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Weldability Issues for Inlay, Onlay and Overlay

Industry-NRC 2011 Meeting on Alloy 690 Research

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Presentation Roadmap

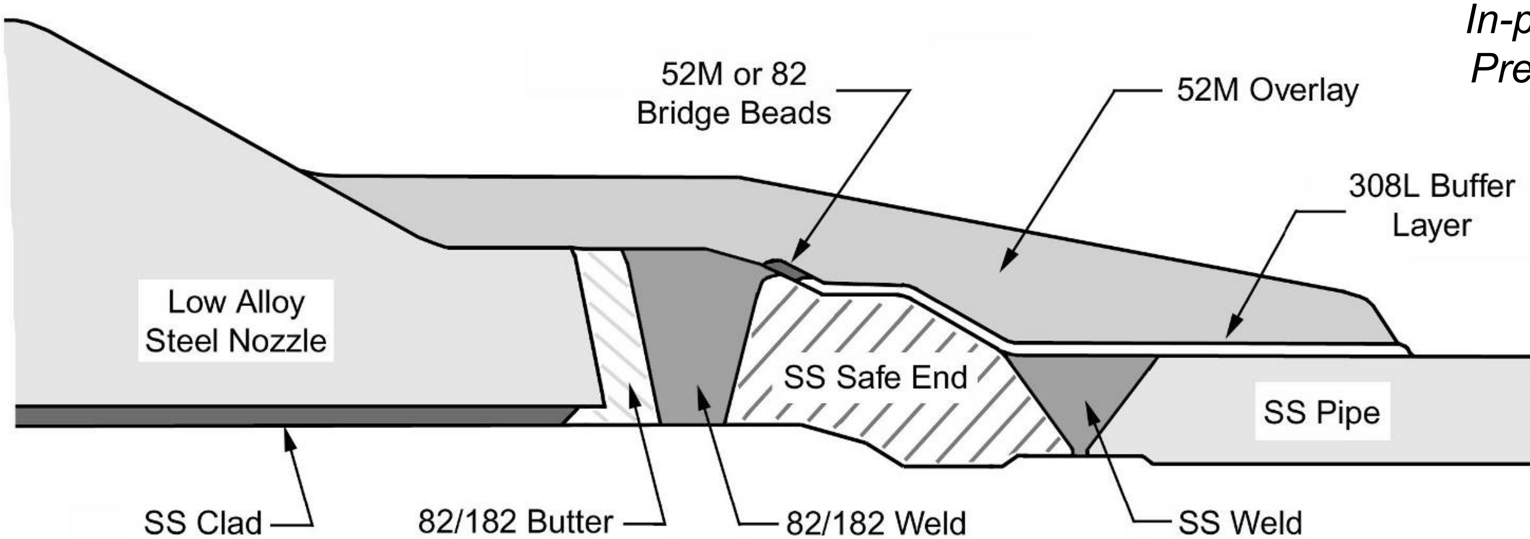
- **Welding Approaches for PWSCC Mitigation**
- **Overview of Cracking Mechanisms (micro-fissuring)**
- **High Cr Nickel-Base Filler Metal Compositions**
- **Weldability Studies and Testing**
  - Transverse Varestraint Test (solidification cracking & DDC)
  - Cast Pin Tear Test (solidification cracking)
  - Strain to Fracture Test (DDC)
- **Filler Metal Susceptibility Comparison**
- **Dilution Studies and Testing**
  - Power Ratio Versus Dilution
  - Dilution Study Using Cast Pin Tear Test
- **Development of New High Cr Filler Metal**

Mitigation and Repair Options – Weld Overlay

- Weld Overlay
  - Full structural or optimized 52M weld overlay is industry accepted method for repair or mitigation of PWSCC susceptible 82/182 welds

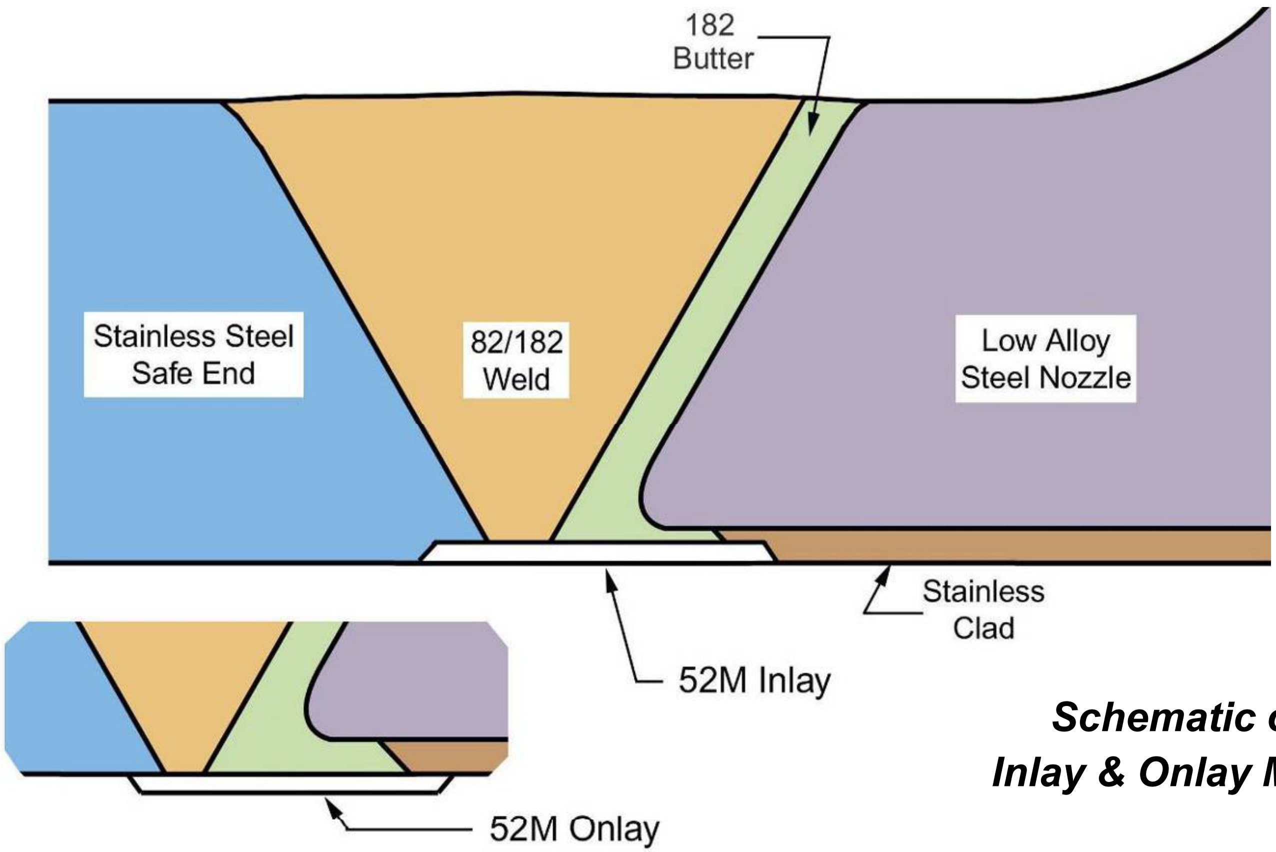
In-process 52M Overlay on Pressurizer Safety Nozzle

Schematic of 52M Structural Weld Overlay



Mitigation and Repair Options – Inlay & Onlay

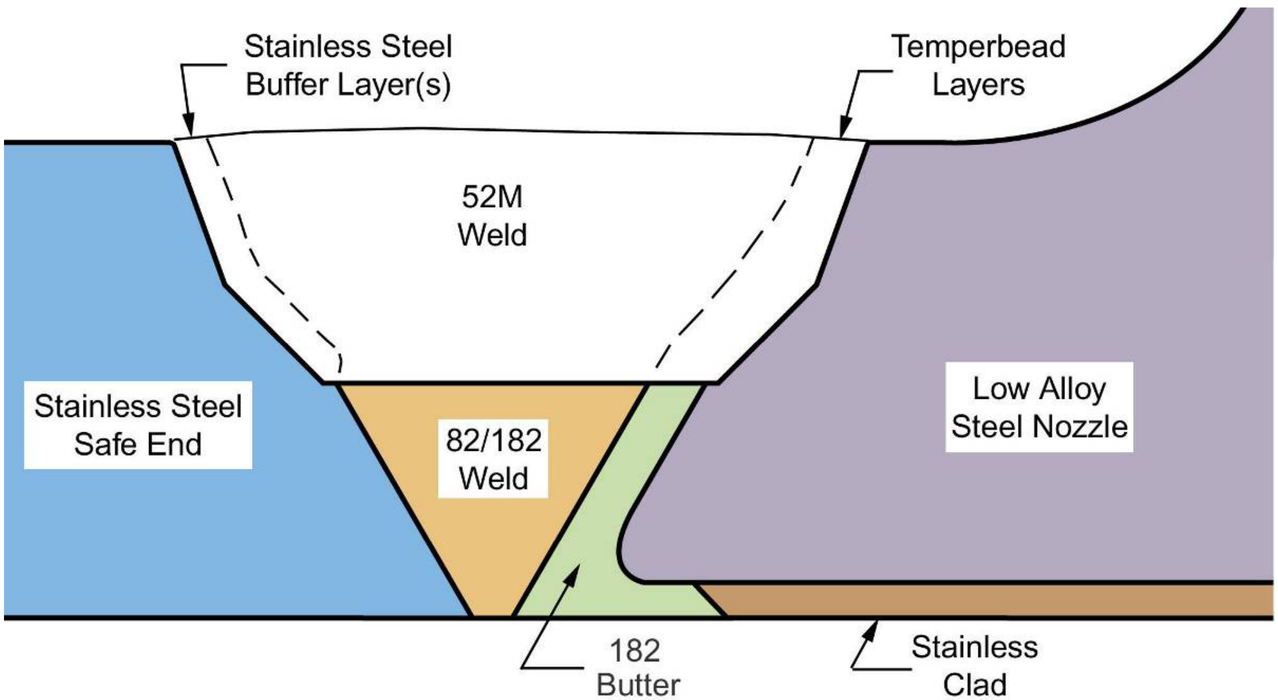
- Inlay / Onlay Weld on Inside Diameter
  - 52M provides barrier between susceptible 82/182 and environment
  - Machine GTAW or underwater laser beam welding process



Schematic of 52M Inlay & Onlay Mitigation

Mitigation and Repair Options – Excavate & Weld Repair

- Excavate Weld & Repair (EWR) – New Approach
  - Machine / grind OD portion of 82/182 DM weld
  - Install PWSCC resistance weld metal (52/52M)



Schematic of 52M Excavate & Weld Repair

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Cracking Mechanism No. 1

- **Solidification Cracking (type of hot cracking)**
  - Occurs in the weld fusion zone at the terminal stage of solidification in the 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

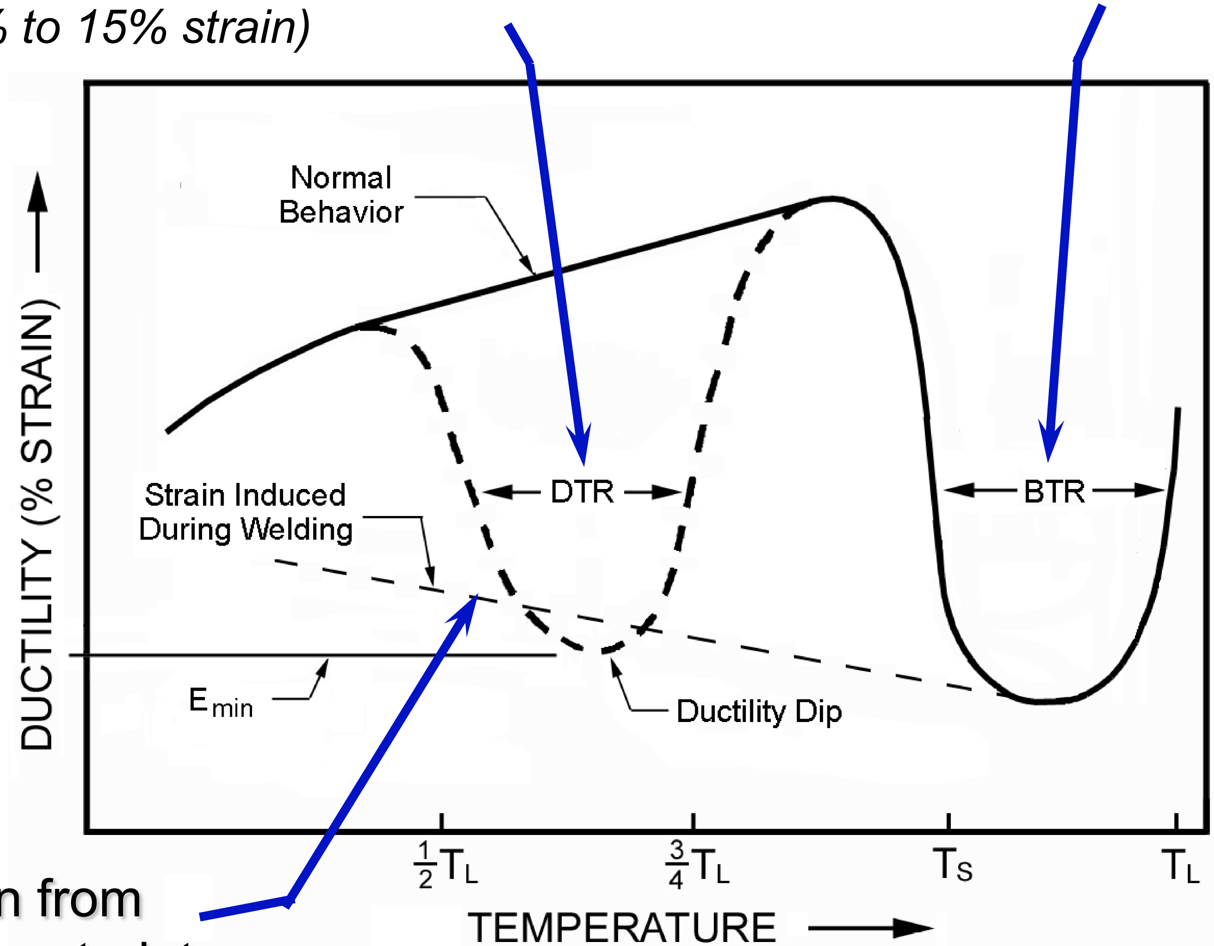
Cracking Mechanism No. 2

- **Ductility-Dip Cracking (DDC)**
  - Typically 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)*

