Joining Technologies for Coal Power Applications

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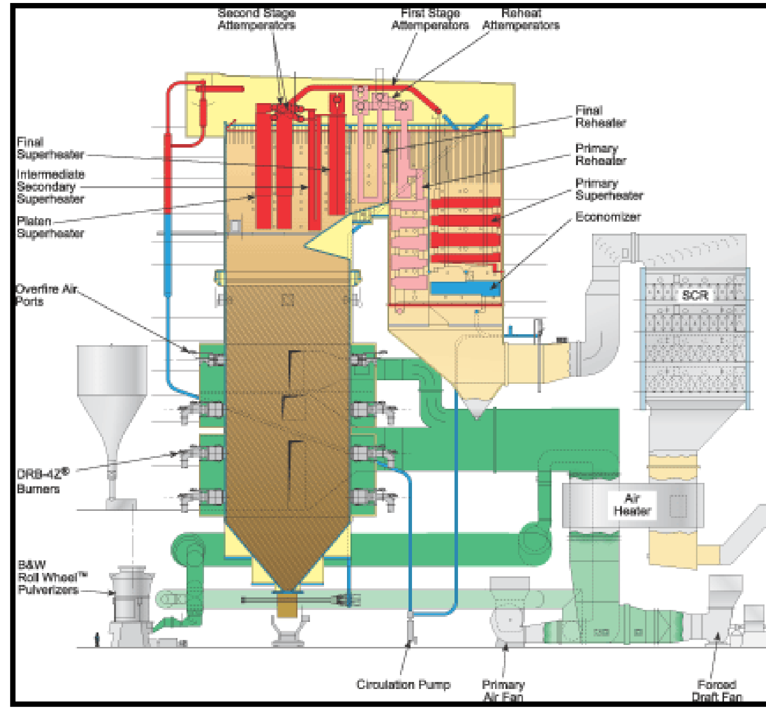
Next Generation coal-fired Power Plants will employ advanced materials

- The next generation of gains in efficient fuel utilization will require a move to higher system pressures and temperatures.
- Advanced ultra super critical designs are calling for some system components to operate at 760C and 5000 psi
- This will require new materials.
- Performance drivers for heavy section components (such as headers and pipes in superheaters and reheaters):



  - **High creep performance and high elevated temperature strength**
  - **Good corrosion/oxidation resistance, both fireside and steamside**
  - **Strong performance in thermal fatigue**
  - **do so at the lowest possible cost**

B&W SCR Boiler

Barriers to implementing new materials

1. Cost
2. Cost
3. Cost vs. Life
4. New materials must be able to be fabricated into components

   Joining, machining, forming needs to be achievable at an acceptable cost

5. Fabrications (not just the materials themselves) need to achieve the design life in-service.

   Joints must be designed so that the assembly achieves long term performance in creep, fatigue, corrosion, etc.

6. Fusion Welding (the most common fabrication technology) can cause serious degradation to the highly customized microstructures and chemistries of advanced alloys

   Fusion welding is usually very successful at producing a joint that can achieve or exceed parent metal strength at both room and elevated temperatures.

   The problem comes in creep, fatigue, residual stress, and corrosion

Technical Challenges around Fusion Welding of Advanced Alloys

<u>Advanced Alloy Class</u>

- NFA / Ferritic ODS Alloys
  - MA 956
  - Kanthal APMT Adv.
- Creep Enhanced Ferritics
  - P91/P92
- Ni based Alloys

<u>Fabrication and Joining Issues</u>

- Can't be fusion welded without destruction of dispersoid
- Weld nugget microstructure unfavorable for critical properties
- Heat input from joining creates unfavorable HAZ properties (Type IV Creep Failure)
- Melt-Solidification process may create deleterious phases for creep or corrosion (large DAS, segregation, possible TCP in Mo bearing Ni alloys)

Joining Technologies for Coal Power Applications

Technology Development Objective:

Develop method(s) of joining next generation materials that result in joints with ideally the same hot strength, creep strength, fatigue, and corrosion/oxidation properties as the base metal.

Explore concepts for producing lower cost fabricated structures to more effectively utilize advanced materials

Approach

Develop an alternative joining technology, Friction Stir Welding and demonstrate the approach on three classes of advanced alloys:

- Nanostructured Ferritics (including Oxide Dispersion Strengthened steels -ODS alloys)
- Creep Enhanced Ferritics (including 9-Cr/1-Mo steels)
- Precipitation Strengthened Nickel-based superalloy Haynes 282

Develop methods to joint dissimilar advanced alloys

NFA to lower cost austenitic (nozzle to tube/pipe or socket)

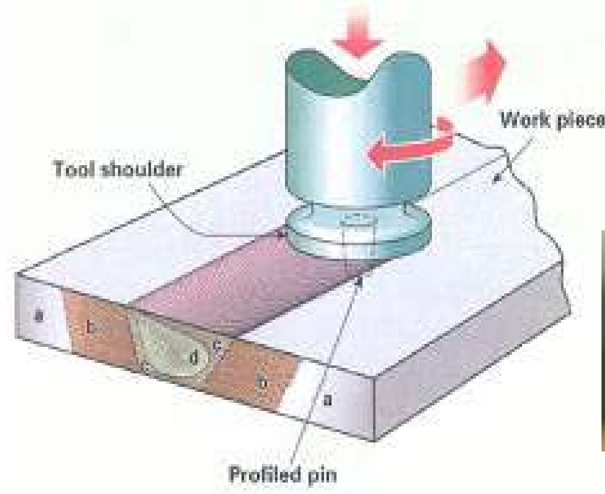
Outline of Talk

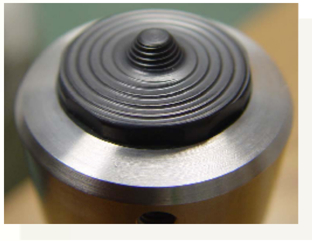
- FSW Overview / Potential Process Advantages
- Case Studies
  - FSW of NFA/ODS
  - FSW of P91 (TMCP Product)
  - FSW of Haynes 282 (Gamma prime strengthened nickel alloy)
  - FSW of MA956 cladding on boiler plate (2.25Cr, 1Mo)

Friction Stir Joining

Solid-state joining processes
(no material melting)

- Spinning, non-consumable tool is plunged into the surface of a material.
- Friction and plastic work energy heats the material sufficiently to lower the flow stress.
- When material softens, the tool is then translated along the joint line causing material in front of the pin to be deformed around to the back, and forged into the gap behind the traveling pin
- The resulting joint is characterized by:
  - Fine-grained "nugget" composed of a recrystallized and transformed microstructure





Economic Advantages

- Single pass method – Faster on thick section welds
- No Consumables
- No Environmental Emission
- No "Expert" Operators
- Lower energy consumption than equivalent fusion weld

Process advantages

- Often lower peak temperature and total heat input than fusion welding, so:
  - Lower residual stress and distortion
  - Reduced HAZ
  - Less sensitization for corrosion
- Higher toughness joint, Better damage tolerance and fatigue performance
- Fine grained nugget less susceptible to hydrogen induced cracking
- Fine grain nugget is more amenable to NDE (x-ray, ultrasonics, etc.)

FSW of NFA / ODS

Kanthal APMT
Kanthal APMT Advanced
MA 956

Friction Stir Welding of 20Cr-5Al-Y-Ti-Hf Ferritic ODS (Sandvik Kanthal APMT)

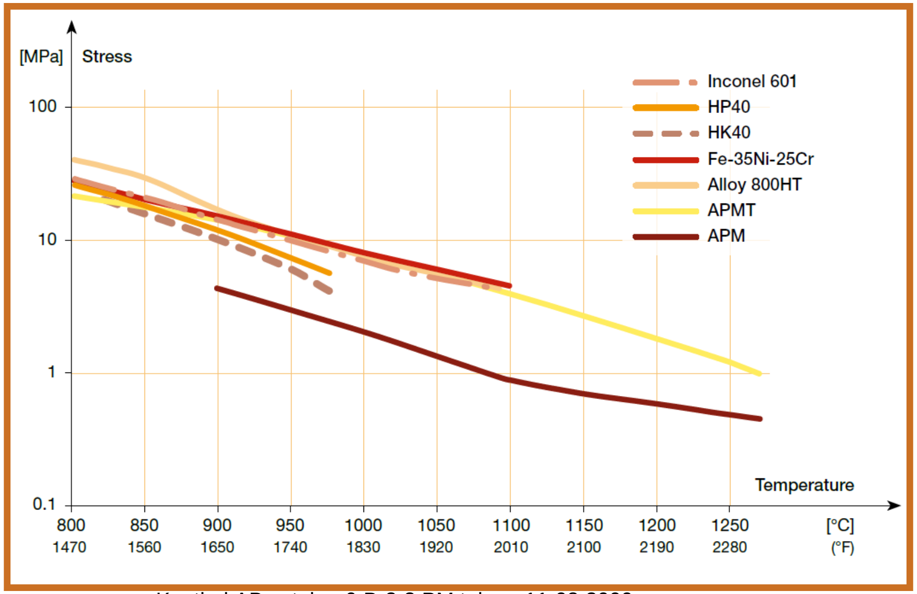
- 20Cr 5Al Ferritic steel with good high temperature creep resistance and oxidation resistance similar to some austenitic steels (contains nanophase carbides and oxides)
- Gas atomized product not an MA alloy
- Alumina former to protect against corrosion and carburization

Composition (wt%)

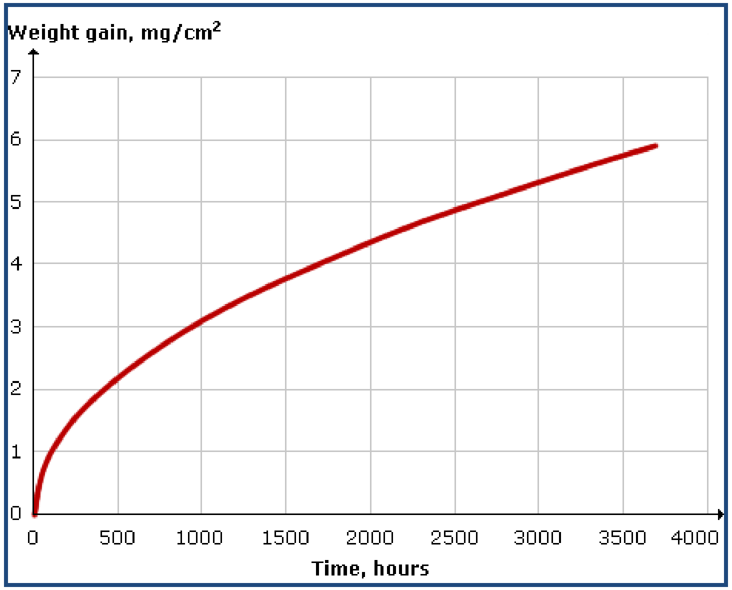
Fe	Cr	Al	Y	Zr	Hf	Ti	C	S	N
balance	20-23	5.0	0.1	0.05	0.1	0.02	0.03	0.002	0.05

G.J. Tatlock et al., Materials and Corrosion 2005, 56, No. 12

10,000 hr Creep Rupture



Kanthal AB catalog 6-B-2-3 PM tubes, 11-08 3000



Designed for very high temperature applications in ethylene production and heating elements

