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Solid State Joining of Creep Enhanced Ferritic Steels

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Department of Energy – Office of Fossil Energy
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Motivation

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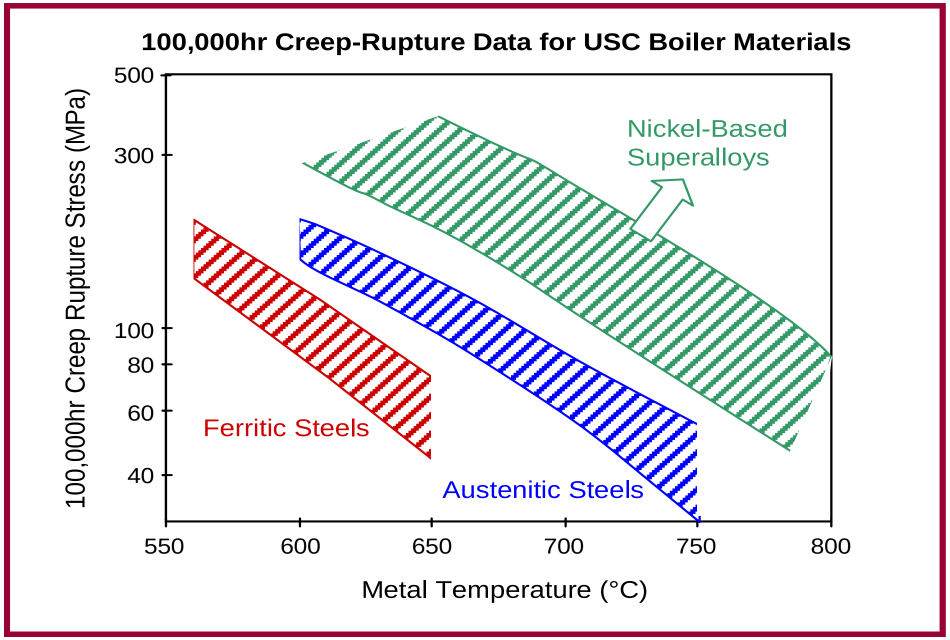

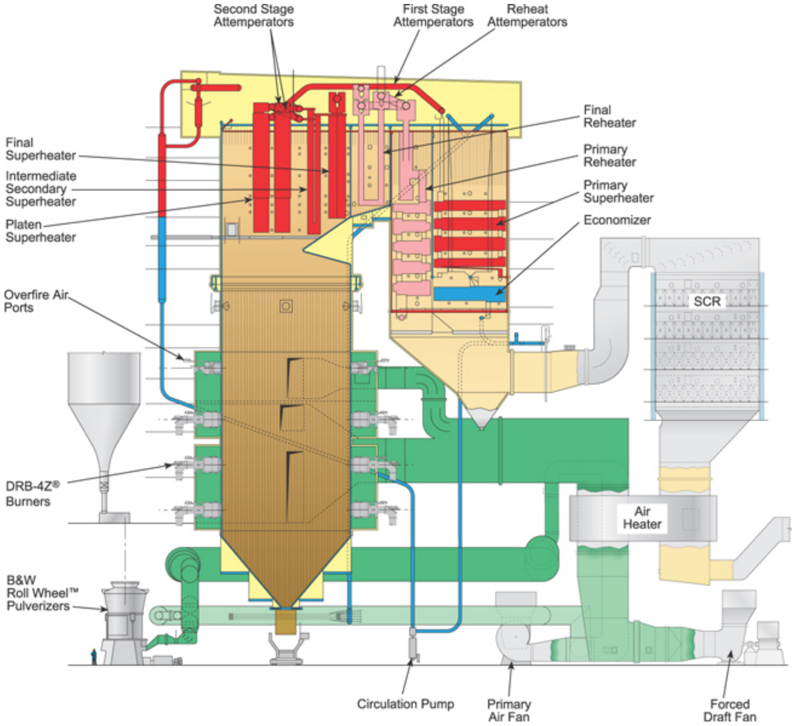

- Creep Strength Enhanced Ferritic Alloys
  - Low-cost, workhorse alloy for applications 570 C to 620 C (piping, waterwall / membrane wall, superheaters (under some designs), reheaters)
- Problem
  - Long term microstructure instability especially in the HAZ of weldments- Type IV Creep failure

Performance issues with welded CSEF steels

Problem leads to difficulty in predicting service life

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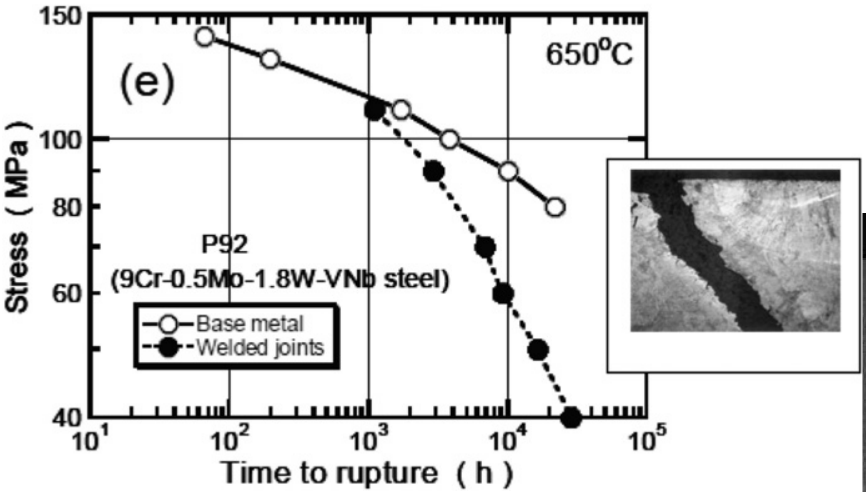
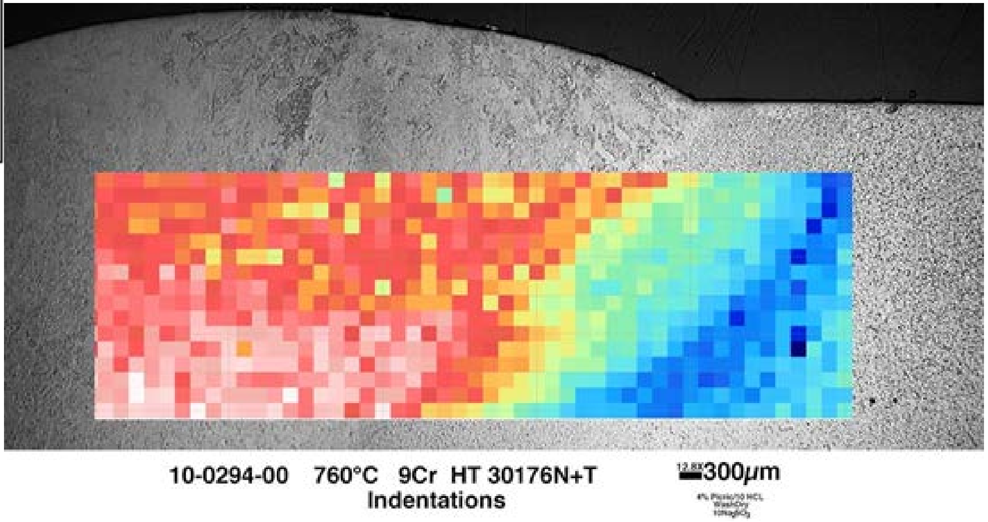
- WSRF can be as low as 0.50 at long creep times (J. Parker, and others).
- This leads to greater allowances in pipe and tube wall thicknesses (higher material cost and heat transfer inefficiency) and/or reductions in operating temperature and/or pressure, that also leads to a reduction in plant efficiency.



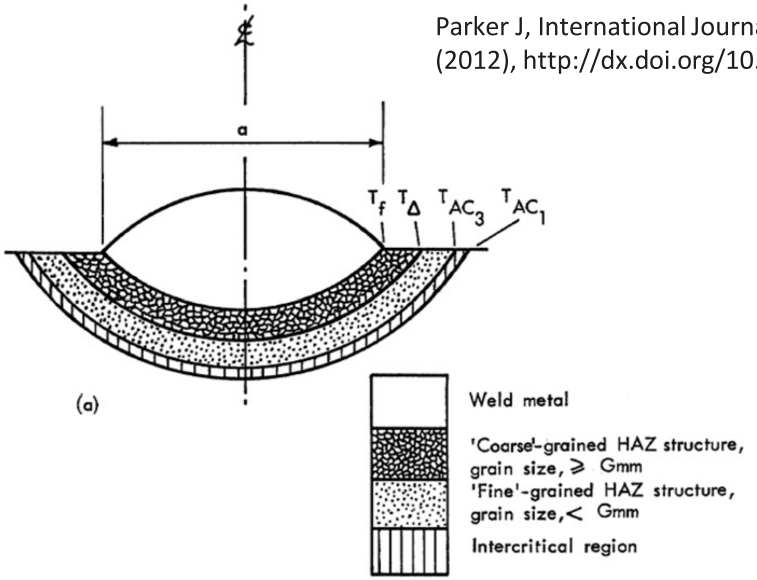
Parker J, International Journal of Pressure Vessels and Piping (2012), http://dx.doi.org/10.1016/j.ijpvp.2012.11.004

- Creep "softness" on the edge of the fine grained HAZ in the ICHAZ



Santella, 2011

Why does Type IV develop?



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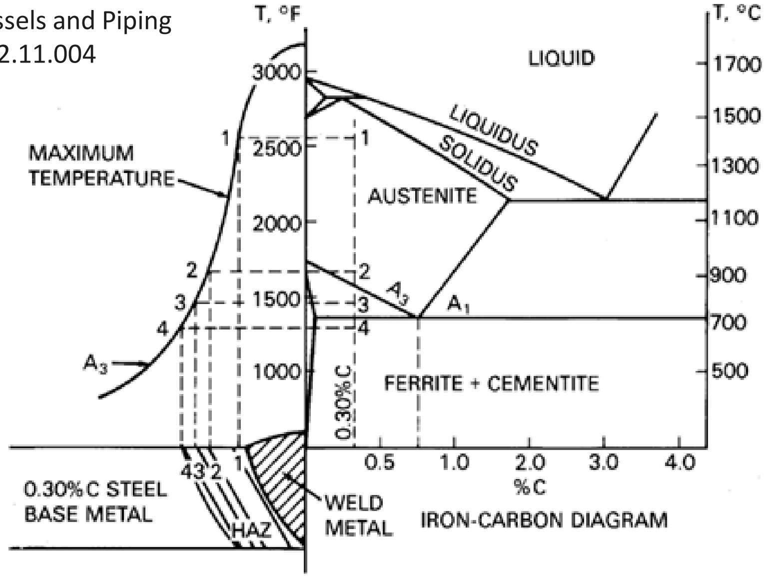


- CGHAZ: $M_{23}C_6$ dissolves, maybe some MX too – big PAG
- FGHAZ: not all precipitates dissolve – smaller PAG

- ICHAZ: Niether the $M_{23}C_6$ nor the MX are dissolved. During the heat cycle they coarsen, which reduces the amount of fine carbides in the intergranular areas. This leads to softening.

- In addition, in the ICHAZ an incomplete transformation to austenite took place – on cooling any austenite that formed goes to untempered martinsite in a matrix of original (and now over aged) tempered martinsite (ferrite). This can create strain concentrations under stress and can initialize locallized creep cavitation.