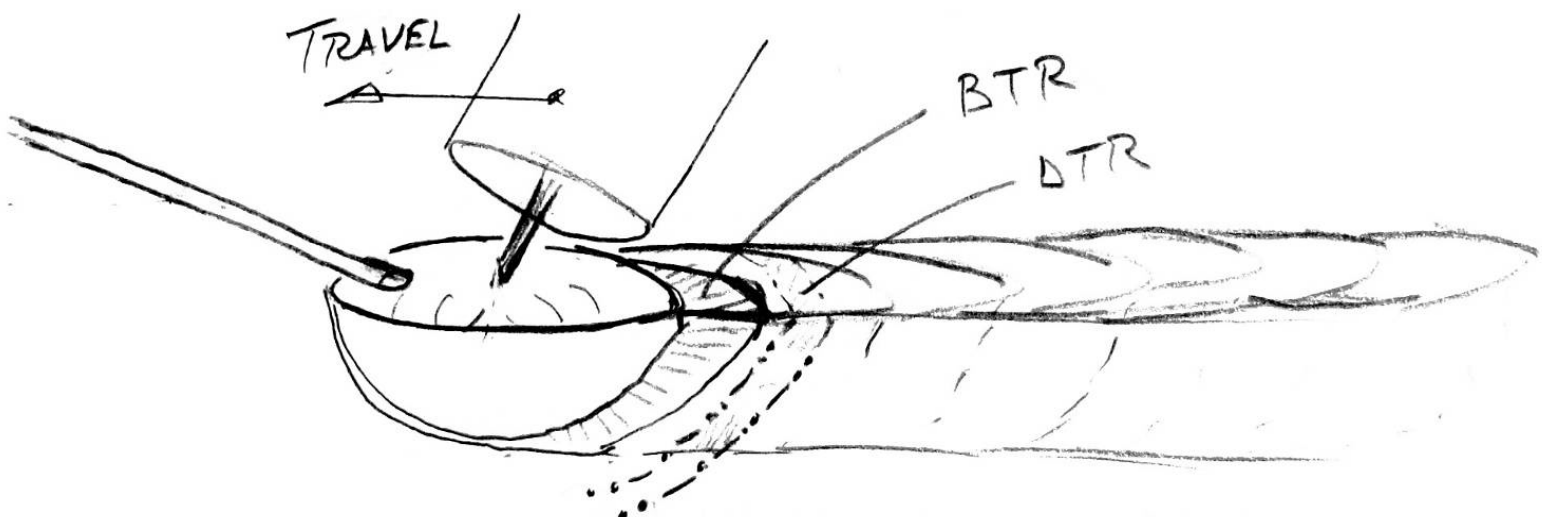
Brittle Temperature Range (BTR) *~ liquidus to terminal solidus range*



applied strain from shrinkage and restraint

Solidification & Ductility-Dip Crack Locations

- **Solidification Cracks**
  - Initiate in the Brittle Temperature Range (BTR)
  - Surface connected or 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

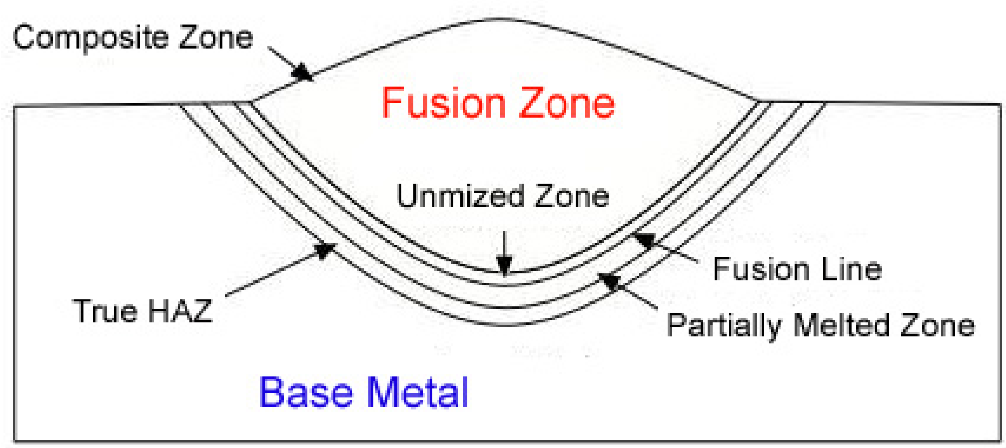


Weld Zone Definitions

- **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

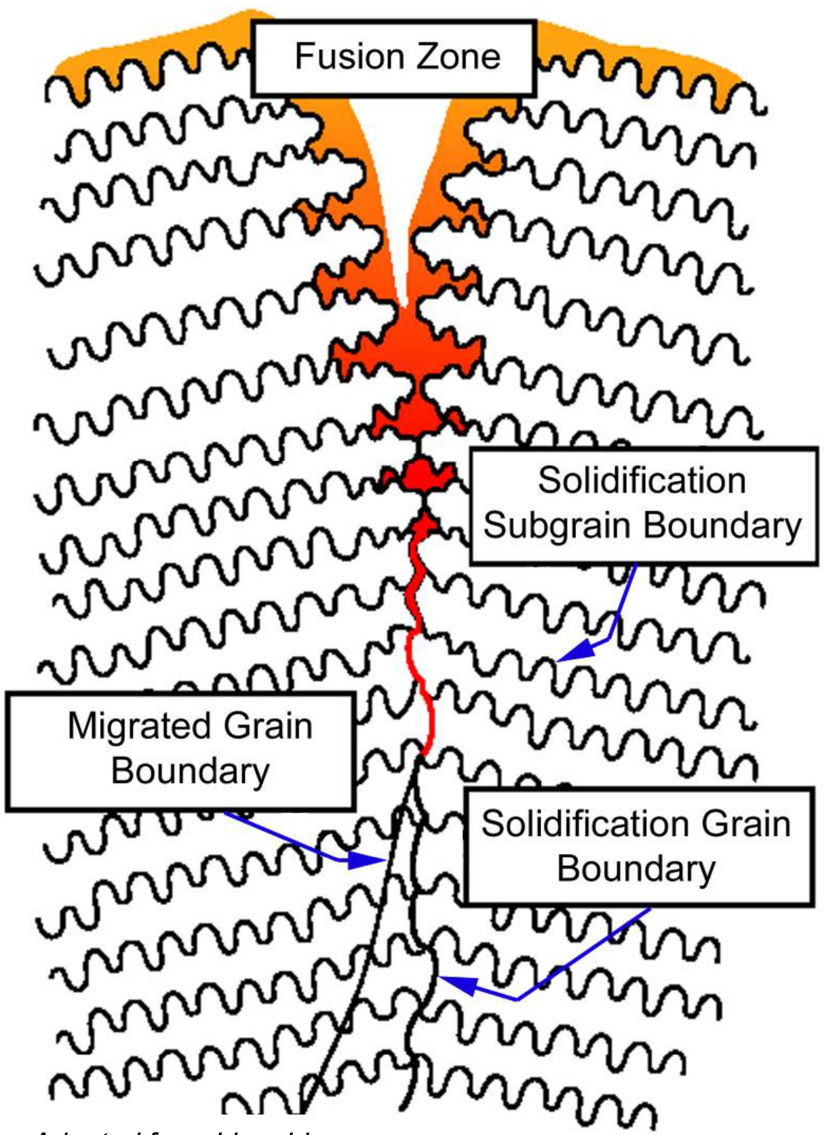
Solidification Cracks Occur in the Fusion Zone



DDC Occurs in the True HAZ

Liquation Cracks Occur in the PMZ

Solidification & Ductility-dip Crack Morphology

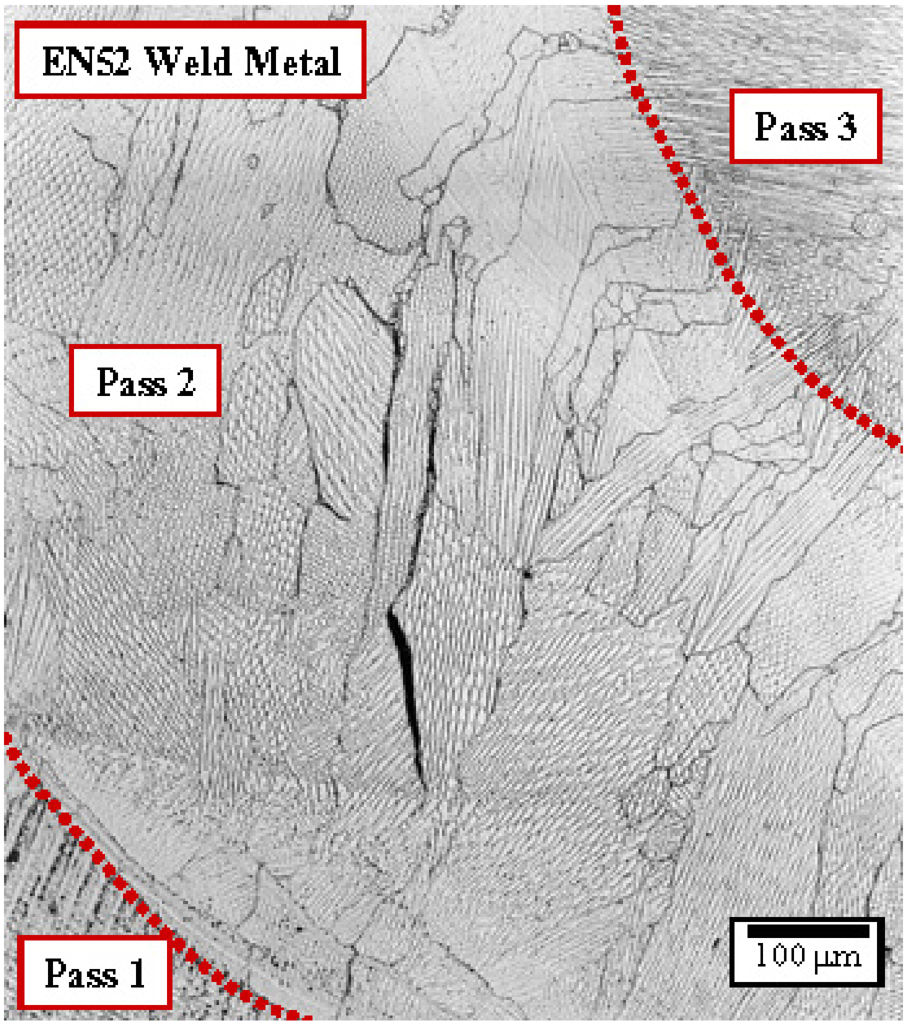


Adapted from Lippold

- **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 cracks in 2nd pass reheated in ductility-dip temperature range by 3rd weld pass
- 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