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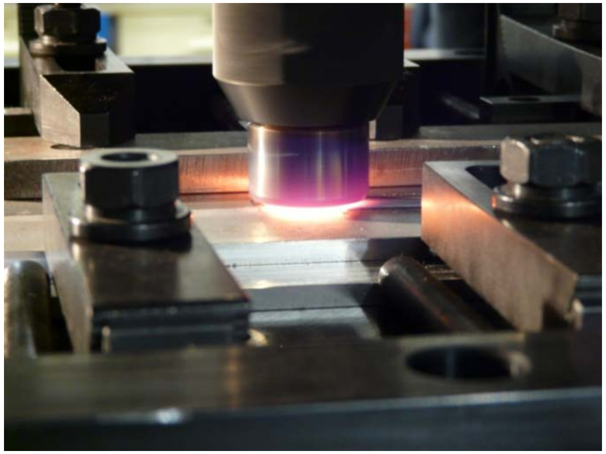
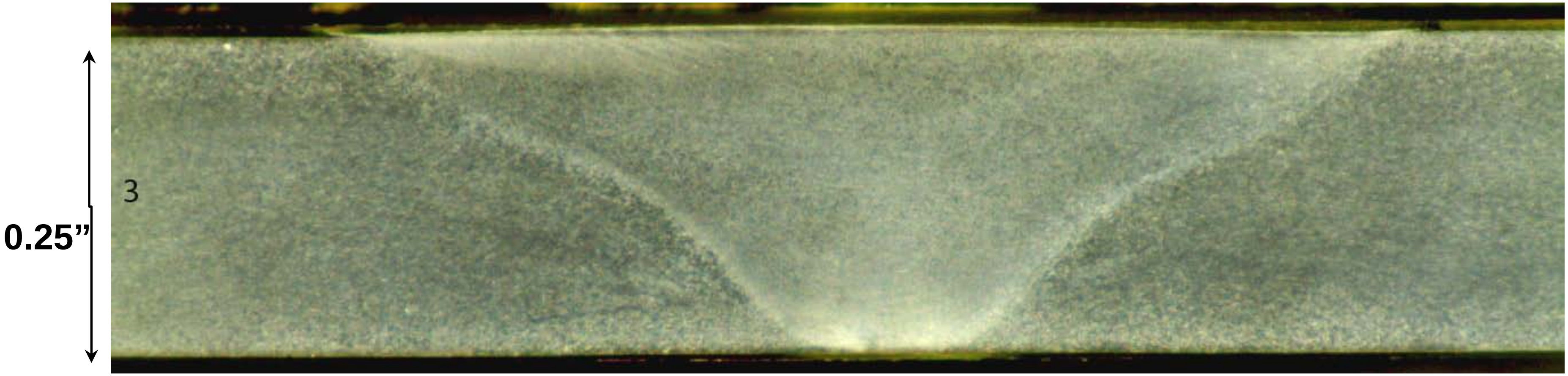
FSW Parametric Study

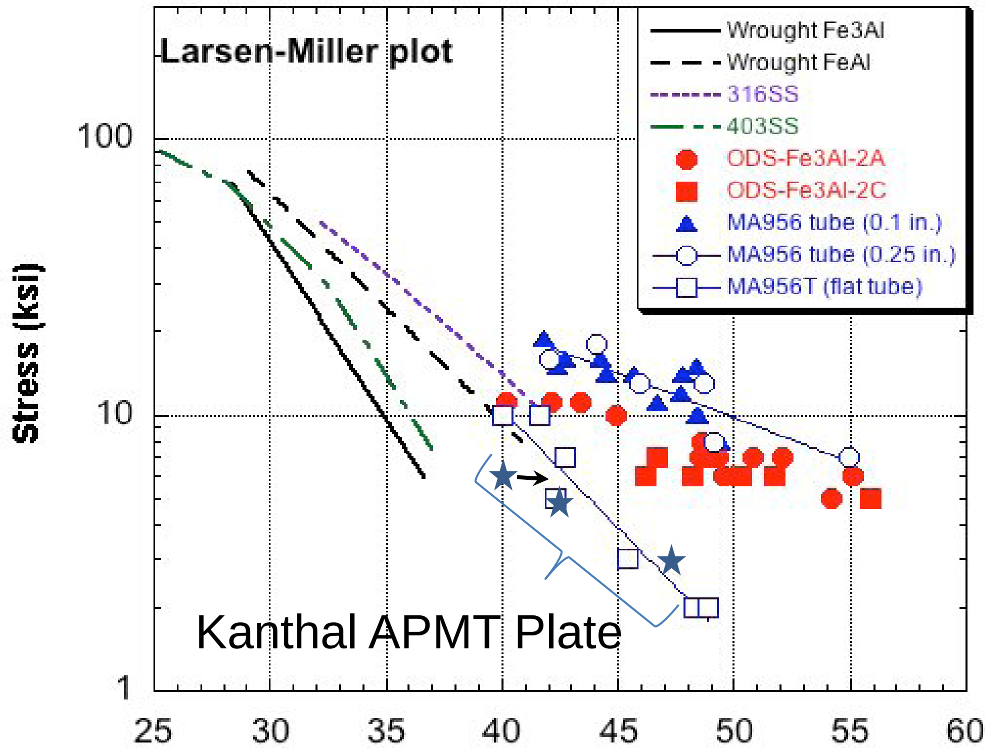
- Tool: PCBN Convex scrolled shoulder stepped spiral pin tool, 0.25” pin length
- Process Variables:
  - Weld speed (4 – 8 ipm),
  - Spindle speed (300 – 600 rpm),
  - Tool load (load controlled at 3000 – 7000 lbs)

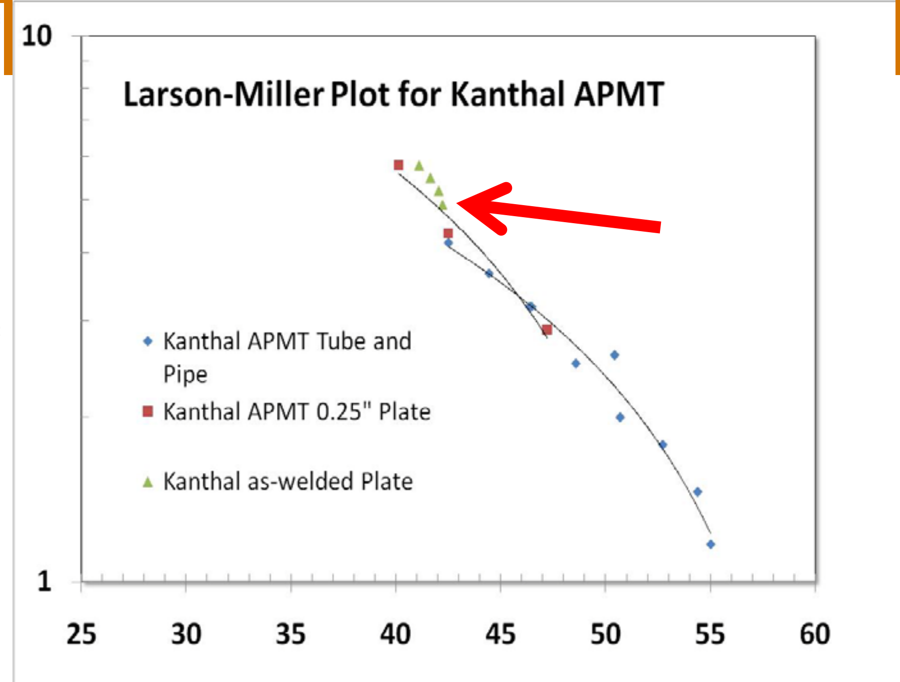




Fully consolidated, defect-free welds were made under a range of process parameters

Creep Rupture data for Kanthal





$$P = [T(F)+460][20+\log t_r(h)](10^{-3})$$

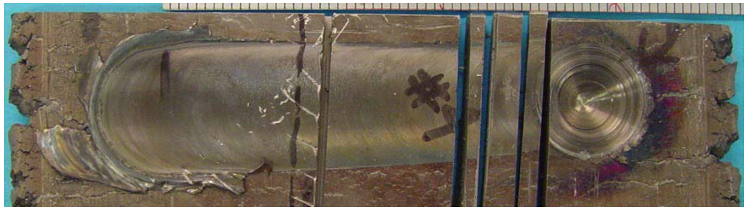
- Creep Rupture Tests on Kanthal Plate Base Material
- Kanthal Weld Material tested at 750ºC
- FSW is producing weld metal with similar creep rupture properties to base material

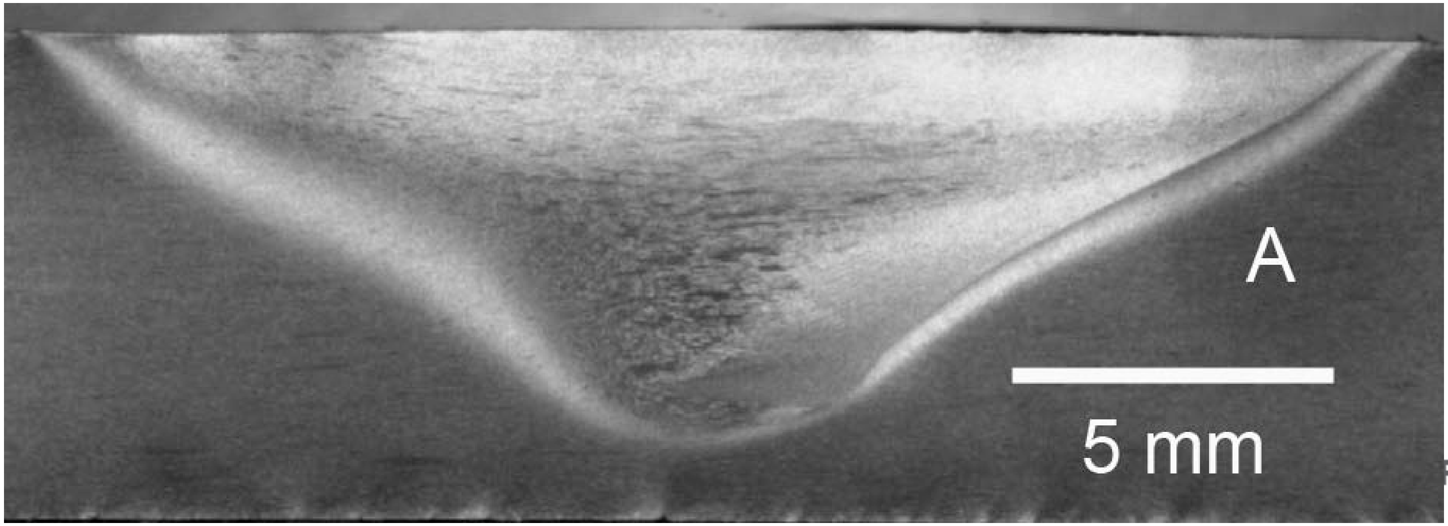
Weld metal data is on trend, slightly higher than base metal

FSW Process studies on hot rolled MA956

Material	Fe	Cr	C	Si	Mn	Al	Ti	Y2O3	Mo
MA956	bal.	18.5-21.5	0.1 max.	NA	0.30 max.	3.75-5.75	0.2-0.6	0.3-0.7	NA
MA957	bal.	13.5-15.2	0.012-0.017	0.02-0.07	0.05-0.12	0.055-0.17	0.95-1.38	0.19-0.28	0.28-0.32
430L	bal.	17	0.02	0.9	0.2	NA	NA	NA	NA

- Process development has resulted in consolidated defect free welds
- Tool: Q60 W-Re-PCBN composite with convex scrolled shoulder with stepped spiral pin, pin length 0.25"
- Process parameters:
  - Weld speed: 2-6 ipm
  - Tool rotational velocity: 200-400RPM
  - Tool loads: 3000-10,000 lbs





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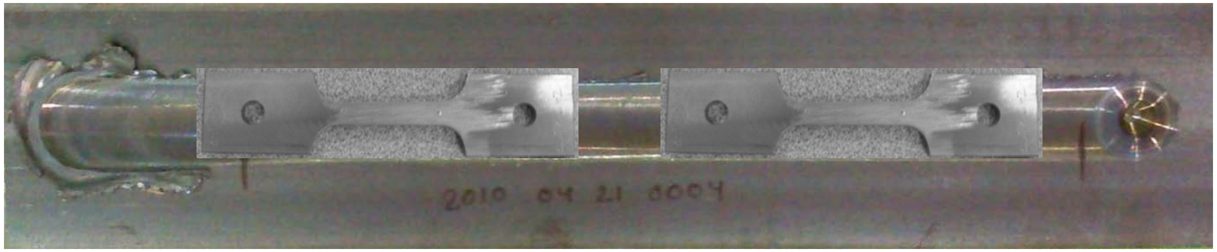
FSW Process studies on hot rolled MA956

- Longitudinal weld metal only creep tests (100MPa, 750°C) will begin in spring 2012
- More MA956 powder ordered from Special Metals and will be processed into plates for further FSW development
- Cross weld tension and creep will be done on plates normalized and tempered after rolling



We expect this to behave in a similar way in creep to the Kanthal, but there is debate in the literature about the effects of FSW on the dispersoids.