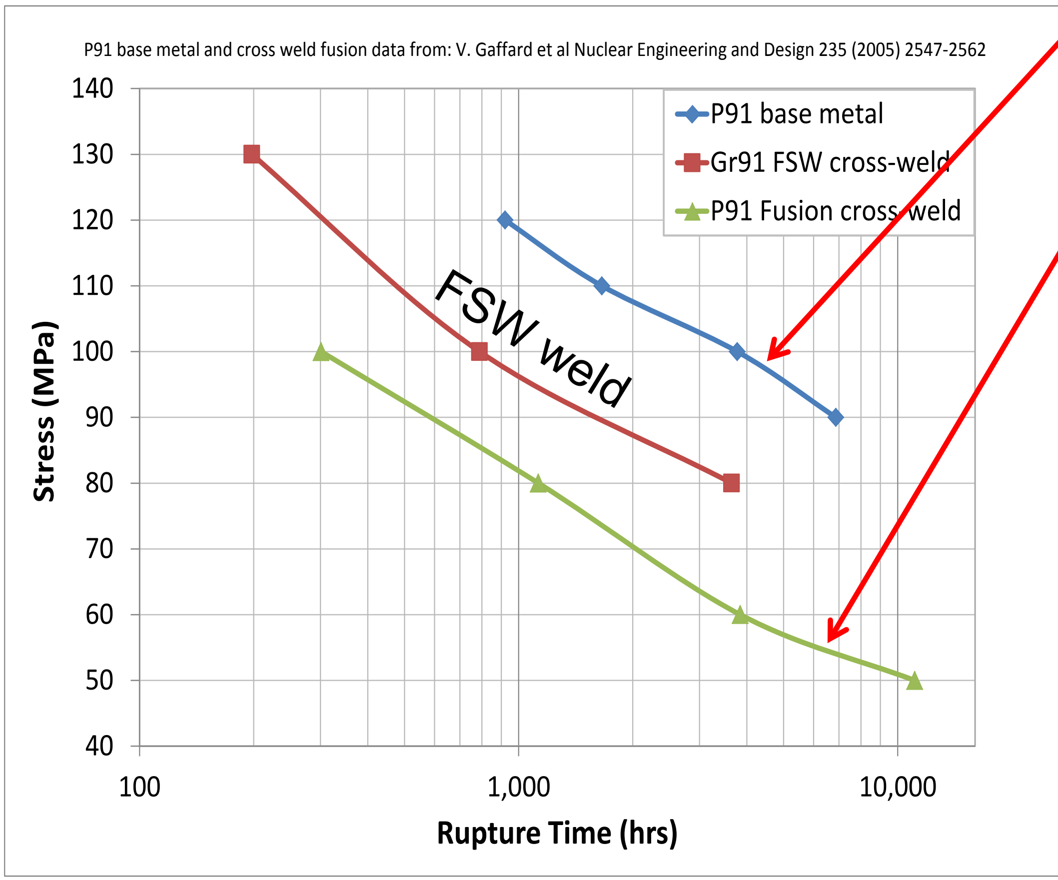
Motivation

Can a new welding process reduce the microstructure degradation that occurs in conventional fusion weldments?

- Solid state welding techniques, like Friction Stir Welding, may be able to introduced a significantly lower energy input to the weld. Potentially creating weldment temperatures only just above AC3. Potentially under AC1.
- If we are above Ac3, can a balance be struck between dissolution of carbides and carbonitrides and the effects of coarsening during PWHT so that the softening in the ICHAZ can be minimized?
- FSW introduces strain (dislocations) to the HAZ, can this help produce a fine distribution of MX during welding or PWHT ?
- Can the overall WSRF can be improved by using Friction Stir Welding?

Creep Results From Previous FE Funded Efforts at PNNL

Gr91 Friction Stir Welds vs Fusion Welds in cross weld tensional creep at 625C



P91 base metal – normalized and tempered

P91 (N&T) welded by submerged arc then PWHT 2 hr 760C

- **FSW weld in Gr91 shows ~3X improvement in creep life over PWHTed fusion weld**
- **Design knockdown in strength is 32% for SMAW with PWHT (WSRF 0.68) vs. 18% for FSW (WSRF 0.82)**

Project Objective

Objectives:

- Develop FSW welds in creep strength enhanced ferritic steels including P91, P92, and a boron/nitrogen (+/-cobalt?) enriched 9Cr ferritic steel.
- Develop a dissimilar Austenitic to Ferritic weld. In these dissimilar joints, type IV failures are also found, exacerbated by the stress concentrations in the joint area due to thermal-mechanical (CTE mismatch) and geometric considerations.

Approach:

- A detailed experimental study into the effect of FSW parameters and PWHT on Gr91, Gr92, and 9Cr-Mo-Co-B on Type IV creep failure
- A detailed experimental study into effect of FSW parameters and PWHT on Type IV creep failure in a dissimilar joint between an advanced Ni alloy and Gr91
- The development of FSW conditions and tools for thicker sections required in a prototype pipe weld in P91.

What is Friction Stir Joining ?

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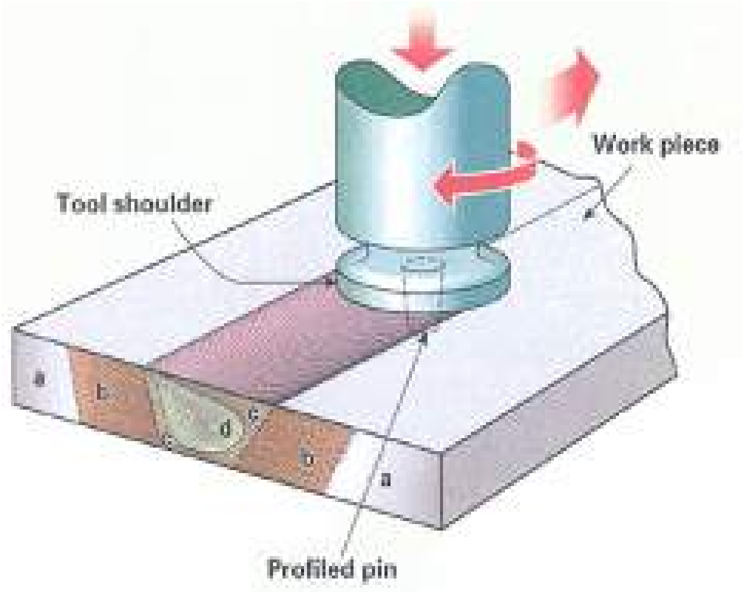
Solid-state joining processes
(no material melting)

- 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 recrystallized grains (d)
  - Surrounded by a mechanically deformed region (c) and a heat affected zone (b)



FSJ was invented and patented by TWI, Ltd. in 1991

Tools for Steels

The Laugh Test

Can FSW be applied to Fossil Energy Applications

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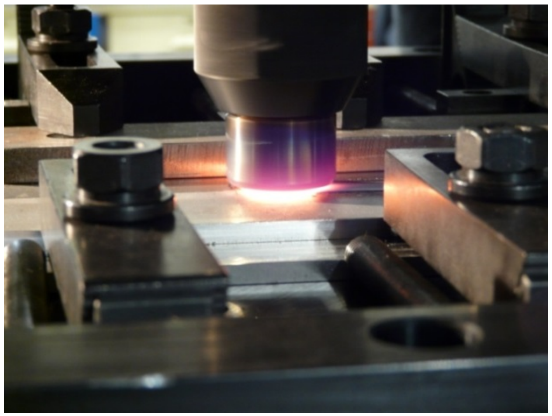
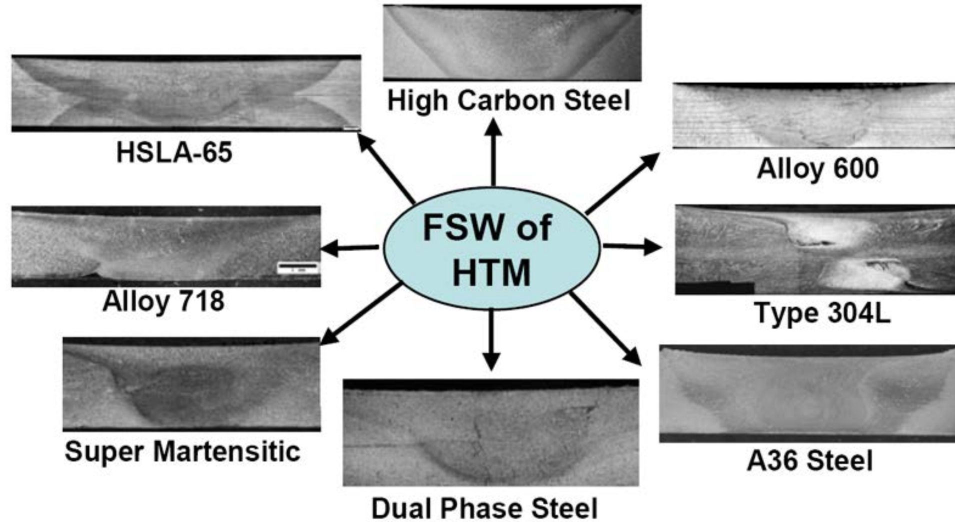
- Can it weld the alloys?
- Can it weld the thicknesses?
- Can it weld the geometries?
- Is it cost competitive with fusion welding?
- Are there Codes and Standards?
- Are the properties acceptable?

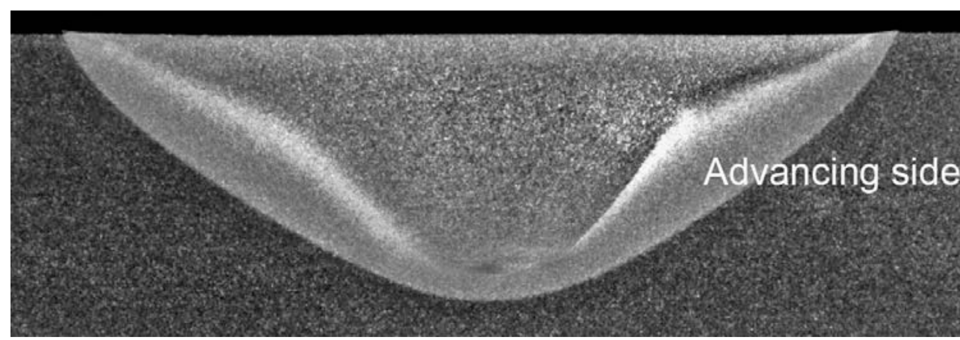
Steel Friction Stir Welding – State of the Art

- Can it weld the alloys? Yes



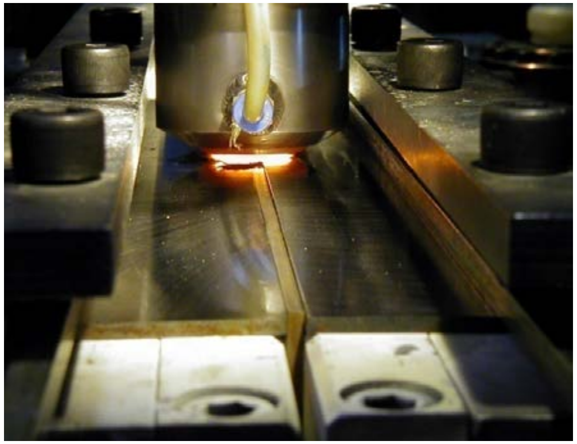


- Can it weld the thicknesses? Some Limits, but tools are improving
  - **We can now reach 3/8" routinely with commercial tooling in most steels and Nickel alloys**
  - **Welds up to 0.67" single pass in HSLA steels have been demonstrated with PCBN/W-Re tooling**
  - **Welds up to 1.1" single pass in API 5L X70 steels have been demonstrated with W-Re tooling**