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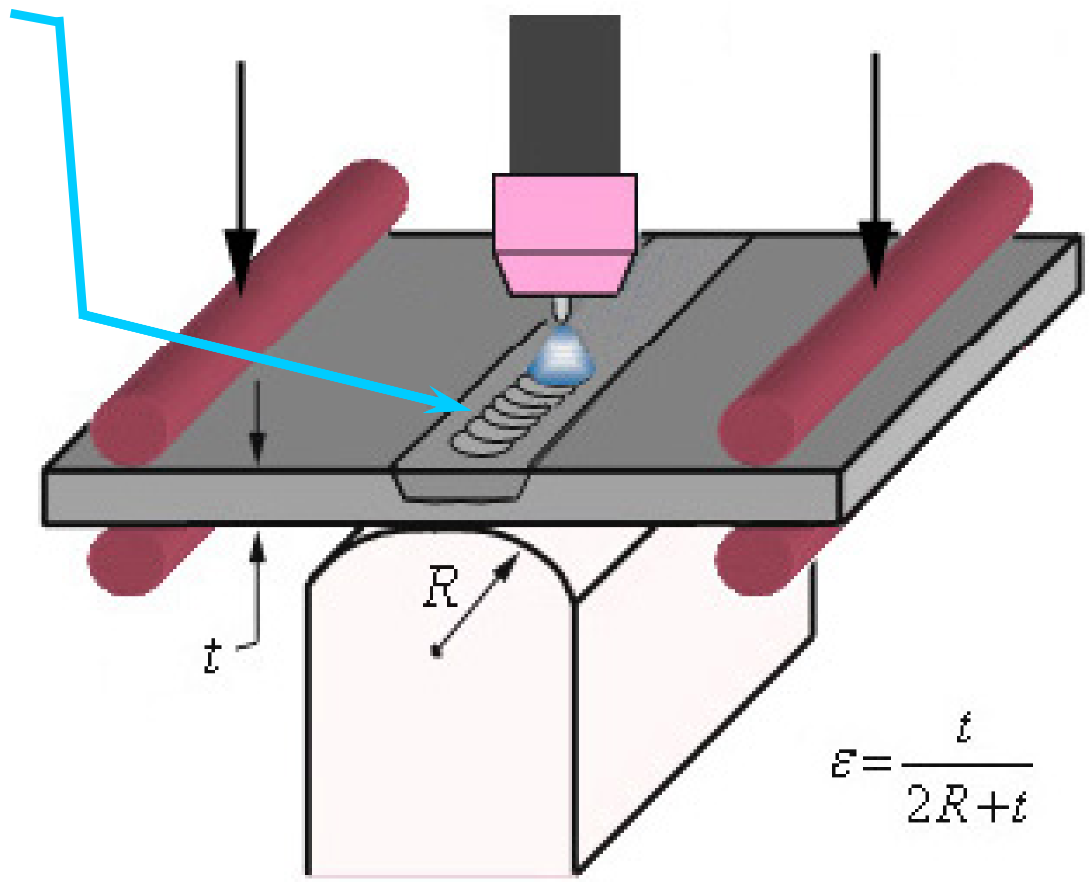
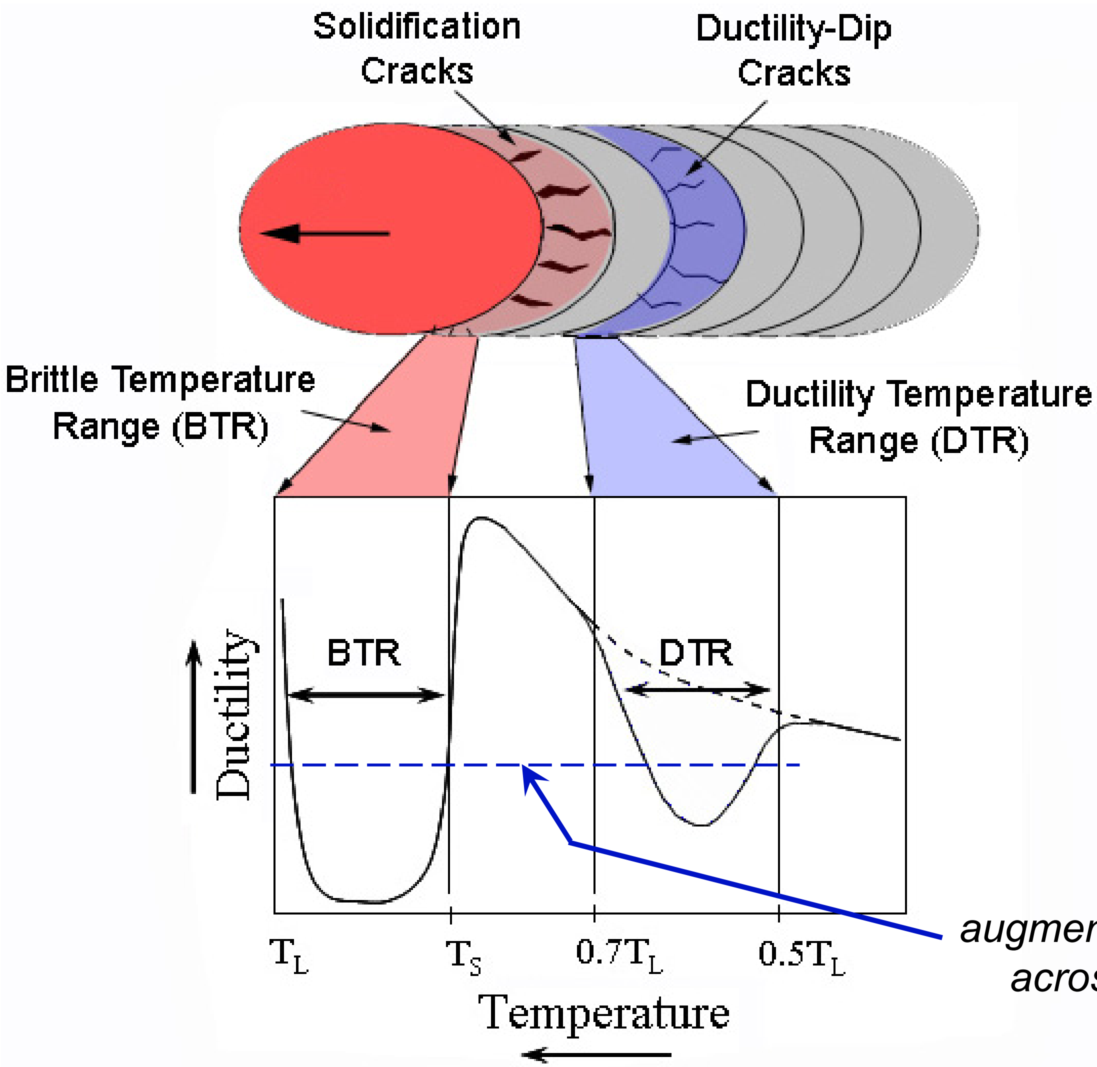
Transverse Varestraint Test Description

- 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



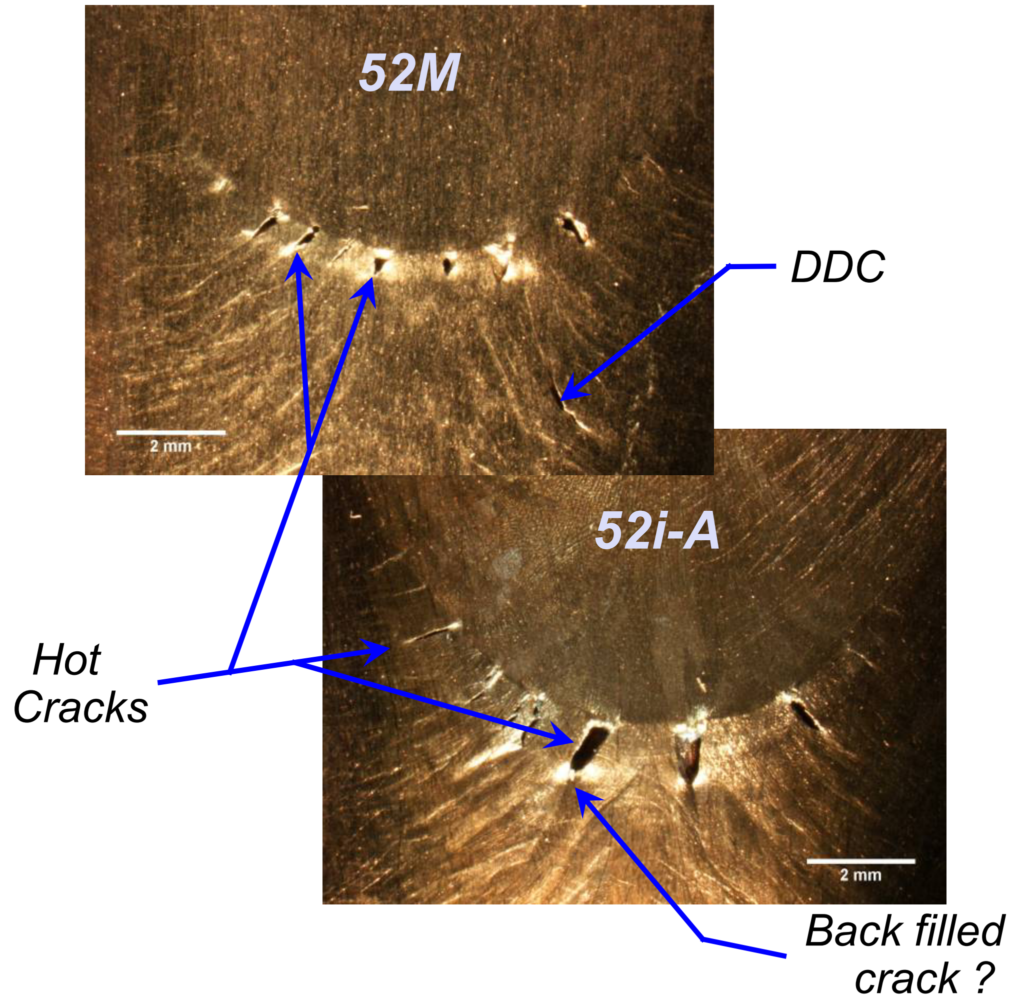
augmented strain is constant across BTR & DTR troughs

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

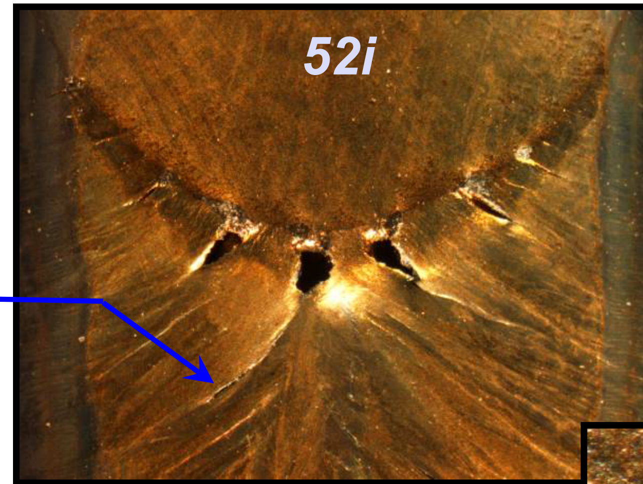
- Maximum crack length (MCL) is measured for each strain level tested
- Maximum crack distance (MCD) is longest crack measured at or above the saturation strain
- Above saturation strain threshold the MCL is essentially constant
- DDC can also be found by the transverse varestraint test



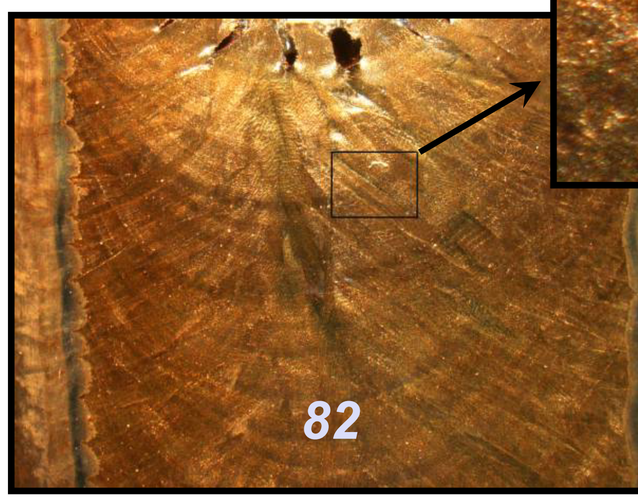
Varestraint Test Results (DDC Resistance)

- Solidification/liquation cracking occurs between T_{liq} and T_{sol}
- DDC occurs between ~$0.75T_{liq}$ and $0.5T_{liq}$

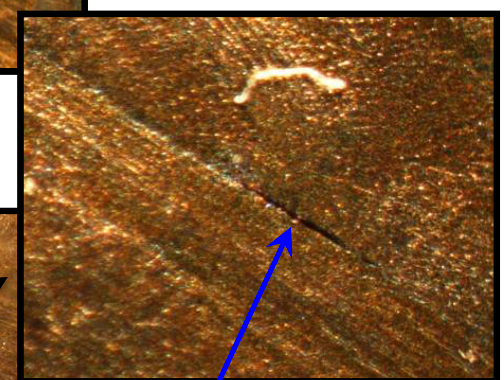
- DDC observed in 52M at 5% strain
- DDC observed in 82 at 7% strain
- DDC observed in 52i at 5% strain



52i at 5% strain (10x)