Summary of progress
FSW in P91

Creep Enhanced Ferritic
(Cast plus TMCP Product)

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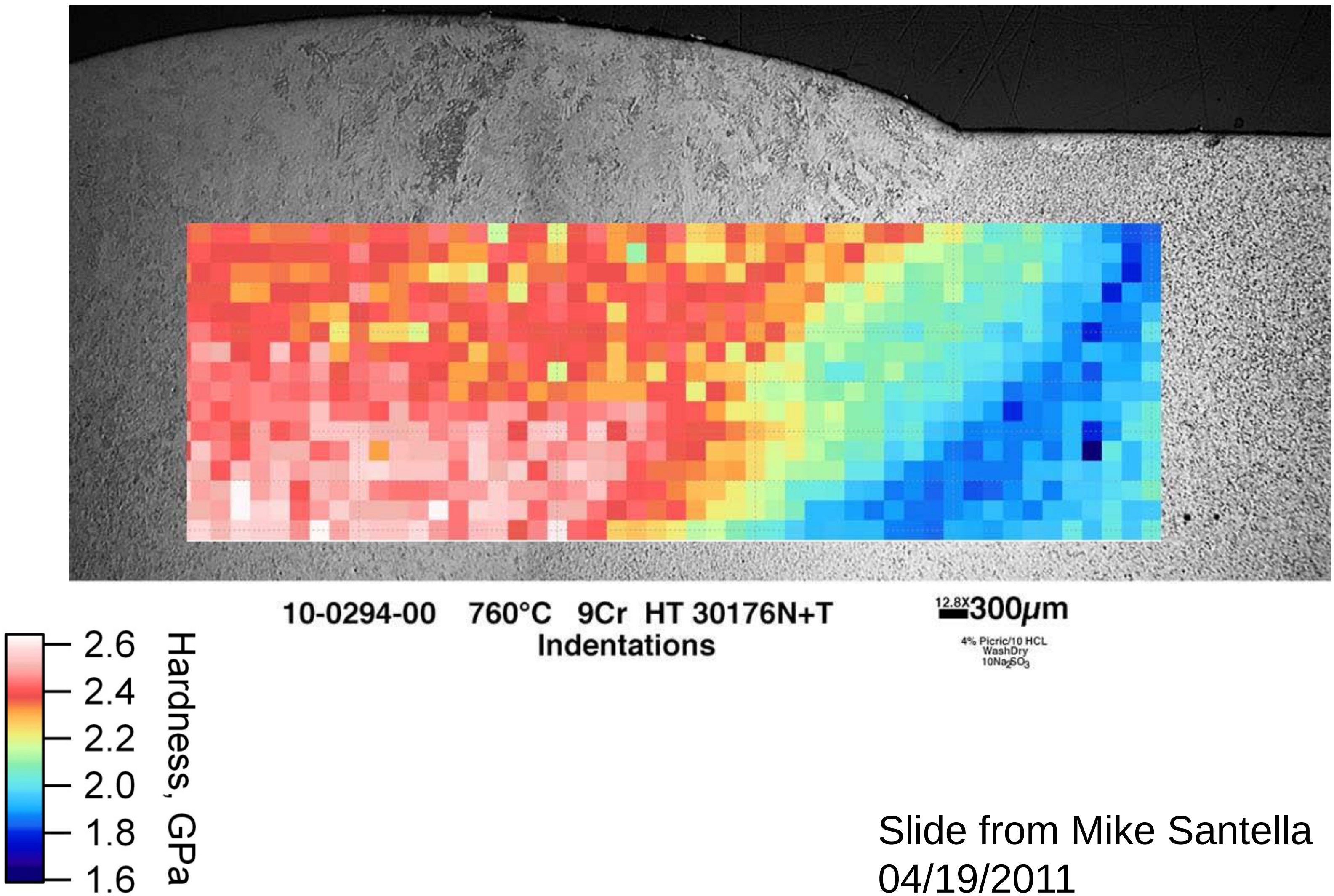
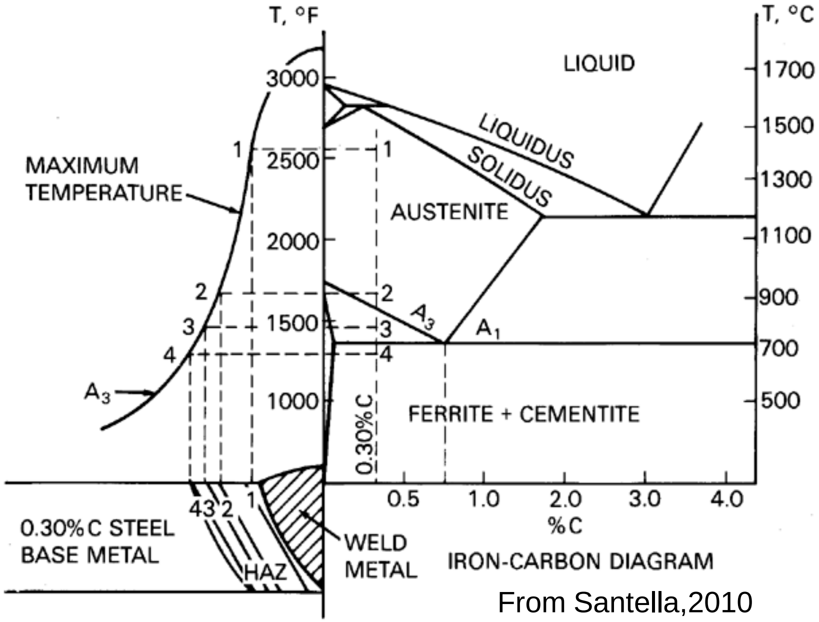
Soft zone in HAZ of 9Cr steel



Slide from Mike Santella - ORNL
04/19/2011

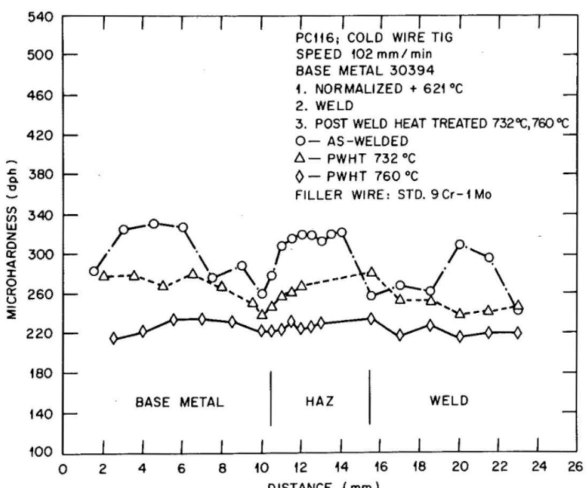
Problem with T91,92-P91,92 outlined by Santella



From Santella,2010

- Type IV Creep Failure

Solutions:
PWHT
Go to 9Cr-B steels



From Santella,2010

FSW may play a role
Lower peak temp and lower time at temp
Higher HAZ property minima?
More gradual property gradient across HAZ

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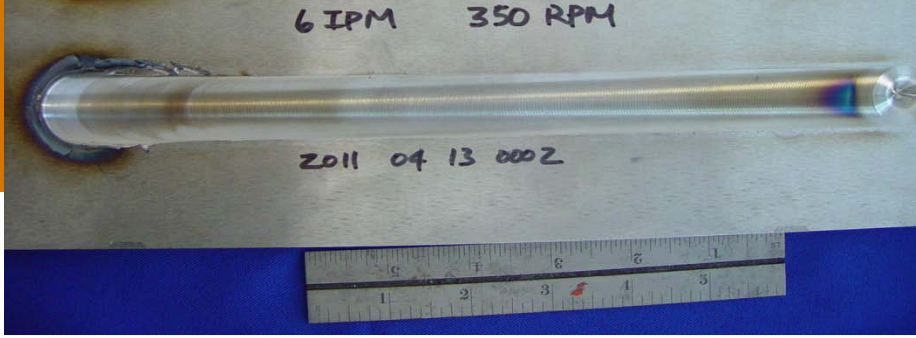
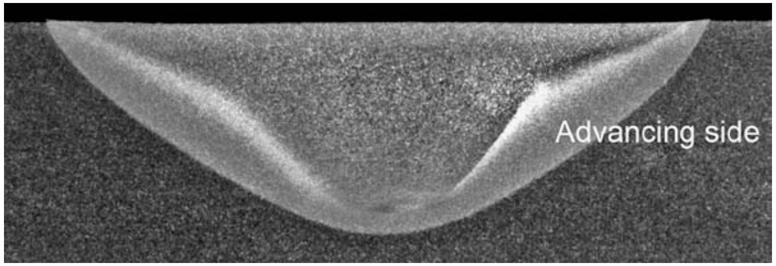
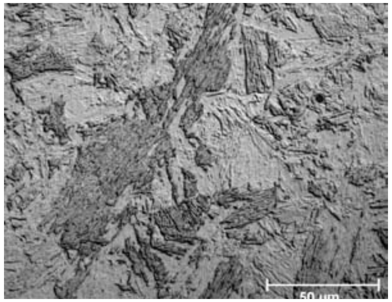
P91 FSW Welds



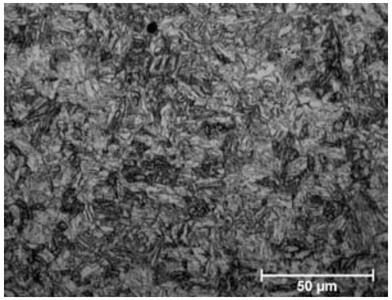
- Previously showed that P91 is easily FSW welded
- Packet and Lath size is reduced with increasing travel speed and is an order of magnitude smaller than fusion weld nugget material
- The hardness in the nugget region is increased as compared to the base metal, but not as much as in fusion welded nugget material
- Slight softening still seen in the HAZ away from nugget boundary



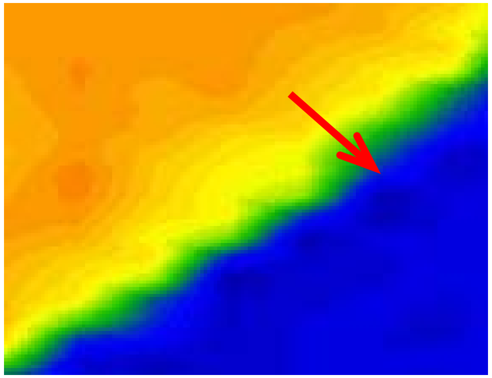
2ipm

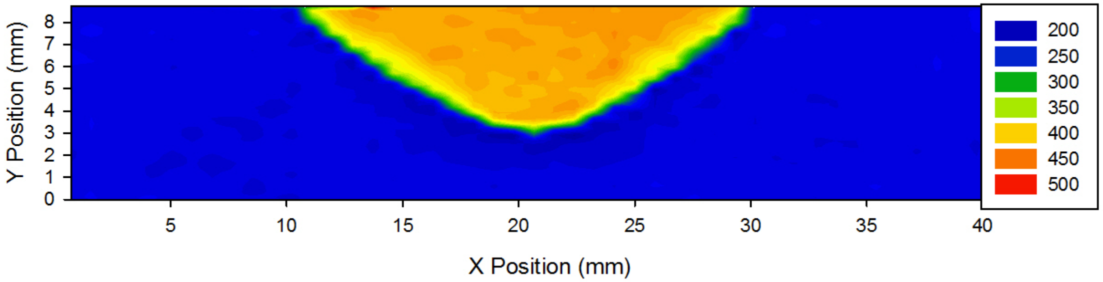


6ipm



FSW in P91 (2011 03 09 0003 @ 3.5")