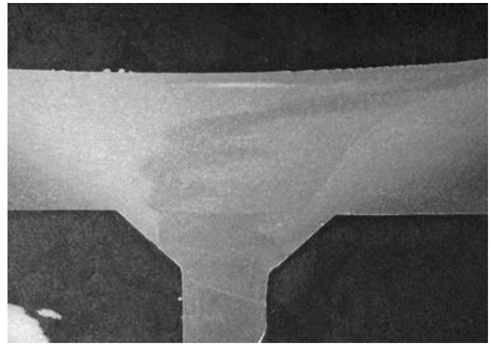


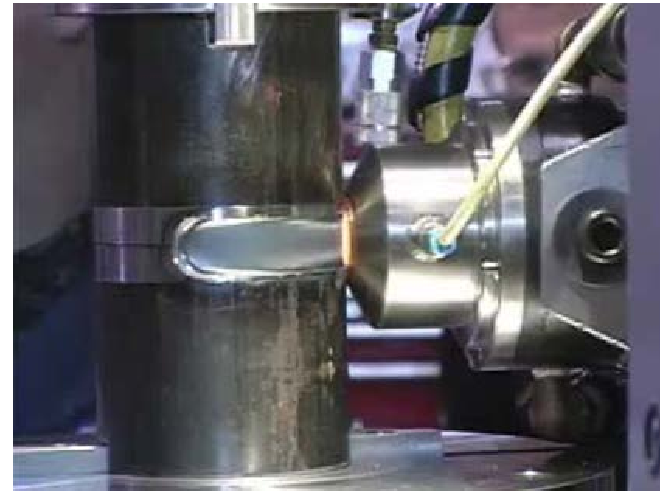
Typical macrostructure of a fully consolidated, defect-free steel FSW weld in Gr 91

Can it weld the geometries?

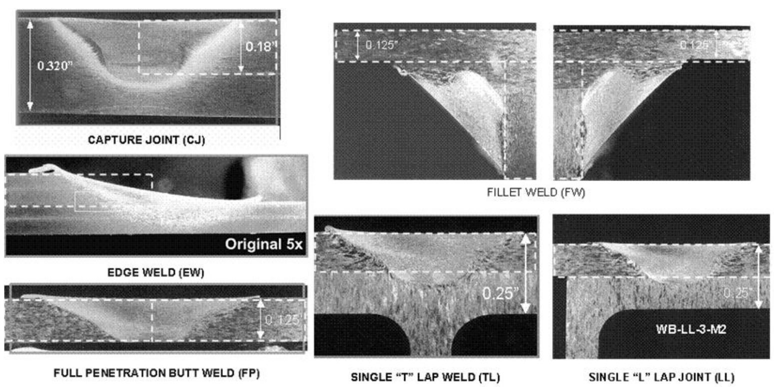


Megastir, Inc.



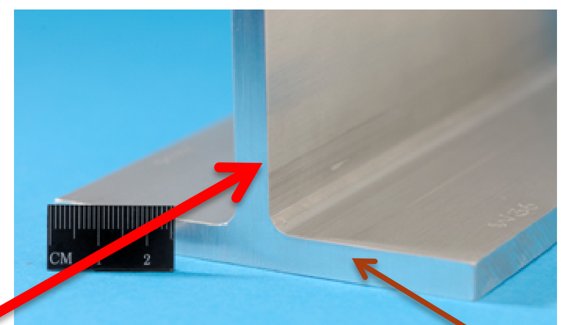


Circumferential butt weld on pipe and tube

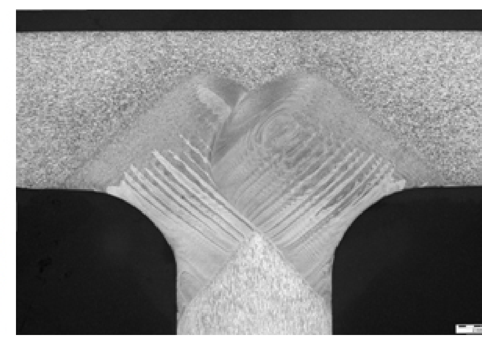


Arbegast 2004

Butt, Lap, Fillet and T Joints



a)



b)

TWI Technology Centre

Membrane wall application?

Imagine this was a tube

Is it cost competitive with Fusion Welding?

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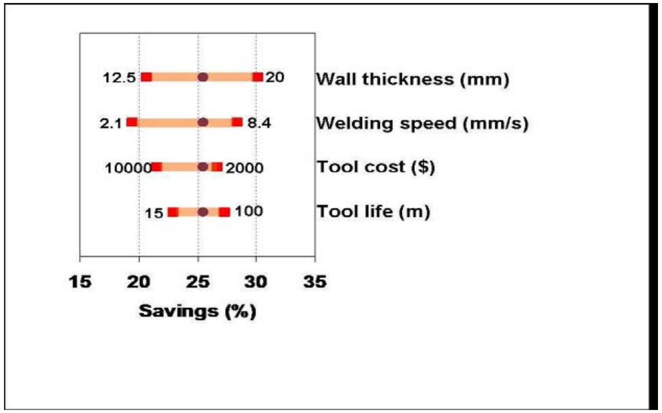
Cost Advantages

- Single pass method – Faster on thick section welds
- No Consumables
- No Environmental Emission (Mn or hexavalent Chrome)
- No "Expert" Operators
- Lower recurring costs (but higher initial capital costs than GTAW/GMAW)
- Lower energy costs
- Reduced downstream costs (from residual stress and distortion management)

Terrestrial Linepipe Cost Sensitivity

7% Cost savings



Offshore Laybarge Cost Sensitivity

25% Cost savings

A. Kumar, D. P. Fairchild, M. L. Macia, T. D. Anderson
ExxonMobil Upstream Research Co., Houston, TX, USA
H. W. Jin, R. Ayer, N. Ma, A. Ozekcin, R. R. Mueller
ExxonMobil Research and Engineering Company, Annandale, NJ, USA:

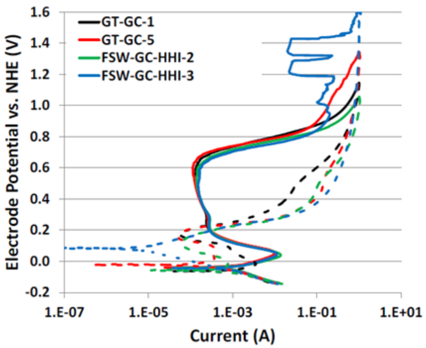
in: Proceedings of the Twenty-first (2011) International Offshore and Polar Engineering Conference, Maui, Hawaii, USA, June 19-24, 2011, Copyright © 2011 by the International Society of Offshore and Polar Engineers (ISOPE), ISBN 978-1-880653-96-8 (Set); ISSN 1098-6189 (Set); www.isope.org

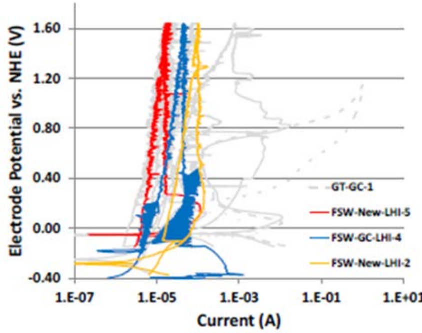
Are there Codes and Standards?

- Generalized Standards Efforts
  - FSW rules language has been added to the new 2013 ASME Section IX
  - AWS Subcommittee C6D – Best Practices Docs being written, training documents for weld inspectors being written
  - Efforts underway in book codes: Section 3 and 8
  - ISO
  - SAE D17.1(aluminum)
  - NASA (aluminum)
- Code Cases
  - 2 approved ASME Code cases running in Section IX
- WPS PQR Environments
  - Qualification for Specific Applications or internal standards (Coiled tubing)
  - Other countries (Sweden and Norway) have down selected FSW as the method to produce closure welds on their long term spent fuel storage systems (2" thick single pass welds in copper) – Government Regulatory approval of process

Property Advantages

- Higher Toughness,Better Damage Tolerance
- Better Fatigue Performance
- Often Lower Total Heat Input:
  - Reduced HAZ degradation
  - Less sensitization in HAZ of Austenitic Alloys
- Lower Residual Stress and Distortion
- Fine grain nugget more amenable to NDE (x-ray, UT, etc.)
- Better results in Creep Rupture
- Better tolerance to gap, fit-up, and cleanliness
- High quality and repeatability (machine technology)





Cyclic Potentiodynamic Polarization (CPP) scans of GTAW welds in 304SS compared to FSW. GTAW shows potential for localized corrosion while FSW shows passivation behavior

Weld Process	Dome Height (mm)	Concavity (Z/X ≤ 0.2)	Convexity (Z/X ≤ 0.1)	Mismatch (Y/X ≤ 0.1)	Undercut (Angle ≥ 90˚)
Single Spot	11.7 ± 0.3	0.22 – 0.23	/	/	/
Twin Spot (across weld)	15.1 ± 0.4	/	/	0 – 0.21	116 - 180
Twin Spot (along weld)	14.3 ± 1.0	0.19 – 0.36	/	0.12 – 0.25	51 - 180
Laser-Plasma	11.9 ± 4.0	0 – 0.28	0.31 – 0.69	/	/
FSW	15.4 ± 0.5	/	/	/	/


No visible distortion in 50' of continuous welding in 4'x8' panels. (courtesy of BYU)

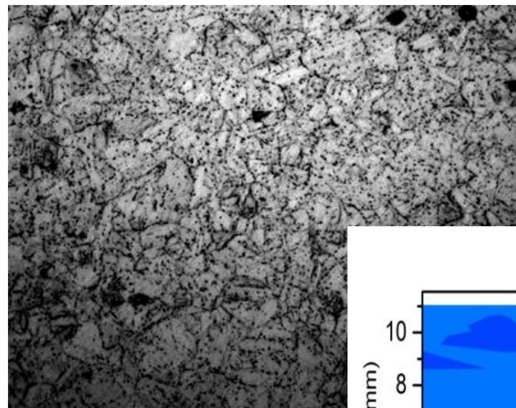
Flat plate FS welds in HSLA65 plate, stay flat !