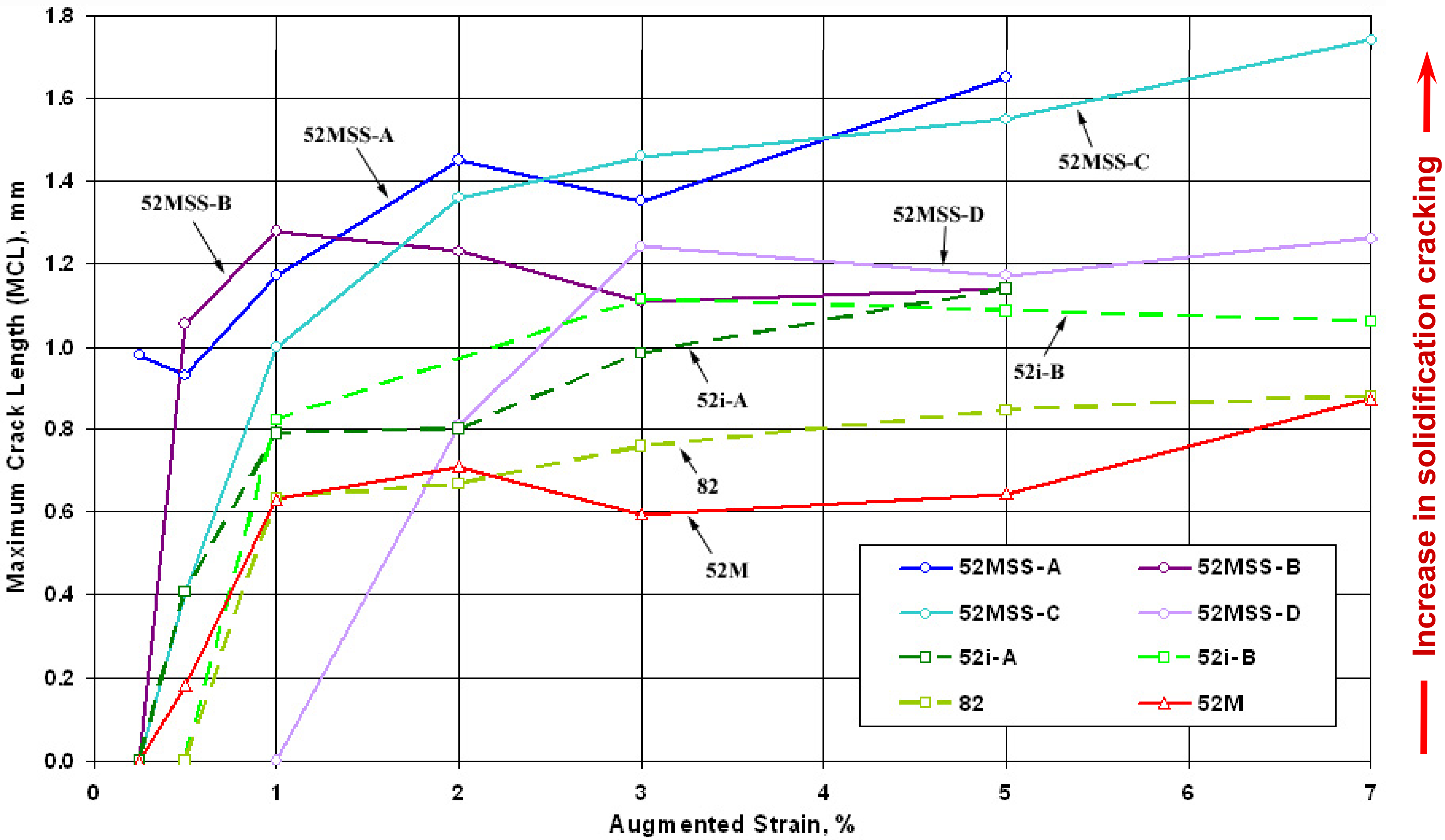


82 at 7% strain (10x)



(40x)

Maximum Crack Length vs Augmented Strain



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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

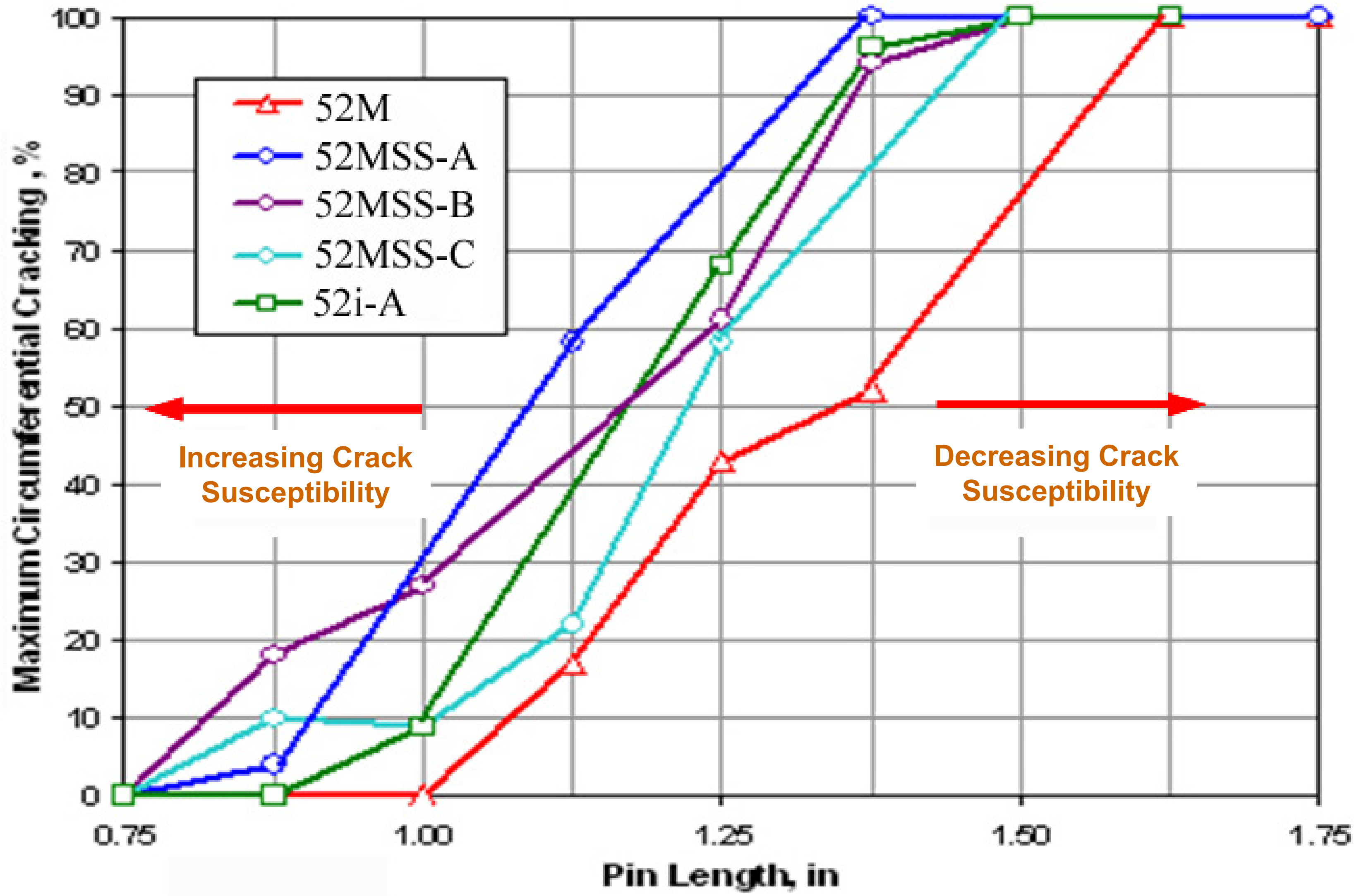
OSU cast pin tear test apparatus

Set of buttons is prepared for each heat

Button is melted by electric arc and cast into pin mold

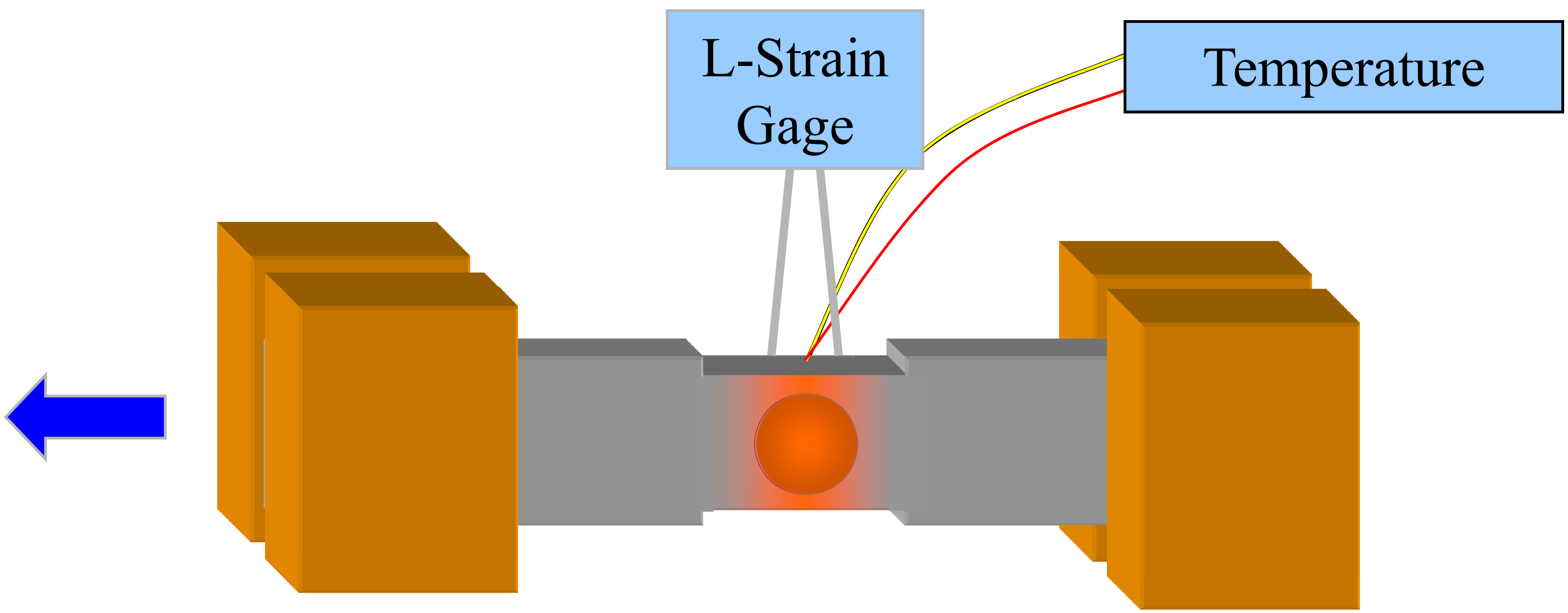
3/8" diameter pins are cast from 3/8" to 2-1/8" gauge length in 1/8" increments. Head and foot of pin restrain gauge length during cooling

Max Circumferential Cracking (MCC) vs Pin Length



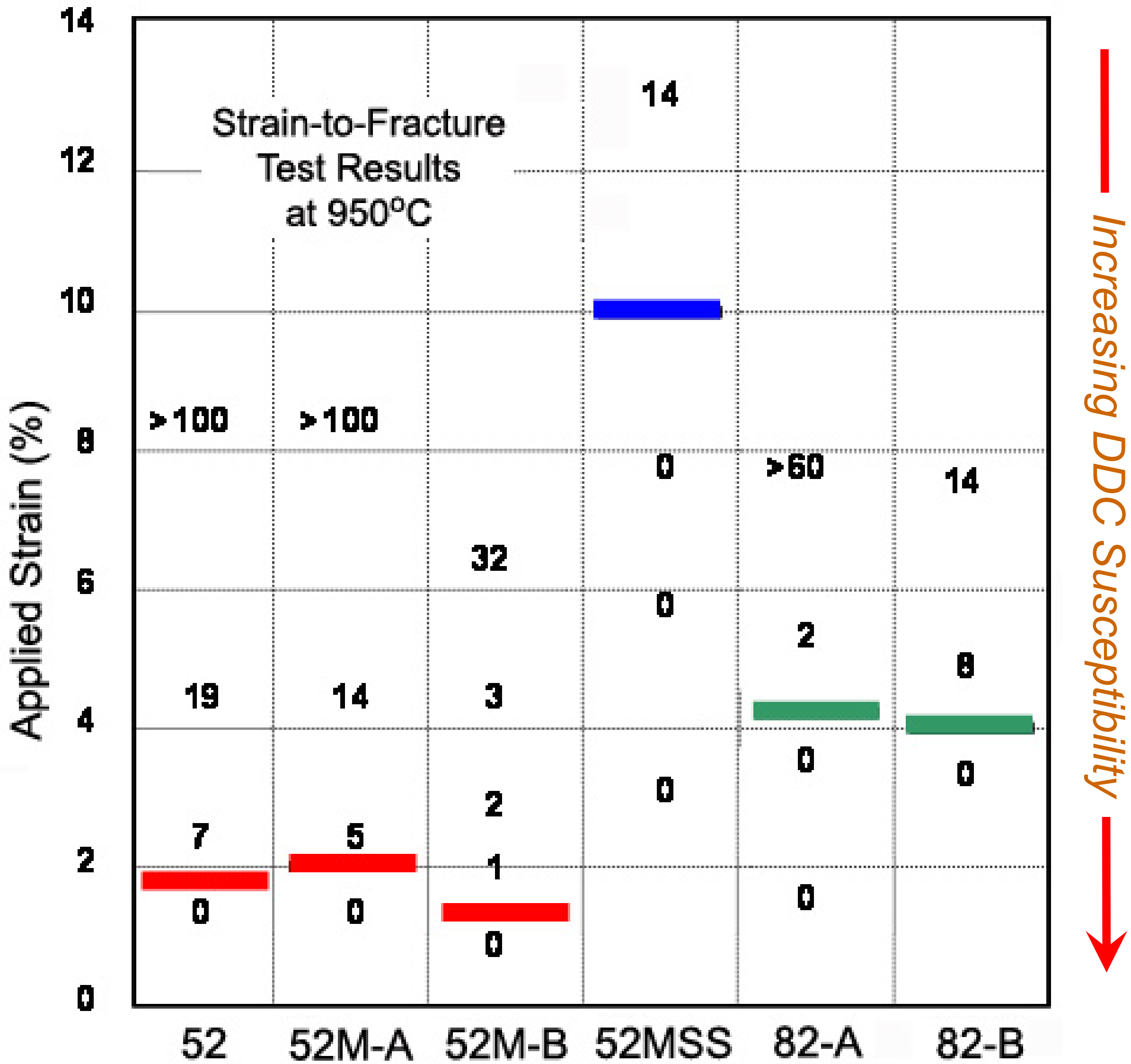
Strain to Fracture (STF) Test Description