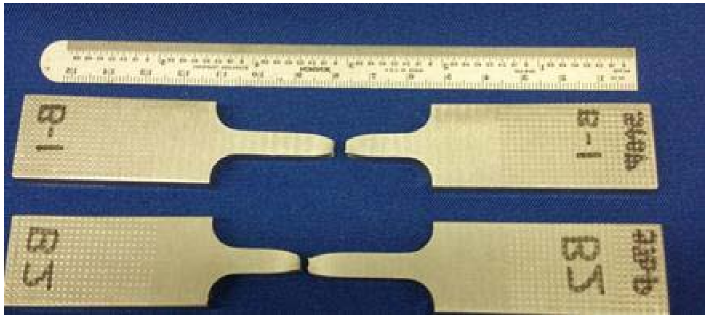




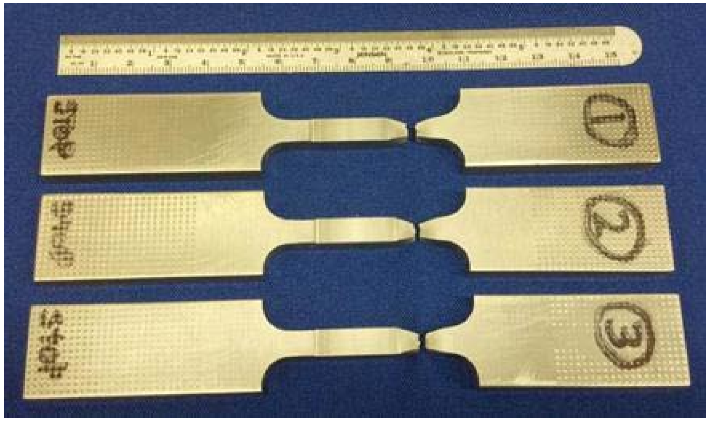
RT Transverse tensile results

- Transverse Tensile results show yield and ultimate is similar between FSW P91 material and P91 base material
- Failure location of FSW P91 is in the parent close to the HAZ on the advancing side of weld

Base metal



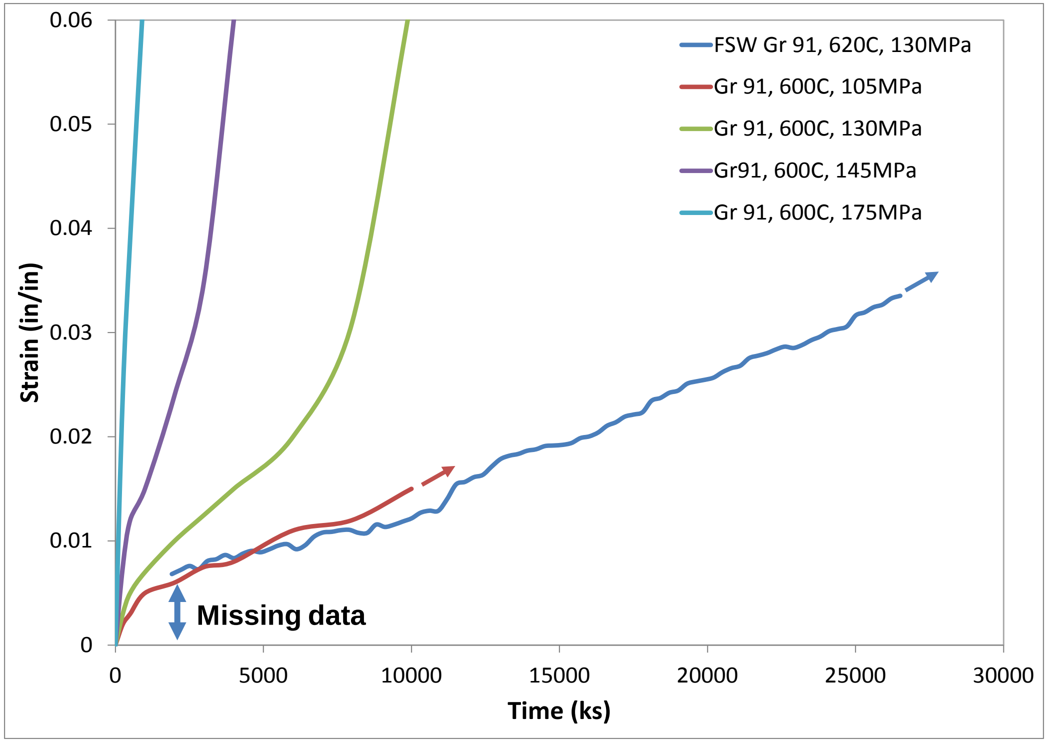
FSW

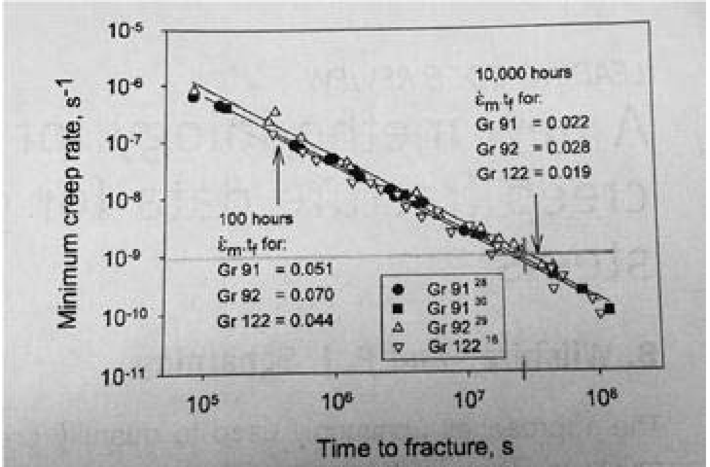


Sample	Yield Stress, 0.2% (ksi)	Ultimate Tensile Stress (ksi)
ASTM standard for A387-G91, class 2 plate	60 min.	85-110
Base metal P91 - 1	72.1	95.1
Base metal P91 - 2	73.2	94.8
FSW P91 - 1	79.5	98.8
FSW P91 - 2	80.1	99.8
FSW P91 - 3	80.0	99.8

Creep results P91 FSW Weld Metal

- **Longitudinal weld metal only specimen has ran for over 7000Hrs at 620C, 130MPa**
- **Strain rate is similar to Gr 91 tested at 600C and 105MPa (Wilshire and Scharning 2008)**
- Sample appears to still be in stage 2 creep with a strain rate of 1.3E-9/sec, implies a rupture time of ~1-2 years.





2 Relationships between minimum creep rate and creep rupture life at 823 to 1023 K for grades 91, 92 and 122 pipe steels[16,28–30]

Next question: Did we affect Type IV creep?

South Dakota School of Mines & Technology

Advanced Materials Processing and Joining Laboratory

Mechanical and Microstructural Evaluation of Friction Stir Processed Haynes® 282® Superalloy

Dr. Christian Widener; AMP Center Director

Dr. Michael West; REU Program Director

Dr. Bharat Jasthi; Research Scientist-III, AMP Center

Ian Markon; Undergraduate Researcher

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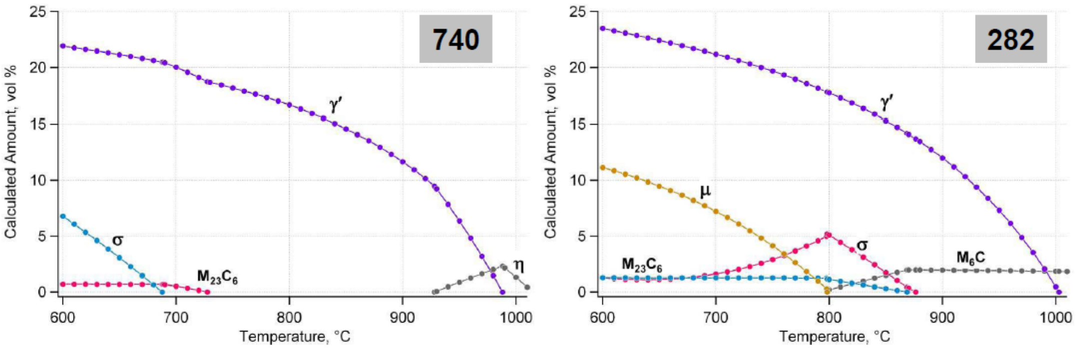
Problem with Precipitation Hardened Ni alloys defined by Santella

- Haynes 282 has excellent creep rupture performance but has creep cavitation and potentially corrosion concern over IN740 due to TCP

Increased Mo reduces γ/γ′ misfit but it also increases TCP phases

	Alloy element, wt%						
Alloy	Ni	Cr	Co	Mo	Ti	Al	Nb
282	Bal.	20	10	8.5	2.1	1.5	---
740	Bal.	24	19.9	0.5	1.5	1.3	1.6



- Mo promotes formation of TCP phases, μ & σ
- TCP phases can be linked to premature creep cavitation

FSW and Friction Stir Processing has been shown to produce much finer TCP in C-22 and to produce TCP intergranular not just on grain boundaries (Jasthi, 2010)

From Santella,2010

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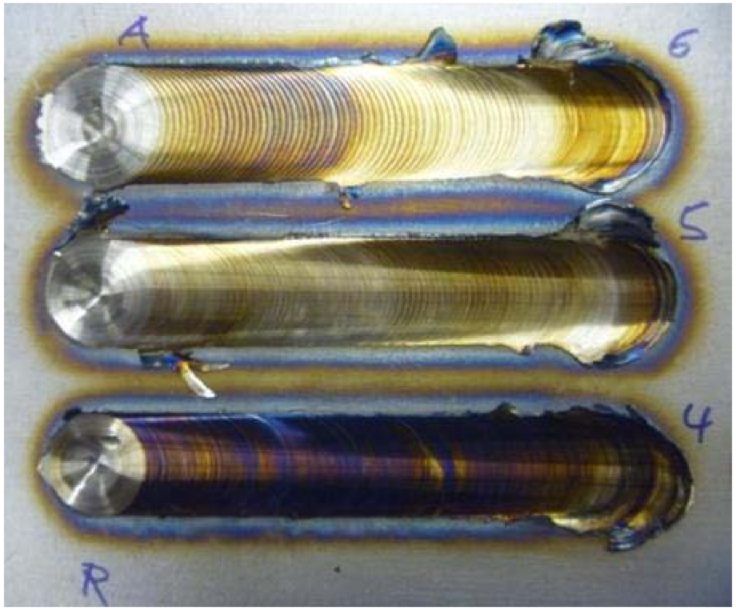
Initial Welding

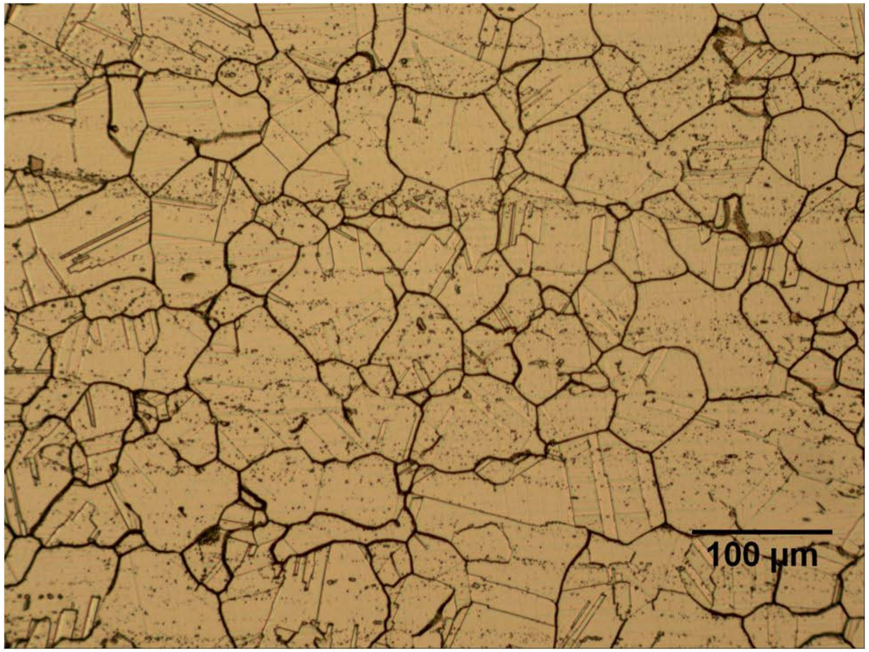
AMP
SDSM&T

Weld	1	2	3	4	5	6
Forge Force	5,000#	6,000#	6,000#	6,000#	6,000#	6,000#
Travel Speed	2.0 ipm	2.0 ipm	2.0 ipm	1.0 Ipm	0.75 ipm	0.5 ipm
Lead Angle	1	1	1	1	2	2