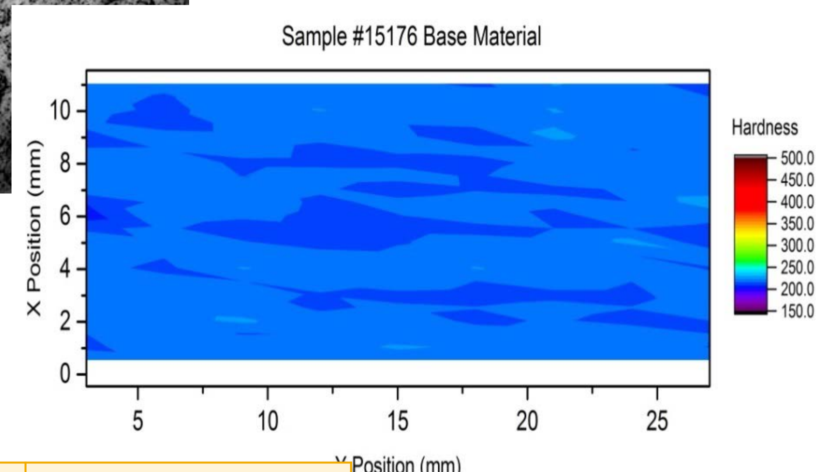
Water wall distortion control in modular fabrication

Current Work on FSW of Grade 91

- ASTM A387-Grade 91 Class 2, Normalized and Tempered
- Tempered martensite (ferrite with carbides + carbonitride precipitates)
- Equiaxed PAG ~10-20um
- Hardness 200-250HV

- ¼” pin Q80 MegaStir tool
- Processing Parameters
  - 2-6 IPM, 100-400 RPM
  - Tool Temperatures 800-950C
- No PWHT in this work – future task
- Analysis
  - Creep
  - Hardness
  - Microscopy





Tool Temperature (°C)	Travel Speed (in./min.)	Rotational Speed (RPM)
800	6	100
800	4	100
865	2	100
950	4	400

Pictures of welds made

- Defect free welds made at a variety of conditions and temperatures

4IPM/100RPM/800C

6IPM/100RPM/800C

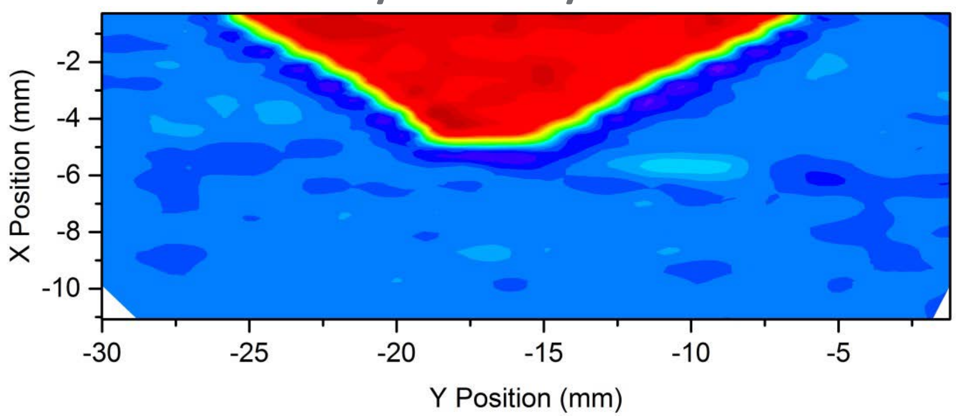
2IPM/100RPM/865C

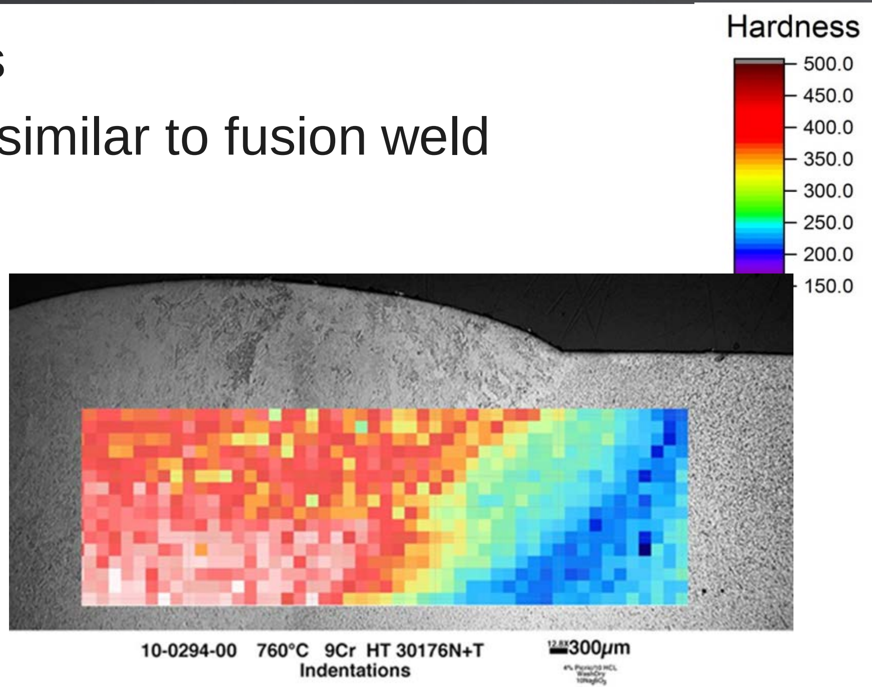
6IPM/400RPM/950C

Hardness

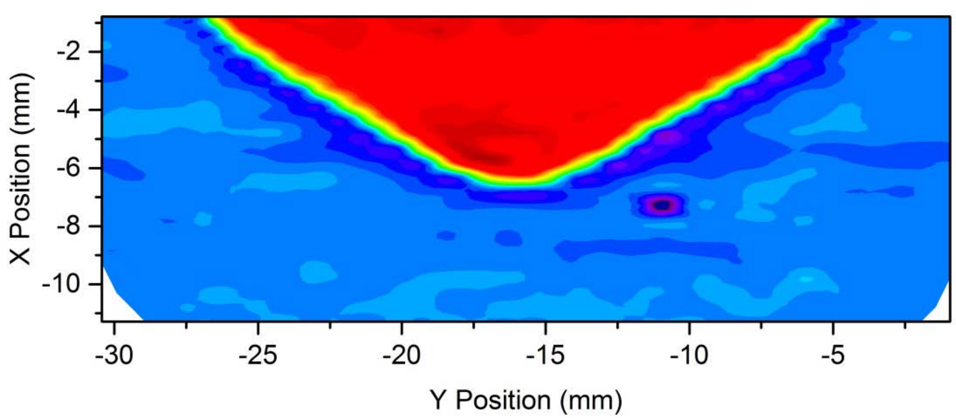
- The nugget/HAZ hardness increases
- Softening on the edge of the HAZ is similar to fusion weld but less pronounced

4IPM/100RPM/800C

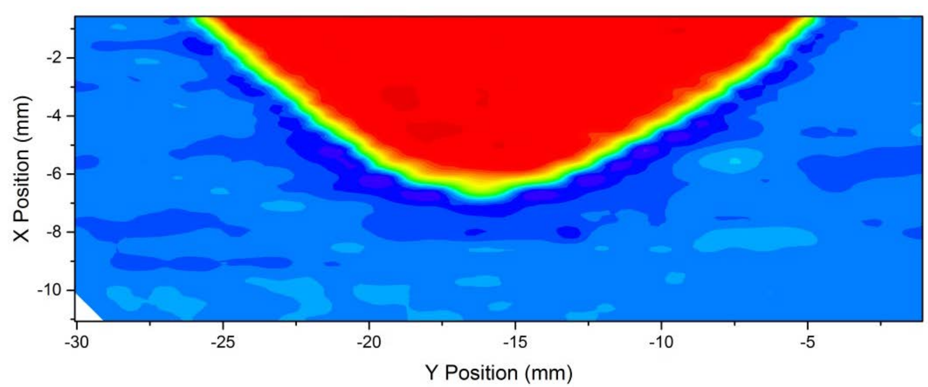




2IPM/100RPM/865C

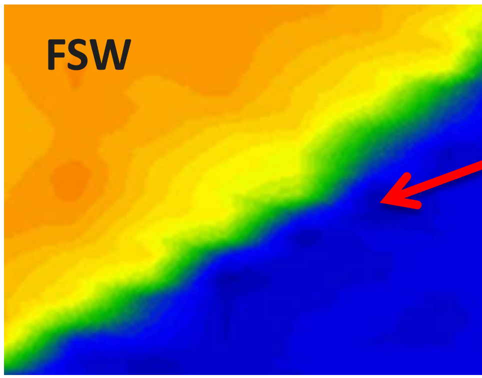


6IPM/400RPM/950C



FSW shows a low hardness area on the edge of the FGHAZ (like a fusion weld but less pronounced)