- 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 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

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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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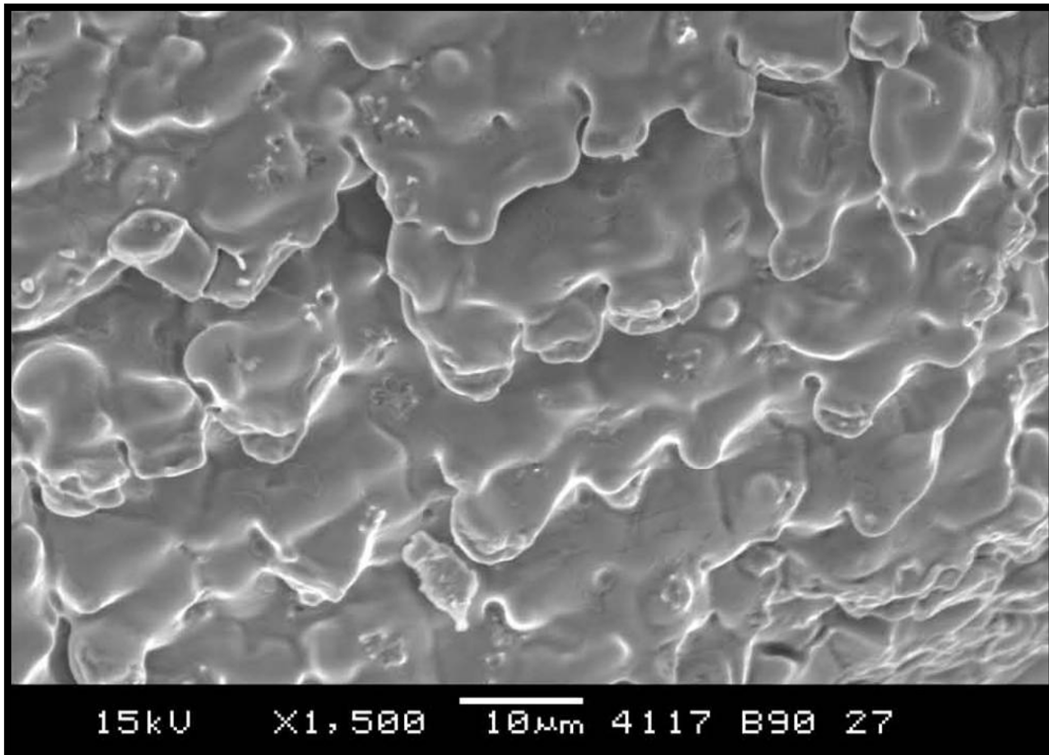
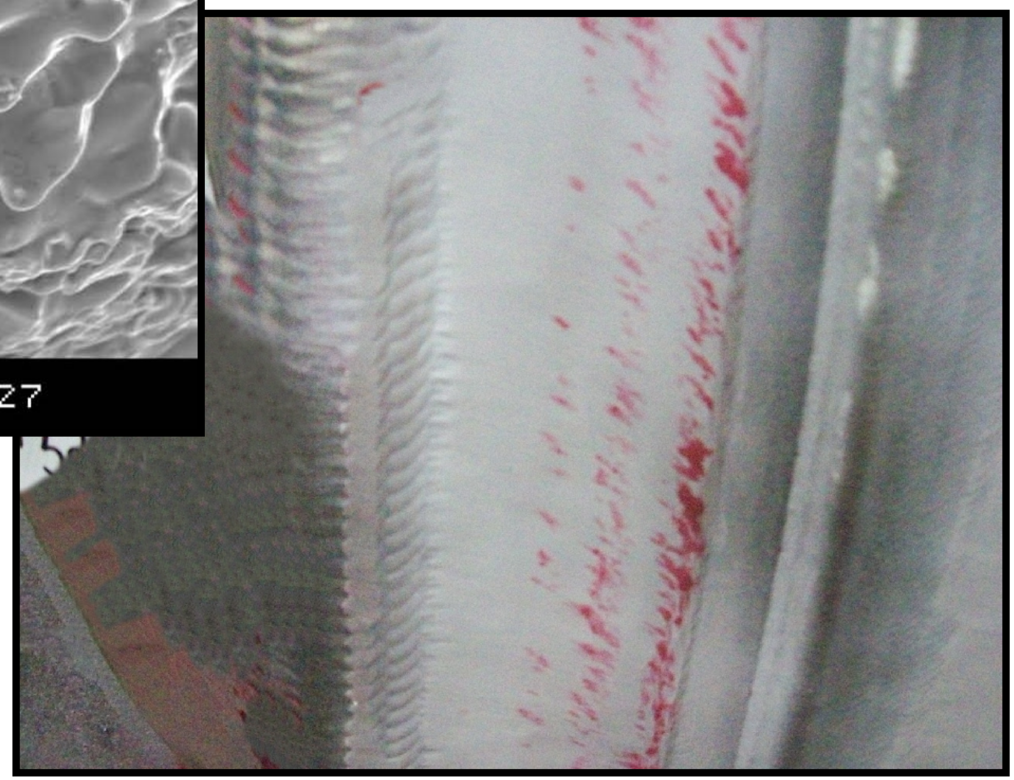
Excessive Dilution by Cast Stainless Steel



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*

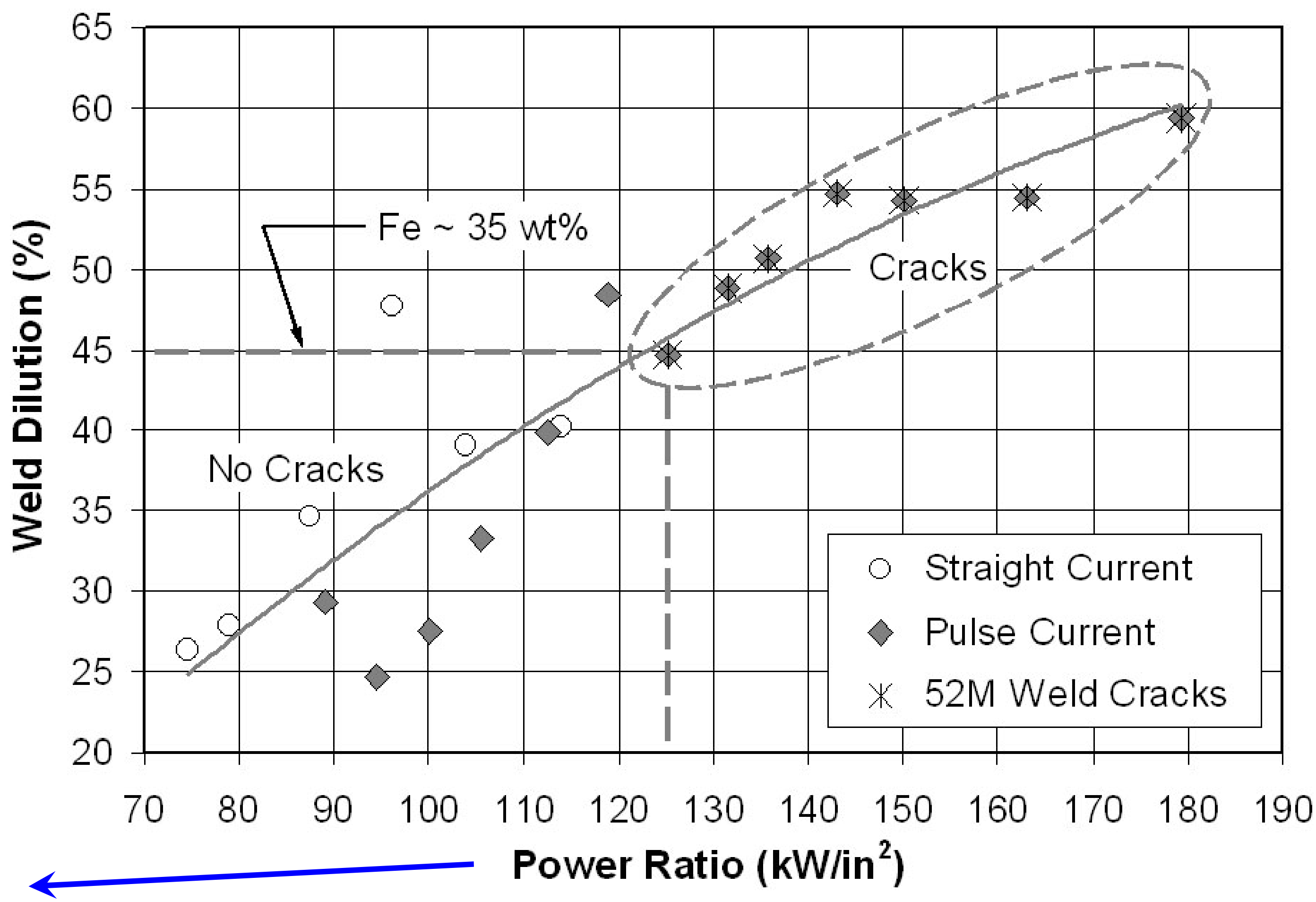
Dilution Testing

- Influence of dissimilar metal dilution on heats and classifications of Alloy 52M
  - Level of dilution with stainless steel that causes solidification cracking

    Testing to date shows 52M diluted with ~35% Fe increases susceptibility to hot cracking
  - S & P and Si threshold(s) that cause solidification cracking
  - Influence of Si on dilution and potential for increasing risk for solidification cracking
  - Optimization of Cast Pin Tear apparatus to improve resolution and sensitivity of test