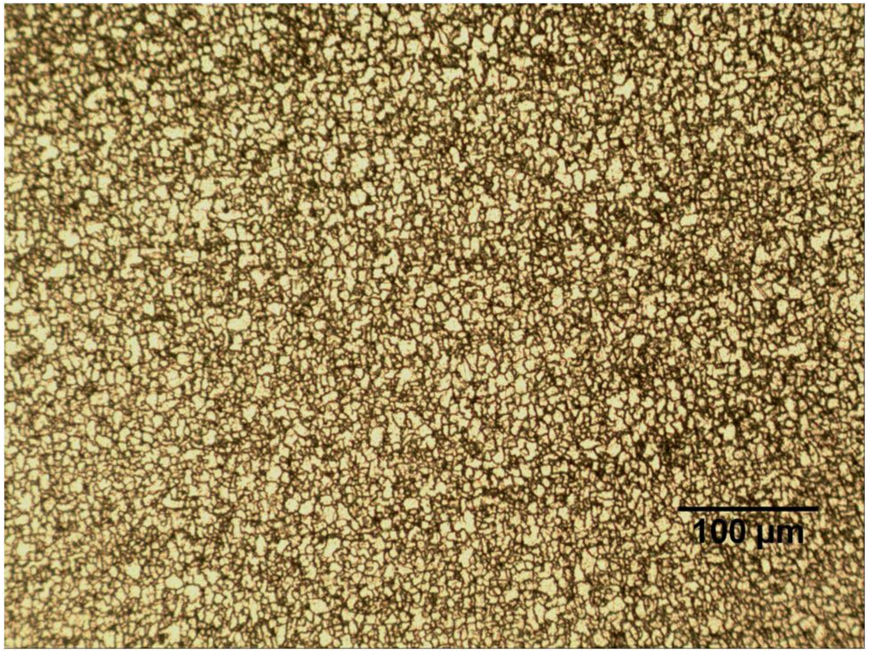


- W-Re 4%Hf-C convex tool
- Thee-inch welds were made in forge control mode at 200 rpm with an initial plunge depth of 0.145”

FSW vs. as received Haynes 282



Microstructure of As-Recieved Haynes 282.

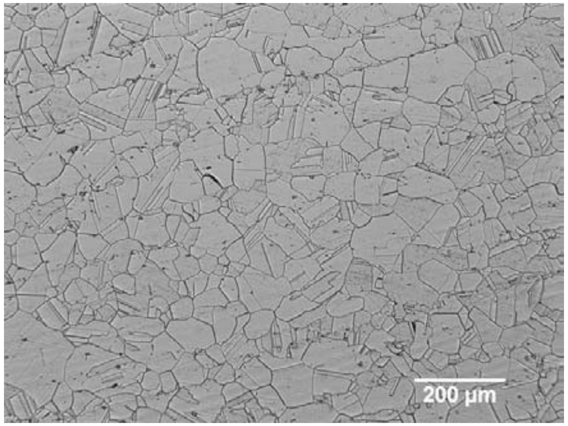


Weld 6 Nugget.

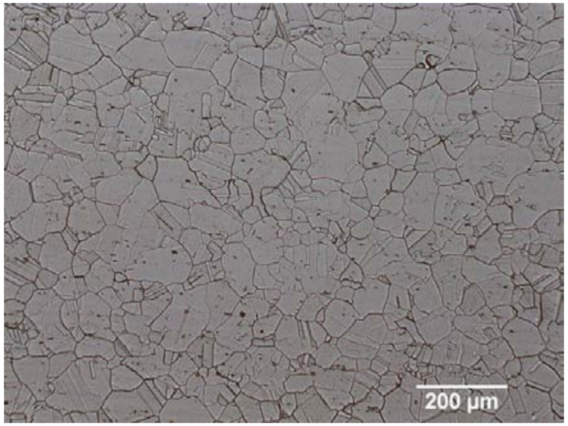
The sample was etched by immersion for approximately 1 minute in a mixture of 15 mL HCl, 10 mL acetic acid, and 10 mL HNO_3.

Grain size analysis of Haynes 282 after HT

- No significant difference in grain size (average size ~ 59µm) observed after standard two-step aging treatment for Haynes 282: 1850F (1010°C)/2 hours/air cool + 1450°F (788°C)/8 hours/air cool

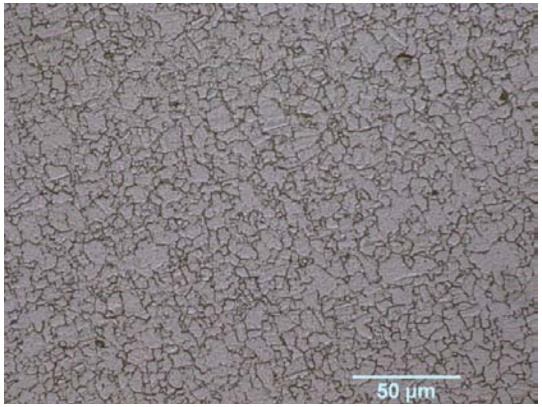


Parent

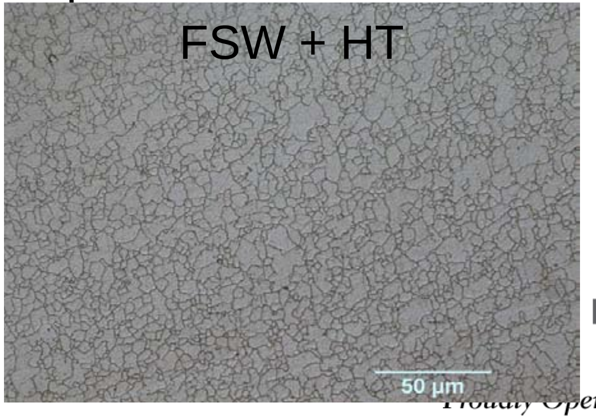


Parent + Aged

- Nugget regions also show no significant difference in grain size with thermal aging. The average grain size is ~ 5 µm



FSW + HT



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Transverse Tensile Properties

- FSW (200RPM, 1IPM, 1°tilt, 7500lbs force) results in higher YS and UTS but reduces elongation in both aged and un-aged conditions as compared to parent Haynes 282

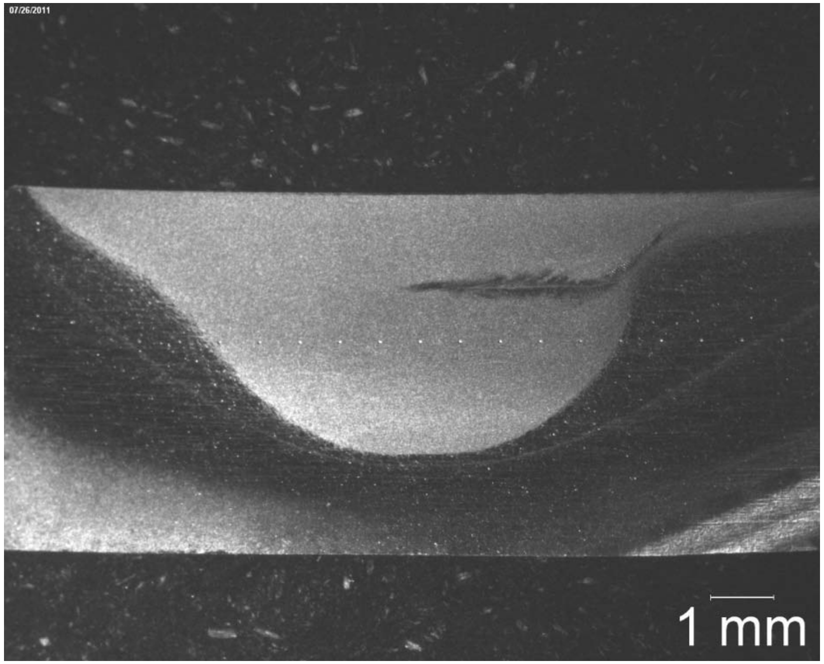
	Yield Strength (Ksi)	Ultimate Tensile Strength (Ksi)	% Elongation
Haynes 282 plate + Aged	103.7	166.4	30
Parent	**60.7**	**117.1**	**64.9**
Parent + Aged	**89.2**	**158.0**	**34.5**
FSW	**65.6**	**123.2**	**29.3**
FSW + Aged	**101.6**	**163.4**	**13.1**

→ *Haynes published values*

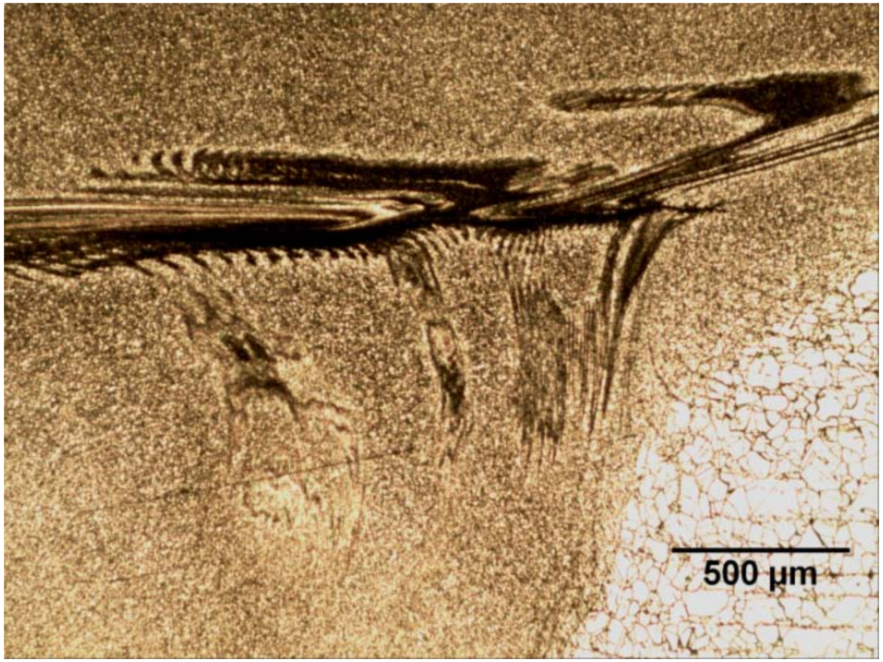
- Average of three samples per condition

Welding Results

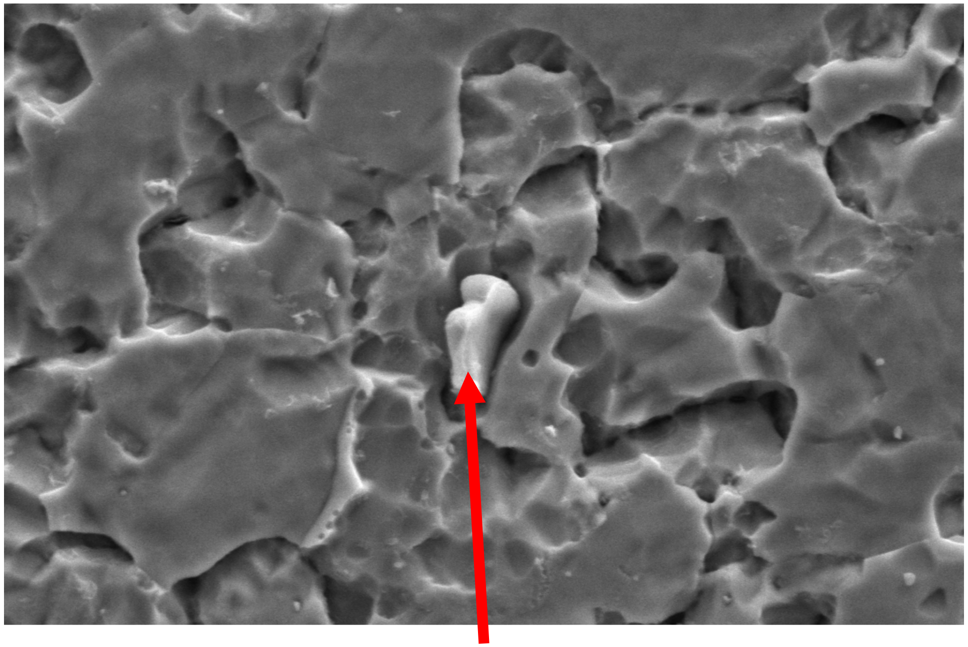
- Advancing side “flow” feature – weld is fully consolidated
- Preliminary analysis shows Mo-rich TCP phases and possible W tool wear fragments