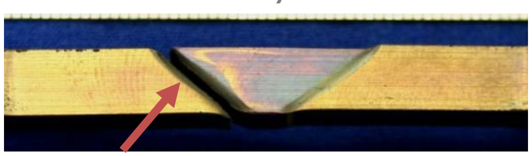
- Physics is still working



FSW also shows a low hardness zone

- FSW welds still fail in Type IV Creep

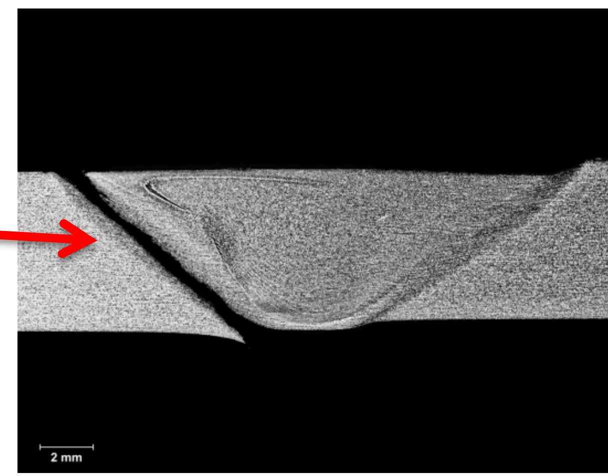
100MPa, 625°C



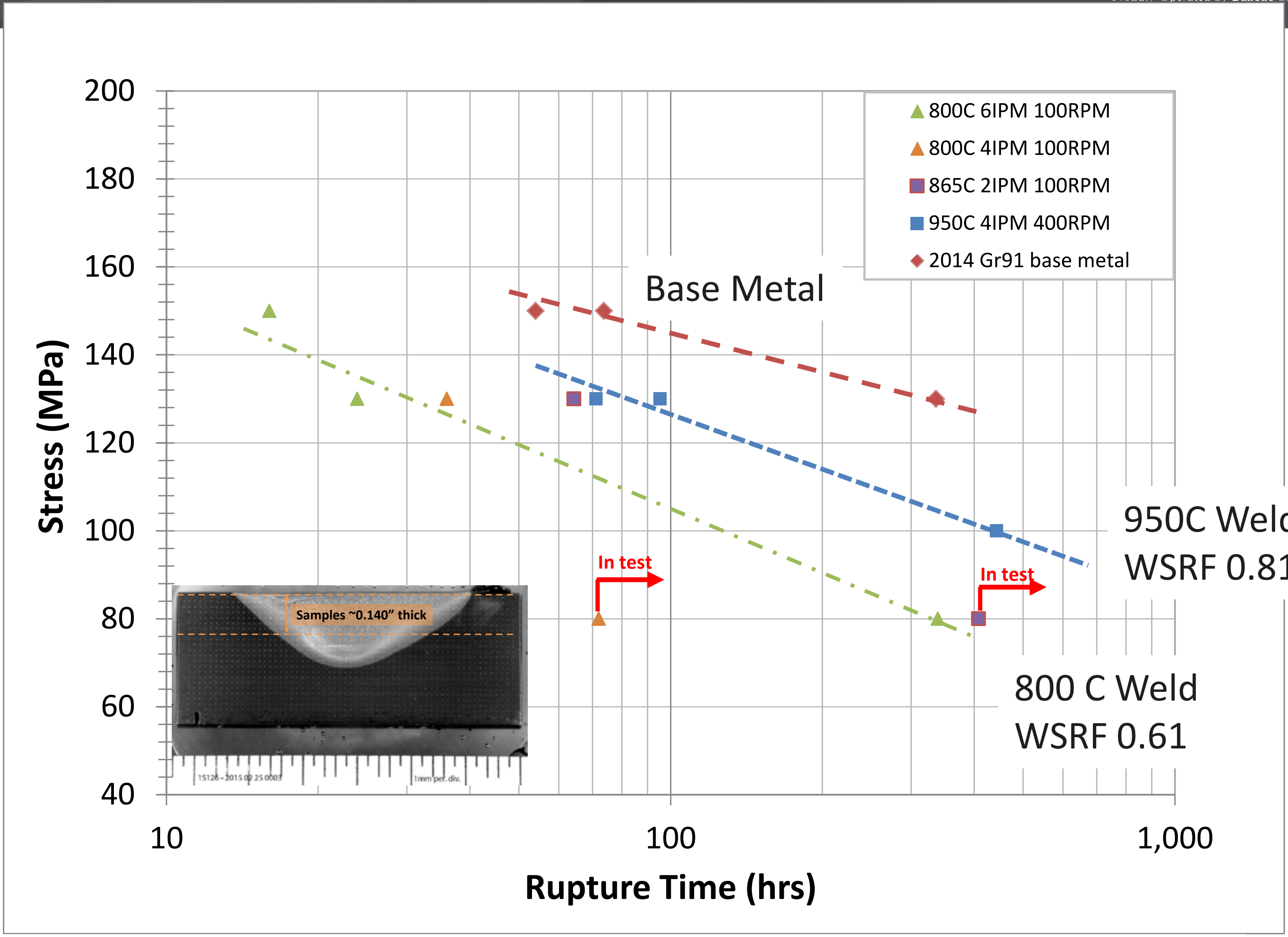
130MPa, 625°C

Type IV failure

FSW also shows type IV cracking



625C Transverse Creep Results



- Preliminary results indicate increase in creep life with increasing weld temperature for weldments without PWHT

Lower Temperature Weld - 800°C
This weld had WSRF of 0.61

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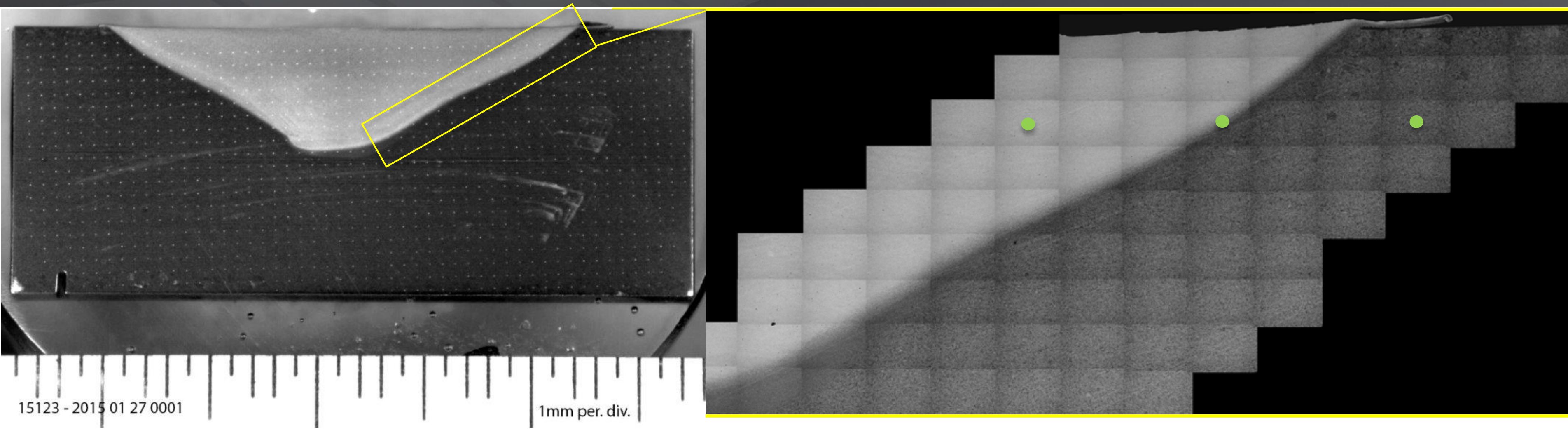
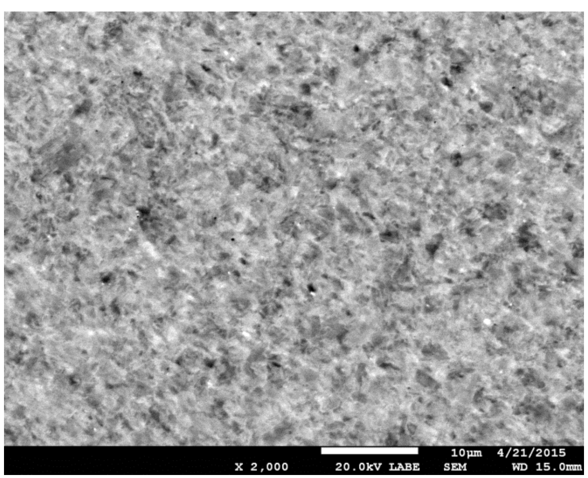
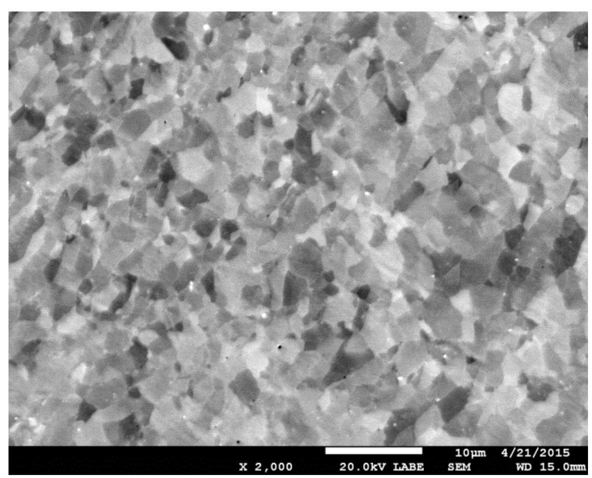


Very distinct grain structures seen in the base metal, FGHAZ & weld nugget (Dynamically Recrystallized and transformed). Weld is substantially finer grained than the base metal. Sharp boundaries.

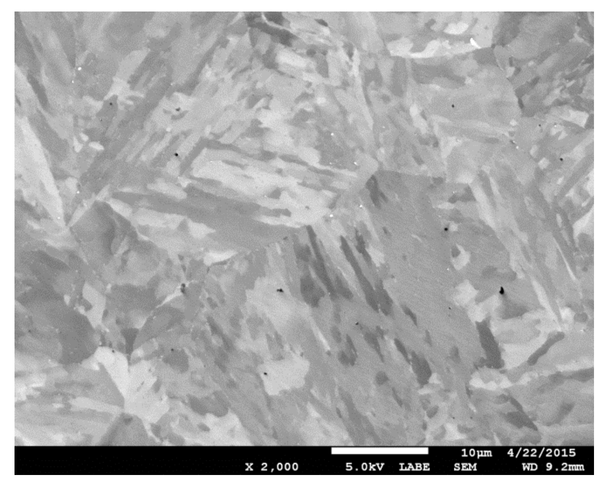
Weld Nugget



HAZ



Base Metal

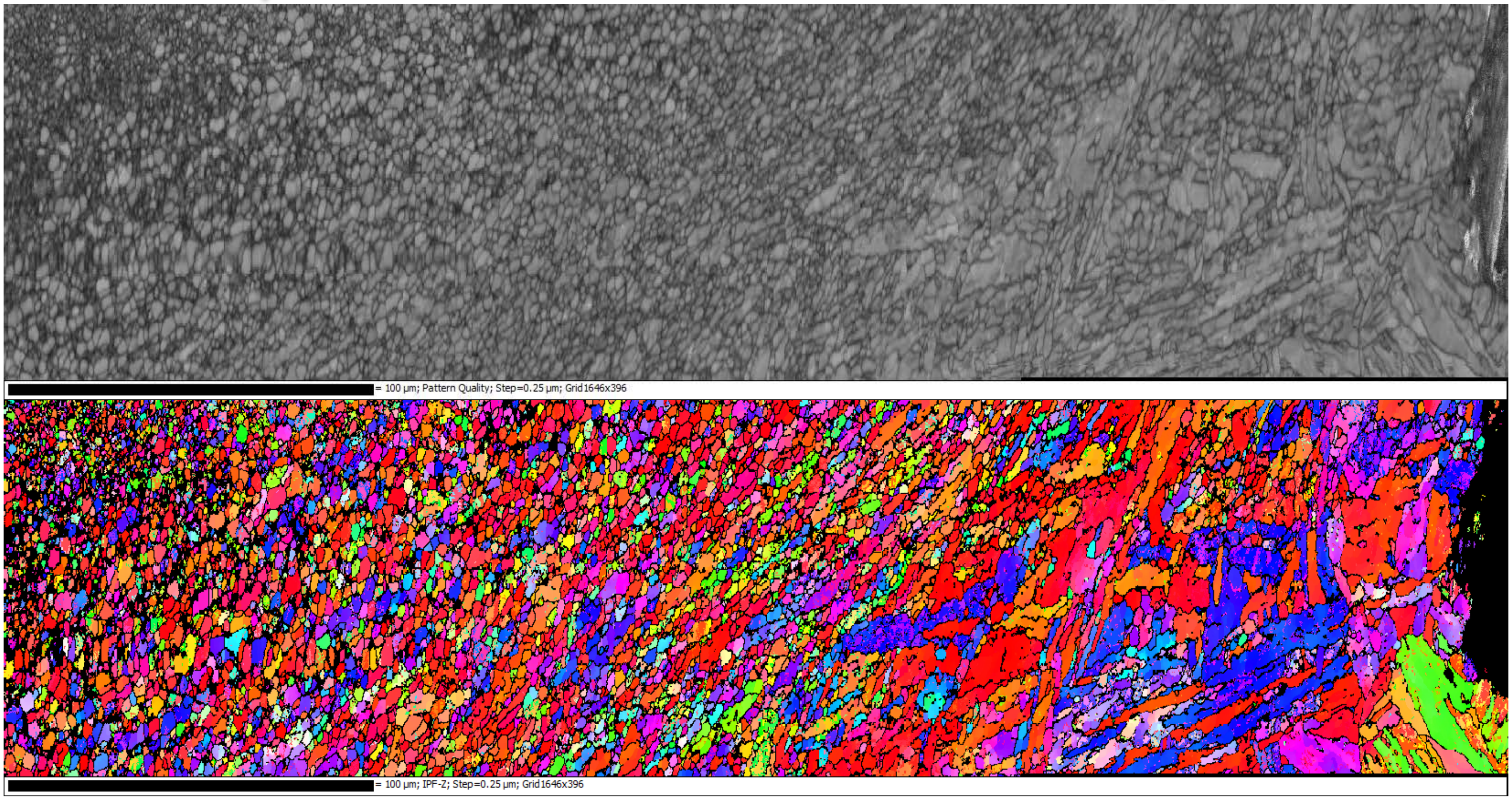


4IPM/100RPM/ 800°C
Near Top, Retreating Side

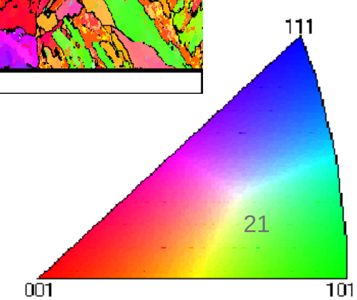
Weld Nugget (Very Fine Grain) | FGHAZ | Base Metal