Solidification Cracking by Dilution with Stainless Steel

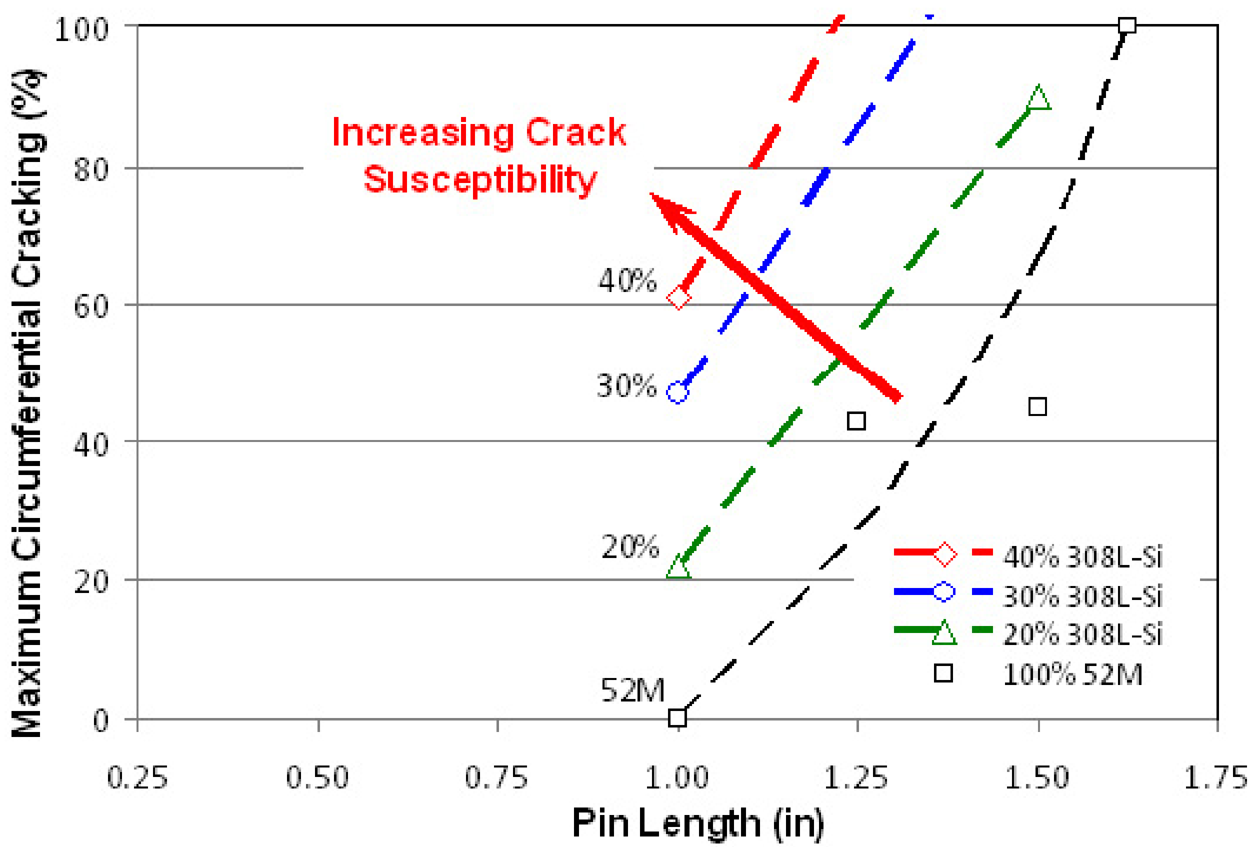
- 52M solidification cracking on 304L plate (not high S) material
- Solidification cracking occurs at high dilution
- Studies show 52M diluted with > 35% Fe is susceptible to solidification cracking



$$PR = \frac{(volt)(amp)}{\left(\frac{WFS}{TS}\right)(A_{wire})}$$

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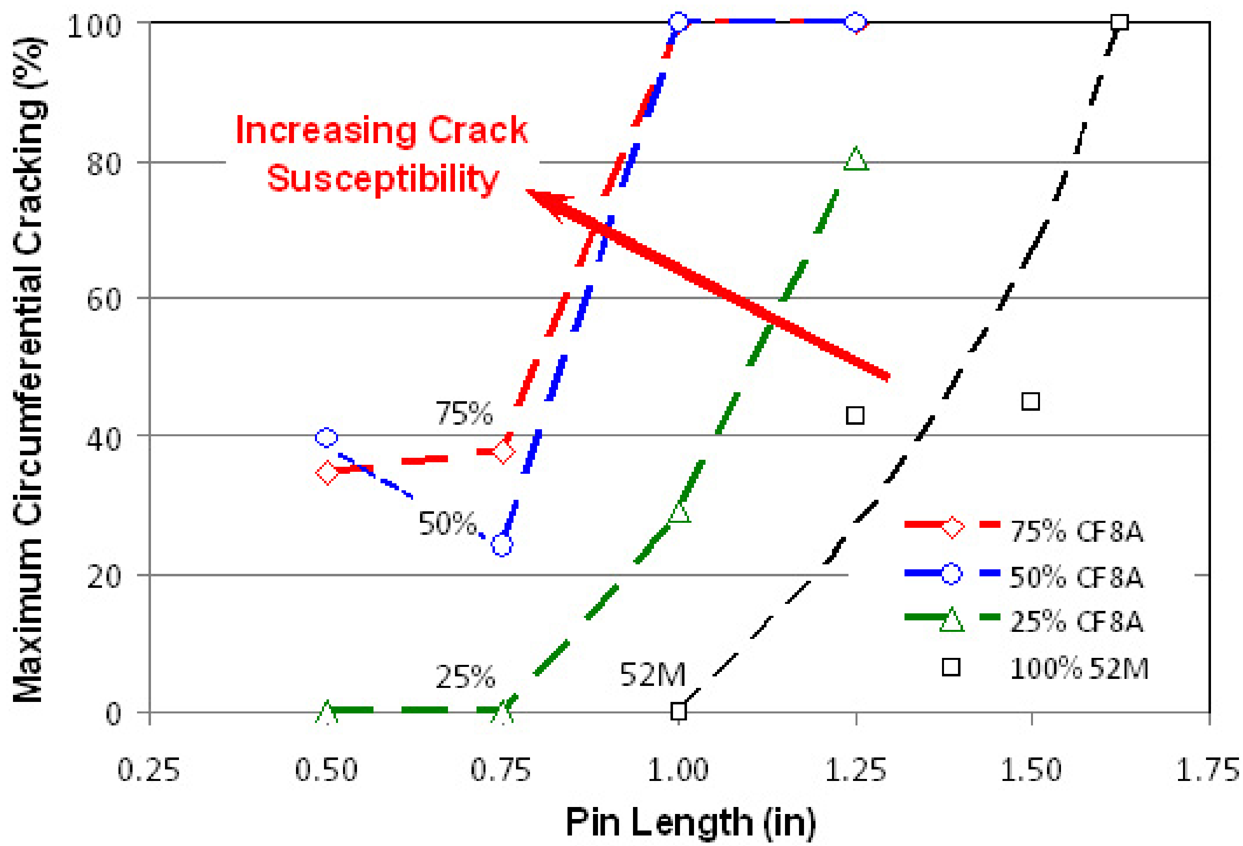
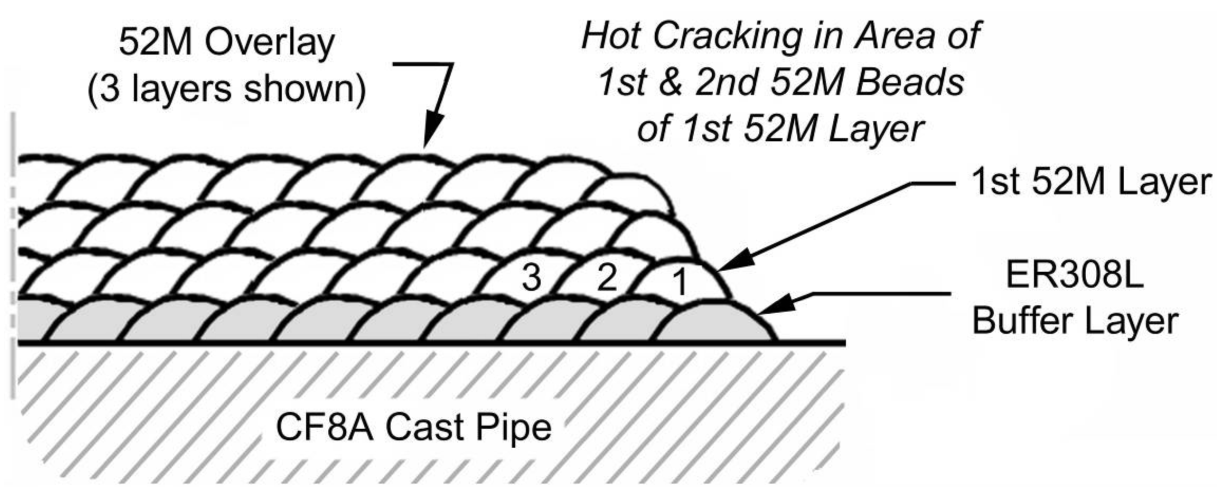
52M Dilution by CF8A *(Preliminary CPTT Data)*