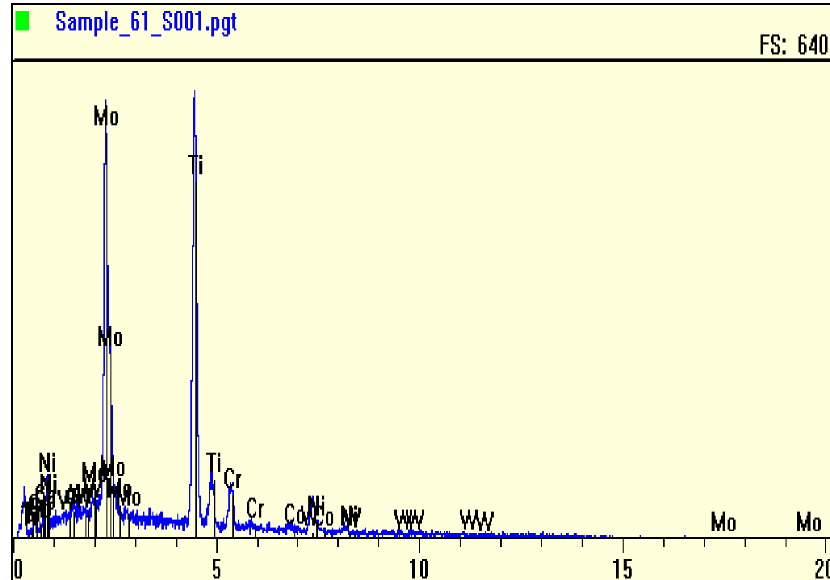
Weld 4 Macrograph



Weld 6 Micrograph



- Initial SEM work discovered bands of Mo-rich second-phase particles, likely TCP phases.

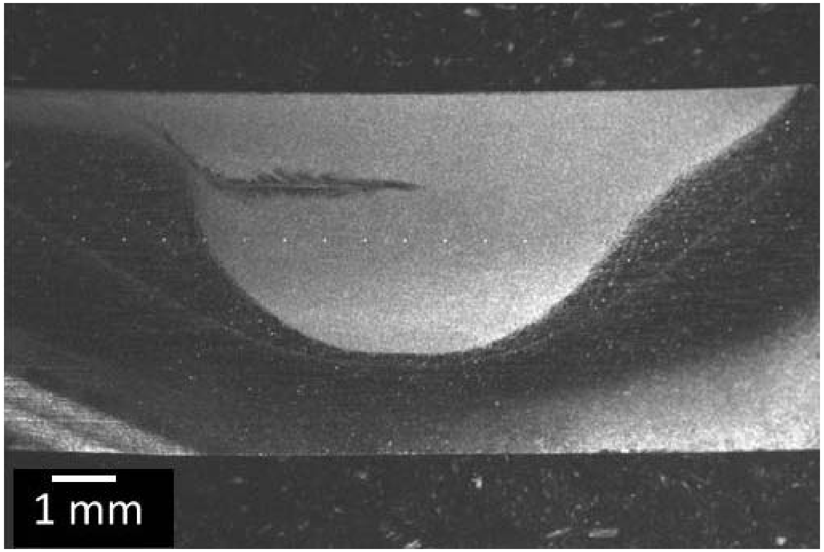


Element	Wt%	At%	At Prop
Al	0.37	0.83	4.0
Ti	51.51	65.15	313.9
Cr	6.98	8.14	39.2
Ni	0.00	0.00	0.0
Mo	40.83	25.79	124.3
Co	0.00	0.00	0.0
W	0.31	0.10	0.5
Total	**100.00**	**100.00**	**481.8**

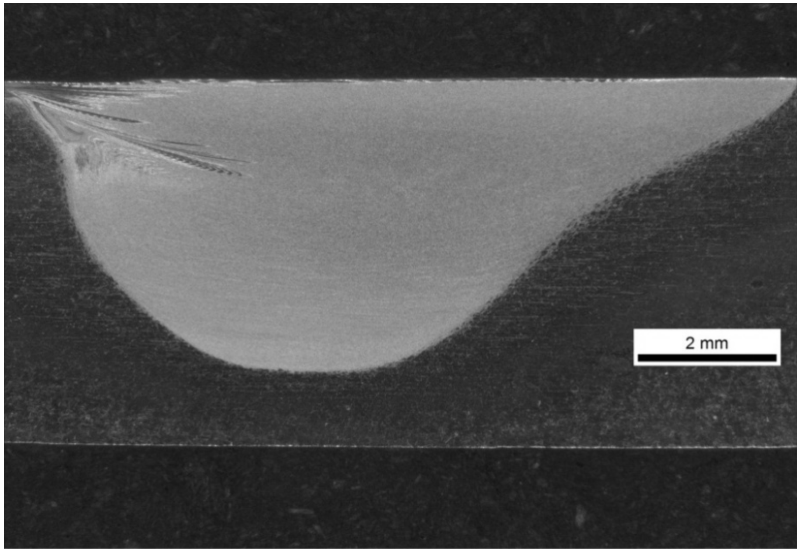
Changing FSW parameters

- Second set of welds made in an effort to eliminate the flow arm feature

6000 lbf , 1 IPM, 200 RPM and 1-˚Tilt
(previous parameters)



7500 lbf , 1 IPM, 200 RPM and 1-˚Tilt
(new parameters)



Lowering the cost of advanced alloy assemblies

FSW of MA956 on boiler plate steel

Develop methods to utilize a high performance material like an NFA/ODS alloy in a selective way thereby lowering the total cost of the assembly

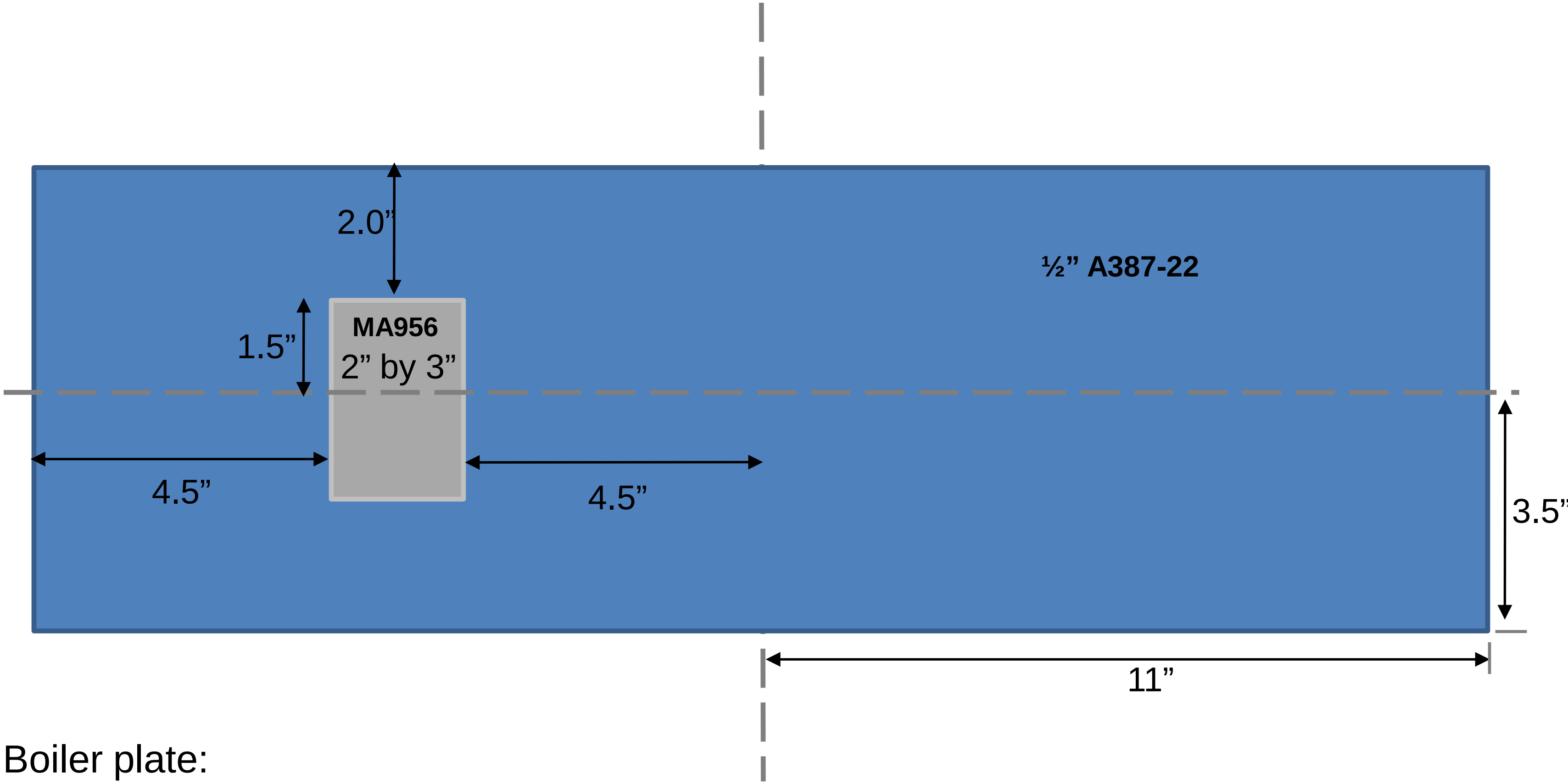
- ODS alloys are currently too costly to employ for bulk materials (large pipe and pressure vessel) in general power plant use.

- This project will investigate a new method to clad ODS alloy sheet and plate onto lower cost ferritic and austenitic substrates using solid state methods

A graded structure with a high value material at the interface with either the fire or steam side, but with a lower cost bulk interior, may be produced at a lower <u>total</u> cost than, for example, a bulk NFA/ODS material.

Plate design

1/8” by 2” by 3” MA956 inlayed into ½” thick A387-class 22, 7” by 22” plate



- Boiler plate:
  - **A387-grade 22 plate** (2.25Cr, 1Mo)
    - Source: ArcelorMittal
- Oxidation resistant ODS steel:
  - **MA 956** - 20% Cr, 5% Al, 0.3% yttria ferritic ODS