Pattern Quality

IPF-Z direction

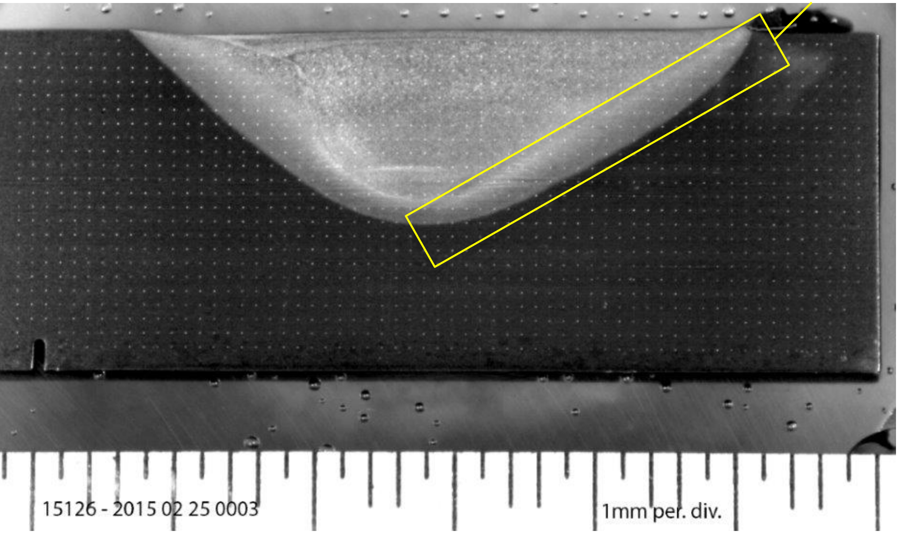


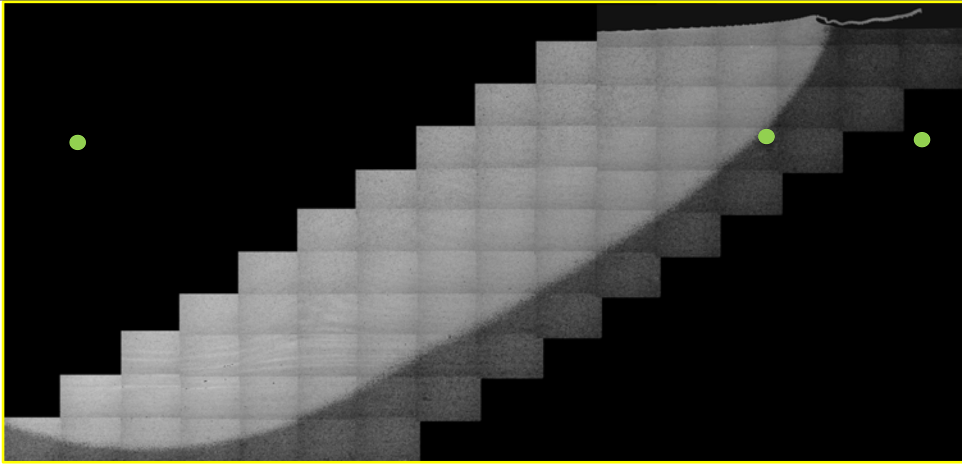
EBSD shows structure change across HAZ



4IPM/400RPM/ 950°C

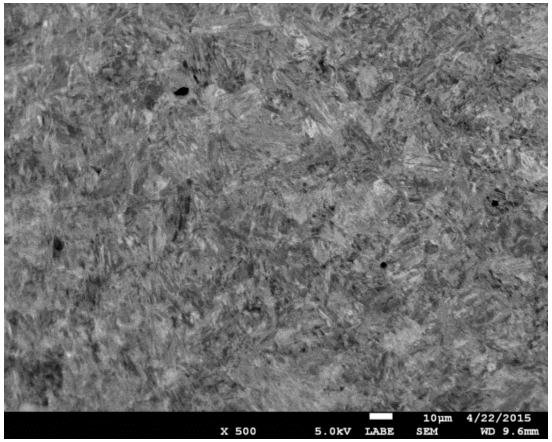
Near Top, Retreating Side



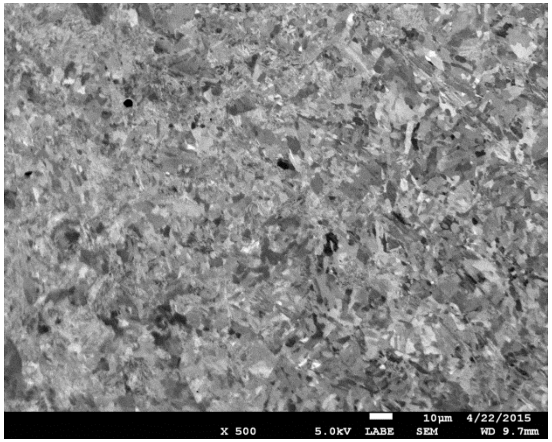


Weld nugget is coarser
HAZ is wider

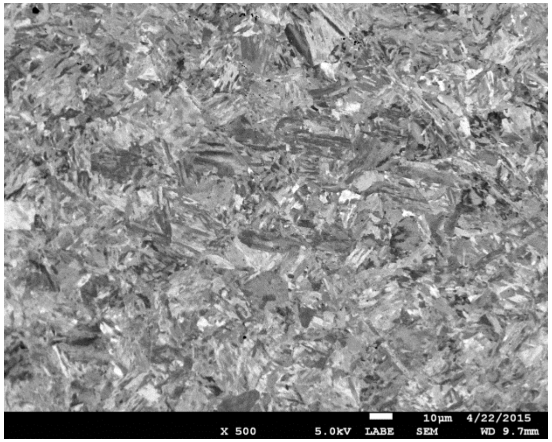
Weld Nugget



HAZ



Base Metal

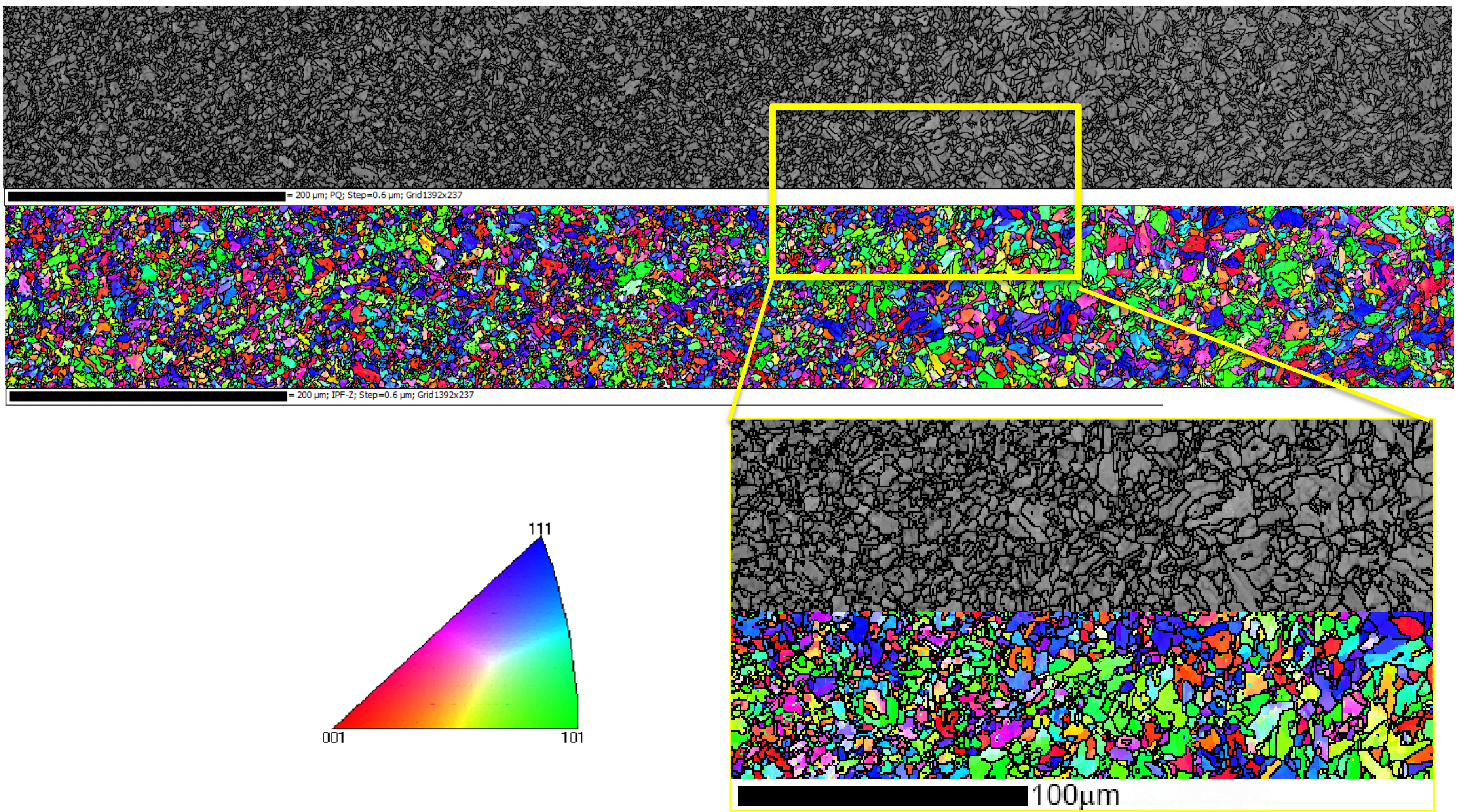


4IPM/400RPM/ 950°C
Near Top, Retreating Side

Hot weld shows wide area of similar grain sized equiaxed structure in the FGHAZ

Pattern Quality

IPF-Z direction



What makes these two welds different?