	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



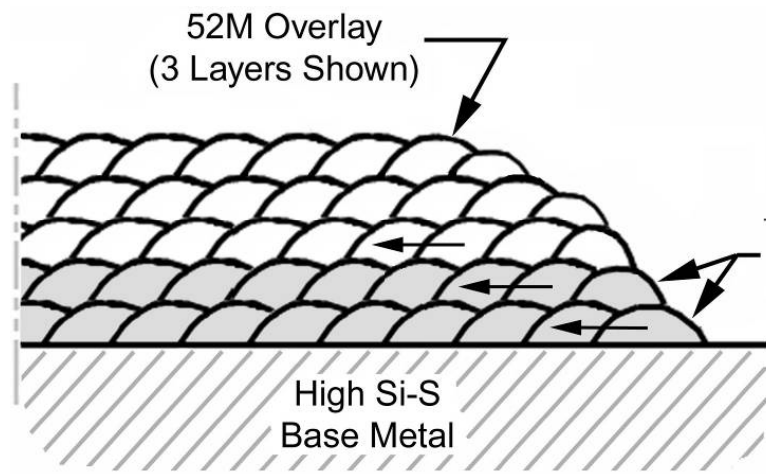
Dilution Control by Buffer Layer

- 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

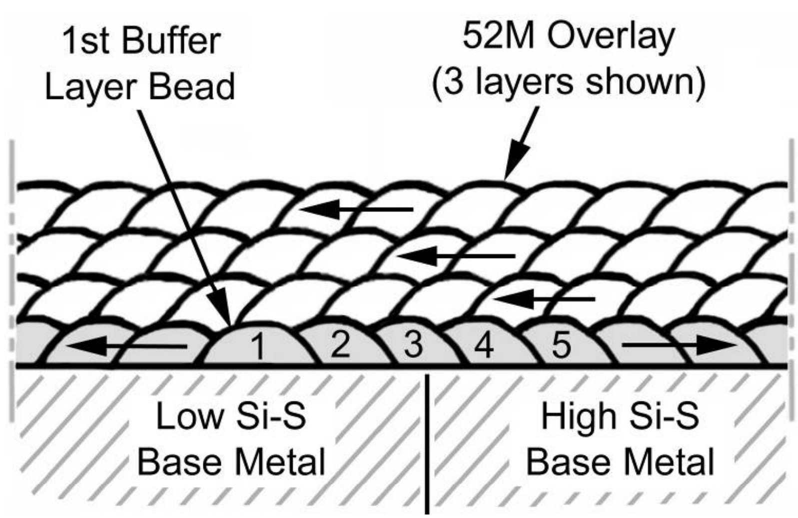


Dilution Control by Bead Placement

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

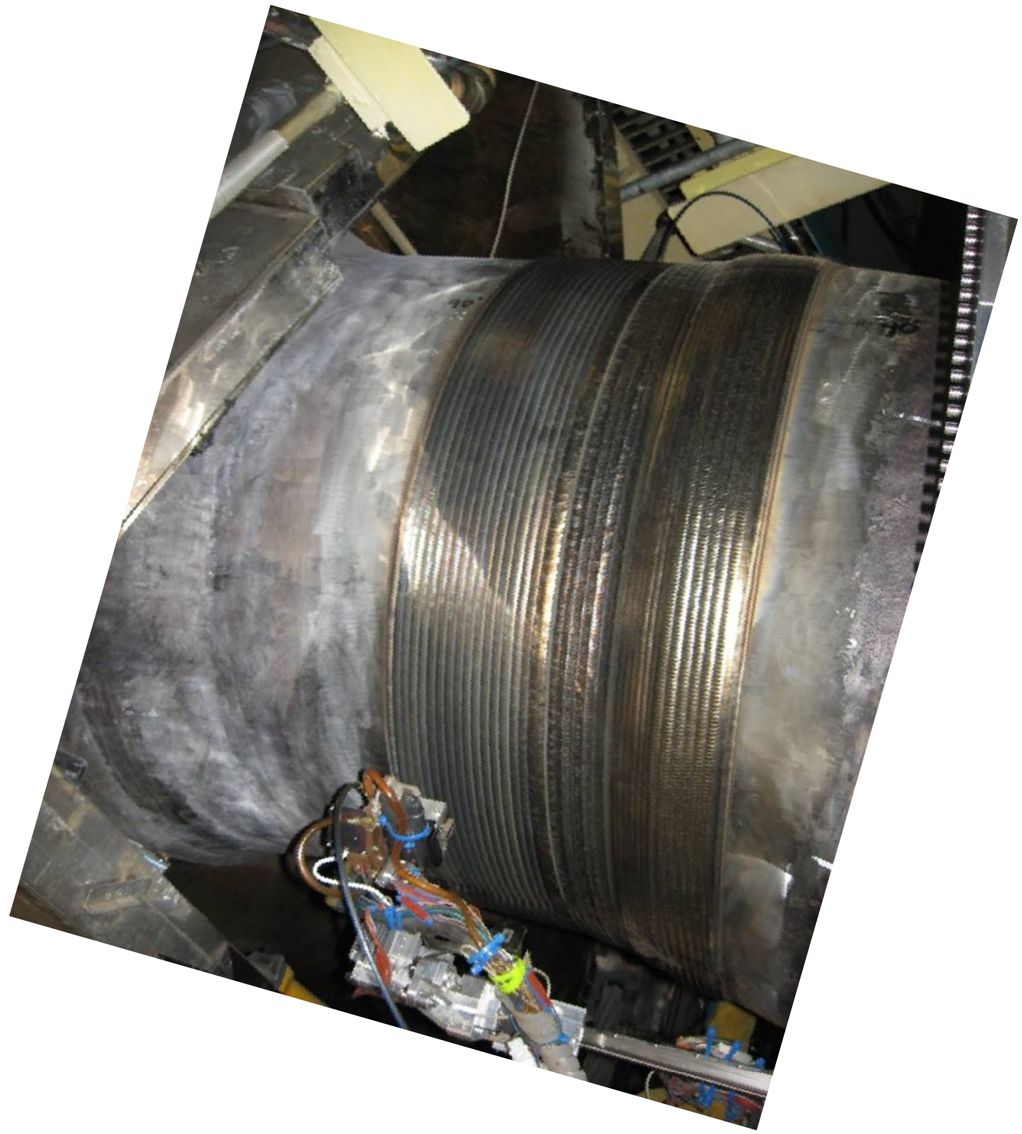


  - Bead placement to minimize dilution with deleterious base material



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



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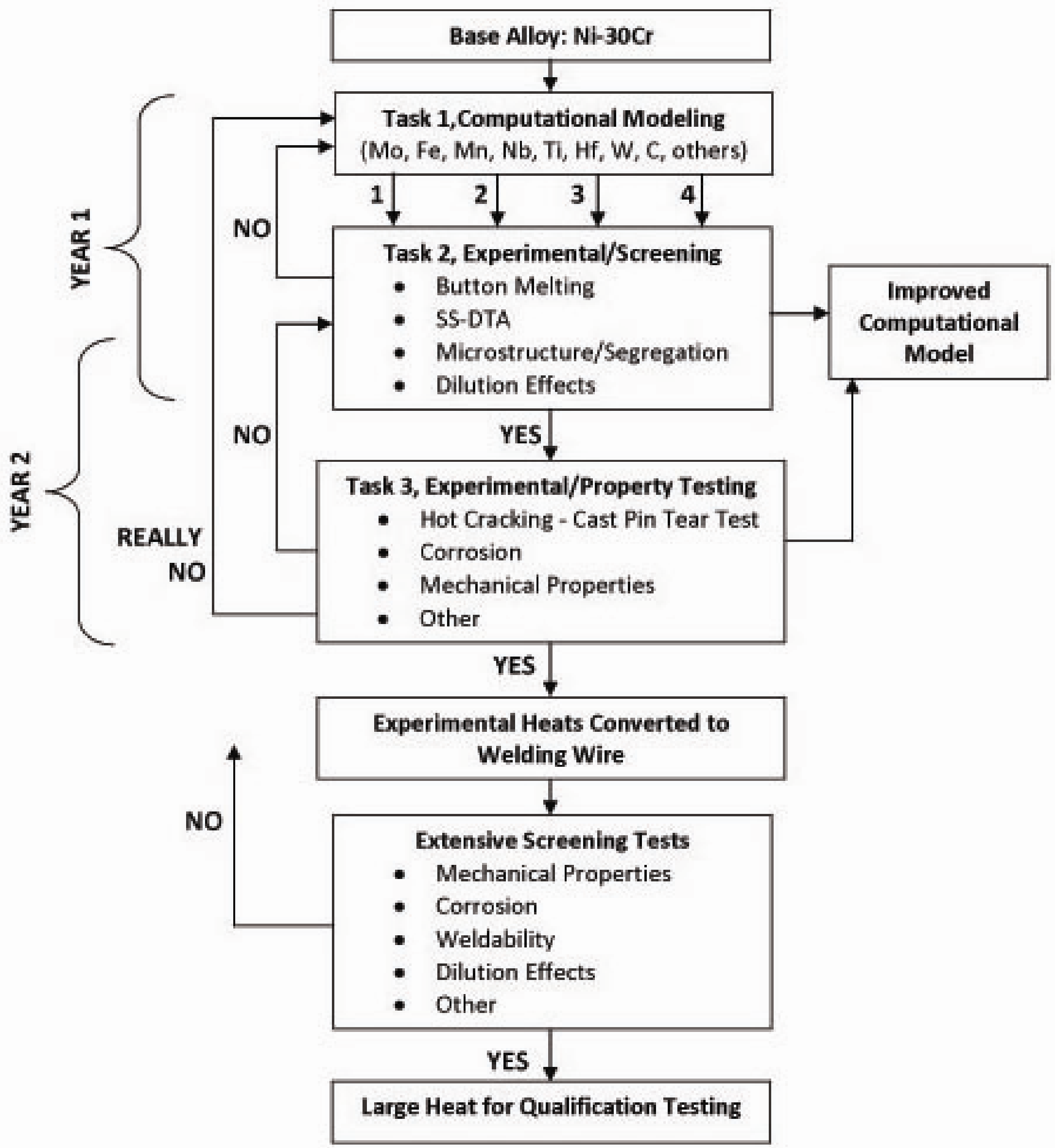
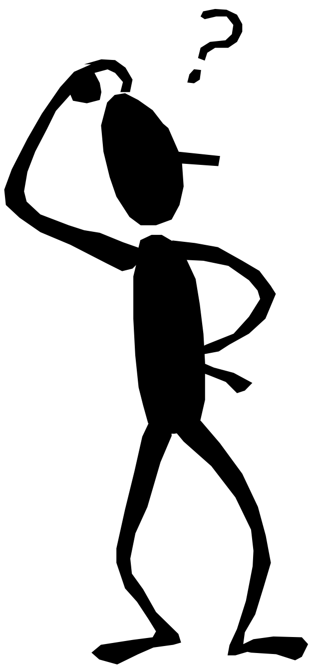
- Overview of Cracking Mechanisms (micro-fissuring)
- High Cr Nickel-Base Filler Metal Compositions
- Weldability Studies and Testing
  - Transverse Varestraint Test (solidification cracking & DDC)
  - Cast Pin Tear Test (solidification cracking)
  - Strain to Fracture Test (DDC)
- Filler Metal Susceptibility Comparison
- Dilution Studies and Testing
  - Power Ratio Versus Dilution
  - Dilution Study Using Cast Pin Tear Test
- **Development of New High Cr Filler Metal**

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

Thank You – Questions or Comments?



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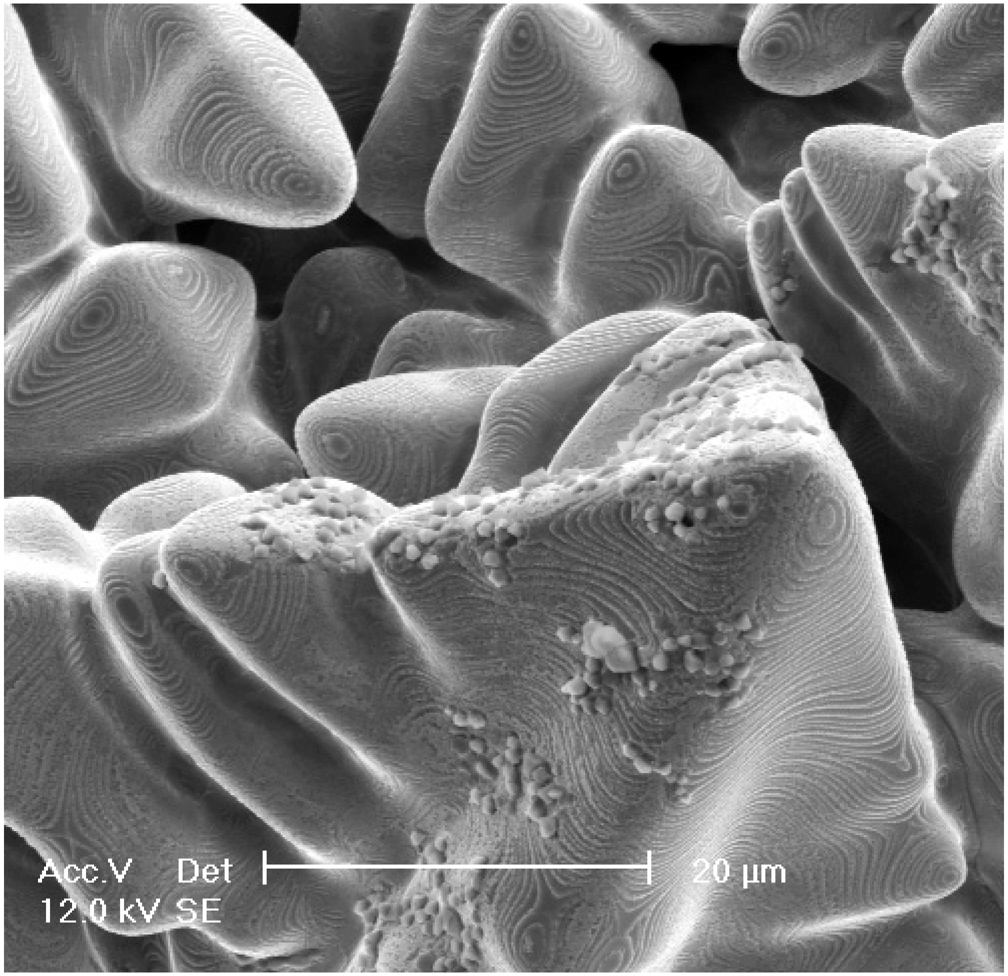
Acknowledgements



52M equiaxed dendrites with eutectic precipitates
(Courtesy of Jeff Rodales and Adam Hope)

EPRI Welding & Repair Technology Center
Project direction and funding

The Ohio State University
Professors:
Boian Alexandrov and John Lippold
Students:
Adam Hope and Ben Sutton
CPTT, Varestraint, Button Melting & Metallography

EPRI Welder & Machinist:
Mike Newman
Fabricated varestraint & STF specimens

EPRI Laboratory Technician
Mary Kay Haven
Metallography

Special Metals, KAPL, ThyssenKrupp
52MSS, MLTS-27, 52i respectively

Explanation of Regions in the Weld and Heat Affected Zone

Industry-NRC 2011 Meeting on Alloy 690 Research

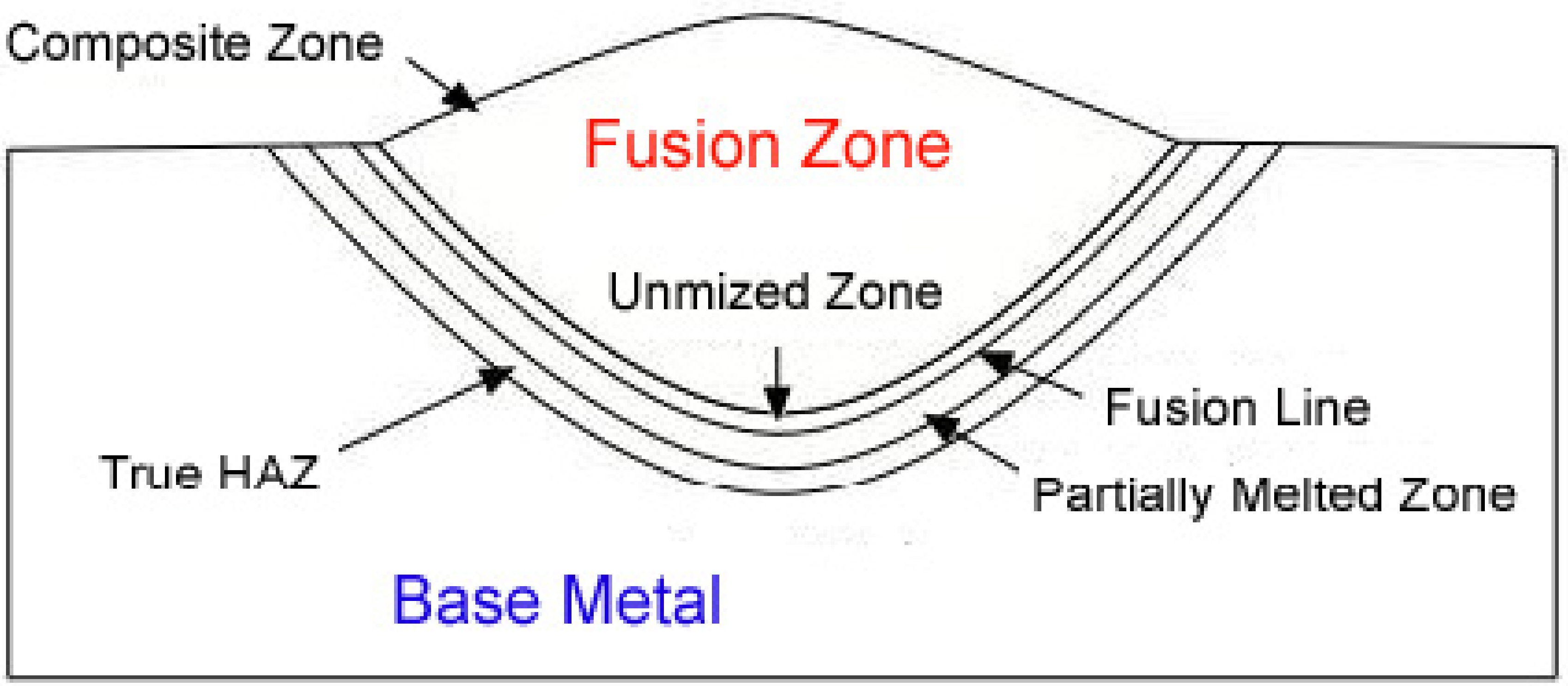
Rockville, MD

June 6, 2011

Steve McCracken & Eric Willis

EPRI Welding & Repair Technology Center

Weld Zones and Nomenclature Overview



Weld Zones and Nomenclature Overview

FUSION ZONE – area of weld with complete melting and resolidification)