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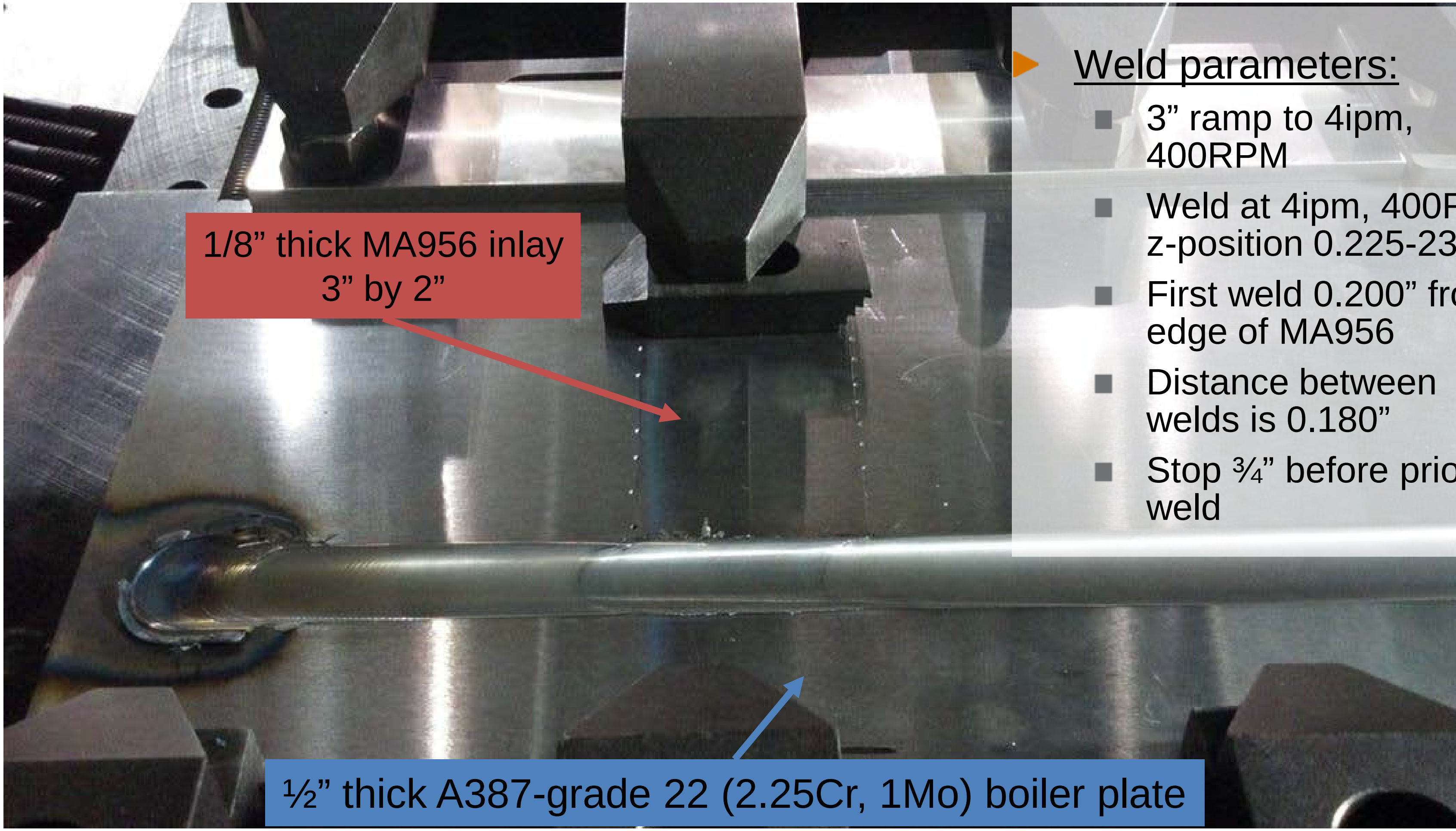
Friction stir weld set up



- <u>Weld parameters:</u>
  - 3” ramp to 4ipm, 400RPM
  - Weld at 4ipm, 400RPM, z-position 0.225-230”
  - First weld 0.200” from edge of MA956
  - Distance between welds is 0.180”
  - Stop ¾” before prior weld

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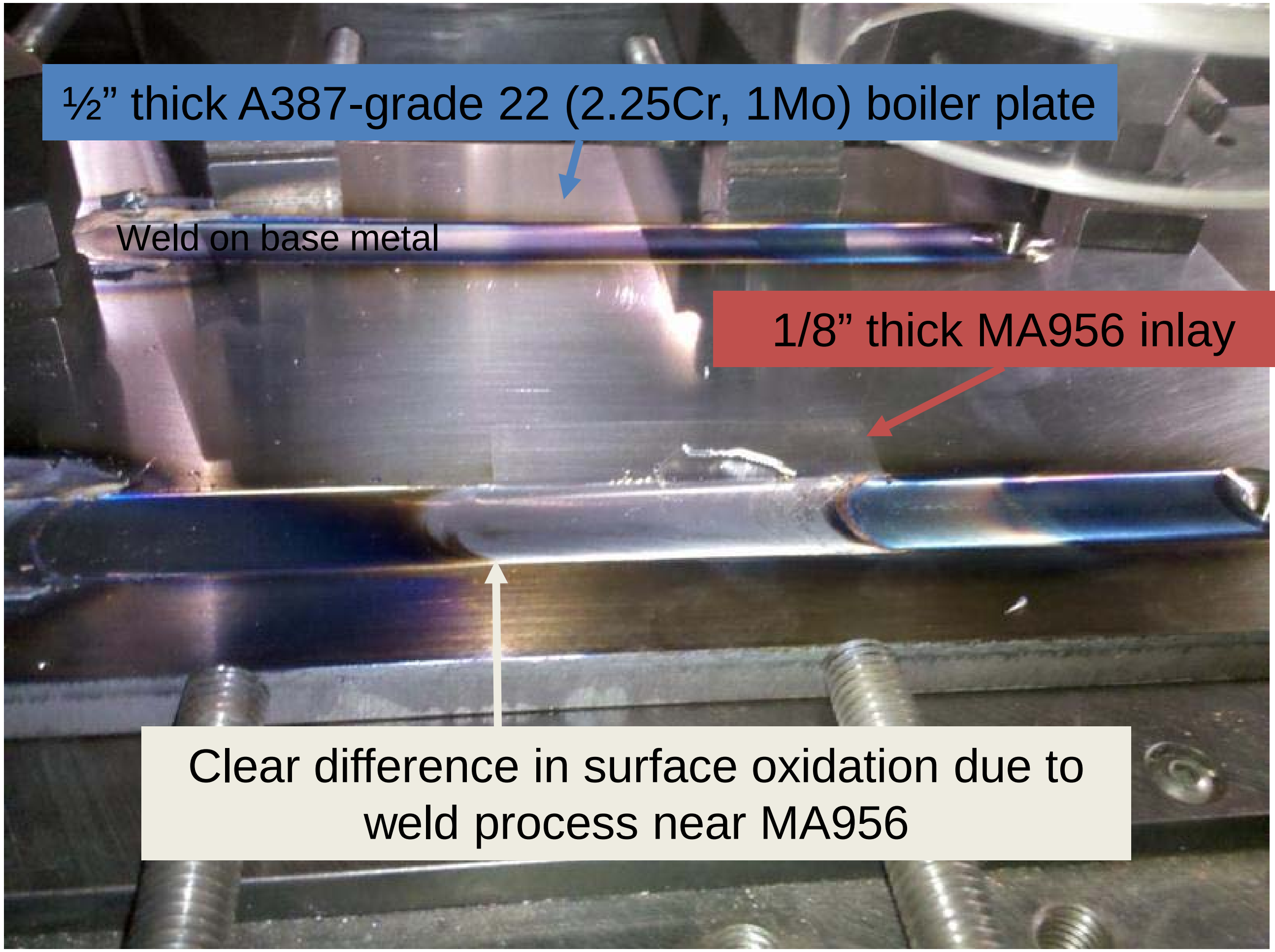
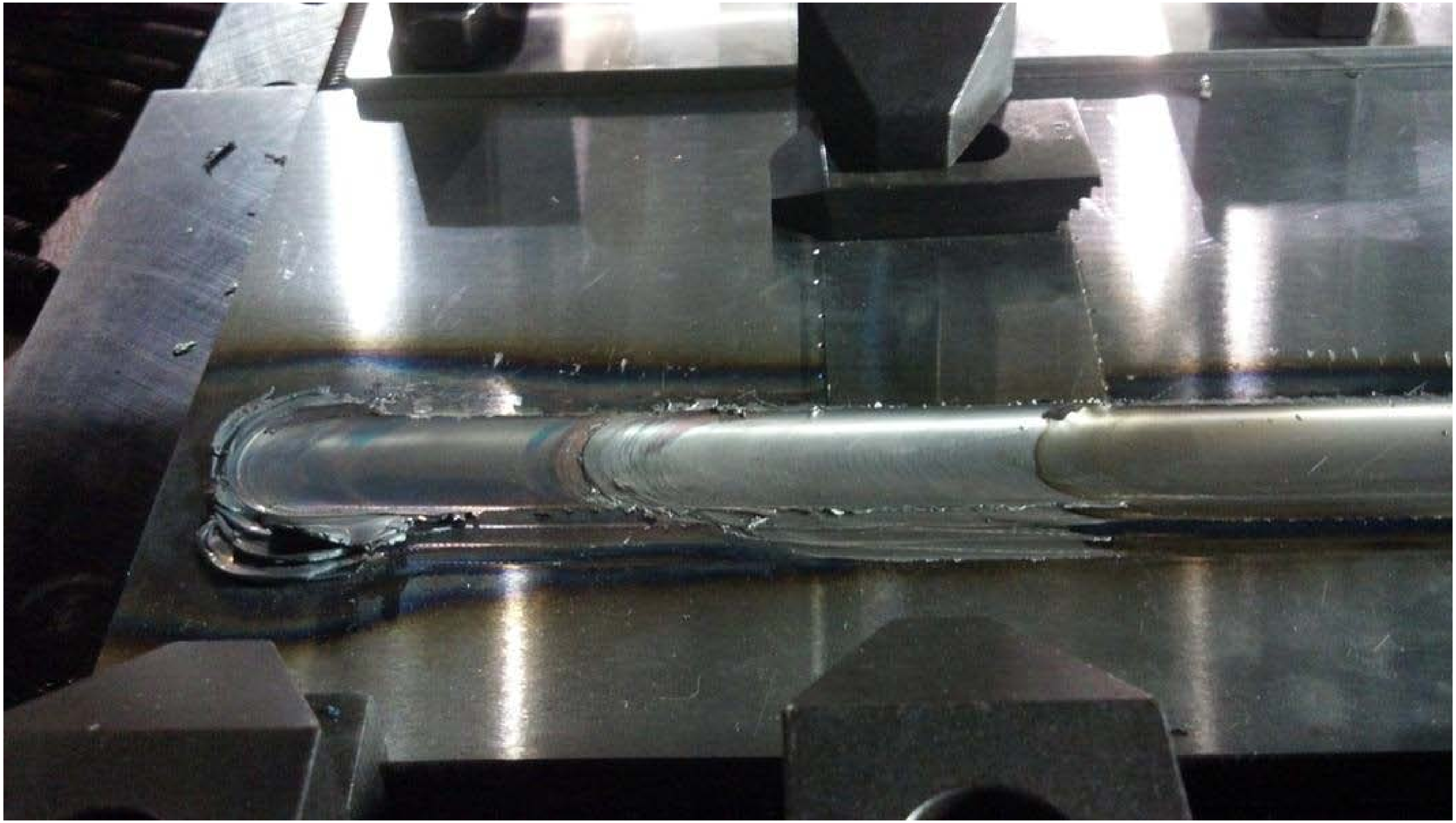
Previous work with low flow cover gas showed more surface oxidation of boiler plate