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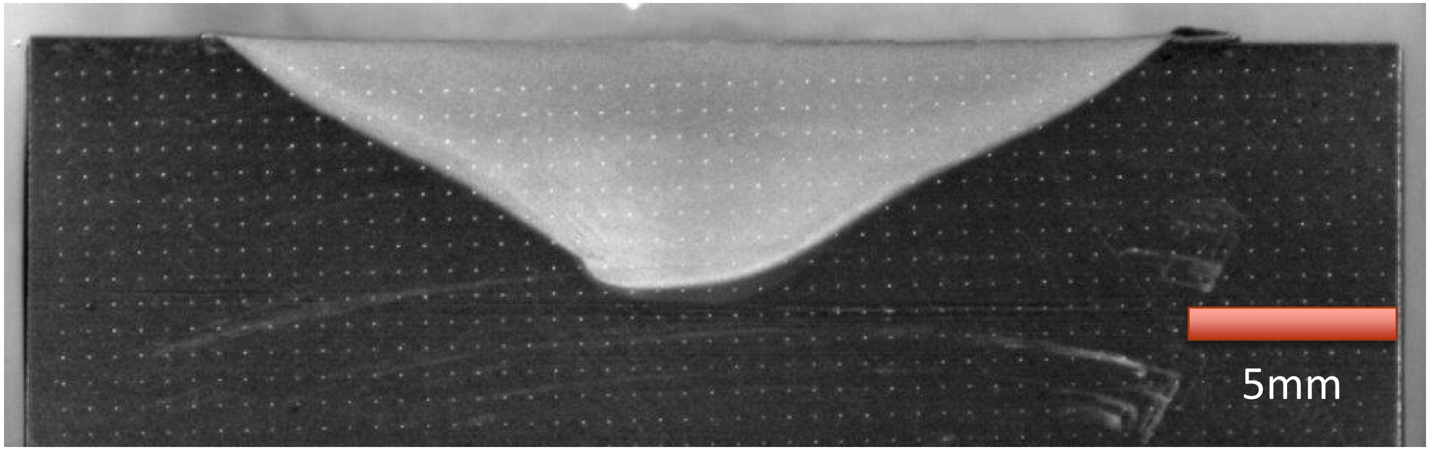
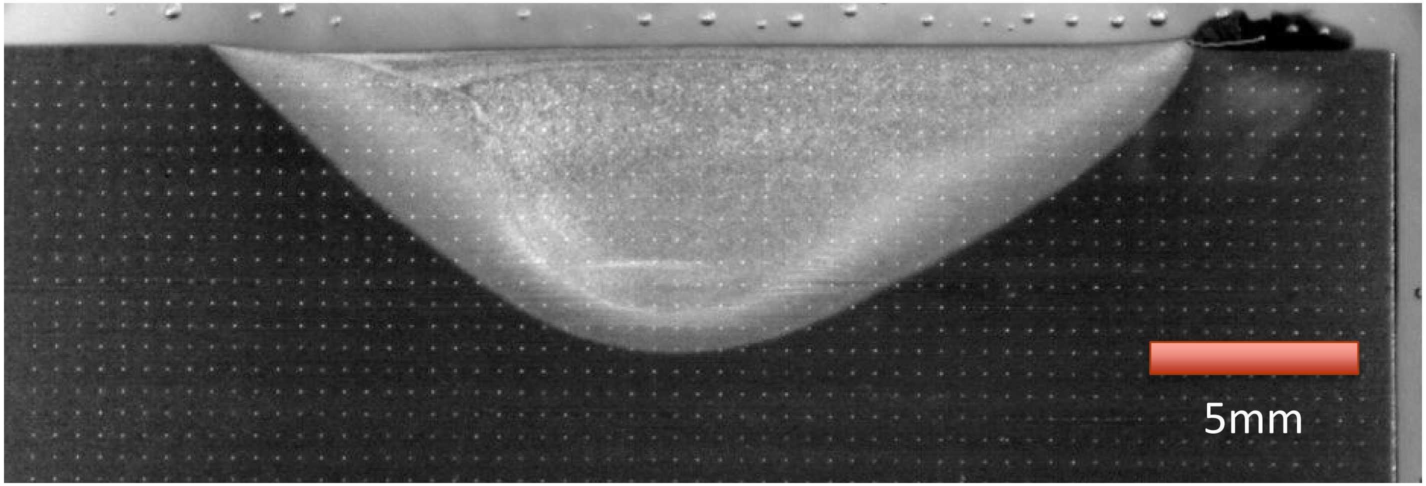


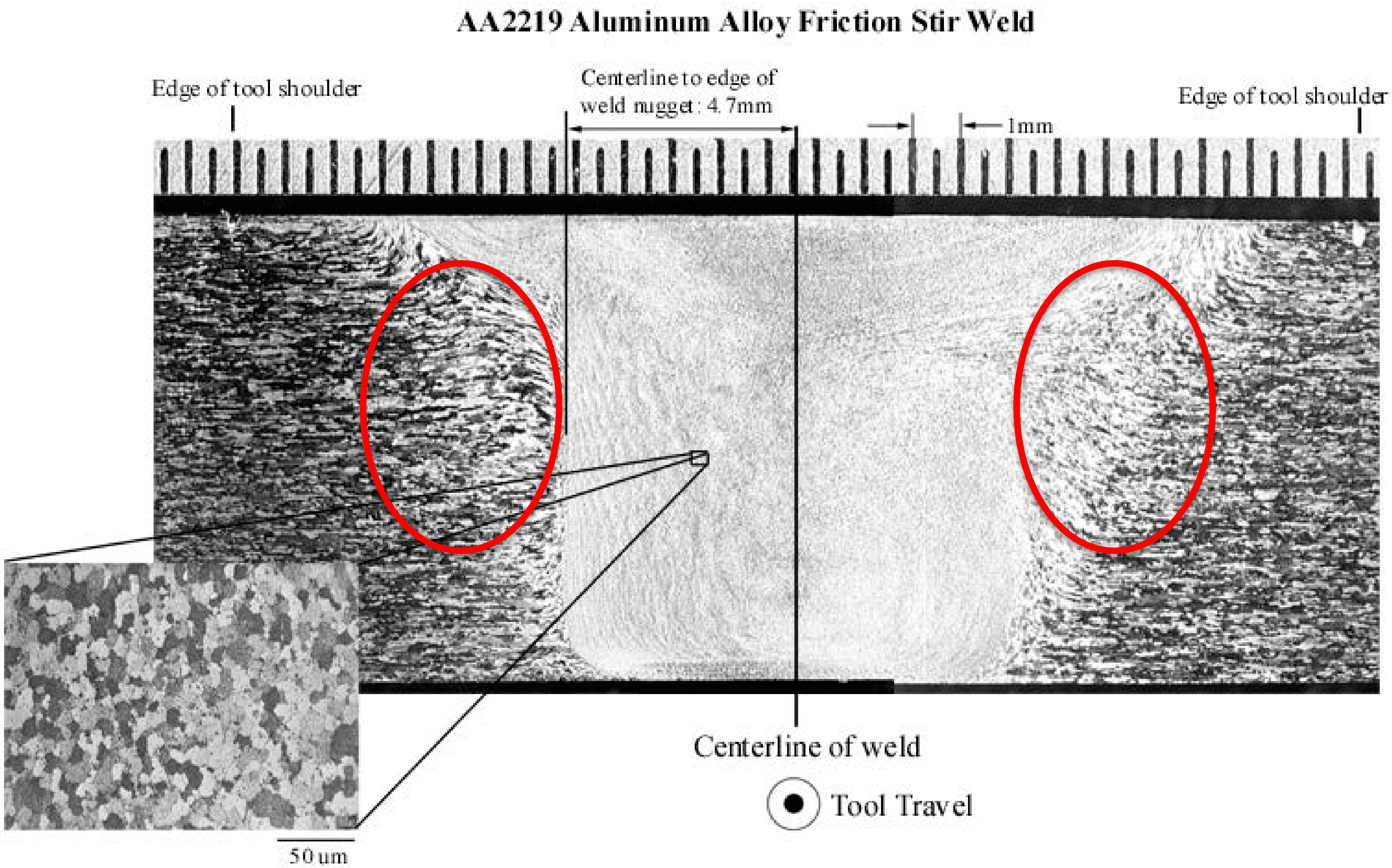
Cold Weld
WSRF 0.61



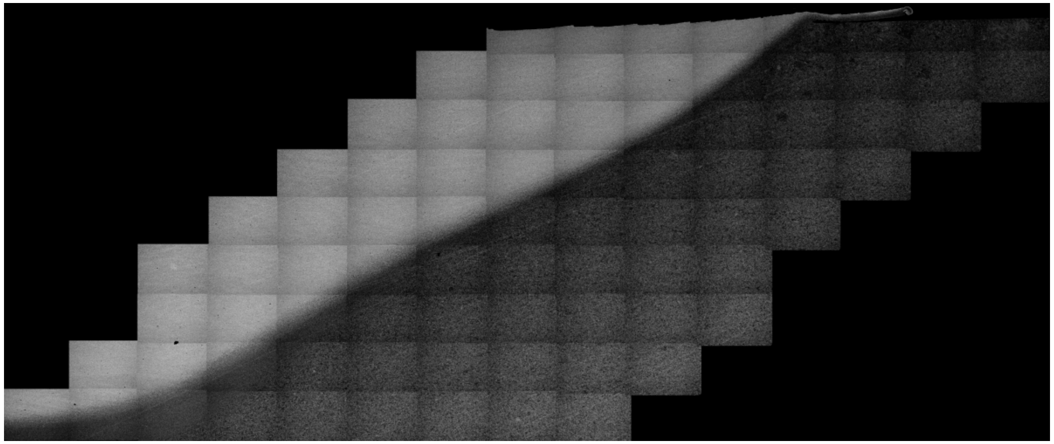
Hotter Weld
WSRF 0.81

- Much wider and diffuse FGHAZ in the hotter weld
- Lower performance cold weld may be because of sharp property gradient

Another possibility
Deformed regions – theTMAZ in FSW

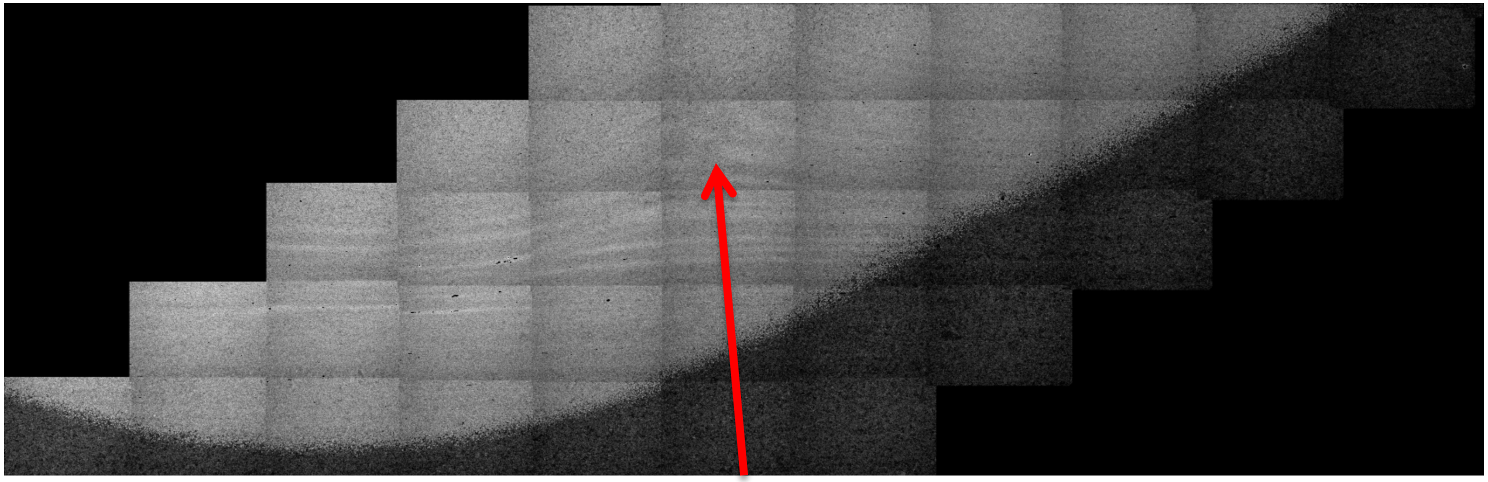


What makes these two welds different? Temp. at the time of FSW straining?



Cold Weld
WSRF 0.61

- AC3 (FGHAZ) is narrow and does not extend far from nugget (DRX zone). Strained area was strained below the austenite phase field.



Hotter Weld
WSRF 0.81

- AC3 (FGHAZ) fully extends into a wide deformed area (seen as convoluted bands from original plate rolled structure). Could the dislocation substructure from FSW welding affect the transformation products and MX distribution in the FGHAZ? This strain is introduced during the time the region is above AC3.