Composite Zone (CZ) – Region where the weld metal is uniformly diluted with the base metal or previously deposited weld metal

Unmixed Zone (UMZ) – Completely melted and re-solidified base metal that does not mix with the composite zone (CZ); laminar melted region of base metal along fusion line; often referred to as the stagnant boundary layer

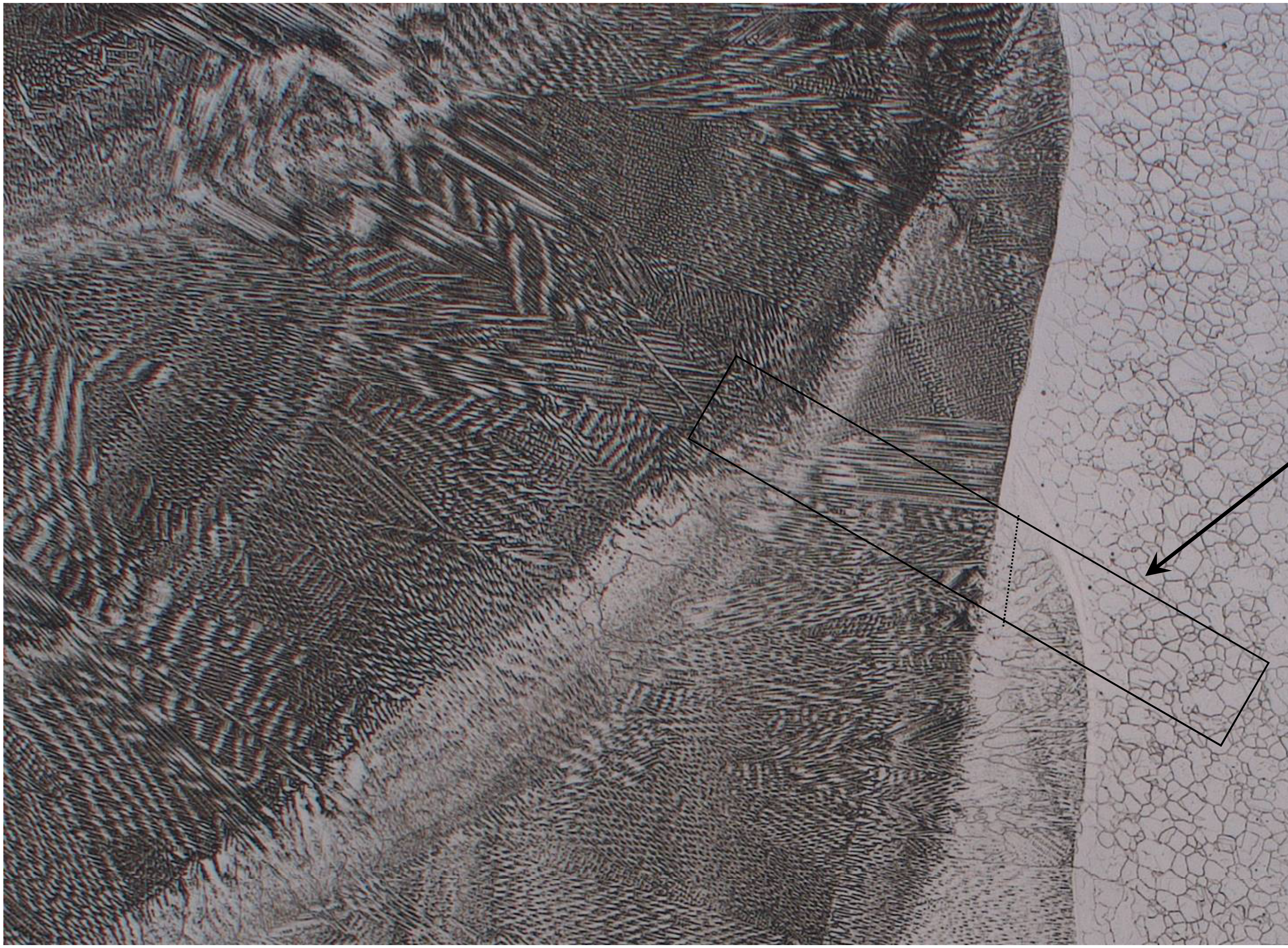
HEAT AFFECTED ZONE – area of base metal with partial melting or solid state reactions

Partially Melted Zone (PMZ) – Transition region in base metal between 100% melting (UMZ at the fusion line) and the 100% solid (true HAZ); liquation (localized melting) at grain boundaries observed; constitutional liquation of certain particles can occur; complete carbide dissolution

True HAZ (T-HAZ) – Un-melted zone in the base metal that is affected by the heating and cooling weld cycles; all reactions are in the solid state; area where carbide dissolution and grain growth can occur

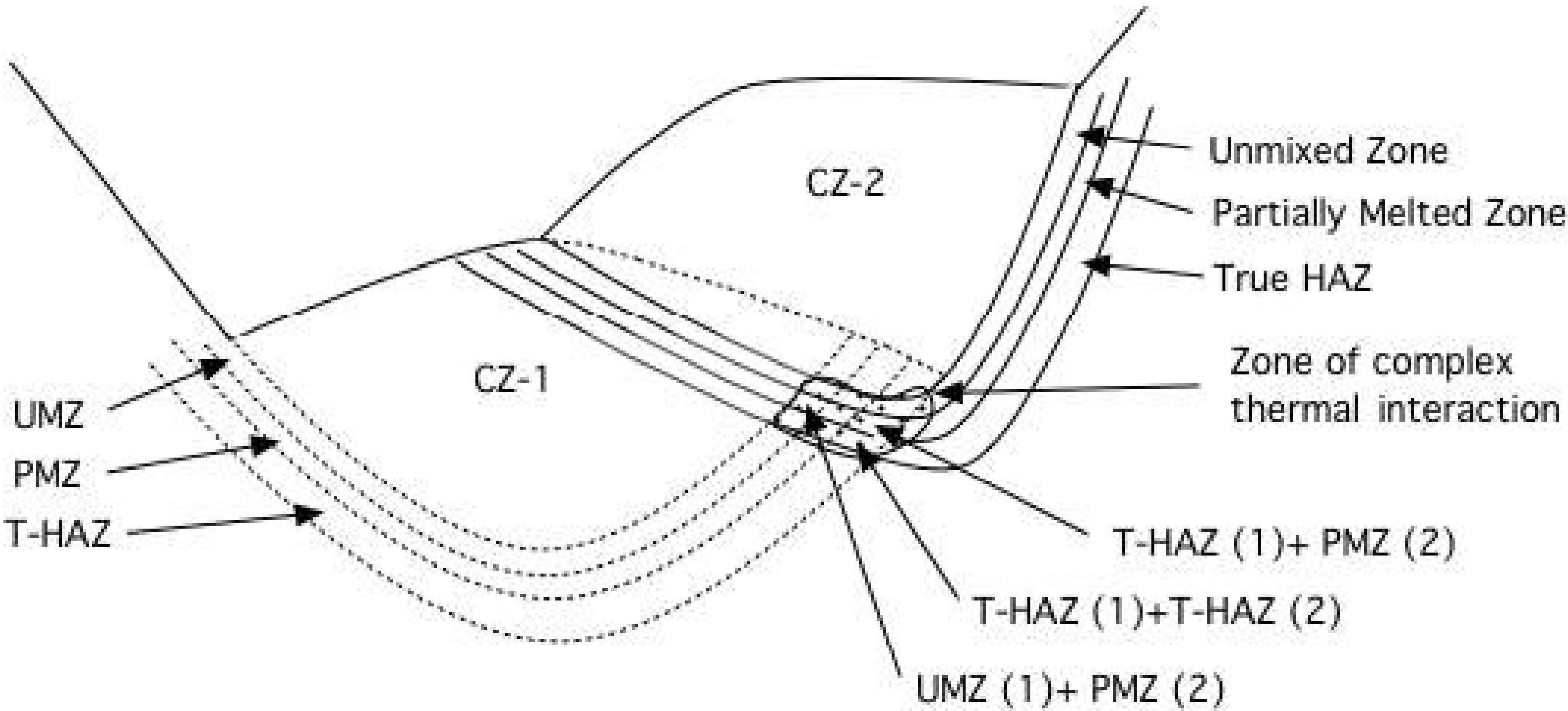
FUSION LINE – dividing line between the Fusion Zone and Heat Affected Zone (line between UMZ and PMZ)

Weld Metal and HAZ for a Multi-pass Alloy 52/690



Complex compositional interactions, mixing, and thermal histories occur in this area

Zones in a Multi-pass Weld



Pass 3 to 1 Weld Metal Traverse

Pass 3
CZ-3

Pass 2
CZ-2

Pass 1
CZ-1

As-deposited
CZ-3

Re-heated zone of
CZ-2 from Pass 3

As-deposited
CZ-1

Re-heated
zone of
CZ-1 from
Pass 2

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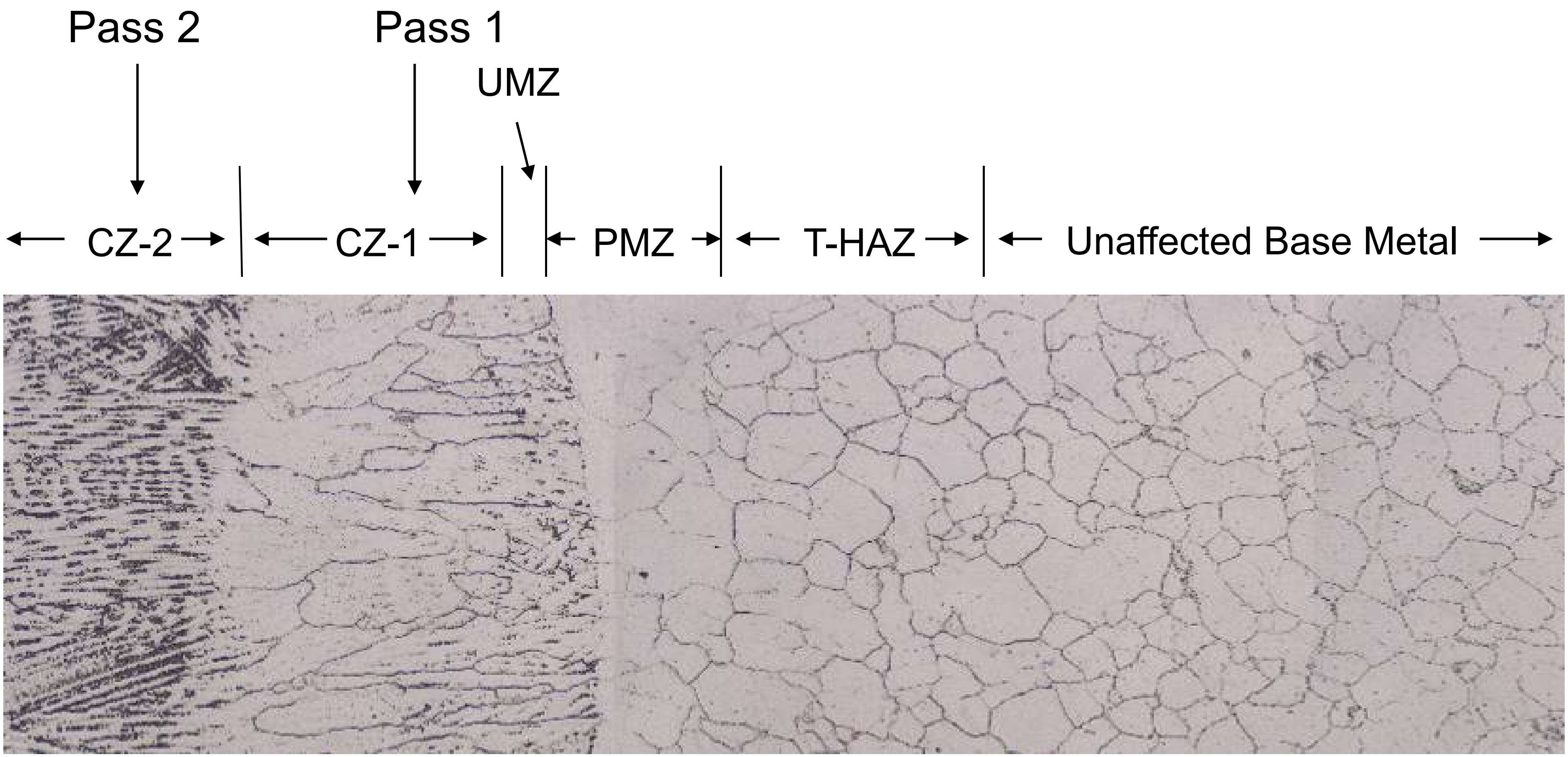
Pass 2 to Unaffected Base Metal Traverse



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