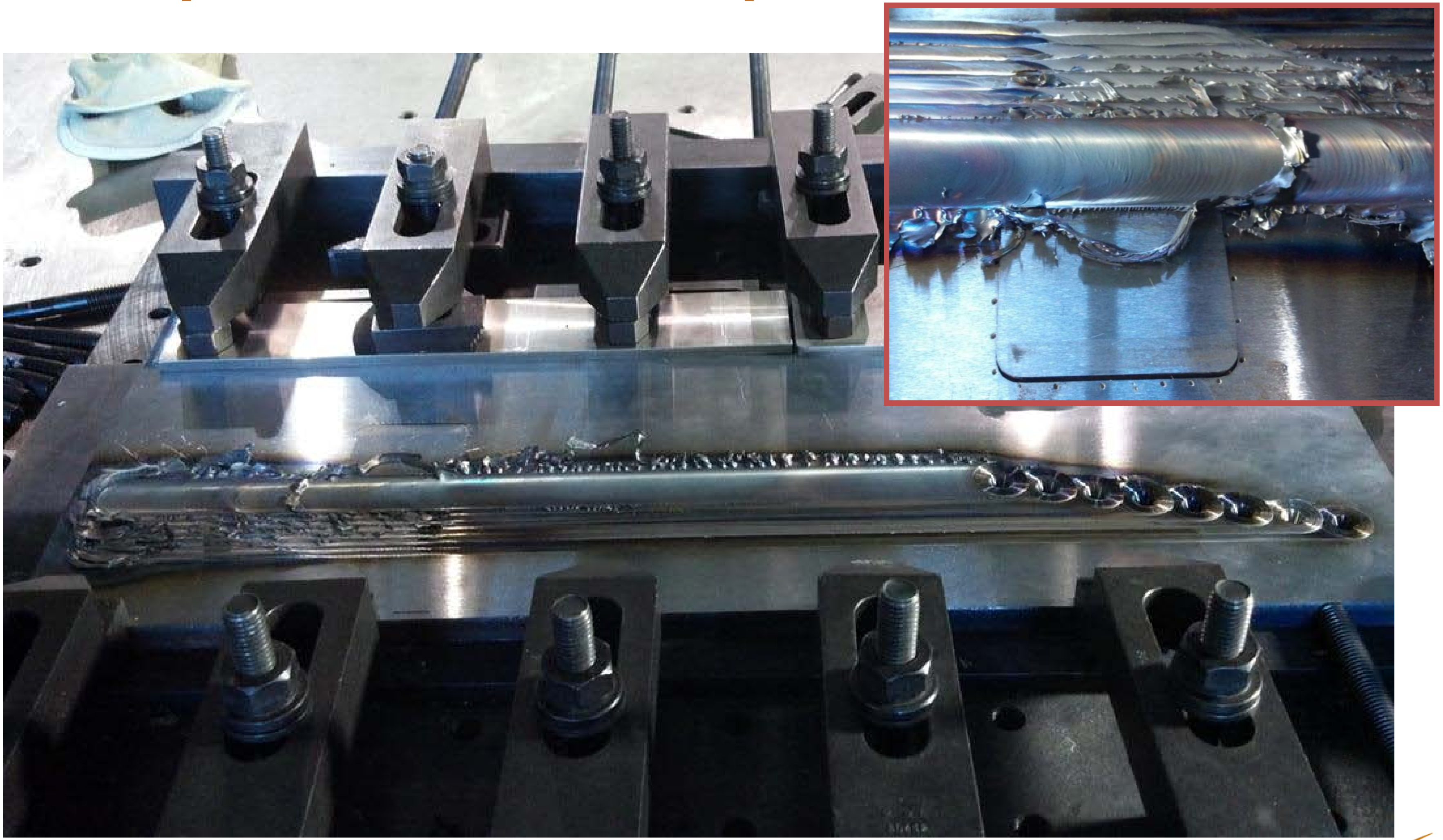


…4th pass, 0.180” from previous



- Flash was removed with chisel prior to next weld
- Material is pulled from the front of the tool and deposited behind the tool with each pass

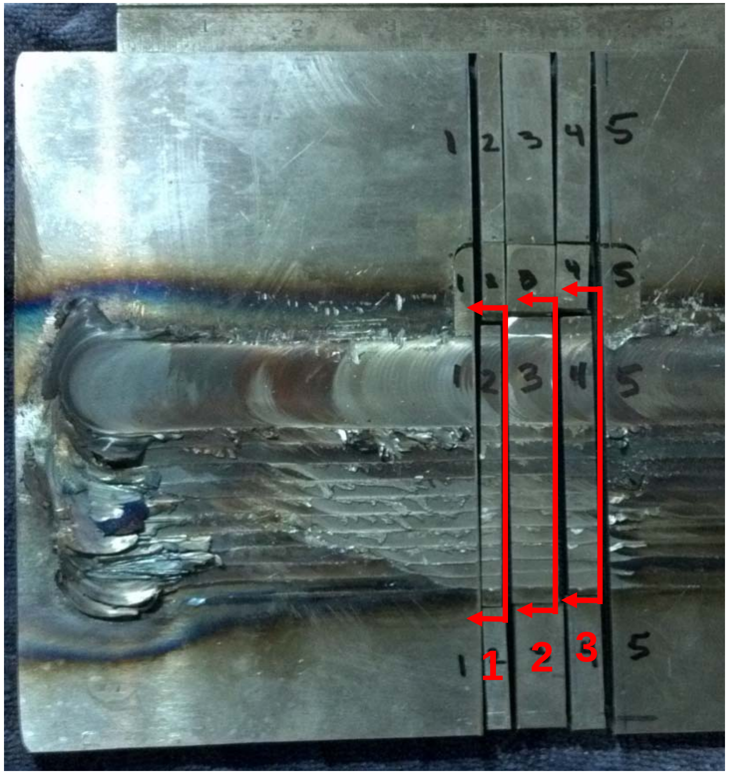
…8th pass, 0.180” from previous



- Clamp over MA956 not used starting with weld #8.
- More flash present
- MA956 edge is lifting slightly and is shorter by ~2mm

Weld cross sectional microstructure

- Three sections (as shown in red):
  - 1) ~0.5” into MA956 overlay
  - 2) ~1.0” into MA956 overlay
  - 3) ~1.75” into MA956 overlay
- Samples cross sectioned, polished to 1um diamond suspension, and etched with nitol



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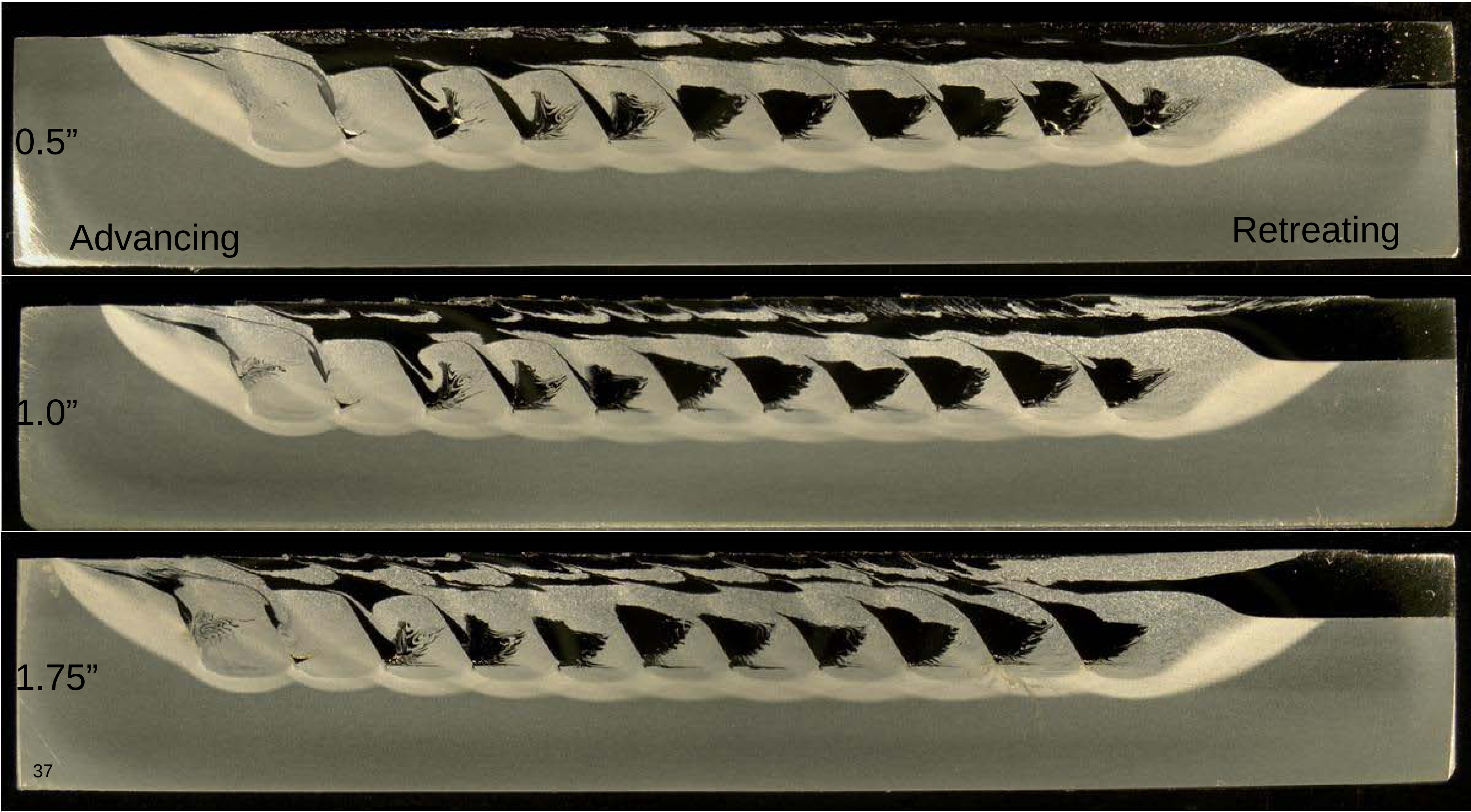
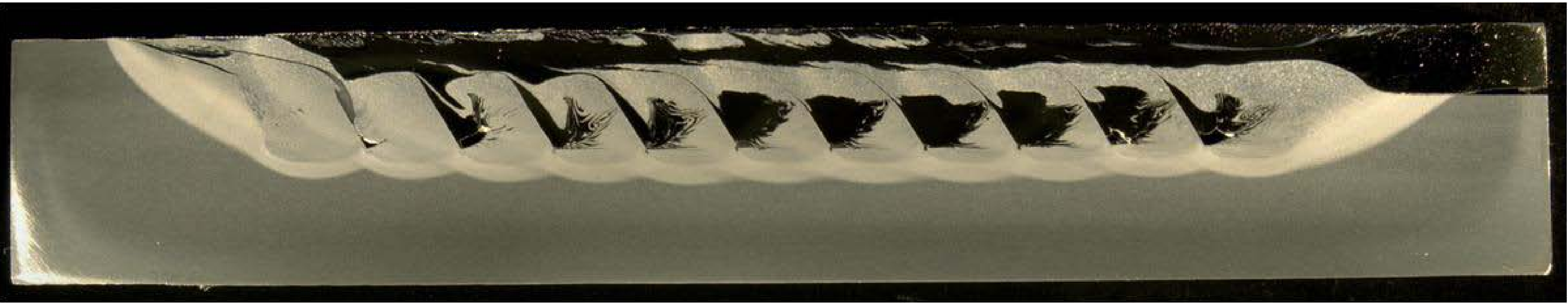
Etched microstructures

- Able to FSW MA 956 to surface of boiler plate steel
- MA956 ODS etched less than A387 and appears black, mixing observed
- Voids in first and last few welds by advancing side of pin



Summary of cladding work



- It is possible to friction stir weld MA956 alumina forming ODS steel onto 2.25Cr1Mo boiler plate steel
- Wrought microstructure results that is very fine grained
- This method is a way of cladding an oxidation resistant ODS onto an lower cost boiler plate steel. Could not have clad an ODS/NFA by melt/solidification processes.
- Potential applications in tube manufacturing (process strip then tube mill)
- Some mixing of the boiler plate at the surface is observed and future work could look at minimizing this by trying different tool designs and weld parameters.

Summary

- **Technology Development Objective**:

  Develop method(s) of joining next generation materials that result in joints with ideally the same hot strength, creep, fatigue or corrosion/oxidation properties as the base metal

- **FSW Joining of ODS/NFA**
  - Kanthal APMT and MA 956 can be successfully Friction Stir Welded to produce mechanically sound welds up to ¼ inch in thickness with current commercial FSW tools
  - FSW welds Kanthal APMT show creep performance at 750C that is virtually identical in the weld nugget as in the parent rolled plate (in the longitudinal or rolling direction)
- **FSW Joining of P91**
  - P91 can be successfully Friction Stir Welded to produce mechanically sound welds with current commercial FSW tools
  - P91 weld metal only specimen is showing over 7000hrs without failure at 620C and 130 Mpa
  - HAZ softening still occurs but it is unknown at present if Type IV creep is less severe in the FSW joined plate
- **FSW Joining of Haynes 282**
  - 282 can be successfully Friction Stir Welded to produce mechanically sound welds with current commercial FSW tools
  - TCP phases can be controlled with proper choice of process parameters
  - Creep and fatigue testing are next steps
- **FSW can be used to clad high value materials that cannot be melted (like NFAs) on to lower cost substrates to reduce assembly cost**

Next Steps

- **MA-956**
  - Weld process development is complete.
  - Creep Testing started (Base material, Nugget only and cross weld creep at 750 C in process)
- **Kanthal APMT - New Project Partner Sandvik**
  - Already use this material in tube form in ethylene production and heater tubes
  - Currently APMT is a low cost, commercially available, ODS. The Y-Ti-Al-O dispersoids and particles are not as fine as a typical NFA. But it may be "good enough" for some A-USC applications (not all components need 750/5000)
- **APMT Advanced** will move to true nanocluster based alloy, using the APMT manufacturing process. Solid state joining will be needed to reliably join this material to itself and to other materials and preserve the microstructure.
- **P91**
  - Weld process development is complete
  - Cross weld tension creep is next (Type IV Failure)

END