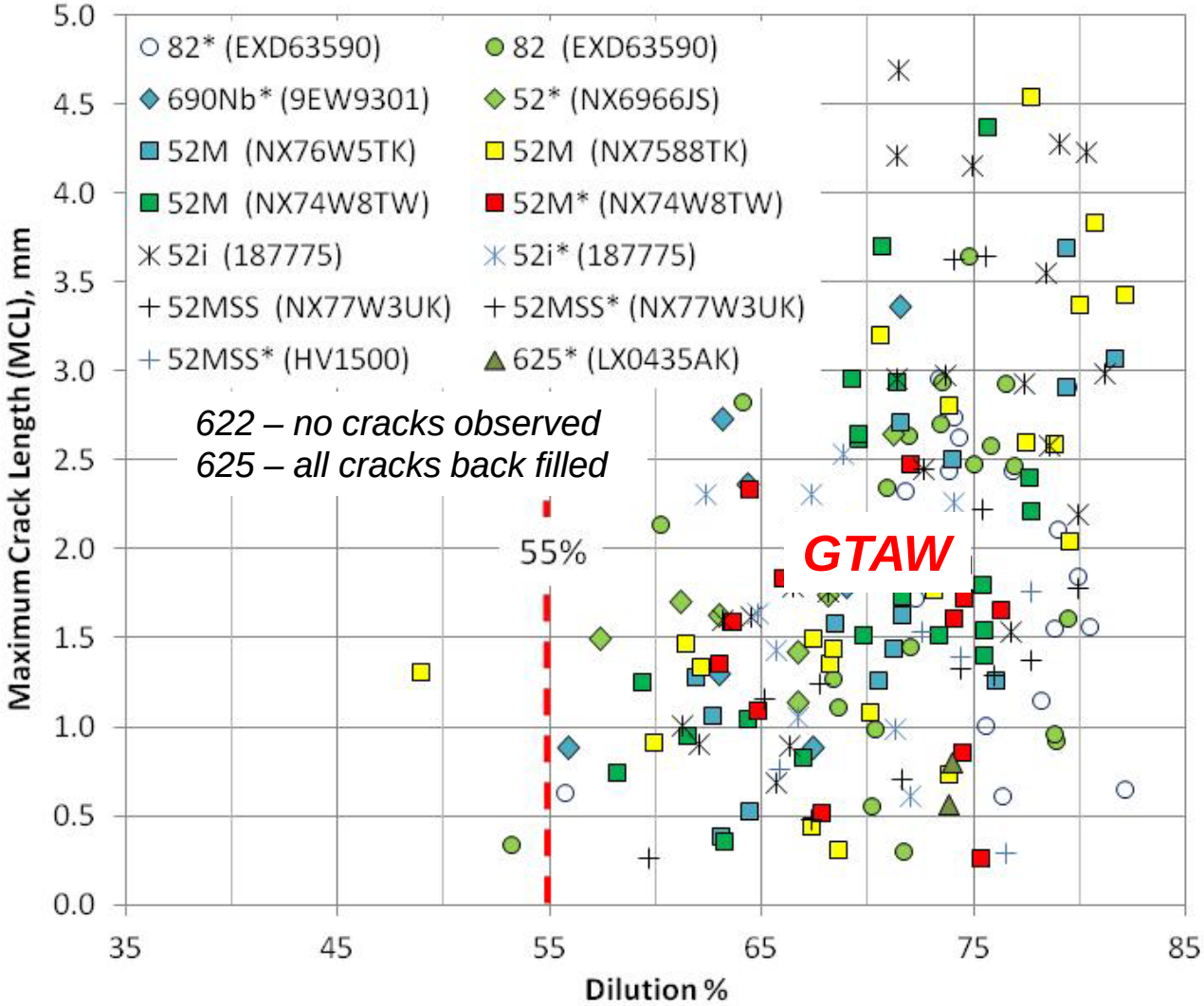
Increasing Si →

Increasing S ↓



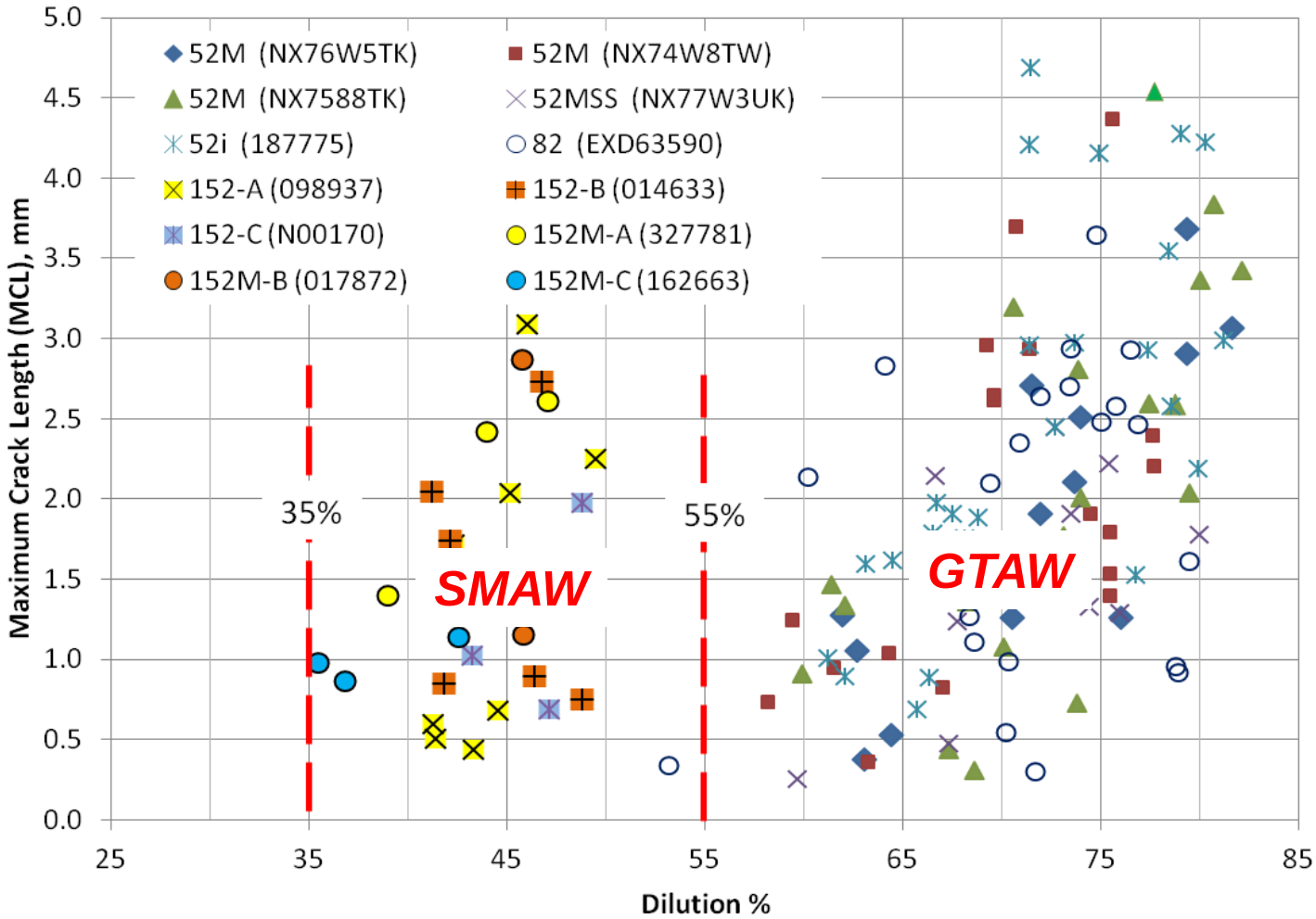
Maximum Crack Length vs Dilution

GTAW Phase 1 & 2



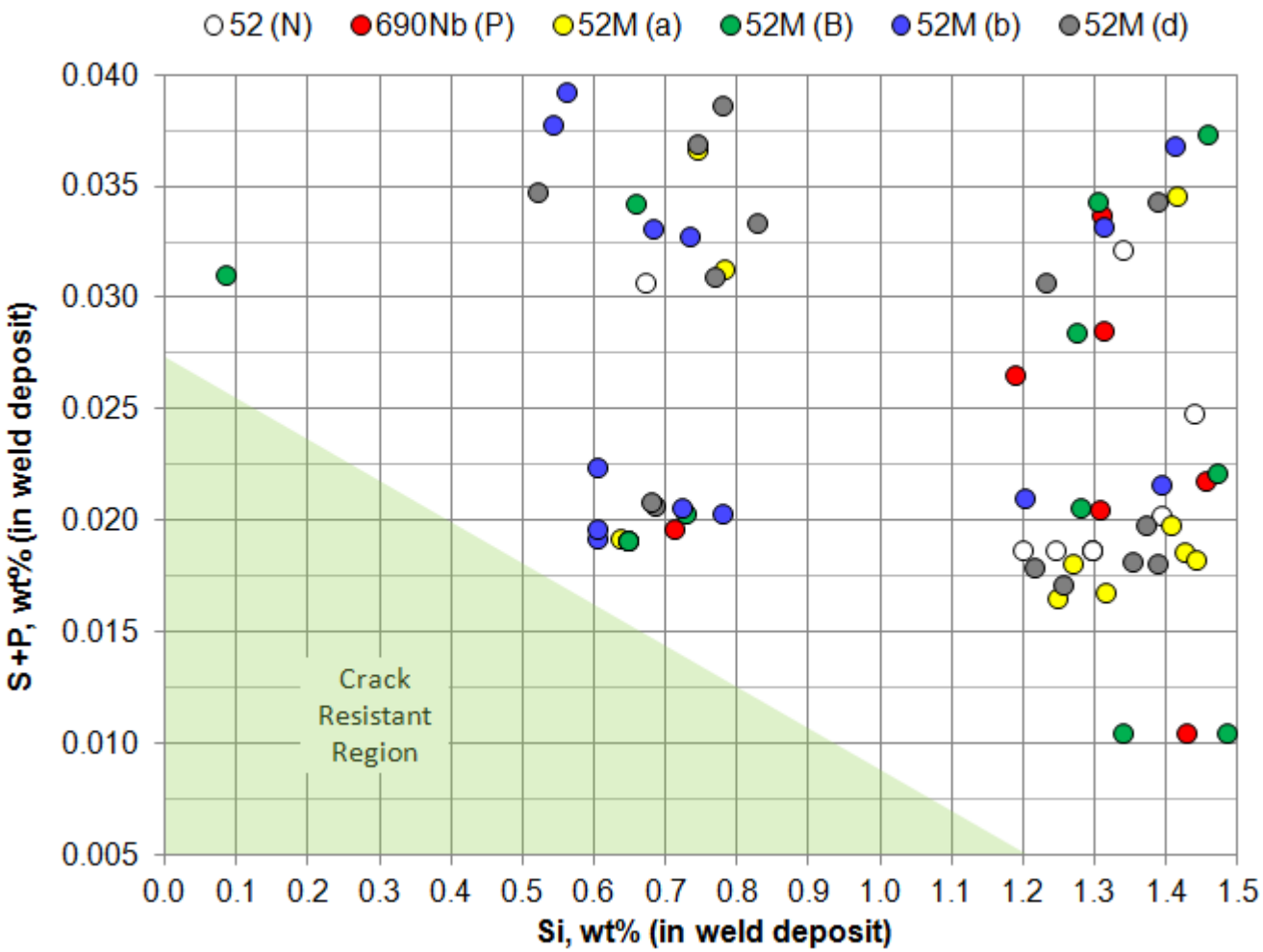
Maximum Crack Length vs Dilution

GTAW Phase 1 & SMAW Phase 3



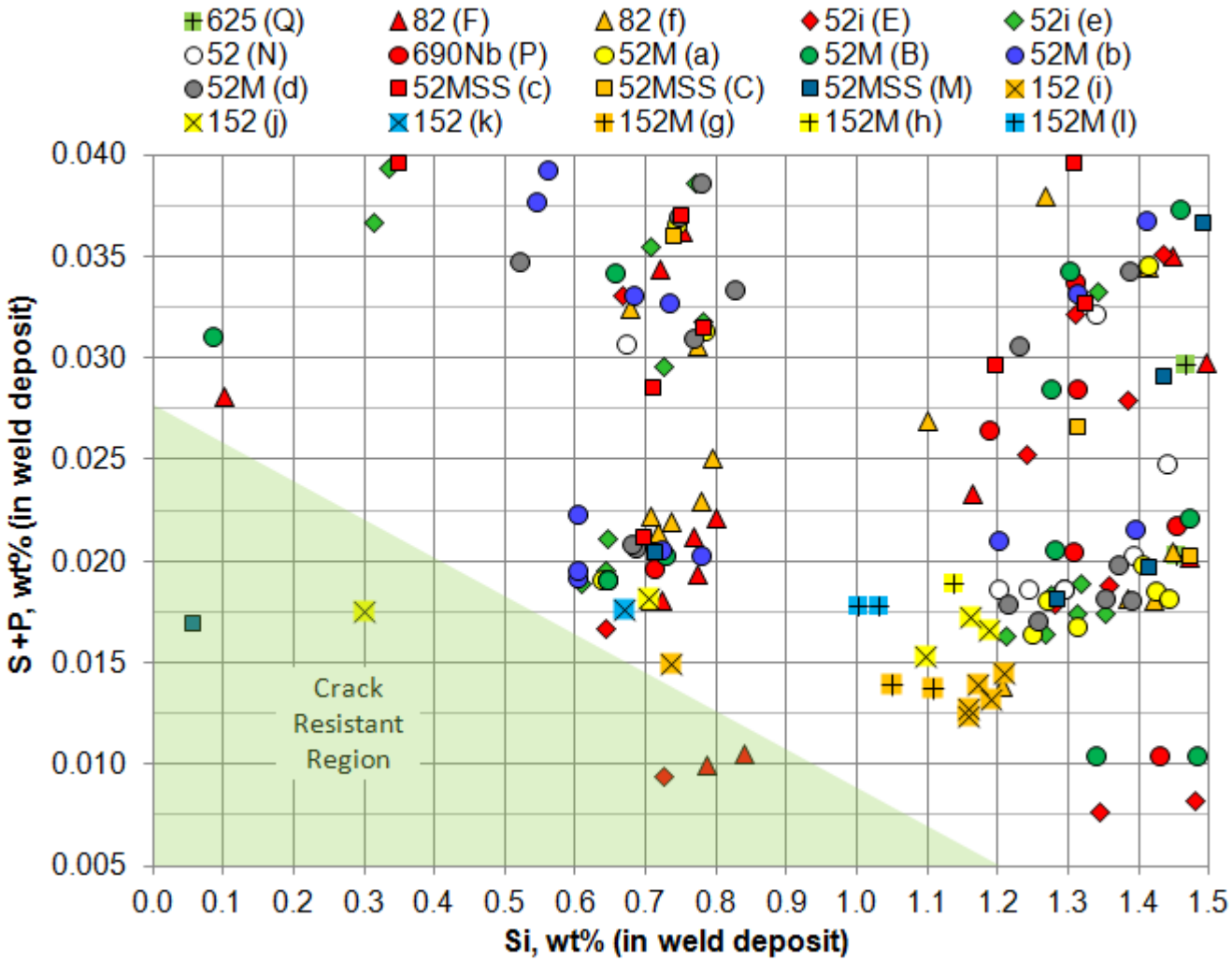
S+P vs Si Plot with Crack Resistant Region

52 and 52M GTAW Phase 1 & 2



S+P vs Si Plot with Crack Resistant Region

GTAW Phase 1 & 2 and SMAW Phase 3