Why is FSW better?

- Ausforming? – strain induced dislocations from FSW in the austenite phase field may help to retain or create a dispersed MX distribution on dislocations upon cooling
- Dislocation substructure may help stabilize $M_{23}C_6$ in other locations than along prior austenite grain boundaries, allowing for better distribution.
  - The hot welds, which performed better, had extended FGHAZs that underwent straining above AC3. The FGHAZ covered a wide part of the weld edge. The cold welds had transformed regions that barely extended past the DRX (nugget) zone and had only narrow areas of material that was strained above AC3.
  - More TEM is needed to see carbide and carbonitride distribution between these two welds and the relationship between carbide distribution and previous strained microstructure from FSW welding.

Or…

- The hot weld had more gradual grain size variation across HAZ
  - More gradual property gradient could result in less severe property gradients (notch effect) on creep cavity initiation.

Next Steps - FSW Trials on other Ferritics

- PWHT response of the Gr91 FSW welds is the next step
  - Post mortem of the failed specimens from as-welded and PWHT cases should help to identify the mechanism of creep failure
- Working to obtain P92. Might be stuck with using flattened pipe unless we can find a supplier of plate. This will force us to normalize and temper after flattening.

- After P92 work the project will target a TBD Ferritic 9 Cr Boron / nitrogen +/-cobalt steel.
  - Interesting aspect of FSW: elements added to steel do not have to also satisfy fusion weldability concerns. High Carbon and Boron present no problems to solid state welds. New chemistries may be considered because of FSW.
- We are currently looking to buy, rent, or beg for any Ferritic 9Cr B/N/Co material from the audience that might be available….please call us.

Conclusions

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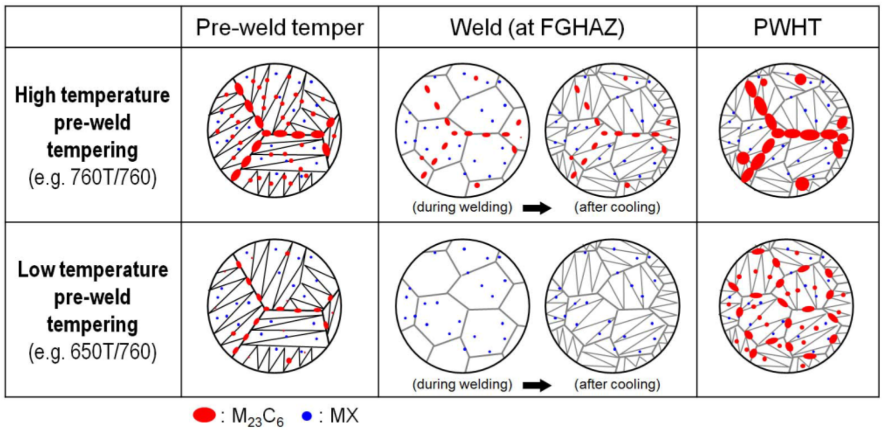
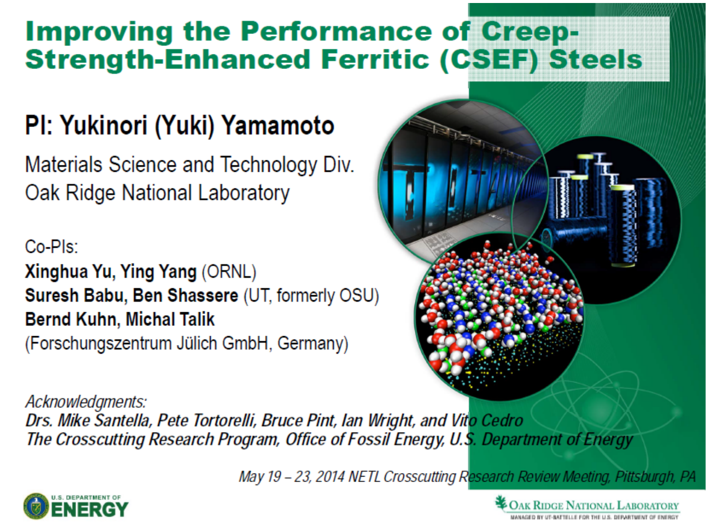
- CSEF steels are Friction Stir weldable
- Creep performance is very good, both of the weld metal and in cross weld tension – current results indicate that tool temperatures greater than 865C are beneficial and can reach WSRF of 0.81 prior to PWHT
- It is possible that WSRF can be raised by more than 10% from fusion welded equivalents and it is possible that FSW may allow for a reduced requirement for PWHT
- Fatigue and creep fatigue are also important failure modes at nozzle or header pipe/manifold intersections due to cycling thermal stresses and pressure pulses in the supercritical fluid at constrictions and sharp radii. FSW, due to the refined microstructures in the joint area, may also be able to show improved properties for fatigue and toughness in these regions as well.
- **FSW allows for enough knobs to be turned in the process to customized heat input. It may be possible to follow a path through thermo-mechanical space that will leave the weld region much closer to the parent microstructure than if it is fusion welded.**

END

Yuki's concepts

Table: Microstructure evolution at fine grain heat affected zone




Improving the Performance of Creep-Strength-Enhanced Ferritic (CSEF) Steels

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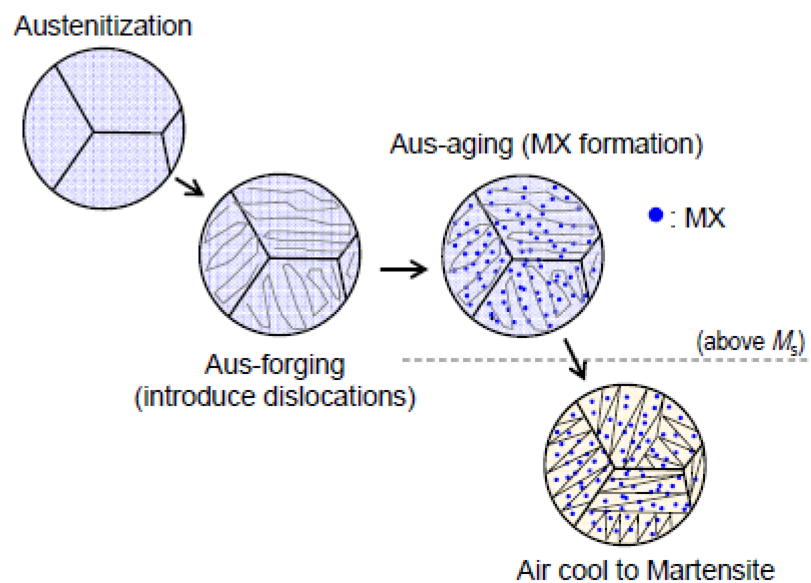
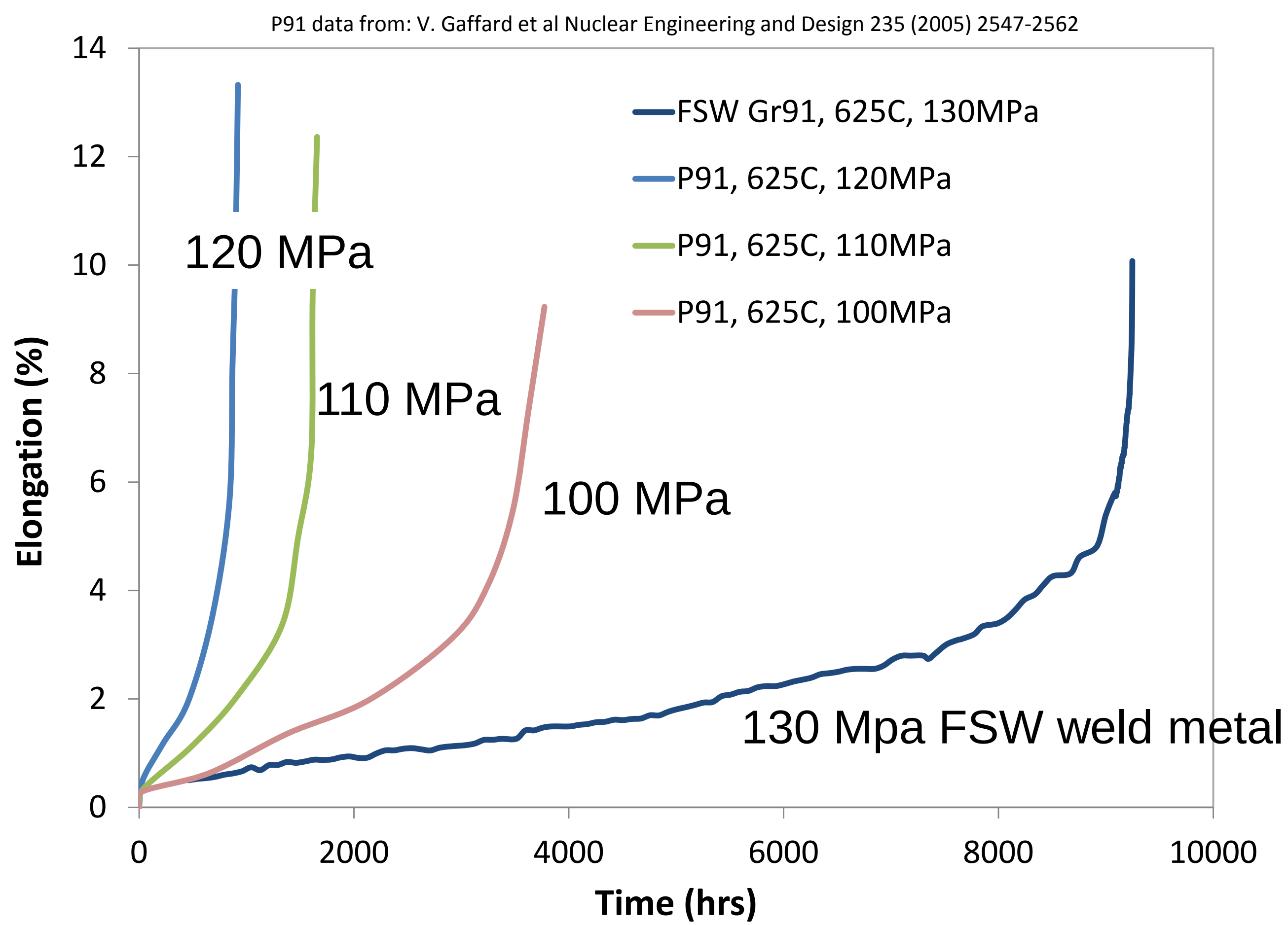


Creep results Gr91 all FSW Weld metal

- FSW all weld specimen ruptured after 9,247hrs at 625ºC/130MPa
  - Minimum strain rate: 1.3E-9/sec, All FSW weld material at 625ºC/130MPa is similar to T91 tested at 600ºC and 105MPa (S. Spigarelli, Mat. Sci. Tech. v.15 p1433-1440 1999)
- Second longitudinal all weld FSW ruptured after 3464hrs at 625ºC/175MPa



- FSW nuggets have better creep performance than base metal
- Why?
- Weld metal has smaller PAG, and martinsite lath length
- harder, higher strength

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Current Program
ASTM 387 Gr91 Class2 FSW Welds

- Gr91 is easily FSW welded.

- Defect free welds in 10mm can be made at a wide range of process parameters.

- Tool / Weld temperatures can be maintained during welding from 740C to 980C
  - <A1 to above AC3