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Conclusions

Hot Cracking From Dilution with Stainless Steel

- Ranking of filler metals tested from most to least resistant

  622 *(crack free)* < 625 *(back filled)* < 52MSS < 52 < 52M <52i

- High silicon in austenitic stainless steel promotes hot cracking in high Cr Nickel-base filler metals
- High sulfur did not strongly promote hot cracking
- Dilution can vary as much as 25% between 0.00005% and 0.034% S base materials
- Dilution control (≤ 55% for GTAW and ≤ 35% for SMAW) is an effective tool to prevent hot cracking of Ni-30Cr weld metals when welding on high Si-S stainless steel

Considerations to Prevent Hot Cracking

Guidelines for Welding with Ni-30Cr Alloys on Stainless Steel

- **Dilution Control**
  - GTAW dilution ≤ 55% (52M, 52i, 52MSS, 690Nb, or 82)
  - SMAW dilution ≤ 35% (152 & 152M)
- **Composition Control**
  - Use base material MTR to evaluate composition effect on welding
  - Maintain following limits in diluted weld deposit

    S < 0.020 wt%; Si < 0.60 wt%; S+P < 0.030 wt%
  - Consider effect of base metal S on dilution and weld parameters
  - Consider influence of joint geometry and welding position on dilution
- **Process Parameter Control**
  - Develop welding parameters and techniques to appropriately control dilution
  - Test weld parameters and understand potential difference of dilution on low versus high S base materials

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